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Seismic response control of a structure isolated by flat sliding bearing and nonlinear restoring spring: Experimental study for performance evaluation

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ABSTRACT

This study presents the outcome of an experimental evaluation of a structure isolated by flat sliding bearing with nonlinear restoring springs. The composite device of flat sliding bearing with nonlinear stiffening springs, which has been proposed recently, has the following advantages: (i) its behavior is similar to that of flat sliding bearing for minor to moderate level of shaking, (ii) for high intensity shaking, the device reduces the peak bearing displacement in comparison to the flat sliding bearing, and (iii) the device minimizes the bearing residual displacement irrespective of intensity of shaking. The experimental study conducted with a steel moment-resisting frame demonstrates that the device is quite effective in reducing the peak and residual bearing displacements. Further, it is found that other parameters such as peak inter-story drift and peak horizontal floor acceleration are not significantly affected by addition of restoring springs. Hence, the proposed system is an ideal candidate for a cost-effective base isolation system.

1. Introduction

Seismic base isolation is a design concept, which involves dynamic decoupling of a superstructure or a piece of equipment from its base to limit the damage caused by strong earthquakes. The prime idea of base isolation is quite old [1]; but it is in the last 4–5 decades that the installation of practical isolation devices became possible through increased industrial capabilities [2]. The first building constructed using the concept of base isolation was the Foothill Communities Law and Justice Center in Rancho Cucamonga, California (US) in 1985 [3].

Passive seismic isolation devices are primarily classified in two categories: spring like isolation bearings and sliding isolation bearings. For controlling structural responses under earthquakes of different intensity levels, a combination of these two systems are also considered [4,5]. A significant amount of research has been carried out for base isolated structures as can be seen from the literatures [6–37].

Sliding-type simple base isolation device dynamically decouples a structure from its base and thus, limits the force transferred to the superstructure. Depending on the level of base excitation, sliding is initiated when the inertial force exceeds the frictional resistance of the slider. For the initiation of sliding of superstructure, the intensity of exciting force must be more than the frictional resistance. The friction between the sliding surfaces also helps in dissipation of vibrational energy. However, the main drawback of simple sliding-type base isolation system is the large bearing displacement that often results in a huge residual displacement during an earthquake. Various isolation systems with restoring mechanism have been proposed so far to overcome this disadvantage.

Mostaghel and Khodaverdian [7] considered a combination of sliding isolation bearing known as resilient friction base isolator with a restoring mechanism. Sliding isolation system with Teflon disc bearings and helical steel springs with bi-linear elastic behavior in shear was proposed by [12]. Friction pendulum system was proposed [6] as an improvement to the sliding base isolation system where the gravity load helps in re-centering and thus, eliminates the necessity of additional restoring mechanism. In case of a friction pendulum system, spherical surface is designed as a bottom slider. An articulated slider along with the superstructure is connected to the bottom slider by friction and it slides on the spherical surface when subjected to an excitation, which is beyond a threshold of friction force. In order to make the friction pendulum isolator adaptive to different intensities of earthquakes, studies with several devices have been conducted such as variable frequency pendulum isolator (VFPI) [38], friction pendulum isolators with multiple sliding surfaces (SIMSS) [25,23,27] and sliding isolator with variable friction (SIVF) [13].

A similar improvement is proposed by Lu et al. [35] who considered the curvature of the sliding surface as a variable parameter. The curvature of the bottom slider was designed in a way that the pendulum provides an initial flexible behavior of the pendulum followed by hardening behavior in order to reduce the force transfer to

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superstructure at low to moderate intensity earthquakes and restrict huge base movement during strong earthquakes. In spite of the restoring capability of the friction pendulum system, the main challenge for its wide usage remains (i) in the fabrication of such spherical device with huge radius and hence, high cost associated with it, (ii) in the installation of such complicated device. In a recent study by Chakraborty et al. [39], a new device has been proposed in order to provide an alternative of the friction pendulum systems (single or multiple spherical surfaces). The device combines a flat sliding isolator with a conical spring. The conical spring requires only one diameter space when it is compressed fully. This makes the system ideal for applications with space constraint. The conical spring renders a stiffening nonlinear behavior with displacement while providing a better lateral buckling resistance. The behavior of this type of device is the same as that of a variable friction pendulum isolator (VFPI). As demonstrated numerically by considering a 4-story steel moment-resisting frame [39], the proposed device provides an adaptive behavior depending upon the intensity of ground excitation. In particular, it was shown that the proposed device reduces the peak bearing displacement significantly along with a tremendous reduction in the residual base displacement as compared to the sliding only system. Further, it is found that the inter-story drift does not increase significantly as compared to the fixed based system.

1.1. Scope

In this study, an experimental evaluation of the base-isolation system as proposed by Chakraborty et al. [39] is carried out considering a model steel moment-resisting frame. Various intensity ground motions were simulated on a uniaxial shake table in the structural laboratory of Indian Institute of Technology Kanpur. The performance objectives of this frame under various intensity ground motions are defined in terms of inter-storey drift, base displacement and residual displacement of the model frame. For comparison of responses, the same model was tested considering a fixed base and a sliding base conditions.

