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Advance model for seismic base isolation Systems of building

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Advanced technologies for structural design and construction have the potential for major impact on the bridge and buildings. One of these technologies is base isolation Systems. Numerous of buildings collapses that have occurred in recent earthquakes has exposed the vulnerabilities in existing buildings. Seismic isolation system is achieved via inserting flexible isolator elements into some part of building to increase energy dissipation. This paper investigates and makes recommendations on the structural performance of building using sliding type seismic isolators. First we develop state-of-the-art analytical models. Then, we introduce new models that can consider large deformation effects and the coupling of the vertical and horizontal response during motion simultaneously. We set up some numerical experiment to evaluate our method and compare viability of the two main isolator types (i.e. sliding and elastomeric) for building. © JASEM

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The root cause of the damaging effects of earthquakes is the unfortunate correlation between the fundamental periods of vibration of major structures and the frequency content of the seismic input (Priestley et al. 1996). Seismic isolation decouples the structure from the horizontal components of the ground motion with elements that have a low horizontal stiffness (Naeim and Kelly 1996). Isolation shifts the response of the structure to a higher fundamental period and increases the damping, thus reducing the corresponding pseudo-acceleration in the design spectrum and attracting smaller earthquake-induced forces.

The philosophy of seismic isolation for improving earthquake resistance of a structure departs from conventional retrofit measures because the latter attempts to strengthen individual elements of bridges while the former improves structural performance by reducing the overall earthquake forces that the structure acquires

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Bridge seismic isolation in the U.S. is a relatively new phenomenon that was addressed by the AASHTO with the Seismic Isolation Guide Specification for the first time in 1991. By this time elastomeric bearings were primarily used in bridge seismic isolation (Stanton, 1998). As new isolator types became available by 1995, the first

Seismic Isolation Guide Specification was essentially rewritten in 1997 to address the advances in the industry. However, the Specification still does not provide guidance about selecting the optimal isolator type for different bridge applications. Despite recent advances in base isolation research, the widespread application of this technology is still impeded by over-conservative attitudes (Mayes 2002; Naeim and Kelly 1996). The responses of state bridge engineers on a survey asking why base isolation is not more widely used revealed that engineers are not comfortable with seismic isolation because they view it as a black box and that there is a lack of certainty on choosing the optimum type of seismic isolation. Furthermore, sliding seismic isolators make up less than 25% of the total number of isolated bridges in North America (Buckle et al. 2006). A better understanding of the impact of isolators on the seismic behavior of bridge response is necessary.

The objectives of this study are to assess the performance of bridges seismically isolated with the FPS, with a particular emphasis on the modeling parameters of the isolators which govern the seismic response of typical bridges. This is accomplished rigorous analytical models of isolators with particular emphasis on the FPS and using these models to investigate the response of SIBs. The intention is to provide support for seismic risk mitigation and insight for the analysis and design of SIBs by quantifying response characteristics. The research tasks to accomplish these objectives are the following:

Identify the characteristic aspects of the FPS that contribute to the force deformation response. Develop the nonlinear kinematics formulation of the isolator model.
Implement the model into a nonlinear dynamic evaluation platform and valid ateresponse using experimental data.

Modify the FPS model to represent the Lead-Rubber Bearings (LRB) force deformation response.

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Compare and quantify the response of bridges as a function of isolator type with emphasis on FPS and LRB

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Investigate parametrically the influence of bridge geometric and material properties, and isolator design parameters on the system's response. If applicable, propose modifications for design of the isolator to improve bridge seismic performance.

