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Seismic response of friction damped and base-isolated frames considering serviceability limit state

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ABSTRACT

The present study evaluates the seismic performance of steel moment resisting frames (MRFs) upgraded with different structural protective systems. For this, three 5 storey steel MRFs (Ordinary moment frame (OMF), intermediate moment frame (IMF) and special moment frame (SMF)) and two 10 storey MRFs (IMF and SMF) were studied. As structural protective systems, friction dampers (FDs), base isolation with lead rubber bearings (LRBs), and a combination of them were considered. The structures were modeled using a finite element program and evaluated by the nonlinear time history analyses. In the nonlinear time history analyses, seven natural accelerograms, namely, 1976 Gazlı, 1978 Tabas, 1986 San Salvador, 1987 Superstition Hills, 1992 Cape Mendocino, 1994 Northridge and 1999 Chi-Chi were taken into account. Roof drift, roof absolute acceleration, relative displacement, interstorey drift ratio, base shear, top storey moment, and hysteretic curve were employed to compare the elastic and inelastic responses of all frames. The results clearly highlighted that the application of FDs with LRB had remarkable improvement in the earthquake performance of the case study frames reducing the local/global damages in the main structural systems and satisfied the serviceability (i.e., fully operational, FO and operational, OP) limit states as well.

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1. Introduction

During a major earthquake, buildings expose to a large amount of seismic energy. If this energy exceeds the lateral load carrying capacity of buildings, damage in a great extent may be encountered. In order to increase the energy dissipation capacity of the structures, or to decrease the seismic damage observed on the structures, within the last few decades many researchers have investigated on structural protective systems. These structural protective systems developed to improve the functionality and safety of the structures, can be classified as, base isolation systems, passive energy dissipation systems and active control systems [1].

Different types of passive energy dissipation systems such as metallic dampers, friction dampers, viscoelastic dampers, viscous dampers, tuned mass dampers, etc. are utilized to mitigate seismic damage [1]. Among the passive energy dissipation systems, with the advantage of high energy dissipation and behavior independent of temperature and velocity; friction dampers (FDs) could be effectively used to diminish the dynamic response of the buildings under seismic loads. The FDs with their rectangular hysteretic behavior similar to an ideal elasto-plastic response have great energy dissipation capacity. In addition to their high energy dissipation capacities, they are economical and their design is simple since the maximum force in the FDs that remains constant is predefined in the design stage [2–4]. Furthermore, since they can be easily hidden in the partition walls, they generally do not disturb the architectural view [4].

In the literature, many FDs have been tested analytically and experimentally. For instance, Pall and Marsh [5] designed a novel protective system, in which braces in a moment resisting frame equipped with the frictional devices and installed at the intersection of the X-brace in a 10-storey frame. These devices manage the resonance of the structure (control the amplitude of the structure), and also dissipate the seismic energy by means of frictional mechanism, thus protected all the main structural elements from yielding. Filiatrault and Cherry [6] tested the effectiveness of FDs installed to 3-storey on a shaking table. Test results revealed that FDs prevented the formation of any damage under severe earthquake record with a peak acceleration of 0.9 g, whereas the ordinary frames were seriously damaged under moderate earthquake. Similarly, a 9-storey steel frame model equipped with FDs and performed on a shaking table [7]. The model was subjected to 10 different real ground motions. As a result, the involvement of FDs improved the seismic performance of the model frame regarding the shear forces and dissipated energy. Filiatrault and Cherry [8] performed a simplified FDs design procedure in which use of those reducing a relative performance index obtained from the dynamic analysis for corresponding specified slip load. In another study conducted by Grigorian et al. [9], a slotted bolted connection energy dissipater device based on the friction

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system was utilized. This device consisted of using brass on a steel frictional surface and designed to dissipate energy via friction during tension and compression loading cycles. The performance of this connection dissipater was analytical and experimentally tested by using a one-storey one-bay diagonally braced frames under the action of several earthquakes. Results showed that the friction system dissipated nearly 85% of the input energy. In the study of Li and Reinhorn [10], a 3-storey reinforced-concrete building was tested experimentally and analytically to show the utilization of FDs on the seismic performance of the frame models. The test results showed that FDs led to structural improvement by reducing the displacement and dissipating energy. Kullmann and Cherry [11] performed an analytical study by using a 6-storey frame with and without FDs. They compared the frame with FDs and the conventional braced frame, and they observed that the performance of the structure was significantly improved by protecting all the main structural elements from yielding. Moreschi and Singh [12] carried out a genetic algorithm to determine the optimum slip load of a 10-story frame equipped with FDs by regarding the yielding level and stiffness of the brace as FDs design criteria. Fallah and Honarparast [13] also dealt with the determination of the optimum slip load and placement of FDs by conducting a multi-objective optimization procedure. In order to obtain favourable slip load, a 10-storey braced frame subjected to 10 earthquake records were used. Montuori et al. [14] offered a design method offered in order to dissipate the seismic energy in moment resisting braced frame with FDs and for that reason the theory of global plastic mechanism was activated at global level. The pushover and time history analyses were used to verify the proposed design method.

