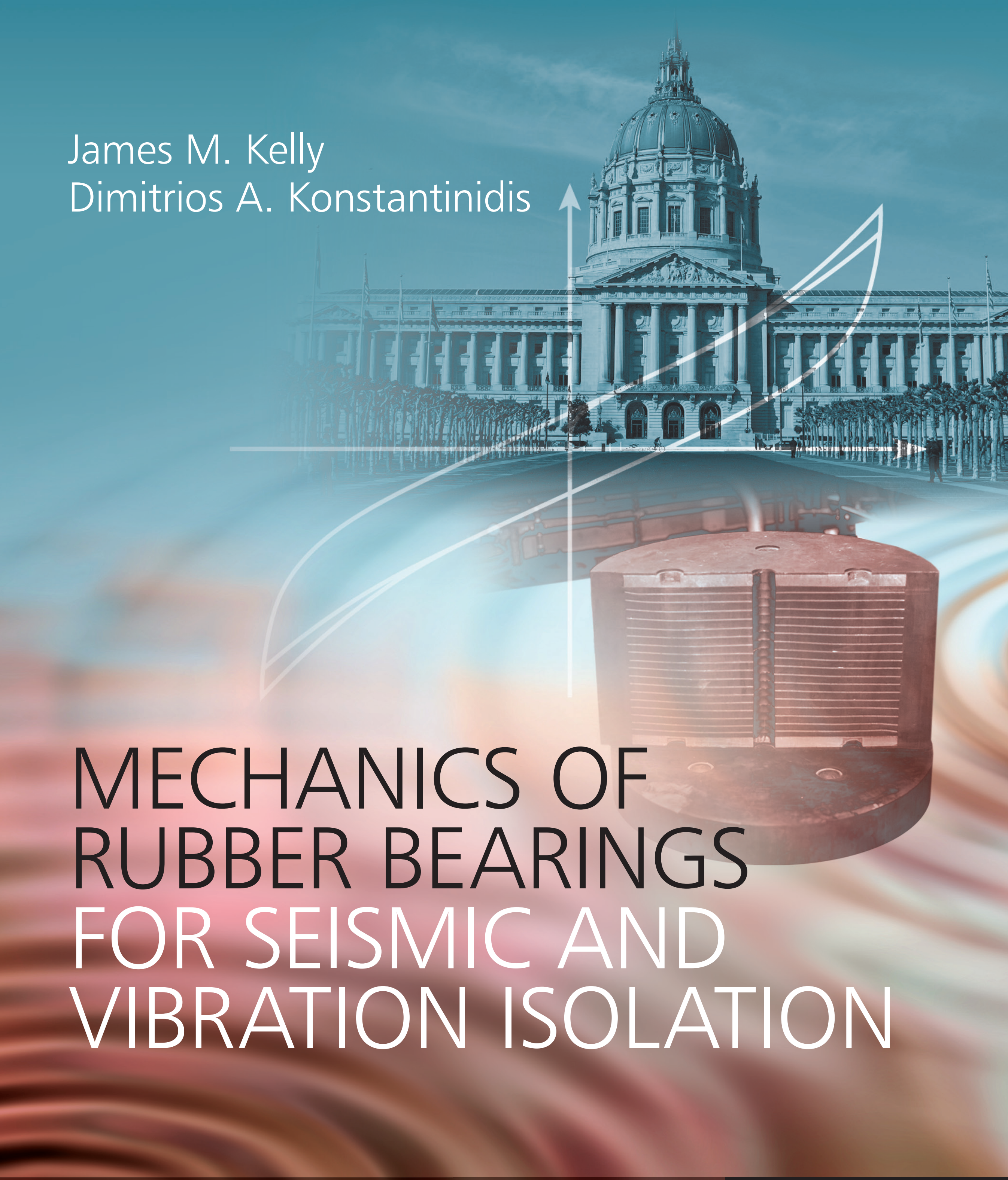

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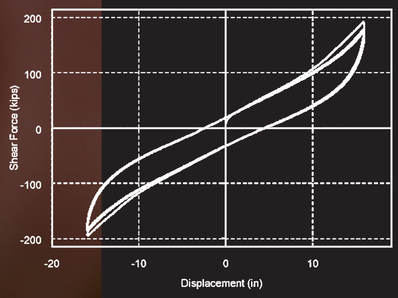

