Performance of Steel Frame with a Viscoelastic Damper Device under Earthquake Excitation

M. H. Mehrabi, S. S. Ghodsi, Zainah Ibrahim, Meldi Suhatril

***Abstract*—**Standard routes for upgrading existing buildings to improve their seismic response can be expensive in terms of both time and cost due to the modifications required to the foundations. As a result, interest has grown in the installation of viscoelastic dampers (VEDs) in mid and high-rise buildings. Details of a low-cost viscoelastic passive control device, the rotary rubber braced damper (RRBD), are presented in this paper. This design has the added benefits of being lightweight and simple to install. Experimental methods and finite element modeling were used to assess the performance of the proposed VED design and its effect on building response during earthquakes. The analyses took into account the behaviors of non-linear materials and large deformations. The results indicate that the proposed RRBD provides high levels of energy absorption, ensuring the stable cyclical response of buildings in all scenarios considered. In addition, time history analysis was employed in this study to evaluate the RRBD's ability to control the displacements and accelerations experienced by steel frame structures. It was demonstrated that the device responds well even at low displacements, highlighting its suitability for use in seismic events of varying severity.

***Keywords*—**Dynamic response, passive control, performance test, seismic protection.

I. Introduction

RECENTLY, there has been extraordinary interest in the investigation and development of structural control techniques with a certain emphasis on improving the reactions of buildings to wind and seismic activity. In civil engineering, structural control has evolved from a concept into a practicable discipline and implemented as part of sensible engineering systems. The key to improved structural performance and predictable damage during earthquakes is to provide an earthquake resistant device for buildings.

Viscoelastic solids exhibit both viscous and elastic characteristics and dissipate energy when undergoing deformation. One type of viscoelastic material (VEM) that has shown promise is synthetic rubber (**SR**), which increases important properties such as stiffness and damping. SR consists of vulcanized rubber filled with carbon black. In the beginning, it was used in highly damped bearing pads for base isolated structures [1], [2] but has since been adapted for use in damper devices as well [3]. VEDs are commonly incorporated in a structure as supplemental dampers acting in parallel to an already existing and independent retrofit system [4]-[6]. VEDs often dissipate energy by pure shear deformation and require additional braces such as chevron and diagonal bracings in the structure acting as supports.

Traditional braces are replaced by V-inverted braces integrating four layers of SR damper, horizontally attached in series between the braces and the upper beam of the storey. Along with this arrangement, the dampers are an essential section of the structure's seismic retrofit system. The key objective of the application is to attain an essential decrease in the earthquake forces brought into the structure and to simultaneously restrict displacements as well as drifts, or further to reduce them in comparison with ordinary braces. The suggested retrofit system for seismic isolation, centered on chevron braces and rubber dampers, is explained initially. The mechanical properties of SR, obtained from tests, are then presented.

A four-storey steel frame is considered with both damped and undamped designs. The undamped configuration is taken as the benchmark and is dynamically compared to the damped structure in which the devices are inserted. Numerical evaluations of the earthquake behavior of the structures under full earthquake intensities are also presented. The seismic simulations are discussed, and the dynamic responses of structures with and without dampers are compared. The obtained results indicate the efficiency of the proposed device to strongly reduce earthquake loads induced into the structure members and to keep displacements and drifts under control. Significant economic benefits for the application are represented by the obtained seismic response reduction levels.

II. Detailed Description of the Damper

The suggested damper uses vertical VE pads sandwiched between steel plates to provide shear resistance and guarantees both stable shear force and reduction of lateral displacement. These rubber pads produce the restoring force required to return the system to its original location. The damper is primarily based on the pushing and pulling of chevron braces as well as slight rotational shear. When a frame structure is displaced in a horizontal direction, the metal plates connected to the chevron braces slide along with the bracings, allowing the chevron members to pull and push the rubbers; for that reason, energy dissipation occurs as bracing members are subjected to tension and compression. Detail of the proposed device is shown in Fig. 1.

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Fig. 1 Rotary rubber damper device

III. Material Testing

To obtain the material properties of the VEM, monotonic, cyclic uniaxial tensile tests, simple shear and shear stress relaxation tests were conducted and the stress-strain responses for each rubber specimen were measured. More details about material testing can be found at [7].

IV. Cyclic Test Results and Analysis

A prototype of the suggested damper was built and underwent a pseudo-static test with increasing amplitude to assess the hysteretic behavior of the device. Fig. 2 displays the setup of the tested sample. A performance test for the VED under a velocity of 3 mm/s was conducted in a 1000-kN universal testing machine in displacement control mode. ABAQUS [8] was used to model the RRBD. The first step was inputting the nominal stress-strain data and choosing the suitable hyperelastic model. The automatic material evaluation module allows selection of multiple models and outputs the data for visualization. Modeling the time-dependent nature of rubber is needed for the completion of the process. The comparison between the experimental hysteresis loops and analysis is depicted in Fig. 3. It is considered that the selected VEM has a good energy dissipation capacity because the hysteresis loops show full ellipse.

