FUNDAMENTALS OF ASEISMIC TECHNIQUES IN BRIDGES

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ABSTRACT:

The design of bridges, the majority of which are long, has to compromise both functional and earthquake resistant requirements, which are conflicting components of the same problem and they impose opposite design requirements. The functional problem, which is mainly critical for the longitudinal direction of the bridge, requires the free contraction and expansion of the deck, due to annual thermal cycle, shrinkage and creep. On the other hand, the earthquake resistance of the bridge is enhanced by implementing monolithical systems as being possible. To improve structural safety and integrity against severe earthquakes, more effective and reliable techniques for aseismic design of structures based on structural control concepts are desired. The differences of bridge damages due to earthquakes in USA, Japan and Taiwan are introduced first in this paper, then an over view on seismic isolation technology as well as other seismic protection technologies adopted and applied to protect the bridges against earthquakes are presented in which a brief review of the earlier and current base isolation devices and aseismic techniques, proposed or implemented, are given, and aspects for future research in the area of isolation of bridges are discussed.

KEYWORDS: Bridge, seismic, base isolation, seismic technologies.

1. INTRODUCTION

Earthquakes give rise to dynamic loads that have a high potential for disastrous consequences for structures, as well as humans. There are different ways in which structures are affected by earthquakes, the vibration of the ground being the most common, but not the only one. Other earthquake effects are ground failures such as *liquefaction* (loss of strength in silt or sand layers due to build-up of pore water pressure), landslides and mudflows (usually triggered by liquefaction); further effects include sea waves *(tsunamis)* and lake waves *(seiches)*. By far, most of the damage due to earthquakes is caused by the ground motion, but other effects can also be quite devastating, as shown, for instance, by the July 1998 tsunami that hit the coast of Papua New Guinea, causing over 2,000 deaths and complete destruction of the villages near the coast.

Damage to a bridge can have severe consequences for a local economy, because bridges provide vital links in the transportation system of a region. In general, the likelihood of damage increases if the ground motion is particularly intense, the soils are soft, the bridge was constructed before modern codes were implemented, or the bridge configuration is irregular. Even a well-designed bridge can suffer damage if nonstructural modifications and structural deterioration have increased the vulnerability of the bridge. Depending on the ground motion, site conditions, overall configuration, and specific details of the bridge, the damage induced in a particular bridge can take many forms. Despite these complexities, the record is clear. Damage within the superstructure is rarely the primary cause of collapse.

Many countries experienced serious bridge damages during the past years. There were several famous earthquakes in USA, such as 1971 San Fernando earthquake, 1987 Whittier Narrows earthquake, 1989 Loma Prieta earthquake, 1994 Northridge earthquake. The Northridge earthquake caused deck collapse of 7 bridges and damages of many bridges. As for Japan, there were over 19 major earthquakes happened from 1923 Kanto earthquake to 1955 Kobe earthquake, and over 5000 bridges damages occurred. Among these earthquakes, the most serious damages were caused by Kobe earthquake. In Taiwan, the most important should be the unforgettable Chi-Chi earthquake. The Chi-Chi earthquake brought in serious damages of 25 opened bridges and visible damages of many under-construction bridges. The major damage patterns in Chi-Chi earthquake include deck and superstructure collapse due to fault rupturing, shear or flexural damage on column, beam movement, capbeam and foundation damage, soil settlement of abutment backfill, deck bulge due to squeezing, expansion joint distortion or squeezing, unseating prevention device damage.

With the occurrence of every major earthquake, there has been in the past, almost a world-wide tendency to increase the capacity demand of the structure to counteract such events. It is only in the last decade that new strategies have been successfully developed to handle this problem economically. The development of computing tools and the availability of tests installations as seismic isolators have promoted the progress of such innovative technologies in which the first application on bridges in North America turns up just at the end of the 80s. Moreover, the end of the cold war in the early 1990s has given birth to the hydraulic dampers technology transfer initially developed from the military needs to civil engineering applications. Three main aseismic technologies are the most used in bridges constructions, that is:

- Seismic base isolation
- Seismic dampers
- Seismic shock transmitters SST

How these ideas can be used in economical resistant design of bridges and implemented is the subject of this paper.

