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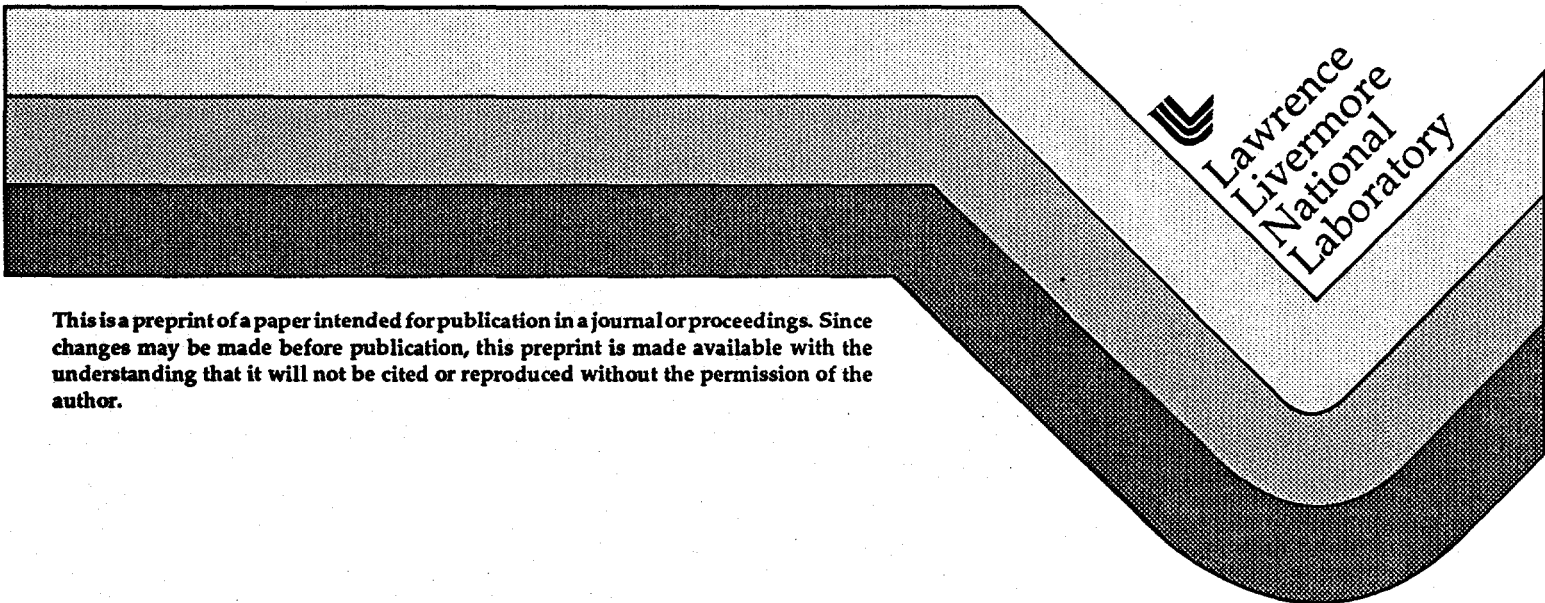
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**Seismic Shock and Vibration Isolation 1995
Part I: Theory, Analysis, and Testing**

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Seismic Shock and Vibration Isolation 1995
PART I: THEORY, ANALYSIS, AND TESTING

INTRODUCTION

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Two basic engineering strategies for the protection of equipment and structures from damages caused by seismic, shock and vibration loadings are, namely, strengthening and isolation. They work on almost totally different principles; the strengthening strategy aims primarily at increasing the "capacity" or the ability of the structure to withstand the dynamic loading by incorporating additional structural materials and components, while the isolation strategy focuses on reducing the "demand" or the transmitted loading on the structure by adding an isolator or isolation system between the structure and the source of the loading. The isolation strategy is also often used for filtering out unwanted vibrations and noises. In practice, the isolation strategy has the advantage of not depending on alterations to the isolated structure and is often the preferred method for applications in equipment and in some structures described in Part II of this publication.

All isolation designs operate on similar principles. The isolator placed between the source and the recipient of loading serves as a load regulator or decoupler; it modifies the amplitude and frequency and dissipates the energy of the transmitted loading. The isolation action usually causes the exchange of a larger isolator deformation for a lower force and stress in the isolated structure. Two papers in this publication detail the principle of seismic isolation. Robinson, in Chapter 1, describes the isolation benefit as the result of shifting the fundamental vibration frequency of the isolated structure from the frequency range of high seismic accelerations to a lower frequency range where the accelerations are lower. Mok and

Namba also in Chapter 1 show the isolation system to be like a "low-pass" filter which has low transmissibility for excitations whose frequencies are higher than the fundamental vibration frequency of the isolated structure. Thus the isolation effect can be accomplished by selecting an isolation system that reduces the vibration frequency to be sufficiently below the frequency range of high seismic ground motions.

