A NEW APPROACH TO ROLLING-BASED SEISMIC ISOLATORS FOR LIGHT- TO MODERATE STRUCTURES

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ABSTRACT:

Based on the concept of reducing seismic demand rather than increasing the earthquake resistant capacity of structures, the use of base isolation has already been recognized as a very effective method to mitigate or reduce earthquake damage potential. Most of the current seismic isolators still have significant up to serious problems which impose restrictions to its proper use and the provided protection level especially for light- to moderate structures. In this study, an advanced rolling-based seismic isolator is proposed for such structures. This isolator is patented and incorporates isolation, energy dissipation, buffer and restoring force mechanisms in a single unit. Furthermore, the proposed isolator offers a significant wind resistance, relatively controllable bearing area, and a great range of horizontal flexibility. Moreover, issues related to construction costs, preventing structural torsion and uplift were thoroughly addressed. In this paper, the mathematical modeling of the proposed isolator as well as parameter identification and model validation is studied. Then, the proposed isolator is investigated via numerical simulation to examine its efficiency and performance level for light-moderate mass building structures excited by different actual ground motion records. The simulation results reveal that the proposed isolator device can isolate seismic transmitted energy effectively under different ground motion excitations while exhibiting robust performance for a wide range of structures.

KEYWORDS: Seismic Isolation, Hysteresis, Simulation, Bouc-Wen Model

1 INTRODUCTION

Historically, aseismic design has been based upon a combination of strength and ductility. For small, frequent seismic disturbances, the structure is expected to remain in the elastic range, with all stresses well below yield levels. However it is not reasonable to expect that a traditional structure will respond elastically when subjected to a major earthquake. Instead, an alternative design approach relies upon the inherent ductility of buildings to prevent catastrophic failure, while accepting a certain level of structural and nonstructural damage.

Situations exist in which the conventional (ductility based) design approach is not applicable when a structure must remain functional after an earthquake, as in the case of important structures (hospitals, police stations, etc.). For such cases, the structure may be designed with sufficient strength so that inelastic action is either prevented or is minimal; an approach that is very costly. Moreover, in such structures, special precautions need to be taken in safeguarding against damage or failure of important secondary systems, which are needed for continuing serviceability. Furthermore, increasing the elastic strength leads to higher floor accelerations that may cause more damage to the housed contents.

Designing earthquake-resistant low- to medium-rise structures is problematic in that their fundamental frequency of vibration is in the range of frequencies where earthquake energy is the strongest, so the building acts as an amplifier of the ground vibrations, with the floor accelerations increasing over the height of the building. Ultimately, the seismic design should reduce the accelerations in buildings to below the level of the ground accelerations. To do this the building must be flexible. Incorporating flexibility in a structural frame can cause problems, however: windows may fall out due to wind loads, partition walls may crack and floors may vibrate under foot. For a low- or medium-rise building, the necessary flexibility can only be achieved by using seismic isolation at the foundation level to shift the structural period away from the period range having the most of earthquake energy while leaving the structure to undergo almost a rigid body motion.

Although the first patents for seismic isolation were in the 1800's, and some patterns were claimed during the early 1900's, it was the 1970's before seismic isolation moved into the mainstream of structural engineering. Because bridges are more natural candidate for isolation than buildings, since they are often built with bearings separating the superstructure from the substructure, isolation was used on bridges from the early 1970's and buildings from the late 1970's.

The first bridge applications added energy dissipation to the flexibility already there. The lead rubber bearing (LRB) was invented in the 1970's, [7, 8, 6], and this allowed the flexibility and damping to be included in a single unit. About the same time, the first applications using rubber bearings for isolation were constructed. However, these had the drawback of little inherent damping and were not rigid enough to resist service loads such as wind, [10].

In the early 1980's developments in rubber technology lead to new rubber compounds which were termed high damping rubber (HDR), [9]. However, both LRB and HDR isolation systems still lack buffer, effective re-centering mechanism, as well as aptitude for low mass structures. In addition, they undergo bearing area reduction as moved laterally which imposes restrictions on the height/width and deformation/height ratios.

