An innovative design strategy called "seismic isolation" provides an economic practical alternative for the design of new structures and the seismic rehabilitation of existing buildings, bridges and industrial equipment. Rather than resisting the large forces generated by earthquakes, seismic isolation decouples the structure from the ground motion and thus reduces earthquake forces by factors of 5 to 10. This level of force reduction is very significant because it may eliminate the ductility demand on a structural system. This fact alone is a very significant benefit for the precast concrete industry.

There are now approximately 100 civil engineering structures that have been constructed using the principles of seismic isolation, including a 12-story...
prefabricated building. Four of the completed structures (two in Japan, one in New Zealand and one in the United States) have been subjected to real earthquakes, with the largest being a Richter Magnitude 6.2 seismic event in New Zealand in February 1987. Although these seismic events have not been major earthquakes, all four of the isolated structures have shown the force reductions expected.

One of the major difficulties facing the precast and prestressed concrete industry in earthquake prone areas of the United States is the provision of adequate ductility in prefabricated structural systems that are used as the lateral load resisting system. Researchers have focused on solutions to this problem, and in September 1986, a PCI workshop was dedicated to this subject area. A paper presented by Mueller at the workshop incorporated the following conclusion:

"To markedly change the market position of precast and prestressed concrete in areas of high seismicity, a more radical approach is needed: base (seismic) isolation. While part of the research and development funds should be spent on determining the actual earthquake resistance of existing systems, a large part should be spent on developing a pre-engineered, prefabricated, modular base isolation system rather than on trying to achieve marginal improvements with conventional concepts. Rather than trying to undercut the competition with cheaper precast and prestressed concrete solutions, the market strategy should be to offer, for the same price as the competition, a better product: an earthquake protected rather than an earthquake resistant system."

Clearly, Mueller’s conclusion indicates significant benefits for the precast industry by combining the advantages of seismic isolation with those of precast and prestressed construction. The completed, 12-story precast Union House in Auckland, New Zealand, described later in this paper, attests to the fact that it is both economic and practical. There are currently five bridges, three buildings and three major pieces of equipment in the United States that have been or are in the process of being constructed using seismic isolation principles. Others are in the design development phase, including an eight-story hospital.

This paper discusses the background, basic concepts, design principles, feasibility and code issues of seismic isolation. A brief summary of the projects completed to date and the longevity and design issues associated with elastomeric bearings are also discussed. In addition, the design force implications for precast and prestressed construction are presented together with a cost-benefit evaluation.

**BACKGROUND**

In an article in *Architecture Magazine* by Chris Arnold, the introduction of innovative solutions to earthquake engineering problems is discussed. The
early part of this background material has been extracted from that article.

“Because of today’s concern for liability, engineering innovations must be exhaustively tested and analytically proven to a degree unknown in the past. Early engineers were respected for their ability to design from first principles and produce designs that were conceptually right even though analytical or laboratory methods did not exist that would remove all doubt. For the most part, the great early engineers removed doubt by force of their personality and confidence. They took risks that would be unthinkable today.

The field of seismic design is, as perhaps befits a subject directly concerned with both life safety and uncertainty, cautious and slow to innovate. In practice, improved seismic design does not represent a market opportunity because seismic safety is generally taken for granted. Like other code-dominated issues, and like airplane safety, seismic safety has never been much of a selling point. Money diverted to improve seismic resistance is often seen as a detraction from more visible and enjoyable attributes.

Improvement in seismic safety, since about the time of the San Francisco earthquake of 1906, has been due primarily to acceptance of ever-increasing force levels to which buildings must be designed. Innovation has been confined to the development and acceptance of economical structural systems that perform reasonably well, accommodate architectural demands such as open exteriors and the absence of interior walls, and enable materials such as steel and reinforced concrete to compete in the marketplace on near equal terms.

The vocabulary of seismic design is limited. The choices for lateral resistance lie among shear walls, braced frames and moment-resistant frames. Over the years, these have been refined and their details developed, and methods of analysis and modeling have improved and reduced uncertainty. But the basic structure has not changed: construct a very strong building and attach it securely to the ground. This approach of arm wrestling with nature is neither clever nor subtle, and it involves considerable compromise.

Although codes have mandated steadily increasing force levels, a building in a severe earthquake may still encounter forces several times above its designed capacity if it were able to remain elastic. This discrepancy between seismic demand and capacity is traditionally accommodated by reserve capacity or ductility of the structural system. The ability of materials and structural members to dissipate energy by permanent deformation — which is called ductility — greatly reduces the likelihood of total collapse.”

Modern buildings contain extremely sensitive and costly equipment that has become vital in business, commerce, education, and health care. Electronically kept 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, 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 Fig. 1).

“In the last decade, an alternative to the brute force response to nature
has finally reached a stage, if not of fruition, at least of application. This approach is obvious and easily explainable at the cocktail party level: Why not detach the building from the ground in such a way that the earthquake motions are not transmitted up through the building, or are at least greatly reduced? This conceptually simple idea has required much research to make it feasible, and only with modern computerized analysis has it become possible. Application has depended on very sophisticated materials research into both natural and composite materials in order to provide the necessary performance.

This new concept, now generally termed “seismic isolation,” meets all the criteria for a classic modern technological innovation. Imaginative advances in conceptual thinking were necessary, as were materials new to the industry, and ideas have developed simultaneously on a worldwide basis. But the method threatens conventional and established design procedures, so the road to seismic isolation innovation is paved with argument, head shaking, and bureaucratic caution. All, to some extent, well-intentioned and necessary, given our litigious society.”

Buildings mounted on an isolation system can prevent most of the horizontal movement of the ground from
Fig. 2. The deformation pattern in an isolated structure during an earthquake. Movement takes place at level of isolators. Floor accelerations are low; the building, its occupants, and its loose contents are safe (from Ref. 43).

being transmitted to the building. This results in a significant reduction in floor accelerations and interstory drifts, thereby providing protection to the building contents and components (see Fig. 2).

The principle of seismic isolation is to introduce flexibility at the base of a structure in the horizontal plane, while at the same time introducing damping elements to restrict the amplitude or extent of the motion caused by the earthquake. The essential feature is to ensure that the period of the structure is well above that of the predominant earthquake input.

The concept of isolating structures from the damaging effects of earthquakes is not new. The first U.S. patent for a seismic isolation scheme was taken out in 1907, and since that time several proposals with similar objectives have been made. Nevertheless, until the last decade, few structures have been designed and built using these principles.

