A Sloping Surface Roller Bearing and its lateral Stiffness Measurement

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Abstract

In this paper the laboratory performance and advantages of a new roller-type seismic isolation bearing for highway-bridge are briefly presented. The new bearing, with steel cylinders rolling on sloping surfaces in two directions, has the feature of keeping the acceleration of the superstructure at a relatively low and constant level while tolerating a relatively large bearing displacement.

In order to develop design guidelines for the roller bearings, it is necessary to first consider how to evaluate its seismic performances. One of the most important parameters in seismic isolation design is the lateral stiffness which directly affects the working period and damping coefficient. The current standard procedure using "effective stiffness" is shown not to be a suitable measure for the evaluation of the seismic performance of the roller bearings and that a different evaluation procedure has to be developed. A major objective of this paper is to present this problem to the participants of the workshop and to seek advice on how to best develop the evaluation procedure.

The Sloping Surface Roller Bearing (SSRB)

Vibration isolation bearings have been discussed by Den Hartog (1956) for mechanical engineering applications and by Naeim and Kelly (1999) in earthquake engineering applications. The sloping surface roller bearing (SSRB) reported herewith is recently developed for seismic isolation.

The conceptual drawing of a single roller type of SSRB is shown in Fig. 1, with its working mechanism shown in Fig. 2(a) and its capability of tolerance of large displacement shown in Fig. 2(b). Fig. 2(b) shows that the displacement of the superstructure, H_D, can be twice as much as the roller displacement, H_B. That is, the bearing can tolerate very large displacement with relatively smaller dimension. A prototype bearing with single roller is shown in Fig. 3(a).

In Figs. 1 and 2, a single layer bearing is shown. For two directional ground motion, two layers, one in each mutually perpendicular direction, can be used. A two-layer assembly is shown in Fig. 3(b). The total height of the bearing will depend upon the vertical load. For example, for 1000 Ton (2000 Kips) vertical load the bearing will have about 30-33 cm (12 – 13″) in the vertical direction.

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The horizontal acceleration is mainly determined by the angle of the sloping surface(See Fig. 2(a)). That is, despite the magnitude of the ground acceleration, the acceleration of the superstructure, A, can be written as

$$A = \alpha g \tag{1}$$

Since the angle of the slope is quite small, around 1.5^0 to 2.5^0, the acceleration contributed by the bearing can be as small as 0.03 -0.05 g, even with an overdamped design, say the damping force is around 0.05-0.10g, the total lateral acceleration can still be kept at less than 0.15g.

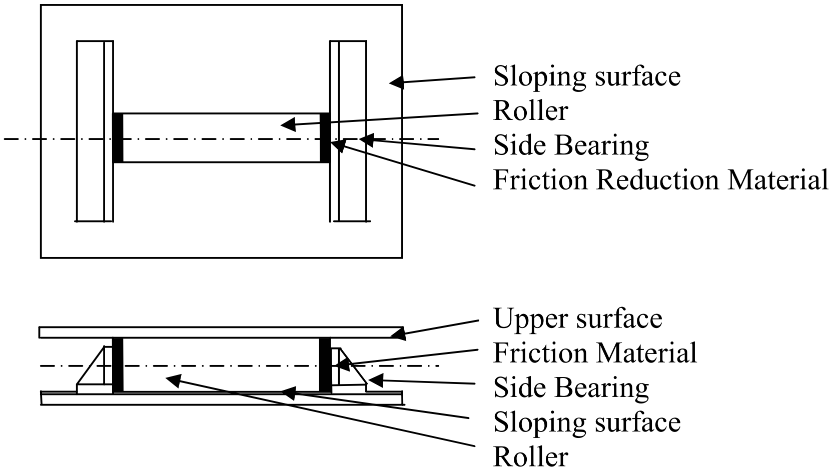

Figure 1. Assembly of a single layer bearing.

