Performance Evaluation of a Seismically-Isolated Bridge Structure with Adaptive Passive Negative Stiffness

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ABSTRACT

A Negative Stiffness Device (NSD) that has been developed for seismic response control of structures is presented herein. The device is purely mechanical in that it utilizes a pre-compressed spring to push a structure away from its equilibrium position and thus induce negative stiffness behavior. The negative stiffness is combined with the positive stiffness of the primary structural framing to produce a system that exhibits an apparent reduction in both strength and stiffness. In this paper, the NSD devices are described along with their response to cyclic testing that was conducted in preparation for shaking table tests of a seismically-isolated bridge model that incorporates the NSDs within the isolation system. In addition, numerical simulation results are presented to illustrate the effect that the NSDs are expected to have on the isolated bridge.

Keywords: Negative Stiffness Device, Bridge Structure, Adaptive Passive, Seismic Protection Device, Performance Measure

Introduction: Next generation Seismic Protection Devices

Bridges are one of the most critical structures in our built environment. In order to protect these vital lifelines, many different types of seismic protection devices have been developed around the world, assessed numerically, tested experimentally and implemented in many bridges. In the past few years, the authors have developed the next generation of these devices, using the concept of negative stiffness, which can significantly reduce the response of structures. The developed Negative Stiffness Device (NSD) is a completely mechanical device that exhibits true negative stiffness behavior using a pre-compressed spring (as contrasted with other similar devices that employ pseudo-negative stiffness (e.g., see Iemura, 2009). The device is regarded as providing "true" negative stiffness since the force produced by the device is displacement-dependent and in a direction opposite to the imposed displacement. Further, the device is considered to be an "adaptive passive" device in that it can mechanically change its behavior base on the deformation of the structure to which it is attached. The NSD has the effect of reducing the dynamic forces in a structure through virtual softening behavior. The reduced forces generally come at the expense of increased displacements, although the displacements can be controlled by implementing a damper in parallel with the device (Nagarajaiah et al, 2010 and Reinhorn et al., 2009). Two prototypes of the device have been fabricated by Taylor Devices, Inc. (a seismic protection device manufacturer) and tested to evaluate their response to cyclic loading. In addition, the effect of the devices on the seismic response of two different three-story structures (one isolated structure with linear behavior and one non-isolated with plastic behavior) has been evaluated via shaking table tests (Sarlis et al, 2011 & 2012 and Pasala et al, 2011, 2012a & 2012b). In the final stage of this project, the NSDs will be implemented in the isolation system of a quarter-scale bridge model (see Fig. 1) and tested on one of the shaking tables at the University at Buffalo NEES (UB-NEES) (Attary et al., 2012).

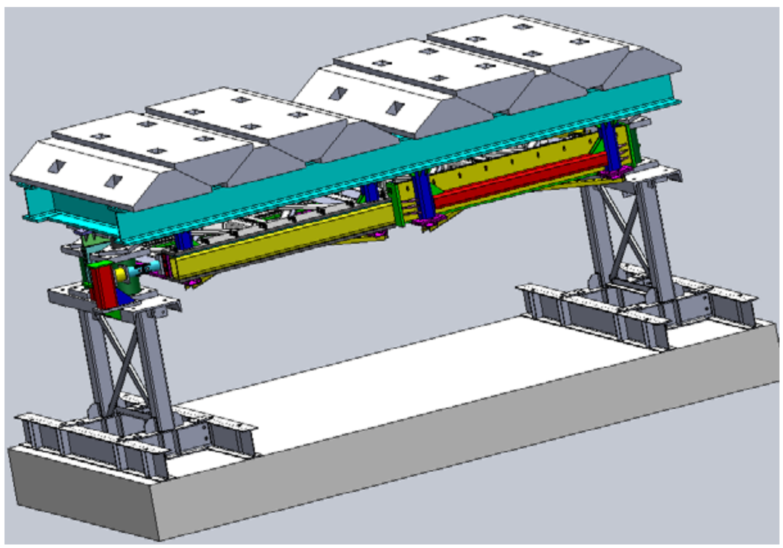

Figure 1. Virtual 3D view of bridge model with NSDs on seismic shaking table at UB-NEES site

