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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.

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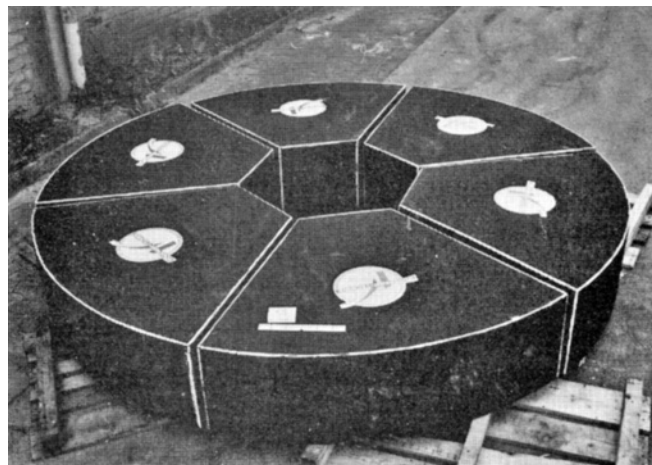
Figure 1.2   2.5-m diameter bearing for the ICC Berlin. Reproduced by permission of Freyssinet, Inc.

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

Figure 1.6   Natural rubber isolator for the Foothill Communities Law and Justice Center showing laminated construction. Courtesy of James M. Kelly. NISEE Online Archive, University of California, Berkeley

during and after an extreme earthquake. The decision to isolate this building was based on a comparison between conventional and isolation schemes designed to provide the same degree of protection. On this basis the isolated design was estimated to cost 6% less than the conventional design (Anderson 1989). For most projects an isolated design generally costs around 5% more when compared with a conventional code

Figure 1.7   Fire Command and Control Facility, Los Angeles, California. Courtesy of James M. Kelly. NISEE Online Archive, University of California, Berkeley

design; however, the design code provides a minimum level of protection against strong ground shaking, guaranteeing only that the building will not collapse. It does not protect the building from structural damage. When equivalent levels of design performance are compared, an isolated building is always more cost effective. Additionally, these are the primary costs when contemplating a structural system and do not address the life-cycle costs, which are also more favorable when an isolation system is used as compared to conventional construction.

A second base-isolated building, also built for the County of Los Angeles, is at the same location as the FCCF. The Emergency Operations Center (EOC) is a two-story steel braced-frame structure isolated using 28 high-damping natural rubber bearings provided by the Bridgestone Engineered Products Co., Inc.

The most recent example of an isolated emergency center is the two-story Caltrans/CHP Traffic Management Center in Kearny Mesa near San Diego, California (Walters *et al.* 1995). The superstructure has a steel frame with perimeter concentrically braced bays. The isolation system, also provided by Bridgestone, consists of 40 high-damping natural rubber isolators. The isolators are 60 cm (24 in) in diameter.

The use of seismic isolation for emergency control centers is clearly advantageous since these buildings contain essential equipment that must remain functional during and after an earthquake. They are designed to a much higher level of performance than conventional buildings, and the increased cost for the isolators is easily justified. Other examples are the San Francisco 911 Center and the Public Safety Building in the city of Berkeley, California.

Other base-isolated building projects in California include a number of hospitals. The M. L. King Jr–C. R. Drew Diagnostics Trauma Center in Willowbrook, California, is a $13\,006$ m^2 ($140\,000$ ft^2), five-story structure supported on 70 high-damping natural rubber bearings and 12 sliding bearings with lead–bronze plates that slide on a stainless steel surface. Built for the County of Los Angeles, the building is located within 5 km (3 miles) of the Newport–Inglewood fault, which is capable of generating earthquakes with a Richter magnitude of 7.5. The isolators are 100 cm (40 in) in diameter, and at the time of their manufacture were the largest isolation bearings fabricated in the United States. Many other hospitals have been built in California since then on rubber isolation systems, some with lead–rubber bearings (i.e., multilayered rubber bearings featuring a cylindrical lead core) and some with high-damping rubber bearings. They include the University of Southern California Teaching hospital, using lead–rubber bearings, completed in 1991. This hospital, which was instrumented with strong-motion seismic acceleration instruments was impacted by the 1994 Northridge Earthquake and performed remarkably well. The peak ground acceleration in the free field (the parking lot) was $0.49g$, which was reduced within the building to around 0.10–$0.11g$ by the isolation system. The Arrowhead Regional Medical Center, part of the County of San Bernardino, was completed in 1998, and the St Johns Medical Center, a private hospital in Santa Monica, in 2001. Two hospitals owned by Hoag Presbyterian in Irvine, one a retrofit and one new, were built on high-damping rubber bearings in the mid 2000s.