Isolators can be active or passive. All isolators described in this publication for seismic isolation are passive and for isolation in the horizontal direction only. Four isolators are discussed in this publication: two are new ideas proposed by Hu, Kirmser, and Swartz and by Shustov in Chapter 4. The other two are well-developed devices and have been used for seismic isolation of buildings and industrial facilities; they are the rubber bearing and the friction pendulum system.

The "stiffness decoupler" isolation system proposed by Hu et. al. is like a flat-sliding-plate isolation system with a built-in self-centering device which returns the isolated structure to its original position at the end of each earthquake. Flat-sliding-plate bearings, used frequently in bridge designs to accommodate thermal expansion, are described by Lee, Hussain, and Retamal in Chapter 3. The bearings by themselves are not regarded as adequate for seismic isolation of buildings in that their isolation action would result in a residual displacement or a relocation of the isolated structure. However, the isolators are viable with the help of a self-centering device. Lee et al. suggest that the required self-centering capability can be provided by the hybrid fluid viscous

damper described in their paper. Shustov's "Shock Evator" design concept is also a sliding isolator but on a curved surface, and the needed restoring force is provided by the weight of the isolated structure.

Rubber is a favorite material for isolators, because of its flexibility and endurance to extremely large deformation. Both natural and synthetic rubber bearings have been used for seismic isolation. To support the large vertical loads, without excessive barreling deformation, bearings for seismic isolation are reinforced in the horizontal direction with steel plates in the form of a laminated rubber-steel composite material. The vertical stiffness of the bearing can be increased by increasing the ratio of the loaded area to the free surface area of the rubber layers (shape factor), and the horizontal stiffness can be reduced by decreasing the area-to-height ratio (or aspect ratio) of the bearing. Robinson, in Chapter 1, lists isolators that have been used for seismic isolation in the world, and rubber bearings of several varieties are clearly in the majority. Reflecting this popularity, this publication contains more than several papers discussing the measurement, control, and prediction of mechanical properties of rubber bearings.

In Chapter 5, Murota and Yoshizawa demonstrate the feasibility of predicting the shear stiffness and damping coefficient of rubber bearings after vulcanization using a finite element heat transfer analysis and an empirical relationship between the rubber property and the vulcanization condition (time and temperature). Mazda, Ootori, Yabana, Hirata, and Ishida report results of dynamic tests of natural and high damping rubber bearings of small shape factor. The small shape factor (5 as compared to the usual value of 30) is intended to reduce the vertical stiffness and thus increase the vertical isolation capability of the bearings. The test results show that the properties of high damping rubber bearings, except the horizontal damping coefficient, are frequency dependent, and the breaking strain of the natural rubber bearing decreases with increasing vertical compressive stress. Ishizuka, Murota, and Fukumori show by testing that the operating axial pressure of a high damping rubber bearing can be increased from 65 kgf/cm² (923 psi) up to 120 kgf/cm² (1703

psi) without significant change in its horizontal stiffness, damping, and breaking strain. Thus it is plausible to reduce cost by using fewer bearings in an isolated building. Fujita, Ishida, Yoshizawa, Nishikawa, and Muramatsu develop an empirical method to determine the test temperature and duration for accelerated thermal degradation tests of rubber bearings. Applying the method, they show that rubber bearings tend to increase in stiffness and decrease in elongation with increasing age, but the changes in 40 years are insignificant. Kulak and Hughes performed a series of tests on three different high-damping elastomers manufactured by three different companies. The tests were performed to find the variations in stiffness and energy dissipation with strain level, loading rate, and cycle number. In addition, they performed tests to examine recovery characteristics of an elastomer. The test results can be very useful for designing seismic isolation bearings. Way and Greaves describe the fabrication process of high damping rubber and define the requirements for quality control during fabrication. In Chapter 8, Clark, Aiken, Kelly, Gluekler, and Tajirian describe a thorough series of tests of reduced-scale high damping rubber bearings for the U.S. Advanced Liquid Metal Reactor program. Horizontal and vertical load tests at several loading histories and rates are to be performed on bearings of several designs and two scales (1/8 and 1/4). They report that the bearings tested show stable and repeatable mechanical properties, and contrary to the foregoing test results by Mazda et al., only the damping property of one rubber compound shows a substantial increase with increasing loading frequency.

The foregoing papers on rubber bearings suggest that the mechanical properties of rubber bearings depend on more than a few factors: the bearing design; the rubber compound; the fabrication process; the loading rate, amplitude, and history; the age of the material, etc. Moreover, the effect of many of these factors are not well understood and quantified. Therefore, the quality and properties of the final product can only be verified by testing. The tests should be performed on virgin and "scragged" (pre-deformed) materials, statically and dynamically at various loading rates and conditions including

failures. The aging effects are being studied using accelerated thermal tests as discussed in the foregoing paper by Fujita et al., or using actual used bearings as discussed in the paper by Way and Greaves. All data indicate that the effect on the stiffness of the rubber is not significant.

