Paper No. 93. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

IMPLEMENTATION OF A HYBRID BASE ISOLATION SYSTEM WITH BREAKING FEATURES

DOUGLAS WAY, KAI-CHEN TU and FARZAD NAEIM

Base Isolation Consultants, Inc. and John A. Martin and Associates, Inc.

ABSTRACT

It has been acknowledged that base isolation can provide a level of protection against earthquake damage that is superior to conventional fixed-base design, especially in the area of building contents. A trend is developing in California to isolate hospitals as indicated in the planning of over 2 million square feet of health care construction in California to date. This is partly due to California's Hospital Safety Act, which requires that all hospitals remain functional "as far as practical" after an earthquake. As more installations are constructed and their performance during actual earthquakes assessed both in California and abroad, the attenuation benefits of the isolation systems have been demonstrated. Current code requirements in the area of base isolation mandate full scale testing of the devices, resulting in stringent requirements in the fabrication of the isolators. The one debatable Achilles heel of the strategy stems from professional uncertainties in regard to near-field earthquake effects. Since data on this subject is lacking, especially for magnitude 7+ events, the approach taken by most regulatory agencies is to incorporate conservatism in the design. This is normally achieved by increasing the velocities of the design response spectra over the long period range. The problem with this approach is that while the isolation system and its associated superstructure can be designed to remain stable for an over-conservative design earthquake, the attenuation features of the system is compromised for lesser events, the occurrence of which is more probable. The challenge to the design profession is now to design systems that incorporates the conservatism that the profession seeks at near-field sites, and at the same time produce effective attenuation features for the lesser events. The design at the Martin Luther King Medical Center begins to address this challenge.

KEY WORDS

Base Isolation; friction; damping; hybrid system; brake

INTRODUCTION

Base isolation is a strategy for earthquake protection whereby the building is decoupled from damaging earthquake ground motions. The devices used in base isolation design involve different types, the most common of which are elastomeric bearings. These isolators are usually configured by controlling the elastomeric layer thicknesses such that their horizontal stiffness is much lower than their vertical stiffness. Steel shim plates are configured between elastomeric layers in such an assembly. The purpose of this design is that a low horizontal stiffness is required to bring the horizontal frequency of the isolated structure to a level that is away from the damaging energy levels of earthquakes and a high vertical stiffness is desirable so that the structure does not rock during an earthquake. Additionally, damping is desirable in an isolation system involving elastomeric bearings in order that horizontal displacement demands of the isolation system are reduced. Reasonable degree of damping in the elastomer mixing process. The degree of damping in the elastomeric bearing will vary depending on the shear strains in the elastomer, ranging from relatively high damping at the low shear strains to lower damping at higher shear strains. If additional damping is required of the isolation system beyond what can normally be achieved through the elastomer, friction dampers can be added to the system of elastomeric bearings to form a hybrid design. These dampers transform earthquake energy into heat which dissipates into the structure. The devices can also be configured for "breaking" features in the event that large displacements are reached, thereby providing "restraining" capabilities to the system. Such a hybrid design has been implemented at the Martin Luther King Medical Center in Los Angeles, California.

MARTIN LUTHER KING MEDICAL CENTER

The Martin Luther King Jr./Charles R. Drew Medical Center (MLK) is a 5 level Trauma Care and Diagnostics Imaging Center located in the County of Los Angeles. Situated within a seismically active area of Southern California and within two miles of the Newport Englewood Fault, it is equipped with a hybrid isolation system of 70 high-damping rubber (HDR) bearings in combination with 12 friction dampers. Volume-wise the HDR bearings are among the largest that have been successfully fabricated, tested and installed to date. They measure 40 inches in diameter with a height of 23". The building is designed for near-field effects from the Newport Englewood fault. Design displacement for the isolation system based on near-field ground motion considerations was 22 inches. See Figure A for the plan of MLK's isolators.

