Shake Table Tests of a Passive-Hybrid Isolation System

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ABSTRACT: The seismic vulnerability assessment of existing structures is becoming of paramount importance in resilient social communities. Seismic isolation(SI) method is proposed as an alternative design /retrofitting technique to conventional earthquake resistant methods. Basicly, SI systems decouple the damaging effects of earthquakes from the structural system by concentrating inelastic deformations at isolation level. Primary objective of this research study is to investigate the effectiveness of the passive-hybrid isolation system for a ¼ scaled three-storey, mass concentric, steel structure. Passive-hybrid isolation system is a combination of high damping rubber bearings (HDRB) and polythetrafluoroethylene (PTFE) sliding bearings. Incorporation of PTFE sliding bearing is associated with the cost issues and vertical load carrying capacity of the isolation system while the HDRB provides the restoring capability of the combined system. Calibration of the finite element model of the test mock-up is done with the help of the shake table tests. Comparative analyses are conducted, under numerical and experimental point of view, to assess the effectiveness and performance of passive-hybrid isolation system in terms drift, amplification of accelerations and energy dissipation. Base shear value of the fixed-based structure is resulted more than 4 times of the seismically isolated cases. Interstorey drifts and amplification of accelerations at floor levels are reduced due to both period shifts and inherent damping of the isolation system of the ¼ scaled steel structure in all test setups.

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1. INTRODUCTION

Traditional seismic design of structures relies on the dissipation of earthquake-induced energy through nonlinear response in selected structural elements. Inelastic actions in structural components are associated with damage which might lead to casualties, direct and\or indirect economic losses. Conventional construction can cause very high floor accelerations in stiff buildings and large interstory drifts in flexible structures. As a consequence of these two factors it is hard to ensure the safety of the building components and contents by the current state of art in construction. Seismic isolation technology was introduced as an alternative design and retrofitting technique to mitigate the effects of earthquakes on structures with its practice-oriented applications. Apart from the stated drawbacks of conventional design methods, estimation of damage level and preservation of functionality are associated with uncertainties. It is essential to keep hospitals, telecommunication centers, fire and police stations operational after moderate or major earthquakes. In this sense, code-based performance limits at operational level can be satisfied by the installation of properly designed seismic isolation systems. Seismic isolation systems generally decouple the superstructure from the damaging effects of earthquakes by concentrating the damage at isolation level (Naeim and Kelly, 1999). The elongation of the fundamental period can substantially reduce the accelerations that can develop in the superstructure. Excessive and permanent deformations at isolation levels are limited by the inherent damping and restoring force capability. Sliding (Flat and Curved Surface Slider Bearings) and elastomeric (Lead Rubber, Natural Rubber and High Damping Rubber Bearings, HDRB) bearings are two most commonly used isolation devices in practice.

Design procedures of seismically isolated structures are implemented into contemporary seismic provisions (FEMA 273, FEMA 356, NEHRP 2003, IBC2012, AASHTO 2010) to ensure an acceptable performance during the entire life of the structure under servicebility conditions and seismic actions. Methods of analysis include single-mode, multi-mode and response history analysis (RHA). Simplified methods, provide reference values and the response history analysis method incorporates the nonlinear representations of isolators. RHA is defined as the most accurate method for the analysis of seismically isolated bridges.

Most of the seismic(base) isolation applications in Turkey are related to enhance the earthquake resistance of bridges. In contrast, building owners were being hesitant to apply this mature technology to structures regarding to the lack of knowledge about seismic isolation systems. Proper applications of seismic isolation systems do not only mitigate the seismic risk but also provide profits to building owners by enabling the cost-effective construction. Widespread applications of seismic isolation technology can be facilitated by prescriptive seismic design guidelines. As per the draft Turkish Code (TASI, 2008), the materials used in the manufacture of HDRB elastomeric isolation units shall conform to the requirements of the Chapter 8.2.2 of the European Standard (prEN 15129-2007) and the design and control of the isolation units will be based on “European Standard EN 1337-3:2005: Structural Bearings - Elastomeric Bearings” (Erdik, 2007). The proposed earthquake protection system consists of sliding and elastomeric isolation units. Flat sliding bearing characteristics are purely based on the coefficient of friction of the sliding surface, regardless of the ground motion characteristics.

