Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Base isolation: Fresh insight

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ABSTRACT: A force of inelastic resistance is mostly conceived as a source of damping vibration, though it is an active force at the the same time, during an earthquake type excitation. For very pliant systems such as base isolated structures with relatively low stiffness and with artificially added heavy damping mechanism, the so called "damping" force may occer even the main pushing force at a major earthquake. Thus, one of the two basic pillars of seismic isolation philosophy, namely the doctrine of usefulness and necessity of strong damping is turning out to be a self-deception. There is a way out: it is necessary to breake with damping dependency. The low friction base isolation in combination with progressive frequency separation has proved to be a much more effective approach.

1 PUSHING FORCE OF INELASTIC RESISTANCE

The flexible mounting by itself does not secure a favourable regime of structural performance in the range of low ground periods or in the case of simple pulses. It is just damping which is intended to shield these particular areas. If displacements of a superstructure should be less than those of the ground, only severe damping in base isolators seems to be good. Otherwise, the structure has to use its own mitigating mechanism of ductility which means that the very goal of seismic isolation has not been achieved.

Normally, we recognize the inelastic resistance as a source of restricting ("damping") periresonant structural responses, but we disregard its another quality: being one of the two pushing mechanisms which transform the earth movement into the forces applied to the structure (the second mechanism is the stiffness).

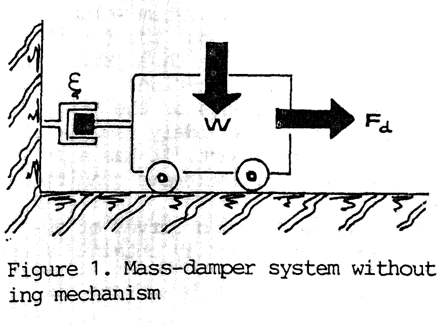

Figure 1. Mass-damper system without restoring mechanism

The destructive potential of damping devices is not a "paper tiger" at all (Shustov, 1991). As an example, consider a mass supported on rollers (Figure 1). The mass is connected to the ground through a viscous damper in absence of spring force. If the mass is disturbed from its equilibrium position by imparting an initial ground velocity $\dot{v}_{max} = gZ/w$ (effective peak ground velocity per UBC-91), the relative to the weight maximum value of the inelastic resistance could be written as follows:

$$\frac{F_d}{W} = \frac{2\xi\, w\, \dot{v}_{max}}{g} = 2\xi Z \qquad (1)$$

Assuming $\xi = 0.4$ and $Z = 0.4$, obtain:

$$\frac{F_d}{W} = 2 \times 0.4 \times 0.4 = 0.32$$

To account for near-fault location this value should be essentially increased. Any elements added to provide extra damping still aggravate the situation by causing high-frequency responses (Kelly, 1990). It is obvious that heavily damped seismic base isolators are not a remedy: they inevitably generate powerful pulses accompanied with violent jerks in the superstructure.

Then, the question arises: why we overlooked the negative effect of damping?

Routinely, we do not take into account that kinematic information from the ground is not transmitted to the top of the structure instantly but in a transient process of running waves propagation. We simply discount that real seismic loads are applied not in the points of lumped mass concentration but in the planes of contact of the structure with the shaking ground. In the case of base isolated systems, the stage when the running wave just covers the height of the isolator and the superstructure still remains undisturbed is of primary importance. By this moment the initial pushing force ("negative quality") associated with the velocity of lateral vibration and with the magnitude of the damping characteristic of the isolator has already developed, whereas the damping in the traditional sense of the word ("positive quality") has not. This effect cannot be distinguished with the help of the analysis which is usually employed in earthquake engineering due to its lack of sufficient resolving power.

In spite of the fact that the first attempts to isolate buildings from potentially shaky ground were probably made thousands years ago, the modern concept of seismic base isolation (flexible mounting + damping) is forein for earthquake engineering: it has not been inherited, it has been borrowed from mechanical engineering. Though the concept is working perfectly in all sorts of vehicles, in base isolation everything is not so smooth because the conditions in both cases are quite different. In a car, for instance, the working stresses in auto parts are far below there ultimate bearing capacities, therefore any overload associated with heavy damping is of no practical importance. Another matter is a building structure. It is intended to perform at a near-to-collapse level, and any extras could become crucial for its safety.