2. THE DIFFERENCE OF BRIDGE DAMAGES DUE TO EARTHQUAKE IN USA, JAPAN AND TAIWAN

Earthquake displacements can cause significant damage to structures and lifelines located on or near the causative fault. Recent fault ruptures from earthquakes have caused failure or near failure on bridges (Japan, 1995; Taiwan, 1999; Turkey, 1999), dams (Taiwan, 1999) and buildings (California, 1971). Earthquake ruptures in the 1971 San Fernando, California earthquake (M 6.7) caused extensive structural damage and resulted in legislation of the Alquist-Priolo Earthquake Fault Zoning Act. This Act prevents construction of habitable buildings on the surface trace of an active fault (defined as having ruptured within the past 10,000 years). However, it may not be possible to relocate many structures and lifelines away from an active fault and loss of these facilities can significantly impact society. Therefore, it is essential to consider the effects of fault rupture displacements when designing structures near fault sources. The 2002 Denali earthquake showed that major lifeline structures can be designed to accommodate fault displacement if the potential for location and size of displacement is known.

USA, Japan and Taiwan are one of the most touched regions by earthquake disaster in the world because of the geographic location in a seismic zone as shown in figure 1. Structure systems of bridges are quite different among USA, Japan and Taiwan as a result bridges damages degree was clearly different.

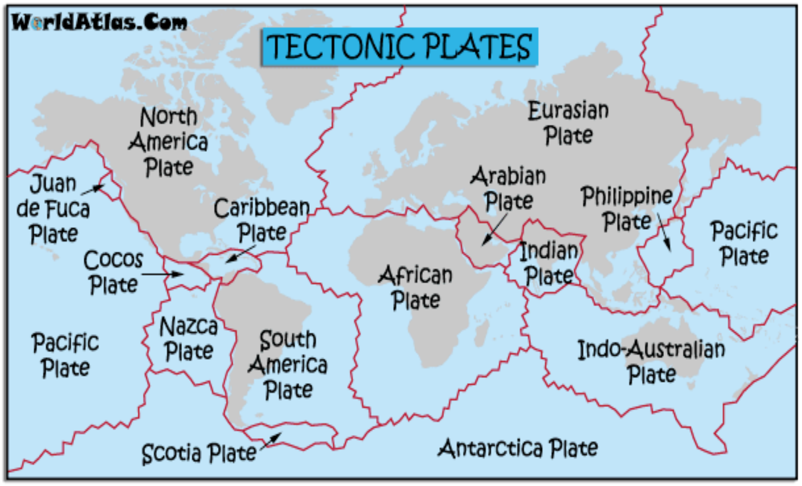


Figure 1. Tectonic plates

Most of the bridges in USA were designed to be rigid between superstructure and substructure, with bearings on out-stretching half-joint hinge support. In Japan, most bridges were designed separately between superstructure and substructure, with bearing on column top. As for Taiwan, the structure system was similar to Japan, only bearing type is different. In Japan more steel bearings were used, but in Taiwan most bridges adopted rubber bearings. Because of the structure feature of USA bridges, it is much harder to extend unseating length and improve structure system while proceeding retrofit compared to Japan & Taiwan. The retrofit works in USA mainly base on plastic-hinge concept which tries to enhance member strength. As for Japan, the work was focused on enhancing column ductility and bearing retrofit. In Taiwan, because the structure system with rubber bearing was quite different, it was found that only none-to-minor damages on column occurred after earthquake. That is, fewer damages on column existed in Taiwan comparing to the other two countries.

