Using Seismic Isolation and Energy Dissipation to Create Earthquake-Resilient Buildings

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ABSTRACT: Seismic isolation with energy dissipation is a technology that has been used in New Zealand since 1978 for bridges and buildings. During this period it has seen limited use, tending to be applied mainly to historically significant buildings, or buildings that have special functional requirements.

Seismic isolation has the ability to significantly improve the seismic performance of existing buildings through a seismic retrofit, or to create new earthquake-resilient buildings. Both of these applications are of greater relevance throughout New Zealand following the Canterbury earthquakes. Consequently, the consideration of seismic isolation is no longer limited to those buildings at the top end of the Importance Level spectrum.

This paper examines the broad technical issues associated with isolation and energy dissipation. It discusses the benefits and costs of seismic isolation, and present guidelines for cost estimation at the feasibility stage of projects. We will explore the cost-benefits for building owners, and discuss whether base isolation can replace earthquake insurance for the building and its contents, and business interruption insurance.

1 INTRODUCTION

Although seismic isolation has been used in New Zealand for close to 40 years and in the United States for close to 25 years and is considered a relatively mature damage resistant technology, there are no indications that its use is increasing. In contrast, China and Japan (with over 2400 buildings completed) design and build many isolated projects each year, with a high proportion of these projects being for housing and commercial buildings. Recently, base isolation has been used in Italy for reconstruction following the L'Aquila earthquake of April 2009 (Calvi 2010).

The benefits of using seismic isolation and energy dissipation devices ("isolators" for simplicity) for earthquake-resistant design are many:

- isolation leads to a simpler structure with much less complicated seismic analysis as compared with conventional structures;
- isolated designs are less sensitive to uncertainties in ground motion;
- minor damage at the design level event means immediate reoccupation;
- the performance of the isolators is highly predictable, so they are much more reliable than conventional structural components (e.g. some ductile walls in the Christchurch earthquakes); and finally,
- even in case of larger-than-expected seismic events, damage will concentrate in the isolation system, where elements can be easily substituted to restore the complete functionality of the structure.

The drawbacks to the wider use of isolation stem directly from the design profession's inability to fully understand and quantify the benefits of the technology coupled with conservative and burdensome code documents.

2 PERFORMANCE IN SIGNIFICANT EARTHQUAKES

One of the early impediments to acceptance of isolation was the demonstrated performance of isolated buildings and bridges in significant earthquakes. The 1994 Northridge, 1995 Kobe, 2011 Christchurch and 2011 Japanese earthquakes provided full-scale tests of base-isolated buildings. The 1994 magnitude 6.7 Northridge event resulted in excess of $20(US) billion in damage and caused significant damage to 31 Los Angeles area hospitals, forcing nine to partially or fully evacuate. The USC University Hospital – the world's first base isolated hospital had no damage at all (Asher et. al 1997). The Los Angeles County General Hospital complex 1km away from the isolated USC hospital suffered $389(US) million in damage.

In the 1995 magnitude 7.1 Kobe earthquake that resulted in excess of $150(US) billion in damage, the world's largest base-isolated computer centre (six stories and 45,000 m^2) suffered no damage at all and, like the USC hospital, was fully instrumented to provide a wealth of recorded data. There was an almost identical 6-storey, non-isolated, reinforced concrete building in the next block that was also fully instrumented. This provided the best side-by-side test of a conventional and isolated structure to date. The base isolated building reduced the earthquake forces across the isolators by a factor of 3.5 with no amplification of forces up the building. The fixed-base building amplified the ground forces by a factor of 3 at the roof. Thus the isolated building reduced the earthquake forces by a factor of 3.5 at the ground level and by a factor of 10 at the roof.