The friction pendulum system is a sliding isolator, in which a self-lubricating slider moves along a concave spherical surface. The necessary restoring force for self-centering action is provided by the weight of the building. During an earthquake, the isolated structure will move, after overcoming the bearing friction, back and forth like a pendulum with a fixed period. In Chapter 7, Zayas and Low describe the theory, development testing and application of the friction pendulum system to industrial tanks. Further details of the development test and analysis of the system are given in another paper by Al-Hussaini, Constantinou, and Zayas in Chapter 4. The application of the system to the U.S. Federal Court of Appeals in San Francisco is described by Amin and Mokha in Chapter 6.

Although energy absorption or damping does not provide the primary benefit of seismic isolation, some damping in the isolation system is essential to suppress the possible resonant vibration of the isolated structure at its fundamental frequency, as shown in the paper by Mok and Namba in Chapter 1. The needed damping can be provided by using isolators with built-in damping like the high-damping-rubber bearings, lead-rubber bearings, sliding-plate bearings and friction-pendulum bearings; or by adding viscous dampers, steel-bar dampers, or lead-extrusion dampers to the isolation system. These dampers operate on different principles, but in general their behavior can be classified as displacement- or velocity-controlled. The viscous damper is a truly velocity-dependent damper while the steel damper is a truly displacement-dependent damper. All these dampers are mentioned in at least one or more papers in this publication. Two papers are devoted specifically to the discussion of dampers: Lee, Hussain, and Retamal in Chapter 3 discuss available linear and nonlinear fluid viscous dampers for seismic isolation and vibration control applications. The authors also

demonstrate, by analysis, the benefit of damping to a structure isolated with various isolation systems and describe some recent applications of the dampers in isolated buildings. Moteki, Ohtsuka, Hayakawa, Nakae, Noguchi, Sugisawa, and Hasegawa in Chapter 5 describe a steel damper and the development of a method for predicting its fatigue life.

As indicated in the foregoing discussions, many tests are needed in the development, fabrication, and application of an isolator or isolation system. Taylor, Shenton and Chung in Chapter 1 propose standard requirements for these tests. To this end, they classify the necessary tests into three categories: (1) Pre-qualification tests are tests conducted during the development. The purpose is to establish the fundamental characteristics of the isolator and the extent of their dependence on various load and environment factors. (2) Prototype tests are tests conducted prior to the fabrication. The purpose is to verify the design properties of the isolator. (3) Quality-control tests are conducted prior to the installation. The purpose is to verify the quality and consistency of the fabrication process. Prototype and quality-control tests are already required by the UBC code for isolated buildings and by the AASHTO code for isolated bridges, although no detailed requirements are specified. In Chapter 6, Sultan and Sheng describe a full-scale prototype test program to be conducted by California Transportation Department on isolators and dampers for highway bridge applications. The list of items to be examined in this test program represents the isolation-system properties of the greatest concern in applications: the stability, range, capacity, resilience, and resistance to service loads; energy dissipation; survivability in extreme environment; resistance to aging and creep; predictability of response, fatigue and wear; and size effects.

Full-scale dynamic tests of seismic isolators and isolated structures are limited by the capacity of available testing machines. Therefore, researchers and engineers look forward to obtaining empirical confirmation of the expected behaviors of isolated buildings by measuring and analyzing the response of isolated buildings during earthquakes. Several papers in

this publication were written for this specific purpose: Ishii, Moteki, Kawai, Yasui, Ishida, and Mazda in Chapter 4 summarize and analyze the response measurements of an isolated building in past small earthquakes. The same building is analyzed numerically in another paper by Ishida, Mazda, Moteki, Ishii, Kawai and Yasui in the same chapter, for the building's performance during a hypothetical, strong earthquake. Using data from small earthquakes, the first paper has projected an excellent performance of the building in large earthquakes, and the second paper numerically confirms this projection. Hueffmann and Sutton in Chapter 4 discuss the proper interpretation of earthquake response measurements of a 3-D isolated structure which is isolated in the vertical direction as well as in the horizontal directions.

Asher, Hoskere, Ewing, Van Volkinburg, Mayes, and Button in Chapter 4 present a thorough analysis of the response of the base-isolated USC Hospital during the 1994 Northridge earthquake. Analysis results are presented for the isolated building in the as-built condition and for the building as if it were not isolated (with its base rigidly attached to the foundation). Moreover, the results of the isolated structure are compared to the responses measured during the Northridge earthquake. The analysis and measured results show excellent agreements in time history and response spectrum at locations throughout the building. The comparison of the results of the isolated and un-isolated buildings show that the ratio of un-isolated to isolated building response varies from 3.1 to 9.6. Thus the protective benefit of isolation is very obvious. The 1994 Northridge earthquake produced one of the strongest excitations a base isolated building has ever experienced. The response of the USC Hospital during the earthquake has been upheld by some as a good demonstration of the benefit of base isolation but has also been ignored by others, declaring that the earthquake was not a critical test for the building (e.g., Shustov in Chapter 4). The thorough analysis reported in the Asher paper should be able to shed some light on this controversy.