Sliding bearings were not used alone as the isolation systems because, although they have high levels of damping, they do not have a restoring force mechanism nor a buffer. Owing to that, a structure on sliding bearings would likely end up in a different location after an earthquake and continue to dislocate under aftershocks. However, the development of the friction pendulum system (FPS), [12], shaped the sliding bearings into a spherical surface, overcoming this major disadvantage of sliding bearings. As the FPS moves laterally it was lifted vertically. This provide a gravitational restoring force but, unfortunately, on the account of structural uplift. Moreover, the high cost of the articulated slider (in FPS) hinder its economic use for light buildings. In real terms, this usually makes the isolators more expensive as a proportion of first cost for light buildings. Another drawback is the increase of the sliding friction coefficient as sliding velocity increases (a characteristic of Teflon, the interface liner).

Although many other systems have been promulgated, based on rollers, springs, cables etc., the market for base isolation now is mainly distributed among variations of LRBs, HDR bearings, flat sliding bearings and FPS. There have been systems proposed to isolate light buildings. However, the fact remains that there are few instances of successful isolation of light structures.

In this study, an attempt to innovate a new, practical, economic, and efficient seismic isolator is presented to overcome important drawbacks of the present-day isolation systems while keeping their main advantages. Such isolator is designed principally to safeguard building structures of light- to medium masses from seismic threat.

2 THE PROPOSED ISOLATOR

An innovative rolling-based seismic isolation device is proposed by the authors for the intention of protecting light and moderate mass structures from seismic hazards. The proposed isolator is globally protected by a patent number P200802043, Spanish Office of Patents and Marks. The main components of the new system are depicted in Figure 2.1. In this study, an example of the patented isolator is designed to support up to 60 tons and provides multidirectional horizontal motion. The isolator's motion is rolling based, in order to reflect a major part of the seismic force. It is mainly made up of a stiff rolling body 1 of certain configurations placed between two stiff circular plates 2 & 3, fixed to the superstructure and substructures, respectively. The contact between these three parts takes place through less stiff plates 4 & 5 as shown. Metallic yield dampers 6 are designed and arranged around the perimeter to provide maximum dynamic performance. The selected forms and arrangement of the components allows for incorporating isolation, energy dissipation, buffer and restoring force mechanisms in a single unit. Furthermore, the proposed isolator offers relatively controllable bearing area and a great range of horizontal flexibility. Moreover, issues related to construction costs, preventing torsion are thoroughly covered to achieve effective and economic isolation.

