Received: 29 March 2018 | Revised: 14 August 2018 | Accepted: 17 August 2018

DOI: 10.1002/eqe.3124

REVIEW ARTICLE

WILEY

Seismic isolation: Early history

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Summary

Seismic isolation or "aseismic base isolation" is an earthquake protection strategy that aims to uncouple the motion of a structure from the ground shaking and thereby reduce structural forces. A most effective and successful seismic protection technology, seismic isolation, is by now a mature and viable alternative to traditional capacity design and has been implemented in numerous bridges, buildings, and other special structures worldwide. This paper records the origins and early developments (up to the early 1990s) of seismic isolation.

KEYWORDS

concave sliding bearings, elastomeric bearings, historical note, response modification, seismic protection

1 | INTRODUCTION

The concept that a structure can be protected from the damaging effects of earthquakes by using some type of support that "uncouples" its motion from the ground shaking has been appealing through the centuries in several civilizations. It is common experience that during ground shaking a squat, free-standing structure will slide provided that the coefficient of friction along the sliding interface is lower than the ratio of the peak ground acceleration to the acceleration of gravity.

In 1870, Jules Touaillon of the city of San Francisco, State of California was issued a US patent for a new and improved method of constructing buildings, so as to render them proof against earthquake shocks. The remarkable drawings appearing in Touaillon's 1870 patent show the elevation of a building supported on an isolation system that consists of an array of opposite facing concave spherical surfaces (c and c′ in Touaillon's drawing shown in Figure 1) that are separated by spherical balls. In his own words Touaillon[1] explains: "… *The upper face of plate c and the lower face of plate c′ are provided with depressions having the form of a segment of sphere with a radius considerably greater than that of the balls … the aforesaid weight will cause the plates c and c′ and the balls to resume their original relative position*". Clearly, Touaillon[1] was aware that seismic isolation is the result of the large radius of his concave spherical surfaces while recentering of the structure is due to gravity. Accordingly, the proposed isolation system back in 1870 brings forward most of the concepts of a modern, state-of-the-art, double concave spherical sliding bearing isolation system.

Nearly four decades after Jules Touaillon's pioneering patent, J. Bechtold from Germany was issued a US patent for an Earthquake Proof Building supported on a rigid-plate which is mounted on loose pebble gravel or on balls of hard material to carry the base-plate freely.[2] In his own words, J. Bechtold[2] explains: "*In the case of earthquakes the danger accrues from the rigid foundation of the buildings, and will be best avoided by standing the whole edifice on a rigid base-plate of suitable carrying power, which base-plate is not in rigid connection with the surface of the earth*". This wording reiterates the two key concepts in modern seismic isolation: A, that of sufficient load carrying capacity; and B, that of sufficient compliance to uncouple satisfactorily the motion of the structure from the ground shaking.

Following the 1908 Reggio-Messina, Italy earthquake that killed some 160 000 people, an Italian Commission was formed consisting of practicing engineers and university professors and one recommendation was to separate the

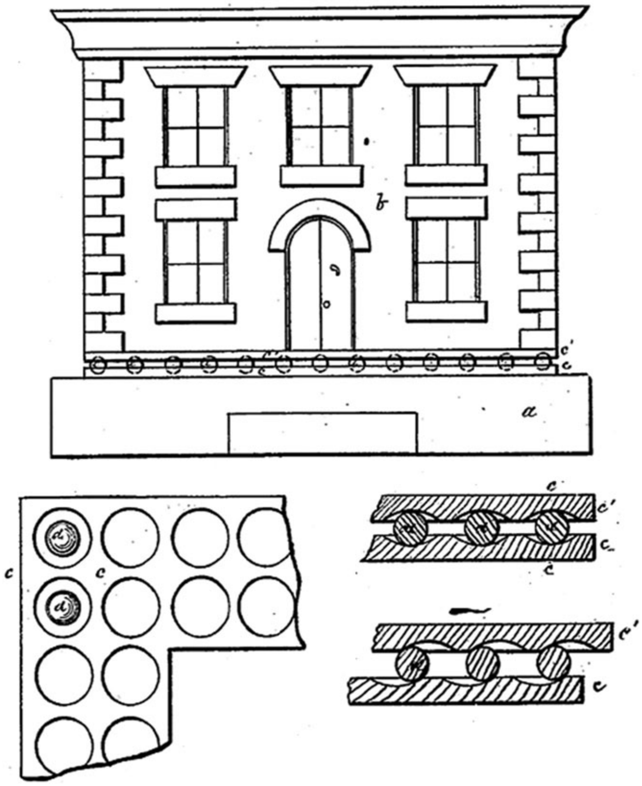

FIGURE 1 Jules Touaillon's 1870 seismic isolated structure is supported on the isolation system c-c′ which consists of an array of opposite facing concave spherical surfaces (see plan view and cross section of the isolation system in details below the structure) that are separated by spherical balls. This 150-year-old seismic isolation system brings forward most of the unique concepts of a modern, state-of-the-art, double-concave spherical bearing isolation system

building from its foundation with a layer of sand or by using rollers; whereas, the other recommendation favored a fixed foundation.[3,4] The Italian Commission eventually decided on the fixed foundation; nevertheless, the alternative recommendation of a building sliding on a layer of sand formally introduces the concept of seismic isolation in Europe. That same year, 1909, J. A. Calantarients, a medical doctor from Scarborough, England applied for a British patent on an earthquake resistant design approach which proposed separation of the building from its foundation with a layer of sand or talk.[5] Calantarients' 1909 application[5] includes a thorough description of wind restrainers that would prevent the building from moving in high winds; while, upon recognizing the large anticipated displacements between the building and its foundation, he showed that special connections are required for the gas, water and sewage utilities.

