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# Lessons from Recent Earthquakes: The Need for More Resilient Cities

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**ABSTRACT**: Safety of occupants is of paramount importance in the design of any structure or system. However, in the aftermath of recent major earthquakes, worldwide attention has increasingly focused on the need for resilient structures and lifelines that are able to return to service quickly following a major earthquake. In this paper, engineering aspects of resilient communities are discussed, focusing on increasing the post-earthquake operability of those structures and lifelines critical to a community's needs in the aftermath of a major earthquake and the ability of occupants to "shelter-in-place" during repairs.

**Key Words**: design criteria, continued occupancy, buildings, bridges, seismic isolation, protective structures, resiliency, resilient communities

## INTRODUCTION

Engineers specializing in the field of earthquake engineering are constantly reminded of the importance of their work by the worldwide occurrence of earthquakes, both great and small. Earthquakes pose a threat to nearly every country in the world. While experimental and analytical research and design studies provide important sources of information for continual improvement of building codes and construction practices, the largest impetus for change comes from the disparity between the observed and expected behavior. Sometimes a region is inadequately prepared for an earthquake, and efforts are made quickly to improve the quality and enforcement of building codes. In other cases, earthquake damages identify shortcomings in fundamental theory or detailing and analysis requirements, and research is carried out to determine appropriate remedies for these problems. In other cases, public expectations regarding the performance of the constructed environment have evolved, and design criteria should change in keeping with these expectations.

Architectural styles, construction types, building codes, quality of engineering and construction, seismic hazard, and public expectations differ significantly from region to region around the world. As such, the performance of structures and lifelines observed in one region may be acceptable to those who live there, even though similar behavior in another region to a similar event might not be viewed positively by those living in that region. Nonetheless, because of the substantial time between the occurrence of design level or greater seismic events in any one region of the world, engineers and public officials can analyze and draw valuable lessons from the performance of structures and systems that occur in other regions of the world. In many cases, these lessons are drawn from individual structures or types of structures regarding fundamental issues of structural mechanics and dynamics. However, there is increasing recognition that the impact of an earthquake on the occupants and owner of a structure depends on more than the degree of structural damage to just that structure, and that an damaging earthquake can transform from a survivable disaster to a catastrophic event if the extent of even moderate damage to structures and lifelines results in the closing of a critical number of key businesses, services and housing units.

Moreover, in many industrialized countries, the public and government officials have come to expect high levels of security in a citizen’s everyday life, whether this is while in the home, traveling and in the workplace. For examples, spalling and cracking associated with formation of plastic hinges are pointed out as structural failures by public media, while they are expected according to *ductile* design principles. As such, it appears that there is a growing discrepancy between the public’s expectations of well being in the face of natural disasters, like earthquakes, and the focus by many engineers on providing the minimum seismic design needed to protect life safety.

Recent earthquakes in China, Chile, New Zealand and Japan have been as large or larger than the maximum levels of excitation considered in the design of typical structures. These events have tested many structures to their limits. In most cases, modern structures have done well. However, it is clear from all of these events that large earthquakes trigger other disasters that compound the disaster and may elevate its status to that of a catastrophe. For example, earthquake ground shaking in China not only leads to the collapse of many individual buildings, but also to an extraordinary number of landslides that caused additional damages and hampered rescue and recovery operations. Both Chile and Japan suffered from the effects of tsunami following the main earthquake ground shaking. The severity of ground shaking in New Zealand, Japan and Chile were large enough to trigger large-scale liquefaction and differential ground displacement. While such issues are often considered in the design of an individual structure, the cascading effects of all of them occurring in a region as a result of the same event and transforming a natural disaster to a catastrophic regional event have only recently come to the forefront of discussions in earthquake engineering.

To accelerate development of cost-effective and robust procedures for seismic resistant design that take into account the particular technological, economic and social conditions prevalent in various regions susceptible to seismic hazards, it is necessary for earthquake engineering specialists from around the world to work together. In this paper, observations from recent earthquakes worldwide are reviewed to identify some new and some old lessons. From these, the need to improve the resilience of buildings, transportation structures and other lifelines is highlighted. For buildings, effective approaches to minimize damage to structural and nonstructural components are stressed. In the case of bridge structures, approaches are examined whereby highway and rail bridges can be used immediately following a major earthquake to facilitate emergency response and promote rapid recovery. Results of shaking table tests, nonlinear dynamic analyses and economic evaluations are presented to illustrate the possible approaches to increase resiliency.

