ELEVATED BUILDING FOUNDATION AND EARTHQUAKE PROTECTOR: NEW FEATURES IN PASSIVE STRUCTURAL CONTROL

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Abstract

The devastating forces of Earth shaking are one of the major problems of the modern civilization. Development of effective, reliable, and inexpensive earthquake-protective technologies may be considered a primary goal of the structural engineering. The latest research at the California State University, Northridge, Department of Civil Engineering and Applied Mechanics, gave rise to the innovative passive control technologies called Earthquake Protector and Elevated Building Foundation which will be described in this paper. These technologies, while working together, may enhance each other's effects and shield the protected building both horizontally and vertically.

State of art/practice

The earthquake-protective passive control devices called *base isolators* often perform a way below the expectations (Shustov, 1993 and 2000). Besides, those devices are, mostly, targeting the protection against horizontal impacts. The vertical components of an earthquake either remain unattended or require rather some intricate system of isolators (Suhara et al, 2004).

Novel Contributions

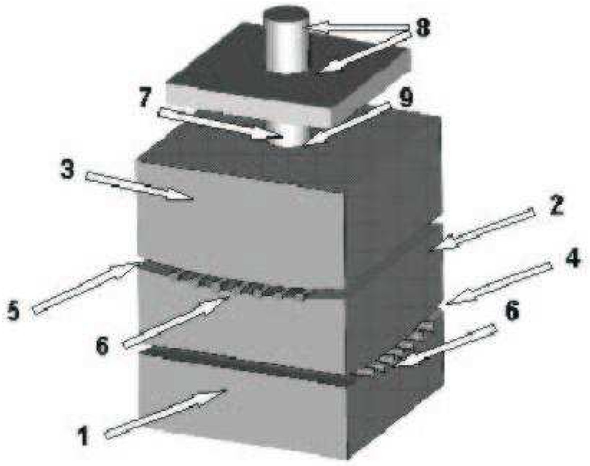

Figure 1. Earthquake Protector.

EARTHQUAKE PROTECTOR (U.S. Patent pending). A system of structural elements called *earthquake protectors* is resting on a building footing and underpinning a building superstructure **8** (Figure 1). The system is intended to shield the building superstructure **8** against lateral impacts of strong earthquakes. Each *earthquake protector* (EP) comprises: three properly configured race pads **1**, **2** and **3** mounted one over another with the lower pad **1** resting on the footing; two circular-cylinder-shaped segmented slide tracks **4** and **5** which are sagged down, located between adjacent race pads and containing freely revolving parallel cylindrical rollers **6** with their axes of rotational sliding being set horizontal and mutually orthogonal; a column stub **7** resting upon a self-lubricating spherical bearing **9** mounted centrically on the upper pad **3** with the top end of the column stub being framed rigidly into the supported superstructure **8**.

During an earthquake, any one-dimensional horizontal movement of the footing is resolved into two orthogonal components, by the following steps: first, the pad **2** will slide on the pad **1** in one of the orthogonal directions relative to the footing; then, the pad **3** will slide on the pad **2** in another orthogonal direction relative to the footing. Finally, a two-dimensional acceleration will be developed and applied to the bottom of the building superstructure **8**.

After the earthquake intensity exceeds a certain threshold, the *earthquake protectors*, due to their controllable isolating periods and extremely low coefficient of friction, will transmit a considerably reduced shearing force and bending moment into the superstructure (Shustov et al, 2004). As a result, it may permit quasi-independent excursions of the footing and superstructure thus preventing any sizable lateral deformations (so called "story drifts") in the protected building superstructure **(**see, e.g., http://www.ecs.csun.edu/~shustov/EP-2005.htm**).**

ELEVATED BUILDING FOUNDATION or EBF (U.S. Patent pending) may help to mitigate both horizontal and vertical shaking of a building superstructure. The new concept (Figure 2) incorporates a massive horizontal plate **1** comparable in weight to the building superstructure and supported above the ground on abutments **2**; those abutments resting on individual footings in the ground **3**. The top surface of the plate **1** bears a protected superstructure **4**. A lower impedance of the seismic waves that propagate vertically via the horizontal stratum encompassing the abutments **2**, in comparison with the stratum of footings in the ground **3** or the stratum of plate **1**, makes transmission of the high frequencies seismic energy into the superstructure 4 furnished with EBF to be decreased considerably.

Figure 2. Elevated Building Foundation.

During an earthquake, both P- and S-waves propagating from the ground vertically into the building superstructure **4** will have to go first through the strata **3**, **2**, and **1**, which constitute EBF, having an effect of a seismic barrier that mitigates all high frequency components of earthquake shaking.