The first known implementation of seismic isolation in modern times was apparently by Frank Lloyd Wright in the design of the Imperial Hotel in Tokyo, Japan completed in 1921. At the site of the hotel, there was an 8-feet layer of fairly good soil and below that a 60 to 70-feet layer of soft mud with minimal shear strength. This layer of mud appeared to Wright as "a good cushion" to relieve the earthquake shaking.[4,6] Wright supported the building on an array of closely spaced short piles that penetrated only as far as the top of the soft mud. Soon after its construction, the Imperial Hotel performed extremely well during the devastating 1923 great Kwanto Tokyo earthquake.

Less than a decade later, R. W. de Montalk from New Zealand was issued a US patent for absorbing or minimizing shock to buildings arising from earthquakes, vibrations caused by heavy traffic, or other disturbances of the earth's surface.[7] In his own words, R. W. de Montalk[7] explains: "*The invention comprises means whereby a bed, which I call a severer, is placed and retained between the base of the building and its solid foundation, the severer being composed of material which will absorb or minimize shocks, thereby saving the building therefrom*". Accordingly, with the term "absorb," de Montalk introduces the concept of energy dissipation—that is the third key concept in the current practice of seismic isolation.

Since the 1920s, there have been a handful of inadvertent events in which some structures have survived earthquake shaking by developing a lower failure mechanism; while, neighboring buildings have collapsed. For instance, several unreinforced masonry buildings were only lightly damaged during the 1933 Long Beach, California earthquake because they were able to slide on their grade beams.[6]

2 | EARLY CONCEPTS OF SEISMIC ISOLATION ADVANCED IN JAPAN

In 1876 the British geologist and mining engineer, John Milne was appointed professor of mining and geology at Tokyo Imperial University where he stayed until 1895. During that period, Milne built an example of a seismic isolated structure that was resting on spherical balls in cast-iron plates with saucer-like edges atop the pile-heads. Above the balls and attached to the building are cast-iron plates slightly concave similar to those below. The building was instrumented and apparently experienced earthquake movement. In 1885, Milne reported his experiment to the British Association for the Advancement of Science.[8]

In 1992, the National Institute of Standards and Technology (NIST) published a two-volume report[9,10] on seismic isolation and passive energy dissipating systems for buildings and other structures. These documents were translated from Japanese and provide guidelines for evaluating isolation and energy dissipating systems together with a directory of the systems used in buildings and other structures. The original reports in Japanese were published by the Building Center of Japan under the sponsorship of the Japanese Ministry of Construction (MOC) which made available these reports to the NIST for their translation into English and for publication.

Volume 1 of the NIST 1992 reports presents a thorough review of the early ideas on seismic isolation advance in Japan. It commences with a paper by Kozo Kawai published in the December 1891 issue of *Kenchiku Zasshi* of the Architectural Institute of Japan with title: "Structures free from the maximum vibrations during earthquake." This paper discusses a building supported on several orthogonal layers of cylindrical logs placed at the foundation of the building. The NIST 1992 report proceeds by discussing several ideas on seismic isolation advanced in Japan following the 1923 great Kwanto earthquake including Okiie Yamashita's 1924 seismic isolation system that consists of two opposite facing concave dishes separated by a spherical ball—a system that is very similar to the isolation system proposed by Jules Touaillon[1] more than half a century earlier—and resembles today's multi-concave spherical sliding isolation system.[11-13] In the late 1920s, Ryuichi Oka proposed a system where the base columns of the building are supported on a hemispherical surface allowing for horizontal displacements at the base of the column; while, friction at the spherical joints provide energy dissipation. This type of early seismic isolation system was implemented in several buildings in Japan including the 1934 reinforced concrete buildings of the Himeji branch and the Shimonoseki branch of the Fudo Chokin Bank. These two applications are also reported by Fujita.[14]

By the early 1980s, systematic research on seismic isolation was being carried out at the University of Tokyo[15]; while various Japanese construction companies have carried out experimental tests on isolation systems with natural rubber bearings.[3]

3 | VIBRATION ISOLATION

During and immediately after World War II, there were major development in the mechanical and aerospace industries, and by the late 1950s vibration isolation was a subject well understood ([16,17] among others) and is defined as the reduction of the response of a system to an induced excitation. In the vibration isolation literature, the reduction of vibrations is attained by the use of a resilient support, and during a steady-state regime, vibration isolation is the complement of transmissibility. Accordingly, with the theory of vibration isolation being well established in the late 1950s, one may expect that the sole difference between vibration isolation (placing equipment atop resilient supporting elements) and seismic isolation (placing entire civil structures atop resilient supporting elements) is merely a matter of scale and that of engineering training. Nevertheless, the fact that even two decades later in the 1970s there was only a handful of seismic isolated buildings ([18-21] among others) was partly due to the distrust that traditional structural engineers voiced to the idea of intentionally introducing flexibility at the foundation level of buildings.[22]

