Seismic Isolation: An Economic Alternative for the Seismic Design & Rehabilitation of Buildings & Bridges

The use of seismic isolation results in a significant reduction in the effects of horizontal earthquake motions, offering greater protection to the structure and its contents.

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Designing new structures, as well as upgrading existing structures, to withstand seismic forces economically has always posed special problems that have not been easily addressed in the past. Rather than resist the large forces generated by earthquakes, an innovative design strategy called *seismic isolation* decouples the structure from the ground motion, providing the ability to reduce earthquake forces by factors of five to ten. This level of force reduction is very significant. When expressed in simple terms, it is equivalent to reducing a Richter magnitude 8.0 event to an event in the range of 5.0 to 5.5. In terms of the eastern United States seismic risk, a structure designed for Seismic Zone 2, when placed on a seismic isolation system, would be capable of resisting at least a Seismic Zone 4 event.

It is generally recognized that it is uneconomical to design a building or bridge to respond in the elastic range to a maximum credible earthquake. The current state of the art provides two options. The first option, which is embodied in most building codes, is to design

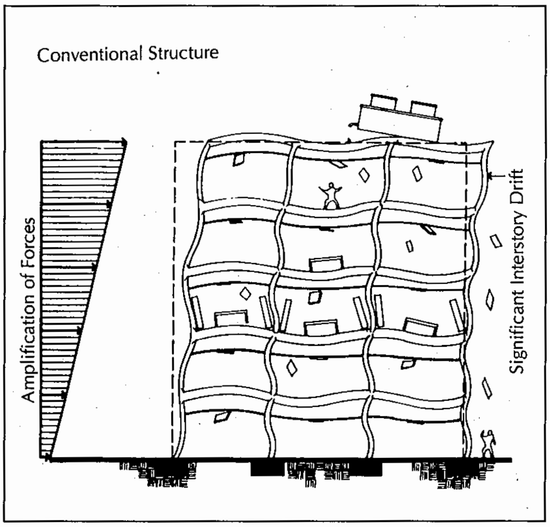


FIGURE 1. The deformation pattern in a conventional structure during an earthquake. Accelerations of the ground are amplified on the higher floors and the loose contents are damaged. Building deformations and distortions could be permanent.

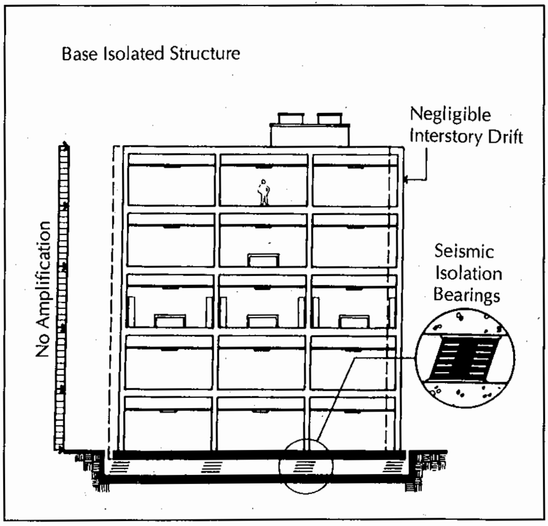


FIGURE 2. The deformation pattern in an isolated structure during an earthquake. Movement takes place at the level of the isolators. Floor accelerations are low; the building, its occupants and its loose contents are safe.

components such as beams and columns for a much lower force level than is inherent in the elastic response spectra for typical earthquakes. Since the demand will then exceed the capacity of these components, inelastic action is inevitable; and these components must be therefore detailed for ductility.

The second option is to reduce design forces by decoupling the superstructure from the damaging components of horizontal earthquake motions. This technique is called seismic isolation and involves the separation of the superstructure from the substructure using isolation bearings.

Many modern buildings contain extremely sensitive and costly equipment that has become vital in business, commerce, education and health care. For example, electronic information control systems and records are essential to the proper functioning of our society. These building contents frequently are more costly and valuable than the buildings themselves. Furthermore, hospitals, communication and emergency centers, bridges, and police and fire stations must be operational when needed most: immediately after an earthquake.

Conventional construction can cause very high floor accelerations in stiff buildings, and large interstory drifts in flexible structures. These two factors cause difficulties in ensuring the safety of the building components and contents (see Figure 1).

Mounting a building on an isolation system can prevent most of the horizontal movement of the ground from being transmitted to the building above. This isolation results in a significant reduction in floor accelerations and interstory drifts, thereby providing additional protection to the building contents and components (see Figure 2).

For bridges the concept is the same, but its implementation is easier since seismic isolation bearings can be used to replace conventional bearings. Seismic isolation provides an elegant solution for the three major retrofit problem areas in existing bridges. It can also provide cost savings in the construction of new bridges. For the eastern United States, the Federal Highway Administration (FHWA) is now requiring seismic design of new construction using the 1983 AASHTO Guide Specifications.[1] Seismic isolation has another attractive feature in that it is generally able to reduce the seismic design forces of beams and foundations below those of other load cases, so that seismic design does not govern.

There are now approximately 125 civil engineering structures that have been constructed using the principles of seismic isolation. Twenty of these completed structures have been subjected to real earthquakes, the largest being a Richter magnitude 6.4 event. All have exhibited the force reductions expected.

Eastern United States Earthquake Issues

The level of seismic risk in the eastern United States has been discussed by Whitman and others,[2] but it is worth noting the two of the three largest United States earthquakes have occurred in the eastern part of the country — in New Madrid, Missouri, and Charleston, South Carolina. The earthquake threat in the eastern United States is therefore real, although the occurrence interval is longer than in the western region of the country.

Seismic risk maps used for design codes are based on a combination of the magnitude of expected events and their occurrence interval. These assumptions lead to some major anomalies in satisfying the intent of seismic design codes for both bridges and buildings. The design philosophy given in the commentary of the design codes asserts that in a major earthquake, the intent of a code-designed structure is to prevent collapse and avoid loss of life, acknowledging that both structural and nonstructural damage will occur.

In evaluating this design intent, both the New Madrid and Charleston areas require a design coefficient of 0.1 to 0.2 effective peak acceleration (EPA) in the latest codes, primarily because of the longer occurrence interval of expected earthquakes. The actual earthquakes that have occurred in New Madrid and Charleston would have had EPAs in the 0.5 to 0.7 range, and it is very doubtful that buildings or bridges designed in the 0.1 to 0.2 EPA level will satisfy the stated intent of the code in a "major" earthquake.

Consequently, for important facilities such as hospitals, emergency centers, communication facilities and transportation systems, a higher level of protection is required which can be achieved by using a longer return period for the seismic risk maps of design codes, or by using a technology such as seismic isolation. Seismic isolation will provide a much higher level of protection than current code design, which can be achieved without additional cost in bridges, since all that is required is to use isolation bearings instead of conventional bearings. In buildings, some additional cost may be incurred; however, the desired increase in safety can be achieved.

Basic Concepts

There are three basic elements in any practical isolation system:

- A flexible support so that the period of vibration is lengthened sufficiently to reduce the force response;
- A damper or energy dissipator so that the relative deflections across the flexible support can be limited to a practical design level; and,
- Rigidity at low (service) load levels such as wind and braking forces.

Flexibility. An elastomeric bearing is not the only means of introducing flexibility into a structure, but it certainly appears to be the most practical and the one with the widest range of application. The idealized force response with increasing period (flexibility) is shown schematically in the acceleration response curve of Figure 3. Reductions in base shear occur as the period of vibration is lengthened. The extent to which these forces are reduced is primarily dependent on the nature of the earthquake ground motion and the period of the fixed-base structure. However, the additional flexibility needed to lengthen the period will give rise to large relative displacements across the flexible support. Figure 4 shows an idealized displacement response curve from which displacements are seen to increase with increasing period (flexibility).

Energy Dissipation. Large relative displacements can be controlled if substantial additional damping is introduced into the structure at

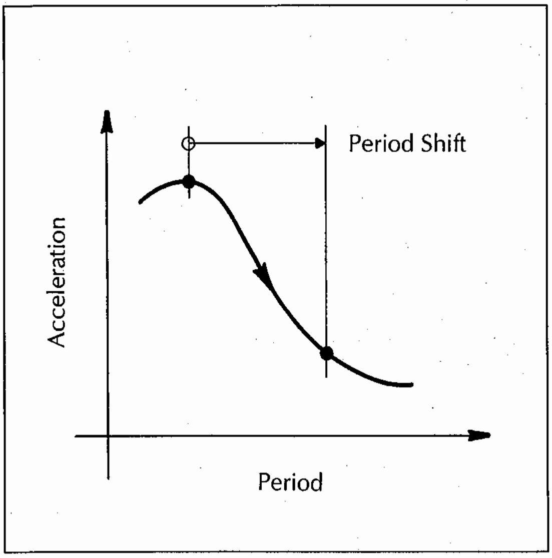


FIGURE 3. Idealized acceleration response spectrum.

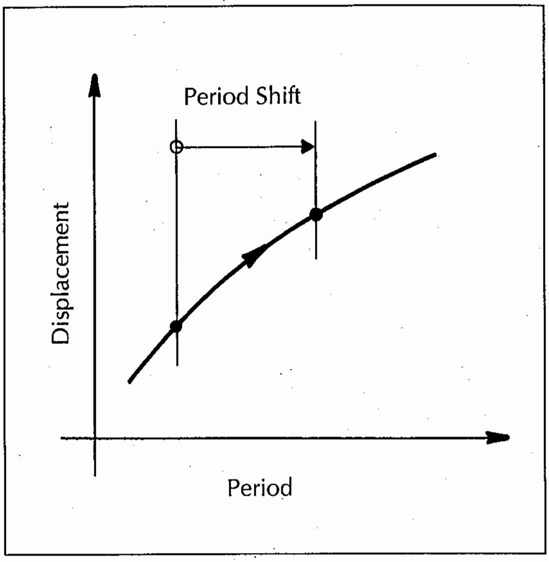


FIGURE 4. Idealized displacement response spectrum.

the isolation level as depicted in Figure 5. Also shown schematically in this figure is the smoothing effect of higher damping.