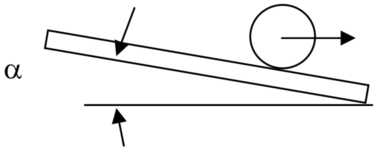

Figure 2(a). Horizontal acceleration of bearing

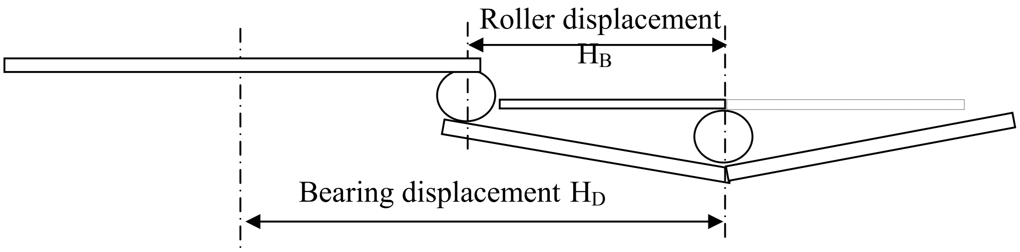

Figure 2(b). Displacement of Roller Bearing

The bearing displacement is also an important design parameter. To reduce the displacement is a challenging task in isolation design. When the ground motion has a large displacement, no matter it is pulse-like or otherwise the bearing displacement can be quite large. In the working range, where the period of the isolation system is longer than that of the major earthquake components, using large damping seems to be the only approach to regulate the displacement. However, large damping will increase the level of the acceleration at the same time. In typical bearing design, compromise is usually made between the acceleration and the displacement.

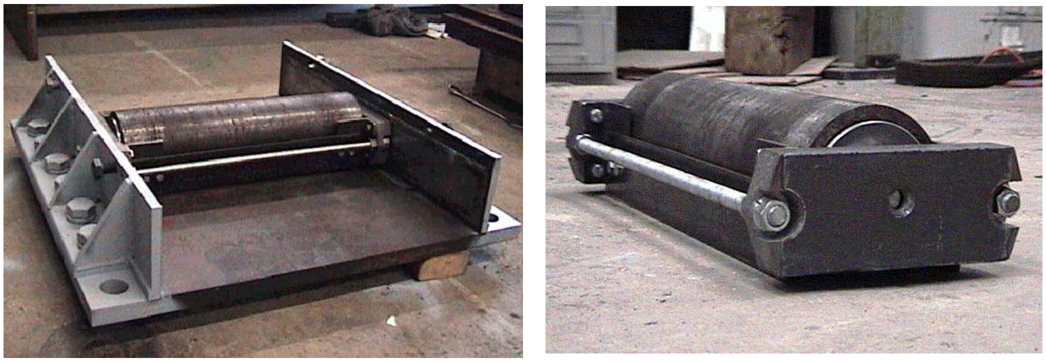

Figure 3(a). Photos of a single layer bearing assembly

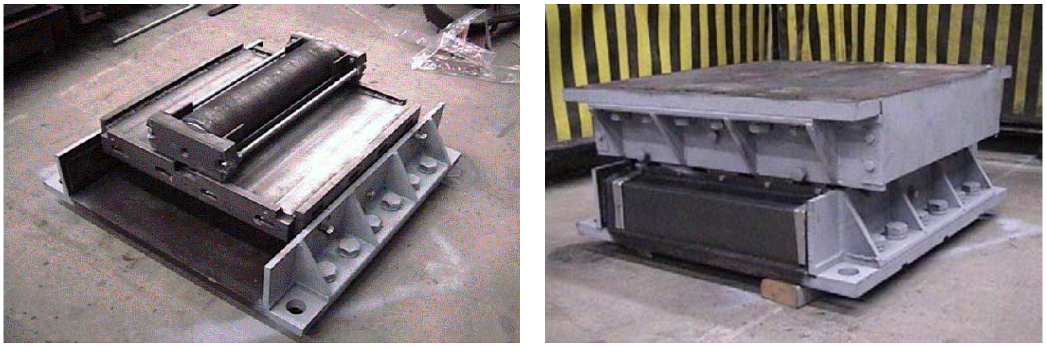

Figure 3(b). Photos of a double layer bearing assembly

For the roller bearing, the acceleration amplitude is almost a constant. The designer should not be concerned with excessive acceleration of the superstructure. Since the acceleration level is relatively small, they can rely on damping to further reduce the bearing displacement. This is an important advantage of the SSRB.