Previous shake table tests in KOERI were based on the protection of buildings by installation of Friction Pendulum (FP) type of isolation system (Uçkan et al., 2005). In contrast, passive-hybrid isolation system aims to utilize the advantages of both elastomeric and sliding type of isolator units. Main objective of this study is to assess the effectiveness and performance of the passive-hybrid isolation systems through numerical analysis and shake table tests. Testing campaign took place in KOERI shake table laboratory. Performance assessments were carried out in terms interstorey drifts, amplification of accelerations and amount of energy dissipation.

2. TEST SETUP AND INSTRUMENTATION

The test set-up consists of a 3-story steel structure and passive hybrid isolation system. The mock-up is placed on the uniaxial hydraulic shake table of KOERI. The ANCO R-148 is a uniaxial horizontal vibration shake table driven by a servo-hydraulic actuator. The table was designed by ANCO Engineers and it is capable of carrying a maximum 10-ton payload on the 3 m x 3 m table, and it is capable of shaking the maximum payload with 2 g acceleration (i.e. two times the acceleration of gravity in the horizontal direction). The shake table is ideally suited to seismic applications, where the hydraulic actuator can produce a stroke of +/- 12 cm (24 cm total stroke). The actuator has a 3-stage servo-valve controlled by an analog inner-loop control system (displacement based), and a digital outer-loop control system (acceleration feedback based). The structural model has a length scale of 4 and, time scale of 2, weighting 6.5 tons (isolated including base) and fundamental period of fixed supported system is 0.21 sec.

2.1. The Passive-Hybrid Isolation System

Earthquake protection system is a combination of two HDRBs and four flat sliding bearings (PTFE). Two different isolation systems were tested on the basis of variation of shear modulus of HDRBs. Elastomeric bearings provided the restoring capability of the combined system. Flat sliding bearings were located below corner columns and high damping rubber bearings were mounted below center columns. Location of isolation devices intentionally configured as shown in Figure 1. Flat sliding isolators are typically located in relatively lighter part of the structure where earthquake-overturning loads are negligible. However, in practice different configurations must be elaborated for the stability and cost-effectiveness of the system. Rigid base slab was used to transmit the vertical load uniformly to the isolation devices. Mechanical properties of HDRB and Flat Sliding Bearings are provided by FIP Industrial.

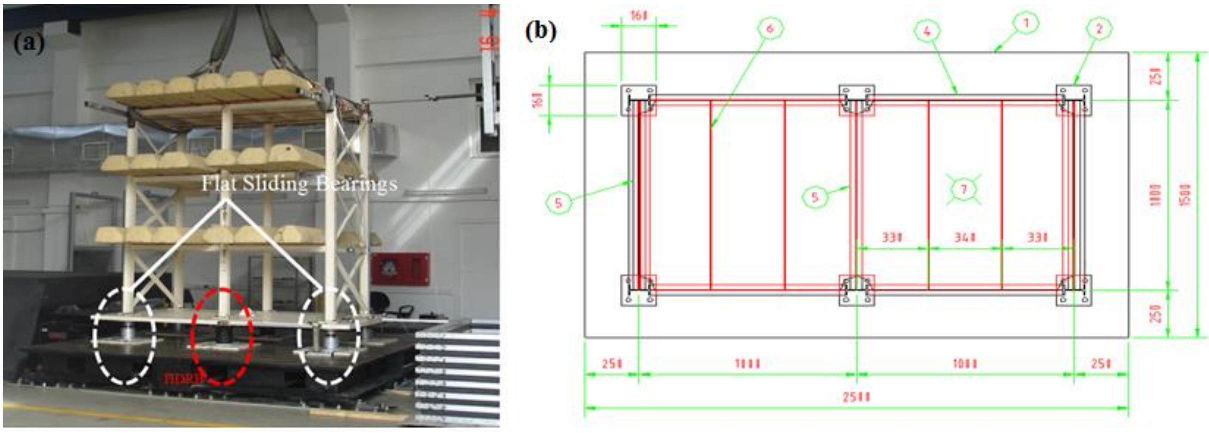

Figure 1. (a) Configuration of Passive-Hybrid Isolation System (b) Plan view of the base slab and floor levels

2.1.1. Governing Equations of High Damping Rubber Bearings

High damping rubber bearings have varying inherent damping properties with respect to the compound of the isolators. Damping properties of high damping rubber bearings can vary in the range of 0.1-0.2 due to chemical additives in the manufacturing process. Yield displacement (Dy) of HDRB is calculated with respect to the total rubber thickness where Dy is assumed to have values between 0.05-0.1 of the total rubber thickness (FEMA 356).