LITERATURE REVIEW

Recent earthquakes have illustrated the vulnerability of bridges to damage and collapse. One of the emerging tools for protecting bridges from the damaging effects of earthquakes is the use of seismic isolation systems. An insightful definition of 'seismic isolation' given by Skinner et al.(1993) is as follows: 'Seismic isolation consists essentially of the installation of mechanisms which decouple the structure, and/or its contents, from potentially damaging earthquake induced, ground or support, motions. This decoupling is achieved by increasing the flexibility of the system, together with providing appropriate damping.' The two fundamental structural improvements provided by seismic isolation is theeduction of lateral forces and the concentration of lateral displacements at the isolation interface (Taylor and Igusa 2004). Seismic isolators are typically installed between piers, abutments, and deck (Priestley et al. 1996). Although patents for seismic isolation schemes were obtained as early as 130 years ago, only in the last four decades has industrial capabilities enabled the manufacturing of practical isolation devices, and only in the last decade has seismically isolated structural design been widely adopted (Taylor and Igusa 2004). Currently, isolation systems are most commonly classified as elastomeric and sliding. The fundamental concept of base isolation was first studied example building on balls by Professor John Milne who was a faculty member in the Mining Engineering Department of Tokyo University between 1876 and 1895 (Naeimand Kelly 1996). The first building that employed a rubber isolation system was a school at Skopje, Yugoslavia in 1969 (Naeim and Kelly 1996). The first seismically isolated building in the U.S.A. was the Foothill Communities Law and Justice Center in 1984-1985 in California, which was located only 19.3 km west of the San Andreas Fault(Taylor and Igusa 2004). The California Department of Transportation (Caltrans) was the first U.S. transportation agency to use seismic isolation on a bridge at the Sierra Point Overlook in 1985 (Taylor and Igusa 2004).

The Friction Pendulum System (FPS) is a sliding type seismic isolator that wasdeveloped in 1986 by Earthquake Protection Systems, Inc. The FPS was first used to retrofit an apartment building in California in 1989 (Naeim and Kelly1996). Since than, the FPS have been used to isolate buildings (Washington State Emergency Operations Center at Camp Murray, the U.S. Court of Appeals Building inSan Francisco), bridges (Benicia-Martinez Bridge in the San Francisco Bay Area, American River Bridge at Lake Natoma in Folsom), and storage tanks (LNG storage tanks on Revithoussa Island near Athens) (Jangid 2005) (Figure 1). The FPS has been incorporated into the design codes.

The FPS consists of a spherical stainless steel surface, an articulated slider and a housing plate (Figure 1). The sliding surface of the FPS consists ofstainless steel and a Teflon-based custom material. The radius of the FPS isolator controls the concavity related stiffness and the isolation period of the structure (Naeimand Kelly 1996). As the slider displaces over the concave surface, a continuous reentering force is provided by the gravity load of the supported mass. Simultaneously ,the friction force opposes the motion of the slider and dissipates hysteretic energy.

$$f = \overbrace{N\,\mu \operatorname{sgn}(\dot{\delta})}^{f_\mu} + \overbrace{\frac{N}{R}\delta}^{f_R}$$

Findings of previous research provide ample evidence that the dynamic response of seismically isolated structures is governed by the characteristics of the mechanisms of the isolators (Dicleli, 2002). This is an indication that the modeling assumptions adopted for the response of the FPS will affect the estimated response quantities of SIBs. The force-deformation response of the FPS is typically modeled using a unidirectional idealization:

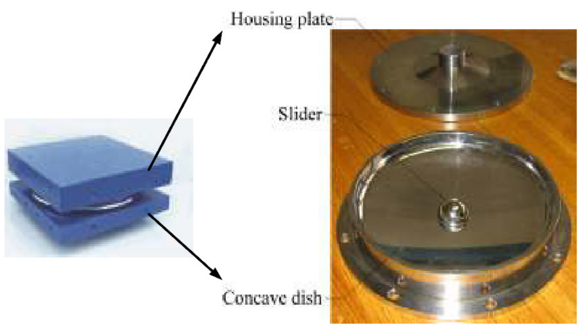

Fig. 1: Components of the FPS

where N is the normal force acting on the sliding surface, μ is the friction coefficient between the sliding surfaces, R is the radius of the concave surface, δ is the sliding deformation, $\dot{\delta}$ is the sliding velocity, and sgn($\dot{\delta}$) is the signum function. The signumfunction is equal to +1 or -1 depending on

whether $\dot{\delta}$is negative or positiverespectively. The force-deformation response of the FPS is further elaborated in Section.