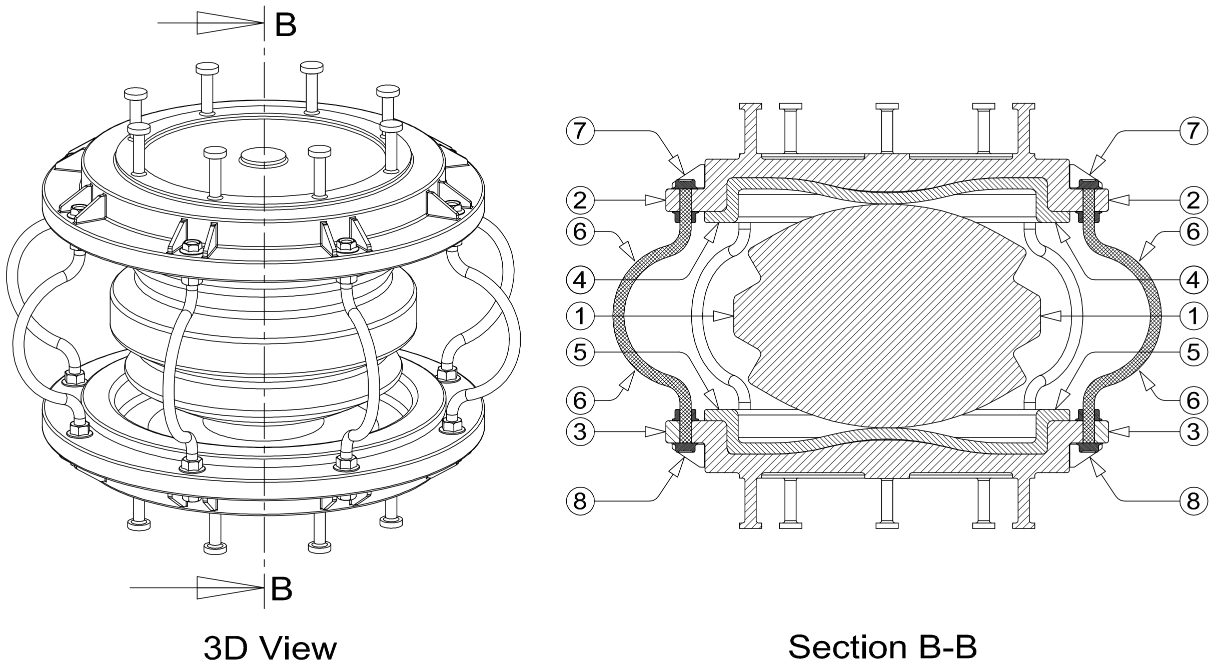

Figure 2.1: (***Left***) 3D View of the Proposed Isolation device; (***Right***) Half Sectional Elevation of the Proposed Isolation device.

3 NUMERICAL SIMULATION

A real-scale bearing of the proposed isolator type is designed, modeled and tested in a machine-like environment by means of the general-purpose finite element analysis software ANSYS *Multiphysics*, [1], product that is employed to capture the whole sources of nonlinearity arising after exciting the isolator. A profound and extensive series of numerically simulated real-scale tests of the proposed seismic isolator was carried out with the objective of fully identifying its mechanical characteristics. These tests include subjecting the bearing to simultaneous generalized horizontal and vertical dynamic loading considering variable axial load as well as variable frequency tests.

4 MODELING, IDENTIFICATION AND VALIDATION

Due to the hereditary nonlinear hysteretic nature of the restoring force offered by seismic isolators, the proposed isolator is expected to exhibit the same behavior but due to the hysteretic energy dissipation mechanism. Accordingly and to better characterize the proposed isolator analytically, the Bouc-Wen hysteretic model, [11] is chosen to represent the time dependent nature of such isolator and to better match its dynamic behavior. The so called *normalized* form of the model proposed by [4] is utilized in this study to capture two advantages: (i) the warranty of a unique input/output behavior for each set of parameters which is ideal for identification purpose; (ii) elimination of parameter redundancy. The restoring force F_b using normalized Bouc-Wen model is expressed as

$$F_\mathrm{b} = \kappa_x\, x(t) + \kappa_w\, w(t), \tag{4.1}$$

$$\dot{w}(t) = \rho(\dot{x} - \sigma|\dot{x}||w|^{n-1}w - (\sigma - 1)\dot{x}|w|^n), \tag{4.2}$$

where κ_x, κ_w, ρ, σ and n are the shape controlling parameters of the hysteresis loop; and $w(t)$ is an auxiliary variable. Furthermore, and to guarantee BIBO stability, passivity, and consistency with physical asymptotic motion, the lower value of the parameter σ is limited to 0.50.

It is common practice to approximate the nonlinear behavior with an *equivalent linear damping and stiffness* and not conduct a nonlinear analysis. The major reason for this approximation is that in linear analysis using mode superposition or response spectrum analysis, the linear stiffness and linear viscous damping can be considered in an exact manner. As per Uniform Building Code [2] and International Building Code [3], the non-linear force-deformation characteristic of the isolator can be replaced by an equivalent linear model through effective elastic stiffness and effective viscous damping. The linear force developed in the isolation system can be expressed as

$$F_{\mathrm{b}} = k_{\mathrm{eff}}\, x_b + c_{\mathrm{eff}}\, \dot{x}_b, \tag{4.3}$$

where k_{eff} is the effective stiffness; $c_{\mathrm{eff}} = 2\beta_{\mathrm{eff}}\, M_{\mathrm{t}}\, \omega_{\mathrm{eff}}$ is the effective viscous damping constant; β_{eff} is a presumed damping ratio; $\omega_{\mathrm{eff}} = 2\pi/T_{\mathrm{eff}}$ is the effective isolation frequency; and $T_{\mathrm{eff}} = 2\pi\sqrt{M_{\mathrm{t}}/k_{\mathrm{eff}}}$ is the effective isolation period.

