Seismic behavior of isolated bridges: A-state-of-the-art review

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ABSTRACT

An update state-of-the-art-review of the behaviour of isolated bridges to seismic excitation is presented. The review includes the literature on theoretical aspects of seismic isolation, parametric behaviour of base-isolated bridges and experimental studies to verify some of the theoretical findings. A brief review of the earlier and current base isolation devices, proposed or implemented, is given, and aspects for future research in the area of isolation of bridges are included.

KEYWORDS

Bridge, seismic, base isolation.

1 Introduction

Seismic isolation is an old design idea, proposing the decoupling of a structure or part of it, or even of equipment placed in the structure, from the damaging effects of ground accelerations. One of the goals of the seismic isolation is to shift the fundamental frequency of a structure away from the dominant frequencies of earthquake ground motion and fundamental frequency of the fixed base superstructure. The other purpose of an isolation system is to provide an additional means of energy dissipation, thereby reducing the transmitted acceleration into the superstructure. This innovative design approach aims mainly at the isolation of a structure from the supporting ground, generally in the horizontal direction, in order to reduce the transmission of the earthquake motion to the structure. A variety of isolation devices including elastomeric bearings (with and without lead core), frictional/sliding bearings and roller bearings have been developed and used practically for aseismic design of buildings during last 20 years in many new buildings in countries like USA, Japan, UK, Italy, New Zealand etc. The detailed review of earlier and recent works on base isolation systems and their applications to buildings had been widely reported by Kelly (1986), Buckle and Mayes (1990) and Jangid and Datta (1995).

Bridges are lifeline structures. They act, as an important link in surface transportation network and failure of bridges during a seismic event will seriously hamper the relief and rehabilitation work. There are many cases of damage of bridges in the past earthquakes all over the world. Due to their structural simplicity, bridges are particularly vulnerable to damage and even collapse when subjected to earthquakes. The fundamental period of vibration of a majority of bridges is in the range of 0.2 to 1.2 second. In this range, the structural response is high because it is close to the predominant periods of earthquake-induced ground motions. For very rigid structures like normal bridges with short piers and abutments the time period is often extremely small. For such structures the response is almost the same as the ground acceleration. The seismic forces on the bridges can be reduced if the fundamental period of the bridge is lengthened or the energy dissipating capability is increased. Therefore, the seismic isolation is a promising alternative for earthquake-resistant design of bridges. Figure 1 shows a typical isolated multi-span continuous deck bridge in which special isolation devices are used in place of conventional bridge bearings. These bearings protect the substructure by restricting the transmission of horizontal acceleration and dissipating the seismic energy through damping. Considerable efforts have been made in the past two decades to develop improved seismic isolation design procedure for new bridges and comprehensive retrofit guidelines for existing bridges. The suitability of a particular arrangement and type of isolation system will depend on many factors including the span, number of continuous spans, and seismicity of the region, frequencies of vibration of the relatively severe components of the earthquake, maintenance and replacement facilities.

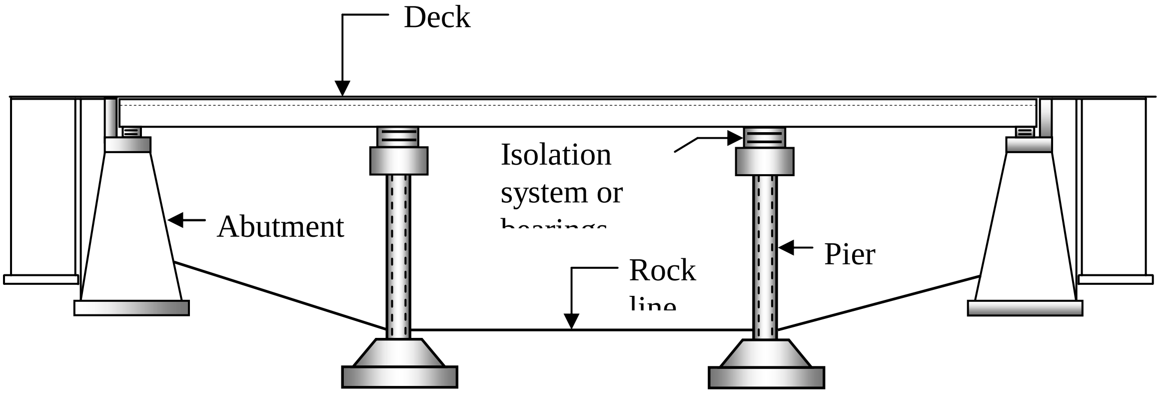


Figure 1: Seismically continuous span bridge isolated bridge.

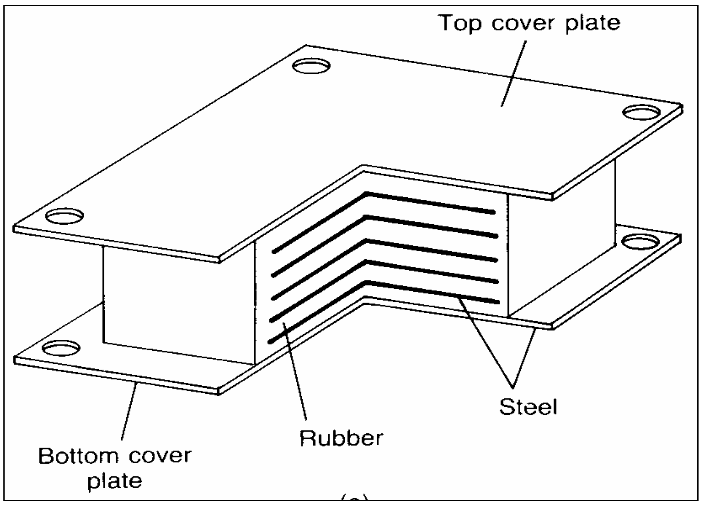
An updated state-of-the-art-review on seismically isolated bridges against earthquake excitation is presented herein. The review briefly covers the characteristics of base isolation devices as such, but puts most emphasis on the theoretical and parametric studies conducted to understand the behaviour of seismically isolated bridges with an indication of their range of applicability and some assessment of their development as backed by the research. The systems presented here are passive control systems but the work related to active and hybrid control of bridges is also summarized. The results of some important experimental tests are also included.

2 Seismic isolation systems

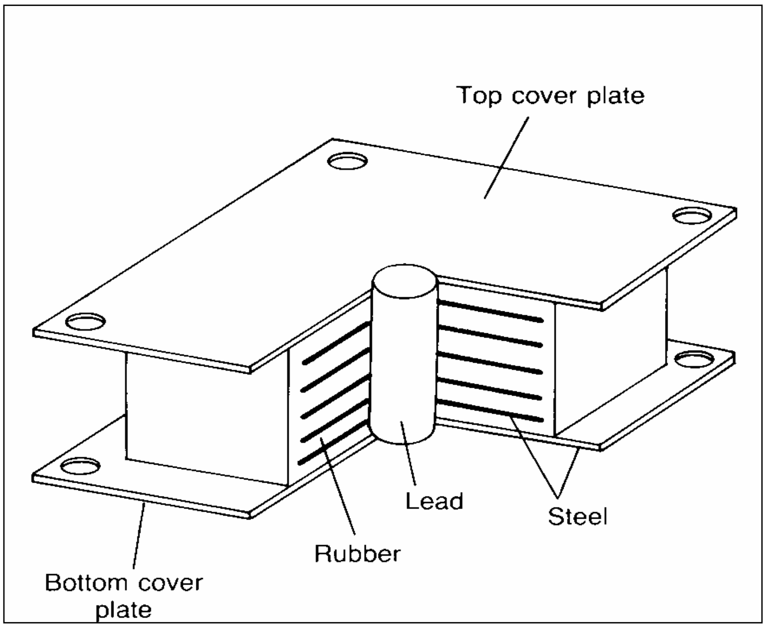
There are two basic types of isolation systems i.e. elastomeric bearings and sliding bearings. The elastomeric bearings with low horizontal stiffness shift fundamental time period of the structure to avoid resonance with the excitations. The sliding isolation system is based on the concept of sliding friction. An isolation system should be able to support a structure while providing additional horizontal flexibility and energy dissipation. The three functions could be concentrated into a single device or could be provided by means of different components. Various parameters to be considered in the choice of an isolation system, apart from its general ability of shifting the vibration period and adding damping to the structure are: (i) deformability under frequent quasi-static load (i.e. initial stiffness), (ii) yielding force and displacement, (iii) capacity of self-centring after deformation and (iv) the vertical stiffness.

2.1 Elastomeric Bearings

The laminated rubber bearing (LRB) is most commonly used base isolation system. The basic components of LRB system are steel and rubber plates built in the alternate layers as shown in Figure 2(a). The dominant features of LRB system are the parallel action of linear spring and damping. Generally, the LRB system exhibits high-damping capacity, horizontal flexibility and high vertical stiffness. The damping constant of the system varies considerably with the strain level of the bearing (generally of the order of 10 percent). The system operates by decoupling the structure from the horizontal components of earthquake ground motion by interposing a layer of low horizontal stiffness between structure and foundation. The isolation effects in this type of system are produced not by absorbing the earthquake energy but by deflecting through the dynamics of the system (Kelly, 1997). These devices can be manufactured easily and are quite resistant to environmental effects. Usually, there is a large difference in damping of a system and the structure and the isolation system, which makes the system non-classically damped. This will lead to coupling of the equations of the motion and to analyse the system correctly complex model analysis is required (Tsai and Kelly, 1993).



(a) LRB System



(b) Lead-rubber bearing.

Figure 2. Elastomeric isolation bearings.