4. However, it is important to underline the fundamental assumptions inherent in this equation: (1) N is constant; (2) $\mu$is constant; (3) the horizontal response is uncoupled in the orthogonal directions; and (4) isolator deformations are small and planar. Thefollowing sections describe theoretical and experimental research performed to quantify the influence of these simplifications

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Mosqueda et al. (2004) performed unidirectional and tri-directional tests on a rigid-block frame supported by four FPS. The authors concluded from the results of the tri-directional tests that the vertical component of the ground motion had negligible effect on the force-deformation response of the FPS. However, the authors noted that rotation of the superstructure in bridges caused by lateral ground motions could significantly influence the behavior of FPS.

Teflon is extremely resistant to attack by corrosive reagents or solvents. Furthermore, this polymer is not hard, but is slippery and waxy to touch, and has very low coefficient of friction on most substances. For all practical purposes the polymer is completely unaffected by water. Its thermal stability is such that its mechanical properties do not change for long intervals (months) at temperatures as high as 250 C. Resistance to wear and to deformation under load, stiffness, and compressive strength of Teflon can be enhanced by the use of different fillers such as glass fibers, graphite, carbon and bronze. The sliding of the two surfaces of the FPS is an integral part of the force-deformation response.

Jangid (2004) performed a parametric study to ascertain the effect of the friction coefficient of FPS on the seismic response of buildings and bridges to near-fault ground motions. The author analyzed a multi-storey building model and a three span continuous deck bridge model under near fault ground motions. The bridge model revealed similar results to those obtained for buildings which implied the presence an optimum value for the friction coefficient of the FPS that minimizes pier base shear and deck accelerations. The author suggested the use of coefficient of friction values between 0.07 and 0.19 for bridge isolators, and 0.05 to 0.15 for building isolators where the near-fault ground motions are expected.

The dynamic performance characteristics of FPS, specifically, stiffness, damping and energy dissipation was found to have relatively low sensitivity to temperature extremes. The performance of the isolators did not change at 49 C o and 40 C. Fatigue tests performed by 10,000 cycles of service movements showed that deterioration from fatigue and wear was not evident. Test results showed that the FPS was mildly frequency dependent. The stiffness and energy dissipation characteristics of the FPS generally increased with increasing periods of the excitation

Seismic isolators serve the common objective of decoupling the structure from the horizontal components of the ground motion to minimize the seismic loads on the load carrying components. However, there exist considerable differences in the vertical response characteristics of elastomeric and sliding isolators. The Lead-Rubber Bearing is a widely used elastomeric isolator. The details of the LRB characteristics are elaborated in Sections 3 and 6. The conventional FPS is essentially rigid under compression and has no tensile load capacity while the LRB has relatively less compression stiffness and able to resist a limited amount of tensile loading. Both the post-yield stiffness and the yield force of the two types of isolators are known to be affected by the normal force being imposed, but at a different rate and form. Normal force-dependent FPS models have been developed previously to show that this effect may result in considerable variation on the estimated isolator response. However, LRB models that account for bi-directional coupling has not yet been extended to account for normal force-dependency and implemented in bridge analyses to the authors` knowledge. High variation of the normal loads may result in fracture and a considerable change in the horizontal response of the isolators (Priestley et al. 1996). It has been shown that excluding the in-plane coupling of the orthogonal response for the isolators may result in significant underestimation of the displacements and forces for both type of isolators (Mosqueda et al. 2004). The bilinear force-deformation idealization of isolators allowed by the Specifications is based on the assumptions that the response is unidirectional and the normal force acting on the isolators is constant. Consequently, the unique response of the isolators may not be adequately captured with this simplified modeling approach. The four types of isolators were the pure friction system, the friction pendulum system, the laminated rubber isolator, and the New Zealand (lead-rubber) isolator. The authors reported base displacements in descending order as the lead-rubber isolator, the laminated rubber isolator, the pure friction system and the friction pendulum system. It was concluded that as long as the isolators' yield strength remained within 4-10% of the superstructure weight, the seismic response is not significantly affected. The effectiveness of the isolators reduced considerably as the superstructure flexibility increased. Increasing the LRB height, which is equivalent to increasing the post-yield stiffness, was found to result in greater period shifts of the bridge.