$$Dy = 0.05 \sim 0.1 \sum t \tag{1}$$

Post-yield stiffness ratio of HDRB is computed as follows in Equation (2)

$$kp = \frac{GA}{\sum t} \tag{2}$$

kp = post yield stiffness
G = shear modulus
A = bonded area
$\sum t$ = total rubber thickness

Yield force is calculated with the help of characteristic strength parameter of the isolation system in the design considerations. Calculation of characteristic strength is shown in Equation(3).

$$Q = \frac{\pi\beta_{eff} k_p D^2}{(2-\pi\beta_{eff})D - 2D_y} \quad (3)$$

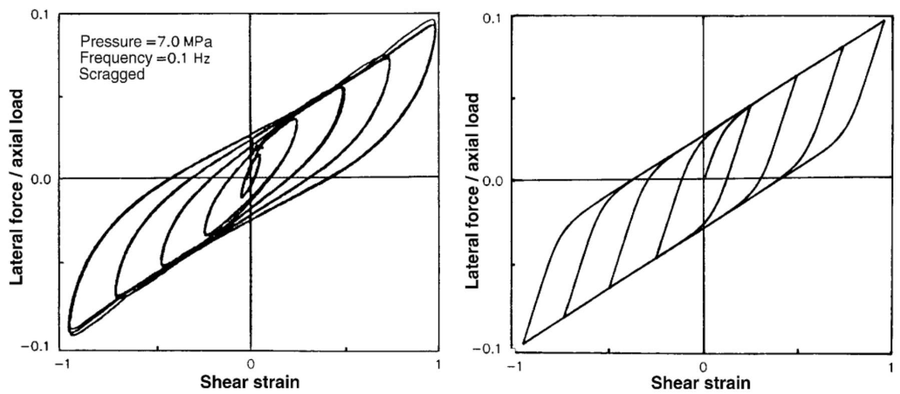

Figure 2. (a)Force-Displacement Loops of a HDRB and (b) mathematical model of HDRB (FEMA 356)

2.1.2. Governing Equation of Flat Sliding Bearings

Characteristics of sliding bearings depend on the velocity and bearing pressure that acts on the sliding isolator.

Calculation of coefficient of friction, μ_s is proposed by Constantinou., et al. (1991)

$$\mu s = f\,\max - (f\,\max - f\,\min)\exp(-a|\dot{U}|) \quad (4)$$

where a denotes the rate parameter.

3. DATA ACQUISITION AND CONTROL SYSTEM

Simulation of input motions and measurements were performed by Data Physics 550 WIN digital data control and acquisition system. Accelerometers were installed to floor levels, base slab and on top of the shake table. LVDTs were used to measure the deformations of the structure at three different levels in the longitudinal direction. Locations of accelerometers and LVDTs are shown in Figure 2.