3. TECHNIQUES REDUCING EARTHQUAKE FORCES

Although the concepts of inelastic spectra and behavior factors, coupled with capacity design principles, clearly dominate current seismic codes, it has to be emphasized that they do not represent the only conceptual framework available for seismic design. Furthermore, an engineer should fully realize that designing a structure on the basis of these concepts means that under earthquakes of intensity equal to or exceeding that of the design event, damage to the structure could be both substantial and extending into a large part of the structure.

Perhaps more importantly, formation of a favorable mechanism does not guarantee that floor accelerations will be low enough to prevent extensive damage to the non-structural elements and the content of the building. These and other concerns have led to the development of alternative conceptual frameworks for seismic design, currently referred to as ‘passive’ and ‘active’ control of the seismic response of the structure. By far the most practical approach is passive control that incorporates the fundamental ideas of *seismic isolation* and provision of *supplemental damping.* These will be discussed in the remainder of this section. Two ways lead to protect a bridge against earthquakes:

3.1. The conventional Method of Seismic Design

In which the structures are designed to dissipate the energy induced by the design earthquake through inelastic deformations. The areas of energy dissipation by inelastic deformations are called plastic hinges. They are typically located at the base of the foundation units above ground level and are detailed for ductile behavior as shown in figure 2. In S6 design code, reducing the elastic forces is represented by the response modification factor R which is ranging between 2 and 5 and depends on the foundation elements type.

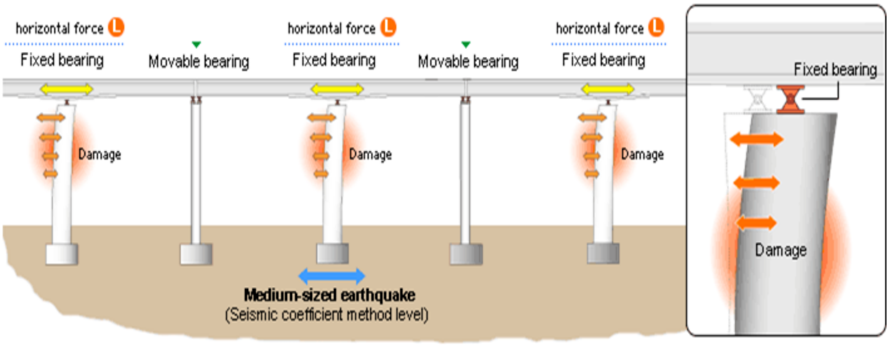


Figure 2. Earthquake forces reducing by the conventional method of seismic design

3.2. Design Method Using Aseismic Technologies

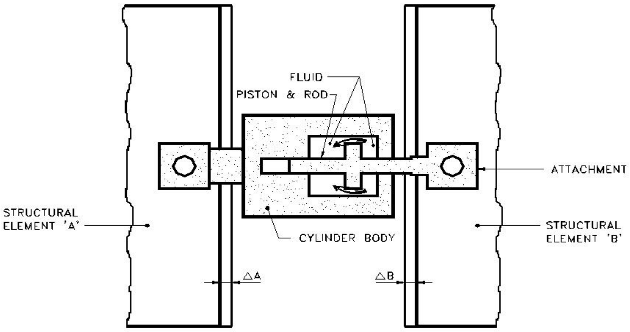
The use of special devices that reduce the seismic forces can be effectively utilized in the structure. By decoupling the structure from seismic ground motions it is possible to reduce the earthquake-induced forces in it. This can be done in two ways:

- Increase natural period of the structure by base isolation,
- Increase damping of the system by energy-dissipating devices.