Material, dimensions, and configuration of each EBF should satisfy a requirement of proper vertical load bearing capacity and that of the adequate compression and shearing forces being transmitted through the EBF into the building superstructure **4**. Unlike most of its predecessors, the EBF should be equally effective for any direction of shaking, and relatively simple for both construction and reconstruction.

Besides, EBF incorporates no moving parts, remains ever ready for performance, and does not require any maintenance during a lifetime of a building structure.

Concepts Validation

To verify validity of the new concepts of seismic protection experimentally, a few 1/8th–scaled models of multi-story buildings on the Earthquake Protectors and with the Elevated Building Foundation had to be subjected to an extensive shake table testing. Therefore, on May 23, 2006, a new research project entitled "SGER: Testing of a New Line of Seismic Base Isolation" entered its experimental stage at the UC San

Diego Large High Performance Outdoor Shake Table (see http://nees.ucsd.edu/). This research is sponsored by the National Science Foundation (Award No.: CMS-0618183) with the operational support of The George E. Brown, Jr. Network for Earthquake Engineering Simulation.

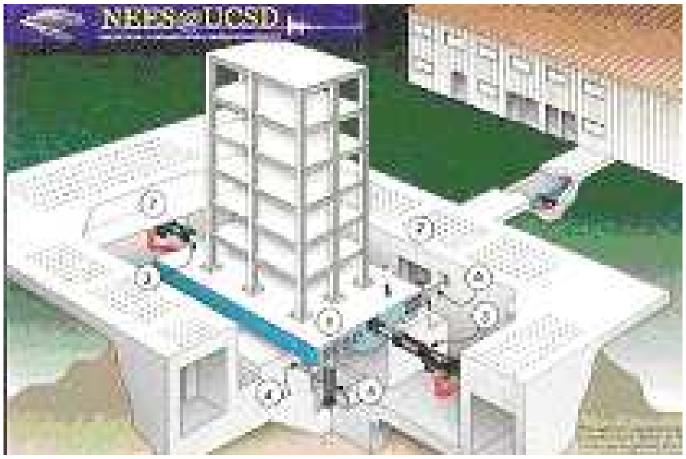

Figure 3. LHPOST at UCSD.

Main technical characteristics of the facility:

- Size of platen	7.6 m x 12.2 m
- Stroke	0.75 m
- Peak velocity	1.8 m/s
- Force capacity	6.8 MN
- Frequency bandwidth	0-20 Hz
- Vertical payload	20 MN

LHPOST is a participant of the George E. Brown Jr. Network for Earthquake Simulation (NEES) and located 15 km away from the main campus of UCSD (Figure 3).

As so far, there have been three building models of identical design to be tested, namely: a 6-story, a 12-story and an 18-story one. The most prominent features of those models are:

- They are built by a group of civil engineering students from the California State University, Long Beach with the full logistical support of Basseri Engineering (Figure 4).

- They are kinematically equivalent to their real building prototypes which means they will deflect horizontally the same way under the same horizontal excitation.

- Each model is an assembly of rigid floor slabs and prefabricated wooden columns one-story high supporting those slabs and tightened together with them with the help of a vertical prestressing through a post-tensioning by external tendons.

- The "prestressing" concept of the building models design was chosen to increase those models' structural redundancy while preserving their visual sensitivity to any kind of lateral excitations.

Figure 4. Building model erection.

Protective System

In order to be able to withstand the real earthquakes' time-histories of accelerations, the model earthquake protectors had to have their horizontal dimensions equal to those of real ones. Besides, to perform properly with the building models, it was necessary to have at least four EP installed (Figure 5).

Figure 5. Four earthquake protectors in the process of assembly.