Shaking Table performance of SSRB

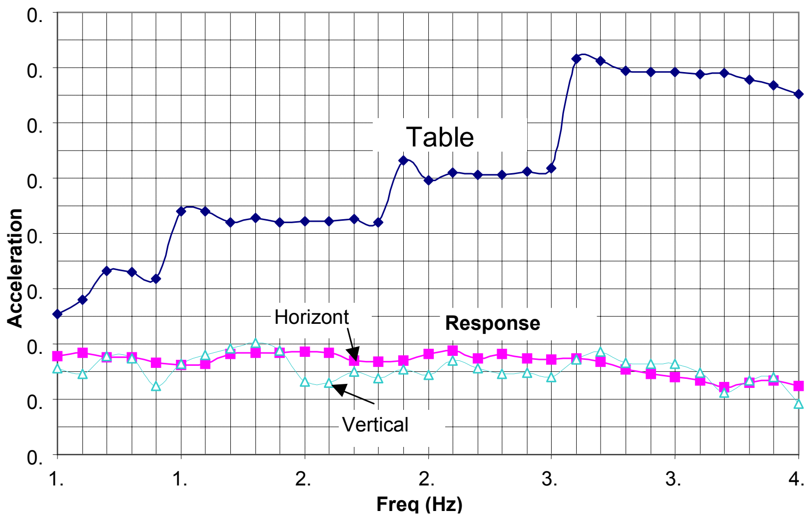

Figure 4. Acceleration level under sweep sine test

Fig. 4 shows results of shaking table test of the first generation prototype bearing, where the slope angle is 4.5^0. These results show that the bearing acceleration response is relatively constant under different input table motions. For the second generation prototype bearing, the angle used is less than 2^0. Fig. 5 shows measured results of the acceleration and base shear from the experiments of the second generation prototype bearing conducted at the University of Nevada at Reno. It is seen that, the acceleration level is almost fixed, despite of the levels of the amplitude of ground motion and the frequencies.