The central issues are to limit the seismic energy entering into the structure from the ground in the first place and then to dissipate as much of it as possible by damping devices. For this aim three main techniques are adopted:

3.2.1. The Use of Shock Transmitters Units (STU)

Sometimes it is advantageous that the seismic energy entering from the ground into the structure does not get localized. Special devices exist which can avoid significant energy accumulation and ensure its distribution to various structural elements. Here, the idea is not to reduce the total seismic energy entering into the structure but to judiciously distribute it amongst all the designated resisting elements. Such devices go by the name of Shock Transmission Units (STUs). Their action is shown in Figure 3, the behavior being similar to a car seat-belt. As Structure A and Structure B move slowly relative to each other, the fluid is able to migrate through narrow orifices from one side of the piston to the other. For rapid movements (e.g., earthquakes) the transfer of fluid is not possible thereby locking the piston to its cylinder. In such circumstances the device acts as a rigid link between Structure A and Structure B.



Note: Arrows show migration of fluid.

Figure 3. Shock Transmission Unit

In bridge structures the inertial force from the superstructure can be transmitted to designated sub-structures. Application of STUs to a 1.0 km long bridge with expansion joints only at the abutments and central pier is shown in Figure 4, wherein the seismic forces are transmitted to three piers in each of the two halves of the structure.

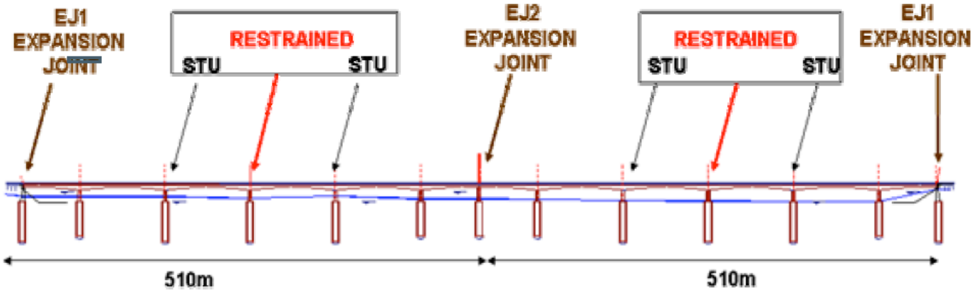


Figure 4. NHAI's Ganga Bridge at Allahabad showing application of STUs

3.2.2. The use of Seismic Dampers

It is a system of energy dissipation mechanism that absorbs a significant portion of the seismic energy, supplemental damping devices can be of different types, including:

Hysteretic Dampers: wherein energy dissipation is taking place by yielding of metals such as lead and mild steel, which have hysteresis loops very close to elastoplastic. A popular isolator that incorporates a damping device is the *lead-rubber* bearing, shown in Figure 5, which is an elastomeric bearing (layers of rubber reinforced with thin steel plates to increase the vertical stiffness) with a lead core which provides both damping (after yield) and resistance to service lateral loads.

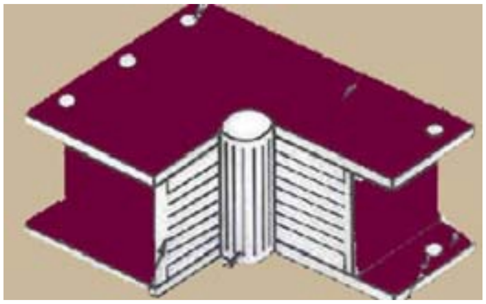


Figure 5. Lead Rubber Bearing (LRB)

Viscous Dampers: such as the oil dampers commonly used in the motor industry, but also newer devices such as shear panels containing high viscosity fluids that have recently been developed in Japan. These mechanical devices are separate from the isolators.

Frictional Dampers: based on the concept of friction between different materials, for instance stainless steel and PTFE (Teflon). Such systems have a number of advantages, but (unlike the previous ones) they need to be supplemented by a restoring force mechanism (i.e. a means for returning the isolated structure to its initial position after a strong earthquake).

3.2.3. Seismic Isolation

Isolating a structure from the shaking ground is a rather old concept, but it is only since the 1970s that practical isolation systems have been developed and used for earthquake protection of buildings and bridges. The concept was initially referred to as *base isolation* but at present the term *seismic isolation* prevails, in view of the fact that the isolating devices do not have to be always located at the base of the structure.

