Passive Stiffness Modification of a Seismically Isolated Bridge Deck under Seismic Excitation

Arcan Yanik
Istanbul Technical University

Unal Aldemir
Istanbul Technical University

This study is on the seismic performance assesment of a seismically isolated bridge structure with passive stiffness modification implementation. Performance of the passive stiffness modification approach is compared with semi-active control implementation on the bridge deck. El Centro NS(north-south) and Kobe EW(east-west) eartquake excitations are used for the dynamic simulations of the passive case. Results are given in a comparative way for the uncontrolled bridge deck, passive stiffness modification implemented and semi-actively controlled, seismically isolated bridge deck (Yanik & Aldemir, 2018). Frequency dependent acceleration, velocity and displacement response transmissibility ratios are defined to examine the results.

INTRODUCTION

There has been a remarkable interest, on passive control and semi-active control of structures, in the area of earthquake engineering for the last decade (Yanik & Aldemir, 2018; Bitaraf, et al., 2010; Behnam & Khoshnoudian, 2012). Some important and up to date studies on semi-active control of structures are given in this paragraph. An implementable proposed predictive control algorithm for suppressing the earthquake response using a nonlinear semi-active damper was defined in (Aldemir, 2010). The performance of a simple 2-DOF base-isolated structure was investigated numerically in this study. Two semi-active control methods for seismic protection of structures using MR dampers were presented in (Bitaraf, et al., 2010). They used a simple shear frame structure incorporating two MR dampers for numerical simulations under two far field and two near field earthquakes. Development of a semi-active control algorithm, based on several performance levels anticipated from an isolated building, during different levels of ground shaking corresponding to various earthquake hazard levels was given in (Behnam & Khoshnoudian, 2012). Their proposed performance-based algorithm was based on a modified version of the well-known semi-active skyhook control algorithm. A fuzzy rule-based semi-active control of building frames, using semi-active hydraulic dampers (SHDs), was presented in (Ghaffarzadeh, et al., 2013). Their control approach was validated by using 3-story and 10 story shear frame structures under El Centro earthquake. A direct semi-active control method is introduced to mitigate the seismic responses of structures equipped with magneto-rheological (MR) dampers was presented in (Mohajer Rahbari, et al.,2013). Their algorithm was applied to control seismic vibrations of a three-story and an 11-story sample shear building that have been equipped with the MR damper control system. A 3-DOF per floor tier building analytical model which can incorporate models of either traditional tuned mass dampers (TMD) or MR dampers (MR-MD) was presented in (Yanik, et al., 2013). Their 2D building plan is converted to a 3DOF tier building and given in They stated that a desired damper force can be calculated from the present values of the state vector and mod-el parameters estimated off-line. A wavelet neural network-based semi-active control model was proposed in order to provide accurately computed input voltage to the magneto-rheological dampers to generate the optimum control force of structures in (Hashemi et al., 2016). Their model was optimized by a localized genetic algorithm and then applied to a nine-story benchmark structure subjected to 1.5× El Centro earthquake. They performed the dynamic analysis in one direction (north-south) and used the benchmark structure numerical model for their validations. A semi-active control strategy, in which H∞ control algorithm was used and magneto-rheological dampers were employed for an actuator, was presented to suppress the nonlinear vibration in (Yan et al., 2016). Their numerical example was a twenty story benchmark building. The application of a semi-active fuzzy based control system for seismic response reduction of a single degree-of- freedom (SDOF) framed structure using a Magneto-rheological (MR) damper was presented in (Braz-Cesar & Barros, 2018). They mentioned that the results of the numerical simulations showed the effectiveness of the suggested semi-active control system in reducing the response of the SDOF structure. Besides semi-active control of structures, this study is related with passive stiffness modification methods and seismically isolated structures. Therefore, the literature review on the passive control studies presented during the last decade, are given below.

Among passive control devices, seismic isolation systems (base isolation systems) are mostly researched and widely applied in practice. Base isolation systems are effective in reducing the inter-story displacements of the superstructure. However, the excessive overturning moments for the base isolated multi-story buildings and the excessive base displacements due to the near fault excitations are the issues to be addressed for these systems (De Iuliis et al., 2008). Two new models for the simplified seismic analysis of seismically isolated highway bridges with massive piers were proposed in (Mao et al., 2017). The dynamic response of a seismically isolated bridge located in the vicinity of a surface fault rupture ("Case A") or crossing a fault rupture zone ("Case B") was calculated by utilizing a near-fault ground motion record processed with and without a displacement offset in (Yang et al., 2017). The effects of vertical excitation on the seismic performance of a seismically isolated bridge with sliding friction bearings and different bearing friction coefficients and different stiffness levels (pier diameter) were discussed using example calculations, and the effects of excitation direction for vertical excitation on the analysis results were explored by (Wang et al., 2016). The failure modes of isolated continuous girder bridge subjected to strong ground motions by developed weighted rank sum ratio method, in combination with developed 3D finite element bridge models were investigated in (Tan et al., 2017). A parametric probabilistic demand hazard analysis is performed over a grid in the isolation bearing parameter space, using high-throughput cloud-computing resources, for a California high-speed rail (CHSR) prototype bridge by (Li & Conte, 2018). Another commonly used passive device is passive viscous damper (tuned mass damper) (Xiang & Nishitani, 2014; Sun & Nagarajaiah, 2014). Probabilistic models for estimating the seismic demands on reinforced concrete (RC) bridges with base isolation was proposed in (Gardoni & Trejo, 2013). Although they are widely studied, the effectiveness of these devices is limited due to the mistuning effect (Casciati & Giulani, 2009). If the tuning frequency of the mass damper differs from the main frequency of the structure, tuned mass damper will have little effect on reduction of seismic responses.

