Seismic isolation for architects

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ABSTRACT: This paper describes the background and content of a book on seismic isolation written especially for architects. The contents and their sequencing are designed to address all significant questions that readers might have about seismic isolation. The aim is to enable readers to make decisions as to whether they want to have some type of involvement in a seismically-isolated building, perhaps as a member of a design team, or as tenant of a seismically-isolated apartment building. Although a thoroughly objective approach is taken to the content, the sheer weight of the positive benefits of seismic isolation promotes and encourages the uptake of this technology. The paper reports on the key findings of the project that are of most relevance to architects and suggests areas for further consideration by structural engineers.

1 INTRODUCTION

Many books and articles on the seismic isolation of buildings have been written for structural engineers. However, these publications are highly technical in nature and therefore are unsuitable for the vast majority of others who design, construct, own, insure and inhabit buildings in seismically-active regions. The purpose of the book then, is to introduce a relatively new game-changing technology to a wider audience.

A project like this could have been undertaken at any time over the last thirty-five years. However, it would have inevitably left unanswered many important questions that are raised when discussing the seismic isolation of buildings. In particular, how confident can we be in seismic isolation and how does this relatively new approach compare to more conventional ones? Is seismic isolation really worth adopting?

Within a period of eighteen days ending 11th March 2011, the answers to these questions suddenly became much clearer. On 22th February the city of Christchurch, experienced a devastating earthquake. While only one base-isolated building in Christchurch, the Christchurch Women's hospital was tested by the earthquake, so was the entire building stock of Christchurch. Several hundred buildings, many designed in accordance with one of the world's most advanced seismic codes, survived without collapse. But tragically, most have subsequently been demolished. This situation raises considerable uncertainty regarding the appropriateness of modern philosophies of seismic design.

Then, on the 11th March, Japan was struck by the massive Magnitude 9 Tohoku Earthquake, centred off the east coast. For the first time, hundreds of seismically-isolated buildings were tested on an unprecedented scale. These two earthquakes demonstrated the effectiveness of seismic isolation as well as deficiencies in current design approaches to earthquake attack, accentuating the benefits of seismic isolation.

The paper introduces the seven main topics of the book which are covered in twelve chapters. Each of the topics; education, applications, confidence, benefits and limitations, economics, design, and maintenance, are reviewed briefly below.

2 EDUCATION

Architects need to be aware that while the capability for horizontal movement is the first requirement for an isolated structure, there are four other requirements as well: vertical support, re-centring, restraint and damping. In practice, movement capability is provided by elastomeric bearings from natural or artificial rubber, or sliding surfaces of Teflon and stainless steel, and otherwise complete separation of the superstructure from the ground. In order to allow almost unrestrained horizontal movement, an isolation system must therefore support the weight of the building. A re-centring or restoring force keeps bringing the superstructure back to its original position while preventing motion during wind gusts. Damping lessens the relative horizontal movement between the superstructure and foundations, reducing both cost of bearings and other details, and the width of gaps that accommodate movement.

Typical seismic isolation hardware meets two or more of the above requirements. For example, lead-rubber bearings meet all five, as do curved sliders, but via totally different mechanisms.

3 APPLICATIONS

A recent overview of seismically-isolated buildings reports that as at 2012 over 6,600 buildings in Japan were seismically-isolated (Martelli 2012). This number includes 4000 houses. China has over 2500 isolated buildings; the Russian Federation, 550 buildings (and bridges); Italy, 300, and the USA, approximately 200.There also are up to several tens of seismically-isolated buildings in other countries including Chile, South Korea, Taiwan, Armenia, and New Zealand.

The types of seismically-isolated buildings in terms of their function and age are extremely diverse. Before exploring some of their typologies it is worth noting the reasons why owners isolate their buildings. Ron Mayes summarizes them as:

- Emergency response,
- Continued business operations,
- Protect contents,
- Reduce damage repair cost,
- Protect architecture, and
- Occupant safety – “peace of mind (Mayes 2013).

We encounter seismically-isolated hospitals and emergency response centres, and buildings housing manufacturing or other functions for whom downtime following an earthquake would be disastrous. The contents of some buildings are more valuable than the buildings themselves. Frequently, owners desire to minimize damage and damage repair costs. Perhaps their investment in seismic isolation is an alternative to paying earthquake insurance premiums and allowing early, if not immediate, re-occupancy of a building following an earthquake. There are also many buildings of historic significance that have been seismically-isolated.

4 CONFIDENCE

When modern seismic isolation incorporating the five requirements noted above was first applied to buildings in the 1980s, its claim for effectiveness was based entirely upon computer modelling and laboratory testing of isolation hardware, like lead-rubber bearings. Those early applications of the then new technology required a certain degree of faith in the theory of seismic isolation as well as in computer analyses. Now, in 2015, the effectiveness of seismic isolation has been demonstrated both in the real world of full-scale testing, and more significantly, in urban centres of several countries.