In the February 2011 Christchurch earthquake the 7 storey Christchurch Women's Hospital was fully operational immediately after the earthquake. The Hospital, completed in March 2005, is the only base-isolated building in the South Island of New Zealand. Its 420 mm isolator displacement capacity and its super-structure ductility capacity of 1.8 correspond to 2000-year return-period demands. Because the structure is not instrumented, estimates of seismic responses must be inferred from observations of soil displaced by sliding moat covers, residual displacements in the isolation system, and first-hand accounts – 200 mm was the approximate movement. Hospital staff indicated that there were significantly fewer reports of non-structural damage in the isolated women's hospital compared to the adjacent fixed-base hospitals in the complex. Damage to the isolated structure was essentially limited to minor cracking of partitions around window openings. Christchurch Women's Hospital is sited on flexible soils, which shows the effectiveness of base isolation is not limited to buildings founded on rock or stiff soils.

In the mammoth Magnitude 9 earthquake off the east coast of Japan in 2011 there were more than 20 base isolated buildings that all performed very well. A base isolated hospital in Ishinomaki (Ishinomaki Red Cross Hospital – refer Figure 1), one of the cities closest to the epicentre, moved about 25 cm in one direction. Fortunately, it was not inundated by the tsunami, but the water stopped not far away. There are videos inside the hospital that have been posted to You Tube:
http://www.youtube.com/watch?v=Pc1ZO7YwcWc, and,
http://www.youtube.com/watch?v=Pc1ZO7YwcWc.

This earthquake started at 2:46pm and strong shaking lasted for more than 2 minutes - keep that time in mind as you watch the video. The first minutes show the actual shaking, whilst the remainder is the immediate response of the facility and staff to the impending arrival of victims; quite simply, one of the most compelling (video) testaments to the benefits of base isolation technology. Notice that the facility is fully operational after the earthquake, with little or no damage to the facility; exactly the performance expected from our hospitals and other critical buildings.

Figure 1. Ishinomaki Red Cross Hospital [left] and detail of the seismic isolation devices (rubber bearings coupled with U-shaped steel dampers) [right]

This demonstrated reduction in earthquake forces provides for the safety of not only the structure itself, but also the contents and all of the architectural, mechanical and electrical components of the building. It should be noted that these non-structural elements comprise approximately 80% of the cost of a typical building.

Isolation provides the design profession with the ability to design a building that protects these elements from earthquake damage and achieve a post-earthquake building that is fully operational.

3 TECHNICAL BENEFITS OF BASE ISOLATION

Despite a proliferation of technical articles on the base isolation technology over the past 30 years there is still not a clear understanding in the profession of the technical benefits that result from it's use in both buildings and bridges.

In building applications the primary benefits are:

1. The ability to reduce the elastic base shear that a building must resist by a factor of 3 to 7 depending on the period of the building, the soil type, the magnitude of the earthquake and the proximity to a fault. This significant reduction in base shear provides the engineer with the ability to eliminate the ductility demand and hence damage to the structural system.
2. The ability of a relatively stiff building to move as a rigid body above the isolators with little or no amplification of forces above the isolators. A fixed base building will amplify the ground accelerations by a factor of 2.5 to 4 at the roof depending on the structural system. When comparing the forces at the roof, a base isolated building will provide a factor of 8 to 12 reduction in the forces compared to the fixed base building. An example of this was the two 6 storey reinforced concrete buildings in the 1995 Kobe, Japan earthquake discussed above. Components of a building that are sensitive to floor accelerations in an earthquake include the mechanical and electrical equipment, the contents, the manufacturing processes, elevators, sprinkler systems and ceiling and lights. The order of magnitude reduction in floor accelerations provided by base isolation greatly enhances the safety of all of these components of a building.
3. The reductions in the base shear and floor accelerations noted above results in a similar order of magnitude (factors of 4 to 8) reduction in inter-storey drift. Components of a building that are sensitive to inter-storey drift in an earthquake include the façade and windows, the partitions, the structural frame and the piping and duct work. The order of magnitude reduction in inter-storey drift provided by base isolation greatly enhances the safety of all of these components.
4. The cost of the structural system in a building is on the order of ± 20% of the total building cost with the remaining 80% being the architectural elements and exterior façade, the

mechanical and electrical components and the contents. Seismic design codes pay a lot of attention to the structural system in order to address the life safety issue but generally do a much poorer job of addressing the earthquake safety of the other elements that constitute 80% of the cost of a building. When the total cost of earthquake damage in a building is assessed much of it occurs to the non-structural elements of the building and the structural engineering profession needs to look at the safety of these elements when assessing the economic benefits that base isolation provides. Such benefits are even more evident if the region is affected by frequent events with significant intensity. The time required to effect these repairs has a significant effect on economic recovery and business continuity.