The dynamic behavior of a bridge deck system, with isolation bearing (seismic isolator) and stiffness modification method is analyzed in this paper. The dynamic simulations are performed under the effect of seismic type and harmonic type of excitations. The bridge deck is idealized by a single degree of freedom (SDOF) dynamic model. El Centro NS(north-south), and Kobe EW(east-west) earthquake excitations are used for the dynamic simulations. Kanai-Tajimi spectrum is adopted for generating the harmonic excitation. For comparison purposes, the semi-active control case, and bridge deck example defined in

(Yanik & Aldemir, 2018), are used in this paper. In comparison with the passive stiffness modification method, two semi-active control policies are considered. These control policies are continuous (pseudo-skyhook) control and bang-bang control. Different damping levels are analyzed to fully understand the behavior of the bridge deck system.

FORMULATION OF THE PASSIVE STIFNESS MODIFICATION METHOD

The uncontrolled bridge deck system and passive stiffness modification case considered in this study are given below.

Uncontrolled Bridge Deck Model

This section of the paper is inspired by (Zhang, 2000; Yanik & Aldemir, 2018). A single degree of freedom (SDOF) bridge deck model is shown in Figure 1 (Zhang, 2000). Figure 1 represents the conventional bridge deck dynamic model without any control element. The dynamic model in Figure 1 can be presented by stiffness k_0 and damping c_0 elements. Dynamic equation of the motion of this bridge deck subjected to seismic excitation can be written as

$$m_0\ddot{x} + c_0\dot{x} + k_0 x = -m_0\ddot{x}_g \tag{1}$$

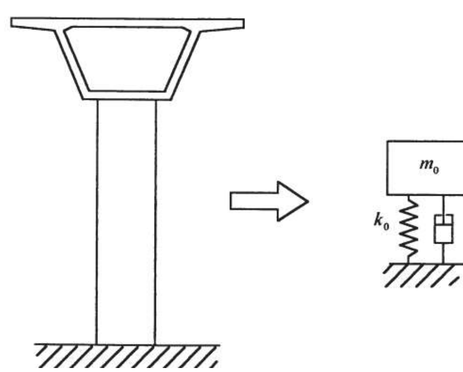
where m_0, c_0, and k_0 are the mass, damping, and stiffness of the bridge deck respectively. In (1), $\ddot{x}$, $\dot{x}$, and x represent the acceleration, velocity, and displacement of the bridge deck in a respective way. For the bridge deck without bearing the circular frequency ω_n and natural period of motion T_n can be expressed as

$$\omega_n = \sqrt{\frac{k_0}{m_0}} \quad , \quad T_n = 2\pi\sqrt{\frac{m_0}{k_0}} \tag{2}$$

The critical damping c_c and the damping c_0 of the bridge deck can be presented as

$$c_c = 2\sqrt{m_0 k_0} \quad , \quad c_0 = 0.05\ c_c \tag{3}$$

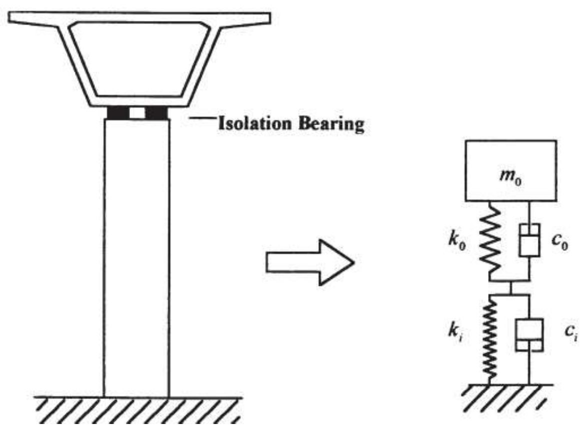
FIGURE 1
SDOF BRIDGE DECK DYNAMIC MODEL (ZHANG, 2000)



Passive Stiffness Modification Method

Passive stiffness modification method is used to investigate the stiffness effect (or natural period) for the earthquake response (response spectra) of the bridge deck with isolation bearing. If we implement an isolation bearing to the bridge deck presented in Figure 1, the system can be idealized as given in Figure 2 (Zhang, 2000). However, mass of the isolation bearing can be neglected.