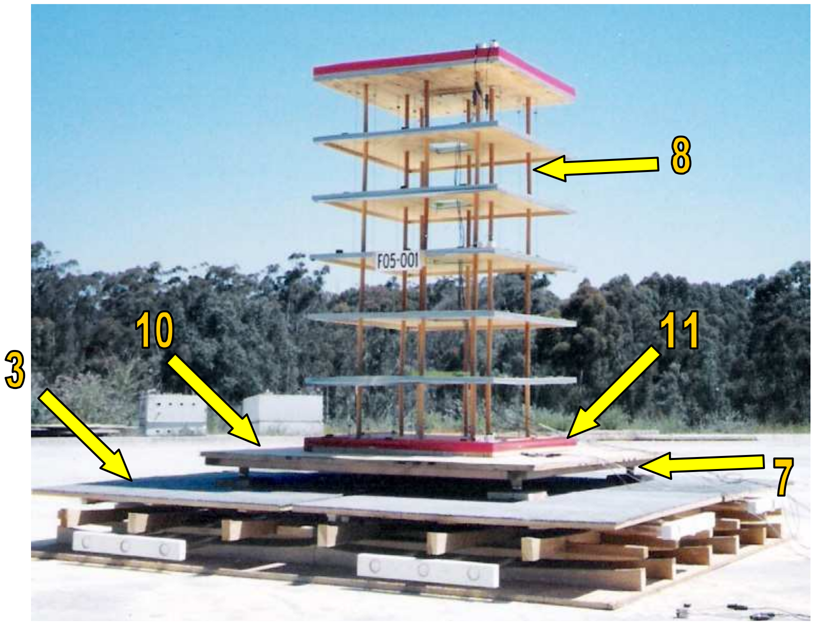

Figure 6. 6-story model supported on four EP.

To create an effect of a rigid framing into the supported superstructure **8**, the top ends of the four column stubs **7**, corresponding to the four EP, should be fixed to a bearing plate **10** (Figure 6). In general, this plate **10** will coincide with the ground floor diaphragm **11**. In our case, due to the fact that the footprint of the building model was considerably less than the bearing area, the ground floor diaphragm **11** was simply resting on top of the bearing plate **10**.

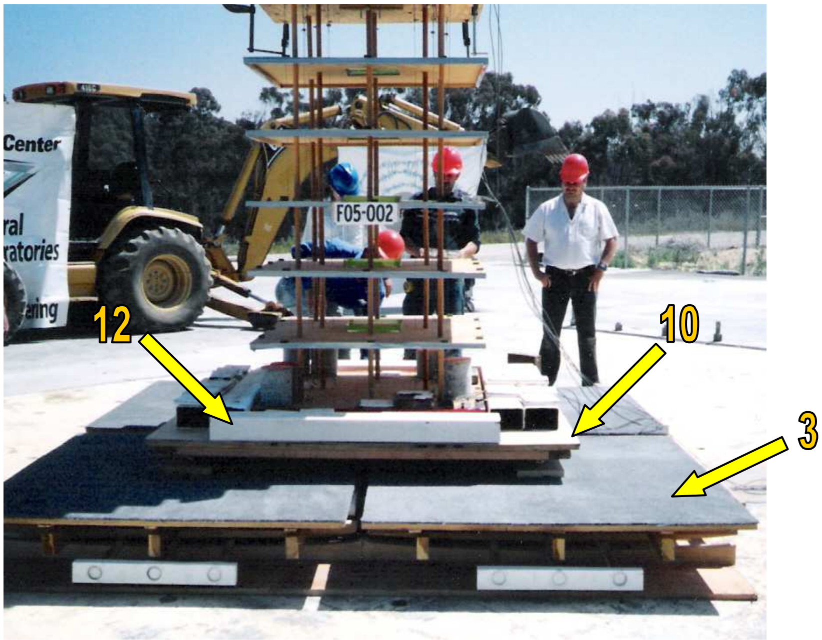

Figure 7. 18-story model on four EP with a EBF imitation.

For the imitation of an Elevated Building Foundation effect, a surcharge **12** was uploaded symmetrically on the bearing plate **10** (Figure 7).

Rollers Testing

One of the major components of the earthquake protector are the rollers which should revolve freely in two orthogonal directions. Besides, the rollers should carry the dead and live loads of the superstructure and may be subjected to severe impact loads. Therefore, prior to the shake table testing, the static tests were performed to determine the allowable bearing capacity and the short and long term deformation of the rollers under the applied loads.

For the purpose of the current research, the test specimens were of 2” diameter × 12” made of acrylic plastic. The plastic rollers were tested on a hydraulic testing machine at the Department of Civil Engineering and Construction Management, California State University, Long Beach (Figure 8).

Figure 8. Acrylic roller testing.

Results of the static testing show that up to the load values equal to 3500 lb, the lateral compressive deformations of a roller do not exceed 1%. In comparison with the other materials tested, namely, the softwood (pine), hardwood (oak), and steel pipes, the acrylic plastic seems to be the most suitable material for the rollers. It provides both a high load bearing capacity and excellent resistance against corrosion and decay at the exposure to weather, water, termites and chemicals. Due to this, the acrylic plastic rods of d = 2” were used as the rollers in the reported research.