The original work on the mechanics of rubber bearings for the vibration isolation of buildings was done at the Malaysian Rubber Producers Research Association (MRPRA—now the Tun Abdul Razac Research Center) in the United Kingdom in the 1960s under the leadership of Dr A. G. Thomas, A. N. Gent, and Dr Peter Lindley and applied first to bridge bearings and then to the vibration isolation of residences, hospitals, and hotels in the United Kingdom.[22-24] The first building to be isolated from low-frequency ground-borne vibrations 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. Vibration isolation has been also applied to concert halls.[22]

4 | EARLY APPLICATIONS OF SEISMIC ISOLATION AROUND THE WORLD

The first use of rubber for the earthquake protection of a structure was apparently in an elementary school in Skopje, Republic of Northern Macedonia. Completed in 1969, the building is a three-story concrete structure that is supported on large blocks of unreinforced natural rubber. Because of the lack of horizontal reinforcement in the bearings, the isolation system is very flexible along the vertical direction; therefore, the horizontal and rocking frequencies of the building are closely spaced resulting in an unfavorable coupling of the horizontal, vertical, and rocking modes. Practical isolation bearings are multilayered laminated rubber bearings with horizontal steel reinforcing layers—a key ingredient in the load carrying capability of the isolation system. Because of the horizontal reinforcing steel plates, isolation bearings are very stiff in the vertical direction, while remain flexible in the horizontal direction, thereby producing the isolation effect.

An early application of natural rubber, laminated isolation bearings was for the seismic isolation of a three-story school in the town of Lambesc near Marseilles, France.[18,19] The isolators used are 300 mm in diameter and have 20 layers for a total rubber thickness of 40 mm. The natural rubber layers are laminated to steel plates, and the school is supported on 152 isolators. The period of the isolated school is around 1.70 seconds. Shake table tests of these isolators, known as Gapec isolators, were carried out on the shake table at the John A. Blume Earthquake Engineering Research Center at Stanford University.[25] Following the shake table tests, Gapec isolators were installed under circuit breakers in an electric power plant in California.[26] Upon the completion of the isolated school in Marseilles, the designer of the isolation system, Giles Delfosse, built three seismically isolated houses in a neighboring community[27] and also designed an isolation system for a three-story building in Toulon, France for the French Navy.[28]

A seven-story reinforced concrete building was built in Sebastopol, Russia, on egg-shaped steel bearings (ovoids) which offer the structure a 3-second long isolation period.[29] When the building is displaced, it is forced to rise; therefore, restoring happens due to gravity.

Seismic isolation was also implemented by the French nuclear industry for the seismic protection of a nuclear power plant in South Africa.[30-33] The French nuclear isolation system consists of laminated neoprene bearings together with lead bronze-stainless steel slip plates atop. The neoprene bearings act as conventional isolators for small earthquakes given that they can only accommodate moderate displacements due to the limited rubber thickness. In the event of strong shaking, sliding takes place along the slip plates. These have been designed to have a friction coefficient of 0.2. Neoprene pads without slip plates have been used for the isolation of a nuclear power plant at Cruas-Meysse in France.[34]

Following the 1976 Tang Shan, China earthquake, it was observed that masonry buildings in which the reinforcement was not carried through to the foundation performed better than buildings in which it was. As a result of these observations, an alternative approach was adopted in China where a separation layer of sand was introduced under the floor beams and above the foundation.[35] Accordingly, the building is seismic isolated by being allowed to slide on a layer of specially screened sand.

The two most widely used steel-laminated isolation rubber bearings are as follows: (1) the lead rubber bearing developed and tested in the Physics and Engineering Laboratory of the DSIR (Department of Scientific and Industrial Research), a government department in New Zealand; and (2) the high-damping rubber bearing developed and tested by the MRPRA and further studied and tested at the University of California, Berkeley.[36]

5 | SEISMIC ISOLATION IN NEW ZEALAND

In the late 1960s, the concept of seismic isolation for civil structures started to develop systematically in New Zealand with a series of experimental and analytical studies led by R. Ivan Skinner, who was the head of the Engineering Seismology section at the Physics and Engineering Laboratory of the DSIR which eventually led to major implementations. Interestingly, these pioneering developments in base (shear) isolation were initially motivated from the design of the South Rangitikei Rail Bridge—a tall railway concrete bridge with stepping piers (see Figure 2 left), which is the first implementation of rocking isolation in modern times.[36,39] The design of the South Rangitikei Rail Bridge was a seminal moment in seismic isolation that fostered the development and testing of base isolation systems for buildings which initially consist of bridge bearings in association with special hysteretic damping devices that used the cyclic plasticity of steel.[37,38,40]

FIGURE 2 View of the South Rangitikei Rail Bridge in New Zealand. The piers are allowed to uplift by 12.5 cm; while the rocking motion is controlled by torsionally yielding steel-beam dampers shown in Figure 3 [Colour figure can be viewed at wileyonlinelibrary.com]