FIGURE 2
BRIDGE DECK WITH ISOLATION BEARING (ZHANG, 2000)



Constant damping is considered in the passive stiffness modification method. The damping ratios used in this method are J_i= 0.05; 0.10; 0.20; 0.30. The stiffness of the system K can be expressed as follows

$$K = k_0 k_i / (k_0 + k_i) \tag{4}$$

where k_i is the stiffness of the isolation bearing. The circular frequency ω_{ni} , and natural period of motion T_{ni} of the bridge deck with isolation bearing can be expressed as

$$\omega_{ni} = \sqrt{K / m_0} \quad , \quad T_{ni} = 2\pi \sqrt{m_0 / K} \tag{5}$$

The combined stiffness of the system which is given with Figure 3 can also be presented as

$$K = 4\pi^2 m_0 / T_{ni}^2 \tag{6}$$

by defining a=K, the stiffness of the isolation bearing k_i can be defined as

$$k_i = (ak_0) / (k_0 - a) \tag{7}$$

In passive stiffness modification method studied in this paper, the following relations should be satisfied

$$k_i > 0 \;\rightarrow\; k_0 > a \;\rightarrow\; k_0 > 4\pi^2 m_0 / T_{ni}^2 \;\rightarrow\; T_{ni}^2 > 4\pi^2 m_0 / k_0 \;\rightarrow\; T_{ni} > 2\pi \sqrt{m_0 / K} \tag{8}$$

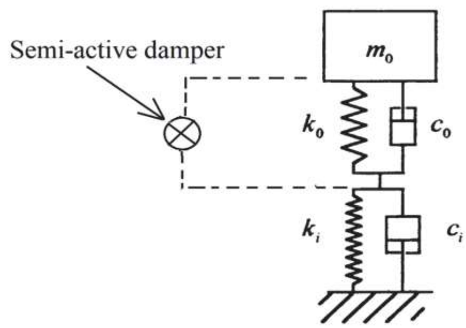
The results obtained from this method, is compared with passive control case, and semi-active control cases that were defined in (Yanik & Aldemir, 2018). The semi-active control cases are presented below.

FORMULATION OF THE SEMI-ACTIVE CONTROL CASES (YANIK & ALDEMIR, 2018)

If we implement a semi active damper to the bridge deck with isolation bearing that is shown in Figure 2, the dynamic model of the system consisting of bridge deck, isolation bearing, and semi-active damper can be obtained as shown in Figure 3. The dynamic equation of the motion of the system with semi-active damper can be simply written as

$$m_0\ddot{x} + (c_0 + c_i)\dot{x} + Kx + f_{\dot{x}} = -m_0\ddot{x}_g \tag{9}$$

FIGURE 3
DYNAMIC MODEL OF THE BRIDGE DECK WITH ISOLATION BEARING AND SEMI-ACTIVE DAMPER



where $f_{\dot{x}}$ is the semi-active damper force, c_i is the damping of the isolation bearing. The two semi-active control cases, that are considered for comparison, with the passive stiffness modification cases are; bang-bang control policy defined in (Lim et al., 2013) and continuous control that was explained in (Renzi & Angelis, 2010). However, in this paper, Bang-Bang control case is found out to be ineffective in uncontrolled bridge deck response reduction. Thus, in the numerical results section, only results from continuous control case is presented, in comparison with passive stiffness modification method. However, the formulation of the Bang-Bang control is given below.

Bang-Bang Control

For the bang-bang control case, the resulting semi-active damper control force can be written as

$$f_{\dot{x}} = c_d \; v \; \dot{r} \tag{10}$$

Here, the semi-active control force f is changed optimally via the semi active control decision variable or valve variable v. In (10), c_d describes the behavior when the semi-active control decision variable v is 0 and $\dot{r}$ is the relative base velocity of the system. The delayed control decision for the bang-bang control $\dot{v}$ is given by (Gavin and Aldemir, 2005)

$$\dot{v} = \left(-1/T_v\right)\left[v - H\left(r\left|\dot{r} + \dot{x}_g\right|\right)\right] \tag{11}$$

where T_v is the response time of the controllable damper, H is the Heaviside step function of the control decision v and r is the base displacement of the system. Because of the Heaviside step function in (11), analytical expressions for the frequency response function cannot be obtained. Frequency response functions for semi-actively controlled structures can however be constructed by numerically integrating the system equations until a harmonic steady state is reached and plotting the ratio of a response amplitude to the excitation amplitude as a function of frequency ratio. In this research, it is obtained that Bang-Bang control case was not effective on reducing bridge deck responses. Therefore, the performance of the continuous control case is compared with passive stiffness modification method.