New impetus was given to the concept of seismic isolation by the successful development of mechanical energy dissipators and elastomers with high damping properties. Mechanical energy dissipators, when used in combination with a flexible isolation device, can control the response of the structure by limiting displacements and forces, thereby significantly improving seismic performance. The seismic energy is dissipated in components spe-
cifically designed for that purpose, relieving structural elements such as beams and columns from energy dissipation roles (and thus damage).

There are now approximately 100 civil engineering structures throughout the world that have been constructed using the principles of seismic isolation, and Kelly and Buckle have both summarized this activity in recent publications.

The advantages of seismic isolation include:
1. The ability to eliminate ductility demand.
2. Significant reduction of structural and nonstructural damage.
3. Enhancement of the safety of the building contents, occupants, and architectural facades.
4. Reduction of seismic design forces.

In addition to the safety issues, the elimination of the ductility demand on the structural system removes one of the major problem areas for the use of precast and prestressed construction in earthquake prone areas of the world. With seismic isolation, reduction factors of 5 to 10 in the elastic forces may be achieved for stiff structures on firm soils, such as low and medium rise buildings, nuclear power plants, bridges and many types of industrial equipment. However, these force reductions are not always available and some tectonic and soil conditions may preclude the use of seismic isolation altogether.

AN IDEA WHOSE TIME HAS COME

As noted above, and discussed in more detail later, the elastomeric bearing and the mechanical damper are fundamental components in most practical seismic isolation schemes. But it is not just the invention of the elastomeric bearing and the energy dissipator which has made seismic isolation a practical reality. Three other parallel, but independent, developments have also contributed to its recent success.

The first of these was the development of reliable software for the computer analysis of structures so as to predict their performance and determine design parameters. Work has been in progress for more than 15 years on the inelastic analysis of structural systems for dynamic loads, and there are many available computer programs. Application to seismically isolated structures is straightforward and correlation studies with model tests show the software to be soundly based.

The second development was the use of shaking tables, which are able to simulate the effects of real recorded earthquake ground motions on different types of structures. The results of shaking table tests over the last 12 years have provided another mechanism to enhance confidence in the way buildings respond during real earthquakes. In addition, the results provide an opportunity to validate computer modeling techniques which are then used on full-sized structures.

A third important development is the skill of the engineering seismologist in estimating ground motions at a particular site. Recent advances in seismology have improved the prediction of site-specific ground motions which take into account fault distances, local and global geology, and return period. These design motions are basic input to the computer modeling of seismically isolated systems and are a vital step in the estimation of system performance.

In summary then, five recent developments are together responsible for the claim that isolation is indeed an idea whose time has come:
1. The design and manufacture of high quality elastomeric (rubber) pads, frequently called bearings, that are used to support the weight of the structure but at the same time release it from earthquake induced forces.
2. The design and manufacture of
mechanical energy dissipators (absorbers) and high damping elastomers that are used to reduce the movement across the bearings to practical and acceptable levels and to resist wind loads.

3. The development and acceptance of computer software for the analysis of seismically isolated structures which includes nonlinear material properties and the time varying nature of the earthquake loads.

4. The ability to perform shaking table tests using real recorded earthquake ground motions to evaluate the performance of structures and provide results to validate computer modeling techniques.

5. The continuing development of procedures for estimating site-specific earthquake ground motions for different return periods.

CONSIDERATIONS FOR SEISMIC ISOLATION

Seismic isolation should be considered if any of the following situations apply:

- Increased building safety, post-earthquake operability and business survivability are desired.
- Reduced lateral design forces are desired.
- Alternate forms of construction with limited ductility capacity (such as precast and prestressed 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 owners, architects and engineers 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 Uniform Building Code (UBC) incorporated in the Structural Engineers Association of California (SEAOC) Recommended Lateral Force Requirements states that buildings designed in accordance with its provisions will:

- Resist minor earthquakes without damage.
- Resist moderate earthquakes without structural damage but with some nonstructural damage.
- Resist major earthquakes without collapse but with structural and nonstructural damage.

These principles of performance also apply to buildings that are rehabilitated to code level design forces.

It is clear that modern design codes do not protect a structure or its contents against damage in a major earthquake. Only life safety is preserved.

Seismic isolation gives the option of providing a building with better performance characteristics than our current code approach. It thus represents a major step forward in the seismic design of civil engineering structures. In the case of building retrofit, the need for isolation may be more obvious: the structure may simply not be safe in its present condition. In such cases, seismic isolation should be compared with alternative solutions, such as strengthening, to determine the cost effectiveness.

SOLUTIONS FOR NONSTRUCTURAL DAMAGE

One of the more difficult issues to address from a conventional design viewpoint is that of reducing nonstructural and building content damage. Often ignored, this can be very expensive to incorporate in conventional design. In fact, the additional cost to satisfy the more stringent bracing requirements of nonstructural elements in a California hospital is about $2 to $4 per sq ft more than that required for a conventional building.

There are two primary mechanisms
that cause nonstructural damage. The first is related to interstory drift between floors, and the second is related to floor accelerations. Interstory drift is defined as the relative displacement that occurs between two floors divided by the story height. Floor accelerations are the absolute accelerations that occur as a result of the earthquake, and in conventional construction, floor accelerations generally increase up the height of the building. Together, these two components cause damage to the building contents, architectural facades, partitions, piping and ductwork, ceilings, building equipment and elevators (see Fig. 1).

There are two different design philosophies that are debated within the structural engineering profession which deal with minimizing nonstructural damage. One argues that stiff buildings are the best solution. Stiff buildings reduce interstory drift, but 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 is true, flexible buildings have much higher interstory drifts, and this accentuates 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 (see Fig. 2), since it significantly reduces both floor accelerations and interstory drift and thus provides a practical solution to the difficult problem of reducing nonstructural earthquake damage.

**BASIC ELEMENTS OF SEISMIC ISOLATION SYSTEMS**

There are three basic elements in any practical seismic isolation system.

These are:

1. A flexible mounting (support) so that the period of vibration of the total system is lengthened sufficiently to reduce the force response.
2. A damper or energy dissipator so that the relative deflections between building and ground can be controlled to a practical design level.
3. A means of providing rigidity under low (service) load levels such as wind and minor earthquakes.