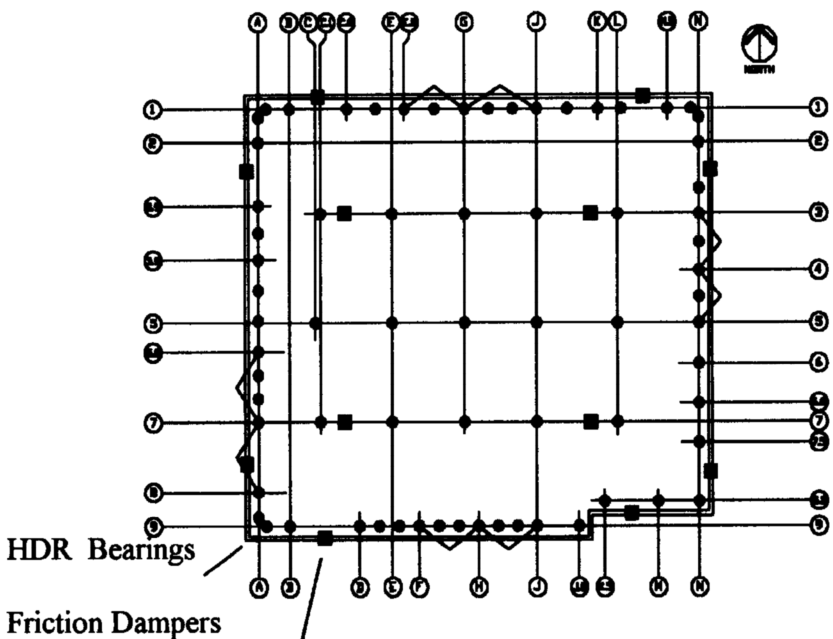

Figure A - Plan of Isolators

In regard to the MLK friction dampers, the design involves the use of a lead-bronze alloy against stainless steel contact surface. Lead-bronze is desirable in a friction damper design in that the material continually self-lubricates with a mixture of lead and its oxide when rubbing against a metal surface.[11] This phenomenon results in a predictable coefficient of friction value between the two surfaces that is independent of velocity, which is desirable from an analytical and performance point of view. The actual value of coefficient of friction will depend on the roughness and type of the material in contact with lead-bronze and the surface treatment of the lead-bronze. The initial coefficient of friction for the MLK friction dampers was measured to be 0.23±0.02 under varying vertical loads during full scale prototype testing. The same value was obtained from retesting after the dampers were allowed to weather for 16 months in Houston, Texas, during which they were subjected to the elements including the Texas rains and humidity.

In the MLK design, flat jacks placed under the damper prestress the surface which bears against the perimeter 2-

story concrete shear wall. The lead-bronze and stainless steel contact surface is also selected because of their corrosion-resistant features. The stainless steel is of a surgical grade. The design incorporates a shear lug which is required to transfer the horizontal friction force into the foundation. A vertical spring in the form of an elastomeric pad is incorporated to control the vertical stiffness of the damper. Such a feature is important for three reasons. First, if the design is placed under a lateral load resisting element which can rotate about the base, the damper can be configured for an axial stiffness which is significantly less than the main elastomeric bearings so that the overturning forces are resisted mainly by the bearings, unaffecting the axial or prestress load on the damper. The damper is designed such that it can be prestressed against the structure to achieve a predictable slip load since the coefficient of friction between the contact surfaces are constant. Second, an elastomeric spring can be designed to bulge laterally by proportioning its shape factor. This bulging phenomenon can serve as a visual indicator that the prestress or vertical load on the damper is in effect. Third, there may be instances where one requires a certain vertical stiffness in the damper because of its interaction with other parts of the structure, for example when the damper is prestressed under a beam. In this case the axial stiffness of the damper needs to be properly coordinated with the flexural stiffness of the beam so that the desirable prestress force on the contact surface is achieved. By vulcanizing the elastomer to the lead-bronze plate, the elastomeric spring becomes an integral part of the damper. Additional steel shim plates can also be incorporated as part of the elastomeric spring to control its axial stiffness. Prestressing of the damper is achieved through flat jacks pressurized and grouted with epoxy and left in place. The damper is also designed for the effects of shortening of heights of the main bearings. Such an effect occurs when the bearings supporting the structure shift laterally during an earthquake. The reduction in height of the bearings is due to reduction in axial stiffness and movement in the volume of elastomer during this shifting action. The net effect of a system with elastomeric bearings undergoing this relatively slight height reduction is that the friction dampers, which have an elastomeric spring, will be subjected to additional vertical loading as a result of this slight "drop" of the structure. The additional loading will cause the damper to exhibit additional horizontal stiffness, the coefficient of friction in the friction damper being relatively constant. As a result, this hybrid isolation system of elastomer bearings in combination with friction dampers will exhibit a horizontal stiffening effect like brakes which will add damping to the system, and thereby reduce the horizontal displacement demands on the isolation system. A "waffle" pattern is tooled into the lead-bronze surface to prevent the "slip-stick" phenomenon that occurs in most friction surfaces and to provide troughs for the collection of lead particles that migrates to the surface during shearing of the damper, and dust. Air under pressure can be used to remove these substances from the waffle-patterned troughs. Finally the fact that the friction dampers are prestressed after all the HDR bearings are installed with their stiffness recorded means that the prestressing operation can be used to "fine-tune" the stiffness and damping characteristics of the isolation system. Figure B shows a photo of the MLK friction damper.