The normalized Bouc-Wen form provides an exact and explicit expression for the hysteretic limit cycle, [4]. Therefore, by using an input signal $x(t)$ as a periodic T-wave along with analytic description of limit cycle, a robust parametric nonlinear, nonrecursive identification method or the normalized Bouc-Wen model was presented, [5]. This method provides exact values of the model parameters in the absence of disturbances, and gives a guaranteed relative error between the estimated parameters and the true ones in the presence of the perturbations. Hence, this identification method is used in this paper.

Subsequently, the values of the identified parameters of the normalized Bouc-Wen are: $\kappa_{\mathrm{x}} = 19.3147$; $\kappa_{\mathrm{w}} = 16.2265$; $\rho = 55.6406$; $\sigma = 1.0223$; $n = 2.1618$. An efficiency measure of the identified parameters is carried out through the model validation.

To check the validity of the identified parameters, both periodic and actual random seismic displacement (El-Centro) input signals are input into the ANSYS, the Bouc-Wen, and the equivalent linear models. Then, the discrepancy between the measured and predicted outputs, F_{m} and F_{b}, is quantified using the L_1 and L_∞-norms and the corresponding relative errors ε:

$$||f||_1 = \int_0^{T_e} |f(t)|\,\mathrm{d}\,t\,; \quad ||f||_\infty = \max_{t\in[0,T_e]} |f(t)|\,; \quad \varepsilon_{1,\infty} = \frac{||F_{\mathrm{m}} - F_{\mathrm{b}}||_{1,\infty}}{||F_{\mathrm{m}}||_{1,\infty}}\,. \tag{4.4}$$

The relative error ε_1 quantifies the ratio of the bounded area between the output curves to the area of the measured force along the excitation duration T_e, while ε_∞ measures the relative deviation of the peak force.

Figure 4.1(a) depicts the input displacement of El-Centro earthquake record to the three models. As shown in Figure 4.1(b) and the relative errors ε_1 and ε_∞, the simple equivalent linear model is only suitable for response spectrum analysis as it well predicts the peak response with small error ($\varepsilon_\infty = 1.45\%$). Whereas the hysteretic Bouc-Wen model can be seen as a very powerful replacement of the experimental prototype for more case studies using both response spectrum and time history analysis. This is asserted by the relatively small error percentages ($\varepsilon_1 = 5.70\%$ and $\varepsilon_\infty = 3.15\%$) and the close match of both measured and predicted output curves observed in Figure 4.1(c).

5 IMPLEMENTATION IN BUILDINGS

An idealized 5DOFs (including the suspended base) base-isolated concrete moment-resisting frame is considered in the present study. This structure is modeled as a shear type structure mounted on isolation systems with one lateral degree-of-freedom DOF at each floor. Following assumptions are made for the structural system under consideration: (1) the superstructure remains within the elastic limit during the earthquake excitation; (2) the floors are assumed rigid in its own plane and the mass is lumped at each floor level; (3) the columns are inextensible and weightless providing the lateral stiffness; (4) the system is subjected to single horizontal component of the earthquake ground motion; (5) the effects of soil–structure interaction are not taken into consideration.