## LESSONS LEARNED AND RELEARNED FROM RECENT EARTHQUAKES

Recent earthquakes in Chile, New Zealand and Japan reiterate many lessons learned in past earthquakes. For example, recent earthquakes remind us of the substantial risk posed by existing structures and lifelines constructed when earthquake engineering concepts were not as advanced as they are today. Tremendous damage was observed in New Zealand in unreinforced masonry structures, and damage was observed in all three countries in reinforced concrete constructed prior to the adoption of modern ductile detailing requirements. Other lessons re-learned include the need for providing a continuous load path, avoiding discontinuities in the lateral-load resisting systems, designing connections to develop the capacities of the elements framing into them, protecting systems from potential failures of the supporting soil, and so on.

There are extraordinary opportunities to learn from these recent earthquakes. Substantial amount of instrumentation was installed throughout Japan, Chile and New Zealand to measure the movement of the ground, water and structures. Moreover, many efforts have been undertaken to document in high detail direct damages and the economic, social, political, medical and other impacts of this damage.

Some newly emphasized lessons and areas for research are described below, with emphasis on lessons from the Great Eastern Japan Earthquake of 2011.

### Effects of ground motions on engineered facilities

Earthquakes in Chile, New Zealand and Japan are often noted as being larger than expected events. While these events were indeed large, generally predictions of future earthquakes are probabilistic in nature. These events should serve as a warning that median probabilistic estimates are not deterministic bounds on what may occur in future events.

Specific ground motion observations are provided below related to subduction zone events, the importance of aftershocks and special issues raised regarding near and far filed ground shaking.

### *Subduction zone events*

The subduction zone ruptures in Chile and Japan illustrate the potential for the damaging effects of such earthquakes to be experienced over a vast geographic area. Strong motion records are often very intense (<2.9 g) and very long (3 minutes). The motions in Japan are particularly complex, showing strong evidence of multiple segments rupturing sequentially along the fault. There are several thousands of records from these earthquake and their aftershocks, especially in Japan, including ones at free field sites, down-hole arrays and in buildings. Efforts are underway to better characterize these features and their effects on structures and soils. The potential of subduction zone events to damage a large numbers of buildings spread over a large geographic region may suggest need for design criteria that mitigate the severity of this damage.

The occurrence of a larger than expected subduction zone event in Japan has prompted considerable discussion of the potential of other large subduction zone events in Japan and other locations around the Pacific Ocean. The possibility of these “larger than expected events” has a substantial influence on predictions of future tsunami, both locally in the region of a fault rupture, but also in transoceanic tsunami waves from sources such as the Cascadia and Aleutian subduction zones in North America, as well as similar zones in Asia and South America.

### *Near and far field motions*

While subduction zone events in Chile and Japan provide new challenges to engineers, damages in Christchurch, New Zealand, and in many instances in the Wenchuan earthquake in China were due to the intensity of shaking that occurred in the near field. Because Japan (and Chile) are susceptible to such near-field fault ruptures, as in the 1995 Hyogo-Ken Nambu earthquake, studies to better understand the special features of off-shore subduction ground motions and on-shore fault ruptures that lead to damage are needed.

In Japan and China, substantial evidence exists for tall buildings and other long period structures being strongly excited by earthquake shaking more than 500 km from the fault. Thus, these types of motions need to be carefully investigated as well.

### *Importance of aftershocks*

Large events trigger large numbers of aftershocks. Better understanding of the number, severity and location of aftershocks is needed. The cumulative effects of multiple aftershocks following large events on engineered structures and soil deposits need to be better understood and perhaps accounted for in design of structures. While aftershocks are generally smaller than the main shock, they can be located substantially closer to a particular structure or community than the main shock, and cause substantially more damage, as observed in Christchurch, New Zealand. Even small accumulations of damage during aftershocks raise questions about the safety of rescue workers and construction crews working on repairs or demolition. There is evidence in Japan (and elsewhere) that aftershocks re-damaged structures where damage from the main shock had already been repaired.

## Large tsunami accompany large earthquakes

The tsunami resulting from earthquakes in Japan and Chile caused severe widespread damage in those countries as well as in other countries around the Pacific Ocean. Tsunami waves, with heights measuring up to 40 meters in Japan, were responsible for the majority of earthquake casualties there and a large portion of the physical damage and loss. There is thus a need and opportunity to benchmark and improve abilities to predict tsunami waves, their interaction with costal geometries and structures, and the regions of expected flooding. The effectiveness of early warning systems and evacuation procedures should be studied. Similarly, there is a need to understand better and improve the behavior of engineered structures to tsunami wave action, impact by debris and scouring. In particular, the effectiveness of evacuation methods and the design of structures as vertical evacuation shelters should be investigated.