2 WAY OUT

There is an alternative to the contradictory damping mechanism of base isolators. It can be found in the utmost lessening the magnitude of inelastic resistance and in substituting its positive, mitigating quality with any sort of tuning out mechanism which satisfies the following requirements:

a. Let the earth move its way.
b. Prevent resonant amplification.
c. Restore the structure in its pre-earthquake position on the foundation.

A new concept embodied in the Antifriction and Multi-Step Base Isolation units (AF&MS BI) is just an alternative one (U.S. Patent 5,056,280). It incorporates the merits of the traditional flexible mounting but without its drawback - a compulsory damping mechanism.

To minimize transmission of the destructive earthquake energy into a structure, to prevent permanent horizontal post-earthquake offsets, to keep the system's ability to resist the wind pressure as well as minor

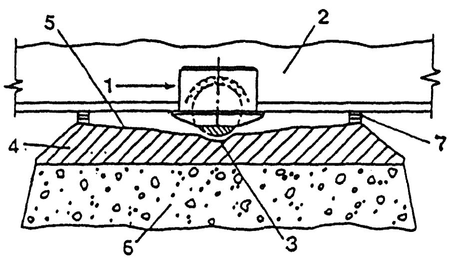

Figure 2. Antifriction and Multi-Step Base Isolation unit

earthquakes without being decoupled from its foundation, the AF&MS BI consists (Figure 2) of a ball transfer unit (1) supporting a superstructure (2) and resting on a depression (3) of a pedestal plate (4). The depression is shaped in compliance with the configuration of the contacting surface of the ball and is centered at the lowest point of the pedestal plate (4) having a concave upper surface (5) and resting on a foundation (6). The depth of the depression at given radius of the ball is governed by the weight of the superstructure and by the design wind load. The force of gravity will keep the superstructure in a steady position on the pedestal plate both at any wind and at slight earthquakes. When magnitude of the earth movement exceeds a certain threshold, the ball gets out of the depression and any transfer of horizontal movement to the superstructure considerably decreases. To seal the serviceable space above the upper surface of the pedestal plate against the dirt and agressive environment, as well as to withdraw the most of the weight from the ball-bearings in the static position (in between the earthquakes), a sliding pad (7) is provided all along the perimeter of the pedestal plate.

To confine the base shear by an acceptable level, the upper surface of the pedestal plate is shaped as a combination of spherical surfaces with successively increasing radii of curvature which are continuously transforming into each other (Figure 3). Maximum vertical grade of every component surface is pre-determined in compliance with the sliding friction of the ball transfer units and with the allowable base shear. Such design of the upper surface provides a multi-step non-destructive softening of the system which results in successive tuning-out the forcibly vibrating isolated structure thus protecting it against resonant amplification.

One of the main components of the AF&MS BI, the Ball Transfer Unit is widely used in stationary and mobile transport. It has a proven history of heavy duty and extreme conditions performance.

The static load-deflection curves of the AF&MS BI systems can be easily obtained with-

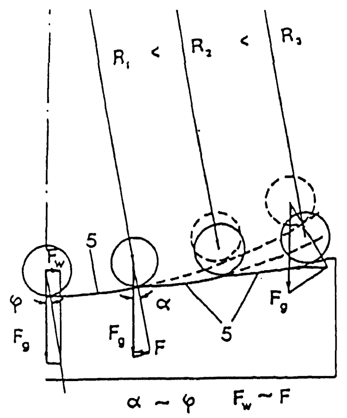

Figure 3. Fragment of a multi-curved pedestal plate with balls in the critical positions

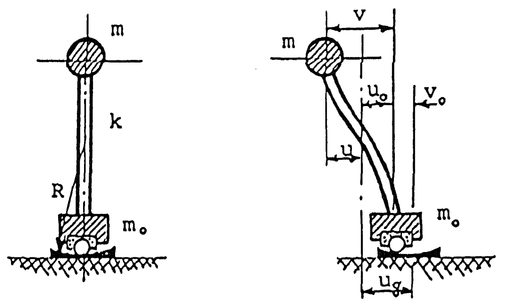

Figure 4. Theoretical model of the AF&MS BI

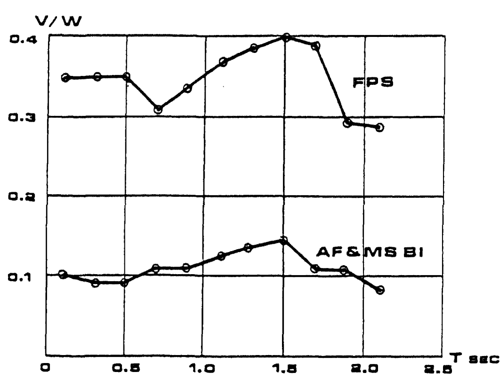

Figure 5. Base isolation spectra of shear for damping-dependent (FPS) and new (AF&MS BI) approaches

out any specific tests: this technology makes it possible to create isolators of any preset properties by merely changing their working surface configuration.