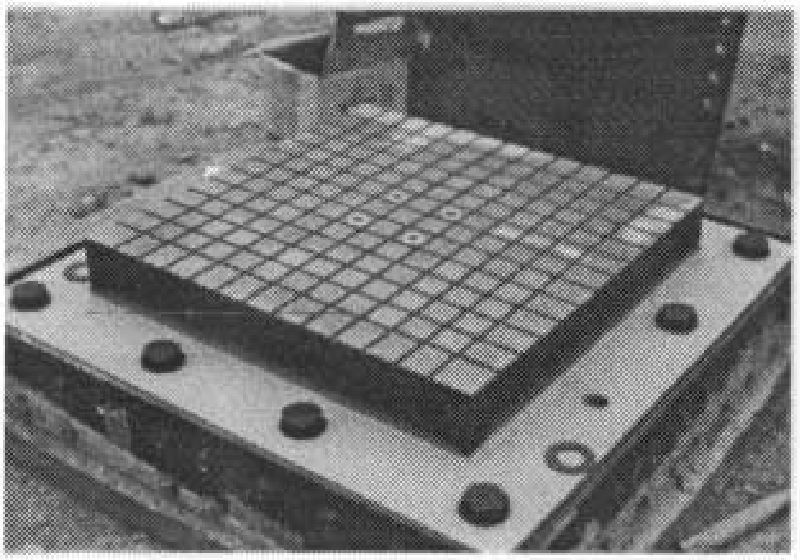

Figure B - MLK Friction Damper

The structure is a 5 story building with a mechanical penthouse located at the upper roof and a full basement. It is a steel structure with braced frames configured at the perimeter to resist lateral loads. Concrete over metal deck is the floor construction. A two story concrete wall exists at the perimeter from the basement level to 2nd floor level to create rigid base for the braced frames. Essentially what has been developed is a 2-story concrete box with 3 intersecting concrete diaphragms. The steel braced frames cantilever from this box.

HDR isolators are located below the basement floor. Most of the friction dampers are located at the perimeter to reduce both translational and torsional response of the structure.

BIC's N-PAD [10] program was used in the execution of the non-linear time history analysis. HDR bearings was modelled as bi-linear elastic elements, friction dampers as two dimensional non-linear element (elastic plastic). Damping in the HDR bearings was assigned as a constant equivalent viscous damping coefficient on a local basis (for every pad). Damping in the friction dampers were taken into consideration as cyclic non-linear hysteretic damping. N-PAD, which uses direct integration techniques for the base, also performs a modal analysis of the superstructure for every time step. Pads are formulated in accordance with "strain space plasticity" theory [12].