The second category of elastomeric bearings is lead-rubber bearings (Robinson, 1982) as shown in Figure 2(b). This system provides the combined features of vertical load support, horizontal flexibility, restoring force and damping in a single unit. These bearings are similar to the laminated rubber bearing but a central lead core is used to provide an additional means of energy dissipation. These bearings are widely used in New Zealand and also referred as N-Z system. The energy absorbing capacity by the lead core reduces the lateral displacements of the isolator. Generally, the lead yields at a relatively low stress of about 10 MPa in shear and behaves approximately as an elasto-plastic solid. The interrelated simultaneous process of recovery, recrystallization and grain growth is continuously restoring the mechanical properties of the lead. The lead has good fatigue properties during cyclic loading at plastic strains and is also readily available at high purity of 99.9 per cent required for its predictable mechanical properties. The lead-rubber bearings behave essentially as hysteretic damper device and widely studied in the past by Kelly et al. (1972, 1977) and Skinner et al. (1975).

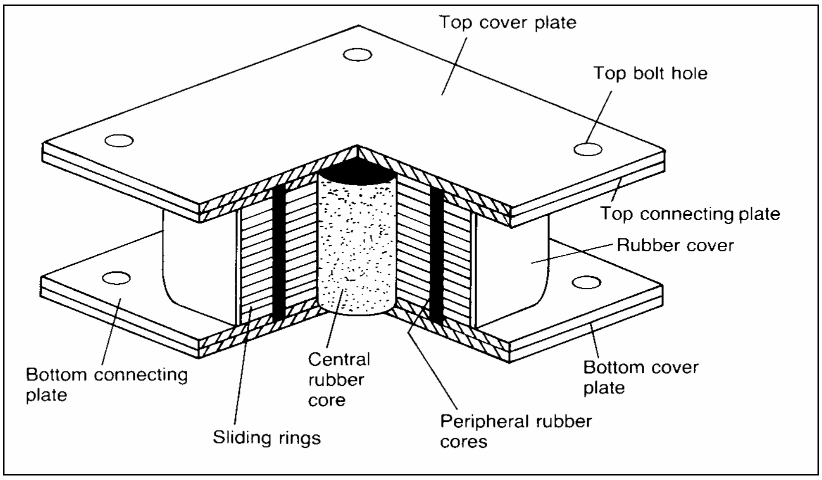
2.2 Sliding Isolation Systems

One of the most popular and effective techniques for seismic isolation is through the use of sliding isolation devices. The sliding systems perform very well under a variety of severe earthquake loading and are very effective in reducing the large levels of the superstructure's acceleration. These isolators are characterised by insensitivity to the frequency content of earthquake excitation. This is due to tendency of sliding system to reduce and spread the earthquake energy over a wide range of frequencies. The sliding isolation systems have found application in both buildings and bridges The advantages of sliding isolation systems as compared to conventional rubber bearings are (i) frictional base isolation system is effective for a wide range of frequency input, (ii) since the frictional force is developed at the base, it is proportional to the mass of the structure and the centre of mass and centre of resistance of the sliding support coincides. Consequently, the torsional effects produced by the asymmetric building are diminished.

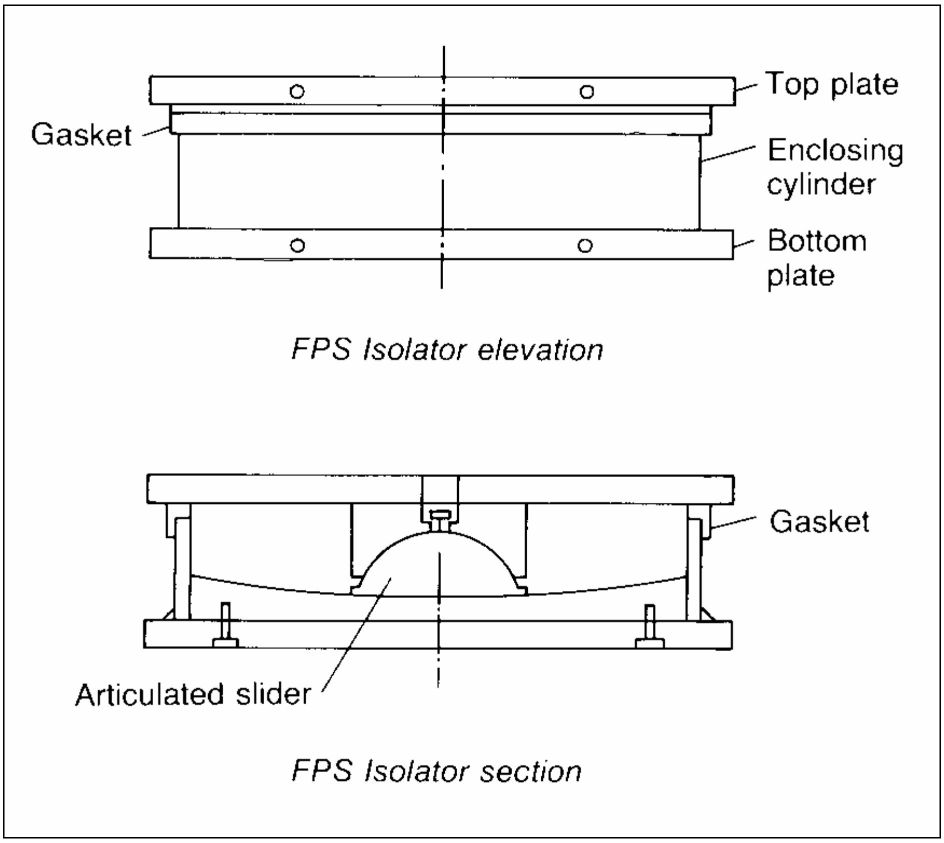
The simplest sliding isolation system is the pure friction (P-F) system. In this system a sliding joint separates the superstructure and the substructure. It has been developed for low rise housing in China (Li, 1984). The use of layer of sand or roller in the foundation of the building is the example of P-F base isolator. The P-F type base isolator is essentially based on the mechanism of sliding friction. The horizontal frictional force offers resistance to motion and dissipates energy. Under normal conditions of ambient vibrations and small magnitude earthquakes, the system acts like a fixed base system due to the static frictional force. For large earthquake the static value of frictional force is overcome and sliding occurs thereby reducing the accelerations. There has been a significant amount of research work on the performance of P-F system in the past by Westermo and Udwadia (1983), Mostaghel and Tanbakuchi (1983), Younis and Tadjbakhsh (1984) and Jangid (1996).

Mostaghel and Khodaverdian (1987) proposed the resilient-friction base isolation (R-FBI) system as shown in Figure 3(a). This base isolator consists of concentric layers of Teflon-coated plates that are in friction contact with each other and contains a central core of rubber. It combines the beneficial effect of friction damping with that of resiliency of rubber. The rubber core distributes the sliding displacement and velocity along the height of the R-FBI bearing. They do not carry any vertical loads and are vulcanised to the sliding ring. The system provides isolation through the parallel action of friction, damping and restoring force.

The concept of sliding bearings is also combined with the concept of a pendulum type response, obtaining a conceptually interesting seismic isolation system known as a friction pendulum system (FPS) (Zayas et al., 1990) as shown in Figure 3(b). In FPS, the isolation is achieved by means of an articulated slider on spherical, concave chrome surface. The slider is faced with a bearing material which when in contact with the polished chrome surface, results in a maximum sliding friction coefficient of the order of 0.1 or less at high velocity of sliding and a minimum friction coefficient of the order of 0.05 or less for very low velocities of sliding.



(a) R-FBI system



(b) FPS System

Figure 3: Sliding type isolation systems.

The dependency of coefficient of friction on velocity is a characteristic of Teflon-type materials (Mokha et al., 1990). The system acts like a fuse that is activated only when the earthquake forces overcome the static value of friction. Once set in motion, the bearing develops a lateral force equal to the combination of the mobilised frictional force and the restoring force that develops as a result of the induced rising of the structure along the spherical surface. If the friction is neglected, the equation of motion of the system is similar to the equation of motion of a pendulum, with equal mass and length equal to the radius of curvature of the spherical surface. The seismic isolation is achieved by shifting the natural period of the structure. The natural period is controlled by selection of the radius of curvature of the concave surface. The enclosing cylinder of the isolator provides a lateral displacement restraint and protects the interior components from environmental contamination. The displacement restraint provided by the cylinder provides a safety measure in case of lateral forces exceeding the design values.

Lin and Hone (1993) have proposed a new system of free circular rolling rods located between the base and the foundation. The most attractive feature of this type of isolator is their low value of rolling friction coefficient, which allows a very low earthquake force to be transmitted to the superstructure. However, such a system suffers from re-entering capability, resulting in large peak and residual displacements. To overcome this Jangid and Londhe (1998) proposed that the shape of rolling rods should be elliptical rather then circular. The low value of the rolling friction coefficient ensures the transmission of a limited earthquake force into the superstructure and the eccentricity of the elliptical rolling rods provides a restoring force that reduces peak base displacements and brings the structure back to its original position.

An important friction type base isolator is a system developed under the auspices of “Electric de France” (EDF) (Gueraud et. al., 1985). This system is standardized for nuclear power plants in region of high seismicity. The base raft of the power plant is supported by the isolators that are in turn supported by a foundation raft built directly on the ground. The main isolator of the EDF consists of laminated (steel reinforced) neoprene pad topped by lead-bronze plate that is in friction contact with steel plate anchored to the base raft of the structure. The friction surfaces are designed to have a coefficient of friction of 0.2 during the service life of the base isolation system. The EDF base isolator essentially uses elastomeric bearing and friction plate in series. An attractive feature of EDF isolator is that for lower amplitude ground excitation the lateral flexibility of neoprene pad provides base isolation and at high level of excitation sliding will occur which provides additional protection. This dual isolation technique was intended for small earthquakes where the deformations are concentrated only in the bearings. However, for larger earthquakes the bronze and steel plates are used to slide and dissipate seismic energy. The slip plates have been designed with a friction coefficient equal to 0.2 and to maintain this for the lifetime of the plant.