Another advantage of the AF&MS BI in comparison, for example, with rubber bearings is the absence of alternating eccentrically applied vertical base reactions which can excite damaging flextural stress waves.

3 HOW IT WORKS

Basic features of the AF&MS BI systems can be derived from the two-degree-of-freedom model shown in Figure 4 where the parameter u stands for absolute, and the parameter v - for relative displacements.

The equation of motion can be written in the form:

$$\begin{cases} m\ddot{v} + r\dot{v} + kv = -m\ddot{u}_o \\ M\ddot{u}_o + m\ddot{v} + (g/R)Mu_o = (g/R)Mu_g + fgM(\dot{u}_g - \dot{u}_o) \times \\ \times |\dot{u}_g - \dot{u}_o|^{-1} \end{cases} \quad (2)$$

where $M = m + m_o$
f is the friction factor,
R is the radius of curvature of the pedestal plate in the point of the ball's instant contact,
$v = u - u_o$

It is easy to see from the first equation that deformation of a superstructure is governed by the external force equal to the inertia force of the mass m rocking on isolators with the acceleration of the center of gravity.

The second equation reveals two components of the external force acting on a superstructure as a rigid body. One of them is proportional to the friction factor f and is acting opposit to the sense of relative velocity $\dot{v}_o = \dot{u}_o - \dot{u}_g$, another is inversely proportional to the radius of curvature R. As long as amplitude of $\dot{u}_o$ is less than that of $\dot{u}_g$, the so called "damping" force is more exciting than damping. Since the moment those values become equal, the further rate of excitation is mostly controlled by the "magic" R: any time the relative displacement v_o riches some preset boundary, the radius R sharply increases thus correspondingly decreasing the external force as well as changing the natural period of the isolated structure.

The computed results for comparison of two contrary concepts in sliding base isolation systems are shown in Figure 5. The first concept is represented by the established Friction Pendulum System (Zayas, 1990) with the following parameters: radius of curvature R = 50 cm, friction factor in isolators f = 0.1. The second concept is the AF&MS BI with the parameters: radii of curvature $R_1 = 50$ cm, $R_2 = 100$ cm, $R_3 = 200$ cm, $R_4 = 400$ cm, $R_5 = 800$ cm, friction factor f = 0.025. The logarithmic decrement of the superstructure in both cases is the same: $\delta = 0.1$.

The time history of the ground displacements used in the computation is governed by the equation

$$u_g = at \sin 2\pi \log_b \left[\frac{(b-1)\,t}{bT_o} + 1 \right] \qquad (3)$$

which represents a "merciless" regime of earthquake imitation based on the principle of consecutive transient resonances (Shustov, 1976). The maximum ground acceleration is taken equal to 628 cm/sec^2.

The comparison of the base shear response spectra for "friction" and "antifriction" seismic isolation systems vividly demonstrates indisputable advantages of the last.

4 CONCLUSIONS

Damping mechanism of any kind under kinematic excitation is simultaneously a driving one. Its "negative", pushing effect is immidiate, where as its "positive", dissipating effect needs more time to fully develop. Therefore, targeting low friction base isolation instead of heavily damped one is proving to be better rewarded.

This does not at all mean that the elimination of damping ability will automatically make a "good" isolator of a "bad" one. Damping reduction does not end in itself: it is a pre-condition for creation of isolation systems with greater frequency separation through a non-destructive softening mechanism.

REFERENCES

Kelly, J. 1990. Base isolation: linear theory and design. Earthquake Spectra, Vol.6, No 2, pp.223-244.

Shustov, V. 1976. Method of earthquake imitation. Certificate of invention No 552 581, USSR, Intl. Cl. G 01V 1/00.

Shustov, V. 1991. New approach to seismic base isolation. Proc. 6th Canadian Conf. on Earthquake Engineering, Toronto, Canada.

Shustov, V. 1991. Multi-step base isolator. US Patent 5,056,280.

Zayas, V.A., Low S.S. and Mahin S.A. 1990. A simple pendulum technique for achieving seismic isolation. Earthquake Spectra, Vol.6, No 2, pp.317-333.