At the Physics and Engineering Laboratory of the New Zealand DSIR in the early 1970s, a fruitful interaction developed between the structural engineers in the Engineering Seismology section and the Materials Science section headed by W.H. Robinson whose expertise included the testing and characterization of plastically deformed metals. As a result, a range of isolators and energy dissipators (response modification devices) based on the plastic deformation of lead, including lead-extrusion dampers, were developed with the first used in the seismic isolated Aurora Terrace and Bolton Street overpasses in Wellington, NZ. Their experience in developing and implementing devices based on plastically deforming lead and other metals led the research group to combine the isolation and energy absorption in a single unit that is the lead-rubber isolator which was the most successful and favorable choice for the seismic isolation of a number of bridges and buildings.[39]

5.1 | The South Rangitikei Rail Bridge and the early introduction of response modification devices

The South Rangitikei Rail Bridge project was initiated at PEL (a research unit within DSIR) in 1971, when the Chief Engineer for NZ Railways approached R. Ivan Skinner about investigating its feasibility. The original design was a stepping A-frame that was allowed to rock atop the pile caps in order to limit stresses in the bridge piers and the supporting foundations.[41,42] For construction purposes, the pier design was eventually changed to the stepping portal frames seen in Figure 2. Professor James L. Beck, now at the California Institute of Technology, had joined PEL in 1970 as a junior research engineer and contributed significantly in the dynamic analysis of the revolutionized design of a stepping bridge with its added damping devices.[37,38,40-42]

The South Rangitikei Rail Bridge is 75 m tall, with six spans of prestressed concrete hollow-box girder, and an overall length of 315 m. At the supports of its free-standing piers hysteretic, torsionally yielding steel-beam dampers are installed between the bottom of the stepping piers and the pile caps to supplement damping during the rocking motions as shown in Figure 3.[37,38] These dampers are activated during the vertical uplift of the piers legs as each pier steps. In addition, a laminated elastomeric bearing is installed at the base of the shear-resisting recess at each pile cap to reduce impact accelerations as the rocking pier alternates pivoting supports from one leg to the other (see Figure 3 left). The torsionally yielding steel-beam damper shown in Figure 3(right) was developed by Professor James Kelly during a 1-year leave from the University of California, Berkeley when he joined the efforts of R. Ivan Skinner and Arnold Heine in the Engineering Seismology group of PEL, DSIR in New Zealand.[37,38]

The rocking isolation concept advanced with the South Rangitikei Rail Bridge back in 1971 was effective in reducing seismic loads on the bridge; while, ensuring recentering. The hysteretic damping during stepping was quite effective because the estimated damping from impact alone as the bridge alternates pivot points is quite low.[41-43]

The utilization of similar response modification devices was then considered in the design of the isolation system of the *William Clayton Building*. Accordingly, the stepping South Rangitikei Rail Bridge is apparently the first application of a seismically isolated structure (rocking isolation) that is equipped with hysteretic dampers; therefore, the first application that introduces the use of response modification devices.[37,38]

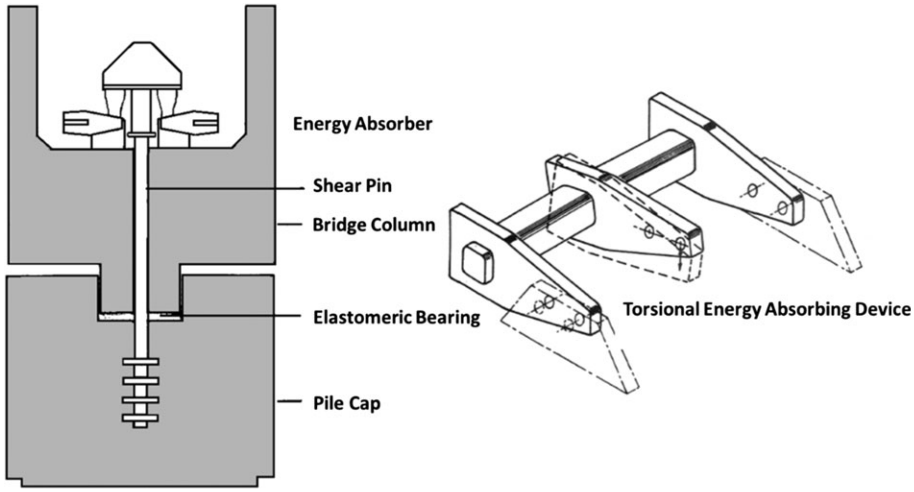

FIGURE 3 Left: Detail of the connection of the torsionally yielding steel-damper at the base of the stepping pier and the pile cap. Right: Schematic of the torsionally yielding steel-beam damper[37,38]

5.2 | The William Clayton Building

The William Clayton Building in Wellington, New Zealand, completed in 1981 and shown in Figure 4, was the first building to be base isolated on lead-rubber bearings schematically shown in Figure 5.[44,45] The isolation bearings are located under each of the 79 columns of the four-story reinforced concrete frame building with plan dimensions 97×40 m.[39,44]

In this pioneering design, horizontal clearance of 150 mm is provided before the base slab impacts the retaining walls. Water, gas, and sewerage pipes, external stairways, and sliding gratings over the separating gap are detailed to accommodate the potential 150-mm isolation displacement.