LOOPS, a subroutine of N-PAD, was used to check N-PAD's output. For every cycle in the time history analysis, LOOPS generates an equivalent stiffness and damping value. The latter is based on the area of the loop and the equivalent stiffness calculated. With LOOPS one can compare the results from the time history analysis, which usually encompass a range of displacements, against test results. By summing all the areas of the loops for one of all of the friction dampers associated with a particular time history, one can calculate the energy or heat dissipated associated with one or all the friction dampers. Figure C shows the N-PAD MLK structural model.

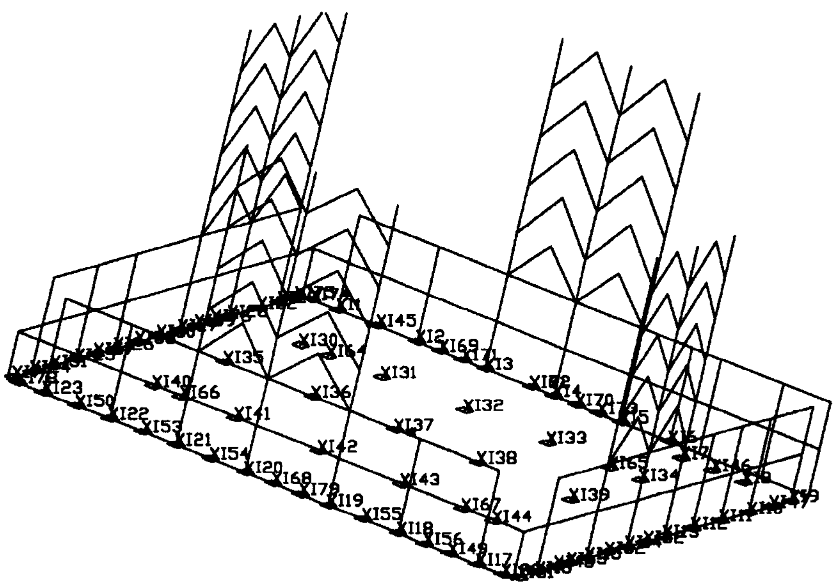

Figure C - N-PAD Model of MLK

HIGH-DAMPING RUBBER

BIC's 243-62 compound, which is on file with LTV of Arlington, Texas, was used in the bearings. The compound was first used for BIC's Foothill Communities Law and Justice Center Project in San Bernardino, California [1]. It has been subsequently used for the 911 Facility [3] for the County of Los Angeles and BIC's Mackay School of Mines Project [4] at Reno, Nevada. Small samples of the rubber were tested at various frequencies. Test results in the form of hysteresis loops are shown in Figure D.

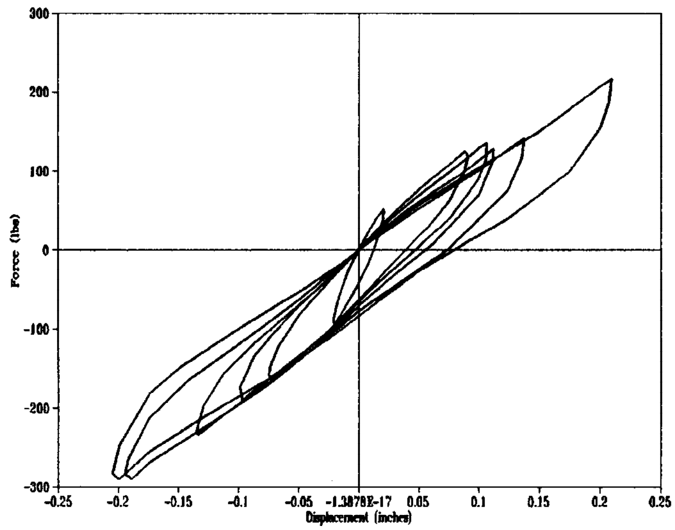

Figure D - 243-62 HDR Hysteresis Obtained at 0.5 Hz

The stiffness of rubber will increase as the material ages. Until recently it has not yet been fully known at what rate and to what extent high-damping rubber recovers from scragging over time, and how much additional stiffness is caused by aging. A 10 year evaluation period is recommended to asses these phenomenon. Now, the Foothill Communities Law and Justice Center HDR bearings, fabricated from BIC's 243-62 compound, are in the process of being evaluated to determine these effects at the Earthquake Engineering Research Center (EERC) in Richmond, California [8]. To date, only one of the four original prototype bearings has been tested. Preliminary results show that stiffness over the 9 year period from initial testing to present has increased by 4%. To what degree recovery from scragging and aging have combined to contribute to the increase has yet to be determined, but the associated effects from both phenomenon are minimal.