One of the most effective means of providing a substantial level of damping (greater than 20 percent equivalent viscous damping) is hysteretic energy dissipation. Figure 6 portrays an idealized force-displacement loop where the enclosed area is a measure of the energy dissipated during one cycle of motion. Mechanical devices that use the plastic deformation of either mild steel or lead in order to achieve this behavior have been developed. Mild steel bars in torsion and cantilevers in flexure have been tested, refined and are now included in several bridge structures.[3] Similarly, lead extrusion devices and lead-rubber (elastomeric) bearings have also been developed and implemented

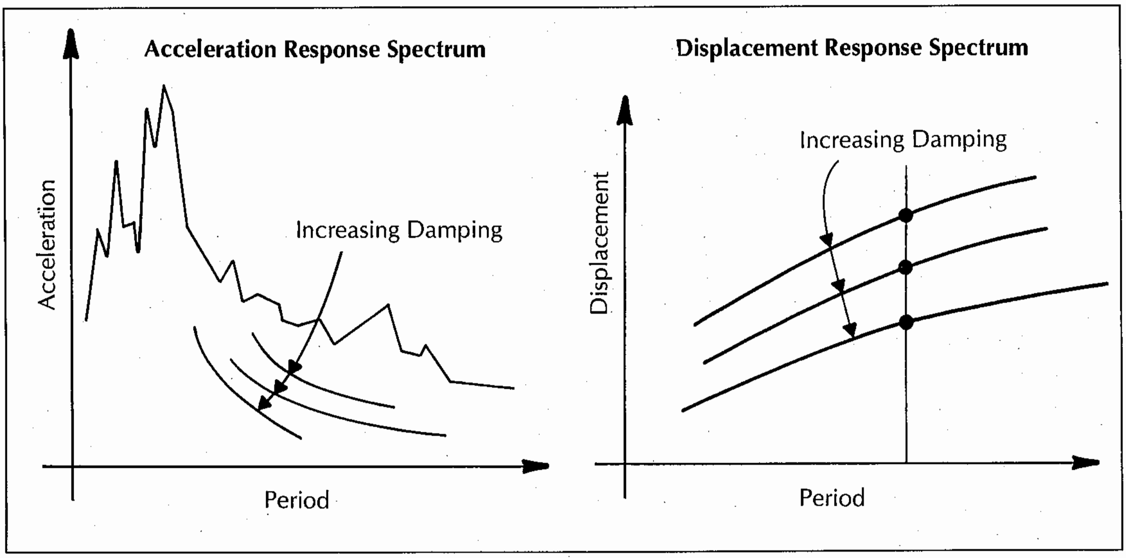


FIGURE 5. Response spectra for increasing damping.

(see Figure 7).[4,5,6]

Rigidity Under Low Lateral Loads. While lateral flexibility is highly desirable for high seismic loads, it is clearly undesirable to have a structural system that will vibrate perceptibly under frequently occurring loads such as wind or braking loads. Mechanical energy dissipators may be used to provide rigidity at these service loads by virtue of their high initial elastic stiffness. As an alternative, some isolation systems use a separate wind restraint device for this purpose — typically a rigid component that is designed to fail at a predetermined level of lateral load.

A listing of the alternative sources of flexibility and energy dissipation are given in Table 1. A more detailed explanation of these concepts can be found in the proceedings of a workshop on base isolation and passive energy dissipation that was conducted by Applied Technology Council.[7]

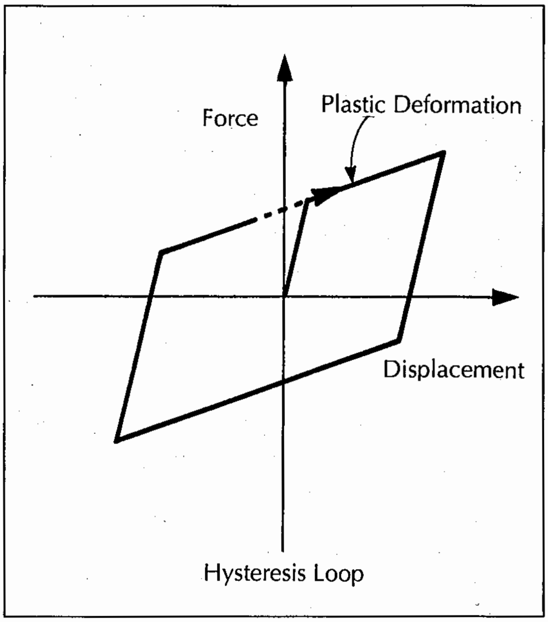


FIGURE 6. Hysteretic force-deflection curve.

Seismic Isolation Design Principles

The design principles for seismic isolation are illustrated in Figure 8. The top curve in this figure represents the elastic forces that will be imposed on a non-isolated structure (from the new Structural Engineers Association of California's Recommended Lateral Force Design Requirements, or SEAOC Blue Book[8]) for a rock site *if* the structure has sufficient strength to resist this level of load. The lowest curve reflects the forces for which the Uniform Building Code (UBC 1988)[9] requires that a

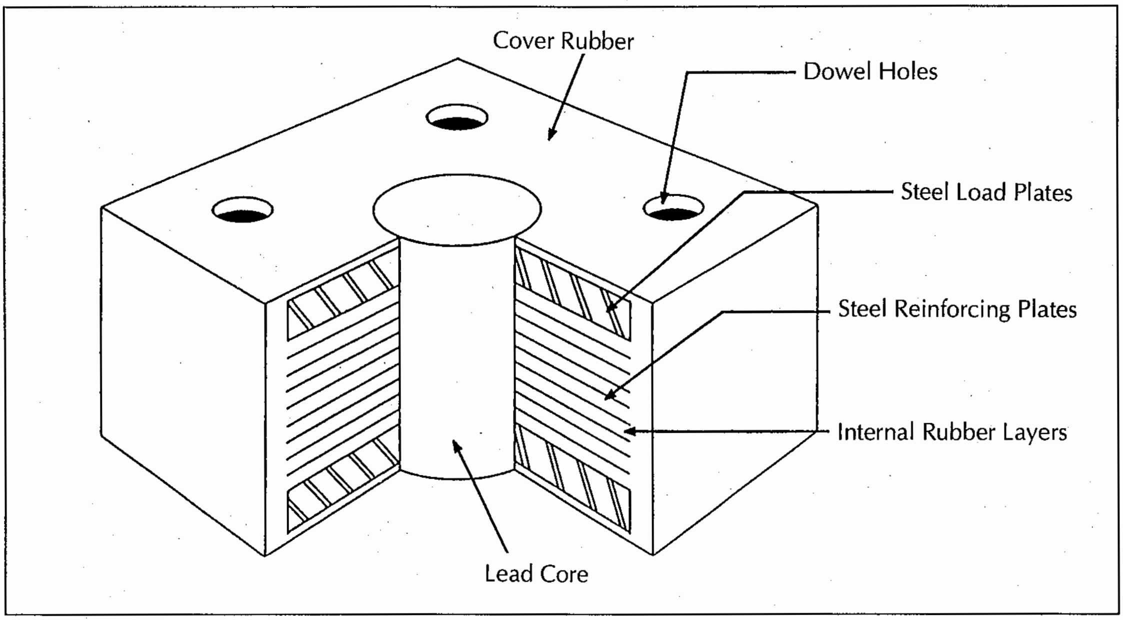


FIGURE 7. Lead-filled elastomeric bearing.

TABLE 1
Alternative Sources of Flexibility and Energy Dissipation

Flexible Mounting Systems	Damping Device/Mechanisms
Unreinforced Rubber Blocks	Plastic Deformation of a Metal
Elastomeric Bearings	Friction
(Reinforced Rubber Blocks)	High-damping Elastomers
Sliding Plates	Viscous Fluid Damping
Roller and/or Ball Bearings	Tuned Mass Damping
Sleeved Piles	
Rocking Systems	
Suspended Floors	
Air Cushions	
Steel Springs	

structure be designed for and the second lowest curve shows the probable strength, assuming the structure is designed for the UBC forces. The probable strength is 1.5 to 2.0 times higher than the design strength because of the design load factors, actual material strengths (which are greater in practice than those assumed for design), conservatism in structural design and

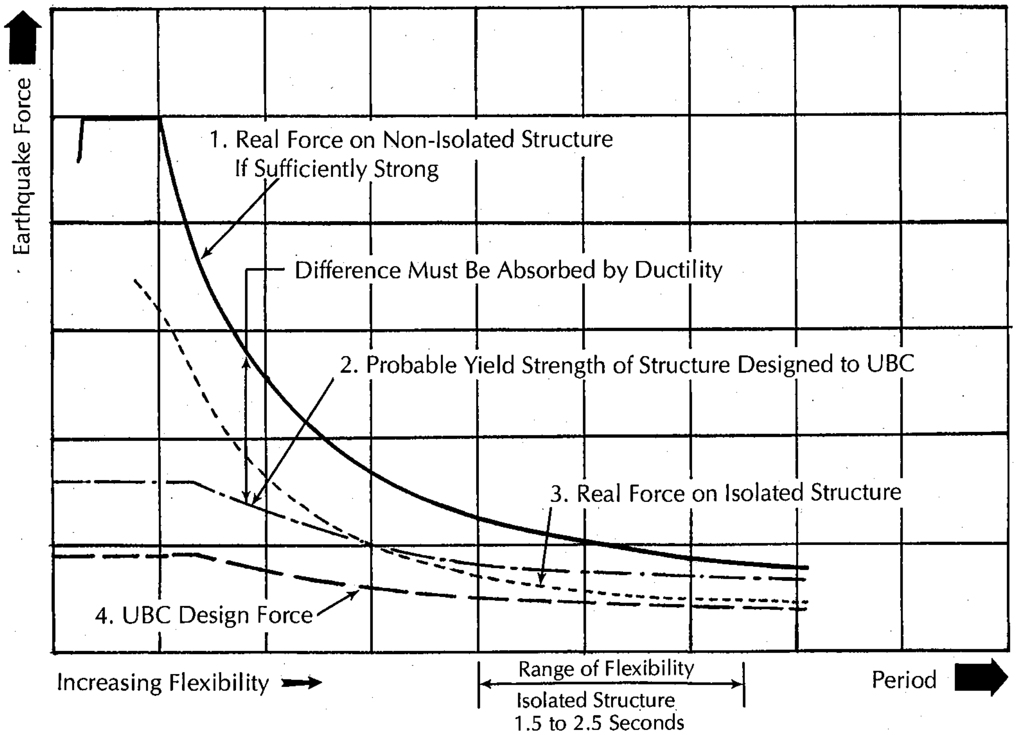


FIGURE 8. Design principles of seismic isolation.