Continuous (Pseudo-Skyhook) Control

The control force of the semi-active damper implemented in the isolation level can be expressed as [20] more information about this control policy can be found in (Gavin & Aldemir, 2005; Karnopp et al., 1974)

$$f_{\dot{x}} = c_d(\dot{r} + \dot{x}_g)H\left[\dot{r}(\dot{r} + \dot{x}_g)\right] \tag{12}$$

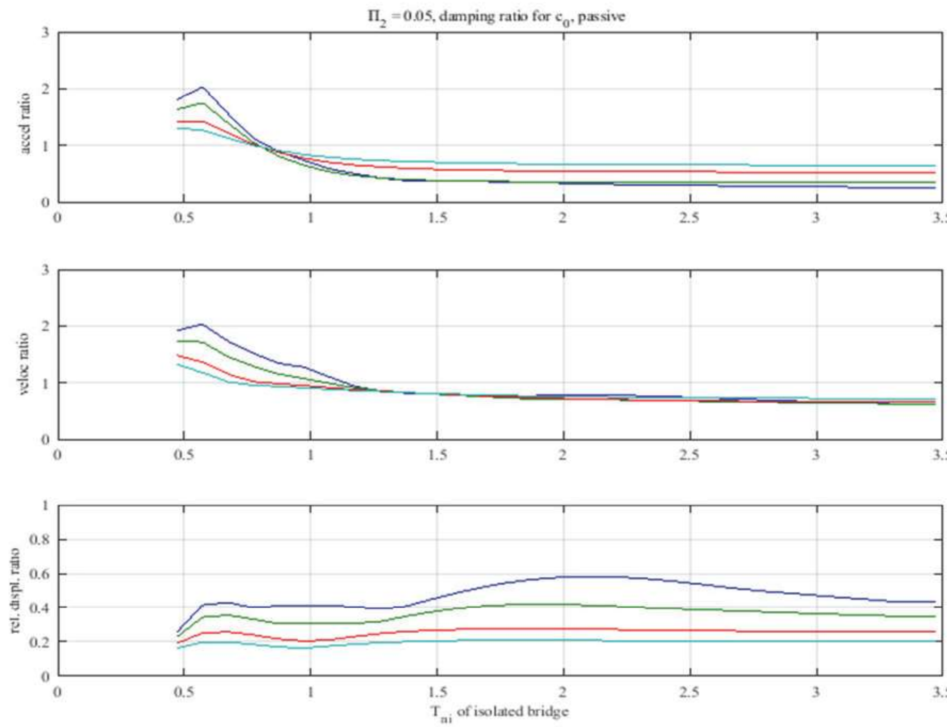
NUMERICAL RESULTS

In this study, a simplified single-degree-of-freedom model of an isolated bridge is used. This model is presented in Figures 1 to 3. For comparison purposes, the same model presented in (Yanik & Aldemir, 2018), is used in this paper. In this model the mass of the bridge deck m_0 is 1065.7 tons, pier stiffness k_0 is $189x10^6$ N/m, structural damping coefficient c_0 is $1.42x10^6$ N/m/s. Without the isolation bearing, circular frequency of the bridge deck is ω_n=13.32 rad/s, natural vibration period of the bridge deck is T_n=0.47 s and c_0 corresponds to %5 of critical damping, c_c=$2.84x10^7$ N/m/sec. With the isolation bearing, circular frequency is ω_{ni}=2.51 rad/s and natural vibration period of the bridge becomes T_{ni}=2.5 s. The critical damping for this system is c_{ci}=$5.4x10^6$ N/m/s. To analyze the performance of the passive stiffness modification method, frequency dependent acceleration, velocity, and displacement response transmissibility ratios $T_a(\omega)$, $T_v(\omega)$ and $T_d(\omega)$ are defined as written below (Gavin, 2014).

$$T_a(\omega) = \max\left|\ddot{x} + \ddot{x}_g\right| / \max\left|\ddot{x}_g\right| \ \ , \ T_v(\omega) = \max\left|\dot{x} + \dot{x}_g\right| / \max\left|\dot{x}_g\right| \ \ , \ T_d(\omega) = \max\left|x + x_g\right| / \max\left|x_g\right| \tag{13}$$

