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Design of re-centering spring for flat sliding base isolation system: Theory and a numerical study

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ABSTRACT

This study addresses the design of nonlinear elastic springs that render an effective re-centering mechanism for a flat sliding base isolation system. A nonlinear stiffening behavior of the elastic spring offers added advantage of re-centering mechanism. The proposed spring-sliding system works in a similar fashion as that of the flat sliding base isolation system supplemented with re-centering mechanism for small to medium level of shaking. For high intensity shaking, the proposed system minimizes the peak bearing displacement in addition to keeping the bearing residual displacement close to zero. To demonstrate the concept of the proposed isolation system, a numerical study is conducted with a steel moment-resisting frame when subjected to ground motions of varying hazard levels. It has been found from this study that the proposed spring-sliding device is effective in limiting the peak bearing displacement and making the residual bearing displacement negligible for varying hazard levels. It has also been observed that the presence of nonlinear spring is in general beneficial in reducing the horizontal peak floor acceleration in comparison to the sliding only for ground motion with moderate hazard levels (i.e., 10% in 50 years).

1. Introduction

The seismic design philosophy for civil engineering structures has undergone a series of modifications based on the performance of constructed facilities under various earthquakes. In the past, the seismic design of a structure was governed by a minimum level of lateral strength requirement. This concept was however modified later by introducing ductility in the design procedures. Earthquakes such as the 1994 Northridge and 1995 Kobe further demonstrated that buildings designed as per contemporary codes may undergo severe damages and the economic loss arising due to damage of structures and/or loss of functionality may be beyond the acceptable level. It was therefore reasoned that the ductility-based criteria may alone not be sufficient to guaranty the desired performance of a structure during earthquakes. As an improvement, the performance-based design philosophy has evolved. In performance-based design of a building, a pre-specified level of performance (performance objectives with an acceptable damage level) is envisioned when subjected to an event of specific hazard level FEMA-356 [1], FEMA-349 [2]. As per FEMA-356 [1], (i) for a minor intensity shaking, normally, a negligible structural damage without hindering the functionality of the system is acceptable and the desired performance level is known as 'Immediate Occupancy'; (ii) in case of moderate shaking, the damage includes major structural damage without collapse, minimal falling hazard and the performance level is known as 'Life safety' [1]; (iii) for a strong shaking the extent of damage can go up to a severe structural damage with probable falling hazard and the performance is the 'collapse prevention'. For a structure, these performance objectives can be achieved by proper design that may include application of innovative devices such as isolation bearings.

For seismic design of structures under strong events, modern design codes envision significant energy absorption through inelastic action of structural components and additional damping devices, if any. Seismic base isolation is a different approach where the force transferred to the superstructure can be minimized. Hence, in this approach, a structure can be protected from severe ground excitations without increasing the force resisting capacity of different structural components. Although the concept of base isolation is not new [3,4], seismic base isolation is getting significantly popular among researchers and engineers since the last four decades or so. A large number of publications highlighting the conceptual and experimental works demonstrates the developments in this area that are also obvious from an increasing number of structures isolated seismically throughout the world [5–30].

Traditionally, the seismic isolation devices are passive in nature. These devices can broadly be classified into spring like isolation bearings or sliding isolation bearings or a combination of the two

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bearing types. Additional damping mechanisms are often associated with these bearings to increase the energy dissipating capacities and thereby to reduce the seismic demand on the building. A good review of different isolation systems can be found in Kelly [3,4]. In addition, a significant amount of research is also going on to include active/semi-active control strategies with passive isolation system to enhance the overall efficiencies [15,31–34].

Sliding type isolation bearings are one of the most effective technology that makes the structure insensitive to the severity of the shaking intensity. The use of flat sliding bearing reduces the inter-story drift by limiting the force transfer from the ground to the structure irrespective of the frequency content of the ground motion. In addition, these bearings provide dissipation of the seismic energy due to friction mechanism. However, the flat sliding bearings alone do not have any re-centering capabilities and thus, may generate significant (permanent) residual displacements. For low friction coefficient, the peak displacement is also very high in such bearings. To overcome these limitations of flat sliding bearings, several sliding-type isolation bearings with restoring provisions have been proposed in the past. Very recently, Nashimura et al. [21] have proposed the use of high friction sliding isolation system to reduce the vulnerability of structures under extreme hazard conditions. It may be noted that the use of a very high friction coefficient to reduce the base displacement also may limit the effectiveness of the sliding isolator for nominal to moderate intensity ground excitation.