The damping measured in small samples are higher than that for the prototype bearings. Since the damping in the small samples was measured at 0.5 hz and the prototype bearing results were calculated from force-vs-displacement plots derived data obtained from tests which were run at over 8-minute cycles, the actual damping in the bearings during an earthquake would be closer to those values obtained from small samples. A mean value of 10% damping was assumed in the N-PAD analysis for the HDR bearings. Another feature of the bearings which needs to be considered is the participation of the shim plates in damping. At over 100% shear strain in the rubber (±15" of displacement in the bearings), the shim plates start bending, contributing to the damping in the bearing. This phenomenon is evident in the ±20" test results which exhibit a stiffening effect at these displacements.

TESTING AND QUALITY CONTROL

Full scale prototype isolator testing and production testing of all isolators were performed. The main purpose of the tests was to check for degradation in the stiffness of the HDR bearings and the horizontal stiffness of the bearings which depends mainly on the stiffness of the rubber. The specifications allow a ±15% swing in the stiffness of the rubber, so the horizontal shear stiffness of the HDR bearings could have varied by as much as 30%. This variation is not important. The more important feature is the total horizontal stiffness of the isolation system. After all the production bearings were tested (to ±15" in shear), they were located according to their measured stiffness. Testing of production bearings to the equivalent of 100% shear strain in the rubber was performed to check the bond between the rubber and the internal steel plates, and the bearings' vertical and horizontal stiffness. Figures J and K show plots of HDR and friction damper test results under lateral shearing respectively.