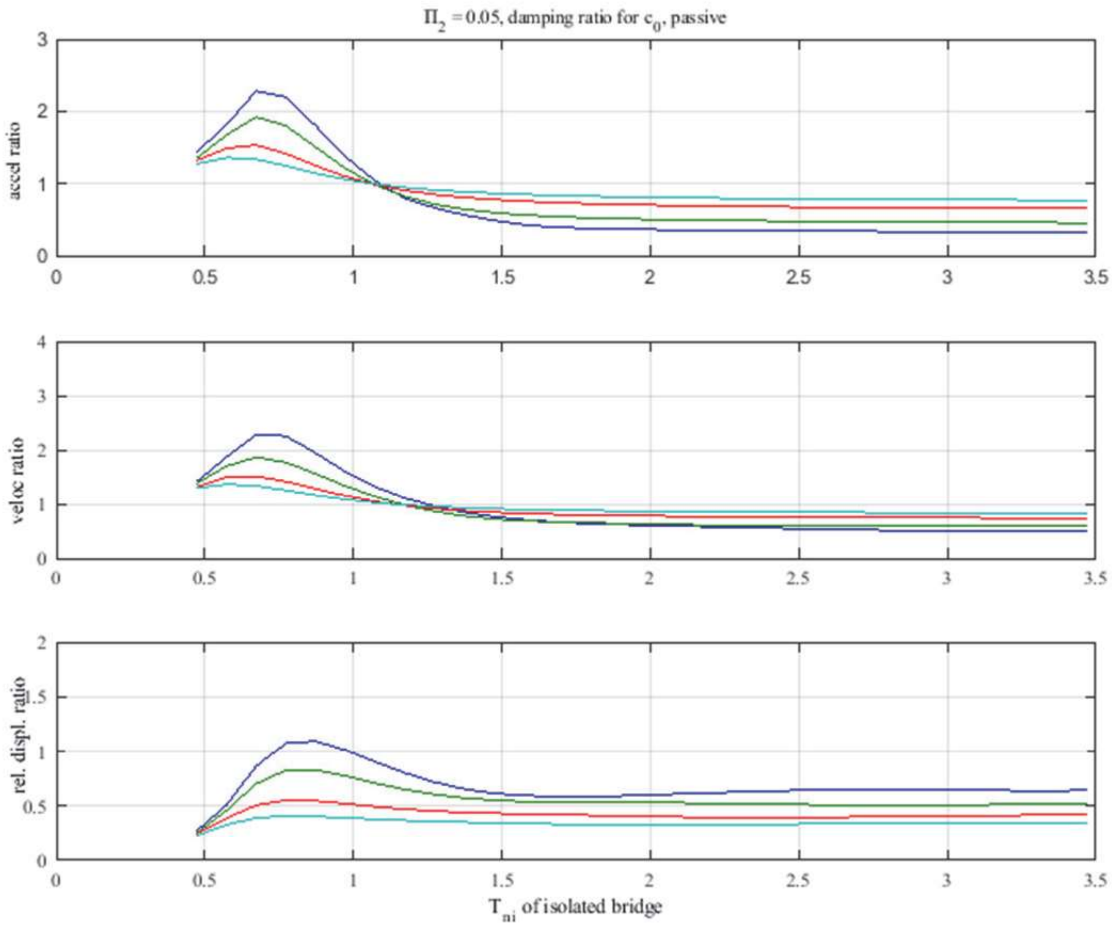
The dynamic analysis is performed for El Centro 1940 NS and Kobe EW excitations. The results for passive stiffness modification method implementation on the bridge deck system, with isolation bearing are given in Figure 4.

FIGURE 4
TRANSMISSIBILITY RATIOS FOR PASSIVE STIFFNESS MODIFICATION METHOD UNDER EL CENTRO NS EXCITATION



Frequency dependent acceleration, velocity and displacement response transmissibility ratios with respect to natural vibration periods, for different stiffness levels are shown in Figure 4 under the effect of El Centro NS earthquake. The curves in Figure 4 represent different damping ratios (J_i) as defined in the section of passive stiffness modificiation method. The blue line represents J_i =0.05 whereas the green line is J_i =0.1, the red line denotes J_i =0.20, and light bluw line stands for J_i =0.30. Π symbol in Fig. 4 is the critical damping ratio and %5. Transmissibility ratios of the bridge deck with passive stiffness modification method under the effect of El Centro EW earthquake are given in Figure 5 for different damping levels.

FIGURE 5
TRANSMISSIBILITY RATIOS FOR PASSIVE STIFFNESS MODIFICATION METHOD UNDER KOBE EW EXCITATION



The comparison for passive stiffness modification method and continuous control cases are carried out considering harmonic, and El Centro NS excitations. Kanai-Tajimi spectrum was used in generating the harmonic excitation. More information about this spectrum can be obtained in (Shinozuka & Deodatis, 1991; Yanik et al., 2016). For harmonic and El Centro NS excitations, transmissibility ratios with respect to frequency ratios, are shown in Figures 6 and 7, respectively (Yanik & Aldemir, 2018). In Figures 6 and 7 the blue line represents damping ratio of J_i=0.1, whereas the green line is J_i=0.2, the red line denotes J_i =0.3, and light blue line stands for J_i =0.4. Passive stiffness modification method implementation under the effect of harmonic excitation is given in Figure 8. The comments and conclusions that are obtained from all the curves presented in this section are given in the conclusion section of this paper.