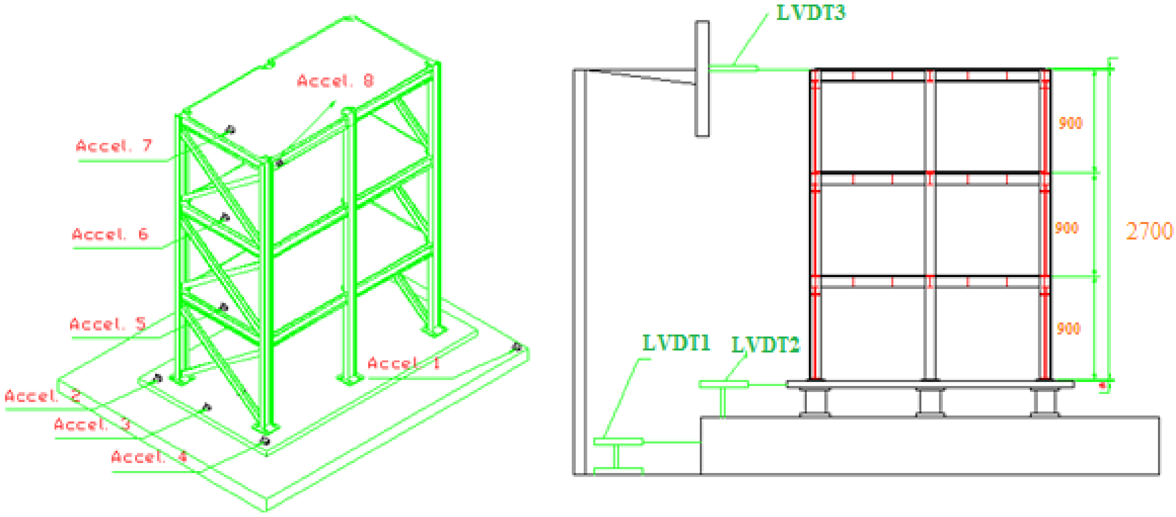

Figure 3. Locations of LVDTs to measure translational displacements

4. TEST RESULTS

Similitude rules are applied for the test setup as mentioned in Section 2. HDRBs named as SI-N 150/136 , SI-S 150/136 on the basis of its compound. The latter HDR bearing has a softer compound and its shear modulus value is 0.4 MPa. Period of the first and second isolated systems are shifted to 0.6s and 1.27s, respectively. Scaled El Centro records and harmonic motions with varying frequency and amplitude are applied as input signals. Amplitudes of El Centro records are gradually increased to investigate the effectiveness of the hybrid passive isolation systems (Figure 4, Figure 5(b)). Linear scale factors were applied to obtain PGA values between 0.06g and 0.56g. Inherent damping characteristics of the combined system under different harmonic motions are shown in Figure 5(a). Transfer functions of two isolated cases are derived from experimental results (Figure 6).

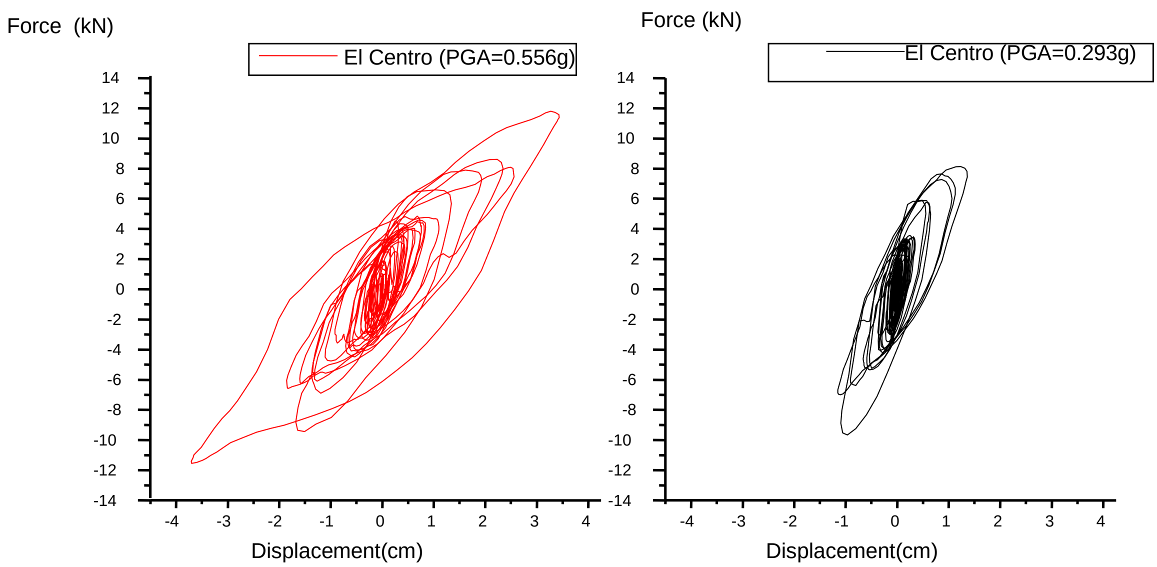

Figure 4. Force-Displacement Loops of the first test setup with normal compound HDRBs under two earthquake different excitations with PGA values of 0.556g and 0.293g