There are two interrelated ideas behind developing a seismic isolation system: the first one is to make the structure much more flexible than it is, by altering the way it rests on the ground, hence shift it to the long period range of the response spectrum that is typically characterized by reduced accelerations and consequently reduced inertial forces; the second is to introduce some kind of 'fuse' between the structure and the ground, whereby the amount of base shear to be transferred from the shaking ground to the structure is controlled by the strength of the fuse. By making the structure more flexible, one might achieve lower seismic forces, but displacements tend to increase. It is therefore essential to also control the amount of horizontal displacement of the isolated structure and an efficient way to do this is by increasing its damping.

Currently used isolation systems are based on the concept of flexible supports; more details are given in the following section.

4. SEISMIC ISOLATION SYSTEMS

Seismic isolation is a response modification technique that reduces the effects of earthquakes on bridges and other structures. Isolation physically uncouples a bridge superstructure from the horizontal components of earthquake ground motion, leading to a substantial reduction in the force demands generated by an earthquake. Uncoupling is achieved by interposing mechanical devices with very low horizontal stiffness between the superstructures (deck and girders) and substructures (columns and abutments) as shown in figure 6. These devices are called seismic isolation bearings or simply isolators. Thus, when an isolated bridge is subjected to an earthquake, the deformation is concentrated in the isolators rather than the substructure elements. This greatly reduces the seismic forces and displacements transmitted from the superstructure to the substructures. A seismic isolator possesses the three important characteristics:

- The flexibility of the isolator: will lengthen the period of vibration of the bridge to reduce seismic forces in the substructure.
- The energy dissipation: limits displacements between the superstructure above the isolator and substructure below.
- An adequate rigidity: is provided for service loads while accommodating environmental effects (Buckle et al., 2006b).

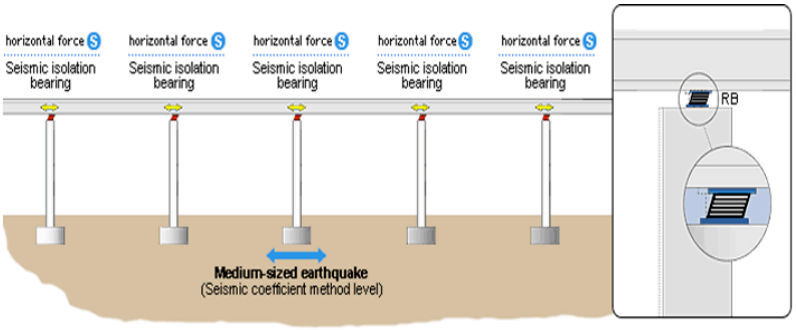


Figure 6. Isolated bridge.

Figure 7 illustrates the effects of flexibility and damping of the isolator on the seismic forces. The solid and dashed curves represent the 5 percent and 30 percent damped (AASHTO, 1999) acceleration response spectra respectively, for stiff soil conditions (Soil Type Π). The increased level of damping, due to the energy dissipated by the isolation system, leads to a further reduction in the seismic forces. It is seen that period shift, or increased flexibility of the system, allows for a reduction in the spectral acceleration on the order of 60 percent, and additional reduction is possible by increasing the overall damping of the system from 5% to on the order of 30%.