FIGURE 6
TRANSMISSIBILITY RATIOS FOR CONTINUOUS CONTROL UNDER HARMONIC EXCITATION (YANIK & ALDEMIR, 2018)

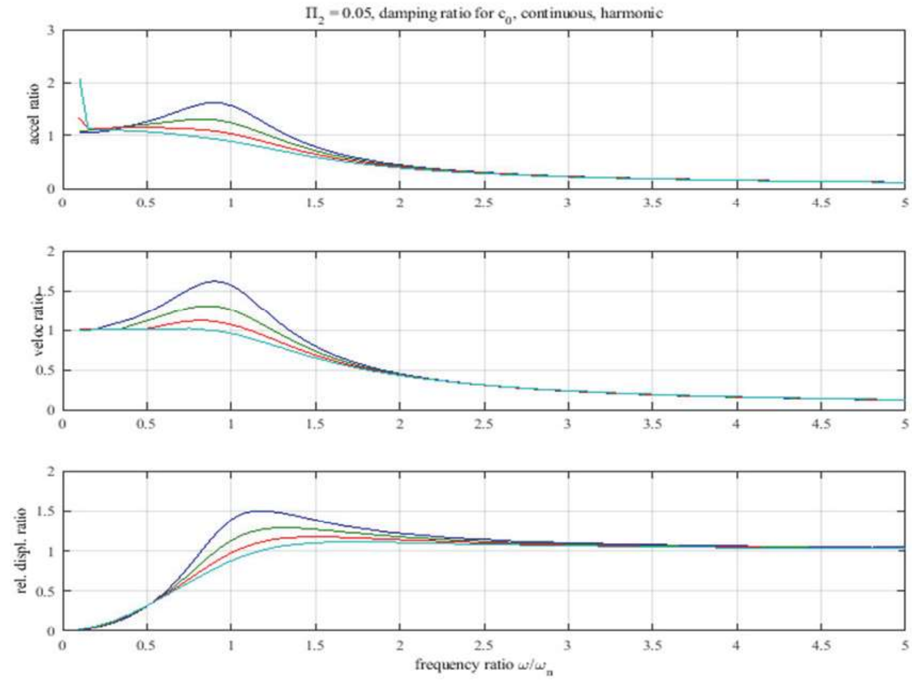


FIGURE 7
TRANSMISSIBILITY RATIOS FOR CONTINUOUS CONTROL UNDER EL CENTRO EXCITATION (YANIK & ALDEMIR, 2018)