Preliminary Testing

The NEES/LHP Outdoor Shake Table is a single DOF testing facility which makes it, seemingly, no good for the intended two-dimensional testing. However, if the tested earthquake-protective module **13** is positioned diagonally on the shake table platen **14** (Figure 10), then any one-dimensional horizontal movement of the shake table will be resolved in each EP into two orthogonal components. Eventually, two-dimensional horizontal accelerations will be developed in each EP and applied to the bottom of building superstructure.

Figure 9. Building model without EQ protection.

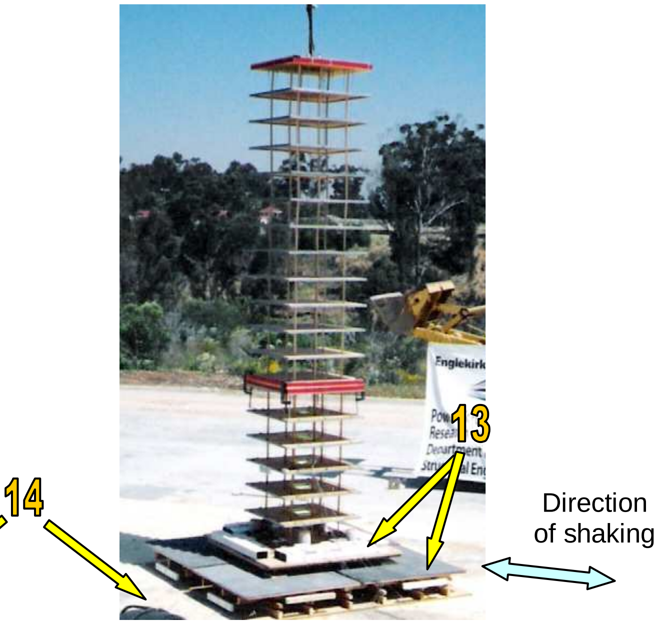

Figure 10. Building model equipped with EP and EBF.

At the first stage of the testing, only time-histories of a few California strong earthquakes such as the 1971 San Fernando and 1994 Northridge were engaged. During those experiments, both the earthquake intensities and additional loads contributing to the EBF were variables. The EBF effects were monitored with the help of a new factor called the *EBF coefficient* **n** equal to $\mathbf{W_L / W_M}$ where $\mathbf{W_M}$ was the weight of the building model (superstructure) and $\mathbf{W_L}$ was the surcharge **12** on the bearing plate **10** (see Figure 7). Some provisional results of the first series of shake table experiments may be observed from the graphs in Figures 11 and 12.

Thus, the graph in Figure 11 demonstrates a considerable mitigating influence of the EBF surcharge value on the maximum horizontal accelerations recorded at different levels of the 6-story model subjected to the 1994 Northridge earthquake (NR-100%).

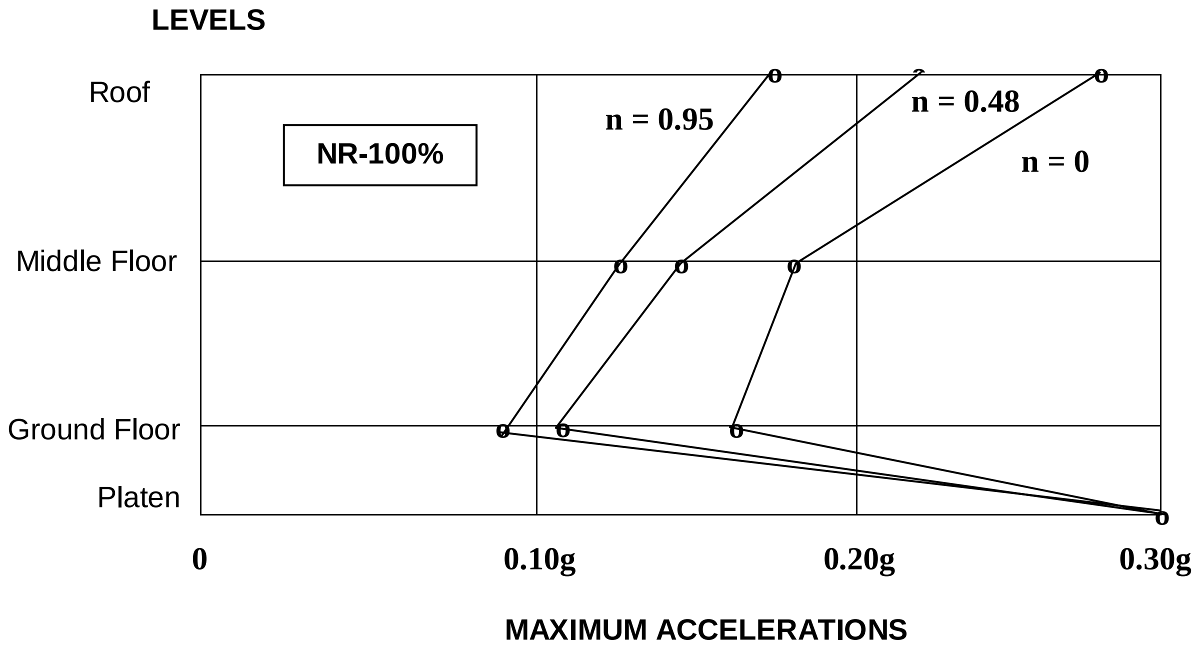

Figure 11. Building model accelerations vs. EBF coefficient n.