other factors. The difference between the maximum elastic force and the probable yield strength is an approximate indication of the energy that must be absorbed by ductility in the structural elements. However, when the building is isolated, the maximum forces are reduced considerably due to period shift and energy dissipation. The forces on a seismically isolated structure are shown by the small dashed curve in Figure 8. If a seismically isolated building is designed for the UBC forces in the period range of 1.5 to 2.5 seconds as shown in Figure 8, then the probable yield strength of the isolated building is approximately the same level as the maximum forces to which it will be subjected. Therefore, there will be little or *no* ductility demand on the structural system, and the lateral design forces are reduced by approximately 50 percent.

Considerations for the Seismic Isolation of Buildings

The need for seismic isolation of a structure may arise if any of the following situations apply:

- A structure designed for a low seismic zone is required to resist a much higher earthquake level.
- Increased building safety and post-earthquake operability are desired.
- Reduced lateral design forces are desired.
- Alternate forms of construction with limited ductility capacity (such as precast concrete) are desired in an earthquake region.
- An existing structure is not currently safe for earthquake loads.

For new structures, current building codes apply in all seismic zones and therefore many designers may feel that the "need" for seismic isolation does not exist because the code requirements can be satisfied by current designs. However, the commentary to the SEAOC Blue Book states that buildings designed in accordance with its provisions will:[8]

- Resist minor earthquakes without damage;
- Resist moderate earthquakes without structural damage, but with some non-structural damage; and,
- Resist major earthquakes without collapse, but with structural and non-structural damage.

These principles of performance also apply to buildings that are rehabilitated to code-level design forces. Caution is required when eastern U.S. seismicity is assessed, because a structure designed to a 0.1 or 0.2 EPA level may in fact collapse if a 0.5 to 0.7 EPA earthquake does occur, as in New Madrid and Charleston. Consequently, these principles of performance developed for the higher seismic zones may not be satisfied if a large eastern earthquake does occur.

Seismic isolation provides the capability of providing a building with better performance characteristics than the current code approach, and thus represents a major step forward in the seismic design of structures.

One of the more difficult issues to address from a conventional design viewpoint is that of reducing non-structural and building content damage. This issue is very often ignored and, when addressed, can be very expensive to incorporate in a conventional design. In fact, the additional costs incurred to satisfy the bracing requirements of non-structural elements in a hospital is on the order of $2 to $4 per square foot more than that required for conventional buildings.

As noted previously, there are two primary mechanisms that cause non-structural damage. The first is related to interstory drift between floors and the second to floor accelerations. Together, these two components cause damage to the building contents, architectural facades, partitions, piping and duct work, ceilings, building equipment and elevators. Seismic isolation significantly reduces both floor accelerations and interstory drift, and thus provides a viable economic solution to the difficult problem of reducing non-structural damage.

In the case of a building retrofit, the need for isolation may be more obvious: the structure may simply not be safe in its present condition should an earthquake occur. In such cases, if seismic isolation is suitable, its effectiveness should be examined and compared with the effectiveness of such alternative solutions as strengthening.

Considerations for the Seismic Isolation of Bridges

Considerable efforts have been made in the United States in the past decade to develop improved seismic design procedures for new bridges and comprehensive retrofit guidelines for existing bridges.[1,10,11] These efforts were spurred in part by the damage caused to bridges during the San Fernando earthquake of February 9, 1971. This earthquake demonstrated the potential inadequacy of past design procedures and the necessity for seismically upgrading bridges that were designed using the pre-1971 procedures.

The 1989 Loma Prieta earthquake provided further evidence of the inadequacy of pre-1971 design procedures, and also showed the tremendous disruption that can occur if bridges are not operational after an earthquake.

Seismic isolation may be applied to both the design of new bridge structures and the retrofitting of existing structures. In general, implementation is straightforward, since most bridges have bearings to accommodate thermal movements, and the substitution of isolation bearings for these standard hardware items is routine.

For new construction, the reduction in elastic column forces by factors of five to ten will provide cost savings of up to ten percent in both the columns and foundations, particularly if piled footings are used.[12] There will also be substantial long-term reductions in the repair costs of seismic damage.

For the eastern United States, the FHWA is now requiring seismic design for new construction using the 1983 AASHTO Guide Specifications.[1] Seismic isolation has another attractive feature in that it reduces the seismic design forces of columns and foundations below those of other load cases, so that seismic design does not govern.

For existing bridges, seismic isolation is an effective solution to the three most common deficiencies in bridges built before the mid-1970s. These deficiencies are:

- Inadequate strength of steel bearings and connections;
- Inadequate strength and ductility of columns and substructures; or,
- Inadequate support length for girders.

The last item is the area in which most of the current U.S. effort in bridge seismic retrofit has been carried out. The California Department of Transportation (Caltrans) has pioneered this work and has so far concentrated on the provision of positive connections between the superstructure and supporting substructure.[13] Measures used to date include longitudinal joint restrainers, transverse bearing restrainers and vertical motion restrainers. Other concepts that have been proposed include bearing seat extensions and the use of shear keys or stoppers.[10,11]

An elegant solution to the above three problem areas can also be achieved by replacement of vulnerable bearings with lead-rubber isolation bearings. This substitution not only solves the problem of inadequate bearing strength, but also provides a solution for the other two problem areas due to the force reduction and displacement control features of these bearings.

Another feature of the lead-rubber isolation bearing is the ability to control the distribution of lateral forces, such as wind and seismic forces, to the substructures. This force control feature is provided by the appropriate sizing of the lead core and total rubber height of the bearing.[5] Like seismic isolation design, the force control feature impacts the global design of the bridge, since lateral forces can be directed away from weaker substructures.

Seismic isolation has been used to retrofit eight bridges over the last three years in California, Washington, Illinois, and British Columbia. There are several new bridges under construction in Illinois and Pennsylvania. Several other projects are now in final design in various states including Massachusetts, Alabama, Maine and New Jersey.

The benefits of seismic isolation for bridges may be summarized as follows:

- Reduction in the elastic forces to which a bridge will be subjected by a factor of between five and ten (based on curves 1 and 2 in Figure 8 and a period shift, due to isolation, from 0.4 to 2.0 seconds).
- Elimination of the ductility demand and, hence, damage to the piers.
- Control of the distribution of the seismic forces to the substructure elements with appropriate sizing of the elastomeric bearings.[5]
- Reduction in column design forces by a factor of at least two compared to conventional design (based on curves 4 and 2 in Figure 8 and a period shift, due to isolation, from 0.4 to 2.0 seconds).
- Reduction in foundation design forces by a factor greater than 2.5 compared to conventional design (based on the fact that conventional design requires higher design forces for the foundations than for columns).

Seismic Isolation Feasibility

Structures are generally suitable for seismic isolation if the following conditions exist:

- The subsoil does not produce a predominance of long period ground motion such as that obtained in the lake bed area of Mexico City.
- The site permits horizontal displacements at the base in the order of six to nine inches.
- The structure is relatively squat.
- The lateral wind loads or other non-seismic loads are less than approximately ten percent of the weight of the structure.

Each project must be assessed on an individual basis and early in the design phase to determine its suitability for seismic isolation. For this assessment, there are differences in evaluating its applicability in new construction and in the retrofitting of existing structures.

A major consideration when assessing the suitability of a structure for seismic isolation is the soil condition and the geology of the site. Generally, the stiffer the soil, the more effective the isolation.

The flexibility of the structure determines how it will respond to a given earthquake motion. The form of the earthquake motion as it arrives at the base of a structure may be modified by the properties of the soil through which the earthquake waves travel. If the soil underlying the structure is very soft, the high frequency content of the motion may be filtered out, and the soil may produce long period motions. An extreme example of this was seen in the 1985 Mexico City earthquake. Lengthening the period of a stiff structure in the lake bed soil conditions will amplify rather than reduce the ground motions; hence, for this type of soil condition, seismic isolation should not be considered.

The retrofitting of existing structures to improve their earthquake safety involves additional considerations, compared with new construction, because of the constraints already present.[14] Some structures are inherently more suitable for retrofit using seismic isolation than others. For example, bridge superstructures are generally supported on steel bearings. Replacement of these bearings with elastomeric bearings is a relatively simple, low-cost operation that will lead to a reduction in earthquake forces and allow the option of redistributing forces away from the weak substructures into abutments more capable of sustaining them.

Buildings are often more difficult to retrofit than bridges. However, seismic isolation may often be an effective solution for increasing the earthquake safety of existing buildings without the addition of new structural elements. Although seismic isolation reduces earthquake forces, it does not eliminate them. Consequently, the strength and limited ductility of an existing structure must at least be sufficient to resist the reduced forces that result from isolation. If the strength capacity of the existing structure is extremely low, then additional strengthening of the structure will be required. In such cases, the economics of significant additional strengthening versus some strengthening and the provision of isolation would need to be studied.