**Flexibility**

Bridge structures, for many years, have been supported on elastomeric...
bearings, and as a consequence have already been designed with flexible mounts. It is equally possible to support buildings on elastomeric bearings, and numerous examples exist where buildings have been successfully mounted on pads. To date, this has been done primarily for vertical vibration isolation rather than seismic protection. More than 100 buildings in Europe and Australia have been built on rubber bearings to isolate them from vertical vibrations from subway systems. By increasing the thickness of the bearing, additional lateral flexibility and period shift for seismic isolation can be attained.

While the introduction of lateral flexibility may be highly desirable, additional vertical flexibility is not. Vertical rigidity is maintained by constructing the rubber bearings in layers and sandwiching steel reinforcing plates between each layer. The reinforcing plates, which are bonded to each layer of rubber, constrain lateral deformation of the rubber under vertical load, resulting in vertical stiffnesses several hundred times the lateral stiffness and comparable to the vertical stiffness of a conventional structural column.

An elastomeric bearing is not the only means of introducing flexibility into a structure, but it certainly appears to be the most practical method and the one with the widest range of application. Other possible devices include rollers,
friction slip plates, cable suspensions, sleeved piles and rocking (stepping) foundations.

Figs. 3 through 7 show the various devices and mechanisms for attaining flexibility in isolated structures.

The reduction in force with increasing period (flexibility) is shown schematically in the force-response curve of Fig. 8. Substantial reductions in base shear are possible if the period of vibration of the structure is significantly lengthened. The reduction in force response illustrated in Fig. 8 is primarily dependent on the characteristics of the earthquake ground motion and the period of the fixed-base structure. Further, the additional flexibility needed to lengthen the period of the structure will give rise to large relative displacements across the flexible mount. Fig. 9 shows an idealized displacement response curve from which displacements are seen to increase with increasing period (flexibility).

However, as shown in Fig. 10, if substantial additional damping can be introduced into the isolation system, the displacement problem can be overcome. It can also be seen that increasing the damping reduces the forces on the structure at a given period and removes much of the sensitivity to variations in ground motion characteristics, as indicated by the smoother force-response curves at higher damping levels.
Energy Dissipation

One of the most effective means of providing a substantial level of damping is through hysteretic energy dissipation. The term "hysteretic" refers to the offset in the loading and unloading curves under cyclic loading. Work done during loading is not completely recovered during unloading and the difference is lost as heat. Fig. 11 shows an idealized force-displacement loop where the enclosed area is a measure of the energy dissipated during one cycle of motion. Mechanical devices which use the plastic deformation of either mild steel or lead to achieve this behavior have been developed,14–18 and several mechanical energy dissipation devices developed in New Zealand19 are shown in Fig. 12.
Fig. 12. Various mechanical energy dissipators.
Many engineering materials are hysteretic by nature, and all elastomers exhibit this property to some extent. By the addition of special purpose fillers to elastomers, it is possible to increase their natural hysteresis without unduly affecting their mechanical properties. Such a technique gives a useful source of damping, but so far it has not been possible to achieve the same level of energy dissipation as is possible with a lead-rubber elastomeric bearing.

Friction is another source of energy dissipation which is used to limit deflections. However, it can be a difficult source to quantify, and reliable systems tend to be of a magnitude more expensive than either of the above mechanisms. A further disadvantage is that most frictional devices are not self-centering, and a permanent offset between the sliding parts is a real possibility after an earthquake.

Hydraulic damping has been used successfully in some bridges and a few special purpose structures. Potentially high damping forces are possible from viscous fluid flow, but maintenance requirements and high initial cost have restricted the use of these particular devices.

Rigidity for Low Lateral Loads

While lateral flexibility is highly desirable for high seismic loads, it is clearly undesirable to have a structural system which will vibrate perceptibly under frequently occurring loads such as minor earthquakes or wind loads.

Lead-rubber bearings (and other mechanical energy dissipators) provide the desired low load rigidity by virtue of their high elastic stiffness (see Fig. 11). Some other seismic isolation systems require a wind restraint device for this purpose—typically a rigid component designed to fail under a given level of lateral load. This can result in a shock loading being transferred to the structure due to the sudden loss of load in the restraint. Nonsymmetrical failure of such devices can also introduce undesirable torsional effects in a building. Further, such devices will need to be replaced after each failure.

Table 1 summarizes the sources of flexibility and energy dissipation that have been discussed here. 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.

<table>
<thead>
<tr>
<th>Flexible mounting systems</th>
<th>Unreinforced rubber blocks</th>
<th>Elastomeric bearings (reinforced rubber blocks)</th>
<th>Sliding plates</th>
<th>Roller and/or ball bearings</th>
<th>Sleeved piles</th>
<th>Rocking systems</th>
<th>Suspended floors</th>
<th>Air cushions</th>
<th>Slinky springs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damping devices/mechanisms</td>
<td>Plastic deformation of a metal: Friction</td>
<td>High damping elastomers</td>
<td>Viscous fluid damping</td>
<td>Tuned mass damping</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**PERFORMANCE OF ELASTOMERIC BEARINGS**

As the application of seismic isolation continues to increase, the design profession is now focusing its attention on the performance of the structural components that make it work. To date, more than 90 percent of the 100 completed isolation projects utilize an elastomeric bearing as the element of flexibility. Furthermore, the more than 100 buildings that are vertically isolated to avoid
subway vibrations all incorporate elastomeric bearings. Some of these applications have more than a 40 year history. In addition to these applications, reinforced elastomeric bearings have been used as bridge bearings for over 40 years and unreinforced elastomeric bearings have been used for over 95 years. The use of elastomeric bearings is, therefore, not new.

What is extremely important from an isolation design perspective is the long term stability of the shear stiffness properties of the bearings, since this provides the period lengthening component of an isolation system. Although the amount of long term data is not extensive, what is available shows that the mechanical properties of natural rubber bearings are stable with time.

Data are available for two case histories of natural rubber elastomeric bearings. One example is of rubber mountings manufactured in 1953 by the Andre Rubber Company for the isolation of a gun testing machine at Fort Halstead in Kent, England. The individual units are natural rubber single layers, 18½ x 8 in. (470 x 203 mm) in plan by 3½ in. (89 mm) thick, bonded between steel plates. The machine is supported on 162 of these in triangular stacks.