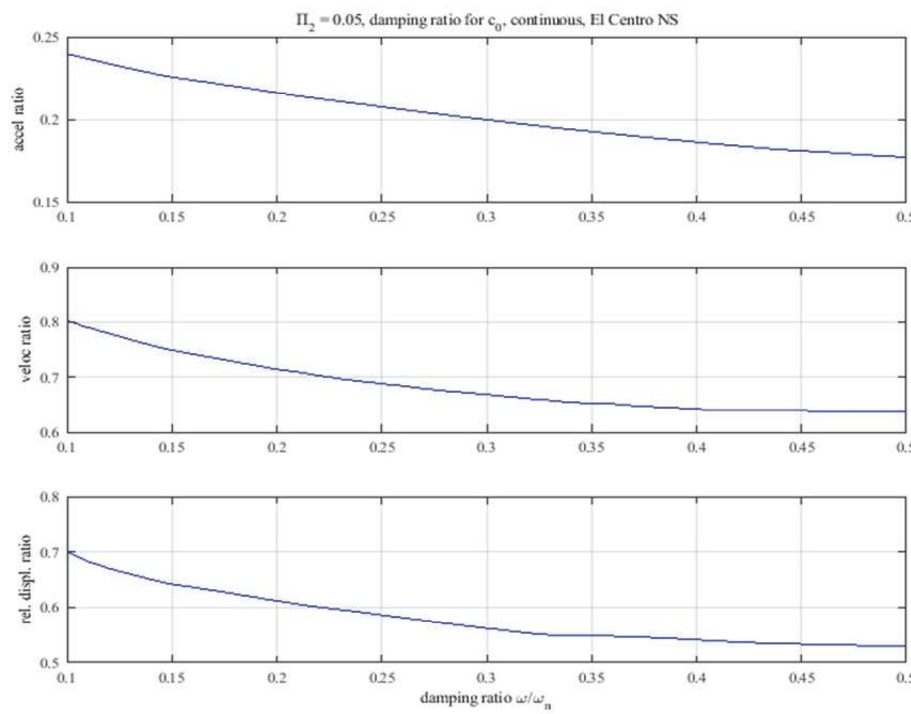
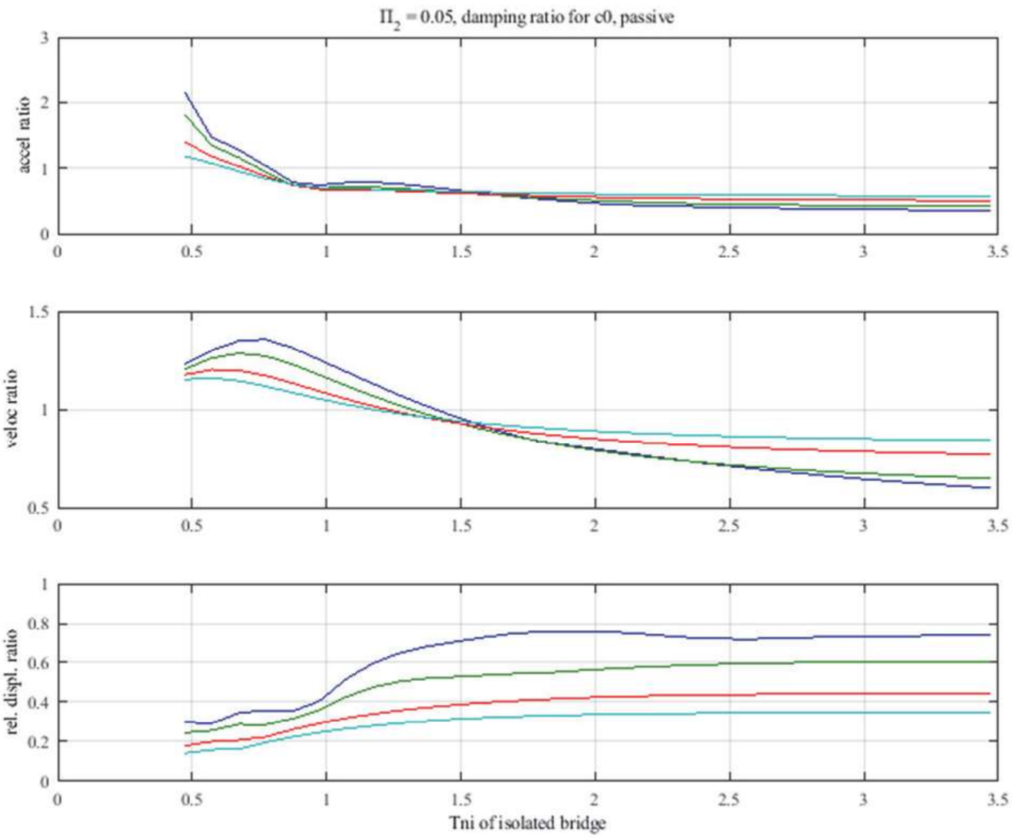


FIGURE 8
TRANSMISSIBILITY RATIOS FOR PASSIVE STIFFNESS MODIFICATION METHOD UNDER HARMONIC EXCITATION



CONCLUSION

In this paper it has been observed that in comparison with passive stiffness modification method, bang-bang control was not effective in reducing the bridge deck responses. Under the effect of harmonic and El Centro NS and Kobe EW excitations, passive stiffness modification method showed reasonable performance on reducing the uncontrolled seismic responses. It was indicated from transmissibility ratios that correspond to harmonic excitation, passive stiffness modification method implementation resulted in smaller relative displacement and velocity ratios than semi-active continuous control case. Besides, the acceleration ratios are at the same extent for passive stiffness modification method and continuous control. For El Centro earthquake, it has been observed that both control cases showed similar uncontrolled bridge deck response reduction performance. Passive stiffness modification method does not require any control device implementation to the structure, and it is more effective than a semi-active damper implementation case with bang-bang control. In addition, it is slightly more efficient than the semi-active damper case with continuous control.

REFERENCES

Aldemir, U. (2010). Predictive suboptimal semiactive control of earthquake response. *Structural Control and Health Monitoring*, 17(6), 654-674.

Behnam, M., & Khoshnoudian, T. (2012). Performance-based semi-active control algorithm for protecting base isolated buildings from near-fault earthquakes. *Earthquake Engineering and Engineering Vibration*, 11(1), 43-55.

Bitaraf, M., Ozbulut, O. E., Hurlebaus, S., & Barroso, L. (2010). Application of semi-active control strategies for seismic protection of buildings with MR dampers. *Engineering Structures*, 32(10), 3040-3047.

Braz-César, M., & Barros, R. (2018). Semi-active fuzzy based control system for vibration reduction of a sdof structure under seismic excitation. *Smart struct syst*, 21(4), 389-395.

Casciati, F., & Giuliano, F. (2009). Performance of multi-TMD in the towers of suspension bridges. *Journal of Vibration and Control*, 15(6), 821-847.

De Iuliis, M., Petti, L., & Palazzo, B. (2008). *Combined control strategy base isolation and tuned mass damper: an effectiveness analysis of its application to non-linear benchmark base isolated structure*. In The 14th world conference on earthquake engineering.