5.3 | Seismic isolation with flexible piles within clearance sleeves

For sites with poor near-surface soil conditions consisting of marine silts and other sediments of dubious quality, the concept of seismic isolation has been achieved by using flexible piles within clearance sleeves. In the early 1980s, two notable implementations of this technology appear in New Zealand: (1) the Union House Building in Auckland, NZ[46] and (2) the Wellington Central Police Station.[47] Theoretical studies on this aseismic design have been presented by Biggs.[48]

Seismic isolation of the Union House was achieved by making the piles laterally flexible with moment resisting pins at each end. The piles were surrounded by hollow steel jackets allowing for 150-mm relative movement, thus separating the building from the shaking ground and making provisions for the anticipated large base displacements. Tapered,

FIGURE 4 The William Clayton Building, completed in 1981 in New Zealand, is the first base-isolated building to be built on lead-rubber isolators [Colour figure can be viewed at wileyonlinelibrary.com]

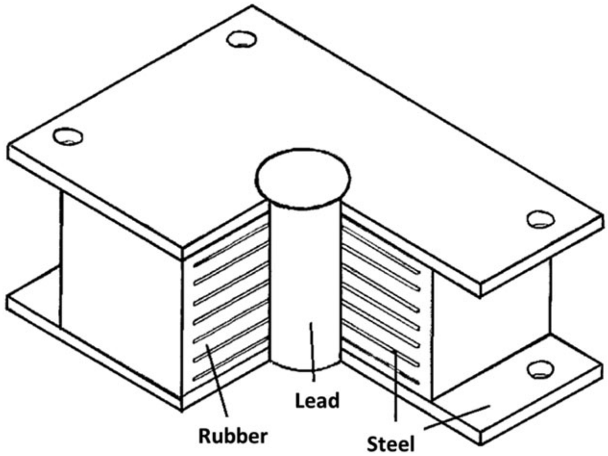

FIGURE 5 Schematic of a multilayered steel-laminated lead lubber bearing[44,45]

cantilever yielding steel dampers provide supplemental energy dissipation. They were installed between the top of the piles and an embedded basement which was structurally independent of the rest of the building.

The seismic design specifications for the Wellington Police Station are considerably more severe than for the Union House in Auckland. The police station is an essential facility required to be in operation after a major earthquake; while, its site is only a few hundred meters from the major active Wellington fault. The flexible piles supporting the structure are enclosed in oversized casings allowing considerable displacement relative to the ground. Energy dissipation to control base displacements is provided by lead-extrusion dampers[49] connected between the top of the piles and the embedded basement in a configuration similar to the one adopted in the Union House. The flexible piles and the lead-extrusion dampers combine to an isolation system with nearly elastoplastic behavior.

5.4 | Road bridges

The use of elastomeric bearings in bridge construction enjoyed an increasing acceptance after World War II. In bridges, traditional, non-seismic bearings accommodate movements such as creep and thermal expansion, and in precast concrete construction they act as seating pads which absorb small installation movements and fabrication misalignment. Initially, small, unreinforced elastomeric bearing pads were used to support short-span prestressed concrete beams.

The construction of larger highway bridges in the 1950s and 1960s resulted in larger loads, and steel-laminated or fiberglass-laminated elastomeric bearings were manufactured to accommodate higher bearing stresses.[50] These bearings are economical and maintenance free, and they have a long history of satisfactory performance. This long and good experience that bridge engineers developed with elastomeric bearings was instrumental in accepting the use of seismic bearings and the concept of seismic isolation for bridges.

In New Zealand, the most common use of seismic isolation is by far in two-span road bridges with moderate span, justifiable purely on the economics of construction. The most common form of isolation system for bridges uses lead-rubber bearings[44,45] usually installed between the bridge superstructure and the supporting piers. The lead-rubber bearings (schematically shown in Figure 5) consist of a number of steel-laminated rubber layers vulcanized together, with a cylindrical lead core inserted in the center. As the bearing deforms under horizontal loading, the cylindrical lead core is subjected to shear plastic deformation and dissipates appreciable energy. The main attraction of the lead-rubber bearing is that it combines the functions of seismic isolation and energy dissipation in a single compact unit. In addition to providing energy dissipation, the lead core also acts like a mechanical fuse that stiffens the bearing under low lateral deformations up to its yield load; therefore, wind and traffic-induced displacements are kept low.

6 | EARLY DEVELOPMENTS ON SEISMIC ISOLATION AT THE UNIVERSITY OF CALIFORNIA, BERKELEY

The design of the isolation system of the stepping South Rangitikei Rail bridge shown in Figure 2 involved the participation of Professor James M. Kelly from the University of California at Berkeley. Following the development of the yielding steel dampers shown in Figure 3, JM Kelly recognized that energy dissipation devices may be more efficient when they operate at larger displacements that will generate larger hysteretic loops; therefore, his interest was directed to seismic isolation.[51] The timing was most fortunate, given that in 1976, the MRPRA approached the University of California, Berkeley to investigate the possibility of using natural rubber bearings for the seismic protection of civil structures.