Seismic rehabilitation of an existing structure provides the ability to confine most of the construction work to the basement level, whereas conventional methods generally require the addition of structural elements to all levels of the building. This trade-off can be very important if the use of the facility during rehabilitation is desired, such as in hospitals.

Code Issues

The history of seismic code development has been an ongoing process since the 1933 Long Beach earthquake.[4] In 1960, a major step occurred with the initial publication of the SEAOC Blue Book. This study was the first comprehensive publication to address the seismic design of structural systems in use at that time. During the past 25 years, this publication has been continually refined and updated to address the design of newer types of structural systems[8,9] and it forms the basis of the Uniform Building Code seismic design provisions.

The current status of U.S. seismic isolation design requirements as of October 1989 is as follows:

- The SEAOC State Seismology Committee adopted in late 1989 an appendix to Chapter 1 of the SEAOC Blue Book entitled "General Requirements for the Design and Construction of Seismic-Isolated Structures." These requirements have been submitted to the International Conference of Building Officials (ICBO) for adoption in the Uniform Building Code. Consideration for the adoption of these design requirements by ICBO will occur in its 1990 code process cycle.
- The Building Safety Board has adopted "An Acceptable Method for Design and Review of Hospital Buildings Utilizing Base Isolation." The Northern and Southern sections of SEAOC completed and submitted a revised version of the document to the Building Safety Board. The revision was adopted by the Building Safety Board in May 1989.
- The AASHTO Bridge Committee is in the process of reviewing seismic isolation code requirements for bridge structures. These requirements have been developed to be compatible with the 1983 AASHTO Guide Specifications for the Seismic Design of Bridges.[1]

Applications

There has been a significant number of seminars, workshops, conference sessions and technical papers on the research and application aspects of seismic isolation, and no attempt is made herein to cite them all, but rather to note the more significant proceedings and seminars.[4,5,6,7,15,16,17] The Earthquake Engineering Research Institute's bimonthly journal, *Earthquake Spectra,* has dedicated a complete issue in May 1990 to the current status of seismic isolation.[18]

Seismically isolated structures have been built in at least 17 countries throughout the world, and there are another eight countries with active research programs in this area. The total number of isolated structures built or under construction is in excess of 125. This number includes 45 buildings (houses, schools, office buildings), 59 bridges, six nuclear-power-related structures, and seven miscellaneous structures (mainly of an industrial nature). Precise numbers are difficult to obtain, but this figure is considered to be a conservative estimate. However, it does not include at least 136 bridges known to be partially isolated for seismic loads in Japan and Italy. Partial isolation (*i.e.,* isolation in one horizontal direction only) has been popular for bridges in several countries for a number of years, and the total number of such systems is probably nearer to 200. As indicated in Table 2, significant progress is also being made in the United States for the implementation of seismic isolation for buildings, bridges and items of industrial equipment. Important facets of some of the projects in the table are noted as follows:

Foothill Communities Law and Justice Center. This project consists of a four-story, concentrically braced steel frame building, 415 by 110 feet in plan, and seated on 98 high-damping rubber isolators (see Figure 9).[7] Completed in 1986, the building site in San Bernardino County is within 14 miles of the San Andreas Fault and within two miles of

TABLE 2
Directory of Seismically Isolated Structures in the United States of America

Structure	Owner	Date	Description
230kV Circuit Breakers (Equipment)	California Dept. of Water Resources	1979	Elastomeric Isolators
Sierra Point Bridge (US 101) [Retrofit]	California Dept. of Transportation	1984/5	Lead-Filled Elastomeric Bearings
Foothill Communities Law and Justice Center	County of San Bernardino	1985/6	High-Damping Elastomeric Bearing
Santa Ana River Bridge [Retrofit]	Metropolitan Water District of Southern California	1986/7	Lead-Filled Elastomeric Bearings
Salt Lake City & County Building [Restoration]	Salt Lake City Corp.	1987/8	Lead-Filled Elastomeric Bearings
Mark II Detector (Equipment)	Stanford Linear Accelerator Center	1987	Lead-Filled Elastomeric Bearings
Main Yard Vehicle Access Bridge [Retrofit]	Los Angeles County Transportation Commission	1987	Lead-Filled Elastomeric Bearings
Eel River Bridge [Retrofit] (US 101)	California Dept. of Transportation	1987	Lead-Filled Elastomeric Bearings
Salt Lake City Manufacturing Facility	Evans & Sutherland	1987/8	Lead-filled elastomeric Bearings
Liquid Argon Calorimeter (Equipment)	Stanford Linear Accelerator Center	1987	Lead-Filled Elastomeric Bearings
All American Canal Bridge [Retrofit]	California Dept. of Transportation	1988	Lead-Filled Elastomeric Bearings
Sexton Creek Bridge	Illinois Dept. of Transportation	1988	Lead-Filled Elastomeric Bearings
USC University Hospital	USC and National Medical Enterprises	1989	Lead-Filled Elastomeric Bearings
Fire Command & Control Facility	Los Angeles County	1989	High-Damping Elastomeric Bearing
Rockwell [Retrofit]	Rockwell International	1989	Lead-Filled Elastomeric Bearings
Toll Plaza Bridge	Pennsylvania Turnpike Commission	1990	Lead-Filled Elastomeric Bearings
Lacy V. Murrow Bridge [Retrofit]	Washington State Dept. of Transportation	1990	Lead-Filled Elastomeric Bearings

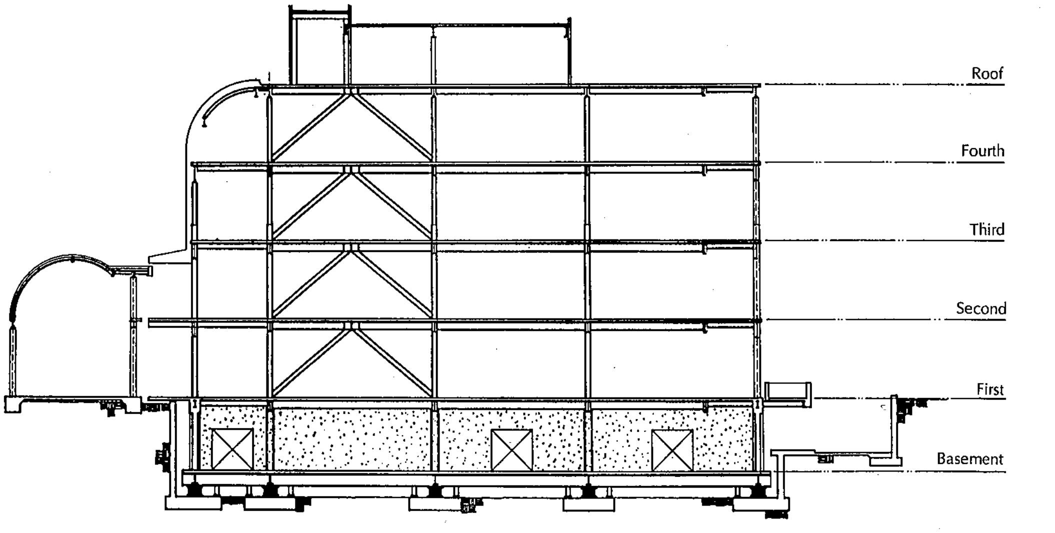


FIGURE 9. Section through the Foothill Communities Law and Justice Center showing the location of the isolators in the sub-basement.

the Sierra Madre Fault. It is therefore in a region of high seismicity, and a full-scale test of this isolated building, by at least a moderate earthquake, is expected in the near future. In fact, a minor event (magnitude 4.9) occurred in Redlands in October 1985, 20 miles from the building. Instruments in the structure showed that the isolators attenuated the effects of the ground motion, albeit very slightly. Other buildings in the vicinity showed amplification by factors of two or three — which is expected in conventional (unisolated) structures.

Evans and Sutherland Manufacturing Facility. This project is a new, four-story manufacturing site for flight simulators (see Figure 10).[4,15] Located near the Warm Springs and East faults, in UBC Seismic Zone 3 in Salt Lake City, the building measures 280 by 160 feet in plan and rests on 98 isolators. The value of the contents and work-in-progress in this building is estimated at $100 million, or approximately 12 times the cost of the structure.

Salt Lake City and County Building. This five-story, Richardson Romanesque Revival structure measures 265 by 130 feet in plan (see Figure 11). Constructed between 1892 and 1894, it is built of unreinforced brick and sandstone. Its 12-story tower is centrally located and is also constructed from unreinforced masonry. As part of a complete restoration package for the building, seismic retrofit using seismic isolation was used. A total of 447 isolators have been installed on the existing foundations and the building weight has now been transferred to the isolators. The structure is thus protected against damage for the design 0.2 g earthquake event. However, the isolators are designed to be stable up to and including a 0.4 g event, should an earthquake greater than the design event be experienced at the site.

Sierra Point Overhead. This project is a highly skewed bridge on ten simply supported spans that vary in length from 26 to 100 feet.[5,6,7] Supported on 27 non-ductile columns, each three feet in diameter, the bridge was at risk seismically. Retrofit by isolation was feasible because existing steel bearings could be removed and replaced by isolation bearings. No column strengthening was necessary because the force reductions were sufficient to ensure elastic behavior.