## Liquefaction- or settlement-related damage to structures

Extensive liquefaction and related phenomena have been observed Chile, New Zealand and Japan in areas near rivers and coastlines. In Japan, permanent vertical and horizontal displacements of the soils supporting a structure's foundation were responsible for much of the damage to structures away from the tsunami-affected zone. Liquefaction and differential settlement also contributed to heavily to damages observed in and near Christchurch, New Zealand. Such damages were seen over a large geographic region, and occurred for a wide variety of soil types and ground motion characteristics. As such, there is an opportunity and need to improve our understanding of the triggering of liquefaction and/or lateral spreading, the deformations that occur, and the consequences of soil spreading and liquefaction on the behavior of supported structures. Methods for repair and restoration of structures damaged by differential settlement need additional study as well.

## Damage to lifelines, industrial facilities, such as nuclear power plants, can exacerbate disasters

There are a multitude of engineering issues raised by the response of the Fukushima Daiichi Nuclear Power Plant to the initial shaking and aftershocks as well as to the tsunami. In addition, more than 20 other fossil fuel and nuclear power plants were taken off line immediately following the earthquake in Japan. Many of these remain off line. These outages have had a critical effect on Japanese businesses and overall quality of life. Special issues related the behavior of nuclear power plants (and other critical and hazardous industrial facilities) to earthquakes and tsunami, the effect of the inoperability of critical electric power lifeline facilities on a community, region and nation, and the special issues related to radioactive or possible chemical/biological contamination, are high priority topics for futher investigation.

## Disruption of Business and Social Systems

Wide spread economic and social disruption has resulted from the damage to housing, schools, hospitals, commercial structures, factories and infrastructure systems in Japan and New Zealand. In many cases, a facility's structural system may not have been substantially damaged, but damage to nonstructural elements and equipment as well as loss of lifelines (power, water, gas, transportation, communications, etc.) rendered it inoperable. Transportation was impaired since several national and local highways were closed due to ground shaking and landslides, and in the tsunami-affected region, many highway and railway bridges were completely destroyed. In some areas, manufacturing and other critical facilities in the tsunami-affected zone suffered little structural damage, but were inoperable due to water damage or the presence of debris. Thus, in addition to general economic, business and related studies, investigations on improving the seismic resistance of the nonstructural components and equipment and operationally critical lifelines are needed.

## The effect of the earthquake shaking on engineered facilities

Modern buildings and other structures are not designed to be damage free during rare earthquakes. While there were substantial numbers of damaged structures in Japan, Chile and New Zealand, many damaged buildings tended to be older with known deficiencies. In Chile, newer tall reinforced concrete buildings suffered damage in part due to extending the use of systems that had behaved well in the past to structures having considerably greater height. In both Chile and New Zealand, newer taller buildings suffered structural damage and total or partial collapse due to discontinuous or irregular structural systems. In many buildings in heavily shaken areas, substantial damage to nonstructural elements caused expensive and disruptive delays in restoring use of a facility.

A particularly significant consequence of the vibration and damage to buildings in Japan is a lack of confidence in the safety of structures. The vibrations of tall buildings in particular, while not indicative of structural damage or danger, frightened many occupants so that they were reluctant to re-enter buildings and in some cases property values diminished greatly.

## RESILIENT STRUCTURES

As noted above, there are many fruitful topics for study to improve the assessment and design of earthquake resistant structures. However, it appears that new issues related to the ability of a building to be repaired quickly following an earthquake, and for a community or region to recover rapidly, are becoming of more concern. As such, many researchers and practitioners worldwide are working to develop economical systems that can dependably permit engineered facilities and lifelines to continue functioning even following a large seismic event.

Such solutions are critical in the case of facilities such as hospitals, emergency command centers, and lifeline systems needed for emergency response and recovery. The types of facilities where post-earthquake functionality should be maintained can be much larger, if consideration is given to facilities needed to ensure rapid recovery of a community or organization. For example, the San Francisco Planning and Urban Research Association (SPUR, 2009) has indicated that many schools, residential buildings, and even retail and commercial buildings are necessary to provide the housing and services that would enable a community to function following an earthquake. Similarly, the vitality and perhaps viability of a business depends on its ability to provide continuous service to its customers.

As such, there is increasing recognition that the traditional approach of designing “ductile” structures for collapse prevention while necessary, may not be sufficient in a modern society. Engineering solutions that can with confidence preserve operations, or provide the promise of minimizing the disruption and cost of repairs following major earthquakes, are needed.