The machine has been in use for nearly 30 years and the bearings are still functioning perfectly. Some spare bearings were manufactured at the same time and were stored beside the machine. Two were selected that could be identified with the original test data. These bearings were retested in February 1983 at the Rubber and Plastics Research Association. One bearing had increased in stiffness by 15½ percent and the other by 4½ percent. This represents a remarkably small change in stiffness over such a long period, and aging mechanisms are such that the probability is that most of this stiffening took place over the first few years; very little further change would now be observed.

Recently, two natural rubber bridge bearings were removed from a motorway bridge in Kent for testing under a Ministry of Transport project. Testing after 20 years of service showed that the shear stiffness had increased by only 10 percent above the original specified value.

It is worth noting that a reasonably large change in shear stiffness can be tolerated in an isolation system before the forces transmitted to the structure by the bearings are significantly affected. For example, a 25 percent change in shear stiffness makes only a 10 percent change in the period, and since most earthquake response spectra are relatively flat in the period range of an isolated structure, there will be little change to the seismic response as a consequence.

### SEISMIC ISOLATION DESIGN PRINCIPLES

The design principles for seismic isolation are illustrated in Fig. 13. The top curve in this figure shows the realistic elastic forces based on a 5 percent ground response spectrum which will be imposed on a nonisolated structure from the new SEAOC Blue Book. The spectrum shown is for a rock site if the structure has sufficient strength to resist this level of load. The lowest curve shows the forces for which the Uniform Building Code requires a structure be designed, 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 other factors. The difference between the maximum elastic force and the probable yield strength is an approximate
indication of the energy which must be absorbed by ductility in the structural elements.

When a building is isolated, the maximum elastic forces are reduced considerably due to period shift and energy dissipation, as shown in Figs. 8 and 10. The elastic forces on a seismically isolated structure are shown by the small dashed curve of Fig. 13. This curve corresponds to a system with approximately 30 percent equivalent viscous damping. If a relatively stiff building with a fixed base fundamental period of 0.8 seconds or less is isolated, then its fundamental period after isolation will be increased into the 1.5 to 2.5 second range (Fig. 8).

This results in a reduced UBC design force (Fig. 13), but more important is that in the 1.5 to 2.5 second range, the probable yield strength of the isolated building is approximately the same as the maximum force to which it will be subjected. Therefore, there will be little or no ductility demand on the structural system. Furthermore, the lateral design forces are reduced by approximately 50 percent when compared to the UBC design forces for a conventional structure.

SEISMIC ISOLATION FEASIBILITY

Structures are generally suitable for seismic isolation if the following conditions exist:
- Height of structure is two stories or greater (unless unusually heavy).
- Site clearance permits horizontal displacements at the base of about 6 in. (152 mm).

![Fig. 13. Design principles of seismic isolation.](image-url)
• Geometry of structure is not slender in elevation.
• Lateral wind loads or other non-seismic loads are less than approximately 10 percent of the weight of the structure.
• Site ground motion is not dominated by long period components.

Each project must be assessed individually and early in the design phase to determine its suitability for seismic isolation. For this assessment, there are differences between new construction and the retrofit of existing structures.

In new construction there are two potential locations for the isolators, as shown in Fig. 14. The sub-basement option has the advantage of minimal architectural disruption, but it requires an additional structural floor. Placing the isolators at the top of the basement columns is more attractive from a first cost perspective, but these columns may need additional strength if elastic performance is required.

Another consideration when assessing the suitability of a structure 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. However, 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 lake bed area of the 1985 Mexico City earthquake. Lengthening the period of a stiff structure on these soil conditions will amplify rather than reduce the ground motions. Hence, for a site on the Mexico City lake bed, seismic isolation should not be considered.

Retrofit of structures to improve their earthquake safety involves additional considerations, compared with new construction, because of the constraints already present. Buildings with sub-basements or piled foundations are more suitable for isolation retrofit. Bridge superstructures are also very suitable since they are generally supported on steel bearings. Replacement of these bearings with elastomeric type bearings is a relatively simple, low cost operation and will lead to a significant reduction in earthquake forces. In addition, it permits the option of redistributing forces away from weak substructures into substructures more capable of sustaining earthquake loads.

Buildings are often more difficult to retrofit than bridges. However, compared to conventional strengthening schemes, seismic isolation is an attractive alternative. This is because few, if any, new structural elements are required above the isolation level; most construction work is confined to the basement level. Conventional methods

---

Fig. 14. Optional locations for seismic isolators in buildings.
<table>
<thead>
<tr>
<th>Country</th>
<th>Constructed facilities</th>
<th>Active organizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belgium</td>
<td></td>
<td>D'Appolonia</td>
</tr>
<tr>
<td>Canada</td>
<td>1 coal shiploader, Prince Rupert B.C.</td>
<td>University of British Columbia, Vancouver, Swan Wooster Engineering, Vancouver, Khanna Consultants Intl.</td>
</tr>
<tr>
<td>Chile</td>
<td>1 ore shiploader, Guacolda</td>
<td>University of Chile</td>
</tr>
<tr>
<td>England</td>
<td>1 nuclear fuel reprocessing plant</td>
<td>Malaysian Rubber Producers Research Association, Rubber Consultants, Ltd., Imperial College of Science and Technology, London, University of Southhampton</td>
</tr>
<tr>
<td>Finland</td>
<td></td>
<td>Imatran Voima Company</td>
</tr>
<tr>
<td>France</td>
<td>4 houses (1977-1982), 1 3-story school, Lambesc (1978), 1 nuclear waste storage facility (1982), 2 nuclear power plants, Cruas and Le Pellirin</td>
<td>Centre National de la Recherche Scientifique, Marseille; Centre d'Etudes Nucleaires de Saclay, Electricité de France, Spie Batignolies</td>
</tr>
<tr>
<td>Germany</td>
<td></td>
<td>GERB — Gesellschaft für Isolierungen; Berlin; Kraftwerke Union; Engineering Decision Analysis; Polensky and Zolher, Frankfurt Jupp Grote</td>
</tr>
<tr>
<td>Greece</td>
<td>2 office buildings, Athens</td>
<td>University of Patras</td>
</tr>
<tr>
<td>Hungary</td>
<td></td>
<td>Technical University of Budapest</td>
</tr>
<tr>
<td>Iceland</td>
<td>5 bridges</td>
<td>Iceland Highway Department</td>
</tr>
<tr>
<td>India</td>
<td></td>
<td>University of Roorkee, Bhabha Atomic Research Center</td>
</tr>
</tbody>
</table>
### Table 2 (cont.). Directory of worldwide base isolation activity excluding the United States.