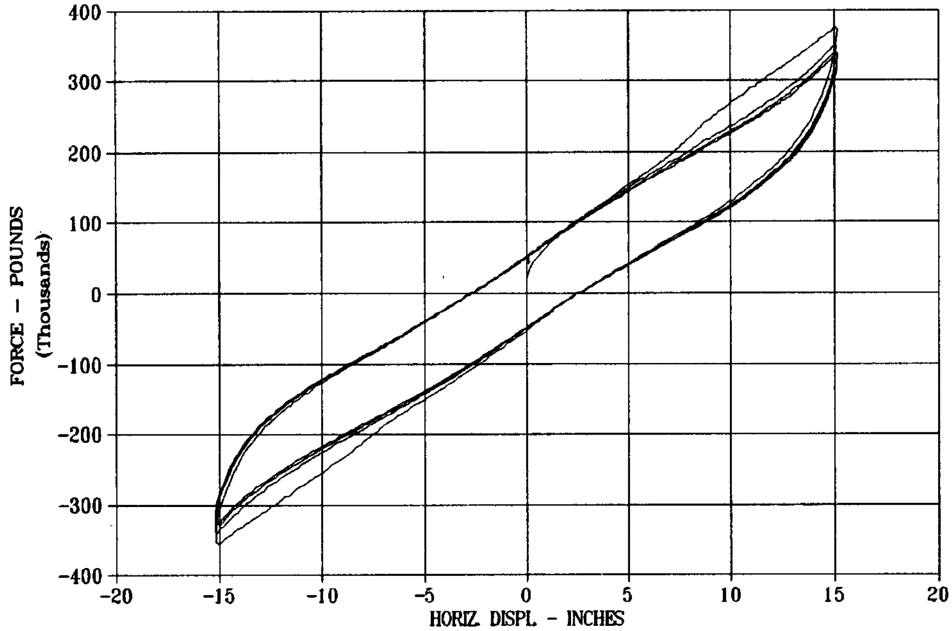

Figure J - Horizontal Force vs Displacement of 40" Diameter HDR Bearing

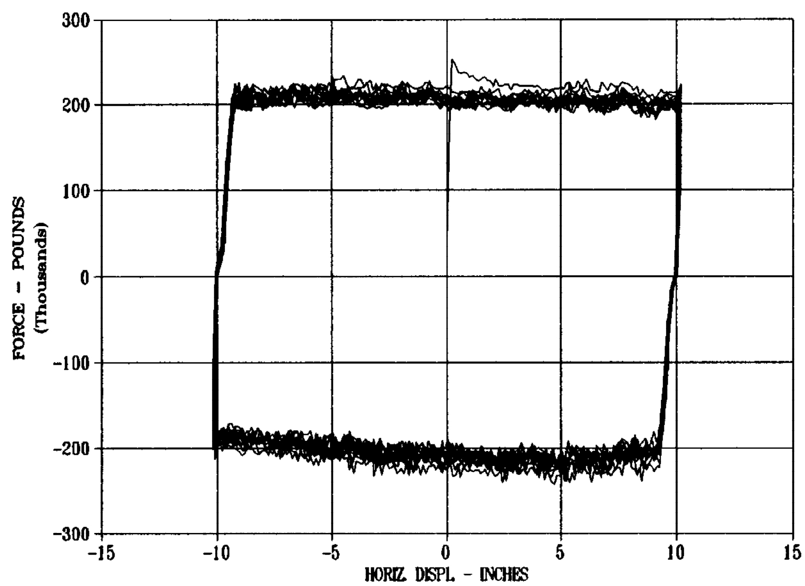

Figure K - Friction Damper Test Results - 10 Full Cycles Under 400 Kips Vertical Load

High-damping rubber must be consistently produced over the course of prototyping and production, during which for the MLK project the total quantity of rubber produced was in excess of 80,000 lbs. To achieve this consistency during the fabrication process, BIC performed quality control during production isolator fabrication. Quality control services is a must. Design is an important component and ensuring that the design criteria is met during production is just as important. It has been our experience in the providing quality control on a number of HDR isolation projects that a series of manufacturing steps need to be continuously monitored, and small rubber samples should be retained from each batch of rubber mixed for testing.

During the mixing and milling of high-damping rubber, additives are usually proportioned manually, and endow the rubber with fillers to achieve certain physical properties. Operator error in proportioning additives, in particular carbon black, can exacerbate variance in material property sets. Despite automatic weighing and checking capabilities, mistakes will be made. Verifying that the mixing operator is following the design recipe on hand at the mixing station, or monitored by computers is essential. Care must also be taken to avoid extended mixing and milling time which adds heat to the rubber, and decreases the rubber's stiffness and damping properties. In some cases, for large batch sizes, a two step mix may be necessary to avoid scorching the rubber due to the excessive amount of heat generated during mixing. In such a process, the majority of the additives, including the anti-oxidants but less the curatives, is mixed in one day to produce a mastic. The second step should occur the next day when the remaining additives are mixed into the mastic to produce the specified compound. In such methods, the total time the rubber is mixed and milled should be recorded. Small samples should be taken from each batch and tested prior to releasing the batch for use in bearing fabrication to ensure that the rubber has the required properties. Use of nonconforming batches of rubber can cause problems later on.

After the rubber has been manufactured, it should be adequately protected from various sources of contamination that will interfere with optimum bond with the steel shim plates. The rubber should be stored off the ground in an environment with reduced lighting conditions and proper temperature controls. While non-air conditioned environments may be acceptable at most times of the year for storage purposes, during hot summer months in humid conditions it is not. Over time under extremely warm temperatures and elevated humidity levels, the rubber will begin to bloom, which occurs when additives, mainly antioxidants, separate from the rubber and rise to the surface appearing as a gray film. Bloom will compromise the bond between the rubber and the metal parts. The amount of bloom should be limited to some small percentage of the sheet surface area before the rubber must be discarded. Some manufacturers will recalendar the rubber, blending the bloom material back into the rubber, but this can affect the material properties. There is no standard to evaluate the degree of bloom that is acceptable. It is best judged by an independent experienced quality control person. Also an environment with elevated humidity conditions will cause the rubber to sweat. The polyethylene sheeting placed on the rubber after mixing should mitigate this problem. Prior to placing the rubber in contact with the prepared metal surface, the rubber sheet should be wiped absolutely dry. Air conditioned environments should be maintained at 70°±5° F to avoid blooming and sweating.