Mechanics of Rubber Bearings for Seismic and Vibration Isolation

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About the Authors

James M. Kelly is Professor Emeritus at the University of California at Berkeley. His undergraduate education was completed at the University of Glasgow, his Master's degree at Brown University and his PhD at Stanford University. He has been a faculty member in the Department of Civil and Environmental Engineering at U.C. Berkeley since 1965. He did pioneering work in dislocation mechanics, dynamic plasticity, impact, and wave propagation. He has carried out numerous large-scale experimental studies of isolation systems, structures with energy-absorbing devices, and structures with piping systems on the large shaking table at the Earthquake Engineering Research Center (EERC) of U.C. Berkeley. In 1971 he developed the first energy-dissipating devices to be used in earthquake-resistant structures. Since then he has led the way in experimental investigations of seismic-isolation rubber bearings, conducting many pioneering studies of seismically isolated structures. In testing hundreds of bearings, he achieved numerous advances, including the application of high-damping rubber for seismic-isolation bearings—used in the first U.S. isolated building and in many buildings and bridges around the world. He has developed theoretical analyses of the dynamic and ultimate behavior of elastomeric seismic isolation at large deformation. He led the development of energy-absorbing devices for the seismic protection of tall structures for which base isolation is not feasible. His test programs have included the first U.S. shake-table investigations of the response of structures containing energy dissipaters, and he has conducted component and system-level experimental and analytical research on many concepts, including yielding steel, friction, viscoelastic, viscous, shape-memory alloy and electro-rheological systems.

Professor Kelly was instrumental in several of the early U.S. energy dissipation applications, consulted on the implementation of viscous dampers for the suspended spans of the Golden Gate Bridge and for the first major U.S. building damper project, the Santa Clara County Civic Center Building, which was retrofitted with viscoelastic dampers following the Loma Prieta earthquake. He worked to develop seismic isolation for low-cost housing in developing countries as a consultant to the United Nations (UNIDO), and has consulted on projects in Armenia, Chile, China, India, and Indonesia, where isolation has been used for residential construction. He was the first in the U.S. to start teaching university-level courses on seismic isolation and energy dissipation. He has conducted short courses and seminars on isolation and energy dissipation worldwide.

His work, which formed the basis for significant advances in the analysis and design of seismic isolation and energy-dissipation systems, is the foundation for many of the base-isolation design codes used today, including UBC, IBC, and CBC. Base isolation has been used for seismic retrofit of major buildings in the U.S., including important historic structures such as the city halls of Salt Lake City, Oakland, San Francisco, Los Angeles, and the Hearst Memorial Mining Building in Berkeley, on all of which he was a peer reviewer.

Professor Kelly, well recognized as an outstanding teacher and lecturer, has directed over thirty doctoral students in their PhD thesis research who have gone on to become noted practitioners, university professors, and researchers worldwide. Many Fulbright Visiting Scholars have come to Berkeley to work with him. In 1996 he published the second edition of his book based on his many years of research and testing at EERC *(Earthquake-resistant Design with Rubber*, 2nd edn Springer-Verlag). In 1999 he published with Dr Farzad Naeim a textbook on the design of seismic isolated buildings (*Design of Seismic Isolated Structures*, John Wiley). He has published over 360 papers over the course of his career.

Dimitrios A. Konstantinidis is an Assistant Professor at McMaster University. He received his Bachelor's (1999), Master's (2001), and PhD (2008) degrees from the Department of Civil and Environmental Engineering at U.C. Berkeley. His research interests and experience lie in the field of engineering mechanics and earthquake engineering with a primary emphasis on seismic isolation, energy dissipation devices, rocking structures, response and protection of building equipment and contents, and structural health monitoring.