5. In item 2 above the discussion was focused on the reduction in peak floor accelerations. In reality this should have been a discussion on the floor response spectra but many structural engineers never consider this from a design perspective. When comparing the merits of different isolation systems it is important to look at the floor spectra because pure friction based systems that have a large reversal in force when the velocity reverses and do not do perform as well as elastomeric based systems in reducing the high frequency content of the floor spectra. As a consequence if two systems were comparable in cost this difference in performance should be an important factor in differentiating between the two systems as the elastomeric systems will provide a higher level of safety for acceleration sensitive elements.

In bridge applications the primary benefits are:

1. The ability to reduce the elastic base shear that a bridge must resist by a factor of 3 to 7 depending on the period of the bridge, the soil type, the magnitude of the earthquake and the proximity to a fault. This significant reduction in base shear provides the engineer with the ability to eliminate the ductility demand and hence damage to the substructure elements. There are a number of new bridge applications that have shown considerable first cost savings in the foundation system as a result of using base isolation technology. With the advent of performance based design, base isolation provides the ability for a designer to achieve a fully operational design without a significant increase in cost when compared to a conventional fixed base design.
2. In bridge retrofit applications by simply replacing the existing bearings with isolation bearings the force reductions provided by base isolation maybe sufficient to avoid having to strengthen the columns and foundations.
3. A design feature of some isolation systems is their ability to distribute lateral loads to substructure elements that are better able resist the loads. So not only are the seismic loads reduced but they can be distributed away from weaker substructure elements if the deck is continuous. This design feature has been used in some building retrofit applications but also has significant potential for bridge retrofits.

4 PERFORMANCE BASED DESIGN PHILOSOPHY

Base isolation is a technology that provides us with the ability to design buildings that remain fully operational after a major earthquake. This is a significant improvement on the performance expected from bridges and buildings designed to meet our current design code (NZS1170.5), which has the following performance expectation:

"...there will be a very low risk at the ULS [Ultimate Limit State] of: (a) structural collapse; (b) failure of parts and elements which would be life threatening to people within or around buildings; (c) failure of a part or elements whose function is critical for the safe evacuation of people from the building."

These provisions are intended to safeguard against major failures and loss of life, not to limit damage, maintain functions, or provide for easy and/or economical repairs.

This performance expectation often comes as a surprise to many owners and architects, who believe they are getting an "earthquake proof" building or bridge when they hire a competent structural engineer to design a code conforming building or bridge. Interaction with the owner in a building project most often occurs through the architect, and the design philosophy inherent in current codes is not often brought to the attention of the owner. This lack of familiarity with current code design philosophy by the architect and owner was, and still is, a significant impediment to the implementation of base isolation for buildings.

There have been some major changes in the past decade as a result of the development of performance based design codes. The first major step in the US was the development of NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA 273). This included 4 performance levels as follows:

- Operational
- Immediate Occupancy
- Life Safety
- Collapse Prevention

For new buildings in the US the Applied Technology Council (ATC) has been under contract to the Federal Emergency Management Agency (FEMA) for almost 8 years to perform a project to develop Next Generation Performance-based Seismic Design Guidelines. The purpose of the project is to develop a series of resource documents that define procedures that can be used to reliably and economically design new buildings or upgrade existing buildings to attain desired performance goals, and to assist stakeholders in selecting appropriate design performance goals for individual buildings.

The project includes the establishment of a methodology for predicting the earthquake performance of buildings characterized in terms of probable life loss, repair costs and time out of service resulting from earthquake effects, expressed in a variety of formats useful to different stakeholders and decision makers. The ultimate goals of performance-based design are the development of practical design criteria that give the building owner and regulator the ability to select a building's desired performance capability as well as to optimize the performance of code-designed buildings, relative to society's needs. While the project is funded under seismic programs, the intent is that the technologies developed in this program will be directly relevant and applicable to other extreme events, such as blast, fire and tornado winds. Reference material on the project can be found: https://www.atcouncil.org/Projects/atc-58-project.html

It is too early to know if the New Zealand codes will develop along a similar track, following the outcomes and recommendations of the Royal Commission.