In 1976, JM Kelly in association with CJ Derham from MRPRA began working on the development of natural rubber bearings for the seismic protection of building and bridges.[52-54] Over a period of about 5 years, this collaboration led to a series of experimental tests, both at the component level (see Figure 6) and on entire isolated structures on the shaking table of the Earthquake Engineering Research Center (EERC) at UC Berkeley (see Figure 7.) The results from these early tests were very promising and led to the first base-isolated building in the United States, the Foothill Communities Law and Justice Center (FCLJC), which was also the first building in the world to use isolation bearings made from high-damping natural rubber developed for this project by MRPRA.[36]

In the early design of isolation systems with rubber bearings, it was customary to have the bearings dowelled to prevent the development of tension in the rubber. This may lead to the possibility of a role-off at the top and bottom surfaces of a bearing when is subjected to large deformations. This has the effect of reducing the stability of the bearing, and it has been analyzed by Simo and Kelly.[55,56] Today, rubber bearings are routinely bolted into place and localized tension in the elastomer is allowed. Another possibility with base isolated structures is the coupling of their lateral-torsional modes and their vertical-rocking modes. These problems have been addressed by Pan and Kelly.[57,58] Experimental and analytical studies at UC Berkeley[59,60] showed that when a rubber-bearing isolation system is used without any additional energy dissipation devices, the resulting orthogonality of the higher modes to the seismic input has the effect of greatly reducing the response of secondary equipment as compared with conventional design.

6.1 | The Foothill Communities Law and Justice Center (FCLJC)

The first base-isolated building to be built in the United States is the FCLJC, which is also the first building in the world to use Malaysian rubber isolators. Located in the city of Rancho Cucamonga about 100 km east of downtown Los Angeles, the FCLJC shown in Figure 8, is a legal services center for the County of San Bernardino. The construction of the building began in early 1984, and it was completed in mid-1985. A total of 98 isolators were used. The FCLJC was designed with isolators at the request of the County of San Bernardino since the building is only 20 km from the San Andreas fault, which runs through the county. Because this fault is capable of generating very large earthquakes on its southern branch, the County has had for many years one of the most thorough earthquake preparedness

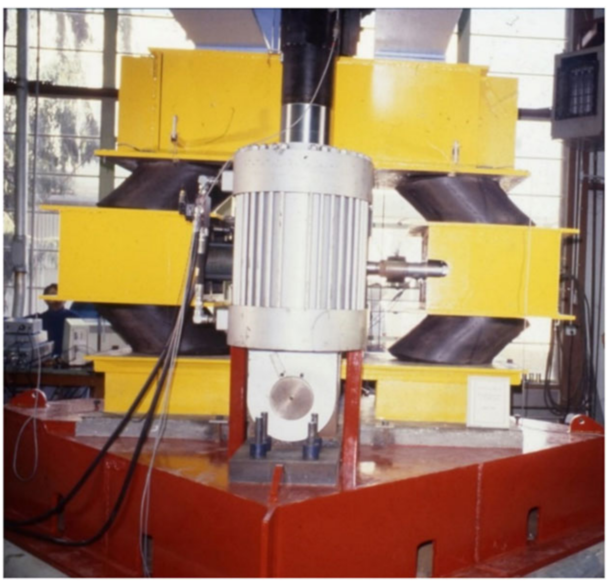

FIGURE 6 Component testing of full-scale natural rubber isolation bearings at the Earthquake Engineering Research Center of the University of California, Berkeley in 1984. Courtesy of James M. Kelly with permission [Colour figure can be viewed at wileyonlinelibrary.com]

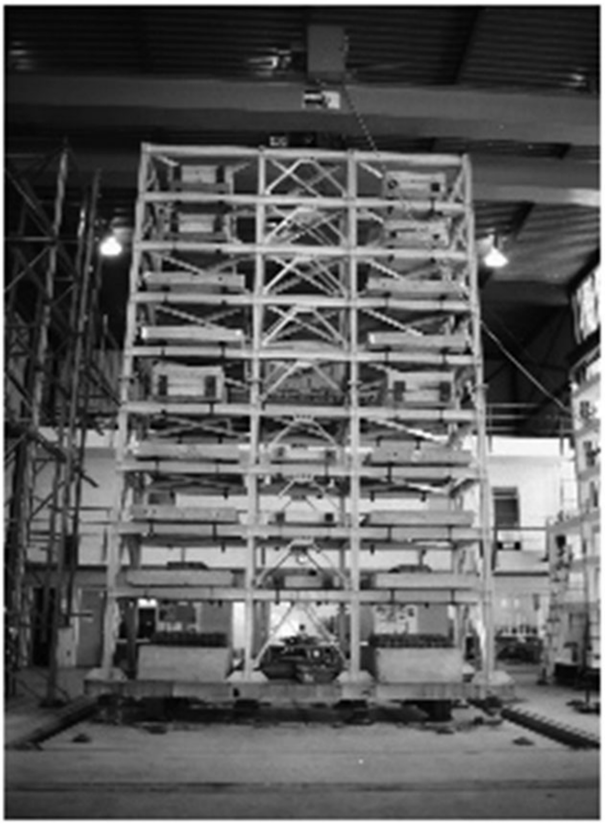

FIGURE 7 Nine-story, ¼ scale model structure isolated on natural rubber bearings being tested on the shake table at the Earthquake Engineering Research Center of the University of California, Berkeley, in 1986. Courtesy of James M. Kelly with permission

FIGURE 8 The Foothill Communities Law and Justice Center (FCLJC), completed in 1985 in Southern California, is the first base-isolated building to be built in the United States. Courtesy of James M. Kelly with permission [Colour figure can be viewed at wileyonlinelibrary.com]

programs in the United States. The building was visited by many structural engineers and architects from all over the world and created an interest in using this technology in other countries.