V. Comparison between the Frame with Dampers and without Dampers

A four-storey steel frame is modeled and analyzed by the inelastic time history method with finite element analysis software ABAQUS in order to investigate the dynamic performance of the steel frame with and without dampers under earthquake conditions. The detailed size of the structure is displayed in Fig. 4.

In seismic analysis, Athens and Northridge waves are selected as the ground motion inputs, and the peak acceleration amplitude is adjusted to 2.0 m/s^2, and the duration is taken as 20s, as shown in Fig. 5.

The displacement histories of the top floor of the frames are shown in Fig. 6. As seen in Fig. 6, implementing RRBD devices in the frame structure causes the oscillations after the main shocks of the earthquake to be damped much more quickly. The values of the bare frames have a maximum of 50 mm and 280 mm. Furthermore, the highest values of the frames equipped with dampers are 28 mm and 190 mm in response to Athens and Northridge earthquakes, respectively. It is notable that the RRBDs are effective within a few seconds of the start of the earthquake activity and it is obvious that the effectiveness varies depending on the frequency content of the earthquake excitations.

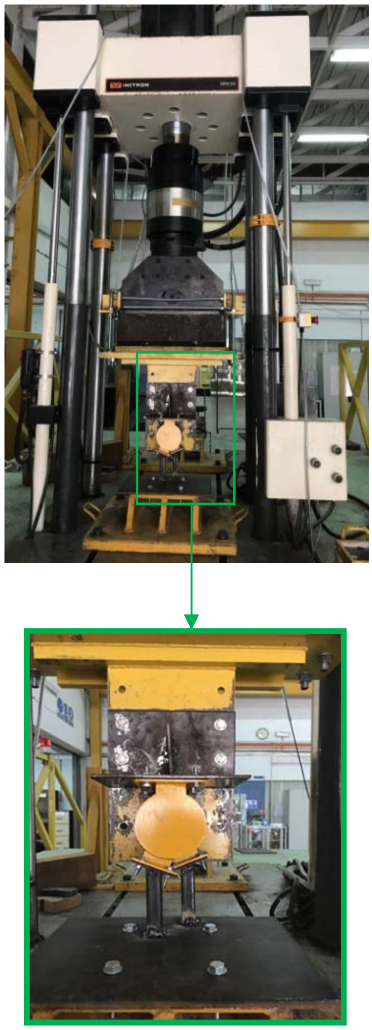


Fig. 2 The RRBD specimen in testing apparatus

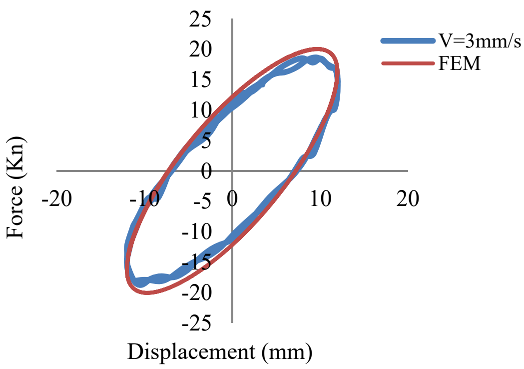


Fig. 3 Force and displacement relationship

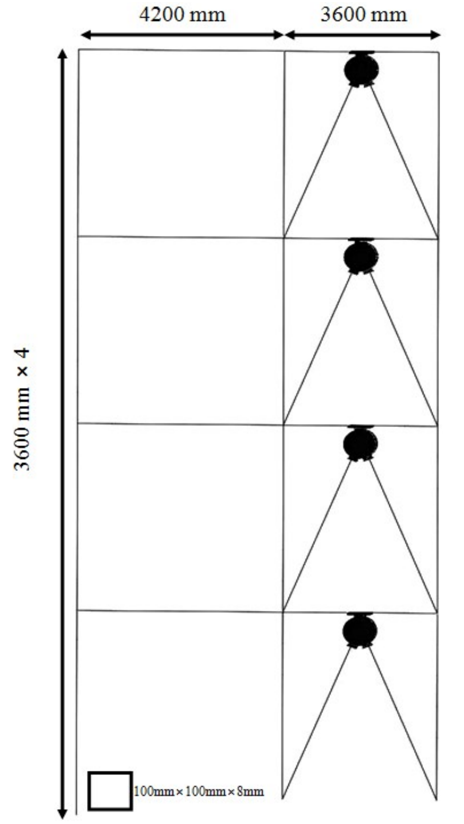
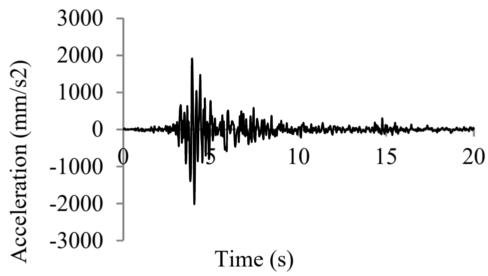