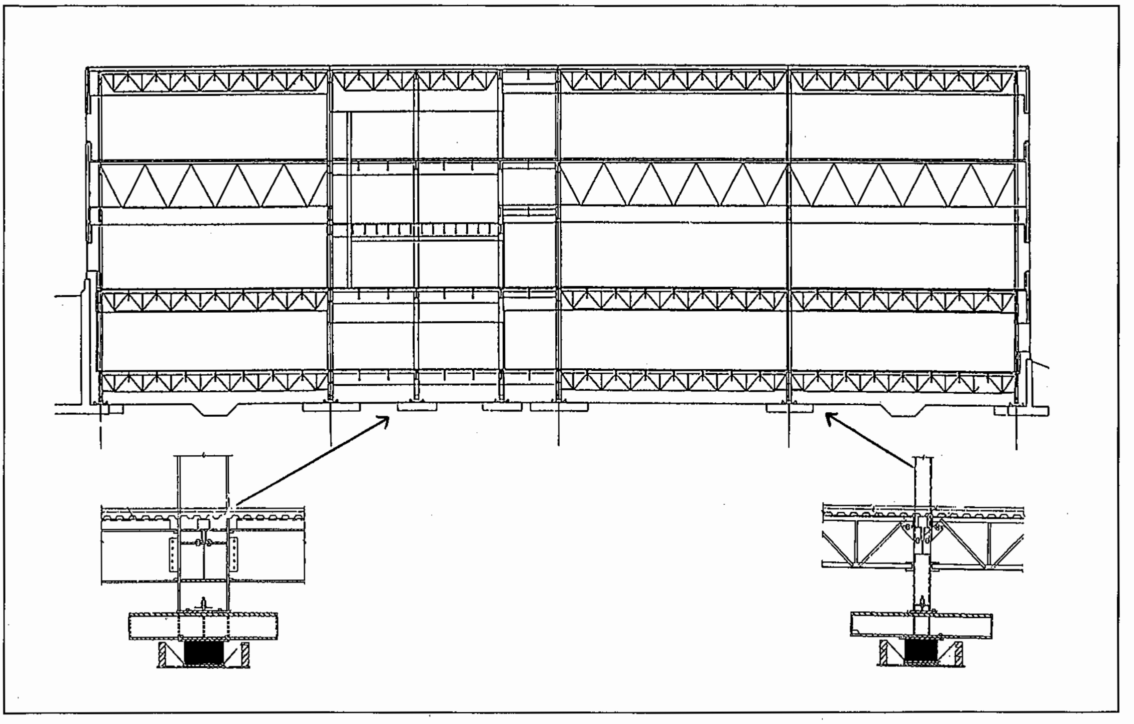


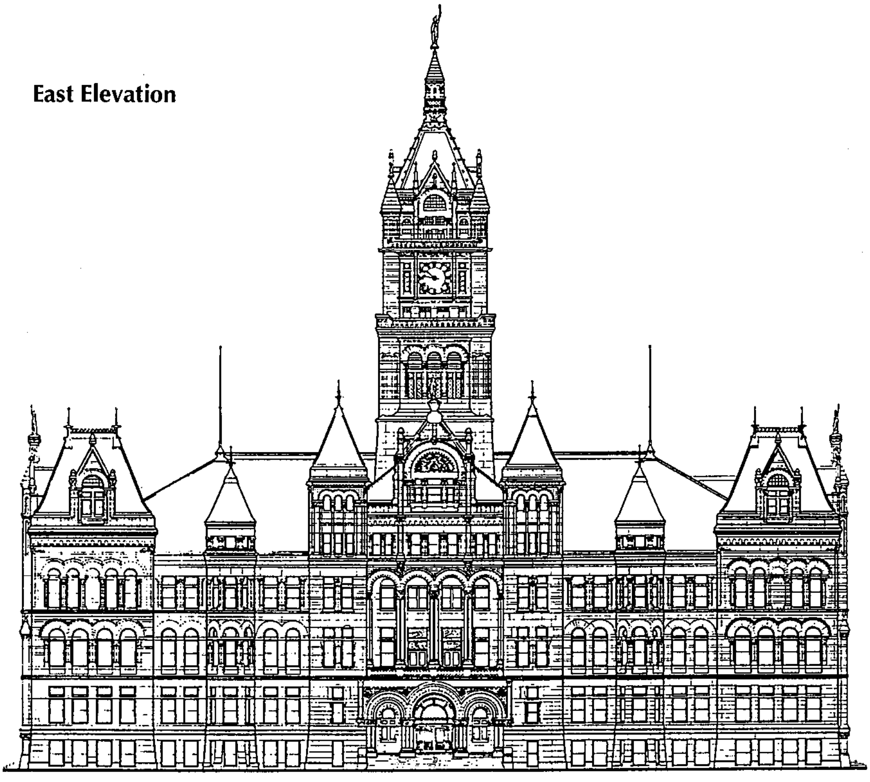
FIGURE 10. Section through the Evans and Sutherland Building in Salt Lake City showing the location of isolators in the sub-basement.

Santa Ana River Bridge. This bridge carries the Upper Feeder water pipeline into the Los Angeles Basin.[5,6] Again, the existing piers and trusses were under-strength and isolation bearings were used to reduce the seismic forces to below the existing pier and truss capacities. No strengthening of the piers was therefore necessary.

Additional Bridge Projects. Other bridge isolation retrofit projects now completed or under construction in California include the Eel River Bridge near Rio Dell, the vehicle access bridge for the Los Angeles County Transportation Commission near Long Beach, and the All American Canal Bridge for Caltrans in Imperial County.[5,6] The first new isolated bridge in the United States is the Sexton Creek Bridge in Alexander County in southern Illinois, near the New Madrid fault. It is a three-span continuous steel plate girder bridge. Two other new bridge projects will be under construction in late 1989, one for the Pennsylvania Turnpike Commission and the other for the Alabama Highway Department.

230 kV Circuit Breaker. The first isolation system to be installed in the United States was for the protection of a 230 kV circuit breaker for the California Department of Water Resources in 1979. Circuit breakers have fragile porcelain columns with limited resistance for lateral loads. In this application, four conventional elastomeric bearings were used to isolate each phase of the circuit breaker. Since the units are relatively lightweight, the isolators are more slender than those used elsewhere.

Mark II Detector. In contrast, the Mark II Detector at the Stanford Linear Accelerator Center is of substantial weight (3200 kips) and is isolated by four isolation bearings.[4] An integral part of the Department of Energy's new Linear Collider at Stanford University, this fragile item of industrial equipment is now protected against damage from a 0.6 g earthquake on the adjacent San Andreas Fault. A second item for the Collider, the Liquid Argon Calorimeter, has also



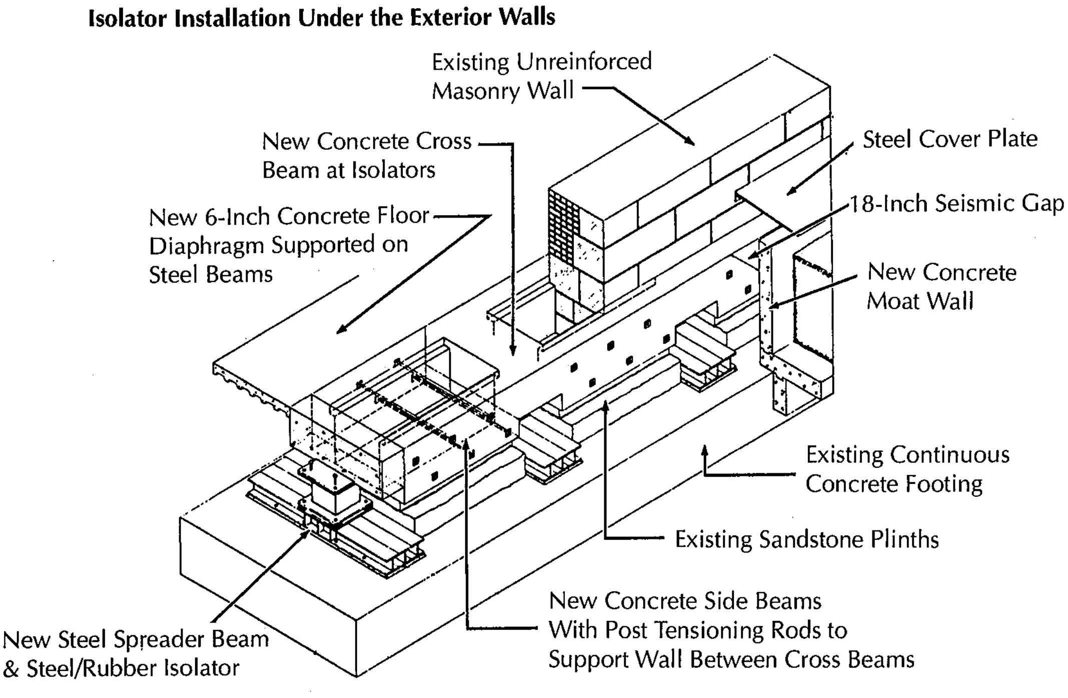


FIGURE 11. Salt Lake City and County Building.