Su et al. (1991) proposed the design of the sliding resilient-friction (S-RF) base isolator. This isolator combines the desirable features of the EDF and the R-FBI systems. It was suggested to replace the elastomeric bearings of the EDF base isolation by the R-FBI units. It means that the friction plate replaces the upper surface of the R-FBI system in the modified design. As a result, the structure can slide on its foundation in a manner similar to that of EDF base isolation system. For low level of seismic excitation the system behaves as R-FBI system. The sliding at the top friction plate occurs only for a high level of ground acceleration that provides additional safety for unexpected severe ground motion.

2.3 Initiating and Limiting Devices

Depending on properties of isolating systems it may be necessary to design initiating or limiting devices (Priestley et al., 1996). The first case applies to system that would be too flexible under non-seismic load (e.g. wind or traffic). Any of various types of knock off shear keys will solve the problem, obviously implying some local damage under earthquake forces. Limiting devices are required to avoid excessive displacement in the isolators in the case of a low probability, extreme seismic event. Some kind of isolation/dissipation devices (e.g. some dampers) shows significant strain hardening when the displacement increases beyond a certain level and generally do not need limiting devices. In other cases, such as lead /rubber bearings that might become unstable under excessive deformations, a limit to the displacements could be obtained with rigid stoppers or with deformable buffers, in case there are concerns on the response of the structure under impact loads. Steel tapered beams or stiff rubber buffers could be used to this purpose. In all cases the structure will be subjected to higher then expected forces, and there will be some ductility demand in the piers.

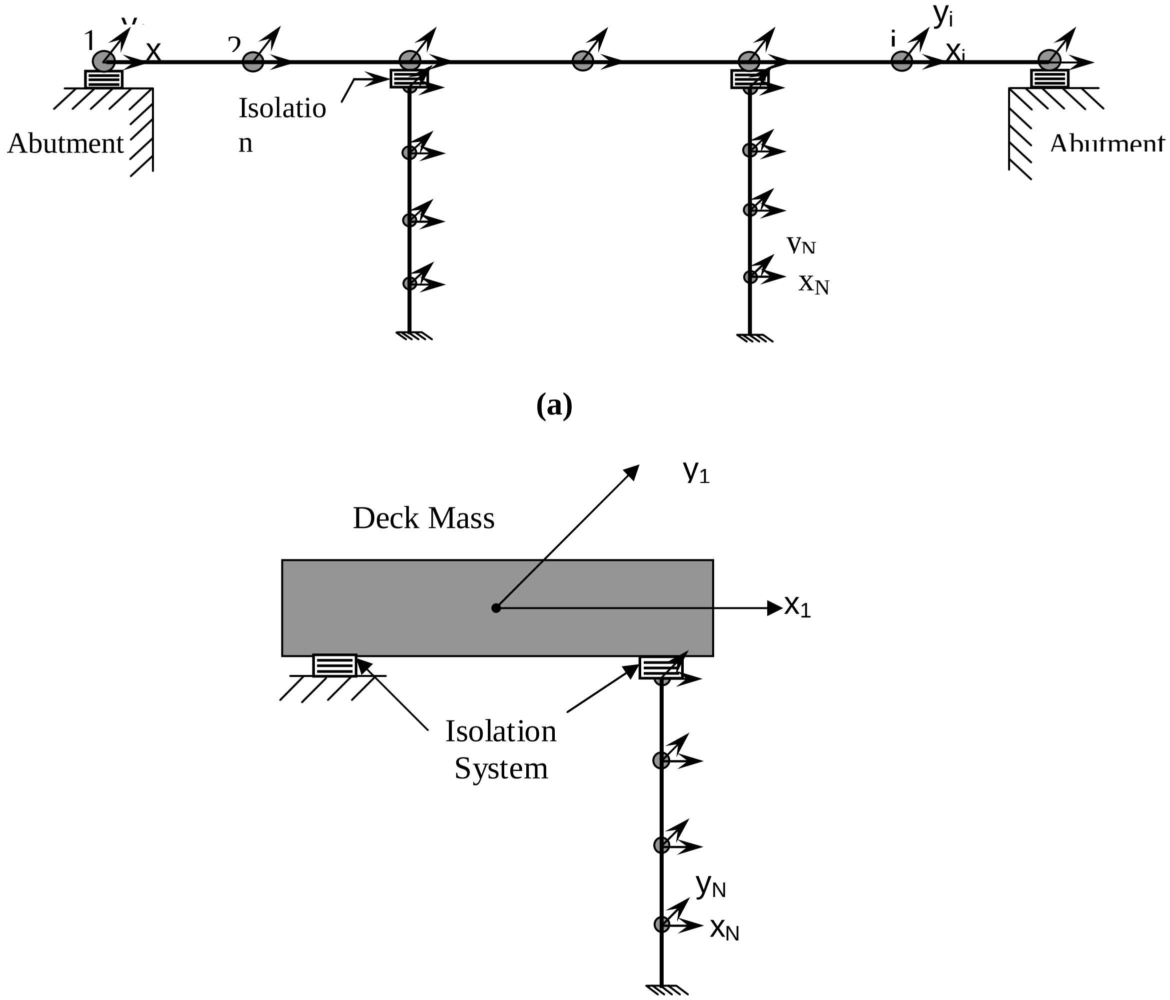
3 Seismic isolation of bridges

In bridges, the base isolation devices can rather easily incorporated by replacing the conventional bridge bearings by isolation bearings. Base isolation bearings serves 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)	20.67×10^9	20.67×10^9
Mass density (kg/m^3)	2.4×10^3	2.4×10^3
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 modelled as shown in Figure 4(a) as a discrete model. It is to be noted that the bridge is also modelled as shown in Figure 4(b) in the past in which the deck is assumed to be rigid. 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.



(a)

(b)

Figure 4: Mathematical modelling of isolated bridges

In Figures 5 to 7, 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.

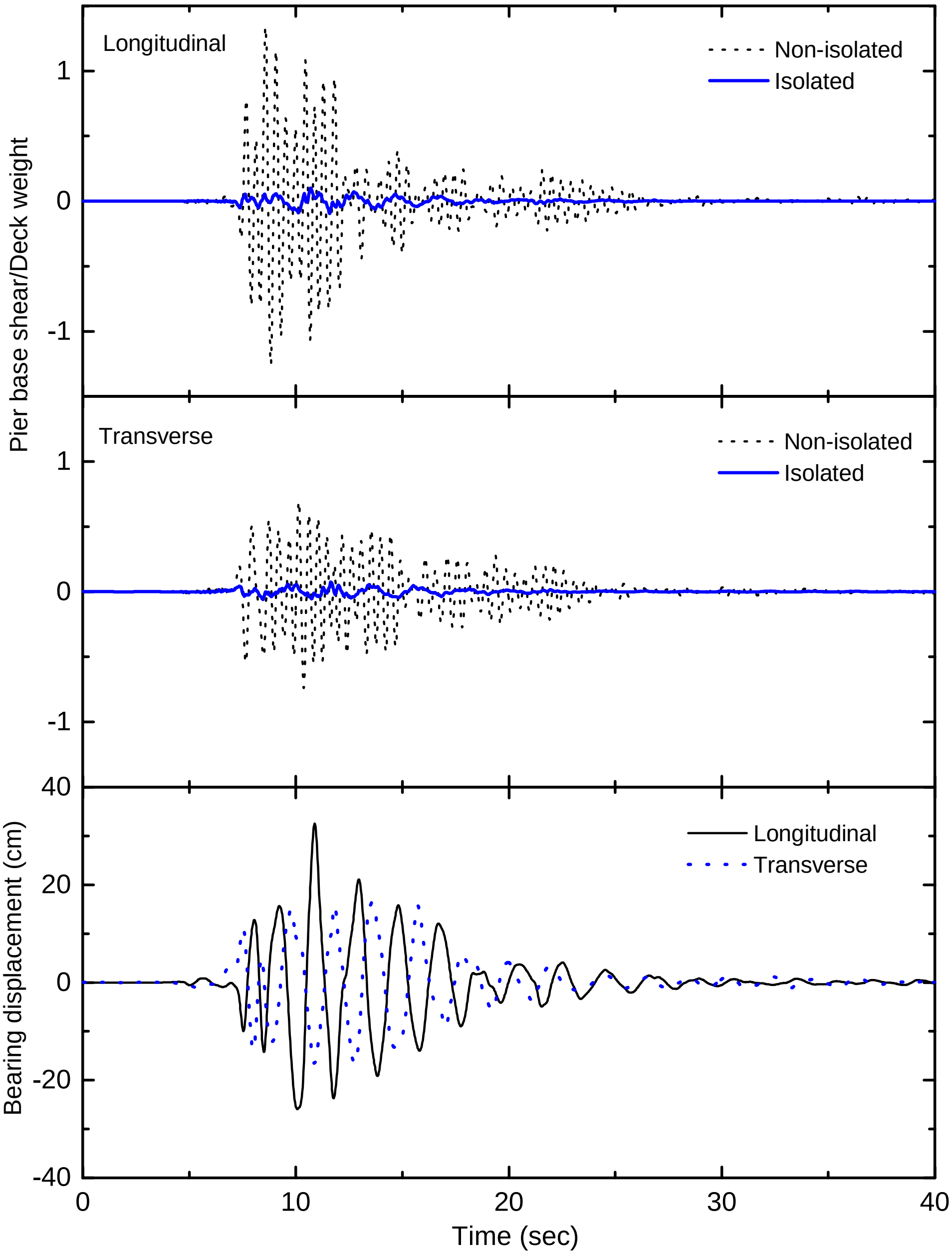


Figure 5: Time variation of base shear and bearing displacement of the bridge isolated by LRB system under Kobe, 1995 earthquake motion.