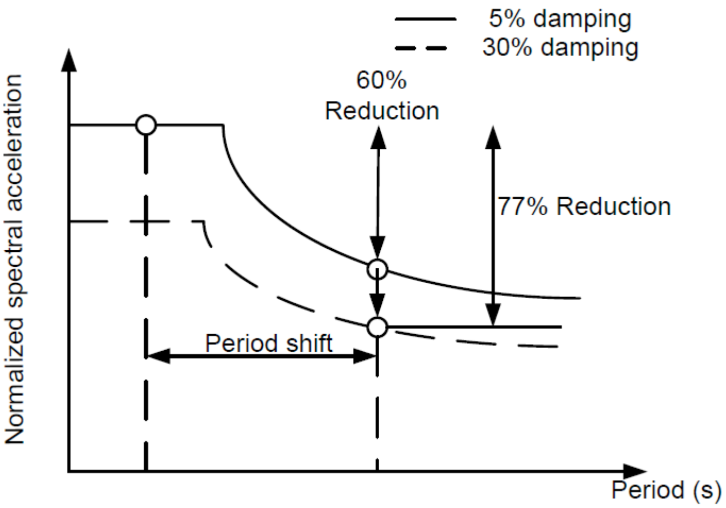


Figure 7. Effects of isolator on the bridge response

The first design guidelines for seismic isolation were issued in California in 1986, and have been subject to several revisions. The current versions of UBC (ICBO, 1997) and NEHRP (FEMA, 1997a) contain provisions that are essentially identical, with the exception of the definition of design earthquake. These provisions include both the equivalent lateral force and the dynamic analysis procedures for seismically isolated buildings, but the restrictions for the former are such that in most practical cases the dynamic approach has to be applied.

In bridges, the base isolation devices can rather easily incorporated by replacing the conventional bridge bearings by isolation bearings. Base isolation bearings serve the dual purpose of providing for thermal movement as well as protecting the bridge from dynamic loads by increasing the fundamental period and dissipating the seismic energy by hysteretic damping. In order to demonstrate the effectiveness of seismic isolation a three-span continuous deck bridge made of reinforced concrete is considered. The properties of the bridge deck and piers are given in Table 1.

Table 1. Properties of the bridge deck and piers

Properties	Deck	Piers
Cross-sectional area (*m*2)	3.57	4.09
Moment of inertia as (*m*4)	2.08	0.64
Young's modules of elasticity (*m*2)	20.67×109	20.67×109
Mass density (*kg*/*m*3)	2.4×103	2.4×103
Length/height (*m*)	3×30 = 90	8

These properties correspond to the bridge studied by Wang et al. (1998) using a sliding isolation system. The bridge is modeled as shown in Figure 8 as a discrete model. The fundamental time period of the piers is about 0.1 sec and the corresponding time period of the non-isolated bridge works out to be 0.5 sec in both longitudinal and transverse directions. The damping in the deck and piers is taken as 5% of the critical in all modes of vibration. In addition, the number of elements considered in the bridge deck and piers are 10 and 5, respectively. Response quantities of interest for the bridge system under consideration (in both longitudinal and transverse directions) are the base shear in the piers and the relative displacement of the elastomeric bearings at the abutment. The pier base shear is directly proportional to the forces exerted in the bridge system due to earthquake ground motion. On the other hand, the relative displacements of the isolation bearing are crucial from the design point of view of isolation system and separation joints at the abutment level.