A review of the current state-of-the-art illustrates that the mechanism of the FPS has been thoroughly studied. The individual response of the conventional FPS has been established with experimental and analytical research. However, there are still issues pertaining to bridge seismic isolation, in particular with the FPS that need further clarification. The three main gaps in the literature were identified as the following:

The FPS has a highly nonlinear response that involves the variation and coupling of different parameters. Previous research considering the effects of different aspects of nonlinearities in the response of the FPS showed that there may be a significant divergence from a bilinear idealization. There is a need to develop a better understanding of the modeling assumptions and the required level of accuracy for the FPS in three-dimensional (3-D) bridge models.

The number of studies that compared the response of SIBs with different isolator types is limited. Available studies in this area did not consider the vertical components of ground motions, used two-dimensional structural models and idealized the force-deformation response of the isolators as bilinear which overlooked some of the distinguishing aspects of the response of the two isolator systems. There is a need for further assessment of the comparative response of SIBs via detailed isolator models that can capture the distinctions in the mechanism of sliding and elastomeric isolators

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Previous research on the parametric effects of design parameters in SIBs have focused primarily on bridges utilizing elastomeric systems and was generally confined to two-dimensional models that excluded the vertical components of ground motions. Further insight on the influence of design parameters in bridges isolated with the FPS is needed.

MATERIAL AND METHODS

The selection and detailed modeling of the bridges considered for seismic isolation with the FPS are presented. Seven models of a three-dimensional (3-D) Multi-Span Continuous (MSC) Steel Girder bridge with different assumptions of the FPS are generated. Nonlinear time history analyses (NLTH) are performed for the bridge to examine the effect of modeling parameters of the FPS on the response. The influence of the variations in isolator normal force, N, and coefficient of friction, in-plane bidirectional sliding interaction, large deformation, Perfects, and the orientation of the FPS isolators are highlighted. Maximum normalized force (MNF) and deformation (MND) of the isolators and column drifts are used as the parameters to characterize the response of the models.

The bridge type selected for the NLTH analysis in this section is an MSC Steel Girder Bridge seismically isolated with FPS isolators. The 3-D SIBmodel was developed in Open Sees. This model includes material and geometricnonlinearities. The bridge has three spans and a continuous slab-on-girder deck with a total of eight steel girders. The seismic isolation of the bridge is achieved via placing FPS isolators under each of the eight girders above the piers and abutments. of the expansion joints at the abutments is 7.7 cm. The FPS isolators are selected to achieve approximately a 2.0-2.5 second fundamental period which corresponds to R = 99 cm with an in-plane displacement capacity of 23 cm. The isolators are assumed to be positioned as the concave dish at the top. The slider diameter has 7.7 cm to ensure pressures below 275 MPa under gravity and earthquake loads in accordance with the recommendations of the manufacturer

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The superstructure is expected to remain within the linear elastic range, thus, the deck elements are modeled using elastic beam column elements, using the composite section properties. The section properties for the columns and the bent beams are created using fiber elements with appropriate constitutive models for both the concrete and the steel reinforcement. The reinforcing steel is modeled as a bilinear material with a yield strength, fys= 414 MPa, and an elastic modulus, Es= 200 GPa. A strain hardening ratioof 0.018 is used for this material (Figure 2). The unconfined and confined concrete behavior is modeled via the Kent-Scott-Park model which utilizes a degraded linearuploading/reloading stiffness and a residual stress. The concrete compressive strength, fc,and associated strain, are 27.6 MPa and 2.10-3 for the unconfined case and 28.5 MPa and (2.062)10-3 for the confined case, respectively (Figure 2). The bridge has footings which are 2.44 m square and use eight piles. The horizontal, kt, and rotational, kr, stiffnesses of the foundation are 130.5 kN/mm and (6.06)105 kNm/rad, respectively.