However, given the number of conventionally designed buildings that are uneconomic to repair, and the increasing cost of earthquake insurance, it appears inevitable that there will be a greater demand for damage limiting structures as part of the Christchurch rebuild. This may assist in the transition to a performance based design codes within New Zealand.

Once design codes for new construction include performance based design concepts, one of the significant obstacles to the implementation of base isolation technology will be eliminated because it will be a designer's responsibility to discuss performance expectations with the owner. What will also be a necessary part of that conversation is a rational discussion of the economic costs and benefits of the alternate design concepts.

5 FIRST COST ISSUES

Many professionals in building applications sight the increase in first cost as a serious impediment to the implementation of base isolation as well as the lack of data on cost/benefit issues. One of the major difficulties in comparing the costs of an isolated building with an operational performance level is that a conventional fixed-base building is rarely designed for the operational performance level. Therefore a comparison of an isolated design and a conventional life safety design is like comparing a Mercedes to a Volkswagen because the performance of the two designs is completely different.

The only example for which an equal performance cost comparison was performed was the 2 story

Fire Command and Control Facility for the Los Angeles County Fire Department. This was a two story braced steel-frame project designed by Fluor Daniel and the building and its contents were to be functional after the maximum design event. Fluor Daniel designed both an isolated and fixed-base building to satisfy this performance requirement and found the isolated building to be 6% less expensive primarily because of the savings realized when seismic hardening and certification of electrical and mechanical equipment was not required.

The USC hospital, which is discussed above, is estimated to have an additional 2% first cost attributable to the installation of base isolation. This first cost premium is minimal when compared to the $389 (US) million repair bill for the adjacent non-isolated Los Angeles County hospital complex resulting from the 1994 Northridge earthquake.

The increased construction costs of a base isolated building are relatively easy to estimate and include the cost of a structural floor versus a slab on grade at the basement level unless the isolators are on top of a basement column, the cost of the isolators, architectural modifications to permit movement of the building and the cost of flexible connectors for mechanical piping and electrical wiring entering a building. Other costs that need to be included are additional design fees, peer review costs and testing and inspection costs. In the retrofit of existing buildings, the base-isolation design has in fact been the less expensive design alternative in many of the retrofit projects.

Other benefits in using base isolation as a retrofit technique include being able to use the building while the isolators are installed as most of the work is confined to the basement area. Avoiding the need to move occupants from a building while it is being retrofitted has significant cost advantages.

In bridge applications the increase in construction cost is not such an important issue. Although an isolation bearing is more costly than a conventional bearing the total bearing cost is less than 2% of the total cost of a bridge and thus a more expensive bearing is still less than 1% of the bridge cost. There have been a number of bridge applications where the savings in the cost of foundation has been of the order of 5 to 10% of the total cost of the bridge so it is possible in bridge applications to have first cost savings. Other additional costs in bridge applications include the additional design fees and the testing and inspection costs related to the isolators.

When initial costs dominate the decision-making process, the cost increase to incorporate seismic isolation has proved to be a significant impediment to its implementation. There is a clear need for a consensus methodology to develop the economic benefits from an owner’s perspective on the use of a technology that provides the operational performance level such as seismic isolation when compared to a life safety design. This methodology should include estimates on the cost of damage and the business interruption costs due to a loss of use of a facility discussed in the next section.