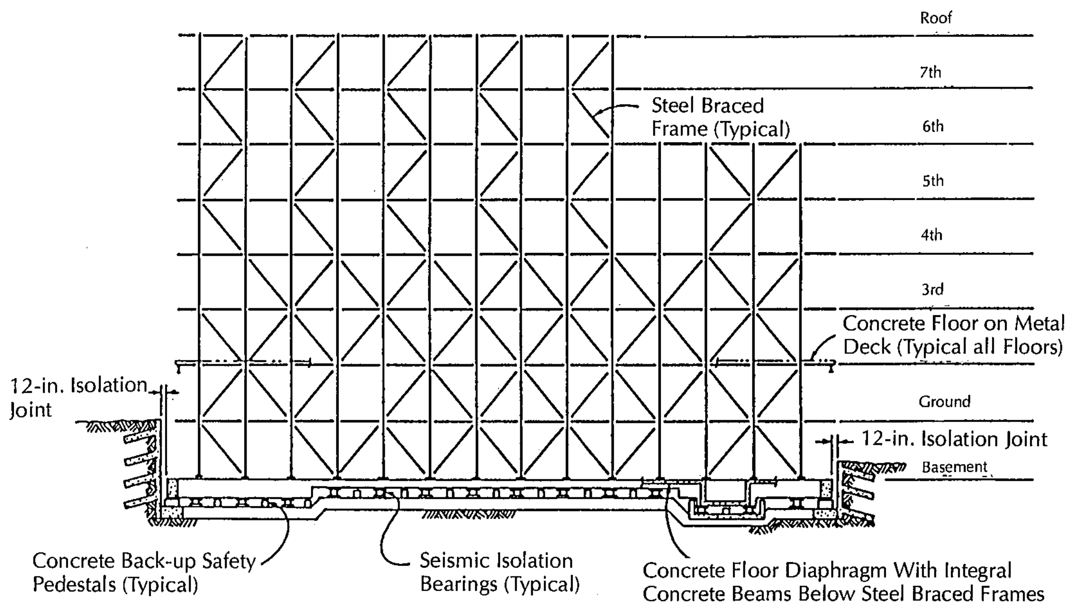


FIGURE 12. The USC Teaching Hospital.

been similarly isolated.

USC University Hospital. Construction is under way for the first seismically isolated hospital in the United States, located in Los Angeles.[4,15] This eight-story structure will be used as a teaching hospital by the University of Southern California. It resists seismic forces with a perimeter steel braced frame and is supported on 149 isolators (see Figure 12). Seismic design input corresponded to a 0.4 g response spectrum increased by 20 percent to account for near-fault effects. The design was reviewed and approved by the California Office of the State Architect.

Fire Department Command and Control Facility. A second project currently under construction is a new Fire Department Command and Control Facility for Los Angeles County.[15] This building is a two-story, steel perimeter braced frame structure that utilizes 36 high-damping elastomeric isolation bearings. The decision to utilize seismic isolation on this project was based on a comparison of two designs (conventional and isolation) that were required to be functional after the maximum design event. This project reflects the first such detailed comparison for two designs to meet a performance specification. In the case of this two-story structure, the isolated structure was found to be six percent less expensive than the conventional design.

Rockwell Manufacturing Facility. A third project currently under construction is the seismic retrofit of a ten-story, reinforced concrete moment frame building for Rockwell International. The building, located in Los Angeles, will be the first to have the isolation system installed at mid-height in existing columns.

The Economics of Seismic Isolation for Buildings

The economic feasibility of seismic isolation in building construction depends on an objective evaluation of the costs and benefits in financial terms. Earthquakes have four principal cost impacts that may influence the decision-making process in the selection of a structural resisting system. These impacts are:

- The initial cost of construction;
- Annual earthquake insurance premium;
- Physical damage that must be repaired after an earthquake to restore the building's pre-earthquake value; and,
- Disruption costs due to building and contents damage (lost rent, revenue, productivity), loss of market share or clients, and potential liability to occupants for their losses and injuries.

Since the performance characteristics of a conventional code-designed building and a seismically isolated structure are significantly different, these four cost issues should be evaluated as part of the decision-making process.

Equal Performance Cost Comparisons

One of the major difficulties in comparing the costs and benefits of an isolated and conventionally designed structure is that its earthquake performance characteristics will be very different. One exception to this rule is nuclear power plants, which require equivalent performance characteristics regardless of the method of construction. Burns and Roe performed a feasibility study for the Electric Power Research Institute on the isolation of a prototype breeder nuclear power plant.[19] Their study concluded that there would be a net cost savings of two percent, or $34 million, on a project cost of $1,760 million.

The only example of a non-nuclear facility for which an equal performance cost comparison has been performed is a new project currently under construction for the Los Angeles County Fire Department. This Fire Command and Control Facility is a two-story braced steel frame structure that is required to be functional during and after the maximum credible design event.[20] The architects and engineers for that project developed both an isolated and conventional structure design to satisfy this performance requirement. It was found that the isolation design was six percent less expensive than the conventional design. The primary reason for the cost difference was the savings realized when seismic hardening and certification of the electrical and mechanical equipment was not required for the isolation design. The architect also reported on the life cycle cost studies that were performed. Using the methodology developed by Ferritto,[21] the present value of future losses were computed for both structures. The results reflected a reduction in losses of a factor of 40 with seismic isolation. While these results may not be precise, they show a strong indication of improved functional performance with seismic isolation.

Earthquake Insurance

Earthquake insurance is becoming more difficult to acquire in high seismic regions, and there is considerable concern within the federal government on the financial stability of the insurance industry should a severe earthquake occur in California. In an attempt to minimize their exposure, insurance companies have considerably increased insurance premiums and deductibles over the past five years. Deductibles of ten percent of the total building value are common and annual premiums are in the one-third to three-quarters percent range of total building value.

If earthquake mitigation measures, such as seismic isolation, are able to reduce earthquake damage below current deductibles ($2 million on a $20 million building), then an owner has the option of incorporating these mitigation measures and incur savings on the annual insurance premium ($100,000 to $150,000 per year on a $20 million building). These insurance premium savings will quickly amortize any additional first costs for the incorporation of seismic isolation.

Earthquake Damage

Structural damage manifests itself in the form of inelastic deformations in the structural members. These deformations can be quantified as ductility demands; that is, the ratio of total deformation in the member to the deformation of the member at first yield.

One of the more difficult issues to address from a conventional design viewpoint is that of reducing non-structural and building contents damage. Often ignored, this consideration can be very expensive to incorporate in conventional design. In fact, the additional cost to satisfy the more stringent bracing requirements of non-structural elements in the Los Angeles Fire Department headquarters building was the primary reason the seismic isolation design option was six percent less expensive than the conventional design.[20]

As noted before, there are two primary mechanisms that cause non-structural damage. The first is related to interstory drift and the second is related to floor accelerations. Together, these two components cause damage to the building contents, architectural facades, partitions, piping and ductwork, ceilings, building equipment and elevators. There are two different design philosophies that are debated within the structural engineering profession that deal with minimizing non-structural damage. One argues that stiff buildings reduce interstory drift, but their opponents state that they produce high floor accelerations. The other school of thought argues that flexible buildings are the solution, because they attract less force and tend to reduce floor accelerations. Although this philosophy is true, opponents state that flexible buildings have much higher interstory drifts, thus accentuating damage to components that are sensitive to drift.

Clearly, a design concept that reduces both interstory drift and floor accelerations combines the best aspects of these two current design philosophies. Seismic isolation is such a concept since it significantly reduces both the floor accelerations and the interstory drift and thus provides a practical solution to the difficult problem of reducing non-structural damage.

Earthquake Damage Cost Estimates

Estimating the actual cost of earthquake damage is difficult, primarily (or fortunately) because major earthquakes have not been frequent enough to develop a broad database. There are two approaches available. The first approach is an experience-based matrix developed, in part, from information obtained from past earthquakes. This method is given in ATC-13.[22]

Theil has developed a present-value formulation that incorporates the ATC experience-based earthquake damage matrix.[7] Thiel's overall conclusions are:

- Seismic isolation is a very important means of controlling the life-cycle cost of seismic exposure; and,
- When disruption costs and the value of building contents are important, seismic isolation has a substantial economic advantage over other systems regardless of initial construction costs, under almost all conditions.

The second approach was developed by Ferritto.[21] He identified damage ratios associated with the two primary structural response characteristics that cause damage: interstory drift and floor accelerations. Tables presenting basic damage ratios and repair multipliers can be found in his paper and in other sources.[4,21,23]

The damage ratios given by Ferritto can be used as a guide to the potential losses that may occur in buildings. The earthquake damage cost is estimated by the following procedure:

$$\textit{Element Damage} = \textit{Cost} \times \textit{Repair Multiplier} \times \textit{Damage Ratio}$$

To obtain the total estimated damage, it is necessary to sum the drift and acceleration related damage components for each building type for each seismic event under consideration. The advantage of Ferritto's methodology is that it can be applied on a project-specific basis and the relative seismic performance of different structural systems, including seismic isolation, can be evaluated. In order to utilize the Ferritto methodology, a detailed analysis of the structure is required to obtain the interstory drifts and floor accelerations.

Because of the uncertainties inherent in predicting earthquake ground motions, the specific dollar estimates that result from these studies should only be used as an indication of the order of magnitude of damage costs. The relative ratio of damage estimates between different structural systems is probably a more meaningful basis of evaluation.

Business Disruption

Another important benefit of seismic isolation is the ability to significantly improve the chances of business survival after a major earthquake. The economics of business survivability following an earthquake would overwhelm a small percent first-cost premium for the incorporation of seismic isolation.

Many firms must remain in business given the nature of their operations within highly competitive global and national marketplaces. Any type of loss exposure, such as an earthquake, for an extended period of time might force the business to close since it might not be able to compete on a timely basis with other firms in other parts of the country or the world, thus further exacerbating the area-wide economic damage that can occur from earthquakes. Businesses need to protect employees, work in progress, inventory and the building itself as well as protect the business from damage suits from employees, clients or even passersby. For most businesses, repairing the damage done is not worth it when compared to the costs of addressing possible exposure to loss events.

The Economics of Seismic Isolation for Bridges

For bridge construction, the economic issues are very different to those for buildings. In bridges, the implementation of seismic isolation simply requires the use of a seismic isolation bearing rather than a conventional bearing. Since bearings are only one to two percent of the cost of a bridge, a 10 to 20 percent increase for the cost of isolation bearings will have very little impact on the overall construction cost. However, in many instances, the use of seismic isolation will reduce the overall construction cost of the bridge, and total construction cost savings of up to ten percent have been achieved with the use of seismic isolation.[12]

For the eastern United States, the FHWA has just begun to require the seismic design of new construction. In conventional construction, this requirement will result in some increase in construction costs, especially in the foundations. Since seismic isolation will generally reduce seismic design forces below the level of other load cases, there should be no additional cost if seismic isolation is used to satisfy the 1983 AASHTO Guide Specifications. Thus, in the eastern United States, seismic isolation should produce cost savings in the construction of new bridges.