The effectiveness of seismic isolation is determined by quite different approaches. It is confirmed each time an isolated building is designed. In most such designs a computer model of the structure including the isolation system experiences several different earthquake records which subject the building to the strong shaking expected in the design earthquake. Confidence in seismic isolation is also grounded in the large body of research that goes back many years. Since then, hundreds of research papers have been presented at conferences around the world, and numerous scholarly books written.

Physical testing has been a vital component since the early development of seismic isolation. Now, entire isolated buildings experience recorded strong motion earthquake records. For example, the largest shaking table in the world, E-Defense, Japan, subjects concrete and steel buildings up to five storeys high to 3-D shaking.

Even though the effectiveness of seismic isolation is extensively demonstrated through computer modelling and physical testing, there is no substitute for measurements and observations during and after damaging earthquakes. Three approaches can evaluate the effectiveness of seismic isolation after an earthquake. We can compare the behaviour of identical side-by-side isolated and conventional buildings, or situations where non-identical isolated buildings are in close proximity. We can also make use of acceleration measurements taken beneath and within individual isolated buildings to gauge the effectiveness of seismic isolation. Finally, we can make general comparisons between the performance of earthquake-affected isolated buildings and conventional buildings. Results from all these approaches which are presented in a large body of research literature confirm that confidence in seismic isolation is well-founded.

5 BENEFITS AND LIMITATIONS

Benefits of seismic isolation are realised before the occurrence of a damaging earthquake, as well as during and after such an event. Many benefits, including insurance premium savings, can be realized even before an earthquake strikes. Others occur during the design phase of a building when they can lead to improved architectural features.

The architectural benefits of reduced inter-storey drifts and possible lower levels of strength and ductility can be exploited in more elegant detailing, and more slender and less regular structure. Numerous case-studies illustrate how architects are taking advantage of seismic isolation to reinforce and achieve a wide range of architectural objectives. Case studies are grouped in four categories of architectural concepts and qualities that encapsulate prevalent architectural concepts and qualities in contemporary architecture (Charleson 2015). The categories most relevant to seismically-isolated architecture are, grounded – floating, stability – instability, heavy – lightweight, and simple – complex (Figs. 1 to 4). Structural configurations, unthinkable in conventional buildings, can be considered in isolated buildings. More slender columns and structural walls are also feasible, as well as simpler and thinner separation gaps. These potential benefits can improve architectural aesthetics.

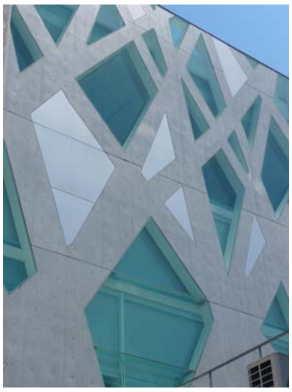

Figure 1. Tod's Omotesando, Tokyo. Toyo Ito 2004. At the base of the building structure is grounded, but higher-up it becomes more delicate.

Figure 2. Tama Art University Library, Hachioji, Tokyo. Toyo Ito, 2007. Part of the two main facades. The columns touch the floors very lightly.

Figure 3. Prada Boutique Aoyama, Tokyo, Front entrance Japan, Herzog & de Meuron, 2003. An example of structural lightness.

Figure 4. Inagi Hospital, Tokyo. Kyodo Architects 1998. A complex butterfly-shape plan.

While the pre-earthquake benefits of seismic isolation are tangible, how much more so are those incurred during and after a large earthquake:

- Reduced trauma to building occupants,
- Reduced injuries to building occupants and passers-by,
- No or minimal structural damage,
- No or minimal damage to architectural (non-structural) elements, and
- No or minimal disruption to building occupancy and function.

In one computer-based study, two three-storey steel braced frame buildings, one seismically-isolated, were subject to many different earthquakes. Seismic isolation reduced inter-storey drifts and floor accelerations by factors between 5 and 20, and 4 and 6 respectively. The magnitude of these reduction factors varied from building to building but have been found to reduce in more flexible, say moment frame buildings, to a factor of 2.0 (Ryan 2010). The effects of such considerable reductions in drifts and accelerations mean no structural damage and minimum damage to architectural elements and building contents.

Limitations of seismic isolation arise from geology, building height, adjacent buildings and site coverage. Not only should sites underlain by fault lines or liquefiable soils be avoided, seismic isolation may not be appropriate for sites with deep soft soils. Typical building isolation systems are also ineffective against vertical shaking.