As a masters student he became interested in the study of rocking structures and conducted research that led to the co-development, with Professor Nicos Makris, of the *rocking spectrum*—a concept analogous to the response spectrum for the single-degree-of-freedom oscillator. He has investigated the seismic response of multi-drum columns, such as those found in ancient temples in Greece, Western Turkey, and Southern Italy, and proposed recommendations against accepted, but unconservative, standard practice in the restoration world. In the earlier stages of his doctoral work, as part of a multi-disciplinary effort to assess the seismic vulnerability of biological research facilities, he investigated the seismic response of freestanding and anchored laboratory equipment, which included an extensive experimental program of shaking table tests of full-scale prototypes and quarter-scale models of equipment. In the later stages of his doctoral work, he begun working with Professor James M. Kelly. He has studied the effect of the isolation type on the response of internal equipment in a base-isolated structure. He has conducted research on the seismic response of bridge bearings which are traditionally used to accommodate various non-seismic translations and rotations of the bridge deck. These included *steel-reinforced rubber bearings*, *steel-reinforced rubber bearings with Teflon sliding disks*, and *woven-Teflon spherical bearings*. The work included seismic-demand-level dynamic tests at U.C. San Diego and U.C. Berkeley, as well analytical investigations and nonlinear finite element analyses utilizing adaptive remeshing techniques to study the behavior of bonded and unbonded rubber bearings under different loading actions. The findings of the study are being used by Caltrans to develop a new

Memo to Designers guideline and support the development of LRFD-based analysis and design procedures for bridge bearings and seismic isolators. The excellent seismic behavior of rubber bridge bearings, which cost less than a tenth of what rubber seismic isolations cost, has prompted him and Professor Kelly to actively promote the use of these bearing as a low-cost alternative for seismic isolation in developing countries, where the cost of conventional isolators is prohibitive.

He has conducted postdoctoral research at U.C. Berkley focusing on the development of a health monitoring scheme for viscous fluid dampers in bridges using wireless and wired communication. The study involved indoor and outdoor experiments on instrumented fluid dampers. The monitoring system that was developed is being assessed by Caltrans for deployment on testbed bridges.

Before joining the civil engineering faculty at McMaster University in 2011, he was Postdoctoral Fellow at the Lawrence Berkeley National Laboratory, University of California. His work there concentrated on the base isolation of nuclear power plants and on the evaluation of the U.S. Nuclear Regulatory Commission’s current regulations and guidance for large, conventional Light-water Reactor (LWR) power plants to a new generation of small modular reactor (SMR) plants.

Professor Konstantinidis is a member of various professional societies and a reviewer in technical journals, including *Earthquake Engineering and Structural Dynamics* and *Journal of Earthquake Engineering*. He has authored 30 publications in refereed journals, in conference proceedings and as technical reports.

Preface

The multilayer rubber bearing is an apparently simple device that is used in a wide variety of industries that include civil, mechanical and automotive engineering. It is so ubiquitous that it may be difficult to believe that it is a relatively recent development, having been used for only about fifty years. The idea of reinforcing rubber blocks by thin steel plates was first proposed by the famous French engineer Eugène Freyssinet (1879–1962). He recognized that the vertical capacity of a rubber pad was inversely proportional to its thickness, while its horizontal flexibility was directly proportional to it. He is best known for the development of prestressed concrete and for the discovery of creep in concrete. It is possible that his invention of the reinforced rubber pad was driven by the need to accommodate the shrinkage of the deck due to creep and prestress load, while sustaining the weight of a prestressed bridge deck. He obtained a French patent in 1954 for his invention, and within a few years the concept was adopted worldwide and led to the extraordinary variety of applications in which multilayer rubber bearings are used today.