Gardoni, P., & Trejo, G. (2013). Probabilistic seismic demand models and fragility estimates for reinforced concrete bridges with base isolation. *Earthq. Struct.*, 4(5), 525-555.

Gavin, H. P., & Aldemir, U. (2005). Optimal control of earthquake response using semiactive isolation. *Journal of Engineering Mechanics*, 131(8), 769-776.

Gavin, H. P. (2014). *Vibrations of single degree of freedom systems. CEE 541. Structural Dynamics lecture notes.* Department of Civil and Environmental Engineering, Duke University.

Ghaffarzadeh, H., Dehrod, E. A., & Talebian, N. (2013). Semi-active fuzzy control for seismic response reduction of building frames using variable orifice dampers subjected to near-fault earthquakes. *Journal of Vibration and Control*, 19(13), 1980-1998.

Hashemi, S. M. A., Haji Kazemi, H., & Karamodin, A. (2016). Localized genetically optimized wavelet neural network for semi-active control of buildings subjected to earthquake. *Structural Control and Health Monitoring*, 23(8), 1074-1087.

Karnopp, D., Crosby, M. J., & Harwood, R. A. (1974). Vibration control using semi-active force generators. *Journal of engineering for industry*, 96(2), 619-626.

Li, Y., & Conte, J. P. (2018). Probabilistic performance-based optimum design of seismic isolation for a California high-speed rail prototype bridge. *Earthquake Engineering & Structural Dynamics*, 47(2), 497-514.

Lim, C. W., Chung, T. Y., & Moon, S. J. (2003). Adaptive bang–bang control for the vibration control of structures under earthquakes. *Earthquake engineering & structural dynamics*, 32(13), 1977-1994.

Mao, Y., Tremblay, R., Léger, P., & Li, J. (2017). New Simplified Method for Designing Seismically Isolated Highway Bridges with Massive Piers. *Journal of Bridge Engineering*, 22(8), 04017041.

Mohajer Rahbari, N., Farahmand Azar, B., Talatahari, S., & Safari, H. (2013). Semi-active direct control method for seismic alleviation of structures using MR dampers. *Structural Control and Health Monitoring*, 20(6), 1021-1042.

Renzi, E., & De Angelis, M. (2010). Semi-active continuous control of base-excited structures: An exploratory study. *Structural Control and Health Monitoring*, 17(5), 563-589.

Shinozuka, M., & Deodatis, G. (1991). Simulation of stochastic processes by spectral representation. *Applied Mechanics Reviews*, 44(4), 191-204.

Sun, C., & Nagarajaiah, S. (2014). Study on semi-active tuned mass damper with variable damping and stiffness under seismic excitations. *Structural Control and Health Monitoring*, 21(6), 890-906.

Tan, P., Huang, J. D., Chang, C. M., & Zhang, Y. (2017). Failure modes of a seismically isolated continuous girder bridge. *Engineering Failure Analysis*, 80, 57-78.

Wang, C., Zhao, J., Zhu, L., & Bao, Y. (2016). Effects of vertical excitation on the seismic performance of a seismically isolated bridge with sliding friction bearings. *Earthquake Engineering and Engineering Vibration*, 15(1), 187-196.

Xiang, P., & Nishitani, A. (2014). Seismic vibration control of building structures with multiple tuned mass damper floors integrated. *Earthquake Engineering & Structural Dynamics*, 43(6), 909-925.

Yan, G., Chen, F., & Wu, Y. (2016). A semi-active H∞ control strategy with application to the vibration suppression of nonlinear high-rise building under earthquake excitations. *SpringerPlus*, 5(1), 1053.

Yang, S., Mavroeidis, G. P., Ucak, A., & Tsopelas, P. (2017). Effect of ground motion filtering on the dynamic response of a seismically isolated bridge with and without fault crossing considerations. *Soil Dynamics and Earthquake Engineering*, 92, 183-191.

Yanik A., Aldemir U. (2018). A Numerical Study on Semi-Active Control of a Bridge Deck under Seismic Excitation. *World Academy of Science, Engineering and Technology, International Journal of Civil and Environmental Engineering*, 12 (8), 773-779.

Yanik, A., Aldemir, U., & Bakioglu, M. (2016). Seismic vibration control of three dimensional structures with a simple approach. *Journal of Vibration Engineering & Technologies*, 4(3), 235-247.

Yanik, A., Pinelli, J. P., & Gutierrez, H. (2013). *Control of a three-dimensional structure with magneto-rheological dampers*. In 11th international conference on vibration problems. Lisbon, Portugal.

Zhang, R. (2000). Seismic isolation and Supplemental energy dissipation (Book style with paper title and editor) in *Bridge Engineering Handbook*. W.F. Chen and L. Duan, Eds. Boca Raton: CRC Press, ch. 41.