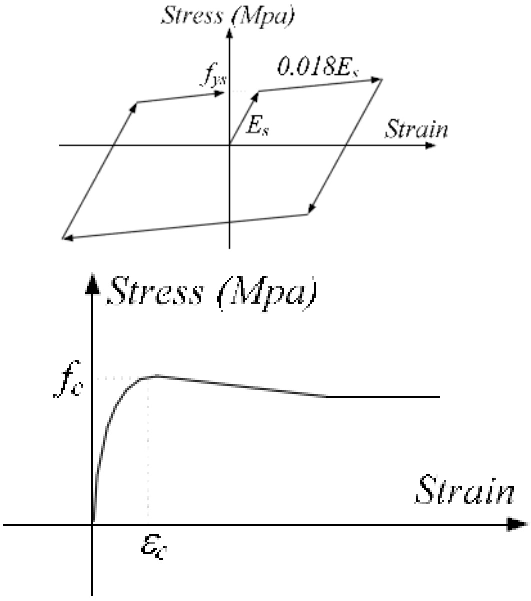

Fig. 2: Constitutive relationships for the modeling of (a) steel material; and (b) concrete material.

-*FPS Models:* Seven SIB models are generated with the above properties where the only difference is in the FPS modeling assumptions. The first model is theoretically exact,i.e., accounts for the variations of the N andμ, has bi-directional coupling of the slidingforces and incorporates P-! effects. The second model is a simplified bilinear model that is insensitive to the variations in N andμ, with uncoupled bi-directional slidingforces and small deformation assumptions. In Model 2, the constant value of N is takenas the corresponding value after gravity load analysis and μas 0.07. The third model isdeveloped to monitor the influence of not accounting for the variations of N on theresponse of the FPS. It is the same model as Model 1 with the only difference ofassuming a constant N of the corresponding value after gravity load analysis. The fourth model is developed to identify the influence of the bidirectional coupling in estimating the response of the FPS. The fifth model is developed to monitor

The sixth model is generated to identify the influence of the FPS orientation. Model 6 is same as Model 1 with the only difference being that the FPS isolators are positioned with the concave dish at the bottom which is accommodated as the corresponding sign shift. These venth model is developed to monitor the influence of the assumptions on the value ofμ. Model 7 is established with the same principles as Model 1 with the onlydifference of having a μthat is constant, i.e. insensitive to variations in pressure andsliding velocity. Model 7 is discussed separately from the other models and analyzed for a constant value of μranging from 0.05 to 0.12 with increments of 0.01.

-*Dynamic Analyses* The modal properties of the SIB in Model 1 are established by assigning lineareffective stiffness to the FPS isolators. The first three modes of vibration are those involving the isolation system which shows that the characteristics and the design of theFPS isolators govern the dynamic response of the bridge (Figure 3). The first three modal periods of the SIB are 2.22 s, 2.15 s, and 1.93 s, respectively. The first mode is longitudinal, the second mode is transverse and the third mode is torsional.

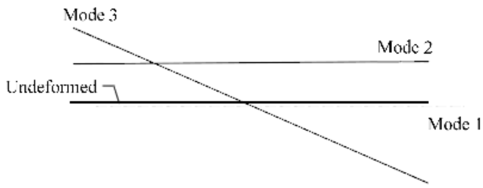

Fig. 3. Mode shapes of the deck

Seismically isolated bridge (SIB) models were subjected to NLTH analyses. OpenSees allows the user to select the integration technique and solution algorithm for the analysis. Newmark's average acceleration time-stepping scheme, which is an unconditionally stable numerical integration algorithm, was used in integrating thenonlinear dynamic equilibrium equations. The equations of motion were solved numerically using the Newton-Raphson method. The time interval for solving the equations of motion was taken as 0.005 s.