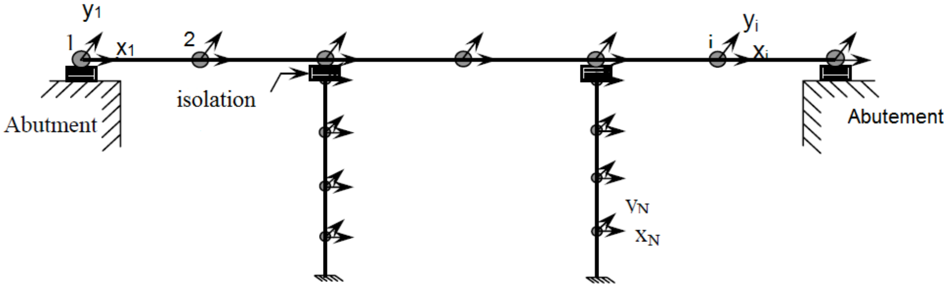
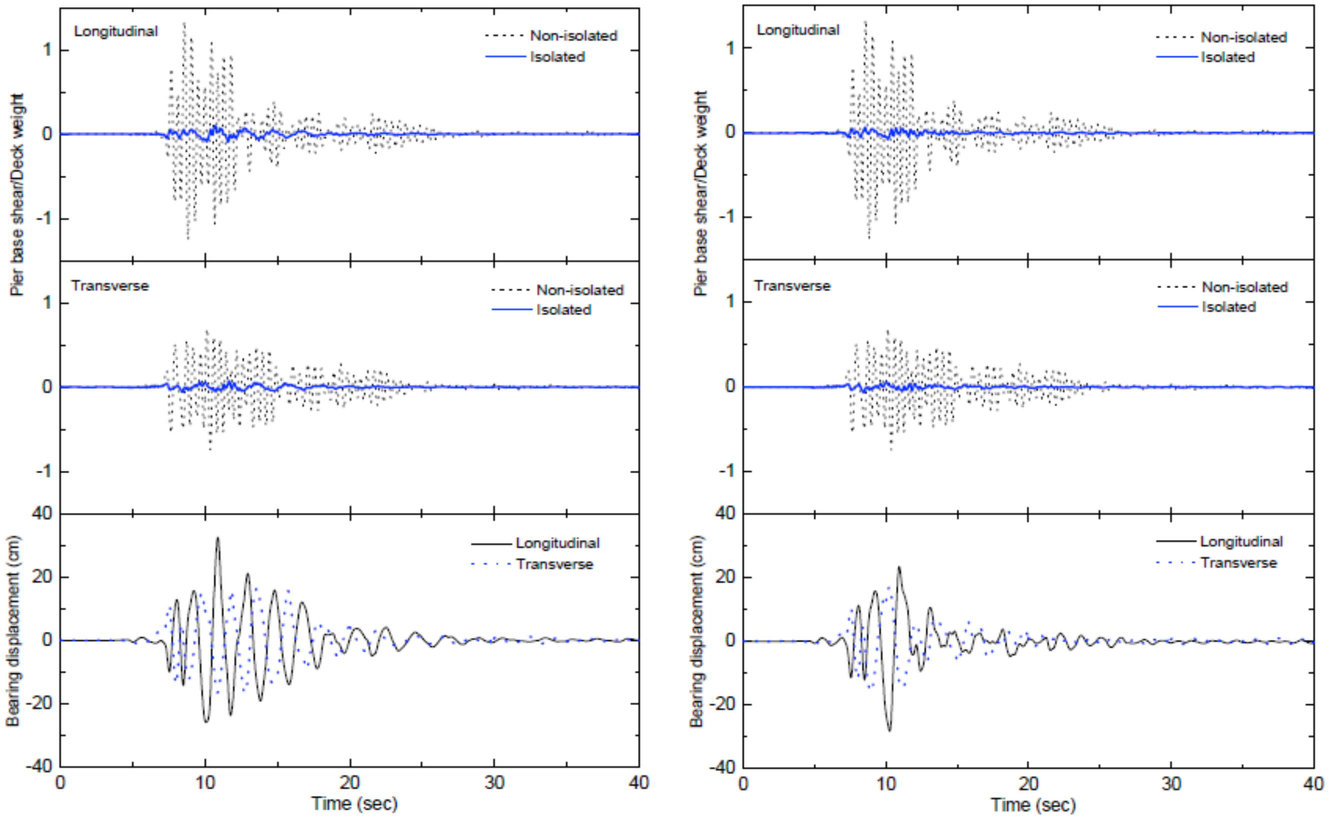