These reinforced rubber bearings in their various forms are a source of fascinating problems in solid mechanics. It is the combination of vertical stiffness and horizontal flexibility, achieved by reinforcing the rubber by thin steel plates perpendicular to the vertical load, that enables them to be used in many applications, including the seismic protection of buildings and bridges and the vibration isolation of buildings and machinery. The horizontal, vertical, and bending stiffnesses are important to the design of bearings for these applications and for predicting the buckling load, the interaction between vertical load and horizontal stiffness, and the dynamic response of structures and equipment mounted on the bearings.

We will cover the theory for vertical stiffness in Chapter 2 and for bending stiffness in Chapter 3. Some of the results in these two chapters are new. The results of Chapters 2 and 3 are used to predict the stresses in the steel reinforcing plates in Chapter 4. The analysis used to calculate these stresses is new to this text and was only recently developed by the authors. Also new and original to this text is the development of a theory for these stresses when the effect of the bulk compressibility of the rubber is included, which is necessary for seismic isolation bearings, but usually not for vibration isolation bearings. In Chapter 5 we study the stability of these bearings, showing how to estimate buckling loads and the interaction between vertical load and horizontal stiffness as well as a new way to calculate the effect of horizontal displacement on the vertical stiffness. One unexpected aspect of these bearings is that they can buckle in tension, and this is covered in Chapter 6. Chapter 7 is concerned with the influence of the flexibility of the reinforcing plates on the buckling load. This could be important in efforts to reduce the weight of bearings in the possible application to low-cost housing. Chapters 8 and 9 present some recent research work by the authors on the mechanics of bearings that are not bonded to their supports, but are held in place by friction. This research includes some experimental work on bearings of this type used as bridge bearings.

The original work on the mechanics of rubber bearings was done at the Malaysian Rubber Producers Research Association (MRPRA, now the Tun Abdul Razak Research Centre) in the United Kingdom in the 1960s under the leadership of Dr A.G. Thomas and Dr P.B. Lindley and applied first to bridge bearings and then to the vibration isolation of residences, hospitals and hotels in the United Kingdom.

The first building to be isolated from low-frequency ground-borne vibration using natural rubber was an apartment block built in 1966 directly above a station of the London Underground. Many such projects have been completed in the United Kingdom using natural rubber isolators, including a low-cost public housing complex adjacent to two eight-track railway lines that carry 24-hour traffic. Several hotels have been completed using this technology, and a number of hospitals have been built with this approach. More recently, vibration isolation has been applied to concert halls.

Some time later MRPRA suggested the use of bearings for the protection of buildings against earthquakes. Dr C.J. Derham, of MRPRA, approached Professor J.M. Kelly and asked him if he was interested in conducting shaking table tests at the Earthquake Simulator Laboratory at the Earthquake Engineering Research Center (EERC), University of California at Berkeley, to see to what extent natural rubber bearings could be used to protect buildings from earthquakes. Very quickly they conducted such a test using a 20-ton model and handmade isolators. The results from these early tests were very promising and led to the first base-isolated building in the United States, also the first building in the world to use isolation bearings made from high-damping natural rubber developed for this project by MRPRA.

The mathematical complexity in the text varies in different parts of the book, depending on which aspects of the bearings are being studied, but the reader should be assured that no more complicated mathematics than absolutely necessary to address the problem at hand has been used.

This text has been written for structural engineers, acoustic engineers and mechanical engineers with an interest in applying isolation methods to buildings, bridges and industrial equipment. If they have a background in structural dynamics and an interest in structural mechanics, they will find that much of the analysis in the text may be applied to their work. The text can be used as supplementary reading for graduate courses and as a introduction to dissertation research.

It will also be useful to those who are charged with preparing or updating design rules and design guidelines for isolated bridges and buildings. The text is the first that attempts to bring together in one place the mechanics of rubber bearings now widely scattered in many journals and reports.