Fig. 4 Frame model for seismic response analysis



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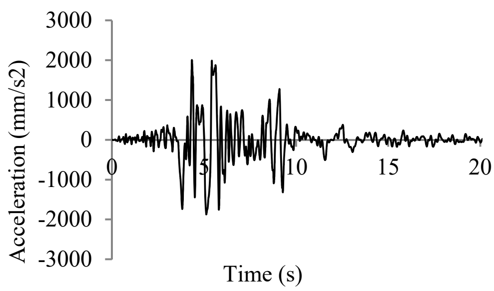
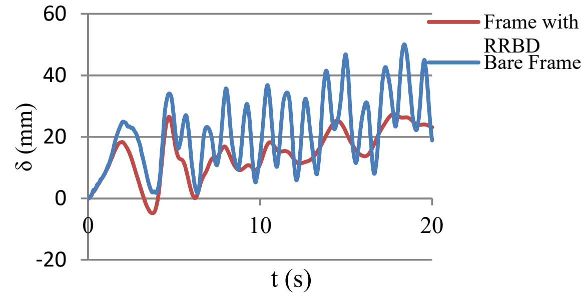


(b)

Fig. 5 Accelerograms used in the seismic analyses; (a) Athens, (b) Northridge

Fig. 7 shows the maximum drift ratio for the two frames under earthquake conditions. Storey drift increases with height. More damage is concentrated at intermediate stories because there is a larger variation in drifts between two consecutive stories at the lower floors compared to the upper floors, indicating a greater growth in displacement response at the lower stories compared to upper stories. Hence, it can be stated that the possibility of damage due to lack of storey stiffness is greater at lower stories in low rise frames.



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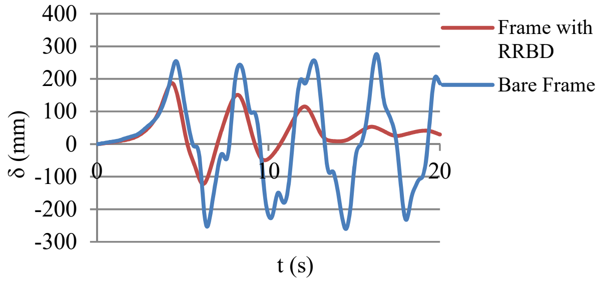
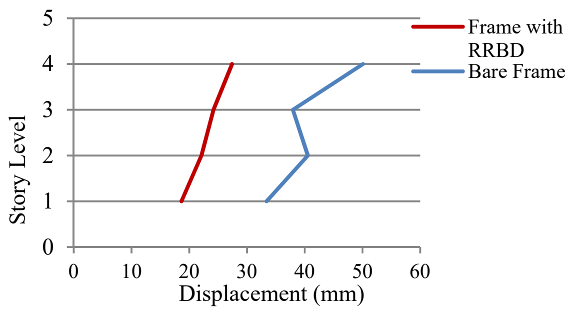


(b)

Fig. 6 Comparison of response histories for tested frame with RRBD and bare frame; (a) Athens, (b) Northridge



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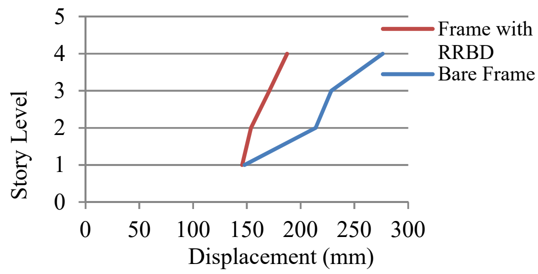

(b)

Fig. 7 Storey drifts of steel frames with and without RRBD for two different ground motions; (a) Athens, (b) Northridge

VI. CONCLUSION

This study proposes placement of a VED device in the concentrically braced system of a steel structure to increase energy dissipation. The device can be economically manufactured and placed in structural frames to protect from structural and non-structural damage in both moderate and extensive earthquakes. The obtained results of the study demonstrated that RRBDs are capable of significantly reducing structural and non-structural damage due to earthquakes and also increasing the seismic reliability of buildings. Maximum tip displacements are reduced by an average of 56.0% and 67% in frames with RRBDs compared to bare frames.

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