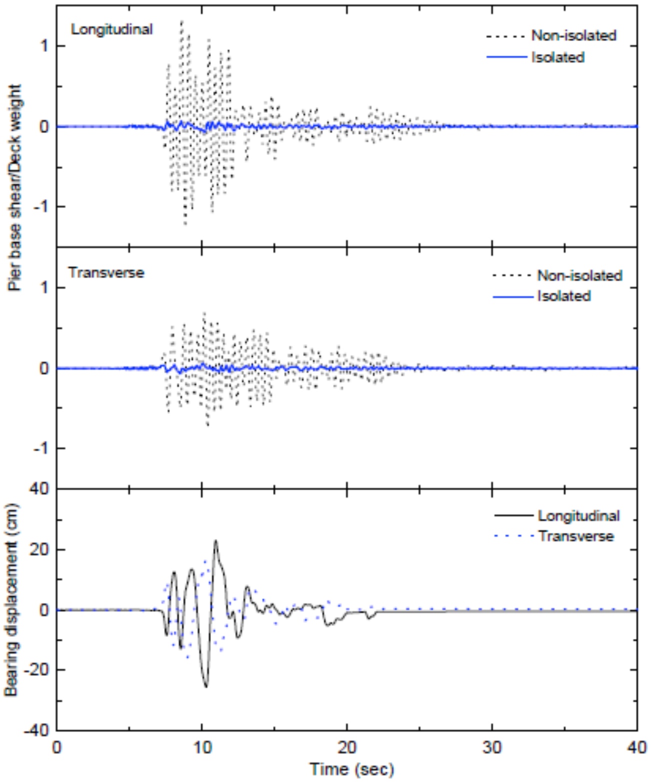
Figure 8. Mathematical modeling of isolated bridges

In Figures 9a, 9b and 9c, the time variation of the base shear in the pier and relative displacement of the bearings of the bridge isolated by the LRB, N-Z and FPS is shown. The LRB system is designed to provide isolation period of 2 sec (based on rigid deck and pier condition) and 10 percent damping ratio. The isolation period for the N-Z and the FPS system is taken as 2.5 sec. The yield strength of the N-Z system is taken as 5 percent of deck weight and the friction coefficient of FPS system is considered as 0.05. The system is subjected to Kobe, 1995 earthquake ground motion in the longitudinal and transverse directions. The base shear in the piers is significantly reduced (about 80 to 90%) for the isolated system as compared to the non isolated system in the both directions of the bridge. This indicates that the isolation systems are quite effective in reducing the earthquake response of the bridge system. The maximum peak displacement of the bearing is 32.87, 27.65 and 31.50 for LRB, N-Z and FPS system, respectively in the longitudinal direction of the bridge.



(a) LRB isolation system

(b) N-Z isolation system



(c) FPS isolation system.

Figure 9. Time variation of base shear and bearing displacement of the bridge isolated by FPS system under Kobe, 1995 earthquake motion.

5. CONCUSIONS

This study shed light on recent and economical techniques for bridge protection against several damages and collapse due to earthquake forces and the effectiveness evaluation of the seismic isolation in bridges construction which has led to the following conclusions:

- Bridges damages during large earthquakes helped engineers to understand their seismic behavior and identify different pathologies and their causes.
- The designer needs to understand how different structural forms will behave in real earthquakes and detail the structure to account for this.
- The retrofit works in USA and Japan base on plastic-hinge concept which enhances column ductility and bearing retrofit.
- In Taiwan, because the structure system with rubber bearing was quite different, it was found that only none-to-minor damages on column occurred after earthquake.
- New technologies particularly seismic isolation of bridges offer attractive alternative which allows economy realization at short and long extent. This discipline is further more supervised by codes and norms.
- The seismic protection is particularly complex: a large number of factors must be taken into account and their treatment must be highly accurate, but still changes as it tries to be even more efficient in preserving human life.

- Investigations of effectiveness of seismic isolation for skew bridges and bridges curved in plan and elevation.
- In spite of favorable conditions and research progress carried out during last years the number of new aseismic technologies in bridges domain is still restraint.
- Finally, random nature factors still existent so, it is impossible to achieve total security.

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