Behavior of Negative Stiffness Device

Properties and characteristics of the NSD devices have been presented in other publications by the authors (Sarlis et al. 2011 & 2012, Pasala et al. 2011, 2012a, & 2012b, and Attary et al. 2012). In anticipation of the shaking table tests of the aforementioned bridge model, the properties of the NSDs were modified to optimize their effect on the structure. The key feature of the device is its negative stiffness, which is controlled by the stiffness and pre-compression of the primary spring. The pre-compression force of the primary springs was reduced to 19.57 kN. In addition, the NSDs are designed to have no effect on the structure until a specified displacement is exceeded. Beyond that displacement, the primary spring is engaged and produces negative stiffness. To achieve such behavior, the device is equipped with two gap-spring assemblies (GSAs) that employ secondary springs. In order to optimize the behavior of the device for the bridge model testing, the GSAs were redesigned such that the negative stiffness is engaged after 0.2 in. of displacement. The modified design of the NSDs results in the analytical force-displacement relations shown in Fig. 2 wherein separate curves are shown for the following cases: 1) NSDs alone, 2) isolation system without NSDs, 3) isolation system with NSDs, and 4) isolation system with NSDs and in series with the bridge piers.

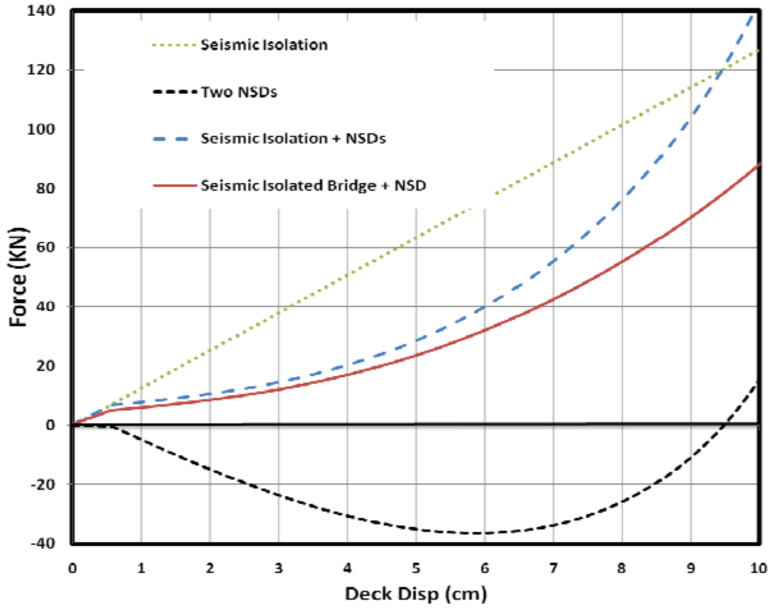

Figure 2 Analytical force-displacement relations for components of isolated bridge model

Having redesigned the NSDs, it was necessary to conduct system identification tests to verify their behavior relative to the analytical model and to calibrate the numerical model to be used within the numerical simulations of the isolated bridge model. To this end, the NSDs were installed within a load frame at the UB-SEESL laboratory wherein they were anchored at the bottom and allowed to displace laterally at the top. A hydraulic actuator was attached at the top of the NSD and was used to impose harmonic motion. A range of tests were performed to consider the effect of frequency and amplitude of motion. The undeformed and deformed shape of the NSD during one of the tests is shown in Figure 3 and, as an example, the force-displacement relation for one of the experimental tests is shown in Figure 4. Note that the data in Figure 4 represents 4 cycles of harmonic motion.