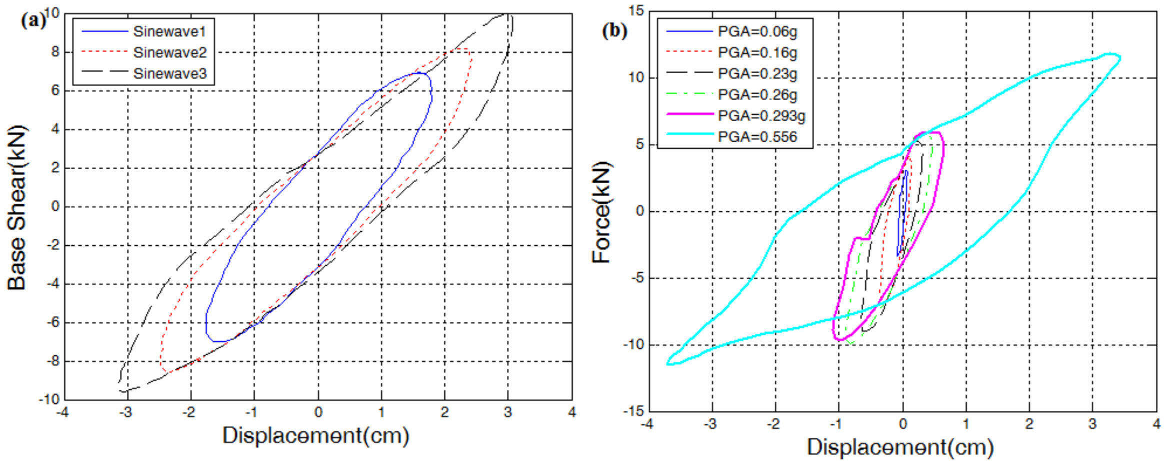

Figure 5. (a) Response of the passive hybrid isolation system under harmonic motions (b) Response of the passive hybrid isolation system under amplitude scaled El Centro earthquake

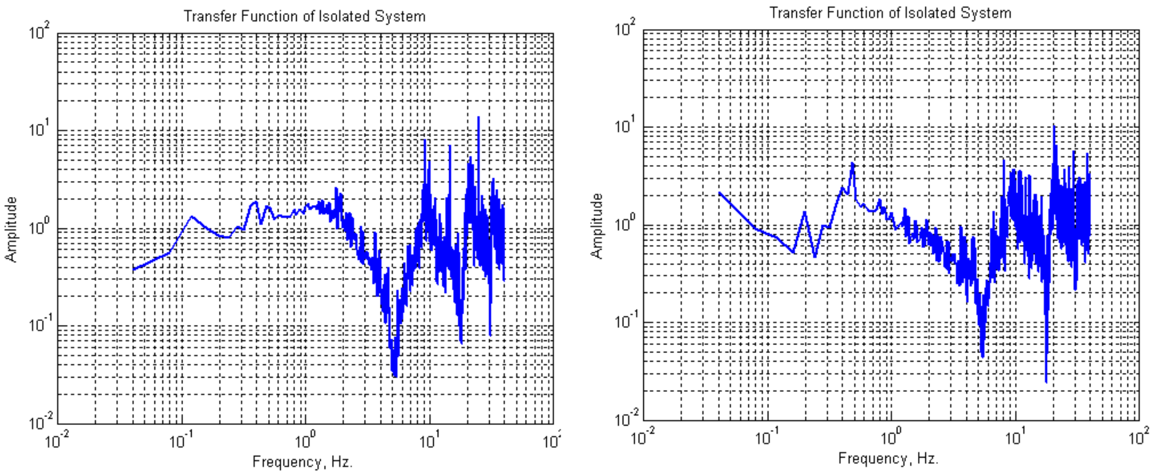

Figure 6. Transfer Functions of two isolated test setup with SI-N 150/136, SI-S150/136

5. CONCLUSION

This paper focuses on the effectiveness and performance of hybrid-passive isolation systems as an earthquake protection system. Test setup consists of mass concentric, ¼ scaled steel structure and passive-hybrid isolation system. The most commonly used passive-hybrid isolation system in practice is the combination of flat sliding bearings(PTFE) and isolation units with restoring force capability. HDRB bearings herein provide the restroing force capability of the proposed system and aim to minimize the permanent displacements after an earthquaka due to lack of restoring force in PTFE. Two types HDRBs are used in the experimental campaign for the comparison of used compound during the manufacturing. Flat sliding bearings contributed to the uniform distribution of vertical loads, dissipation of the energy and reducing the cost of combined system. Test results exhibited effectiveness of the passive-hybrid isolation system by shifting the fundamental period of the structure and reducing the interstorey drifts and amplification of accelerations. Base shear of the fixed system is computed more than 4 times of the isolated cases. Deamplification of accelerations at base slab are measured approximately half of the input ground motions in all cases. Results confirmed the promise of the proposed system in enhancing the earthquake resistance. Comprehensive and comparitive studies are required to assess the performance of the system under bidirectional or tri-directional near-field earthquakes regarding to proper representation of the demand. Moreover, mass eccentric and asymmetric configurations must be addressed in future studies. Reduction of the peak acceleration at base slab level were higher for relativelty high amplitude earthquake records.

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