To minimize post-earthquake disruption, a structure or system must be able to limit the damage occurring in structural and nonstructural components, and should not exhibit permanent displacements. Structures could simply be made stronger so that they remain essentially elastic for the level of earthquake for which resilience is desired. However, this strength-based approach (1) requires more materials that add to the cost and carbon footprint of the structure, and (2) results in higher accelerations that necessitate special attention in the design of nonstructural components, equipment and contents. Moreover, such strength approaches are only as good as the estimates of future shaking.

While many types of structures that behave nonlinearly are being explored to enhance resilience, many share the following characteristics:

1. They are designed with an explicit nonlinear deformation mechanism that has only a modest strength in order to reduce cost as well as in-structure accelerations,
2. They incorporate highly durable and/or easily replaceable energy dissipation devices to reduce forces and displacements in structural and nonstructural elements not associated with the nonlinear deformation mechanism, and
3. They exhibit self-centering characteristics that minimize permanent lateral and vertical displacements of the structure.

Systems considered include ones with beams, columns, walls, braces and systems that exhibit origin-oriented hysteretic loops (Fig. 1a); this behavior is often achieved by use of a combination of yielding or friction to provide hysteresis and use of gravity or post-tensioning to provide self-centering capabilities. In some cases special materials, such as shape memory alloys, can be used alone to provide these hysteretic characteristics.

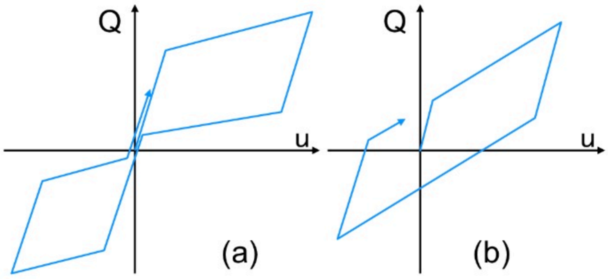


Figure 1 Hysteretic Loop Shapes for (a) Self- Centering Elements and
(b) Traditional Isolation Devices

Another approach is to install viscous or similar damping devices. When installed in flexible systems that remain essentially elastic during the response, viscous dampers can be quite effective in reducing forces, accelerations and drifts in the structure. However, traditional design approaches in the US do not focus on limiting drifts and accelerations to levels necessary to achieve resilience.

Viscous dampers and elements having self-centering characteristics are typically installed pervasively throughout a structure. Where large nonlinear deformations are expected during the dynamic response, such systems may limit forces and accelerations experienced by structural and nonstructural elements, but they may not be able to limit displacement-related damages.

An alternative approach is seismic isolation. While seismic isolation has been in use for several decades, design codes and guidelines are often formulated to provide seismic performance comparable to fixed base buildings. While it is presumed that isolated buildings perform better than traditional structures, generally building codes permit substantial damage in the event of major earthquakes.

## Isolated facilities

For resilience, it is convenient to consider a limit on peak story drifts and residual displacements. The drift limit should prevent significant yielding of the structural elements that might result in damage requiring inspection and repair, and permanent residual displacements. Drift should also be limited to prevent damage to nonstructural elements that are sensitive to relative displacements between stories. It can be shown on the basis of first principles that steel braced frames will begin to buckle or yield bracing elements at a story drift ratio of about 0.25% to 0.4% drift, where as moment frames in steel or concrete will yield at a drift ratio around 0.9% to 1.25%. Many types of cladding and partitions begin to display damage at a drift ration of about 0.3% with significant damage occurring by a drift ratio of 1%. Thus, in setting design criteria it is necessary to consider drift limits considering likely damage to both structural and nonstructural elements. From the above example, it is technically feasible, and perhaps economical, to isolate a moment resisting frame, but it is likely that substantial damage will occur in partitions, cladding, elevators and so on, before the structural system yields. Thus, depending on the type of nonstructural elements utilized, braced frames (or shear walls or other stiff systems) may be more consistent with the requirement of limiting damage to nonstructural components. However, it may not be necessary to preclude all damage to nonstructural elements during the resilience targeted event, so long as continued functionality is preserved and the occupants are able to “shelter-in- place“ during repairs.

Many types of nonstructural elements, equipment and contents are sensitive to in-structure accelerations. To prevent acceleration related damages, it is necessary to consider a limit of floor level accelerations, or on the characteristics of pseudo-acceleration spectrum at each floor. For simplicity, we might consider a design were in the floor level accelerations are limited to 0.4g, though other values may be appropriate for certain types of elements and equipment.

While near or completely elastic behavior in the portions of the facility away from the isolation plane will eliminate the possibility of residual displacement in those locations. Some isolation systems may tend to have residual displacements. The acceptability of residual displacement in the isolation system following an intense earthquake should be carefully considered. If accounted for in the initial design with regards to accessibility and functionality of utilities, residual displacements in the isolators may not impair post-earthquake functionality, and thus be acceptable. Re-centering an isolated building following an earthquake may be economical in certain cases, if needed. In other cases, isolators can be designed to minimize residual displacements in the isolation plane.