In addition to new buildings, there are a number of very large retrofit projects in California using base isolation, including the retrofit of the Oakland City Hall and the

Figure 1.8 The Oakland City Hall, Oakland, California. Courtesy of James M. Kelly. University of California, Berkeley

San Francisco City Hall, both of which were badly damaged in the 1989 Loma Prieta earthquake, and the Los Angeles City Hall.

When it was built in 1914, Oakland City Hall was the tallest building on the west coast. Its height was later surpassed by the Los Angeles City Hall, which was completed in 1928. The seismic rehabilitation of Oakland City Hall (Figure 1.8) using base isolation was completed in 1995, and it was at the time the tallest seismically isolated building in the world. It was once again surpassed when the seismic rehabilitation of the Los Angeles City Hall retrofit was completed in 1998, making that structure now the tallest seismically isolated building in the world. The Oakland City Hall isolation system uses 110 bearings ranging from 74 cm (29 in) to 94 cm (37 in) in diameter. A moat was constructed around the building to provide a seismic gap of 51 cm (20 in). Installing the isolators proved to be very complicated and required shoring up of the columns, cutting of the columns, and transferring of the column loads to temporary supports. In order to protect the interior, the columns were raised not more than 2.5 mm (0.1 in) during the jacking process. The cost of the retrofit was very

Figure 1.9   The Los Angeles City Hall, Los Angeles, California. Reproduced from Brion Vibber, Wikimedia

substantial – about \$84 million – with the isolators comprising around 2.5% of that figure. Details of the retrofit are given in Walters *et al.* (1995).

The Los Angeles City Hall, shown in Figure 1.9, is a 28-story steel frame building completed in 1928. The total floor area is close to 82 728 m^2 (912 000 ft^2). The lateral resistance is provided by several different elements, including steel cross-bracing, reinforced concrete walls, and interior clay hollow core tile walls, with the most of the superstructure stiffness provided by masonry infill perimeter walls. The building was damaged in the 1994 Northridge earthquake, with the most severe damage occurring on the 25th and 26th floors, which have the characteristic of soft stories. The base isolation retrofit scheme (Youssef 2001) uses 416 high-damping natural rubber isolators in combination with 90 sliders and is supplemented by 52 mechanical viscous dampers at the isolation level. In addition, 12 viscous dampers were installed between the 24th and 25th floors to control

Figure 1.10   The San Francisco City Hall, San Francisco, California. Courtesy of James M. Kelly. University of California, Berkeley

interstory drifts at the soft-story levels. The total cost of this retrofit was estimated to be around $150 million, with the isolators comprising $3.5 million of that figure.

The San Francisco City Hall, shown in Figure 1.10, was built in 1912 to replace the original city hall that was destroyed in the 1906 San Francisco Earthquake and was itself damaged in the 1989 Loma Prieta Earthquake. The repair and retrofit of the building included an isolation system with 530 lead–rubber bearings. The project involved a great deal of internal restoration and redecoration and was very expensive, but the isolation system and its installation accounted for only a small portion of the cost.

Other major base isolation retrofit projects using natural rubber bearings are the City of Berkeley administration building called the Martin Luther King Jr Civic Center and the Hearst Memorial Mining Building on the University of California, Berkeley campus (see Figures 1.11 and 1.12).

The use of isolation for earthquake-resistant design has been very actively pursued in Japan, from the completion of the first large base-isolated building in 1986. Up to the late 1990s, all base-isolation projects in Japan had to be approved by a standing committee of the Ministry of Construction. As of June 30, 1998, 550 base-isolated buildings had been approved by the Ministry of Construction, but nowadays this approval is no longer necessary, and it is quite difficult to keep account of the number of base-isolated buildings. Many of the completed buildings have experienced earthquakes, and, in some cases, their response has been compared with adjacent conventionally designed structures. In every case where such a comparison has been made, the response of the isolated building has been highly favorable, particularly for ground motions with high levels of acceleration. The system most commonly used in the past has been undamped natural rubber

Figure 1.11 Hearst Memorial Mining Building on the University of California, Berkeley campus. Courtesy of Ian D. Aiken. SIE, Inc.

bearings with additional mechanical dampers using steel, lead or friction. However, there has been an increasing use of high-damping natural rubber isolators. There are now many large buildings that use high-damping natural rubber bearings. An example is the computer center for Tohoku Electric Power Co. in Sendai, Miyako Province.