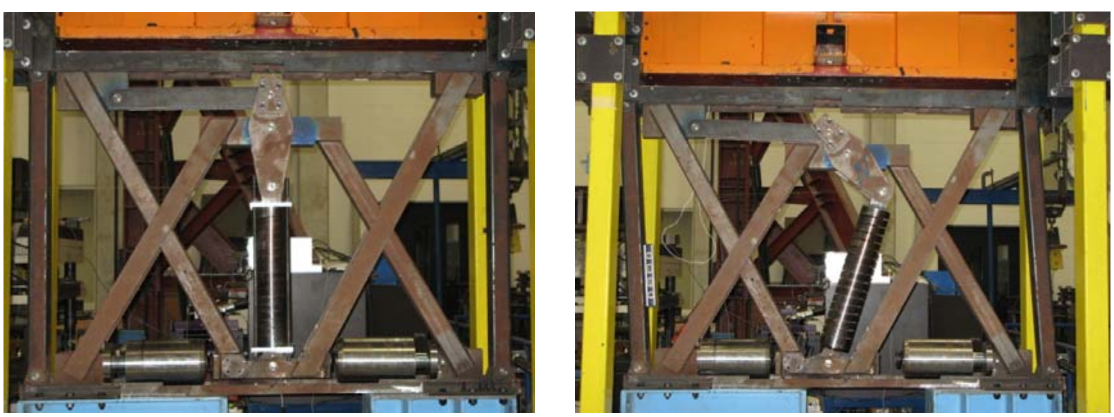

Figure 3 Undeformed and deformed shape of negative stiffness device

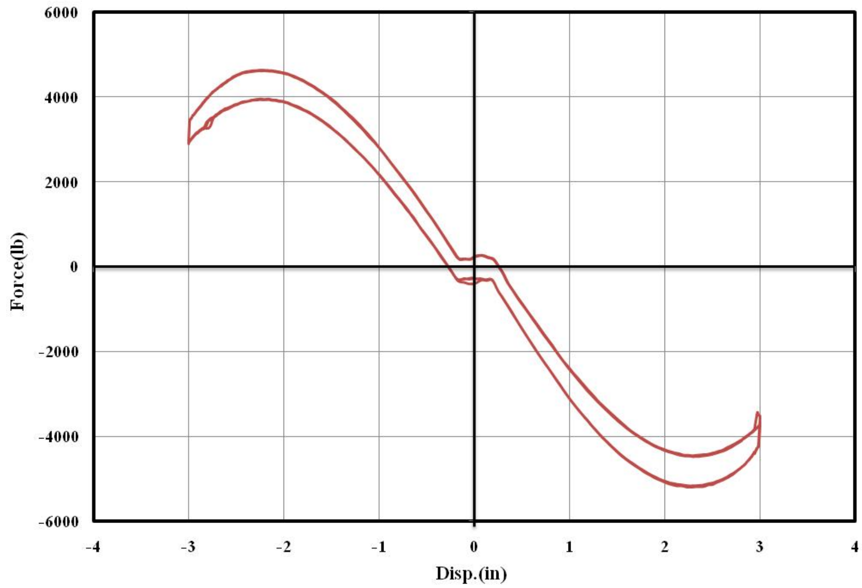

Figure 4 Force-Displacement relation of NSD (North) from harmonic testing (frequency = 0.01 Hz, amplitude = 3 in.)

Numerical Simulations and Performance Measures

Using the software SAP2000, a detailed 3D numerical model of the bridge test specimen was developed (see Fig. 5) and subjected to a number of historical earthquake records, some of which were scaled based on limitations of the anticipated shake table tests (see Table 1). The simulations were performed for four different bridge configurations: 1) Isolated Bridge (IB), 2) Isolated bridge with the NSDs (IB-NSD), 3) Isolated bridge with passive viscous dampers (IB-PD), and 4) Isolated bridge with NSDs and passive viscous dampers (IB-NSD-PD).

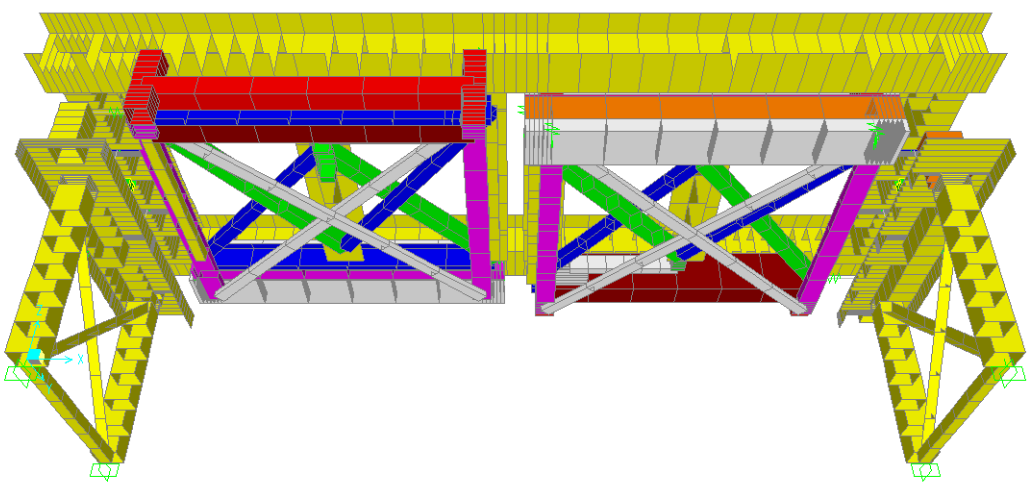

Figure 5. Numerical model of isolated bridge with NSDs (model developed using SAP2000)