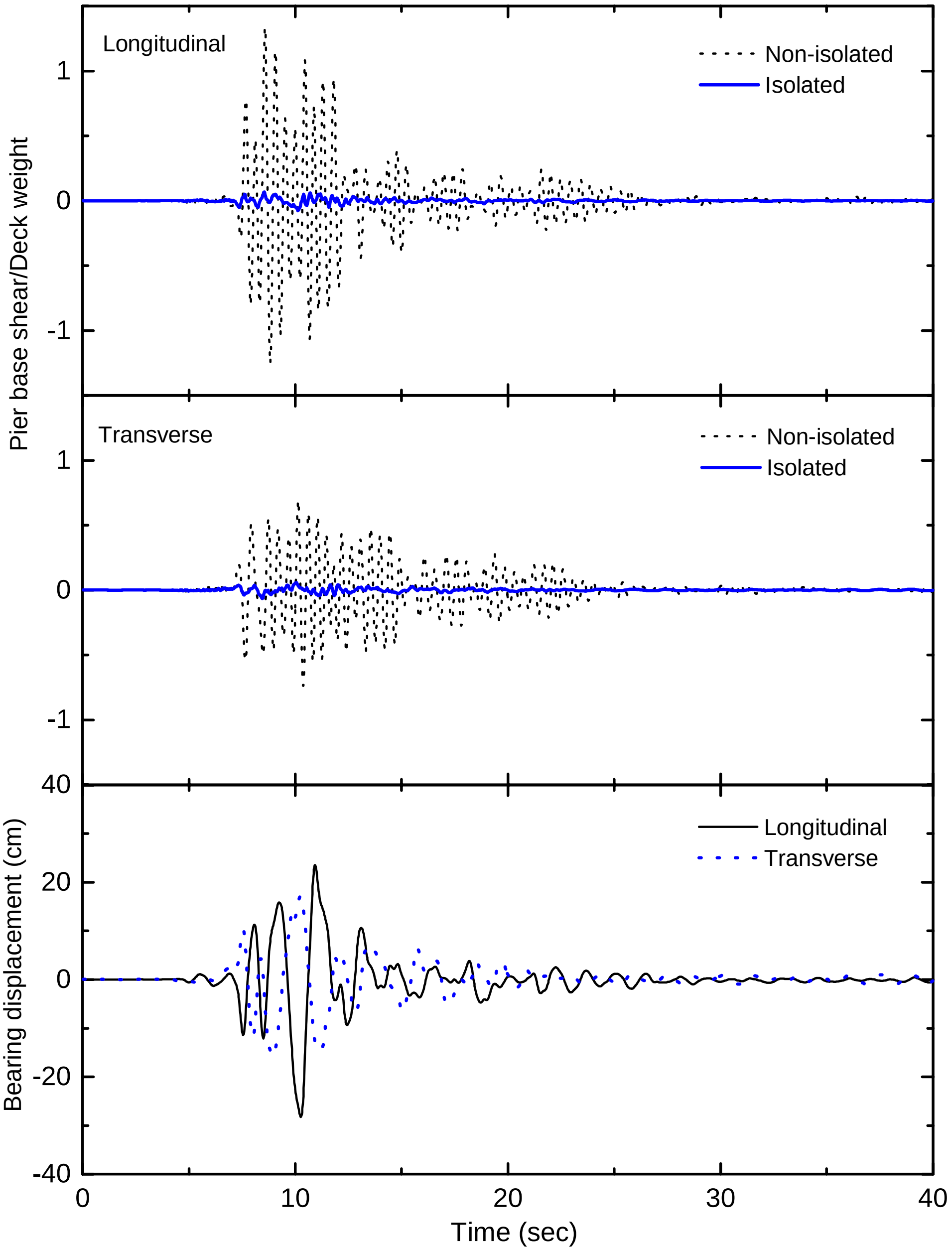


Figure 6: Time variation of base shear and bearing displacement of the bridge isolated by N-Z system under Kobe, 1995 earthquake motion.

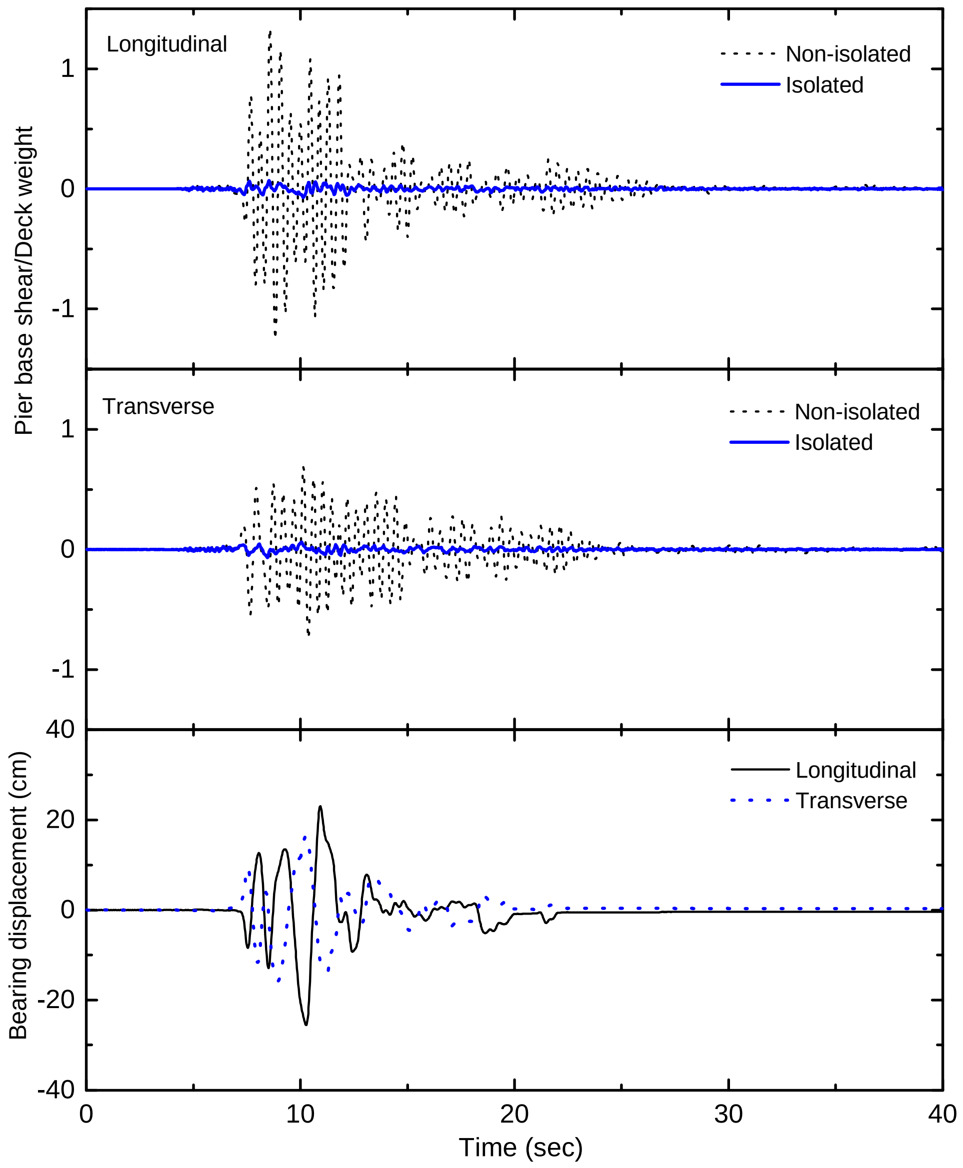


Figure 7: Time variation of base shear and bearing displacement of the bridge isolated by FPS system under Kobe, 1995 earthquake motion.

3.1 Analytical Study

There had been several analytical studies in the past to demonstrate the effectiveness of seismic isolation for earthquake-resistant design of bridge. Li (1989) studied the response of a typical three-span bridge structure with a seismic isolation system consisting of rubber bearings and hysteretic dissipaters in longitudinal direction. The non-linear equations of motion were derived for first mode of vibration and the stochastic response to filtered white noise ground acceleration is determined using equivalent linearization technique. A procedure is also developed for optimal design of bridge isolation system with hysteretic dampers. It is concluded that hysteretic damper act most effectively when mounted on a stiff supporting structure, their effectiveness decreases with increasing flexibility of the supporting structure. It is also concluded that, larger the value of maximum allowed isolator displacements is used the more effective is the isolation system.

Ghobarah and Ali (1989) proposed a simple design procedure for highway bridges, which aims at optimum balance between the shear forces transmitted to the supports and tolerable deck displacements for isolated highway bridges using the inelastic response spectra approach. Simplified charts are presented which provide a design aid for new bridges as well as the retrofitting and upgrading of existing ones. The method is shown to be simple and reasonably accurate. It takes into account the flexibility of the pier and is suitable for a code-type approach.

Briseghella et al. (1989) presented a design approach for applying base isolation technologies to typical medium-span continuous concrete deck bridges. A method for constructing non-linear response spectra for rigid-plastic systems is explained in which a direct strength-displacement relationship is obtained without depending on the elastic period.

Constantinou et al. (1991) proposed an isolation system consisting of multi-directional sliding Teflon bearings and displacement control devices. The displacement control devices provide re-centering capability and displacement control during earthquakes and rigidity under service loads. It was observed that device could provide rigidity to a bridge deck for service loads up to 5 per cent of deck weight and displacement control and significant energy dissipation in strong earthquake motions of 0.6*g* peak acceleration. It is also reported that combined sliding disc bearing and displacement control isolation system reduced the deck inertia forces by a factor of 2.5 in comparison to a conventional design.