The building houses the computers for the billing and production records of the electric power utility. It is a six-story, $10\,000$ m^2 ($108\,000$ ft^2) structure and is one of the

Figure 1.12 Bearings for Hearst Memorial Mining Building on the University of California, Berkeley campus. Courtesy of James M. Kelly. University of California, Berkeley

larger base-isolated buildings in Japan. To accommodate a large number of mainframe computers and hard disk data storage equipment, the building was designed with large internal clear spans to facilitate location of this equipment. As a result of its height, the large column spacing, and the type of equipment in the building, the column loads are very large. Bridgestone provided a total of 40 bearings of three different sizes – 90 cm (35 in), 100 cm (39 in), and 120 cm (46 in) in diameter – to isolate the building. The vertical loads range from 400 tons (880 kips) to 800 tons (1760 kips). Construction of this building began in March 1989 and was completed in March 1990. The isolation system proved simple to install. All of the bearings were placed within three days and their base plates grouted after a further six days. The total construction cost, not including the internal equipment, was $20 million; the cost of the isolators was $1 million. This building represents a significant example of buildings housing expensive and critical equipment, and many more such structures were built in Japan in the following years.

One of the largest base-isolated buildings in the world is the West Japan Postal Computer Center, which is located in Sanda, Kobe Prefecture. This six-story, 47 000 m^2 (500 000 ft^2) structure is supported on 120 rubber isolators with a number of additional steel and lead dampers. The building, which has an isolated period of 3.9 s, is located approximately 30 km (19 miles) from the epicenter of the 1995 Hyogo-Ken Nanbu (Kobe) earthquake and experienced severe ground motion in that earthquake. The peak ground acceleration under the isolators was 400 cm/s^2 (0.41g) and was reduced by the isolation system to 127 cm/s^2 (0.13g) at the sixth floor. The estimate of the displacement of the isolators is around 12 cm (4.8 in). There was no damage to the isolated building; however, a fixed-based building adjacent to the computer center experienced some damage.

The use of isolation in Japan continues to increase, especially in the aftermath of the Kobe earthquake. As a result of the superior performance of the West Japan Postal Computer Center, there has been a rapid increase in the number of applications of base isolation, including many apartments and condominiums. In recent years the number of base-isolated buildings in Japan built each year has been around 100, and the total number is probably around 1500 (Kamada and Fujita 2007). This does not include single family homes of which there are around 3000, but not all of these use rubber bearings, although rubber bearings play an auxiliary role in many. The latest concept to be applied in Japan is the idea of *isolated ground*. In Sagamihara City near Tokyo an artificial ground, in fact a large concrete slab, with 21 separate buildings of 6–14 stories has been built on 150 isolation devices which include many very large rubber bearings (Terashima and Miyazaki 2001). With this approach any concerns for overturning and unacceptably large displacements are eliminated. It seems to be a very promising method of extending this technology to large complexes of high-rise condominium buildings.

The emphasis in most base isolation applications up to this time has been on large structures with sensitive or expensive contents, but there is increasing interest in applying this technology to public housing, schools, and hospitals in developing countries where the replacement cost due to earthquake damage could be a significant part of the country's Gross National Product (GNP). Several projects are under way for such applications. The challenge in such applications is to develop low-cost isolation systems that can be used in conjunction with local construction methods, such as masonry block and lightly reinforced concrete frames. The United Nations Industrial Development

Organization (UNIDO) partially financed a joint effort between the Malaysian Rubber Producers' Research Association (MRPRA, now the Tun Abdul Razak Research Centre) of the United Kingdom and the Earthquake Engineering Research Center (EERC) of the University of California at Berkeley to research and promote the use of rubber bearings for base-isolated buildings in developing countries.