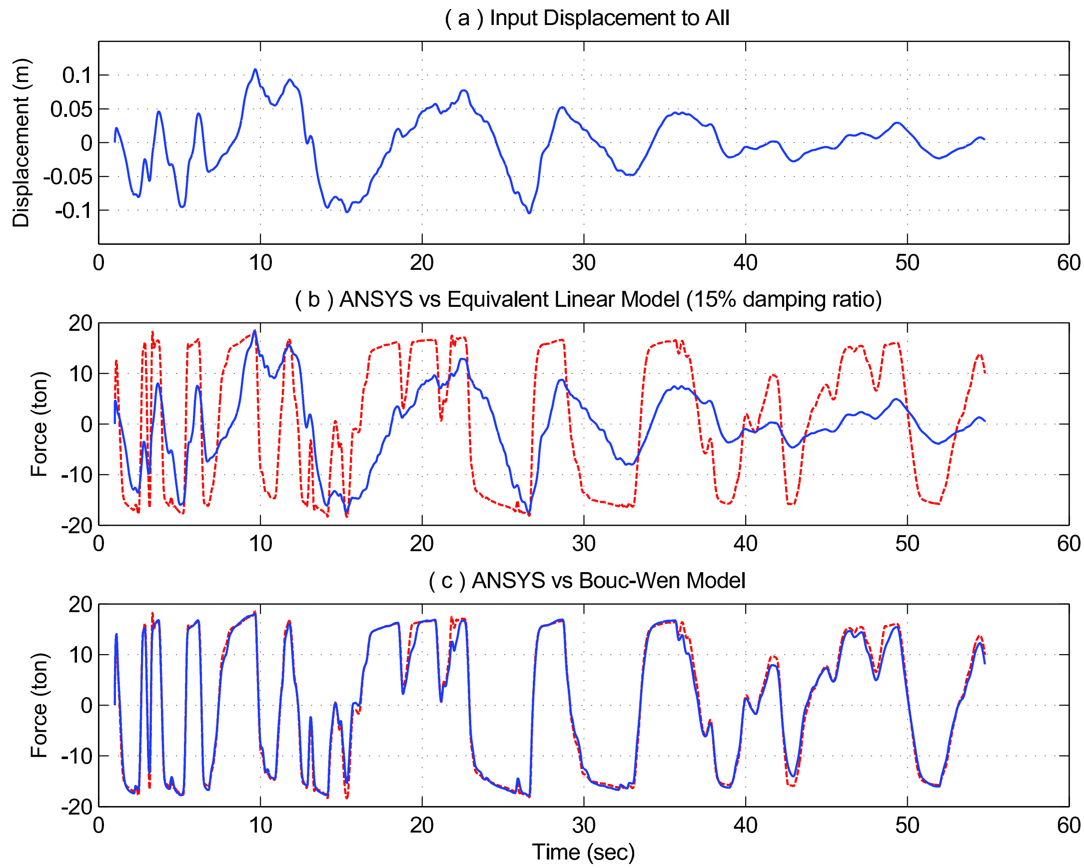

Figure 4.1: **(a)** Input displacement into ANSYS, Equivalent Linear and Bouc-Wen Models; **(b)** ANSYS output vs Equivalent Linear Model Output, Relative Errors $\varepsilon_1 = 51.60\%$ and $\varepsilon_\infty = 1.45\%$, respectively; **(c)** ANSYS output vs Bouc-Wen Model Output, Relative Error $\varepsilon_1 = 5.70\%$ and $\varepsilon_\infty = 3.15\%$, respectively. ANSYS Output (- - -), Models Output (——) .

For this system, the governing equations of motion are obtained by considering the equilibrium of forces at the location of each DOF. The equations of motion for the superstructure under earthquake ground acceleration are expressed in the matrix form as

$$[M_\mathrm{s}]\{\ddot{x}_\mathrm{s}\} + [C_\mathrm{s}]\{\dot{x}_\mathrm{s}\} + [K_\mathrm{s}]\{x_\mathrm{s}\} = -[M_\mathrm{s}]\{r\}(\ddot{x}_\mathrm{b} + \ddot{x}_\mathrm{g}), \tag{5.1}$$

where $[M_\mathrm{s}]$, $[C_\mathrm{s}]$ and $[K_\mathrm{s}]$ are the mass, damping, and stiffness matrices of the superstructure, respectively; $\{x_\mathrm{s}\} = \{x_1, x_2, \dots, x_\mathrm{N}\}^T$, $\{\dot{x}_\mathrm{s}\}$ and $\{\ddot{x}_\mathrm{s}\}$ the unknown relative floor displacement, velocity and acceleration vectors, respectively; $\{\ddot{x}_\mathrm{b}\}$ and $\{\ddot{x}_\mathrm{g}\}$ are the relative acceleration of base mass and earthquake ground acceleration, respectively; and $\{r\}$ is the vector of influence coefficients.