Mayes et al. (1992) presented an overview of the basic concepts and design principles of seismic isolation and discussed the objectives and philosophy of the provisions of American Association of State Highway and Transport Officials (AASHTO, 1991) and concluded with a procedure to compare the performance of isolation systems with different damping values.

Maragakis and Saiidi (1993) compared four linear uni-directional analytical models of base isolated bridges and developed simplified linear models for these structures. These were used to develop a three-dimensional non-linear model for base-isolated bridges and used for the evaluation of the effects of base isolation on pier ductility demand.

Mahin (1993) postulated a preliminary seismic design method for simple bridges isolated by sliding systems based on conservation of displacement and energy for long and short period ranges of structural response. The approach focuses on estimation of overall displacements of the deck level of the bridge. A special non-dimensionalized form of the equations of motion is introduced to assess the adequacy of this design approach and to identify through a parametric investigation, the variation of response indices with changes in ground motion, isolator and structural characteristics.

Hwang and Sheng (1993, 1994) evaluated the effectiveness and equivalent damping ratio for an equivalent elastic system of bridge with lead-rubber bearings as per specifications of the AASHTO (1991). It is concluded that the equivalent damping ratio determined using AASHTO procedure might decrease with respect to increase of the inelastic deformation of lead-rubber bearings. Further, Hwang et al. (1994) also validated the equivalent linear model of the isolated bridge specified by California Department of Transportation (CALTRANS) based on their predictions of maximum inelastic seismic responses.

Wang and Gould (1994) studied the effects of pier uplift on sliding isolated highway bridges for a symmetrical two-span continuous deck bridge. Pier uplift is found to enhance the effectiveness of sliding isolation for a highway bridge, especially for piers with inadequate lateral strength capacity. The elastic behaviour of the pier is possible, while the seismic performance of a sliding isolated highway bridge is affected minimally by the pier uplift. These benefits are achieved with a relatively small amount of pier uplifting.

Lam and Davidson (1995) implemented the system identification procedure that minimizes the differences between the power spectra of the field and simulated data to enable the non-linear properties of a base isolated bridge to be determined. The accuracy of the method is demonstrated by comparing the displacement time histories of the recorded and simulated data. For the bridge used in the case study, it was found that local modes of vibration provided a major contribution to the base moment of the piers, a feature not directly accounted for in the design procedure.

Jangid and Banerji (1995) found out the response of bridges isolated by the P-F system in longitudinal direction. The behaviour of the P-F system is modelled as a rigid-plastic. It is shown that the P-F devices installed between superstructure and substructure can reduce the base shear in the piers considerably. The main disadvantage of P-F system is that there is no re-centering force, as a result, there is large peak and residual sliding displacements.

Monti et al. (1995) analysed continuous six-span isolated bridge subjected to the seismic inputs at various supports to investigate the effects of the spatial variation of earthquake motion. Bridges of varying stiffness and ductility have been designed, as in current engineering practice, for synchronous motion with and without isolating devices. The results obtained were used in assessing the relevance of non-synchronous input motion on the ductility demand in the piers of conventional bridge structures and on the isolator displacements of isolated bridges. It was seen that the piers designed for synchronous input remains in the elastic range also in the case of hardening isolators.

An equivalent linear model for the seismic analysis of base isolated bridges with bi-linear hysteretic bearing and modifications in the design specifications that can be readily applied by practising engineers had been suggested (Hwang, 1996; Hwang and Chiou, 1996; Hwang et al., 1996a, 1996b). In addition, the equivalent damping ratios calculated for a single-degree-of-freedom system subjected to a generated AASHTO design earthquake may be larger than 30% for a wide fundamental range. As a result, three-dimensional inelastic time-history analysis may be necessary. As an alternate approach, empirical formulas for the calculation of equivalent period shift and equivalent damping have been proposed and validated. The system composite damping ratio is obtained both by classical and non-classical damping assumptions. The composite-damping ratio formulated in the study is compared with that obtained from the modal strain energy method. It is observed that the composite damping ratios determined on the basis of classical damping and non-classical damping are almost identical for seismically isolated bridges defined in AASHTO (1991).

Mayes (1996) described how the force-reduction and force-redistribution advantages of seismic isolation could benefit the design and economics of bridges (for both new and retrofitted) in the central and eastern United States.

Delis (1997) addressed the analysis and design issues of a seismically isolated continuous steel bridge located in a highly seismic area. Two types of isolation systems are considered namely the friction bearings and friction bearings with non-linear fluid viscous dampers. A non-linear 3-D time history analysis was performed using several ground-input motions. It is seen that the earthquake forces are drastically reduced due to bearings. Further, the increased displacement demands at abutments are accommodated with specially designed expansion joints that allow large seismic movements in both horizontal directions.

Calvi and Pavese (1997, 1998) presented displacement-based designs approach using a linear equivalent single degree-of-freedom model. The preliminary design of an isolation system for existing bridges is based on the definition of a "structure regularity" which allows the estimation of whether the response of the real structure will be similar to that predicted in the preliminary design phase. The efficiency of the approach is also shown in designing the isolation system for a highly irregular bridge. In addition, an optimisation procedure which has become a proposal for a design method has been implemented in an efficient software program and applied to a large number of cases which confirmed the soundness of the principles adopted in the design philosophy. The design approach assumes that a displacement profile predicted using a linear equivalent model will be reproduced by the envelope of the maximum displacement obtained from a series of non-linear analyses, considered to be representative of the real response.

Tsopelas and Constantinou (1997) studied the bridges with E-shaped steel dampers. The action of E-shaped dampers is first to provide rigidity against service loads at selected locations and, second is to yield and dissipate energy in seismic excitation. The behaviour of E-shaped device is a function of its geometry and material properties. This behaviour is nearly elasto-plastic with small post-yielding stiffness. It is demonstrated that significant permanent displacements develop, particularly in earthquakes with shock loading characteristics. It is concluded that elasto-plastic isolation systems may be very useful when sufficient displacement capacity is provided and provisions for bridge re-centering or bearing replacement are made.

Anderson and Mahin (1998) postulated a preliminary seismic design method for simple base-isolated bridges based on conservation of displacement and energy for the long and short-period ranges of structural response. The approach focuses on estimation of overall displacements of the deck level of the bridge, which overcome the limitations of equivalent linear idealization and more explicitly acknowledges the non-linear inelastic behaviour presented in the isolated systems.

Iemura et al. (1998) shown that when seismic isolation systems are installed, a reasonable inelastic design method is required. Since the conventional inelastic design method takes into account bridge piers, it is hard to design seismic isolators that can cope with the interaction between seismic isolators and bridge piers. Therefore, a design procedure for isolated bridges is proposed using the relationship between seismic isolation systems and piers with respect to their energy dissipation.

Li and Xin (1998) used differential equation model for describing the hysteretic restoring force model of isolation bearings. The Wilson-theta and fourth-order Runge-Kutta methods are combined to develop a computer program for the non-linear seismic response analyses of isolation systems for bridges. The example of a three-span continuous bridge with isolation bearings is investigated and the isolation effects were discussed.

Braga et al. (1998) discussed the official guidelines issued in Europe and Italy to regulate the design of isolated bridges using the elastomeric bearings and elasto-plastic elements. The design philosophy aims at ensuring adequate protection with respect to two limit states or performance levels: the first one being the limit of fully elastic response and the second one being a state where the structure is still undamaged while the isolating elements are close to their ultimate deformation. The detailed requirements on the behaviour of the isolating elements so that they can reliably fulfil their protective roles are also specified.

Tsai and Huang (1998) presented seismic behaviour of FPS isolated curved bridges with a complex three-dimensional geometry. An extract three-dimensional finite element formulation for FPS bearing and a new shell element are developed to analyse the whole system. Significant reductions in stress response have been observed for the bridges with FPS isolators when compared to those without isolators.

Wang et al. (1998) proposed a simple and efficient method for analysis of continuous multi-span bridge with sliding system subjected to harmonic and real earthquake ground motion.

Using this method the feasibility of using the FPS bearings for seismic isolation of bridges had been confirmed.

Unjoh and Ohsumi (1998) studied the earthquake response characteristics and the design method of the super-multi-span continuous girder bridges with the seismic isolation design concept. Further, analytical study on the limitation of continuous length of girder, the effects of ground characteristics and the spatial difference of input ground motion on the earthquake response characteristics was also carried out.

Jankowski et al. (1998) presented analysis of pounding between superstructure segments of an isolated elevated bridge induced by the propagating seismic wave. High-damping rubber bearings, used as isolation devices, are modelled by proposed non-linear formulation and the significance of the bearing model for pounding is indicated. The results of the study show that pounding leads to the increase or decrease of the forces acting on piers, depending on the gap size between the segments of superstructure.

Pagnini et al. (1998) introduced a mathematical model and discussed the response of a pier-device-span system exposed to seismic excitation. The equations of motion in the state variable space are obtained by applying the substructure technique, matrix condensation and modal synthesis. The study represents the preliminary step towards the formulation of a probabilistic model of the seismic response of the system using the equivalent linearization technique. Further, Pagnini and Solari (1999) studied the dynamic response of bridge piers with aseismic devices by the stochastic equivalent linearization technique. The seismic acceleration is schematised through a Gaussian stationary random process. The study of the complex modes of the linearized system gives an interpretation of the mechanical behaviour which leads to a formal elementary solution and highlights some phenomena which are typical of hysteretic systems, particularly those marked by the weak hardening.