The collaboration between UC Berkeley and MRPRA led to the planning of an international conference in Kuala Lumpur in 1982 sponsored by the Malaysian Rubber Research and Development Board and organized by the Rubber Research Institute of Malaysia. This was the first ever conference to be devoted entirely to the topic of seismic protection for buildings and bridges using Malaysian natural rubber. The conference was endorsed by the United Nations Industrial Development Organization and through their efforts participants from 20 countries came to the conference, thus exposing the approach to a wide range of potential users in seismic areas of the world.

7 | EARLY SEISMIC RETROFITS OF HISTORIC BUILDINGS USING ELASTOMERIC BEARINGS

The reduction of ground induced accelerations above isolators renders seismic isolation an attractive seismic protection strategy for brittle structures such as historic buildings. The first application of seismic isolation to retrofit a historic building is the seismic retrofit of the Salt Lake City and County Building shown in Figure 9. Construction on this iconic masonry-and-stone-bearing-wall structure started in 1890, and the building was occupied in 1894. In 1934, the Salt Lake City and County Building experienced appreciable ground shaking from the 12 March 1934 Hansel Valley earthquake which prompted the removal of the statues over the main building entrances and the statue atop the clocktower.[61] The seismic isolation retrofitting of this historic structure happened in the mid-1980s. A total of 447 lead rubber bearings were inserted on top of the original strip footings of the building with a new concrete structural system built above the isolation bearings.[61]

The successful seismic isolation retrofitting of the Salt Lake City and County Building was the forerunner of other historic landmark seismic isolation retrofitting projects with elastomeric bearings including the Oakland, San Francisco, and Los Angeles City Halls.[62]

8 | SLIDING ISOLATION SYSTEMS

Sliding systems are by far the simplest isolation system. They are part of our common experience, and they can be implemented by simply introducing a layer of sand as was done for masonry buildings in China in the late 70s.[35] During the 1970s, sliding systems were the subject of appreciable theoretical analysis. Crandall and Lee[63,64] investigated the uniaxial and biaxial response of a sliding mass subjected to a stationary random process with zero mean; while, Mostaghel and Tanbakuchi[65] investigated the response of sliding structures subjected to earthquake shaking. Up to the early 1980s, very little experimental work was done on large-scale sliding structures until the proposal of the single concave friction pendulum isolator that was invented by Victor Zayas.[66]

The single concave friction pendulum (FP) represented the first practical sliding isolator in which the restoring force is provided by gravity. The single concave FP isolator and its derivatives which are sliding bearings with multiple concave spherical sliding surfaces[11-13] found extensive applications and revolutionized seismic isolation with their ability to deliver very large displacement capacities and vertical and shear load capacities. The first experimental shake table study of the single concave FP was conducted in 1987 at the University of California, Berkeley[67] using a two-story highly versatile model (weight in the range of 80 to 120 kN) in which many effects were studied, including superstructure flexibility, distribution of mass, asymmetry, and vertical ground motion effects.[68] Shortly after that another study was conducted at the State University of New York at Buffalo using a 230-kN, six-story steel moment frame model.[69]

FIGURE 9 The Salt Lake City and County Building is the first historic building in the USA to be seismic retrofitted with seismic isolation. A total of 447 lead rubber bearings were instead on top of the original strip footings of the building with a new concrete structural system built above the isolation bearings[61] [Colour figure can be viewed at wileyonlinelibrary.com]

The same four single concave FP isolators were used in the Berkeley and Buffalo studies. Figure 10 shows views of the single concave sliding isolators in the Structural and Earthquake Simulation Laboratory of the University at Buffalo in 1998.

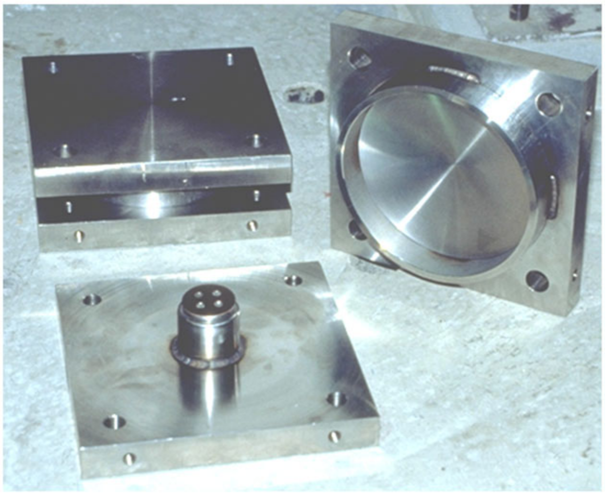

FIGURE 10 Single concave friction pendulum (FP) isolators at the University at Buffalo, circa 1998. Courtesy of Michael C. Constantinou with permission [Colour figure can be viewed at wileyonlinelibrary.com]