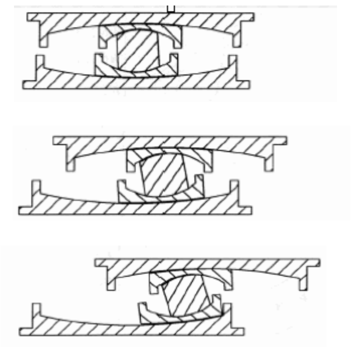
For resilient designs, it is necessary to identify a level of shaking at which resilience is desired. This may be expressed as a fraction of the maximum considered earthquake, or in terms of the confidence with which resilience can be achieved over the life of the structure (i.e., 50% confidence that the facility will remain operational following an earthquake having a 10% probability of exceedence in 50 years, or a 90% confidence that the structure will be inoperable due to earthquakes for less than 3 days during the life of the structure). It is expected that different facilities will likely have different criteria, depending on their use and importance to the community or owner. For example, some structures would be expected to be operable immediately, while others might be acceptable in terms of resiliency if their function is restored within 90 days. In all cases, a high confidence of collapse resistance is assumed. For the purposes of this paper, resiliency for the maximum considered event is targeted, consistent with important or critical facilities.

## Isolation systems

It has been noted that the design of isolated structures can be problematic due to the apparent over- or under-conservativeness of some design provisions, and also because of challenges encountered when designing isolated systems to resist intense near-field ground motions. To resist large near-fault ground shaking, relatively large and strong isolators are often necessitated to control displacements and maintain isolator stability. In these cases, isolators may not act effectively, especially for small events, and require relatively large design forces and trigger excessive accelerations in the superstructure [Morgan and Mahin, 2007]. Similarly, traditional designs have relied on isolation systems that have essentially bilinear hysteretic loop shapes with effective periods in the 2-3 sec. range (Fig. 1b). This type of isolator may develop large forces (and thereby drifts and accelerations) in the supported structure due to the large lateral isolator forces that may develop in large earthquakes. Thus, efforts are underway to improve isolation for small events, limit drifts for larger events, and reduce floor accelerations.

Several approaches are being pursued at Berkeley and elsewhere to overcome these impediments to resilience, including novel combinations of elastomeric isolators acting in series with sliding bearings, and elastomeric bearings acting in parallel with nonlinear viscous dampers.

Another promising approach is the Triple Pendulum Slider [Earthquake Protection Systems, 2007]. This device has three independent pendulum mechanisms (Fig. 2). By strategically selecting friction coefficients and the effective radius for each pendulum mechanism, hysteretic characteristics can be optimized for occasional, rare and very rare events. Figure 3 shows hysteretic loops for different combinations of friction coefficients and radii. Isolator displacements up to +/- 2 m are currently feasible.



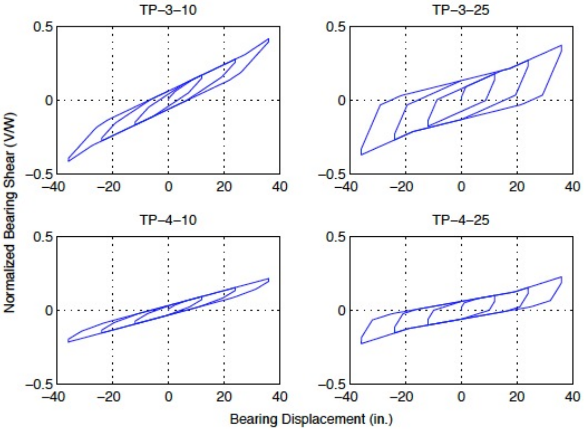


Figure 2 Triple Pendulum Bearing

Figure 3 Representative Hysteretic Loops

## Isolated Building Tests and Analyses

Tests (Fig. 4) and analyses (Morgan and Mahin, 2011) demonstrate that the TP devices can be designed to achieve about the same isolator displacements for a large event, but with smaller drifts and accelerations in the superstructure and with a far greater degree of isolation during smaller events (Fig. 3) [Morgan and Mahin, 2011]. Numerical simulations were conducted of a three-story structure similar to that shown in Fig. 4 subjected to the suite of SAC ground motions corresponding to a 2% probability of exceedence at a site in metropolitan Los Angeles (Somerville, 1997). For TP bearings with an effective period of 4 seconds and damping of 10% (see TP-4-10 plot in Fig. 3) the computed median isolator displacement is 770 mm, but the peak median story drift is less than 0.4% and the peak median floor level acceleration is less than about 20% g. Thus, for this type of isolation, high confidence of resilience can be obtained for even MCE level excitations.