Table 1 Ground motions used in numerical simulations

No.	**Earthquake**	**Record**	**M_w**
1	Northridge, 1/17/1994	637-270	6.69
2	Loma Prieta, 10/18/1989	CAP-000	6.93
3	Kocaeli, Turkey, 8/17/1999	DZC-270	7.51
4	Northridge, 1/17/1994	NWH-090	6.69
5	Chi-Chi, Taiwan, 9/20/1999	TCU-129-E	7.62
6	Chi-Chi, Taiwan, 9/20/1999	TCU-065-E	7.62
7	San Fernando, 2/9/1971	PCD-254	6.61
8	Cape Mendocino, 4/25/1992	PET-090	7.01
9	Kobe, 1/16/1995	KJM-000	6.90
10	Northridge, 1/17/1994	SYL-00	6.69

In order to evaluate the effectiveness of the NSD, the following six Performance Measures (PM) (Reigles and Symans, 2005) are defined and used to compare the response of the system with NSDs relative to the response without the NSDs:

$$PM_{V1} = \frac{Max\ base\ shear\ of\ isolated\ bridge\ with\ NSD}{Max\ base\ shear\ of\ isolated\ bridge\ (Without\ NSD\ and\ Damper)} = \frac{Max\ |V^{NSD}(t)|}{Max\ |V^{IB}(t)|}$$

$$PM_{V2} = \frac{Max\ base\ shear\ of\ isolated\ bridge\ with\ NSD\ and\ viscous\ damper}{Max\ base\ shear\ of\ isolated\ bridge\ with\ viscous\ damper} = \frac{Max\ |V^{NSD+PD}(t)|}{Max\ |V^{IB+PD}(t)|}$$

$$PM_{V3} = \frac{Max\ base\ shear\ of\ isolated\ bridge\ with\ NSD\ and\ viscous\ damper}{Max\ base\ shear\ of\ isolated\ bridge} = \frac{Max\ |V^{NSD+PD}(t)|}{Max\ |V^{IB}(t)|}$$

$$PM_{D1} = \frac{Max\ Disp.of\ deck\ of\ isolated\ bridge\ with\ NSD}{Max\ Disp.of\ deck\ of\ isolated\ bridge} = \frac{Max\ |D^{NSD}(t)|}{Max\ |D^{IB}(t)|}$$

$$PM_{D2} = \frac{Max\ Disp.of\ deck\ of\ isolated\ bridge\ with\ NSD\ and\ viscous\ damper}{Max\ Disp.of\ deck\ of\ isolated\ bridge\ with\ viscous\ damper} = \frac{Max\ |D^{NSD+PD}(t)|}{Max\ |D^{IB+PD}(t)|}$$

$$PM_{D3} = \frac{Max\ Disp.of\ deck\ of\ isolated\ bridge\ with\ NSD\ and\ viscous\ damper}{Max\ Disp.of\ deck\ of\ isolated\ bridge} = \frac{Max\ |D^{NSD+PD}(t)|}{Max\ |D^{IB}(t)|}$$

Note that the deck displacements defined in the performance measures are defined as displacements relative to the ground. Of course, for an isolated bridge, it is expected that these displacements are similar to displacement across the isolation plane since the lateral stiffness of the bridge piers is much higher than that of the isolation system. A summary of the PM values for each ground motion in Table 1 is shown in Fig. 6. Note that a PM value smaller than unity indicates that the NSDs were effective in reducing a particular response quantity. As expected, the effect of the NSDs is to reduce the base shear for all cases considered while the deck displacement is increased in a number of cases. In general, the effectiveness of the NSDs in reducing base shear depends on the degree to which they were activated which depends on the displacement demand on the devices. The effect of the viscous dampers in controlling displacement is evident by comparing the plots for PM_{D1} and PM_{D3} where the only difference is the addition of the dampers.