The corresponding equation of motion for the base mass under earthquake ground acceleration is expressed by

$$m_\mathrm{b}\,\ddot{x}_\mathrm{b} - c_1\,\dot{x}_1 - k_1\,x_1 + \eta F_\mathrm{b} = -m_\mathrm{b}\,\ddot{x}_\mathrm{g}, \tag{5.2}$$

where m_b and F_b are the base mass and restoring force developed in the isolation system, respectively; c_1 and k_1 are the first story damping and stiffness, respectively; and η is the number of isolators. The restoring force developed in the isolation system, F_b is modeled alternatively using the normalized Bouc-Wen hysteretic model (4.1), (4.2) and the equivalent linear one (4.3).

6 RESULTS AND DISCUSSION

In this study, the supporting structure is chosen as a 5DOFs (including the suspended base) reinforced concrete moment resisting frame modeled as a shear building, where all the five vibrational modes are included in the analysis. The modal periods of the designed structure are 0.214s, 0.075s, 0.050s, and 0.042s, where the damping ratio for all modes is fixed to 2% of the critical and a mass participation factor of 0.898 for the fundamental mode in the horizontal direction.

To achieve effective isolation, it is necessary to increase the period of the isolated structure to shift the design acceleration to lower values. Accordingly, the considered example structure has a fundamental period of 0.214s and 3.400s in non-isolated and isolated conditions, respectively. This can guarantee the elimination of a great deal of seismic forces affecting the structure. The isolation bearing in this example is designed to remain stiff under the expected wind loads that are taken as 0.120 ton/m^2 including compression and suction. Just after exceeding that limit it starts yielding.