A current test program setup is shown in Fig. 5. This shows a simple shaking table capable of one-dimensional motion. In this case, the test specimen is designed with replaceable plastic hinges, made from clevises and replaceable steel rods. The rods are machined and located to produce a desired stiffness and moment capacity for the plastic hinge. In this case, various amplitudes and distributions of strength are provided, based on US building codes as well as other alternatives. These studies show that current US design provisions can result in significant yielding of the superstructure prior to the isolators reaching their ultimate displacement capacity and that the typical distribution of strength used for design in the US results in weak story behavior. Superior behavior is achieved where the strength of the structure is increased to remain elastic until the ultimate displacement capacity is reached and the distribution of story strength is consistent with that that existing when the bearing displacement capacity is reached.

This setup is also being used to as a hybrid shaking table, where the behavior of the isolated structure to various soil conditions and structural pedestals is examined by including a numerical model of the supporting soil or substructure in the shaking table controller.

Figure 4 Test of 3-Story Isolated Building

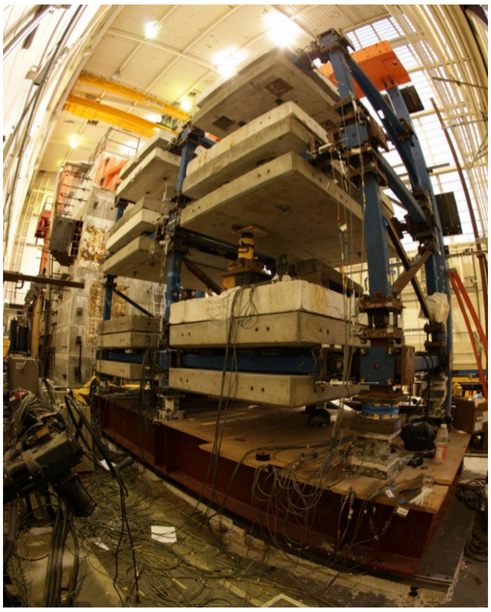


Figure 5 Test of 3-Story Yielding Superstructure

A number of challenges remain in the design of seismically isolated structures. One of these is the development of structural systems and non-structural components that are complementary in the attainment of resilience. Some structural systems are too flexible and result in significant damage to nonstructural systems. Similarly, many nonstructural elements are so fragile that they suffer substantial damage even if drifts less than 0.25% are realized on average.

Moreover, current seismic isolation systems only provide protection for motions in the horizontal direction. Vertical vibrations are not isolated, and in some cases may be amplified. Damage to nonstructural elements can occur in such cases. While this damage maybe less than in fixed base systems, damage may occur that will require special consideration when evaluating the resilience of a system.

## RESILIENT BUSINESSES

A business or service center may be located in a structure that is able to protect the occupants, nonstructural components and structural system, but still not be able to continue operations following an earthquake. As noted by the SPUR Resilient Communities initiative (SPUR, 2009), businesses need to have staffing, raw materials, a means of distributing products or services, and various utilities and services in order to operate. As such, a growing number of consultants are providing services related to post-disaster emergency management and business continuity.

For staff to return to work (once the facility is restored to operability), they need housing, schools for their children, food, transportation, health care, and minimal utilities needed to live. The business will also need utilities such as water, power, sewerage, telecommunications, Internet services, and so on. They need access to banking and other business related services. Raw materials need to be shipped and delivered, and final products or services need to be sent to customers. In many cases, raw materials, suppliers, packaging, and shipping services will be located in the same region damaged by the earthquake and also not functioning. Thus, the operation of modern industrial societies is highly interdependent and the success of a region in carrying out business and industrial operations can be rapidly eroded by the failure of a few key services or lifelines.

Similarly, businesses and services well outside of the earthquake shaken area may be vulnerable to business interruption due to closure of businesses located in regions shaken by the earthquake. Thus, careful attention to supply chains in business operations is needed to insure adequate reserves of parts or redundancy in component suppliers.

## RESILIENT COMMUNITIES

For a business to operate, it needs to be in a community that is functional following a large earthquake. For small and moderate earthquakes, local neighborhoods and communities can come to the aid of those who have suffered earthquake damage, and traffic can be rerouted and other lifelines rapidly restored. However, as the area effected by the ground shaking grows, and the extent of damage increases, it is difficult for neighboring areas to provide adequate relief. If housing is damaged moderately or severely so that many cannot stay in their homes, they will need to find temporary housing or move to other areas. If a factory or business is damaged, it may shift staff and operations to other locations. If workers cannot get food, or other services, they cannot work in their normal jobs or help with repairs. Thus, a critical balance is needed to maintain adequate housing, lifeline services, and business for a community to operate and recover rapidly from a large earthquake. While the balance of resilient facilities, lifelines, and services is a matter of public policy, realization of this balance and attaining a resilient society is a matter of engineering.