The graph in Figure 12 represents a snapshot of the maximum horizontal accelerations corresponding to up to the three-fold intensities of the same Northridge earthquake, namely, of NR-100%, NR-200%, and NR-300%. Surprisingly, the 6-story model on Earthquake Protectors with the *EBF coefficient* **n** = 0.48, almost ignores those huge inertia forces on the surface of shake table and responds with no more than a 25% increase of the superstructure accelerations to the 300% increase of the earthquake magnitude.

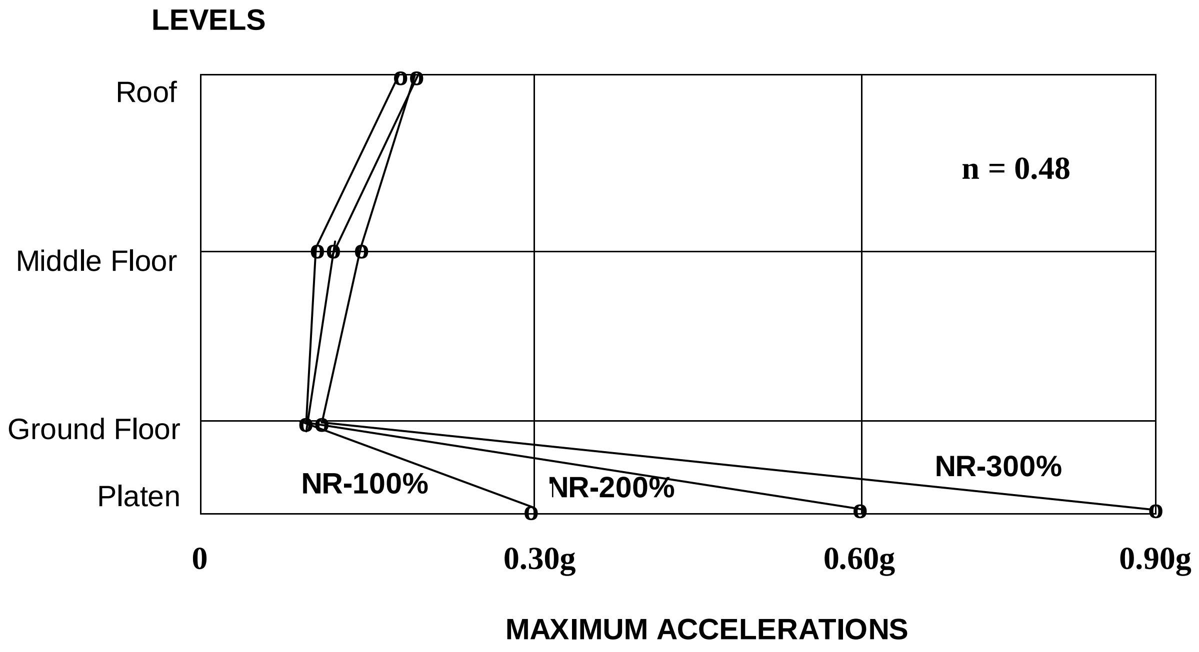

Figure 12. Building model accelerations vs. earthquake intensity.

Comparative Demonstration

To compare a seismic performance of the building models with and without new technologies, it would be persuasive to test some two identical models, like those shown in Figures 9 and 10, simultaneously. However, by the time the TV crews from the local CBS, NBC and ABC stations came up to the LHPOST site for the coverage, there were only 6- and 12-story models available. Therefore, the more earthquake-vulnerable 12-story model was put on EP with EBF while the relatively stiff and stable 6-story one was fixed directly to the shake table. The moment of truth is presented in Figure 13.

Figure 13. Building models with (right) and without (left) earthquake-protective devices.

Conclusions

This research will continue. However, it is obvious now that the Earthquake Protector and Elevated Building Foundation technologies, while working together, may enhance each other's effects and protect the buildings both horizontally and vertically.

Acknowledgements

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