Construction Cost Studies of New Buildings

The database of construction cost studies is increasing; of those available, some are much more detailed than others. Some of the published data is based on completed projects, some from projects designed but not yet constructed, and the rest is from comparative studies of already constructed conventional facilities. A summary of the published data is as follows:

Los Angeles County Fire Command and Control Facility.[20] This two-story project currently under construction showed a six percent cost savings due to the unique equivalent performance cost comparison that was performed and discussed in detail earlier.

Union House.[24,25] This twelve-story precast, prefabricated building in Auckland, New Zealand, showed a three percent first cost savings in addition to a reduction in construction time by three months. This project was unique in that the engineers took full advantage of the reduced design forces and the elimination of ductility demand resulting from the use of seismic isolation.

Foothill Communities Law and Justice Center.[26] This building was the first U.S. project to incorporate seismic isolation. The project was well into the design development phase when it was decided to employ seismic isolation and, as a consequence, a significant redesign effort was required. The total overall construction cost increase was four percent on a $33 million project. Additional structural costs of $645,000 arose from the need for a structural basement floor slab, which originally was to be of slab-on-grade configuration, and the double concrete walls that were required around the retaining wall basement area of the building. Furthermore, shear walls under the transverse braced frames were added to prevent uplift from developing. Offsetting these costs were reductions in steel costs from changing the moment frame to a braced frame, and the elimination of all the moment connections associated with the original fixed-base design. Because the decision to utilize seismic isolation was made in the latter stages of design development, some of the other items that increased the construction cost might have been avoided if isolation had been considered in the preliminary design phase of the project.

Evans and Sutherland Manufacturing Facility.[27] This structure is a four-story moment frame building located near the Wasatch fault in Salt Lake City. It was a fast-track project and the decision to incorporate seismic isolation was made at the conceptual design phase. Preliminary costs for conventional and isolated designs were developed and the benefits of seismic isolation assessed by the project design team. Based on this evaluation and the recommendation of the design team, Evans and Sutherland decided to incorporate seismic isolation. The structural engineers decided to design the structural framing system for the UBC Code forces required for conventional design and, consequently, there were no structural framing cost savings. The additional structural cost was the basement structural floor (versus a slab-on-grade) and the heavy "fail safe" system used. Based on cost data developed by the contractors, the cost premium for incorporating seismic isolation was five percent or $400,000 on an $8 million project. Important in the decision to employ seismic isolation was protecting the building contents, including work in progress, the value of which exceeded $100 million.

USC University Hospital.[28,29] Construction began in early 1989 for the first hospital in the world to incorporate seismic isolation. It is an eight-story perimeter braced steel frame building with an irregular configuration in plan. The decision to incorporate seismic isolation was made in the preliminary design phase of the project. Structural cost comparisons for conventional and isolated structures were developed and the benefits of seismic isolation assessed. The structural engineers determined that the cost savings in the structural frame were sufficient to pay for the new structural ground floor slab and the isolation system. These savings were confirmed by the contractor. The additional cost of mechanical and architectural details was 1.3 percent and there was a 1.4 percent cost savings in the soil nailed retaining wall used in the isolation design versus the conventional retaining wall. Consequently, there was no net additional cost for incorporating seismic isolation on this hospital project.

Tandem Computers Manufacturing Facility.[30] This series of new four-story braced steel frames incorporating both office and manufacturing facilities has been designed, but construction has not yet begun. This project is unique in that the seismic isolators are to be installed at the top of the parking level columns. As a consequence, there is no additional cost for a new structural basement floor as was the case in all previous examples. The cost study performed by the structural engineers indicated a 0.75 percent cost premium for incorporating seismic isolation with this top of the column installation scheme. Some savings in non-structural component bracing were anticipated, but were not included in the cost estimate.

Veterans Administration Hospital, Loma Linda.[31] A feasibility study was undertaken on seismically isolating a completed Veterans Administration Hospital in Loma Linda, California. The probable deduct and added costs for incorporating seismic isolation were $4.9 million and $3.9 million, respectively. It should be noted that the isolator price used in these costs has been changed from the original reference and is based on recently completed U.S. projects. The total project cost was not given, but it is estimated at $80 million based on a price of $120 per each square foot. Thus, seismic isolation in this reasonably detailed hospital design example resulted in a savings of about 1.2 percent.

Medical Building, Salt Lake City.[32] The probable deduct and added costs for incorporating seismic isolation for this $20 million medical facility were $716,000 and $305,400, respectively. Thus, the use of seismic isolation resulted in a cost savings of $400,000, or two percent, on the total project cost.

Construction Cost Studies of Existing Buildings

Retrofitting existing structures to improve their earthquake safety involves additional considerations when compared with new construction because of the constraints already present. Structures with existing basements and/or piled foundations are inherently more suitable for seismic isolation retrofit,[4] although when all the technical limitations are assessed, only about one in eight existing buildings are suitable isolation candidates.

Seismic isolation can be an effective solution for increasing the earthquake safety of buildings of historical value without the addition of new structural elements that detract from the very features that make the building worth preserving. A particularly dramatic example of the retrofitting of a historically important building is the Salt Lake City and County Building.[14,33,34] This structure represents the only completed building retrofit project in the United States to date, although a building for Rockwell International is currently being retrofitted. A number of detailed cost studies have been performed on other projects which are summarized as follows:

Salt Lake City and County Building.[14,33,34] This project was the subject of a detailed study of three alternate retrofit schemes: seismic isolation; Agbabian, Barnes and Kariotis (ABK) methodology; and UBC strengthening. These three schemes were developed in sufficient detail to permit cost estimates and an evaluation of performance. This cost and performance evaluation study resulted in the selection of seismic isolation over the other two options for design development. Although detailed cost numbers of this comparative study have not been published, Bailey and Allen state that the cost of the UBC strengthening scheme and the isolation scheme were comparable, and that the ABK method was slightly less expensive.[34] The decision to use seismic isolation was made by the Salt Lake City Council based on the considerably better performance that results from the use of seismic isolation. The complete architectural and historic restoration, and seismic rehabilitation work was estimated to be $24 million. The construction contract awarded in February 1987 was $4 million below the estimate. The approximate value of the seismic isolation work reported by the contractor was $4,414,000 including the cost of the 447 seismic isolators. This sum includes removal and replacement of the first floor; removal of brick and stone for isolators and side beams; installation of base isolators and flat jacks; steel spreader beams and cover plate for seismic isolation gap concrete and reinforcing steel for side beams; the moat wall, cross beams, post tensioning materials and labor; change order amounts attributed to the seismic isolation work; and proportional amounts of contractor field overhead, home office overhead and profit. In addition, the contractor reported that the sum of approximately $530,000 is attributable to other seismic upgrading work — particularly the wall anchors, the required gunite work, and the structural steel stiffening of the end gables.

Masonic Hall, San Francisco.[35,36] A cost comparison study was performed with funding from the National Science Foundation on the seismic rehabilitation of this 101,000 square foot building using both conventional and seismic isolation methods. The costs of the two schemes were almost identical at $2.4 million. Some of the costs included in the isolation scheme were unique to this building and would not have necessarily appeared in other cases.[35] Nearly $500,000 in additional structural work was required above the isolation system in order to stiffen the building and to alleviate the very poor quality of concrete in certain areas. In addition, the wall in contact with the adjacent building had to be replaced in order to permit the design movement across the isolators. The conventional scheme also required extensive removal and replacement of the interior architectural finishes. The structural work associated with the conventional scheme was $1.7 million and an additional $0.5 million was assumed for architectural refinishing. However, the architectural refinishing associated with the conventional scheme would not be of the same quality as the existing finish. To duplicate the existing finish would cost an additional $2.0 million.[35] Thus, to get identical finishes, the conventional scheme would be significantly more expensive.

Department of Defense Essential Facilities. Two detailed project cost studies have recently been performed for the Department of Defense. Although the results of neither study have been published, both showed that seismic isolation was the less expensive alternative. The first study was performed on an existing nine-story hospital. Since a sub-basement area was available, most of the retrofit work was confined to this nonfunctional area of the hospital, thus permitting the retrofit work to be performed without disturbing the functionality of the facility. The second study was performed on a six-story essential Navy storage facility. Again, a sub-basement area at the foundation level was available and most of the retrofit work could thus be performed without disturbing the operational capability of the facility. The structure is 600 feet long and 120 feet wide, with a total floor area of 432,000 square feet. The cost of a conventional upgrade was $8.8 million, whereas the cost of an isolated upgrade was $7.6 million, a savings of 14 percent.

Conclusion

Several practical seismic isolation systems have been developed and implemented in recent years as interest in the application of this technique continues to grow. Although seismic isolation offers significant benefits, it is by no means a panacea. Feasibility studies are required early in the design phase of a project to evaluate both the technical and economic issues. If seismic isolation is appropriate from a technical and first-cost perspective, then significant life-cycle cost advantages can be achieved. Thus, seismic isolation represents an important step forward in the continuing search for improved earthquake safety.

A seismic rehabilitation scheme using isolation principles has been implemented for the existing City and County Building in Salt Lake City and another, for Rockwell International in Los Angeles, is currently under construction. The Salt Lake City scheme required strengthening the bases of the unreinforced masonry walls and piers, and the installation of lead-rubber isolation bearings below the first floor level. The use of seismic isolation significantly reduces the earthquake-induced acceleration of the building and the corresponding inertia forces. Because of this reduction in forces, the required reinforcement and disruption of architectural finishes in the remainder of the masonry superstructure is minimal.