Resilient engineered facilities and businesses and services are critical as noted above. Also, lifelines such as transportation, power, water, sewers and so on are also needed. To this end, it is necessary to assess and design such infrastructure in terms of its criticality to post-disaster functionality of a community. Thus, hardening of water and electrical distribution systems may be needed. Nodes such as bridges, power plants, telecommunication centers, server farms, and so on may need to be designed with resilience as a design criteria.

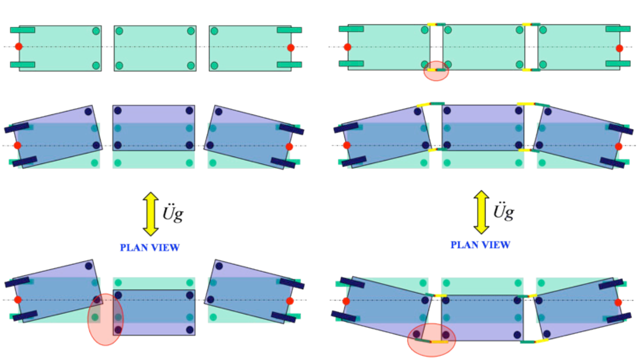
For example, bridges are a particularly vulnerable aspect of highway and railway transportation systems. Improved methods of designing bridges to withstand large earthquakes without significant damage or additional cost are the subject of considerable recent research. For example, various types of recentering bridge columns have been suggested, along with bridge piers that are allowed to uplift during earthquakes. As with buildings, several strategies for improving the resilience of bridges are being explored associated with advanced materials that do not exhibit damage like cracking or spalling until substantially larger deformation demands compared to current conventional materials, viscous and other supplemental energy dissipation devices, and so on A commonly used strategy to achieve post-earthquake functionality is seismic isolation.

### Isolated bridges for improved resilience

Seismic isolation is especially easy to implement for bridges where decks are attached to the supporting columns and abutments via elastomeric or other bearings. To develop improved understanding of the behavior of seismically isolated bridges and gain confidence in design methods, a series of tests and analyses of isolated bridges has been recently completed at Berkeley (e.g., Anderson, 2003). These studies included a variety of different isolator types, bridge dynamic properties, and earthquake characteristics. Three generic types of isolator bearings were considered, including lead rubber bearings, high damping bearings, and friction pendulum bearings. Extensive studies were made to characterize bearings subjected to 3D loading, and to assess the effects of aging. Bridge systems tested include one and two span bridges having substructure periods ranging from nearly zero to more than 2 seconds. More than a dozen bridge configurations were tested to assess the effects of mass eccentricity, stiffness eccentricity, bridge substructure period, bearing type, in-situ variations in bearing properties, yielding of supporting columns, and earthquake excitations. One of the bridge models tested appears in Fig. 6.

Such experimental results were used to develop improved numerical models of the isolation bearings, and to assess the sensitivity of system response to different design parameters, and to uncertainties in these parameters. Various provisions of the AASHTO Guideline Specification [1999] such as those related to treatment of bidirectional excitations were assessed in Anderson and Mahin [2003, 2004]. Overall, good performance was noted for all of the isolated systems studied.

Figure 6 Shaking table test specimen of simple supported bridge with different substructure stiffness



(a) (b)

Figure 7 Interaction of segments in multi-segment bridge system, (a) conventional system and (b) segmental displacement control

***Segmental displacement control concept***

A multi-segment isolated bridge system will inherently develop relative displacements between adjacent bridge segments, thereby raising the possibility of damaging bridge decks, isolators and non-structural components such as expansion joints. Therefore, seismically isolating a bridge must also incorporate a method to control the relative displacements between bridge decks while still preserving the desired seismic response of the bridge system. Segmental Displacement Control (SDC) design was recently introduced by Earthquake Protection Systems of Vallejo, California, to achieve this goal and provide a more resilient bridge system. This concept is the subject of intense investigation.

Using seismic isolation concepts previously stated, the decoupled superstructure decks are connected at the expansion joints by lock-up guide devices. This device contains user-defined properties in accordance with the performance of the isolated bridge system and its fundamental demands. However, the primary purpose of the lock-up guide is to resist the relative transverse displacement between bridge decks, thereby allowing for protection of the non-structural components and a more resilient structural system.