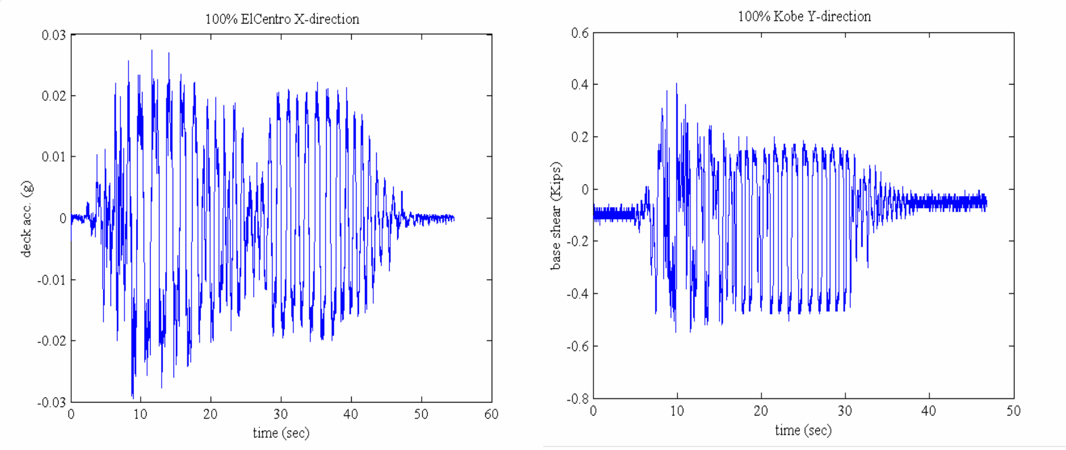

Figure 5. Acceleration and base shear levels under earthquake excitation

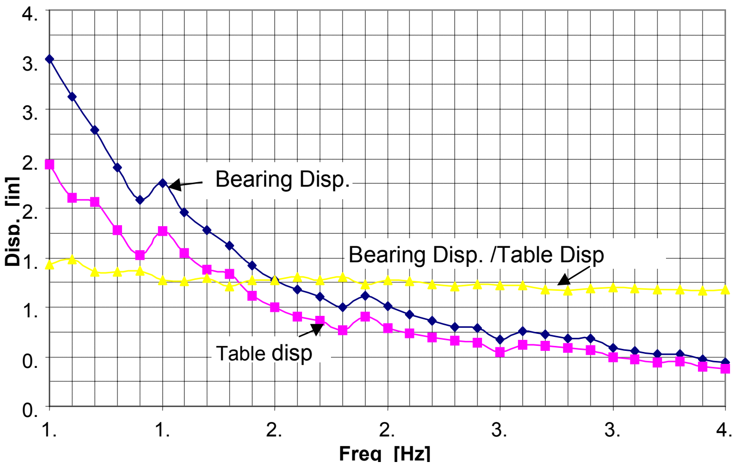

Figure 6. Bearing displacement under sweep sine excitation

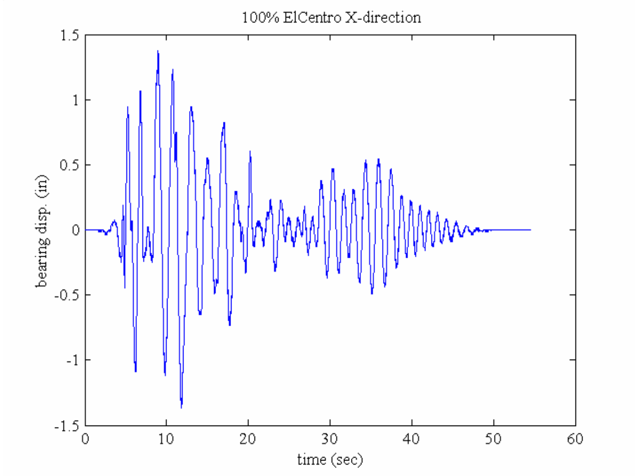

Figure 7. Bearing displacement under earthquake excitation

Figure 8. Overview of the deck of the model bridge

Fig. 6, shows the bearing displacement of the first generation bearing (4.5° angle) under sweep sine excitation. It is seen that the ratio of the bearing displacement vs. the table's movement is also nearly constant. In Fig. 7, we show the typical bearing displacement of the second generation of roller bearing under El Centro earthquake excitation conducted at the University of Nevada at Reno. Because the bridge model is 2/5 down scaled, the real displacement for a full scaled bridge should be 2.5 times larger, which is 3.5 inches. It is a reasonably small value. Fig. 8 shows the test setup at Reno, where the bridge superstructure is supported by two separate shaking tables at its ends.

The AASHTO Approach of Bearing Evaluation

While the roller bearing has certain distinct advantages, its performance evaluation cannot be readily carried out using current method. One of the problems is the value of lateral stiffness. In the following the concept of stiffness in seismic isolation design is firstly reviewed, followed by an explanation of the problem area of evaluating the roller bearing.

Seismic isolation design by means of the design response spectrum uses mainly two parameters, the period and the damping coefficient, which directly relate to the lateral stiffness of isolation bearings. Denote **M** and **K** as the mass of the superstructure and the lateral stiffness respectively, the period of the isolation system, T, is given by

$$T = 2\pi\sqrt{\frac{\mathbf{M}}{\mathbf{K}}} \tag{2}$$

Denote the energy dissipated by the bearing system in one sinusoidal cycle as E_d and the maximum bearing displacement as D_A respectively. The damping ratio, ξ, is defined as

$$\xi = \frac{E_d}{4\pi\left(\frac{\mathbf{K}\,D_A^2}{2}\right)} = \frac{E_d}{2\pi\,\mathbf{K}\,D_A^2} \tag{3}$$

In seismic isolation design the damping coefficient is solely determined by the damping ratio.