An important recommendation by the bridge engineering community is the use of design earthquakes that have a 2% probability of exceedance in 50 years (an earthquake with a mean recurrence interval of 2475 years) (FEMA 1997). Thegeometric mean of the longitudinal and transverse component of each record is scaled to match the spectral value of 0.118g at a period of 2.22 s corresponding to a 2% probability of exceedance in 50 years hazard level earthquake in Memphis, TN. The response spectra of the scaled ground motion records for 5% damping, ξ, and their median are given in Figure 4

The three components of the acceleration histories of each scaled ground motion are applied to the SIB models (Figure 5). The in-plane orthogonal components of the earthquakes are oriented to result in the maximum demands on the columns for all cases.

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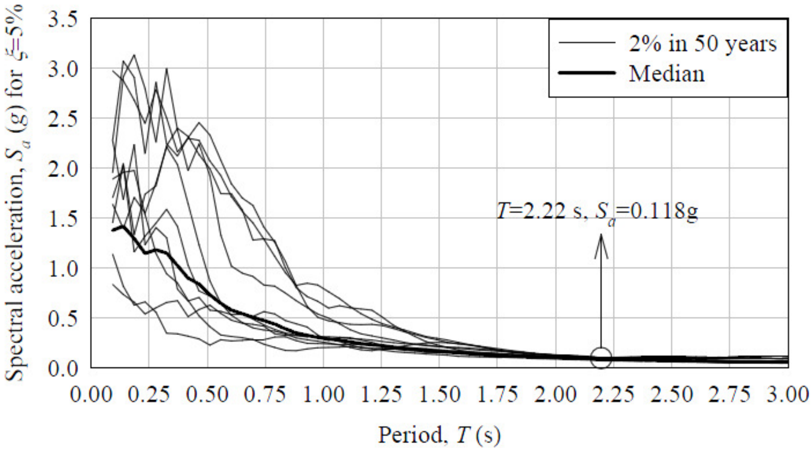


Fig. 4 Response spectrums for the suite of ground motions

The SIB models were first analyzed for gravity loads and sequentially subjected to NLTHanalyses using simultaneously the longitudinal, transverse and vertical acceleration records of the given earthquake. It is found from the gravity load analysis that each isolator above the pier and the abutments carry a gravity load , No, of approximately 125kN and 258 kN respectively (neglecting the normal load variation between the isolators at the exterior and the interior ends at the same pier and abutment).

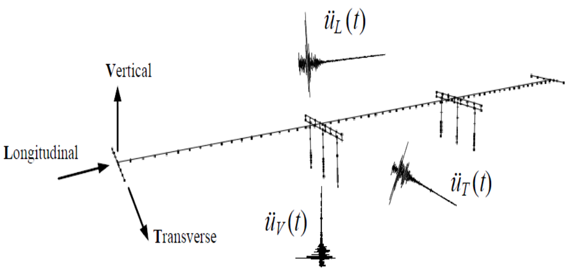


Fig. 5 Orientation of the 3-D bridge model.

The structural response of the isolators and columns along the same transverseaxis were essentially the same. Therefore, the results are presented for one of theisolators on top of the piers and the abutments and one of the columns.

Result and discussion: It was observed from the NLTH analyses of Model 1 that the maximum allowable displacements at the expansion joints were exceeded in an all records except MorganHill, Gazli and Nahanni. This indicates that pounding would occur between the abutment and the deck in the longitudinal direction. The impact forces in the deck are difficult to correlate to damage levels and may impede the utilization of the full capacity of the isolators. Additionally, uplift took place between the sliding surfaces of the FPS isolators in the vertical direction for all of the records except for the Loma Prieta, Helena and Landers. The time-history of the N/No of the Model 1 FPS isolator for the Nahanniearthquake is given in Figure 6. The maximum allowable N is limited by the allowable pressure of 310 MPa on the slider, which corresponds to N/No=5.4. This ratio was not exceeded during any of the NLTH analyses, however, during the Nahanni earthquake apeak value of N/No=3.51 was reached. This substantial increase is indicative of a proportional increase in the post-yield stiffness and yield force of the isolator. It is observed from Figure 6 that the contact between the two sliding surfaces was lost at least once which resulted in N/No=0. This uplift caused instantaneous yet complete loss of stiffness of the isolators during the earthquakes. However, due to the indeterminacy of the model there was no instability.