Savage et al. (1999) carried out analytical study for the Slough Bridge at Rio Vista, California, on retrofitting of the bridges. The piers were deficient, and the proposal to retrofit them was found to be costly due to working in underwater condition. The abutments on the other hand were more accessible and less expensive to retrofit. By using isolation/dissipation devices the piers were relieved of their seismic demand. It is found that the isolation bearing retrofit cost just about the 50 percent of conventional retrofit.

Mutobe and Cooper (1999) conducted non-linear time history analysis of the Benicia-Martinez Bridge with FPS system and using ADINA and compared to those of other non-linear codes. The behaviour predicted by the system of elements used in ADINA produced results that matched very closely with other programs.

Saiidi et al. (1999) developed a non-linear model for the time-step analysis of bridges subjected to two orthogonal horizontal components of earthquake motion. Elastomeric isolators with or without lead cores were used and hysteretic behaviour of the isolators, the columns, abutments and shear keys was taken in to account. The non-linear analysis showed that, contrary to linear theory predictions, the use of isolators does not necessarily increase the displacement of the superstructure. Furthermore, it was also shown that properly designed isolators could reduce the ductility demand in RC Bridge columns substantially.

Hayashikawa et al. (2000) studied the non-linear behaviour of steel towers of cable-stayed bridges subjected to major three-dimensional earthquake ground motions. It is shown that the seismic performance of steel towers with passive control device is effective in reducing the reaction forces at the tower basements.

Sugiyama (2000) compared dynamic characteristics for a bridge with sliding type isolation system and a bridge with a LRB type system under earthquake motion. The results showed that, from the point of view of reduction of the girder acceleration, a sliding type base isolation system is more effective than a LRB in the case that a stronger earthquake affects the bridge although the relative displacement between the superstructure and the substructure is considerably large. It has also been revealed that no significant difference is recognised between these two types of base isolation systems in the case of a relatively weak earthquake.

Abe et al. (2000) studied the seismic response of three bridges with lead-rubber bearings, high damping rubber bearings and natural rubber bearings. Their seismic performance is evaluated through comparison between identified stiffness and damping values from observed records and predicted values from the loading test on each device. The analysis revealed that the base isolation effect is present in all bridges, while contribution of the minor friction element can significantly influence the performance.

An identification algorithm to investigate the dynamic properties of a base-isolated highway bridge equipped with lead rubber bearing was developed by Tan and Huang (2000). A linear model was used for the pier while a bi-linear model was used for lead-rubber bearings. It is concluded that physical parameters obtained through the proposed identification process may provide a basis by which various warning systems for an isolated bridge can be established.

Kim et al. (2000) investigated the efficiency of using dissipating restrainers at expansion joints for preventing collapse of highway bridges in the event of an earthquake. The restrainers consist of a non-linear viscous damper and an elastic spring connected in parallel or in series. Two-dimensional finite element analysis using bilinear hysteretic models for bridge substructure joints and non-linear gap elements for expansion joints is performed on bridges with one or two expansion joints. The analytical study demonstrates that the energy dissipating restrainers are effective in reducing the relative opening displacements and impact forces due to pounding at the expansion joints, without significantly increasing ductility demands in the bridge substructures.

Wilde et al. (2000) studied the seismic response of bridges with LRB and shape memory alloys (SMA) which provides stiff connection between the pier and the deck for small external loading. The proposed isolation system utilizes the different responses of the SMA at different levels of strain to control the displacements at various excitation levels. At the same time the hysteresis of the SMA is used to increase the energy dissipation capacity.

A combination of helical springs and fluid dampers is proposed as isolation and energy dissipation devices for bridges subjected to earthquake loads by Parvin and Ma (2001). Vertical helical springs are placed between the superstructure and substructure as bearings and isolation devices to support the bridge and to eliminate or minimize the damage due to earthquake loads. Since helical springs provide stiffness in any direction, a multidirectional seismic isolation system is achieved which includes isolation in the vertical direction. To reduce the response of displacement, non-linear fluid dampers are introduced as energy dissipation devices. Time history analysis studies conducted show that the proposed bridge system is sufficiently flexible to reduce the response of acceleration.

3.2 Parametric Study

Most of the studies primarily attempt to investigate the parametric behaviour of seismically isolated bridges including the identification of their optimum characteristics. The parameters that are mostly considered in the study include time period of the superstructure, time period, damping, and yield characteristics (yield strength or yield displacements) of the isolator and the ratio of predominant frequency of excitation to the frequency of the isolator. For friction type base isolators, the most important parameter is the coefficient of friction of sliding surface. The variations of response of the system with these parameters provide useful information for understanding the dynamic behaviour of such systems.

Ghobarah (1988) studied the seismic response of single and two-span highway bridges with lead-rubber bearings modelled as a bi-linear spring. The influence of important parameters such as the isolator's stiffness, pier stiffness and pier eccentricity on the effectiveness of seismic isolation was investigated.

Ghobarah and Ali (1988) investigated the response of a three-span bridge isolated by the lead-rubber bearings subjected to earthquake motion. The effect of deck stiffness on the seismic responses had been studied. It was found that typical two or three span highway bridges could be designed for base isolation, assuming the rigid bridge deck behaviour in horizontal direction without significant loss of accuracy. The yield strength of lead core as 4 per cent of the bridge weight has been recommended as a reasonable balance between reduced forces in piers and increased forces on abutments.

Turkington et al. (1989a,b) studied the response of two and four-span bridges to real earthquake ground motion using three models. The first model represented a bridge superstructure supported by bearings on a rigid foundation and consisted of a mass connected to bi-linear spring rigidly fixed at the other end. The bearing shear properties are modelled by a bi-linear spring. The second model represented a combination of elastomeric and lead-rubber bearings with piers of different height. The piers were modelled by elastic beam elements. The pier and bearing model are combined to form third model. It is shown that lead-rubber bearings combined with elastomeric bearings can distribute seismic forces between abutment and pier. It is also found that the presence of lead shifts the natural period of the structure and increases the amount of damping, which reduces the displacement response.

Turkington et al. (1989c) conducted a parametric study of bridges seismically isolated by lead-rubber bearings. It is concluded that the LRB combined with elastomeric bearings provide an effective means of distributing the response forces between piers and abutments. It is also concluded that a characteristic of earthquake records affects the performance of LRB. Vibratory earthquake records generally results in greater amount of additional damping than do impulsive earthquakes and larger magnitude earthquakes generally results in greater period shifts.

Thakkar and Maheshwari (1995) studied a seismic response of a base isolated bridge by varying different parameters such as soil stiffness, embedment depth, hydrodynamic pressure and earthquake response spectrum. Elastomeric bearing is seen to be effective in reducing seismic response of substructure on rocky sites. The increase in embedment depth also causes reduction in bending moments and shear forces in the substructure. The use of elastomeric bearing in place of rocker-roller bearing is seen to be beneficial from seismic considerations.

Eftekhari and Zadeh (1996) discussed the effects of isolators and their locations on the dynamic behaviour of isolated bridges. The behaviour was analysed of materials and isolators assumed to be linear to study the effect of variation of the different isolator parameters such as stiffness of the deck, piers and elastomeric bearings. In addition, the non-linear behaviour of isolators was also investigated.

Adachi et al. (1998) conducted analytical study on seismic behaviour of seismic isolator and RC bridge column system. A parametric study using a 2-DOF system was carried out to propose an equivalent 1-DOF using equal energy principle. Dolce (1998) studied the seismic behaviour of a railway bridge equipped with seismic isolation/dissipation devices. A typical bridge of the new Italian high-speed railway line under construction having elasto-plastic behaviour is considered and the parameters characterizing the response of such devices (threshold force, post-yield stiffness) are varied. The actual advantages of seismic isolation in comparison with conventional design of railway bridges are highlighted and some indications on the optimal choice of the behavioural parameters are also obtained.

Tongaonkar and Jangid (1998) investigated the seismic response of bridges with a sliding isolation system between the superstructure and substructure. Frictional force of the isolation system is assumed to have ideal Coulomb-friction characteristics. In addition, a linear restoring force is also provided by the isolation system. Seismic response of the isolated bridge system in both longitudinal and transverse directions is obtained by solving the non-linear equations of motion (non-linearity due to sliding system) in the incremental form using Newmark's method. The system is subjected to real earthquake ground motion in both horizontal directions and the effects of isolation parameters on the peak response of isolated bridge were investigated.

Reinhorn et al. (1998) examined the effects of variation of the ratio of isolator and pier yield characteristics on the response of isolated bridges. It has been recognized that, due to low redundancy and domination of the deck mode of vibration, isolated bridges are extremely sensitive to the characteristics of the ground motion. After yielding, the stiffness properties and the periods of the deck-bridge system may be entirely dominated by the secondary stiffness of the isolators because of the larger mismatch with the support stiffness. This study investigated the sensitivity of bridge response to small variations of the post-yield stiffness of the isolation system. Since the deck contributes most of the mass of the bridge, analytical models for design tend to diminish the attention to the masses of the piers and to the vibration modes they induce. However, in deck isolated bridges the local modes of tall massive columns may contribute substantially to the drift demand of the respective isolator-pier systems. The response implications of neglecting the column mass in modelling of bridges are also studied.

Kawashima and Shoji (1998) presented analysis on the interaction with emphasis on the yield force level of the isolator device. It was found from the analysis that the post-yield stiffness and the yield force level of the device are important to predict the non-linear response of the pier. The device with zero post-yield stiffness develops the hysteretic response at the device and when the force of the device with positive yield–stiffness increases to the yield force of the pier, significant hysteretic behaviour of the pier occurs.