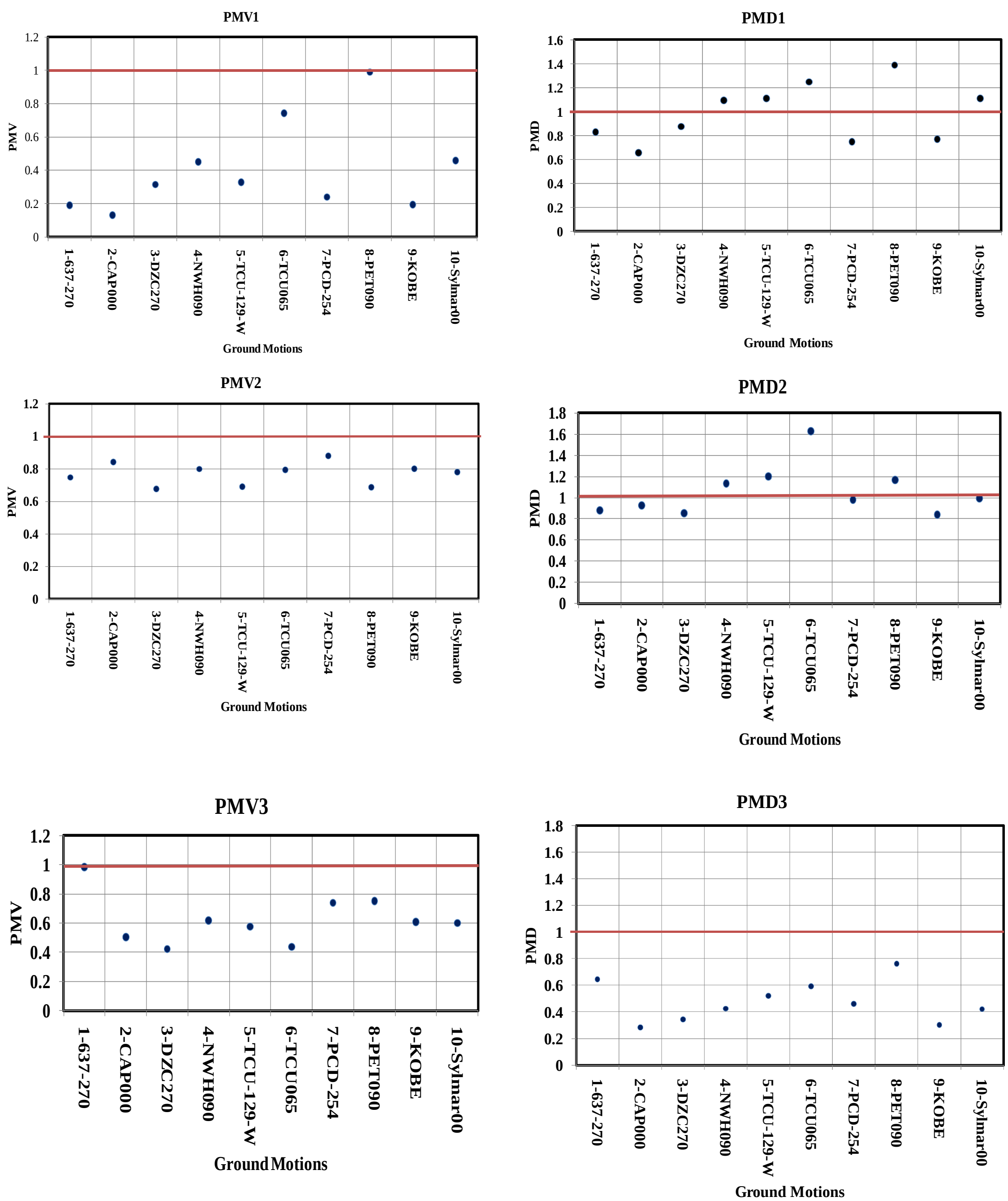

Figure 6. Values of force and displacement performance measures for various ground motions

It should be noted that the analytical model of the NSD used in the simulations is idealized in that it does not account for the dynamics of the device, friction at the pinned connections, and the flexibility of the steel framing members within the device. As demonstrated by Sarlis et al. (2011), these effects help to explain details of the device behavior but have limited practical significance. As shown in Figure 4, cyclic testing does reveal some degree of hysteretic response, which may be attributed to friction at various locations within the device. The hysteretic response may be viewed as a positive feature of the device in that it results in a device that provides both negative stiffness to reduce forces and damping to limit displacements.