<table>
<thead>
<tr>
<th>Country</th>
<th>Constructed facilities</th>
<th>Active organizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iran/Iraq</td>
<td>1 nuclear power plant, Kanun River (1978)</td>
<td>Israel Institute of Technology, Haifa</td>
</tr>
<tr>
<td></td>
<td>1 12-story building, Teheran (1968)</td>
<td></td>
</tr>
<tr>
<td>Israel</td>
<td></td>
<td>Israel Institute of Technology, Haifa</td>
</tr>
<tr>
<td>Italy*</td>
<td>3 viaducts</td>
<td>Autostrade, Roma</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TESIT, Milano</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Polytechnic of Milan</td>
</tr>
<tr>
<td>Japan*</td>
<td>1 airport control tower</td>
<td>Taisei Corporation, Tokyo Kenchiku, Okumura Corp., Obayashi-gumi, Ltd., Oiles Industry, Sumitomo</td>
</tr>
<tr>
<td></td>
<td>3 residential houses</td>
<td>Construction, Takenaka Komuten Co., Kajima Corp., Shimizu Construction Co., Ministry of Construction, University of Tokyo, Tohoku University, CRIEPI/Federation of Electric Power Companies</td>
</tr>
<tr>
<td></td>
<td>5 research laboratories</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 museum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3 office buildings</td>
<td></td>
</tr>
<tr>
<td>Mexico</td>
<td>1 4-story school, Mexico City (1974)</td>
<td>Gonzales Flores, Consulting Engineer</td>
</tr>
<tr>
<td>Middle East</td>
<td>Storage tanks for liquid propane and butane†</td>
<td></td>
</tr>
<tr>
<td>New Zealand</td>
<td>2 office buildings, Auckland and Wellington (1982 and 1983)</td>
<td>Physics and Engineering Laboratory, DSIR</td>
</tr>
<tr>
<td></td>
<td>37 bridges</td>
<td>University of Auckland</td>
</tr>
<tr>
<td></td>
<td>2 industrial structures (chimney and boiler)</td>
<td>Ministry of Works and Development</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beca, Carter, Hollings &amp; Ferner</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Holmes Consulting Group</td>
</tr>
<tr>
<td>Roumania</td>
<td></td>
<td>Polytechnic Institute of Jassy</td>
</tr>
<tr>
<td>South Africa</td>
<td>1 nuclear power plant, Koeberg</td>
<td></td>
</tr>
<tr>
<td>Soviet Union</td>
<td>1 7-story building, Sevastopol</td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td></td>
<td>Swiss Federal Institute of Technology, Zurich</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Seisma A.G.</td>
</tr>
<tr>
<td>Yugoslavia</td>
<td>1 3-story school (1969), Skopje</td>
<td>University of &quot;Kiril and Metodij&quot;</td>
</tr>
</tbody>
</table>

* Both Italy and Japan also have a large number of partially isolated bridges which are not included in above table.
† These five tanks are only partially isolated for seismic loads and have therefore not been counted in above table.
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. There are approximately 100 isolated structures already built or under construction. Precise numbers are difficult to obtain, but this figure is considered to be a conservative estimate—the actual figure is increasing rapidly because of the activity in Japan, New Zealand, France and the United States.

This number includes 31 buildings (houses, schools, research laboratories, office buildings), 49 bridges, 6 nuclear power-related structures, and 9 miscellaneous structures (mainly of an industrial type). However, it does not include 136 bridges known to be partially isolated for seismic loads in Japan and Italy.

This figure is also an underestimate. Partial isolation (i.e., isolation in one horizontal direction only) has been popular for bridges in several countries for many years, and the total number of such structural systems is today probably closer to 200.

Table 2 summarizes this activity by country (alphabetic order), giving a list of known constructed facilities as well as consultants, governmental agencies and research establishments who are active in seismic isolation. Examination of this table will show that significant activity has taken place in China, Japan, Europe and New Zealand.

Of interest to the precast concrete industry from this list is the 12-story prefabricated concrete Union House in New Zealand. The completed structure and a section through the building is shown in Figs. 15 and 16. This building uses sleeved piles to provide flexibility and steel cantilever plates as energy dissipators.
Fig. 16. Section through Union House showing sleeved piles and steel energy dissipators.
APPLICATIONS IN THE UNITED STATES

Table 3 lists eleven known applications of seismic isolation in the United States. It can be seen that significant activity has taken place in this country during the past 2 years. A short description of each project follows.

Buildings

The Foothill Communities Law and Justice Center in San Bernardino County, California, is a five-story, concentrically braced steel frame building, 415 x 110 ft (126 x 33.6 m) in plan, and seated on 98 high-damping rubber isolators as shown in Figs. 17 and 18. The structure is clad with glass fiber reinforced concrete panels. Completed in 1986, the building is sited within 14 miles (23 km) of the San Andreas fault and within 2 miles (3.2 km) of 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 at Redlands in October 1985, 20 miles (32 km) 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 acceleration amplification by factors of 2 to 5 — which is expected in conventional (nonisolated) structures. Despite the small size of this earthquake, the performance of this building, as recorded by the California Strong Motion Instrumentation Program, is encouraging evidence that isolation is indeed beneficial to the structure.

The Salt Lake City and County Building is a five-story, Romanesque style structure measuring 265 x 130 ft (80.8 x 39.6 m) in plan (see Fig. 19). Constructed between 1892 and 1894, it is built of unreinforced brick, masonry, and sandstone. A 12-story clock tower is centrally located and is also constructed from unreinforced masonry.

As part of a complete restoration package for the building, seismic retrofit using isolation is currently under construction. A total of 447 lead-filled isolators are being installed on existing foundations, and the building weight will be transferred to the isolators beginning the summer of 1988. When complete, the structure will be protected against damage for a 0.2g earth-
Fig. 18. Section through the Foothill Communities Law and Justice Center showing location of isolators in sub-basement.
Table 3. Directory of seismically isolated structures in the United States (completed or under construction as of February 1988).