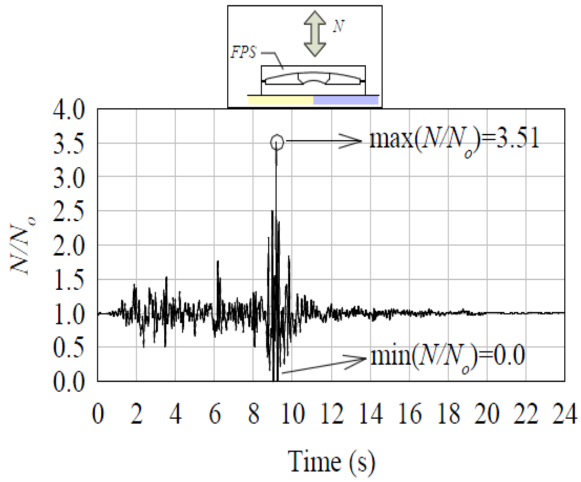
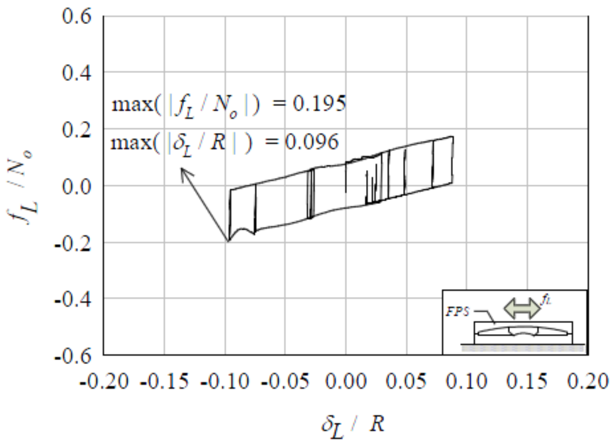


Fig.6 Time history of the N/No for the FPS during the Nahanni earthquake NLTH analysis.

Figure 7 shows the normalized force-deformation (NF-ND) histories of the FPS isolators on top of the piers among Models 1 to 4 in the longitudinal direction of the bridge during the N. Palm Springs record. Model 1 can capture the abrupt changes in isolator force and instances of uplift in the vertical direction. These two aspects of the isolator response could not be observed in Model 2. Additionally, Model 2underestimated both the MNF and the MND in comparison to Model 1. These differences between Model 1 and Model 2 NF-ND histories can be explained by theresponse observed in Models 3 and 4. Model 3 was unable to capture peak isolator forces indicating that the normal components of the ground motion were influential in this response quantity. Although Model 4 was able to account for the significant variations in isolator forces, the peak isolator force was overestimated and the peak isolator deformation was underestimated. This implies a stiffer isolator response when the bidirectional effects are neglected.



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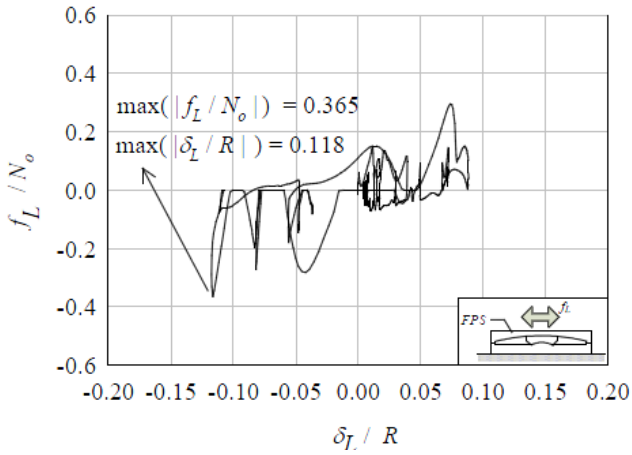