As indicated above, it can be difficult to simultaneously reduce forces and displacements in the isolated bridge structure. As a means of illustrating the effectiveness of the various isolation systems in simultaneously reducing both of these quantities, the base shear and displacement performance measures can be combined in a single plot (see Fig. 7). In such a plot, the best systems are those which remain under unity for both axes. As shown in Fig. 7, the NSDs are effective in reducing forces in the bridge piers (base shear) but they may increase the deck displacement in some cases. The addition of viscous dampers (without NSDs) can be used to reduce the displacements but may lead to somewhat increased forces. Using both NSD's and viscous dampers in parallel can, in some cases, result in simultaneous reduction of forces and displacements.

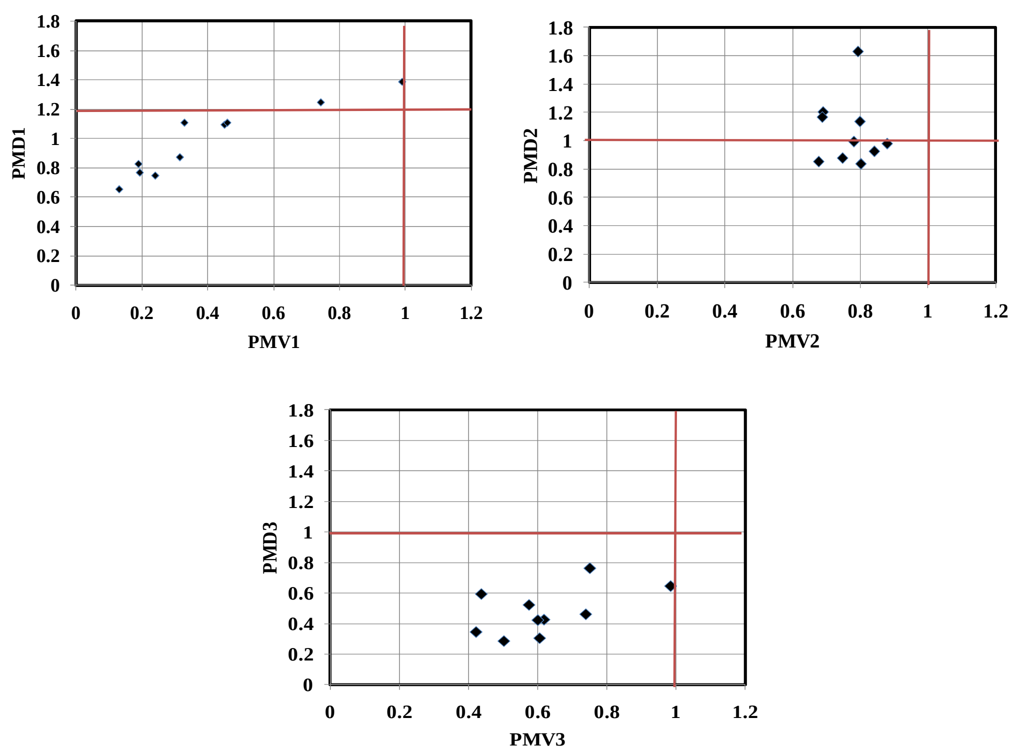

Figure 7. Simultaneous evaluation of force- and displacement-related performance measures

Another approach to quantifying the performance of the NSDs in terms of simultaneous consideration of force and displacement response is via a Combined Performance Measure (CPM) (Reigles and Symans, 2005) as defined below.

$$CPM_1 = \left(\frac{Max\ |V^{NSD}(t)| - Max\ |V^{IB}(t)|}{Max\ |V^{IB}(t)|} + \frac{Max\ |D^{NSD}(t)| - Max\ |D^{IB}(t)|}{Max\ |D^{IB}(t)|}\right)$$

$$CPM_2 = \left(\frac{Max\ |V^{NSD+PD}(t)| - Max\ |V^{IB+PD}(t)|}{Max\ |V^{IB+PD}(t)|} + \frac{Max\ |D^{NSD+PD}(t)| - Max\ |D^{IB+PD}(t)|}{Max\ |D^{IB+PD}(t)|}\right)$$

$$CPM_3 = \left(\frac{Max\ |V^{NSD+PD}(t)| - Max\ |V^{IB}(t)|}{Max\ |V^{IB}(t)|} + \frac{Max\ |D^{NSD+PD}(t)| - Max\ |D^{IB}(t)|}{Max\ |D^{IB}(t)|}\right)$$