Mostaghel and Khodaverdian [6] and Zayas et al. [5] considered a combination of sliding isolation bearing known as resilient friction base isolator with a restoring mechanism of friction-based pendulum system. Yang et al. [7] conducted a mathematical study on the responses of the multi-degree-of-freedom structure with sliding bearing with an imaginary spring for the convergence of the analytical discontinuities. Constantinou et al. [8] provided a good review of different sliding-type isolation systems and their applications. Later, Constantinou et al. [10] proposed a sliding isolation system consisting of Teflon disc bearings and helical steel springs with bi-linear elastic behavior in shear. The performance of this system has been demonstrated for high frequency rich (1940 El Centro earthquake, 1978 Japanese MiyagikenOki earthquake, etc.) to low frequency rich (1985 Mexico City earthquake) excitations. Further, studies have been conducted for improving the performance of the sliding base isolation system. Friction pendulum system has been found to be an innovative solution to overcome the drawbacks of the sliding isolation system. The conventional friction pendulum system [5] consists of an articulated sliding isolator that slides on a spherical surface. However, in spite of having a restoring mechanism and sliding facilities, the system has not gained popularity in mitigating the seismic vulnerability of structures due to its huge size and cost involvement. Moreover, a constant radius of curvature for the concave surface limits the performance of the structure to a specific excitation level.

As a continuation to the study of Zayas et al. [5], a variable frequency pendulum isolator (VFPI) associated with a sliding concave foundation was introduced, by Pranesh and Sinha [13] and Hamidi et al. [35]. VFPI has oscillation frequency increasing with the sliding displacement and the restoring force has an upper bound so that the force transmitted to the structure is limited. Afterwards, a number of study have been carried out for different friction pendulum types of passive sliding isolators such as sliding isolators with multiple sliding surfaces (SIMSS), sliding isolator with variable friction (SIVF) and sliding isolator with variable curvature (SIVC). In case of SIMSS the isolator has more than one spherical sliding surface that allows for a larger sliding displacement with relatively smaller size of the isolator [20]. As a development, recently, the effectiveness of use of multiple sliding surface has also been demonstrated by [19,22,24,25] to render passive smart isolation system. SIVF has a constant radius but adaptive friction coefficient that possess variable damping along with the base displacement [13]. Panchal and Jangid [36] implemented the SIVF for seismic isolation of the liquid storage tank under near fault ground motion and compared with the normal friction pendulum system. Their study demonstrated that the seismic response was within the desirable range for VFPS. Another similar group is the sliding surface with variable curvature where the isolation stiffness is adaptive in nature. Lu et al. [29] designed the geometry of the sliding surface of SIVC considering stiffness as a variable design parameter. In his study, the curvature of the variable surface was designed in such a manner that the restoring force showed a softening behavior at the beginning followed by a hardening nature. The softening behavior is to resist the excessive superstructure acceleration that may arise for a higher stiffness of the restoring mechanism.

Gluck et al. [37] considered base isolation with controlled stiffness (CS) damper, where the springs are connected at angle to the superstructure and the desired force in the CS damper is provided considering active optimal control law. It may be noted that in this device, the springs are arranged in such a way that the resulting force-deformation behavior of the damper becomes nonlinear. Hence, the device provides a restoring mechanism even when no control mechanism is applied.

1.1. Scope of this work

As mentioned by Mokha et al. [9], the sliding-type bearing (with or without weak restoring mechanism) is a passive one that has been widely used by engineering profession due to its reliability and frequency insensitivity to ground motions. In addition, in a sliding isolation system, the vertical load is not carried by the horizontal force providing mechanism making it easy to design for engineering applications. In this study, a flat sliding bearing coupled with a nonlinear elastic spring is proposed for effective base isolation with restoring mechanism. The stiffness of the nonlinear spring increases with its deformation rendering a behavior similar to that of the VFPI. To demonstrate the effectiveness of the proposed system, a four-story steel moment-resisting frame is considered. The performance objectives of this frame under various intensity ground motions are defined in terms of inter-story drift, base displacement and residual displacement of isolators. Performance of the proposed system is then evaluated by performing nonlinear time history analysis. For comparison of response, a system with sliding friction bearing only and a fixed-base system are also considered. In addition, the effectiveness of the nonlinear spring over a linear spring is demonstrated as well. Further, the internal diameter of the spring is varied to recognize an optimum value for which the inter-story drift, base displacement and the residual displacement can be optimized.

2. Modeling of proposed isolator

The proposed isolation system consists of flat sliding bearings along with nonlinear springs. A schematic diagram showing a two-dimensional frame isolated by the proposed system is shown in Fig. 1. A typical flat sliding bearing consists of a top slider that slides through a bottom surface, which is rigidly connected to the foundation. Two nonlinear springs on either sides of the base mat are connected in such a way that the springs are unstretched when the structure is in central position. Once the structure starts sliding during ground excitation, the spring which is undergoing compression imposes a nonlinear (stiffening) restoring force to the structure. For a very low excitation, the inertia force on