PROJECT PARTICIPANTS:

Furon of Athens, Texas manufactured all the prototype and production isolators, including friction dampers. Elastomers were supplied by LTV of Arlington, Texas. Furon's test rig located in Athens, Texas was used to perform the tests associated with the HDR bearings and friction dampers. It is configured to be able to press a vertical load of 4000 kips while horizontal actuators can deliver 1000 kips with a ±24" stroke maximum. Additional limitations of the test rig are that it can not perform a tension test and maximum horizontal displacements it can accommodate is 23-24 inches.

Architects for the project are Landon Wilson and KDG of Los Angeles. Structural Engineers are John A. Martin Associates of Los Angeles. Seismic isolation design and quality control services were provided by Base Isolation Consultants of San Francisco. Los Angeles County is the owner.

REFERENCES

1. Tarics, A.G., Way, D., and Kelly, J.M., "The Implementation of Base Isolation for the Foothill Communities Law and Justice Center," Report to the National Science Foundation and the County of San Bernardino (Grant No. CEE-821758C), November 1984.

2. Way D., and Lew, M., "Design and Analysis of a High-Damping Rubber Isolation System (Case History of the Foothill Communities Law and Justice Center)," ATC-17 Proceedings of a Seminar and Workshop on Base Isolation and Passive Energy Dissipation (Funded by NSF Grant No. ECE-8419853), San Francisco, California, March 12-14, 1986, pp. 83-92.

3. Anderson, T.L., "Seismic Isolation for the Los Angeles County Fire Department," Seismic Engineering: Research and Practice, American Society of Civil Engineers, San Francisco, California, 1989, pp. 615-624.

4. Way, D., and Howard, J., "Seismic Rehabilitation of the Mackay School of Mines, Phase III, with Base Isolation," Earthquake Spectra, Vol. 6, No. 2, May 1990, pp. 297-308.

5. Rosenbaum, D.B., "Hybrid Isolation a First," Engineering News Record, The McGraw-Hill Construction Weekly, September 26, 1994.

6. Cho, D.M., Retamal, E., and Mann, D., "The Los Angeles County Emergency Operations Center, on High-Damping Rubber Bearings to Withstand an Earthquake Bigger than the "Big One," Proceedings of ATC-17-1 Seminar on Seismic Isolation, Passive Energy Dissipation, and Active Control (Funded by NCEER Grants 89-6003 and 91-5521, and NSF), San Francisco, California, March 11-12, pp. 209-220.

7. Payne, A.R., "The Dynamic Properties of Carbon Black-Loaded natural Rubber Vulcanizates. Part I," Journal of Applied Polymer Science, Vol. VI, Issue No. 19, 1962, pp. 57-63.

8. Kelly, J.M.., Draft paper in progress, January 1995.

9. Tarics, A.G., Kelly, J., Way, D., and Holland, R., "Quality Assurance and Control of Fabrication for a High-Damping Rubber Base Isolation System," ATC-17 Proceedings of a Seminar and Workshop on Base Isolation and Passive Energy Dissipation (Funded by NSF Grant No. ECE-8419853),San Francisco, California, March 12-14, 1986, pp. 455-464.

10. Way, D., and Jeng, V., "N-PAD - A Three Dimensional Program for the Analysis of Base-Isolated Structures," Seismic Engineering: Research and Practice, American Society of Civil Engineers, San Francisco, California, 1989, pp. 169-178.

11. Pavot, B. and Polus E., "Aseismic Bearing Pads", Tribology International, June 1979.

12. Yoder, P.J.., "A Strain Space Plasticity Theory and Numerical Implementation," P.h.D. Thesis, Caltech.