Seismic isolation provides a less dramatic performance improvement for high buildings as compared to those that are lower-rise. Nevertheless, now there are numerous isolated buildings in Japan over 20 storeys high and this trend continues in other countries (Fig. 5). For example, a 25 storey isolated office tower has just been completed in Jakarta. A fixed-base period of approximately 2.0 seconds was increased by a further 2.5 seconds with isolation. This achieved significant reductions in inter-storey drifts and forces within the building. These translate to overall improved seismic performance such that immediate occupancy is expected after the design earthquake (Hussuain 2012).

The effectiveness and application of seismic isolation can be limited by adjacent buildings. It makes little sense to isolate a building that is adjacent to one that is more vulnerable. All buildings must be set-back on their sites to avoid pounding neighbouring buildings. For seismically-isolated buildings, almost all horizontal movement occurs at the plane of isolation. Therefore, irrespective of the building height a wide seismic gap is required at ground level. A 400 mm wide separation gap around three sides of a 10 m by 20 m site reduces the gross floor area by 10%. This is potentially a significant hidden cost of seismic isolation.

6 ECONOMICS

It is impossible to say how the cost of a seismically-isolated building differs from that of a conventional building with a high degree of accuracy. A large number of factors are at play. However, first we must check we are comparing like with like. Comparing the construction costs of these two types of buildings is like comparing the cost of an ordinary motor vehicle to one with advanced safety features. There is no doubt about the superior safety performance, for which we should expect an increased price.

Few studies have compared the initial costs of seismically-isolated buildings to conventional buildings *with the same seismic performance*. Unfortunately, special buildings, often housing essential facilities, rather than typical buildings are reported upon. Furthermore, the studies do not capture the reduction in downtime and other benefits seismic isolation provides.

Drawing upon eight case-studies mainly in the USA, Mayes (1990) reports a range of cost of construction increases up to 5% and 3% savings. Japanese experience is summarized: “Generally, for a building with less than about ten stories, the initial construction cost is several percent higher than for the building without isolation, but for structures more than ten stories, there is almost no difference in construction cost” (JSSI 2013). In New Zealand, a study of four isolated hospitals completed between 2005 and 2013 revealed that the total additional cost of seismic isolation was 3% of their construction costs (Charleson and Allaf 2012). Since hospitals are heavily serviced, the additional isolation costs for most other building types can be expected to be slightly greater. In an European example involving the fast-track build of 4,500 apartments after the damaging 2009 L’Aquila earthquake, Calvi (2010) reports that seismic isolation represented 2% of the total cost.

Almost all of the additional costs of seismic isolation are incurred in the vicinity of the isolation plane. This means the cost of isolation per square metre of construction is reduced by increasing the numbers of storeys. Additional costs arise from a possible additional suspended floor, isolation devices such as bearings, provision of moats or rattle-space including retaining walls, and moat covers which are usually required, unless the isolation plane is above or at ground level. Movement joints between adjacent buildings add to the costs, as well as detailing of flexible electrical and other services, stairs and elevators that cross the isolation plane, and increased design and peer review fees.

Even for seismically-isolated buildings with normal occupancy, like apartment or office buildings, some structural savings will partially off-set the additional costs of seismic isolation. Cost savings other than to primary structural framing are likely as well. In isolated buildings, mechanical and electrical plant and architectural elements, like suspended ceilings, require less bracing in order to prevent overturning and sliding.

All published life-cycle analyses for buildings located in high seismic hazard areas of western North America and New Zealand consistently demonstrate the cash flow benefits of seismic isolation (Ryan 2010, Whittaker 2012, and Cutfield 2014). For example, Terzic and others (2012) calculate a *minimum* 3% return on investment over a 50 year time frame. They exclude potential insurance savings and acknowledge even more attractive results for seismic isolation if downtime estimates are refined. Whittaker (2012) makes a compelling case for owners of seismically-isolated buildings to self-insure. He shows that the annual costs of earthquake damage, business interruption, insurance premium assuming no reduction for the isolated building, and annualised deductible are similar for owners of conventional and seismically-isolated buildings. An update of Whittaker’s spreadsheet shows that since the spike in insurance premiums immediately after the Canterbury earthquakes has reduced from approximately 1% to 0.25%, the annualised cost of an uninsured (self-insured) isolated building is 7% of that of an insured isolated building.

7 DESIGN

The successful introduction of any new technology into a design and construction project necessitates additional communication and a higher level of collaboration between members of the design team. Once a decision to seismically-isolate is made, the intensity of collaboration increases. Later in the design process detailed design of architectural details is undertaken. It is worth noting that the 2011 Tohoku, Japan, earthquake showed that the performance of the details left a lot to be desired. Although in principle, the provision for unrestrained and damage-free movement is straightforward, it is more difficult to achieve in practice. Saiki and others' (2013) survey of over 300 isolated buildings revealed that 30% experienced damage to movement joints. Even though the movements were in most cases far less than the maximum design displacements, joints did not function as intended by their designers. Defects were observed due to the location of joints, obstructions in their immediate vicinity, and lack of maintenance.