Tongaonkar and Jangid (2000) investigated the effectiveness of elastomeric bearings for seismic isolation of bridges. A parametric study is conducted to investigate the effects of bearing parameters (such as stiffness and damping characteristics) on the effectiveness of isolation for the bridge system. It is shown that the elastomeric bearings are quite effective in reducing the seismic response of bridges. Further, the effectiveness of the elastomeric bearings is significantly influenced by the stiffness and damping properties. In addition, a comparison of the response of an isolated bridge with a linear isolation system is carried out with the corresponding non-linear model of the elastomeric bearings. The results of the two models were found to be comparable.

Koh et al. (2000) developed a method to evaluate the cost effectiveness of seismic isolation for bridges in low and moderate seismic regions, for calculating the minimum life-cycle cost of seismically isolated bridges under specific acceleration levels and soil conditions. Input ground motion is modelled as a spectral density function compatible with a response spectrum for combination of acceleration coefficient and site coefficient. Failure probability is calculated by spectrum analysis based on random vibration theories to simplify repetitive calculations in the minimization procedure. The results show that seismic isolation is more cost effective in low and moderate seismic regions than in high seismic regions. The correlation was weak between soil types and the cost effectiveness of the seismic isolation system in low and moderate seismic regions, but was strong in high seismic regions.

Chaudhary et al. (2000) proposed identification of system parameters from seismic accelerations recorded on a base-isolated bridge to examine the performance of various components of bridges. The study proposed a two-step system identification method for identifying structural parameters from strong-motion records. The first step entails identification of complex modal parameters of a non-classically damped base-isolated bridge-pier-pile-foundation system for which necessary theoretical formulations are first derived. In the second step, a global search scheme is introduced to identify the structural parameters of the system corresponding to the identified modal parameters. The proposed system identification method was applied to two base-isolated bridges such that the recorded responses at the pier cap and girder are successfully recreated for one main shock and four aftershocks of the 1995 Kobe earthquake and modal and structural parameters are identified. Performance of the base-isolation system is evaluated by comparing the physical properties of the bearings, determined from experimental data, with the identified values and is found to be satisfactory in both bridges.

Sawada et al. (2000) studied the non-linear interaction between pier and isolator in seismically isolated bridges subjected to extreme earthquakes. Isolated bridges with reinforced concrete piers and lead-rubber bearings are modelled as a 2-DOF system and investigation focused on the effects of the primary structural parameters such as yield strength ratio on the displacement ductility of both pier and isolator. To identify the range of yielding strength ratio as all the restrictions on some typical non-linear responses of isolated bridges under severe earthquakes are satisfied, a practical procedure using the contour diagrams for those responses is introduced.

Ceravolo et al. (2000) examined the possible uses and advantages of seismic isolation at the base of girder bridges. The attention was focused in particular on the feasibility of adopting a system based on abutment of the horizontal stiffness of foundation piles, as it was obtained by piles partly un-confined by surrounding soil. Eight bridges with standard characteristics, representing a sufficiently wide class of girder bridges were subjected to real seismic excitation and a parametric analysis was conducted with the aim evaluating the optimal characteristics of the isolation and applicability of the technique.

Liao et al. (2000) studied the parameters that may affect the bridge responses with respect to base shear reduction and displacement amplification of a highway bridge subjected to near-fault ground motions recorded during the Chi-Chi earthquake. Chaudhary et al. (2001) studied the performance of various components of bridge system using identification of system parameters with the help of multiple sets of records made on base-isolated Yama-age bridge in Japan. The effectiveness of base isolation and effects of soil-structure interaction on the overall performance were investigated by comparing the identified and physical parameters.

Franchin et al. (2001) discussed three aspects related to the method of analysis for linear or linearized isolated bridge namely (i) classical modal analysis, using real modes and the diagonal terms of the modal damping matrices, still provide a fully acceptable approximation, (ii) parametric study conducted shown that none of the linearized expressions in current use gives satisfactory results for both the displacement and the force responses, a requirement for a reliable design of an isolated bridge and (iii) a rational, approximate procedure for equivalent damping applicable to all types of structures with non-proportional damping, which in the case of bridges can be shown to reduce to the expression provided in the Japanese bridge design guidelines.

3.3 Experimental Study

A number of experimental studies have been reported on the load deformation behaviour of different isolation devices and response characteristics of structural models isolated by different isolators in the past. Kelly et al. (1985) and Buckle and Kelly (1986) studied quarter-scale models of straight and skewed bridge decks mounted on plain and lead-filled elastomeric bearings subjected to earthquake ground motion using the shaking table. The deck response was compared to determine the effectiveness of mechanical energy dissipaters in base isolation systems and the mode of failure of base-isolated bridges. The control of translational and torsional displacements by the lead dissipaters for both in-phase and out-of-phase abutment motions were studied to determine if the seismic performance of skew bridges, in particular, can be improved. A simple analysis of the limit state of an isolation bearing is described and results of tests carried out to verify the analysis are presented.

Constantinou et al. (1992) and Kartoum et al. (1992) conducted analytical and experimental studies to get the response of bridges supported by an isolation system consisting of sliding Teflon bearings subjected to real earthquake ground motion. To restrict the displacements at isolator level, the displacement control devices over the abutments were proposed.

Earthquake simulation test of a bridge model was made using N-Z bearings and LRB with hinge roller bearings to evaluate the effectiveness of lead rubber bearings for aseismic design of bridges by Wei et al. (1992). It is concluded that these bearings due to vertical support, lateral flexibility and energy absorption capability are better suited for bridge isolation as compared to LRB.

Goto et al. (1992) discussed about devices to absorb collisions between the base-isolated bridge girder and the abutment during major earthquakes. A knock-off type abutment to deal with conditions found in Japan, namely, high seismicity and heavy highway traffic, was studied through experiments. A design method, which considers the post-yield mechanism of a knock-off device, was proposed and a non-linear numerical simulation analysis assured it to be applicable in actual use. A field study that applied this type of knock-off abutment to an actual base-isolated bridge also assured its practical utility.

Robinson (1993) while carrying out studies on seismic isolation found that in New Zealand, it is standard practice for the seismic isolation option to be considered for both new and retrofitted bridges, and to a lesser extent, specialised structures and buildings. A special lead-extrusion damper and lead-rubber bearings were developed for this specific purpose. Okamoto et al. (1995) performed shaking table tests of a quarter-scale model of bridge with a sliding type isolation system composed of a sliding bearing and a rubber restoring force device. The results were presented regarding the effect of the isolator on shear force of pier, design and the material used for the sliding displacement, the effects of the residual displacement on the practicability of sliding material with varying friction coefficient and proper selection of the stiffness of the restoring force device.

Tsopelas et al. (1996a) carried out experimental study of seismically isolated bridges using four spherically shaped FPS bearings. The experimental results demonstrated a substantial improvement in the ability of the isolated bridge to sustain seismic excitation under elastic condition. Tsopelas et al. (1996b) carried out experimental study of seismically isolated and non-isolated bridges. The system considered here consisted of sliding bearing and rubber restoring force devices. Fluid viscous dampers were utilised to withstand level 2 Japanese design motion. A substantial reduction of the seismic substructure forces in comparison to non-isolated bridges was observed. The bearing displacements were found to be less than 160 mm in prototype scale.

Mori et al. (1996) studied the behaviour of laminated bearings with and without lead plug under compression load when used in seismic isolation of bridges. It is concluded that there is a large difference between the measured compressive stiffness and the calculated compressive stiffness. However, the empirical relationship for the bearing compressive stiffness proposed by Derham (1982) is found to perform well. The compressive stiffness of LRB with lead plug is same as that without it after the lead plug started to carry axial load.

Igarashi and Iemura (1996) evaluated the effects of the implementation of the lead-rubber bearing as seismic isolator on a highway bridge structure under seismic loads using the substructure hybrid loading (pseudo-dynamic) test method. The seismic response of the isolated bridge structure was successfully obtained. The effectiveness of isolation is examined based on acceleration and displacement amplifications using earthquake response results. The hybrid loading tests assuming linear and non-linear characteristics of the pier are carried out to investigate the effect of the non-linear behaviour of the bridge piers on the seismic response of the superstructure.

Two analysis models for high damping rubber bearings were proposed based on shaking table tests of a seismically isolated bridge deck by Hwang and Ku (1997). These analysis models are established using the modified Gauss-Newton system identification method and the fractional derivative Kelvin model based on sinusoidal test results. The test produced a maximum shear strain in the bearing of approximately 100 percent. Two existing equivalent linear models specified by the AASHTO and the Public Works Research Institute of the Japanese Ministry of Construction are also characterized using sinusoidal test results. The predicted seismic responses of the test structure by the proposed models and the two equivalent linear models were compared with the measured responses. It is concluded that the proposed models can predict the seismic responses of the bearing better than the two equivalent linear models. For practical applications, the fractional derivative Kelvin model is implemented into an interaction procedure adopted by the current design practice. An evaluation of the convergence of iteration and the accuracy of prediction is conducted.

Dolce and Marnetto (1998) showed the main experimental results on the mechanical behaviour of some selected shape memory elements. The conceptual design of a family of energy dissipating devices having full re-centering and high-energy dissipation capabilities, as well high resistance to large strain cycle fatigue and great durability, had described. The experimental behaviour of the devices is shown by the results of cyclic tests on the devices and of shaking table tests on scaled frame models. Finally, the applicability to bridges is demonstrated by an example.

Ando et al. (1998) conducted forced and free vibration tests on Ohito Viaduct Bridge 2, seismically isolated by lead-rubber bearings, to study the behaviour of the bridge. The resonant frequencies found to depend significantly on exciting force because of amplitude dependence of equivalent stiffness isolator. It is also reported that stiffness of isolator depends strongly on displacement amplitude even in linear range. Ogawa et al. (1998) conducted experimental studies to investigate an isolation system consisted of PTFE bearings and rubber springs. The system was found to be efficient in reducing the displacement response of the isolated structure, which utilizes frictional energy dissipation and rubber springs.