Base isolation systems aimed at reducing the reduction of the seismic effects on the structure have been initially considered as one of the most effective approaches in the design of new buildings and has gained increasing acceptance during the last two decades for the seismic retrofit of existing buildings [15]. The concept and theory of the base isolation is based on separation of the building from the ground and placed the base isolation system in order to reduce the destructive effect of seismic excitation. Commonly two type of base isolation systems; such as sliding systems and elastomeric bearings are available. The sliding systems are designed to dissipate the seismic forces by providing frictional sliding and limiting the transfer of shear while the elastomeric bearings are designed to eliminate horizontal earthquake forces by providing a layer with low horizontal stiffness [16, 17]. Three types of elastomeric bearings are generally used in the structures: natural rubber bearing (NRB), lead rubber bearing (LRB), and high damping rubber bearing (HDRB) [18]. For example, LRB contains many rubber layers and steel shims with lead plugs placed in the middle part of the rubber as shown in Fig. 1(a). The steel shims within the bearing cause the lead-plug to deform in shear, thereby providing damping whose behavior can be seen in Fig. 1(b) [19]. The main distinctive feature of the LRB is that possess immense vertical stiffness to carry the exerted load while providing flexibility in the horizontal direction [20]. Moreover, LRB is able to shift the natural period of structures due to the bearings with high flexibility, thus prevent the resonance of structures subjected to ground motions.

In recent years, several researchers investigated the response of the base isolation systems through experimental and analytical studies. For instance, in the study of the Kareem [21], the wind effect on the response of various base-isolated buildings equipped with tuned mass dampers was investigated. It was observed that the placement of the tuned dampers into appropriate level i.e. base or top and the design parameters of the isolator changed the response of the buildings. Liang et al. [22] also studied the wind-induced response of the base isolated frames especially for the tall buildings. The results showed that the base isolated tall buildings were very susceptible to wind storms. Furthermore, the optimum design parameters of isolator should be computed as to surmount the acceleration and displacement response of the buildings. Providakis [23] conducted the pushover analysis on the seismic response of steel-concrete composite buildings isolated by LRB and evaluated the effect of isolator height with setting three different cases for composite buildings. Moreover, both analytical and experimental study was performed to evaluate the performance of the high damping rubber bearing with the glass fiber layers under a set of 12 real ground motions in the study of Mordini and Strauss [24]. The results revealed that the strengthened rubber bearing enable to prolong the period of the superstructure and mitigate the acceleration and so verified the design parameters. Zordan et al. [25] proposed a comprehensive study proposed with regarding the three equivalent models assessed by the time history analysis and the optimal damping ratio computed by a genetic algorithm. When considered the maximum displacement and the isolation period of other models, the proposed model achieved to acquire the presumed LRB displacement less than 5% error. It was analytically and experimentally studied the effect of the variation of the isolation period and stiffness ratio for a 15-storey reinforced concrete frame. The interstorey drift responses were reduced by 33% compared to fixed base frame [26].

In the light of the previous researchers, in this study, the applications of different structural protective systems allocated as a seismic isolation system, or as a passive energy dissipation system over the height of the structure or both were investigated. For this, three 5-storey steel moment resisting frames (MRFs) as ordinary moment frame (OMF), intermediate moment frame (IMF) and special moment frame (SMF), and two 10-storey MRFs as IMF and SMF were utilized. Firstly, as passive energy dissipation device, FDs were applied at the middle bay of the frame through the height of the framed structures. Then, as seismic isolation systems, LRB isolation systems were applied. Finally, both structural protective systems, FDs and LRB isolation systems were applied to the case study MRFs together. Nonlinear time history analyses

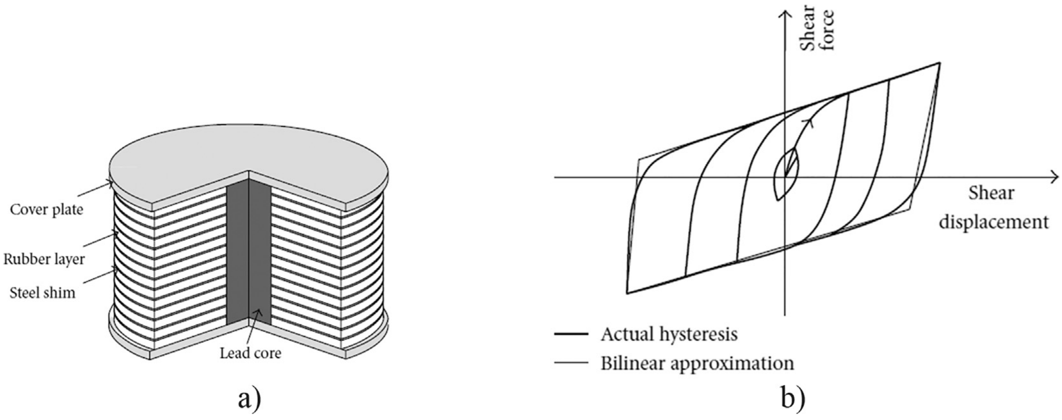

Fig. 1. Shematic representation and hysteretic behavior of lead-plug bearing [19].

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