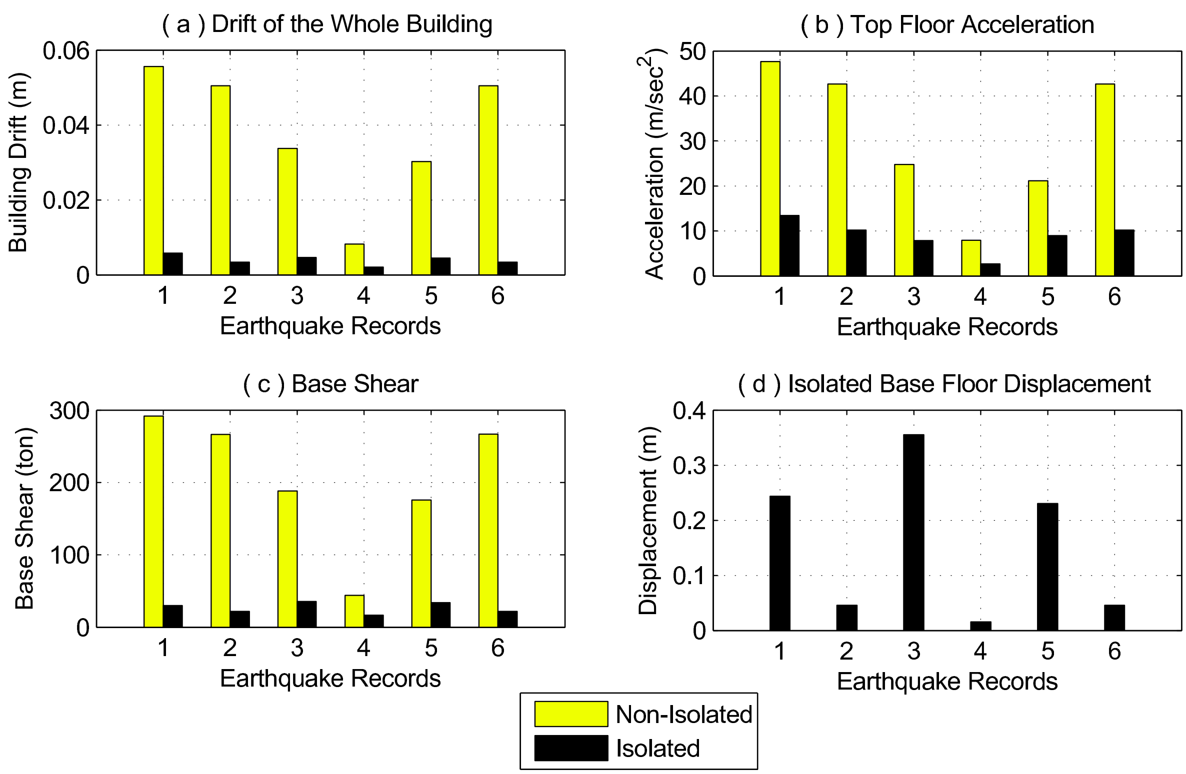

Figure 6.1: **(a)** Drift of the Whole Building for 6 Earthquake Records (i.e. relative lateral displacement between top and base floors); **(b)** Acceleration of the Top Floor; **(c)** Building Base Shear, (isolated vs non-isolated); **(d)** Base Displacement of the Isolated Building; The 6 Earthquake Records are: (1) San Fernando, (2) Northridge, (3) Kobe, (4) Parkfield, (5) New Hall-1, (6) Santa Monica-2.

The dynamic analysis is repeated for 33 different actual ground motion records while only some popular records are selected in this paper due to space constraints. This is to assure that all the significant modes are excited and to better decide the isolator efficiency and, moreover, to check the isolator performance and the provided protection level. Furthermore, and in order to achieve more realistic results, the structural and dynamic characteristics of the building, as well as the real nonlinear parameter of the isolator are well considered in the accomplished full nonlinear analysis to capture all nonlinearities arising from exciting the proposed hysteretic isolation device.

Figure 6.1 shows the ability of the proposed isolator to reflect a great proportion of the seismic force affecting the example structure. Based on the peak L_∞ norm, the whole building drift expressed as the relative displacement