Robson and Harik (1998) performed dynamic testing on a highly skewed, three-span, seismically isolated, pre-stressed concrete slab-on-girder bridge. The pullback, quick-release method of testing was used, a first for this bridge type. A simple new quick-release mechanism was employed with relatively low lateral test force. Also, a new method of attaching the pullback cable to the bridge was implemented. After testing, a three-dimensional finite element model of the bridge was created. An optimisation program was used to refine, or calibrate, the model to match experimentally determined natural frequencies and mode shapes. This automated, systematic optimisation of model parameters produced an accurate analytical representation of the bridge.

Pinto et al. (1998) described large-scale pseudo-dynamic tests on seismically isolated bridges carried out at the ELSA Laboratory. Two alternative solutions were adopted, one solution with isolation/dissipation (I/D) devices over the abutments and over all piers, and another solution with I/D devices over the central short pier only, where the demands concentrated for the conventionally designed structure. The dissipation of energy was totally concentrated in the I/D devices and the bridge piers were completely protected. It is, seen that the fully isolated bridge requires significant clearances at the abutments in order to accommodate the dynamic displacements in those zones. Also, it is seen that partial isolation is more economical (one isolator against five for the full isolation solution), the partial isolation exploits in a more effective way the deformation capacity of the lateral piers.

Adachi et al. (2000) conducted shake table tests to study the non-linear seismic response behaviour of a seismic isolator and a reinforced concrete bridge column system. The global system response was dominated by the primary mode even if the non-linear behaviour was found at both the seismic isolators and the column. The simulation results using ordinary models of the seismic isolators and the column can express the test results quite well and the global response can be simulated using an equivalent 1-DOF model with proper damping factor.

Identification of system parameters with the help of records made on base-isolated bridges during earthquakes provides an excellent opportunity to study the performance of the various components of such bridge systems. Chaudhary et al. (2001) examined the soil-structure interaction (SSI) effects in base-isolated bridges by comparing the identified and physical stiffness of the substructure components. It is found that SSI is relatively pronounced in bridges founded in weaker soils and is more strongly related to the ratio of pier flexural stiffness and horizontal foundation stiffness than soil shear modulus alone. However, substantial reduction in shear modules is observed for moderate seismic excitation and this effect should be taken into account while computing foundation impedance.

3.4 Application of Seismic Isolation for Bridges

The seismic isolation had been successfully used several countries using the elastomeric and sliding bearings. A total of 255 isolated bridges namely 5 in Iceland, 49 in New Zealand, 12 in Japan, 21 in the United States and 168 in Italy - had been built (Priestley et al., 1996). Lead-rubber bearings were used in three Italian bridges and in 66 of the other 87 bridges, showing clearly that this is the preferred choice except in Italy, where more frequently, some dampers (in most cases a steel damper) is coupled with traditional sliding support. Seismic isolation and energy dissipation devices can also be used in retrofitting the bridges (Buckle and Mayes, 1989; Penzien, 2001). These are used to replace vulnerable support bearings by which the bridges-system’s flexibility can be increased considerably, lengthening the fundamental periods resulting in reduced horizontal seismic forces but increasing superstructure displacements. Seismic isolation systems such as lead-rubber bearing and FPS are most commonly used in retrofitting existing bridges.

Kelly et al. (1984) studied the retrofit of an existing freeway overpass undertaken to improve earthquake performance via the installation of lead-rubber bearings between the superstructure and the supporting columns. Before the retrofit, the columns of the bridge were capable of resisting approximately one-quarter of the design site earthquake but the lead-rubber bearings are shown to improve this performance.

Parducci and Mezzi (1992) discussed great number of highway bridges in Italy provided with seismic isolating devices. As a typical example of the criteria for the design of such structures, the bridges of a new highway are described. They are composed of various continuous multi-span sections. The seismic isolating systems have been designed on the basis of the dissipating behaviour of the elasto-plastic restrainers. The general considerations concerning the design of optimum structural configuration suggested by the use of seismic isolation were also discussed.

Matson and Buckland (1995) presented the experience gained in the seismic evaluation and retrofit of major bridges on the west coasts of Canada and the United States. These includes Golden Gate Bridge South Approach retrofitted with isolation bearings, Granville Bridge, an eight-lane truss bridge was retrofitted with cable restrainers and rubber bumpers. Also, in the Burrard Bridge truss was fitted with lead-core base isolation bearings. These case histories provide examples of seismic retrofitting by means of reducing the forces by de-tuning, absorbing energy, providing ductility, limiting travel and strengthening.

The Sacramento River Bridge at Rio Vista, California had been retrofitted using seismic isolation (Abbas et al., 1996). The retrofit of the bridge consists of seismic isolation of the bridge deck in the steel truss approach spans, and use of passive energy dissipaters at the tower column base connections. Extensive non-linear dynamic time history analyses were also performed to evaluate the performance of the isolation and energy dissipation systems.

The seismic upgrading of a motorway overpass bridge, situated in Chalastra just outside Thessaloniki, Greece, 130-m-long, six-span pre-stressed bridge of the Gerber type resting on five-reinforced concrete piers and two reinforced concrete abutments was done. The retrofitting was carried out by replacing the existing steel bearings with elastomeric ones of high damping (15%) each with varying height each, so that the required resistance in the system pier-cup-piles for gravity loading and earthquake would be less than the available one (Penelis et al., 1988).

A seismic retrofit strategy was developed for the Poplar Street Bridge over the Mississippi River at St. Louis for the Missouri Department of Transportation (Capron, 1999). The 660 m long structure consists of two parallel five-span continuous roadways with an orthotropic steel plate deck and variable depth steel box girder. The seismic evaluation considered three levels of design earthquakes and identified deficiencies in the bearings, reinforcement splices in the columns and piers, and one foundation. The retrofit strategy included adding force transmitters or dampers to the existing expansion bearing piers, adding transverse shear blocks to the beam seats etc.

The I-40 Mississippi River bridge, was built in the late 1960s has a total length of 5.3 km situated at the southeastern edge of the New Madrid seismic zone. The Arkansas and Tennessee Departments of Transportation conducted retrofitting of the bridge where existing bearings were replaced by friction pendulum bearings. The overall construction cost and the extent of retrofit work was significantly reduced by switching from the existing bearings to the isolation bearings (Imbsen et al., 1999).

A high-damping rubber bearing had been used in a large-scale pedestrian bridge spanning over railway lines in the Shizouka City (Higashi-Shizouka pedestrian bridge) for more flexibility of the structure and greatly reducing the power of earthquakes and, consequently, enhances resistance against shock (Iwata et al., 2000). The safety of the bridge structure was confirmed through non-linear dynamic analysis, as well as through a hybrid earthquake-loading test (pseudo-dynamic test).

A six-span continuous pre-stressed concrete twin cell box girder bridge has an overall length of 244.8 m, Yama-age bridge situated on National Highway number 294 in Japan Tochigi, is the first bridge in Japan, which is base-isolated with high damping rubber bearings (Chaudhary 2001). This bridge performed very well during 1995 Kobe earthquake.

3.5 Active and Hybrid Control Strategy for Bridges

Apart from the passive control of the bridge structures, there had been studies for active and hybrid control strategies for better earthquake protection bridges. Nagarajaiah et al. (1992) developed a control algorithm for friction controllable sliding isolation system for bridges including the effects of stick-slip phases. The developed algorithm is used to verify the accuracy of the algorithm with continuous sliding assumption and to establish its limits. Comparisons with experimental results were presented and effects of stick-slip phases on the response were also evaluated.

Reinhorn et al. (1993) presented three control algorithms for the hybrid system applied to bridges. Two of these algorithms are verified experimentally, and the third is verified with an analytical model. The results show that the hybrid system is capable of significantly improving the seismic response of the bridges. Yang et al. (1993) presented a method for controlling seismically excited bridges by using variable dampers. A simulation study using a continuous girder bridge is conducted to examine the effectiveness of the control algorithm in reducing the absolute acceleration of the bridge girder and the relative displacement between the girder and the supports. Simulation results indicate that the performance of the control method is excellent.

Yang et al. (1994, 1995) presented control methods for hybrid protective systems for bridges. The control methods are based on the theory of variable structure system or sliding mode control. Simulation results demonstrate that the control methods are robust with respect to system parametric uncertainties and performance is quite remarkable. Sensitivity studies are conducted to evaluate the effectiveness of hybrid protective systems and passive sliding isolators for reducing the response of seismic-excited bridge structures.

Fideliu (1998) presented classical optimal control strategy with full known state for seismic response control of cable-stayed bridge. The parameters for control strategy are proposed based on energetic interpretation for the optimisation index and applied to a three-dimensional cable stayed bridge, equipped with many active devices. The results had shown excellent performance, validating the proposed strategy. Symans and Kelly (1998) investigated the effectiveness of a hybrid system containing semi-active dampers through an analytical and computational study of the seismic response of a bridge. The results show that such a system may prevent or significantly reduce the structural damage during an earthquake.

4 Concluding Remarks

The review on the literature on the subject reveals that works on the following areas are still inadequate and deserve attention of future research for more understanding of the subject and for providing definite guidelines for design:

- Investigations of effectiveness of seismic isolation for skew bridges and bridges curved in plan and elevation.
- Effect of special correlation of earthquake ground motion on the response of seismically isolated bridges.
- Earthquake response of bridges with sliding systems and lead-rubber bearing with soil structure interaction.
- Earthquake response of seismically isolated regular bridges considering soil-water structure interaction.
- Analysis and feasibility of semi-active control devices for aseismic design of bridges.

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