<table>
<thead>
<tr>
<th>Structure</th>
<th>Owner</th>
<th>Date</th>
<th>Description/Engineers</th>
</tr>
</thead>
<tbody>
<tr>
<td>230kV Circuit Breakers</td>
<td>California Department of Water Resources</td>
<td>1979</td>
<td>Elastomeric Isolators/Delfosse</td>
</tr>
<tr>
<td>Sierra Point Bridge Retrofit</td>
<td>California Department of Transportation</td>
<td>1984/5</td>
<td>Lead-filled elastomeric bearings/Caltrans, DIS</td>
</tr>
<tr>
<td>(US101)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foothill Communities Law and</td>
<td>County of San Bernardino</td>
<td>1985/6</td>
<td>“High-damping” elastomeric bearing (filled rubber)/ Reid</td>
</tr>
<tr>
<td>Justice Center</td>
<td></td>
<td></td>
<td>and Tarics, J.M. Kelly, MRPRA</td>
</tr>
<tr>
<td>Santa Ana River Bridge Retrofit</td>
<td>Metropolitan Water District of Southern</td>
<td>1986/7</td>
<td>Lead-filled elastomeric bearings/Lindvall-Richter, DIS</td>
</tr>
<tr>
<td></td>
<td>California</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salt Lake City and County</td>
<td>Salt Lake City Corporation</td>
<td>1987</td>
<td>Lead-filled elastomeric bearings/Forell Elsesser, E.W.</td>
</tr>
<tr>
<td>Building Restoration</td>
<td></td>
<td></td>
<td>Allen &amp; Associates, DIS</td>
</tr>
<tr>
<td>Mark II Detector (equipment)</td>
<td>Stanford Linear Accelerator Center</td>
<td>1987</td>
<td>Lead-filled elastomeric bearings/SLAC, DIS</td>
</tr>
<tr>
<td>Main Yard Vehicle Access Bridge</td>
<td>Los Angeles County Transportation Commission</td>
<td>1987</td>
<td>Lead-filled elastomeric bearings/Southern California Rail</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Consultants, DIS</td>
</tr>
<tr>
<td>Eel River Bridge Retrofit (US101)</td>
<td>California Department of Transportation</td>
<td>1987</td>
<td>Lead-filled elastomeric bearings/Caltrans, DIS</td>
</tr>
<tr>
<td>Salt Lake City Manufacturing</td>
<td>Evans and Sutherland</td>
<td>1987</td>
<td>Lead-filled elastomeric bearings/Reaveley, DIS</td>
</tr>
<tr>
<td>Facility</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Argon Calorimeter (Equipment)</td>
<td>Stanford Linear Accelerator Center</td>
<td>1987</td>
<td>Lead-filled elastomeric bearings/SLAC, DIS</td>
</tr>
<tr>
<td>All American Canal Bridge</td>
<td>California Department of Transportation</td>
<td>1987</td>
<td>Lead-filled elastomeric bearings/Caltrans, DIS</td>
</tr>
</tbody>
</table>

Note:
1. DIS = Dynamic Isolation Systems, Berkeley, California.
   MRPRA = Malaysian Rubber Producers Research Associates.
   Caltrans = California Department of Transportation.
quake event. Further, the isolators are designed to be stable up to and including a 0.4g event, should an earthquake greater than the design event be experienced at the site.

The Evans and Sutherland Building in Salt Lake City is a new, four-story, steel moment frame manufacturing facility for flight simulators. The building measures 280 x 160 ft (85.4 x 48.8 m) in plan and rests on 98 lead-filled elastomeric bearings.

**Bridges**

The Sierra Point Overhead is a highly skewed bridge on ten simply supported spans which vary in length from 26 to 100 ft (7.93 x 30.5 m) as shown in Fig. 20. Supported on 27 nonductile columns, each 3 ft (0.91 m) in diameter, the bridge was particularly vulnerable because it could resist only 25 percent of the design event for the site. Retrofit by isolation was feasible because existing steel bearings could be removed and replaced by lead-rubber isolation bearings. No column strengthening was necessary because the factor of 6 reduction in force was sufficient to ensure elastic behavior.

The Santa Ana River Bridge carries the Upper Feeder water pipeline into the Los Angeles Basin for the Metropolitan Water District of Southern California as shown in Fig. 21. The existing piers and steel trusses were understrength and isolation bearings were used to reduce the seismic forces to below the existing capacities. No strengthening of the piers or trusses was then necessary.

Other bridge isolation retrofits recently completed or under construction include the Eel River Bridge for Caltrans 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, all in California.

**Industrial Equipment**

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. These 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. This was necessary to obtain the required period shift and, as a consequence, stability issues were a concern in the design.

In contrast, the Mark II Detector at the Stanford Linear Accelerator Center is of substantial weight [3200 kips (14200 kN)]. Its isolation by four lead-filled elastomeric bearings is now complete. An integral part of the Department of Energy’s new Linear Collider at
Fig. 20. Sierra Point Overhead, U.S. Highway 101 near San Francisco, California.

Fig. 21. MWDSC Pipeline Bridge over Santa Ana River, Riverside County, California.
Stanford University, this fragile item of industrial equipment is now protected against damage for a 0.6g NRC response spectrum, which is representative of the earthquake anticipated on the adjacent San Andreas fault. A second item for the collider, the Liquid Argon Calorimeter, is also being isolated in the same way.

CODE CONSIDERATIONS — STRUCTURES AND ISOLATORS

Recognizing the growing importance of seismic isolation as an approach to reducing structural response due to earthquakes, the Structural Engineers Associations of Northern and Southern California created committees to develop necessary guidelines for the design of seismically isolated buildings. The Northern group (SEAONC) completed tentative design guidelines for conventional buildings in September 1986, and these are now being reviewed by the State Seismology Committee for possible adoption in the Uniform Building Code. In January 1987, the Building Safety Board of the California Office of Statewide Health Planning and Development adopted "An Acceptable Method for Design and Review of Hospital Buildings Utilizing Base Isolation."

The background on the approach and objectives of the SEAONC document for the isolation of conventional buildings is provided in the document’s introduction, an extract of which is given below:

"The advantages of seismic isolation and the recent advancements in isolation system products have already led to the design and construction of a number of seismically isolated buildings and bridges in California and Salt Lake City. This activity has, in turn, identified a need to supplement existing codes with design requirements developed specifically for seismically isolated buildings. This need is shared by the public which requires assurance that seismically isolated buildings are ‘safe’ and by the engineering profession which requires a minimum standard upon which design and construction can be based. Accordingly, the Base Isolation Subcommittee of the Seismology Committee of the Structural Engineers Association of Northern California has developed the following seismic isolation design requirements to supplement the 'Recommended Lateral Force Requirements and Commentary' (Blue Book) document."