In addition to the test requirements discussed earlier, the following major considerations for

the design of seismically isolated structures are discussed in this publication: soft sites, surface waves, near faults, upper-structure flexibility, upper-structure uplift, wind loads, and design analysis methods.

Soft sites, surface waves, and near faults can amplify earthquake ground motions in the low-frequency range where the vibration frequency of a typical isolated structure lies, and thus can reduce if not eliminate the isolation benefit. In Chapter 2, Graves and Somerville discuss the amplification in deep sedimentary basins. They show that the amplification in the basins is not only due to the soft deposits but also due to the trapping and focusing of the wave energy as surface waves. Only a 2-D or 3-D model taking into account the wave propagation and soil variations in the lateral directions can adequately describe the ground motions in basins. Results from 2-D models show a significantly greater amplification of the ground motions in the low frequency range that results from the conventional 1-D model. In the same chapter, Smith, Graves, and Abrahamson examine the effects of the rupture directivity of a near fault. They show that rupture propagation and fault slip toward the site can cause a large increase in the low-frequency ground motions normal to the fault. They described two methods to account for the effect.

A flexible structure may have very low vibration frequencies and therefore may not be able to receive significant isolation benefits. In Chapter 1, the analysis by Mok and Namba confirms this belief. They show that the upper-structure flexibility increases the transmissibility of seismic loads into an isolated structure and thus reduces the isolation effects. The degradation of the isolation will increase with decreasing separation between the fundamental frequencies of the isolated and un-isolated structures.

An isolated structure should have lower overturning moment than the same structure un-isolated, due to the overall reduction and redistribution of the earthquake forces in the isolated structure. However, since sliding isolators have no resistance to tensile loads while rubber bearings have low resistance, the possible uplift of isolated structures during earthquakes

should be evaluated and possibly restrained. In Chapter 4, Wang, Amin, and Mokha analyze the factors affecting the uplift and the restraint effect provided by link beams and floor diaphragms on the response of isolated structures. They conclude that base uplift does not necessarily occur for a slender isolated structure on a sliding isolation system and a full uplift restraint would reduce the effectiveness of the isolation system.

A seismic isolation system should have sufficient rigidity for resisting the lateral force generated by winds. Lead rubber bearings and steel dampers are commonly used in the isolation system to meet the requirement. Hart, Lobo, Srinivasan, and Asher in Chapter 3 explore a new approach: using viscous dampers in the upper structure to reduce the wind-induced vibration response of an isolated structure. Their numerical analysis results show that the maximum displacement can be significantly reduced by employing a limited number of dampers.

The 1991 Uniform Building Code specifies a static procedure for calculating and distributing lateral forces in isolated structures, which is similar to the existing procedure for un-isolated structures. However, the use of the procedure for isolated structures is rather limited, reflecting the general concern about the foregoing-discussed effects of soft sites, near faults, flexible upper structures, and uplift. As pointed out by Naeim and Lew in Chapter 1, the static procedure is not applicable to most isolated buildings in California, and "all seismic isolated buildings in California have been subjected to a rigorous series of dynamic non-linear time-history analysis." Naeim and Lew suggest that the static, response spectrum, and time history analysis methods offer different benefits and can be advantageously used at various stages of the design and analysis. Simplified methods like the static procedure in UBC and the method developed by Takayama and Tada in Chapter 4 allow the user to see the relationship between the response of the isolated structure and the property of the isolated system. Therefore they are more effective than others for preliminary designs. Nevertheless, there exists no better method for determining the safety of the final design than the time-history analysis - not

mentioning the difficulties in performing nonlinear time-history analysis. Kitagawa and Midorikawa in Chapter 1 indicate that, in Japan, a time-history analysis using site-specific ground motions is also required for all isolated buildings whose design has not been proven as "inherently" safe. This publication contains many time-history analyses of isolated structures. The papers by Al-Hussaini, Constantinou, and Zayas and by Asher, Hoskere, Ewing, Van Volkinburg, Mayes, and Button in Chapter 4 also present comparisons of analysis and measured results.

In summary, the papers in this publication provide comprehensive and up-to-date coverage on the technology of seismic isolation, including historical and theoretical background; expected and realized benefits; and design, analysis, and test requirements. It is hoped that the publication encourages the exchange of ideas and stimulates the creation of new ideas among fellow contributors to the advancement of the technology.