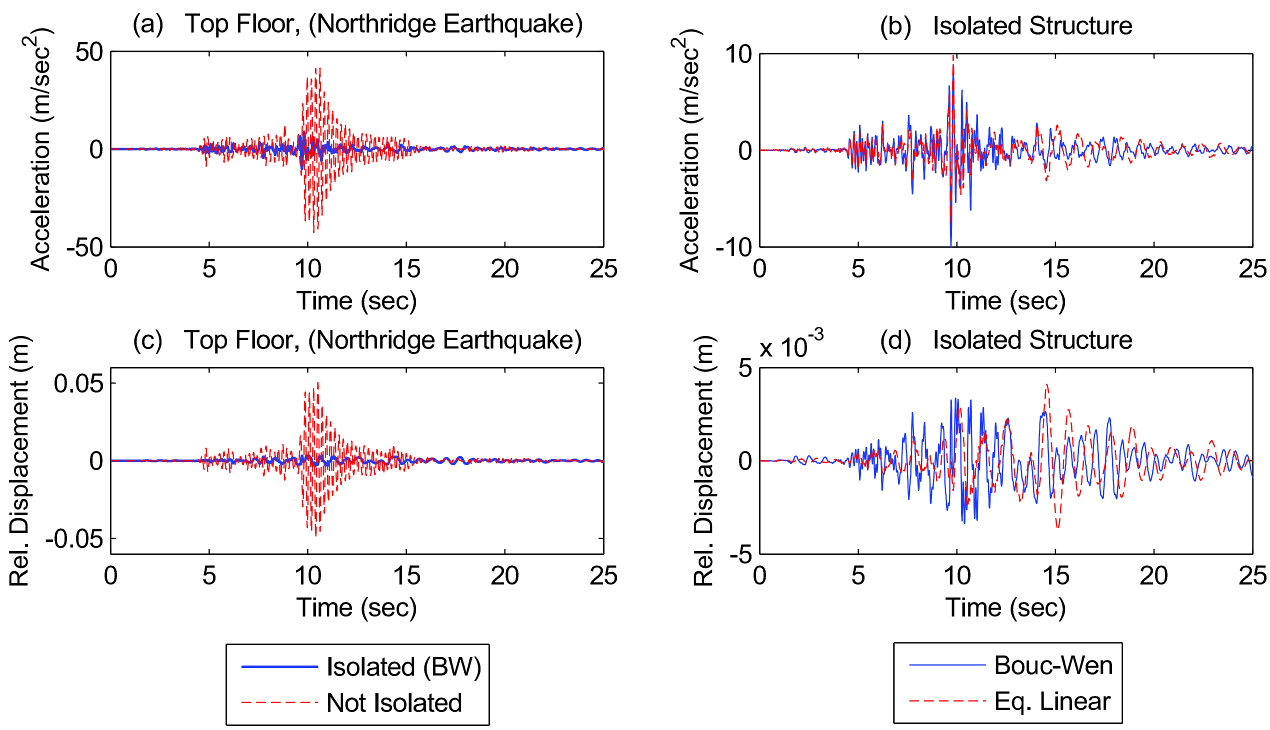

Figure 6.2: **(a)** Top Floor Acceleration, Isolated vs not Isolated; **(b)** The Top Floor Acceleration Using the Bouc-Wen Hysteretic Model vs the Equivalent Linear one, in an Isolated Structure, the variation = $\pm 1\%$; **(c)** Top Floor Relative Displacement, Isolated vs not Isolated; **(d)** The Top Floor Relative Displacement Using the Bouc-Wen Hysteretic Model vs the Equivalent Linear one, in an Isolated Structure, the variation = $\pm 3\%$ (Northridge Earthquake).

between the topmost floor and the base floor is reduced significantly as shown by Figure 6.1(a). It is evident that utilizing the proposed isolator dropped off up to 93% of the whole building drift in the case of Northridge and Santa-Monica-2 earthquakes, and likewise, the reduction in top floor acceleration shown by Figure 6.1(b) attained 76% for the same seismic records.

Considering the structural base shear, the effect of rolling mechanism (upon which the proposed isolator is based on) in cutting off the seismic load path before being transmitted into the structure becomes apparent. Up to 92% of the base shear is reflected as demonstrated by Figure 6.1(c) in the case of Northridge and Santa-Monica-2 earthquakes. However, this decrease in both acceleration and drift as well as structural base shear is accompanied with some lateral displacement due to rolling. As shown in Figure 6.1(d), these rolling displacements are in a reasonable range and are small if compared to the building dimensions. Furthermore, the built-in restoring and damping mechanisms allow for efficient restoration of the isolated equipments and damping. What's more, the inherent buffer prevents any undesirable excessive displacements in the lateral direction.

To investigate the dynamic response of the isolated structure over the full time history of excitation, Figures 6.2(a and c) show the efficiency of using the proposed isolator on reducing acceleration of the top floor and the whole building drift, respectively. Figures 6.2(b and d) indicate the possibility of selecting the equivalent linear model to predict the dynamic behavior of the proposed isolator if the comparison is based on the L_∞ norm with reasonable accuracy.

7 CONCLUSIONS

In this study a new approach of base isolation systems has been introduced. The proposed isolation bearing is an attempt towards the ideal seismic isolation of light- to moderate structures. The performance of the proposed device in isolating a 5DOFs structure has been studied using a variety of actual seismic records. The numerical investigation showed the effectiveness of the device in the reduction of the building's acceleration, drift, and base shear for all earthquakes under consideration to great extents in some cases while keeping reasonable base floor motion. Thus, the proposed isolator is a robust isolation device that is very effective in controlling the response of seismic excited light- to moderate structures.

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