The concept of SDC is shown in Figure 7, where the fundamental behavior of an isolated bridge with three deck segments is displayed in plan view. The dotted horizontal line references the centerline of the bridge and is parallel to longitudinal motion. The middle bridge deck is fully supported by bearings that allow longitudinal and transverse displacement, shown as circles. However, the end bridge decks are restrained in the transverse direction at the abutments by one-dimensional bearings (or shear keys), shown as rectangles. A real-life bridge would typically have more than three decks in series and each segment may be continuous over one or more span. Thus, Fig. 7 is a simplification of a test set up indicated in Fig. 8.

Another function of the lock-up guide is to allow a prescribed amount of longitudinal translation between adjacent decks. This translation will allow thermal movement of the bridge, but during a major event or when the prescribed longitudinal displacement capacity is exceeded, the connection “locks up”, providing a restraining stiffness that is characteristic of the lock-up guide dimensions and material properties. Locking up the bridge system is not only beneficial for expansion joints and other nonstructural elements, but also for reducing the probability of bridge deck unseating.

To validate the effectiveness of SDC design for isolated bridges, an experimental program was designed to impose a series of ground motions on a one-quarter scale isolated bridge model on a shaking table. Cases with and without lock up guides were tested.

For instance, imposing three simultaneous components of the 1994 Northridge, CA, Sylmar ground motion record, the maximum transverse relative displacement between bridge decks was approximately 43 mm, as seen in Figure 9, correlating to 172 mm for a full-scale bridge. This amount of full-scale displacement will most likely damage the expansion joints. However, the experiment with the lock-up guide installed shows relative transverse displacements only 30% of those measured without the restraints. This is critical to prevent damage to non-structural components. It is noteworthy to mention that the TPF bearings tend to minimize relative displacements between segments, as their dynamic properties are independent of the amount and location of the supported mass. In any event, the forces needed in isolated systems to limit these relative displacements is relatively modest.

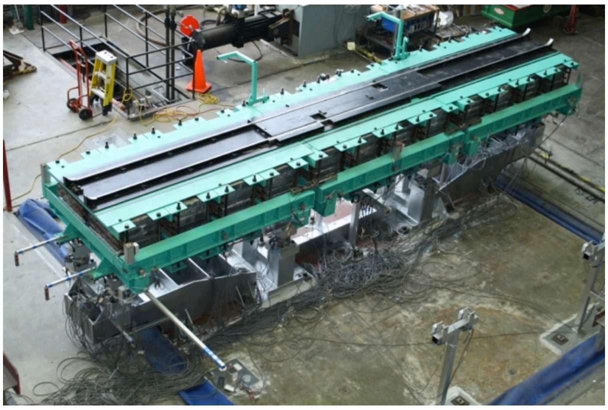


Figure 8 Three-segment segmental displacement control test set up with slab rail system installed over bridge decks

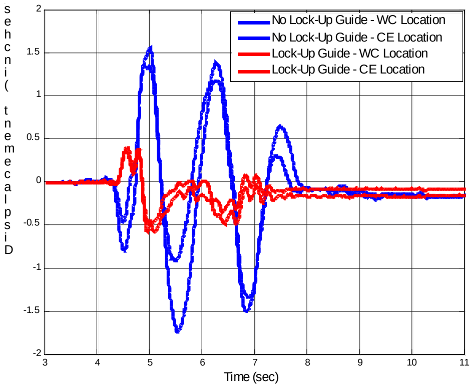


Figure 9 Relative transverse displacement between center and end segments with and without lock up guides (1 in = 25.4 mm)

Overall observations suggest segmental displacement control strategies have great potential for preserving non-structural components and achieving a more resilient bridge system because of reduced transverse relative displacement between bridge decks. Noteworthy is the fact that the centerline of the bridge remains continuous helping preserve driver safety and facilitating the use of this system for railway bridges. Such segmental displacement control may be useful for other types of large isolated structures.

## CONCLUSIONS

The technology and design approaches described in this paper provide several alternative ways to achieve durable building and transportation structures that increase post-earthquake serviceability and reduce the need for repair. By permitting structures to undergo significant inelastic deformations during seismic events, yet suffer little damage that would require post-earthquake repairs and impair operability, structural engineers can achieve designs that are durable, dependable, and economical in terms of initial construction cost and the potential losses that might occur in the event of a damaging earthquake. As such, these approaches address the basic principles articulated by sustainable design and seismic resiliency.

Additional research is needed to refine these concepts, especially with regards to (1) reducing cost and increasing speed of construction, (2) reducing the societal and ecological impacts of construction, (3) and refining concepts such as those presented herein and developing more generally applicable design guidelines for resilient structures.

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