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1

History of Multilayer Rubber Bearings

Multilayer rubber bearings are widely used in civil, mechanical and automotive engineering. They have been used since the 1950s as thermal expansion bearings for highway bridges and as vibration isolation bearings for buildings in severe acoustic environments. Since the early 1980s, they have been used as seismic isolation devices for buildings in highly seismic areas in many countries. Their appeal in these applications is the ability to provide a component with high stiffness in one direction and high flexibility in one or more orthogonal directions. The idea of using thin steel plates as reinforcement in rubber blocks was apparently suggested by the famous French engineer Eugène Freyssinet (1879–1962). He recognized that the vertical capacity of a rubber pad was *inversely* proportional to its thickness, while its horizontal flexibility was *directly* proportional to the thickness. He is of course best known for the development of prestressed concrete, but also for the discovery of creep in concrete. It is possible that his invention of the reinforced rubber pad was driven by the need to accommodate the shrinkage of the deck due to creep and the prestress load while sustaining the weight of a prestressed bridge deck. In any case, he obtained a French patent in 1954 for "Dispositif de liaison élastique à un ou plusieurs degrés de liberté" (translated as "Elastic device of connection to one or more degrees of freedom"; Freyssinet 1954; the patent, with an English translation, is given in the Appendix). It seems from his patent that he envisaged that the constraint on the rubber sheets by the reinforcing steel plates be maintained by friction. However, in practical use a more positive connection was desired, and by 1956 bonding of thin steel plates to rubber sheets during vulcanization was adopted worldwide and led to the extraordinary variety of applications in which rubber pads are used today.

This combination of horizontal flexibility and vertical stiffness, achieved by reinforcing the rubber by thin steel shims perpendicular to the vertical load, enables them to be used in many applications, including seismic protection of buildings and bridges and vibration isolation of machinery and buildings.

Mechanics of Rubber Bearings for Seismic and Vibration Isolation, First Edition. James M. Kelly and Dimitrios A. Konstantinidis.

The isolation of equipment from vibration via anti-vibration mounts is a well-established technology, and the theory and practice are covered in several books, papers, and reviews; the survey by Snowden (1979) is an example. Although the isolated machine is usually the source of the unwanted vibrations, the procedure can also be used to protect either a sensitive piece of equipment or an entire building from external sources of vibration. The use of vibration isolation for entire buildings originated in the United Kingdom and is now well accepted throughout Europe and is beginning to be used in the United States. Details of this method of building construction can be found in Grootenhuis (1983) and Crockett (1983).

The predominant disturbance to a building by rail traffic is a vertical ground motion with frequencies ranging from 25 to 50 Hz, depending on the local soil conditions and the source. To achieve a degree of attenuation that takes the disturbance below the threshold of perception or below the level that interferes with the operation of delicate equipment (e.g., an electron microscope), rubber bearings are designed to provide a vertical natural frequency for the structure about one-third of the lowest frequency of the disturbance.

The first building to be isolated from low-frequency ground-borne vibration using natural rubber was an apartment block built in London in 1966. Known as Albany Court, this building is located directly above the St James' Park Station of the London Underground. This project was experimental to a certain extent, and the performance and durability of the isolation system in the years since its construction was monitored for several years by the Malaysian Rubber Producers Research Association (MRPRA, now the Tun Abdul Razak Research Centre) in conjunction with Aktins Research and Development (Derham and Waller 1975).

Since then, many projects have been completed in the United Kingdom using natural rubber isolators. These have included Grafton 16, a low-cost public housing complex that was built on a site adjacent to two eight-track railway lines that carry 24-hour traffic. In this project the isolators produced a vertical frequency of 6.5 Hz to isolate against ground motion in the 20 Hz range. Several hotels have been completed using this technology, for example, the Holiday Inn in Swiss Cottage in London. In addition, a number of hospitals have been built with this approach, which is particularly advantageous when precision diagnostic equipment is present.

More recently, vibration isolation has been applied for use in concert halls. In 1990, the Glasgow Royal Concert Hall, which is sited directly above two underground railway lines, was completed in Glasgow, Scotland. The building has a reinforced concrete structural frame that is supported on 450 natural rubber bearings. In addition to housing the 2850-seat concert hall, it also contains a conference hall and a number of restaurants.