6 BUSINESS DISRUPTION AND COST/BENEFIT ISSUES

As we have painfully learned in many recent disasters, the major economic issues relate not only to the direct cost of earthquake damage, but also to the business disruption costs associated with the loss of one or more buildings for significant periods of time. These include:

- Loss of production or operations
- Loss of sales or services
- Loss of ongoing R&D in some industries (e.g., the biotech industry)

These losses translate into major economic issues for a corporation including:

- Loss of revenue
- Loss of market share
- Loss of stock value

Clearly, these business disruption costs overwhelm any first-cost considerations, but in too many instances, project personnel focus entirely on first-cost issues and never look at the longer-term bigger picture cost/benefit analysis. The process of business decision-making includes business opportunity, return on investment, liability and risk control, and market share. Earthquakes have four principal cost impacts which may influence the decision-making process for construction of new buildings: 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 a loss of the buildings function (lost rent, revenue and productivity), loss of market share or clients and potential liability to occupants for their losses and injuries.

It has been shown that the use of base isolation technology will reduce earthquake damage costs well below the level of today's deductibles, which are in the 5% to 10% range and going up. Furthermore, whilst insurance usually covers the cost of earthquake damage, it may not fully cover the major business disruption costs as discussed above, especially market share. In Christchurch this has often been a substantial business cost, where the need to move to alternative premises whilst buildings are rebuilt or repaired, can have a large impact on market share.

As a result, an owner has an interesting choice if they use base isolation. An owner can choose not to carry earthquake insurance because the deductible will never be exceeded. Furthermore, base isolation eliminates the need to worry about business disruption costs because the building will be operational after the earthquake. Consequently, one option for an owner is not to carry earthquake insurance and invest the annual insurance premium in the additional cost of providing base isolation. In most cases this option will pay for the additional isolation cost in a 3- to 10-year time frame. In this way a simple total cost of ownership analysis will often show that base isolation is a cost-effective solution despite any first cost premium, and this is without considering higher rentals than may be received for an isolated building.

The advantages of base isolation may be even more relevant for retrofitting of an existing building. A rough guideline for the cost of retrofitting base isolation to an existing building would be $5,000 per square metre of plan area at the plane of isolation. As base isolation would reduce, or eliminate, the strengthening works for the superstructure, this may be a cost effective solution if compared with other strengthening/repair interventions, or the construction of a new building. For heritage buildings, base isolation can offer other aesthetic benefits that may make isolation a preferred option, outside of any cost consideration.

Any additional time and effort expended on a project, without additional compensation for the design team, results in reduced profit and overhead for the design firm. This, clearly, has negative implications if design professionals are relied upon to promote the implementation of newer technologies that require additional design effort. Consequently, if innovative earthquake-mitigation measures are to be seriously evaluated in the design phase of a project, the owner should be prepared to pay some additional design costs. This then means that the owner must either be the initiator, or at least a consenting party, to investigate the potential benefits of mitigation measures such as seismic isolation.

Base isolation is a preventative measure against the effects of earthquake damage, whereas insurance of a fixed base building is a band aid after-the-fact approach that does not cover any of the very costly business interruption items mentioned above.

7 CONCLUSIONS

There have been a number of issues identified that have impeded the more widespread use of base isolation technology in New Zealand and the United States. The two main impediments identified are the lack of any requirement to explicitly consider the effects of earthquake damage in the ULS design of a fixed base building, and to convey this information to the owner and/or occupant. The development and implementation of performance based design codes, and a building rating system, may remove this obstacle by making it the designers responsibility to discuss and agree the expected performance of the building with the owner or tenant.

The other main impediment to isolation, is the assumption that it is costly, and hence, only suitable for use in high importance level buildings. Certainly, base isolation of such buildings can be extremely cost effective, and in fact, result in a cheaper first cost building compared to a fixed base design.

However, as the insurance market in New Zealand changes to reflect current practice in other regions of high seismicity, such as the US and Japan, we can expect insurance deductibles to rise further towards the 10% to 15% mark. In this context, base isolation can be a more cost-effective solution than fixed based structures when total cost of ownership is considered, despite the first cost premium for base isolation.

Isolation offers the benefit of damage resistant design, and potential for immediate occupation, or continued operation, which is more difficult to achieve with a fixed based solution.

In summary, base isolation and energy dissipation is cost-effective solution that should be seriously considered for rebuilding, repair and strengthening of buildings in Christchurch to provide step change in resilience of the building stock in Canterbury.

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