Equations (2) and (3) show that the stiffness is an important factor in isolation design. Generally, a stiffness of a system is defined as the capability of a structure or system to resist deformation under applied loading. Or,

$$\mathbf{K} = \frac{F}{D} \tag{4}$$

Equation (4) is a measure of the applied force per unit deformation. It is also a measure of the capability of a system that can restore the potential energy of the deformed structure. In Equation (3), the term $\frac{\mathbf{K}\,D_A^2}{2}$ is actually the restored potential energy of the isolation system when the maximum displacement D_A is reached. In an isolation system, this potential energy can be transformed into kinetic energy, $\frac{\mathbf{M}\,V^2}{2}$, in which V denotes the velocity. Thus, with an approximate sinusoidal vibration in resonant status,

$$\frac{\mathbf{K}\,D_A^2}{2} = \frac{\mathbf{M}\,V_A^2}{2} \tag{5}$$

Where V_A is the maximum velocity when the system damping is ignored. This gives,

$$V_A = \frac{2\pi}{T} D_A. \tag{6}$$

From the above one can obtain the definition of the period, as given by Equation (2).

Equation (4) is the standard definition of stiffness in structural engineering. It is for a linear system under sinusoidal vibration. For systems that do not have a pure sinusoidal vibration, the response can be analyzed by multiple sinusoidal forms with the help of the Fourier Transform. When the component with fundamental period dominates, the concept of period can still be used. In isolation design, most bearings are nonlinear. In order to utilize the above concept an effective stiffness, K_{eff}, has been defined and used, referred to as the AASHTO approach.

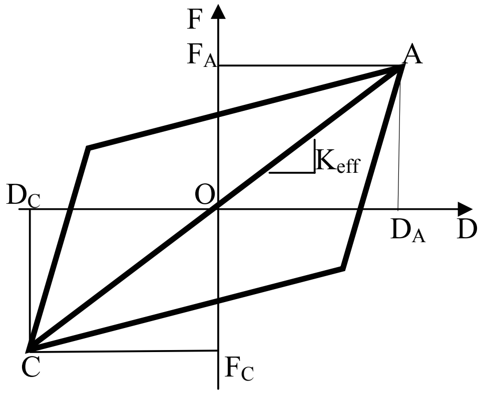

Figure 9. Bi-linear relationship of force vs. displacement

As shown in Fig. 9, the effective stiffness is defined by the slope of line AOC, or

$$K_{eff} = (F_A - F_C)/(D_A - D_C) \tag{7}$$

Where, D_A and D_C are the zero velocity displacements, and F_A and F_C are the resistant forces at the zero velocity displacements. With the effective stiffness, the percentage of critical damping can be measured by Equation (3), by replacing K with K_{eff} and D_A with design displacement D_0. where,

$$D_0 = (D_A - D_C)/2 \tag{8}$$

It has been shown that this approach is reasonably reliable for evaluation of systems having velocity-dependent characteristics. Typically the system has a definite structural period and the percentage of critical damping measured by equation (3) is less than 30%(AASHTO).

Challenges of Roller Bearing Evaluation

It is inappropriate to evaluate the roller bearing by using the AASHTO approach. The basic reason may be explained as follows: The roller bearing separates the superstructure from the ground or piers with a constant restoring force when the superstructure is on either sloping sides (see Fig. 2(b)). The system does not have a structural period as can be observed from the results of the sweep sine experiment, shown in Figs. 4 and 6. Thus, it is displacement-dependent rather than velocity-dependant.

The difference between the displacement-dependent isolation device and the velocity-dependent device can be seen by comparing the force-displacement loop of the roller bearing with that of the bi-linear model in Fig. 9.