Another concert hall is the International Convention Centre in Birmingham, England, which was completed in 1991. Home of the City of Birmingham Symphony Orchestra, the building comprises ten conference halls and a 2211-seat concert hall. The entire complex was built at a cost of £121 million and is supported on 2000 natural rubber bearings to isolate it from noise from a main line railway running in a tunnel near the site.

The International Congress Center (ICC) in Berlin (Figure 1.1), Germany, constructed between 1970 and 1979, was Berlin's largest post-war project. It is 320 m (1050 ft) long, 80 m (260 ft) across and 40 m (130 ft) high. It has a cubic content of 800 000 m^3 (1 000 000 yd^3), and the total weight of steel in the roof is 8500 tons (18700 kips). A

Figure 1.1 The International Congress Center (ICC) in Berlin, Germany. Reproduced from Hans-Georg Weimar, Wikimedia

"box-in-box" construction, developed specially for this center, permits several functions to be held simultaneously under one roof. The building is supported on neoprene bearings (Figure 1.2) which range in size up to 2.5 m in diameter that can carry loads of 8000 tons (17600 kips; Freyssinet International 1977). They were constructed in segments which were placed in position with space between the segments to allow for bulging of the neoprene layers – described in the literature on the center as *a kind of architectural*

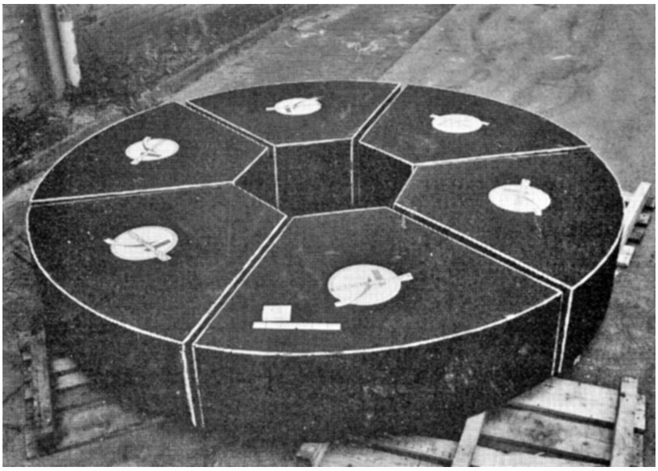

Figure 1.2 2.5-m diameter bearing for the ICC Berlin. Reproduced by permission of Freyssinet, Inc.

shock absorber – and were intended to exclude outside noise and absorb vibrations from an adjacent highway and railway. ICC Berlin has over 80 halls and conference rooms, with seating capacities ranging from 20 to 5000, with a sophisticated information and direction system. The largest hall (Hall 1) can seat up to 5000 and has the second-largest stage in Europe.

Two recent applications of vibration isolation to concert halls in the United States are the Benaroya Concert Hall in Seattle, Washington, completed in 1999 and the Walt Disney Concert Hall in Los Angeles, California, completed in 2003. The first uses rubber bearings to mitigate ground-borne noise from trains in a tunnel below the hall. The Walt Disney Concert Hall is built directly above a loading dock for an immediately adjacent building. The interesting thing about these two buildings is that they are located in highly seismic areas, yet there was no attempt on the part of the structural engineers for either project to combine both vibration isolation and seismic isolation in the same system. Experimental results of tests done at the shake table at the Earthquake Engineering Research Center of the University of California, Berkeley, many years before the construction of these two concert halls, demonstrated that it was possible to design a rubber bearing system that would provide both vibration isolation and seismic protection. In the concert hall projects, lateral movement of the bearings that support the buildings is prevented by a system of many vertically located bearings, the additional cost of which is substantial and could have been avoided by appropriate design.