To date, a number of base-isolated demonstration projects have been completed. In most cases an identical structure of fixed-base construction was built adjacent to the isolated building to compare their behavior during earthquakes. There are demonstration projects in Reggio Calabria, Italy; Santiago, Chile; Guangdong Province, China; and Pelabuhan Ratu, Indonesia.

One of the demonstration projects completed under this program is a base-isolated apartment building in the coastal city of Shantou, Guangdong Province, an earthquake-prone area of southern China. Completed in 1994, this building is the first rubber base-isolated building in China. This demonstration project involved the construction of two eight-story housing blocks. Two identical and adjacent buildings were built; one building is of conventional fixed-base construction, and the other is base-isolated with high-damping natural rubber isolators. The design, testing, and manufacture of the isolators was funded by the MRPRA from a grant provided by the UNIDO. The demonstration project was a joint effort by the MRPRA, the EERC, and Nanyang University, Singapore. Details of this project can be found in Taniwangsa and Kelly (1996).

As part of the UNIDO support, several rubber technologists from a rubber company in Shantou went to the MRPRA laboratory and were trained in the manufacture of rubber isolators. The city of Shantou provided a site, and a factory producing rubber isolators was established in this city. This company has supplied isolators for projects all over China, many of them large complexes of perhaps 30–40 identical eight-story multi-family housing blocks. It also supplied isolators for buildings in Japan and in Russia.

In 1994 construction of a base-isolated four-story reinforced concrete building in Java, Indonesia, was completed (Figure 1.13). The construction of this demonstration building was part of the same UNIDO-sponsored program to introduce base isolation technology to developing countries. In order for this new technology to be readily adopted by building officials, it was essential that the design and construction of the superstructure of the isolated building did not deviate substantially from common building practice and building codes used for fixed-base buildings.

The demonstration building in Indonesia is located in the southern part of West Java, about 1 km (0.6 miles) southwest of Pelabuhan Ratu. The building is a four-story moment-resisting reinforced concrete structure, accommodating eight low-cost apartment units. The building is 7.2×18.0 m (24×59 ft) in plan, and the height to the roof above the isolators is 12.8 m (42 ft). The walls that enclose each apartment unit are made out of unreinforced masonry with special seismic gaps filled with soft mortar. A common building practice in Indonesia, this type of seismic gap separates the walls from the main structure. This building is supported by 16 high-damping natural rubber bearings. The isolation bearings are located at the ground level and are connected to the superstructure using an innovative recessed end-plate connection, as

Figure 1.13   Demonstration building in Pelabuhan Ratu, West Java, Indonesia. Courtesy of James M. Kelly. University of California, Berkeley

opposed to the more usual bolted connection. This use of a recessed end-plate connection proved to be cost-effective and very easy to install. The bearings were designed and manufactured by the MRPRA in the United Kingdom. To achieve overall economy of fabrication, installation, and maintenance of the isolation system, two different high-damping natural rubber compounds were used, and a single bearing size was selected so that only one mold was necessary for the fabrication process. The dynamic properties of the bearings were confirmed by full-size bearing tests. Details of this project can be found in Taniwangsa and Kelly (1996).

Nuclear power plants are another example of a type of structure for which seismic isolation can be extremely beneficial. Nuclear structures are generally very stiff and heavy, thus the benefits of a large-period shift can be obtained easily without resorting to long-period isolation systems. Also, as will be shown later, it is much easier to design stable isolators for heavier loads than light loads. Because the response of a base-isolated structure is dominated by the lowest mode, i.e., the structure moves in an approximately rigid-body manner, the stress analysis of the structure is greatly simplified. A substantial level of design effort in nuclear facilities is devoted to the dynamic analysis of equipment and piping systems. The conventional design involves computing floor spectra for each

level, and, in some cases, multiple input spectra when piping systems or equipment items are attached at more than one level, and then broadening these spectra to account for uncertainties in the analysis.

In an isolated structure, however, because the dominant mode is a rigid-body mode with all the deformation concentrated at the isolation level, all parts of the building move in the same way at the low isolation frequency. The response uncertainties are reduced, multiple input spectra are not needed, and the peaks in all the floor spectra are at the low frequency of the isolation system, which is generally much lower than equipment or piping frequencies (Yang *et al.* 2010).