Note that, if the value of CPM is less than zero, the system with NSDs produces an overall improvement in performance relative to the system without NSDs. As shown in Fig. 8, the NSDs reduce the base shear in the bridge model significantly as compared to the isolated bridge without the NSDs. Although it might be expected that adding the NSDs to the isolation system would generally increase the displacements, in some cases the displacements are reduced. Thus, as noted previously, it is possible for the NSDs to simultaneously provide a reduction in forces and displacements in the system. The addition of passive dampers (PD) in parallel with the NSDs results in increased forces and reduced displacements relative to the isolated bridge with NSD alone. Although the base shear increases, it is still less than for the case where the bridge only employs isolation bearings. Thus, the isolation system that employs both NSDs and PDs is regarded as providing good performance with regard to both forces and displacements (the primary function of the NSDs being to limit forces while the PDs limit displacements).

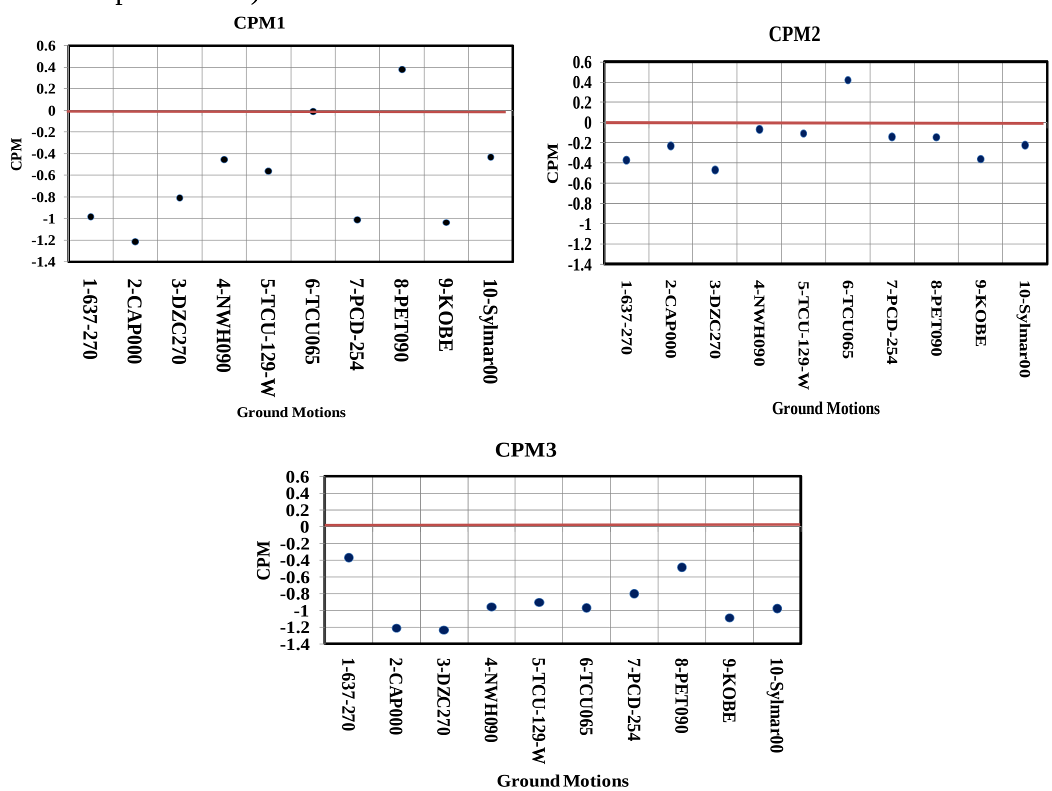

Figure 8. CPM values for different ground motions

Conclusions

In this paper, the performance of a seismically-isolated bridge structure that incorporates negative stiffness devices was examined via numerical simulations and using various performance measures. The numerical simulations demonstrated that the use of NSDs within the isolation system can significantly reduce the peak base shear. Although in some cases the NSDs produce a reduction in peak deck displacements, it is expected that they will generally increase the displacements. To address this issue, passive dampers can be added in parallel with the NSDs. The passive dampers decrease the displacements but will generally increase the base shear in such a way that the base shear is still less than the case in which the bridge only employs isolation bearings, thus providing good overall performance with regard to both forces and displacements. Furthermore, this study has demonstrated that NSDs are effective in cases where the isolation system that incorporates the NSDs is supported on a flexible layer (i.e., the bridge piers) rather than being directly connected to the foundation of the structure.

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