"Rather than addressing a specific method of seismic isolation, the document provides general design requirements applicable to a wide range of possible seismic isolation schemes. In remaining general, the design requirements rely on mandatory testing of isolation system hardware to confirm the engineering parameters used in the design and to verify the overall adequacy of the isolation system. Some systems may not be capable of demonstrating acceptability by test and, consequently, would not be permitted.

In general, acceptable seismic isolation systems will:

- Remain stable for required design displacements.
- Provide increasing resistance with increasing displacement.
- Not degrade under repeated cyclic load.
- Have quantifiable engineering parameters (e.g., force-deflection characteristics and damping).

"The design requirements are based on a severe level of earthquake ground motion which corresponds, approximately, to a 500-year return period event as described by the recommended ground motion spectra of the Blue..."
Book. The isolation system, including all connections and supporting structural elements, is required to be designed (and tested) for the full response effects of this level of ground motion.

There are several codes throughout the world that provide criteria for the design of elastomeric bearings. These provisions vary in their specific requirements but generally address the following issues:

- Shear displacement
- Vertical displacement
- Rotational capacity
- Vertical loads
- Stability

In essence, these criteria cover the design aspects of elastomeric bearings subject to vertical loads and induced shear (thermal, creep) displacements. However, these two conditions are not sufficient to cover the additional effects imposed by earthquakes. Consequently, the existing criteria must be modified to include earthquake loads. Elastomeric bearings which are used for seismic isolation may be subjected to large, earthquake induced displacements. Earthquakes are infrequently occurring events and the factors of safety required under these circumstances will be different than those required for more frequently occurring loads.

Since the primary design parameter for earthquake loading is the displacement of the bearing, the design guidelines must be capable of incorporating this displacement in a logical and consistent manner. Current AASHTO design requirements for elastomeric bearings in the United States limit vertical loads by use of a limiting compressive stress and therefore do not have a mechanism for including the simultaneous effects of seismic lateral displacements.

The British Specification BE 1/76 and its more recent successor, BS 5400, recognize that shear strains are induced in reinforced bearings by both compression and shear deformation. In these codes, the sum of these shear strains is limited to a proportion of the elongation-at-break of the rubber. The proportion (1/2 or 1/3) is a function of the loading type.

These British codes are probably the most widely used elastomeric bearing specifications in the world. They have served as the basis of bearing design in Great Britain, Australia, New Zealand, and parts of Europe and Asia. Since the approach used in BE 1/76 and BS 5400 incorporates shear deformation as part of the criteria, they can be readily modified for seismic isolation bearings.

**DESIGN FORCES FOR PRECAST CONSTRUCTION**

One of the benefits of seismic isolation is its ability to eliminate the ductility demand on a structural system. This helps alleviate one of the current constraints on the design of precast moment frames, since they must qualify as "ductile moment-resisting frames" if they are intended to resist earthquake induced lateral loads. In addition to eliminating the ductility demand, the force reduction feature of seismic isolation may also reduce the design forces for some structural systems.

Englekirk and Selna give a summary of the design forces required by the Uniform Building Code (UBC) for prefabricated concrete systems. Their development of design forces is summarized herein to provide a comparison with the forces that would be required for the seismic isolation design of a prefabricated system.

The design base shear for buildings is developed in Section 2312 of the 1985 UBC as:

\[ V = ZIKCSW \]

where

- \( V \) = total lateral force or base shear force
Z = numerical coefficient dependent on seismic zone  
K = numerical coefficient dependent on structural resisting system  
C = numerical coefficient dependent on period of building  
S = numerical coefficient for site structural resonance  
W = total dead load of building  
The base shear for prefabricated systems can be reduced to:  
\[ V = 0.14 \times KW \]  
if the value of CS is taken as its maximum and Z and I are assumed to be equal to one.  
For comparative purposes, Englekirk and Selna included load factors (U) and reliability factors (φ) such that:  
\[ V = 0.14 \left( \frac{KU}{\phi} \right) W \]  
For the purpose of comparing the UBC design forces with those required for seismic isolation, the φ factor will be taken as unity. In this case, the base shear \( V_N \) is defined as follows:  
\[ V_N = 0.14 \times (KU)W \]  
**Moment Frames**  
As stated above, the Uniform Building Code in high seismic zones does not permit the use of any frame which does not qualify as a "ductile moment-resisting space frame" (if it is intended to resist earthquake induced loads). However, if we can assume this requirement can be met, and if we restrict the discussion to low rise, ductile, moment-resisting space frames with a period less than 0.8 seconds, a K coefficient of 0.67 and load factor of 1.4, the design base shear \( V_N \) required by the UBC is:  
\[ V_N = 0.14 \times (0.67 \times 1.4)W = 0.13W \]  
**Wall Panels**  
Wall panels which provide lateral earthquake bracing are classified as shear walls. When these panels are the primary vertical load carrying system, the building is classified as a box system with \( K = 1.33 \). Load factors for this type of system are 1.4. Thus, for low rise buildings with a period less than 0.8 seconds, the design base shear \( V_N \) is:  
\[ V_N = 0.14 \times (1.33 \times 1.4)W = 0.26W \]  
**Diaphragms**  
Loading criteria for diaphragms are a function of the loading criteria for the structure. It also depends on the location of the diaphragm in the structure and the force levels anticipated at the floor in question. Maximum values would govern in most cases for prefabricated concrete buildings. Thus:  
\[ V_N = 0.3 \times (U)W \]  
\[ = 0.3 \times (1.4)W \]  
\[ = 0.42W \text{ (diaphragm shear)} \]  
**Seismic Isolation**  
Seismic isolation involves a trade-off between lower forces and increased displacements across the isolator. As forces decrease, displacements increase. In addition, the forces on an isolated structure are a function of the soil type. For comparative purposes, a paper by Kelly et al. provides a preliminary design procedure for a lead-rubber isolation system. For the highest seismic zone \( (Z = 1) \) and for isolation periods of 2.0 and 2.5 seconds, the maximum elastic base shear \( V_{sl} \) and relative isolator displacement obtained from the procedure in Ref. 39 are shown in Table 4.  
The soil types \( S_1, S_2, \) and \( S_3 \) are defined in Ref. 34. In essence, they are rock, medium to stiff clays, and soft soils, respectively. Table 4 illustrates the force-displacement trade-off as the period of the isolated structure increases, and it also illustrates the increase in both force and displacement as the soil condition softens.  
If an isolated structure is designed to...
resist the elastic base shear forces $V_{si}$ given in Table 4, then the structure will respond elastically without ductility demand on the structural system.