Thus using an isolation system allows a high degree of standardization, with equipment qualification processes simplified through reduced seismic levels. A further benefit is that if the regulatory environment changes during the life of the plant, mandating an upgrade of the seismic input, the response of the equipment may not be greatly affected. If there is more than a negligible increase in the design forces at the isolation frequency, it is a relatively simple matter to reduce the overall stiffness of the isolation system and maintain the original equipment standards.

Because nuclear plants are a natural application of base isolation technology, it is no surprise that one of the earliest applications of the technology was a nuclear facility. Completed in 1980, the Koeberg Power Plant in South Africa was both the first base-isolated nuclear power plant and one of the first base-isolated buildings (Renault *et al.* 1979; Plichon *et al.* 1980). The power plant, designed by Électricité de France and built by Spie Batignolles, has two 900 MW$_e$ standardized units, which had been qualified for seismic inputs up to 0.2g. The nuclear island is constructed on 1829 aseismic bearings on concrete pedestals. Standard bridge bearings were used, consisting of multilayer neoprene bearings topped by bronze slip plates which slide on stainless steel plates attached to the underside of the upper base mat. These bearings were designed in the early 1970s when the technology of rubber isolators was such that the maximum lateral displacements were quite small, of the order of 5 cm (2 in). If the bearings reach this displacement, the sliding plates are expected to slip and provide further displacement. Because of subsequent developments in isolator design and manufacturing, it is unlikely that this design will be used again; in fact, a subsequent isolated nuclear power plant building by Électricité de France at Cruas uses only rubber pads.

The Cruas Nuclear Power Plant (Postollec 1982), shown in Figure 1.14, comprised four 900 MW$_e$ PWR units supported on 3600 neoprene isolators, was constructed on an isolated nuclear island. The designers decided to isolate Cruas because the seismicity of the site exceeded that for which all previous examples of this standardized plant had been designed. The buildings and equipment of the standardized plant were designed for the basic EDF spectrum anchored at 0.2g, whereas at Cruas the required spectrum was 0.3g. In order to utilize the standardized plant design, the use of an isolation system was necessary.

Another French nuclear application of isolation consists of three large, spent-fuel storage tanks at a reprocessing plant at La Hague, France, built by COGEMA (Bouchon 1988). The three tanks are on a single reinforced concrete base mat, 1.65 m (5.4 ft) thick, supported on rubber pads on pedestals. The use of the isolators produced simplifications in the design process as compared with conventional construction.

Figure 1.14   The Cruas-Meysse nuclear power plant. Courtesy of James M. Kelly. University of California, Berkeley

Other countries besides France were also interested in applying isolation technology to their nuclear facilities. During 1987–1993, the Japanese Ministry of International Trade and Industry (MITI) funded a large program of seismic isolation research for nuclear applications. Directed by the Central Research Institute of Electric Power Industry (CRIEPI) and involving the CRIEPI research laboratory at Abiko, numerous construction companies, plant manufacturers, and rubber companies, this program covered all aspects of seismic isolation and focused primarily on the application of seismic isolation to liquid-metal fast breeder reactors (FBR). The program was extremely comprehensive, and the results are available in a great many reports, mainly in Japanese. A number of these reports have been translated into English, generally appearing in the proceedings of SMiRT and Post-SMiRT Symposia.

In the United Kingdom, the use of isolation for a nuclear facility specifically for seismic protection is limited to a pipe bridge at a British Nuclear Fuels reprocessing facility in the north of England. Although a gas-cooled reactor with a prestressed concrete containment built on rubber pads, the primary goal of this application was to control stresses due to shrinkage and thermal effects. The Central Electricity Generating Board (CEGB) sponsored a program of isolation studies in the late 1980s intending to develop an isolation system for a standardized plant design. The proposed system used both natural rubber bearings and viscous dampers. The natural rubber bearings were to be made of a compound which was exactly linear in its shear response and without damping; the viscous dampers (provided by GERB of Germany) were intended to be entirely linear in velocity, thus producing a system which exactly matched the linear mechanical model used in the dynamic analysis of the plant.

The material to be covered in this book focuses on the mechanics of rubber bearings used in isolation systems. The analysis will be mainly linear and will emphasize the simplicity of these systems. Many of the results are new and are needed for a proper understanding of these bearings and for the design and analysis of vibration isolation or seismic isolation systems. It is hoped that the advantages afforded by adopting these natural rubber systems – their cost effectiveness, simplicity, and reliability – will become apparent to designers and their use will continue to expand.