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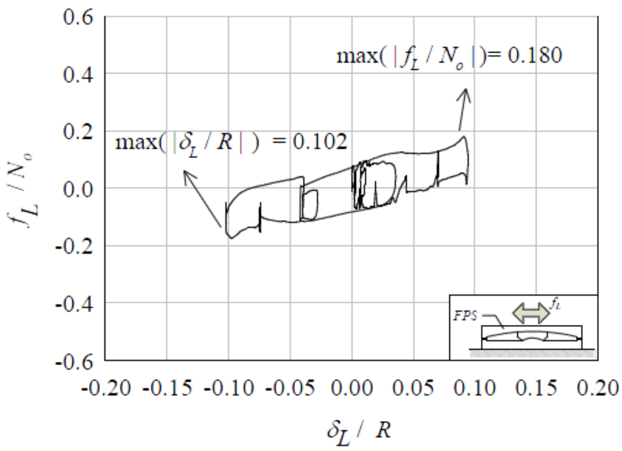

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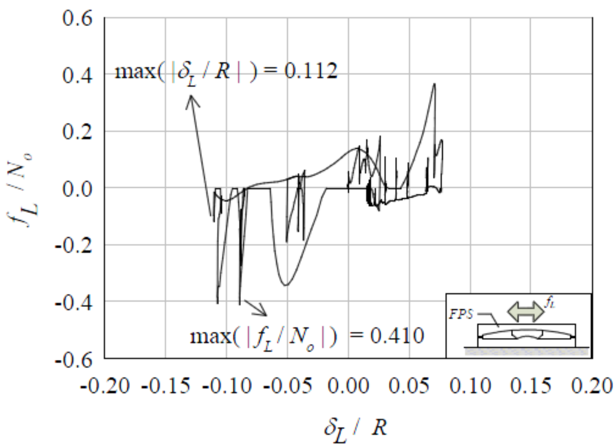

(d)

Figure 7 Force-deformation history of the FPS in the longitudinal directions on top of the pier for the N. Palm Springs earthquake record with (a) Model 1 (b) Model 2 (c) Model 3 and Model 4.

The influence of the isolator modeling parameters on MNF, MND and dmax for the suite of ground motions is illustrated via box plots. Box plots are a useful way of presenting the graphical description of variability of data (Montgomery2005). This information provides an overview of the expected demands on the isolators and the structural system as well as the scatter in the results. The statistical interpretation of the results are presented with numerical values of the median and plots of the 10th,25th, 10th, 75th, and 90th percentile cumulative probabilities.

Conclusion: In this section, the modeling of a typical highway bridge seismically isolated with the FPS has been presented. The influence of FPS modeling assumptions on normal force, N, and friction coefficient, μ, orthogonal coupling and large deformation, $P-\Delta$,effects in a seismically isolated multi-span continuous (MSC) steel girder bridge has been highlighted via nonlinear time-history (NLTH) analyses. The following conclusions are made:

The simplified bilinear idealization of the FPS response was unable to capture thevariability in the results. This model underestimated the maximum column drifts(dmax) by up to 31%. This was mainly a result of not accounting for the effects ofvertical components of ground motions, bidirectional coupling and the variablemagnitude of the friction coefficient.

The uplift and pounding of the deck in the vertical direction had notable affects in the response of the FPS that in one case caused an increase of up to 3.51 times inthe initial gravity load acting on the isolators (No).

Excluding the bidirectional coupling of the FPS isolators generally resulted in overestimating the isolator maximum normalized forces (MNF) and underestimating the isolator maximum normalized displacements (MND). This indicates an overestimation of the stiffness of the isolators.

The incorporation of the effects of orientation and the exact concave geometry of the FPS in to the response had negligible affects. This is mainly a result of the MND remaining under 0.20 for the suite of ground motions

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The peak MND of the isolators among the suite of ground motions acquired negligible variations among all the modeling assumptions. However, the median MND was influenced by the assumptions in the magnitude of μ

The structural demands transferred by the isolators to the abutments and the pierswere significantly different. Abutment forces were twice of those at the piers in the

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