Seismic isolation offers particular advantages to bridge structures. Reductions in earthquake loads can be significant and savings can be achieved in the foundations of new designs along with improved seismic performance (elastic response). Isolation also offers an elegant solution to many of the common retrofit problems encountered in existing bridges. Limited experience to date has shown that isolation can be adapted and implemented to meet a wide variety of different site and bridge conditions.

Current available information on the construction cost of incorporating seismic isolation in new buildings indicates that it depends on two primary variables: the design force level of the conventional building and the location of the plane of isolation. For essential facilities, such as hospitals, the cost of incorporating seismic isolation has varied between ±2 percent, primarily because conventional hospitals require higher design force levels than conventional code designed buildings. For UBC-designed buildings, a cost premium of 0.5 to 5.0 percent has been required for the incorporation of seismic isolation because there is not sufficient cost savings in the structural framing system to offset the cost of isolators and the new basement structural floor. For the one project that had the isolators installed at the top of the basement level columns, the cost premium was only 0.75 percent. For the precast, prefabricated Union House in Auckland, New Zealand, a cost savings of three percent was achieved because the structural engineers utilized the ability of seismic isolation to eliminate the ductility demand on the structural system.

For the retrofit of existing buildings, seismic isolation may only be technically applicable in one out of approximately eight buildings. When it is technically feasible, it has the attractive feature that most of the construction work is confined to the basement area. Retrofit construction costs, when compared to a conventional code force level upgrade, have been shown to be comparable in cost. For essential facilities, a conventional upgrade requires a higher design force level than a UBC upgrade; in two recent detailed cost studies, seismic isolation was shown to be 15 to 30 percent less expensive than a conventional upgrade. In addition, disruption to the operation of the facility was avoided during construction with the use of seismic isolation.

One of the major difficulties in comparing the costs and benefits of a conventional and an isolated structure is the significant difference in their performance characteristics. In the only such design performed to date, a critical Fire Command and Control Facility for Los Angeles County required designs for both a conventional and isolated two-story structure that meet the same stringent performance criteria. In this case, the isolated design was shown to be six percent less expensive. If equivalent performance designs are not performed, the costs and benefits of different structural design schemes can only be assessed by calculating and comparing the four principal cost impact factors:

- Construction cost
- Earthquake insurance premium
- Physical damage that must be repaired
- Disruption costs, loss of market share and potential liability to occupants for their losses

Earthquake damage studies have shown that seismic isolation can reduce the cost of earthquake damage by factors of four to seven. Furthermore, the estimated dollar value of earthquake damage in an isolated building has been shown to be less than the currently available ten percent earthquake insurance deductible.

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REFERENCES

1. *Seismic Design Guidelines for Highway Bridges,* Report ATC-6, Applied Technology Council, 1981. Also published by Federal Highway Administration as Report FHWA/RD-81/081, 1981; adopted by AASHTO as *1983 Guide Specifications.*

2. Jacob, K.H., ed., *Proceedings from the Symposium on Seismic Hazards, Ground Motions, Soil-Liquefaction and Engineering Practice in North Eastern America,* National Center for Earthquake Engineering Research, Technical Report 87-0025, December, 1983.

3. Blakeley, R.W.G., "Analysis and Design of a Bridge Incorporating Mechanical Energy Dissipating Devices for Earthquake Resistance," *Proceedings of a Workshop on Earthquake Resistance of Highway Bridges,* Applied Technology Council, Report No. ATC-6-1, January 1979, pp. 313-342.

4. Dynamic Isolation Systems, *Seismic Isolation of Buildings,* Seminar Notes, Berkeley, California, October 1988.

5. Dynamic Isolation Systems, *Design of Lead-Rubber Bearings for Bridges,* handbook, Berkeley, California, 1988.

6. Buckle, I.G., & Mayes, R.L., "Seismic Isolation of Bridge Structures in the United States of America," *Proc. Third U.S.-Japan Workshop on Bridge Engineering,* Public Works Research Institute, Ministry of Construction, Tsukuba, Japan, 1987, pp. 379-401.

7. Applied Technology Council, *Proceedings of a Seminar and Workshop on Base Isolation and Passive Energy Dissipation,* ATC Report No. 17, Palo Alto, CA, 1986.

8. Structural Engineers Association of California, *Lateral Force Requirements,* San Francisco, 1988.

9. International Conference of Building Officials, *Uniform Building Code,* Whittier, California, 1988.

10. *Seismic Retrofitting Guidelines for Highway Bridges,* Report ATC-6-2, Applied Technology Council, 1983. Also published by Federal Highway Administration as Report FHWA/RD-83/007, 1983.

11. Buckle, I.G., Mayes, R.L., & Button, M.R., *Seismic Design and Retrofit Manual for Highway Bridges,* Computech Engineering Services, Berkeley, California. Also Published by Federal Highway Administration as Report FHWA/RD-86/006, 1986.

12. Billings, I.J., & Kirkcaldie, D.K., "Base Isolation of Bridges in New Zealand," *Proc. Joint US- New Zealand Workshop on Seismic Resistance of Highway Bridges,* Applied Technology Council, Report 12-1, Redwood City, 1985.

13. Zelinski, R.J., "California Department of Transportation Bridge Earthquake Retrofitting Program," *Proc. Second Joint U.S.-Japan Workshop on Performance and Strengthening of Bridge Structures and Research Needs, San Francisco, 1985, pp. 213-217.*

14. Mayes, R.L., Sveinsson, B.I., & Buckle, I.G., "Seismic Isolation: An Economic Rehabilitation Alternative," Construction Specifier, July 1987, pp. 76-92.

15. *Seismic Engineering: Research and Practice, Proc. ASCE Structures Congress,* May 1989.

16. Kelly, J.M., *A Seismic Base Isolation: Its History and Prospects,* Joint Sealing and Bearing Systems for Concrete Structures, Publication SP-70, American Concrete Institute, 1982.

17. Buckle, I.G., *Development and Application of Base Isolation and Passive Energy Dissipation: A World Overview,* Applied Technology Council Report No. 17, Palo Alto, California, March 1986.

18. Earthquake Engineering Research Institute Journal, *Earthquake Spectra,* May 1990.

19. *Seismic Isolation Studies for Liquid Metal Fast Breeder Reactor Plants,* Burns and Roe, Inc., Dec. 1983.

20. Anderson, T.L., "Seismic Isolation for the Los Angeles County Fire Command and Control Facility," *Proceedings of Seismic Engineering, ASCE Structures Congress,* May 1989.

21. Ferritto, J.M., "Economics of Seismic Design for New Buildings," *ASCE Journal of Structural Engineering,* Vol. 110, No.12, December 1984.

22. Applied Technology Council, *Earthquake Damage Evaluation Data for California,* Applied Technology Council, Report No. 13, Palo Alto, California, 1985.

23. Kelly, T.E., Mayes, R.L., & Weissberg, S.M., "Earthquake Damage Estimates of Conventional and Isolated Structures," *Proceedings of Seismic Engineering, ASCE Structures Congress,* May 1989.

24. Boardman, P.R., Wood, B.J., Carr, A.J., "Union House — A Cross Braced Structure with Energy Dissipators," *Bulletin New Zealand Society for Earthquake Engineering,* Vol. 16, No. 2, 1983, pp. 83-97.

25. Mayes, R.L., Buckle, I.G., & Jones, L.R., "Seismic Isolation — A Solution to the Earthquake Problems of the Precast Industry," *Prestressed Concrete Institute Journal,* Vol. 33, No. 3, May/June 1988.

26. Tarics, A.G., Way, D., & Kelly, J.M., *The Implementation of Base Isolation for the Foothill Communities Law and Justice Center,* Report to the National Science Foundation and the County of San Bernardino, November 1984.

27. Reaveley, L.D., Mayes, R.L., & Sveinsson, B.I., "Seismic Isolation of a Computer/Flight Simulator Research and Development Facility," *Proceedings of Seismic Engineering, ASCE Structures Congress,* May 1989.

28. Myers, D.W., "Softening the Jolt of the Big One," *Los Angeles Times,* Real Estate Section, July 23, 1989.

29. Asher, J.W., & Van Volkinburg, D.R., "Seismic Isolation of the USC University Hospital," *Proceedings of Seismic Engineering, ASCE Structures Congress,* May 1989.

30. Honeck, W., & Forell, N., "Case Study of Base Isolation for a New Building, Tandem Manufacturing Facility," *Proceedings of a Seminar on Base Isolation and Passive Energy Dissipation,* Applied Technology Council, Report No. 17, March 1986.

31. Vaidya, N.R., & Eggenberger, A.J., *Feasibility Evaluation of Base Isolation for the Seismic Design of Structures,* D'Appolonia Report 82-1365 to the National Science Foundation, January 1984.

32. Tarics, A.G., "Cost Considerations of Base Isolation," *Proceedings, International Conference on Natural Rubber for Earthquake Protection of Buildings and Vibration Isolation,* Kuala Lumpur, February 1982.

33. Walters, M., Elsesser, E., & Allen, E.W., "Base Isolation of the Existing City and County Building in Salt Lake City," *Proceedings of a Seminar on Base Isolation and Passive Energy Dissipation,* Applied Technology Council, Report No. 17, March 1986.

34. Bailey, J.S., & Allen, E.W., "Seismic Retrofitting: Salt Lake City and County Building," *APT Bulletin,* Vol. XX, No. 2, pp.32-44.

35. Tarics, A.G., Kelly, J.M., & Way, D., *The Seismic Rehabilitation of Existing Buildings Using Base Isolation,* Report to National Science Foundation and the Malaysian Rubber Research and Development Board.

36. Kelly, J.M., *The Economic Feasibility of Seismic Rehabilitation of Buildings by Base Isolation,* Report No. UCB/EERC-83-01, Earthquake Engineering Research Center, University of California, Berkeley, 1983.