### Design Force Comparisons

In order to facilitate a comparison of the preceding design forces, the following assumptions are made. The nonisolated structure has a period of less than 0.8 seconds. When isolated, this same building has a period of 2 seconds. For the diaphragm comparison, it is assumed that the distribution of the base shear force for an isolated structure is uniform up the height of the building. The ratios given in Table 5 are the design base shear forces $V_{ni}$ for a conventional, prefabricated structure divided by the elastic base shear $V_{sr}$ of an isolated structure given in Table 4.

It is clear from the ratios in Table 5 that seismic isolation can provide reduction factors ranging from 1.30 to 2.40 in the design base shear forces for a wall panel type building. For moment-frame type structures, isolation design forces would be similar to current code levels for soil types $S_1$ and $S_2$, and there would be a 50 percent increase for soil type $S_3$.

### COST-BENEFIT EVALUATION

The cost-benefit issue is an important one for prefabricated construction since it is very difficult, if not impossible, to satisfy the current building code ductility requirements in high seismic zones. A solution to this problem is therefore required before the economics of isolation becomes an issue for the precast industry.

Seismic isolation clearly offers an innovative and practical solution to the ductility problem because it avoids the need for ductility altogether. In addition, isolation also decreases the design forces for wall panel buildings and diaphragms. For moment frames, the design forces required in using seismic isolation are similar to those currently required for conventional ductile concrete construction.

The economic feasibility of seismic isolation depends on an objective evaluation of the costs and benefits in financial terms. Typically, the costs of seismic isolation will be identified during the design phase of a project; these are
First costs. Benefits from seismic isolation, such as reduced design forces, may reduce first costs but most likely will result in comparable initial costs to those of conventional construction. Some studies have shown that even under adverse conditions the difference in first costs rarely exceeds 2 percent. On the other hand, the designer of the prefabricated Union House reports a 3 percent first cost savings in addition to a reduction in construction time by 3 months.

Long term benefits result from a reduction in earthquake damage costs. For a true comparison, the various costs and benefits must be reduced to the same monetary base or equivalent dollar value. Seismic isolation will be justified economically if the benefits, or cost reductions, exceed the additional cost, if any, of isolation.

Cost effectiveness of seismic isolation is assessed by assigning dollar values to the costs and benefits obtained. Factors to be considered include:

- Cost of isolation system
- Cost of changes to accommodate isolation
- Savings in structural system
- Reduced repair costs
- Reduced earthquake losses
- Continuing operability and survivability of a business

Cost comparisons should include both seismic isolation and any alternative scheme, such as the provision of a stronger structural frame and equipment bracing, that will achieve the same level of seismic protection. For the precast industry, it may simply mean the ability to compete in a new market.

If mechanical system performance is important, then cost savings in equipment bracing alone may dominate the decision to select isolation. The cost of bracing mechanical systems to meet the California Hospital Code ranges from $2 to $4 per sq ft more than that required by the Uniform Building Code. However, life cycle cost reductions are potentially the most dramatic, and when assessed, overwhelm any first cost considerations. It should be noted that, implicit in current codes is the acceptance of structural and nonstructural damage during an earthquake; the cost of this plus the loss of function of the building should be included when assessing life cycle cost.

Another important and perhaps overwhelming benefit is the ability of seismic isolation to significantly improve the chances of business survival after a major earthquake. The National Fire Protection Association has shown that 70 percent of the companies that suffer a major fire are out of business within 3 years, regardless of whether or not they are insured. The economics of business survivability following an earthquake would thus overwhelm a 1 to 2 percent first cost premium for the incorporation of seismic isolation.

First cost studies should incorporate consideration of the factors given in Table 6.

Life cycle cost studies are difficult to perform because the data base of information is so small. There are two approaches to addressing the life cycle cost issue. Thiel has developed a present value formulation which incorporates an experience based earthquake

<table>
<thead>
<tr>
<th>Cost increases</th>
<th>Cost reductions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic isolation systems</td>
<td>Savings in structural system</td>
</tr>
<tr>
<td>Architectural details to accommodate isolation</td>
<td>Savings in curtain walls (reduced drift requirements)</td>
</tr>
<tr>
<td>Special mechanical and electrical details</td>
<td>Additional design costs</td>
</tr>
<tr>
<td>Additional design costs</td>
<td>Savings in nonstructural component bracing</td>
</tr>
</tbody>
</table>
damage matrix. Thiel’s overall conclusions are:
• That seismic isolation is a very important means of controlling the life cycle cost of seismic exposure.
• That 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.

An alternative method of evaluating earthquake damage costs is to utilize the work of Ferritto. His study of a typical Navy building recognized the two primary components of interstory drift and floor acceleration that cause earthquake damage. Ferritto developed damage matrices in an attempt to quantify the damage resulting from these two components. For a specific project, his methodology enables a comparative assessment of the costs of damage that would result from a conventional design and from an isolation design.

CONCLUSION

Several practical systems of seismic isolation have been developed and implemented in recent years, and interest in the application of this technique continues to grow, as evidenced by the approximately 100 structures constructed to date. 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 its inclusion is appropriate after a technical and first cost evaluation, then significant life cycle cost advantages can be achieved. Thus, seismic isolation represents a very important step forward in the continuing search for improved earthquake safety.

From the perspective of the precast and prestressed concrete industry, seismic isolation offers an immediate solution to the current problem of ductility demand on structures in high seismic zones. Isolation is particularly attractive because it avoids the need for ductility in structural members. The alternative strategy is to engage in a long, difficult and expensive research program to make precast and prestressed members more ductile.

It is recognized that there are difficulties to be overcome if seismic isolation is to be implemented by the precast industry, but at least there is light at the end of the tunnel. Seismic isolation meets all the criteria for a classic modern technological innovation, and it provides the potential for the precast concrete industry to compete in the higher seismic areas of the United States. This is a significant step forward for an industry wishing to expand its market opportunities.
REFERENCES


* * *

Note: Discussion of this paper is invited. Please submit your comments to PCI Headquarters by February 1, 1989.