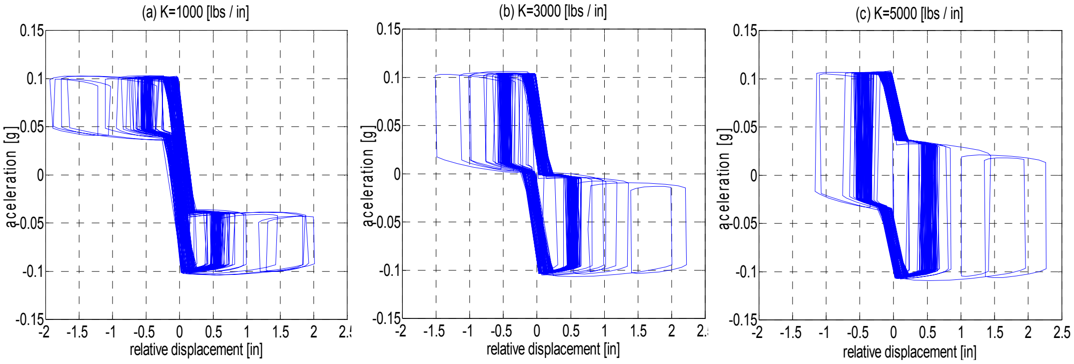

Figure 10. Experimental acceleration displacement loops of different spring stiffness for input sinusoidal wave 0.6 g 3.5Hz (1st generation roller bearing)

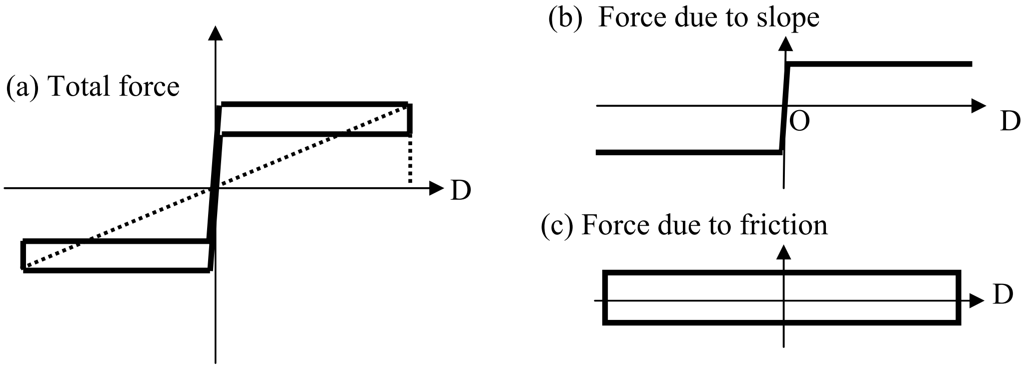

Figure 11. Force vs. displacement of the roller bearing

In Fig. 10, several measured acceleration-displacement loops of a prototype roller bearing (first generation) are shown, where the symbol K is the stiffness of an “internal absorber” and it is not the lateral stiffness. Further, the driving frequency is form 0.2 Hz (period = 5 sec) up to 5Hz (period =0.2 sec). In those experiments, the results shown are for 3.5 Hz driving frequency. (The rest of the tests have similar results.) Based on the experimental results such as those shown in Fig. 10, we approximate the force-displacement loop of roller bearings by decomposing it into two idealized parts, one each due to slope and friction, as shown in Fig. 11.

Figure 9 and Fig. 11 show that, the isolation system having velocity-dependent characteristics will restore much energy transmitted from the ground as the displacement increases. Part of energy will be dissipated by damping and part of it will be transformed into kinetic energy. For the isolation system having displacement-dependent characteristics such as the roller bearings, not too much energy is stored and can be transformed into kinetic energy later and that the period of the roller system can not be defined.

The experimental results of the roller bearing have shown that the isolation system with displacement-dependent characteristics has certain distinct advantages, such as: small acceleration, small base shear and large displacement tolerance. To apply this type of isolation system to engineering structures, certain evaluation procedure based on principles of structural dynamics will have to be established. The current method established from the principles of statics is more suitable for the type of bearings with strong velocity-dependent characteristics.

Summary

The following may be briefly summarized:

Roller bearings have the advantage of fixed and very low superstructure acceleration because its lateral stiffness is nearly a constant and it has no “period effect” to the superstructure. With this property, the designer can focus more on how to reduce the relative displacement of the structure. For this purpose, adding damping plays an important role.

The current evaluation method is not suitable for roller bearings due to their strong displacement-dependent characteristics. A new evaluation approach considering dynamic properties of the bearings is necessary. This is the current research effort of the authors.

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