2. Building model and isolator

In the experimental study, a three-storey single-bay steel moment-resisting frame model was considered as shown in Figs. 1(a) and (b). The height of the first storey was 0.75 m and the height of each of the remaining two stories was 0.5 m. The floor plan of the model was 1000 mm × 900 mm. The beams and the columns were considered as square solid sections made of mild steel. The beam and column cross-sections were 10 mm × 10 mm and 12 mm × 12 mm, respectively. Four circular ties, each of 10 mm diameter were used to connect every two adjacent columns, at a height of 75 mm from the base. The mass was simulated by attaching two steel plates (10.4 kg each) on each floor. The masses were attached to the frame with hooks in such a way that they do not alter the stiffness of the frame in the direction of shaking. Hence, the total mass of the model was 103.8 kg including the mass of the steel plate, all beams and columns.

The experimental model was scaled as per the law of similitude considering the existing steel-moment-resisting-frame (SMRF) buildings in California as a prototype. In obtaining the model parameters, length scale was considered to be 8, moment of inertia scale was considered to be 8×10^6 and the mass scale was considered to be 3200. The scale factors were considered in a way that the fundamental frequency of the model represented the fundamental frequency of the prototype SMRFs. The experiment was conducted considering fixed, sliding and sliding with spring base conditions as shown in Fig. 2. The details of experimental setup along with the base conditions are described in the following subsections.

2.1. Sliding base condition

The experimental set up for sliding base condition is described in Fig. 2(b). In order to simulate sliding base isolation, four steel plates of dimension 100 mm × 100 mm were rigidly attached to the column base. In addition, four large steel plates of dimension 450 mm × 380 mm, with 450 mm in the shaking direction, were placed centrally below the model and were rigidly connected to the shake table. Thus, the smaller dimension steel plates along with the frame were placed on the larger dimension steel plates. The smaller steel plates may be identified as the top sliders that slide over the larger steel plates known as bottom slider at an instant when the base shear in the model frame exceeds the threshold value of friction between the top and bottom sliders. The dimensions of the base plate (bottom sliders) was decided from a dynamic analysis in OpenSees [40] such that the maximum base movement doesn't exceed the clear dimensions of the base plate. In the analysis, the flat sliding bearing element was used at the base and the behavior of the slider was simulated using Coulomb friction model. In order to obtain the Coulomb friction coefficient, characterization of the frame with top and bottom steel slider plates was performed for friction.

2.2. Sliding with nonlinear spring base condition

The desired nonlinear behavior of the restoring mechanism can be achieved from conical springs (commonly known as battery springs). The working philosophy of such a spring and its application as a restoring mechanism to a base isolation building is described in the study of [39]. In a conical spring, the larger loop of the spring grounds first because of the higher flexibility as compared to the other loops. After grounding of each loop, the stiffness of the spring increases and thus, the spring provides a multi-linear, hardening type force deformation behavior. The stiffness of the spring between two successive grounding can be expressed as follows:

$$\frac{F}{\delta} = \frac{GJ}{\left\{\frac{1}{32}(D_f-D_S)^3 + \frac{1}{8}(D_f-D_S)^2 D_S + \frac{3}{16}(D_f-D_S)D_S^2 + \frac{D_S^3}{8}\right\}2\pi N} \tag{1}$$

where D_f is the larger diameter of the tapper section that grounds first among the active loops if the spring force increases, D_S is the smallest diameter of the tapered section, G is the shear modulus of the wire of the spring, J is the polar moment of inertia of the spring's wire section and N is the active number of loops participating in the total deformation of the spring. In this study, conical spring is assumed to be made of steel with shear modulus $G = 8 \times 10^{10}\ \mathrm{N/m^2}$. Fig. 3 shows the photograph of the conical spring fabricated as a restoring mechanism along with the sliding isolator in the experiment. In fabricating the conical spring, the total height (H_0) was considered to be 120 mm, the number of loops (N) was considered to be 7, the larger diameter (D_f) was taken as 100 mm, the smaller diameter (D_s) was taken as 20 mm and the wire thickness (D_t) was taken as 4 mm.

For the selection of the conical spring parameters, the utility as well as ease of fabrication were considered as follows:

- The spring length (i.e., H_0) should be such that it can be accommodated within the space available between the bottom slider and the column.
- The pitch of the spring (i.e., H_0/N) should be adjusted in such a way that the base sliding can take the spring to various stages of its force-deformation behavior (i.e, linear for mild motions to nonlinear for strong motions).
- The wire diameter (i.e., D_t) of the spring should be such that it renders a very low initial stiffness.
- The ratio of the diameter of the larger loop to the smaller loop (i.e., D_f/D_s) should be considered in a way that the rate of change in spring stiffness should be large enough to render the hardening