Architects are responsible for the design of the moat area and cover plates. Cover plates are available in many different forms, ranging from simple highly-visible surface-mounted plates to those that are concealed. They may incorporate additional complexity to provide fire resistance across the gap.

As well as moat covers and other flooring movement joints, capacity for seismic movement is also required where an isolated building connects to another building, be it isolated or not, at the roof, up walls and along and across ceilings. Some architectural elements are designed to be sacrificial in a large event, perhaps steel supports and frangible lining panels. This was the detailing philosophy adopted for the connection between the buildings shown in Figure 6.

Figure 5. The 26-storey high Yozemi Tower, Tokyo.

Figure 6. Rankin Brown Building, Wellington. The vertical black painted thin metal covering is part of the wall movement joint between the seismically-isolated building to the left and the fixed-base building to the right. Sacrificial steel elements and frangible interior linings will need replacement after a large earthquake.

8 MAINTENANCE

Once constructed, a seismically-isolated building has unique maintenance requirements. Just like elevator and fire alarm systems need regular inspection and maintenance, so also isolation systems. The consequences of an isolation system being compromised, say by building materials blocking a seismic movement gap, or by bearings suffering severe corrosion, are very serious (Figs. 7 and 8). The safety of the entire building is at risk.

A maintenance programme therefore needs to address seismic isolation vulnerability from both natural and human threats. We believe that a maintenance programme should be as legally binding as those for elevators and fire alarm systems that are regularly inspected and maintained for annual Building Warrant of Fitnesses. The compliance schedule should include the seismic isolation system at the time the building owner applies for Building Consent to begin construction.

Figure 7. After 20 years exposure to moisture this pot sliding bearing is in urgent need of replacement. (Chris Gannon)

Figure 8. A view of a horizontal stainless steel plate with its protective plastic sheet folded back. When installed 20 years ago the stainless steel would have had a mirror finish. The coefficient of friction will be far greater than that assumed by the designers. (Chris Gannon)

9 ISSUES FOR STRUCTURAL ENGINEERS

Considerable international variance regarding technical aspects of seismic isolation design remains. Martelli (2013) states that "SI [seismic isolation] is considered as an additional safety measure (with consequent additional construction costs) in some countries (Japan, USA), while in others (including Italy) the codes allow to partly take into account the reduction of the seismic force acting in the superstructure". As another example, in Japan, the design earthquake is approximately a 500 year event, but in the USA, isolator displacement is based on a 2500 year return period (Becker 2010). Pan (2005) points out that in Japan a factor of safety of 1.5 is used to determine the horizontal isolation clearance dimension. Designers in the USA, however, are not required to use a factor of safety. Some designers from Japan, China, USA, Italy and Taiwan are attempting to standardize design procedures internationally (Feng 2012). New Zealand engineers should join this effort.

A conservative approach to determining the movement gap width is essential. Movements calculated for some soil sites subject to bi-directional near-fault ground motions are up to 15% greater than expected (Ozdemir 2010), and movement increases at corners of buildings due to torsion can reach up to 30% in long buildings (Kircher 2006). Wider movement gaps may also assist in future-proofing. For example, the 150 mm gap around the William Clayton Building, Wellington that was constructed in 1981, although based upon the best seismological advice of the day, is now considered too narrow. We recommend that even though the risk of severe structural damage in a seismically-isolated building is very low, structural engineers should identify and articulate the collapse mechanism to satisfy themselves, their clients and others, of the overall structural robustness.

10 CONCLUSIONS

This paper discusses the content of a proposed book on seismic isolation written from an architectural perspective. Given this project's emphasis upon recent and current practice, it is appropriate to consider the future of seismic isolation. How might it develop in the coming years?

The extent to which it will be adopted depends on two major factors. The first is the frequency and severity of future damaging earthquakes. As witnessed after every large earthquake in an urban setting, the reality of human casualties and collapsed and badly-damaged buildings leads to an surge in seismically-isolated buildings. The second factor that will influence the extent of the adoption of seismic isolation is the quality of the performance of seismically-isolated buildings. If they continue to out-perform convention construction, building owners will be inclined to adopt seismic isolation. Over-confidence in this still relatively new technology must be avoided.

Other drivers as well will promote seismic isolation to building owners. Structural design procedures are undergoing rationalisation and simplification. The insurance industry is becoming better acquainted with the benefits of seismic isolation, and on-going research and development is likely to lead to lower-cost isolation devices. All these advances are expected to result in safer buildings and communities, as more building owners, architects and engineers request or recommend the application of seismic isolation in their buildings.

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