Seismic isolation can also be provided by multilayer rubber bearings that, in this case, decouple the building or structure from the horizontal components of the ground motion through the low horizontal stiffness of the bearings, which give the structure a fundamental frequency that is much lower than both its fixed-base frequency and the predominant frequencies of the ground motion. The first dynamic mode of the isolated structure involves deformation only in the isolation system, the structure above being to all intents and purposes rigid. The higher modes that produce deformation in the structure are orthogonal to the first mode and, consequently, to the ground motion (Kelly 1997). These higher modes do not participate, so that if there is high energy in the ground motion at these higher frequencies, this energy cannot be transmitted into the structure. The isolation system does not absorb the earthquake energy, but rather deflects it through the dynamics of the system. This type of isolation system works when the system is linear, and even when undamped; however, a certain level of damping is beneficial to suppress any possible resonance at the isolation frequency. This damping can be provided by the rubber compound itself through appropriate compounding. The rubber compounds in common engineering use have an intrinsic energy dissipation equivalent to 2–3% of linear viscous damping, but in compounds referred to as *high-damping rubber* this can be increased to 10–20% (Naeim and Kelly 1999).

The first use of rubber for the earthquake protection of a structure was in an elementary school, completed in 1969 in Skopje, in the Former Yugoslav Republic of Macedonia (see Figure 1.3). The building is a three-story concrete structure that rests on large blocks of natural rubber (Garevski *et al.* 1998). Unlike more recently developed rubber bearings, these blocks are completely unreinforced so that the weight of the building causes them to bulge sideways (see Figure 1.4). Because the vertical and horizontal stiffnesses of the system are about the same, the building will bounce and rock backwards and forwards in an earthquake. These bearings were designed when the technology for reinforcing

Figure 1.3 The first rubber isolated building: the Pestalozzi elementary school completed in 1969 in Skopje. Courtesy of James M. Kelly. NISEE Online Archive, University of California, Berkeley

rubber blocks with steel plates – as in bridge bearings – was neither highly developed nor widely known, and this approach has not been used again. More recent examples of isolated buildings use multilayered laminated rubber bearings with steel reinforcing layers as the load-carrying component of the system. These are easy to manufacture, have

Figure 1.4 Unreinforced bearing in the Pestalozzi school building in Skopje. Courtesy of James M. Kelly. NISEE Online Archive, University of California, Berkeley

Figure 1.5 Foothill Communities Law and Justice Center, Rancho Cucamonga, California. Courtesy of James M. Kelly. NISEE Online Archive, University of California, Berkeley

no moving parts and are extremely durable. Many manufacturers guarantee lifetimes of around 50 or 60 years.

The first base-isolated building to be built in the United States was the Foothill Communities Law and Justice Center (FCLJC), a legal services center for the County of San Bernardino that is located in the city of Rancho Cucamonga, California, about 97 km (60 miles) east of downtown Los Angeles (see Figure 1.5). In addition to being the first base-isolated building in the United States, it is also the first building in the world to use isolation bearings made from high-damping natural rubber (Derham and Kelly 1985) (Figure 1.6). The FCLJC was designed with rubber isolators at the request of the County of San Bernardino. The building is only 20 km (12 miles) from the San Andreas fault, which is capable of generating very large earthquakes on its southern branch. This fault runs through the county, and, as a result, the county has had for many years one of the most thorough earthquake-preparedness programs in the United States. Approximately 15 794 m^2 (170 000 ft^2), the building is four stories high with a full basement and was designed to withstand an earthquake with a Richter magnitude 8.3 on the San Andreas fault. A total of 98 isolators were used to isolate the building, and these are located in a special sub-basement. The construction of the building began in early 1984 and was completed in mid-1985 at a cost of $38 million (Tarics *et al.* 1984). Since then, many new buildings have been built in the United States on seismic isolation systems.

The same high-damping rubber system was adopted for a building commissioned by Los Angeles County, the Fire Command and Control Facility (FCCF), shown in Figure 1.7. This building houses the computer and communications systems for the fire emergency services program of the county and is required to remain functional