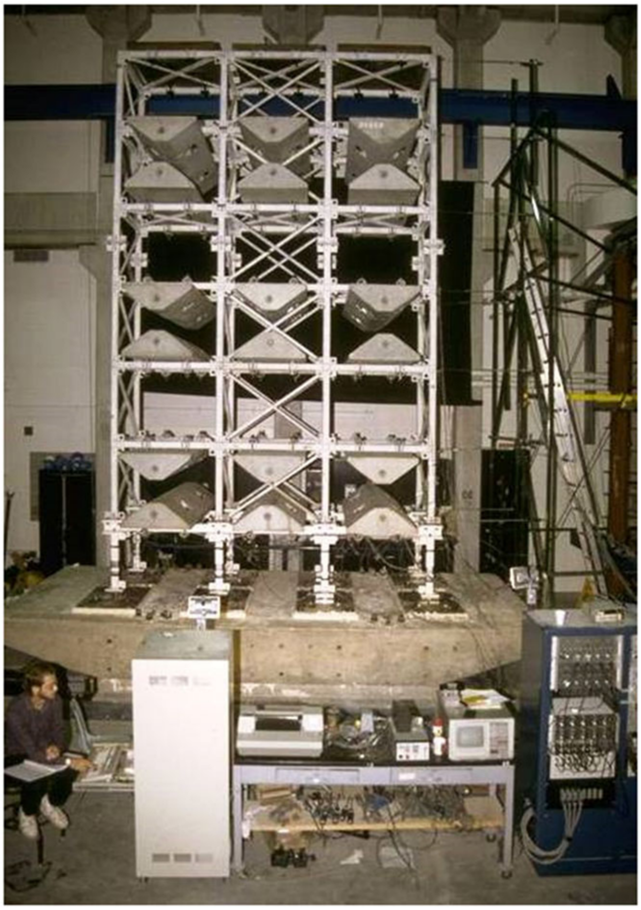

FIGURE 11 Seven-story model on the seismic simulator at the University at Buffalo, circa 1991. Courtesy of Michael C. Constantinou with permission [Colour figure can be viewed at wileyonlinelibrary.com]

The results of these studies were instrumental in the validation of models that describe the behavior of the isolator. These models were implemented in the 3D-BASIS class of programs for the analysis of seismically isolated structures.[70,71] These models and computer programs served as the basis for the commercial software SAP2000 used nowadays in the analysis of seismically isolated structures.

More experimental studies followed at the University at Buffalo under the leadership of Professor Michael Constantinou utilizing bridge and taller slender building models that allowed the observation of isolator uplift for the first time.[72,73] Images of the models are shown in Figures 11 and 12. The tested seven-story model had a weight of 211 kN and lagged a base with the eight isolators installed directly below columns. The bridge model had a weight of 158 kN.

The first important application of the single concave FP isolators was in the seismic retrofit of the iconic US Court of Appeals in San Francisco in 1993[74] shown in Figure 13.

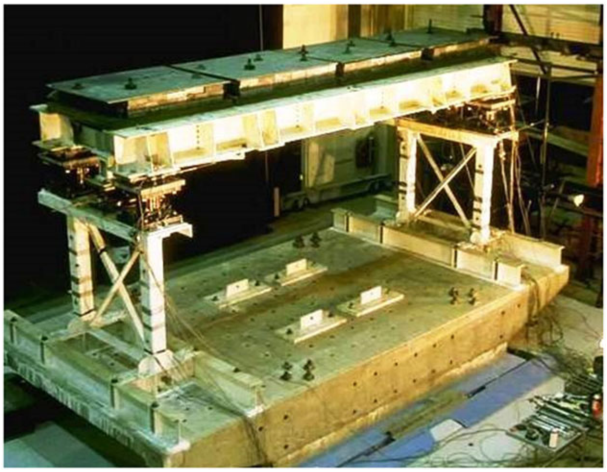

FIGURE 12 Bridge model on the seismic simulator at the University at Buffalo, circa 1992. Courtesy of Michael C. Constantinou with permission

FIGURE 13 The US Court of Appeals in San Francisco, California is the first building in the USA to be isolated on a single concave, sliding isolation system in 1993. Courtesy of Michael C. Constantinou with permission [Colour figure can be viewed at wileyonlinelibrary.com]

Fundamental in the development of the concave spherical sliding isolator is the understanding of friction at the microscopic and macroscopic levels so that prediction of the behavior of these isolators over their lifetime and in various environmental conditions can be made. Starting in 1987, research at the University at Buffalo concentrated on the behavior of sliding interfaces and studied the effects of velocity, pressure, temperature, contamination, corrosion, and aging.[75-77] These resulted in the development of the concept of bounding analysis and of Property Modification Factors for isolation systems that are specified for the analysis and design of seismic isolated structures in US and European standards.[78]

9 | CONCLUSIONS

By the early 1990s, seismic isolation had evolved to a viable and dependable seismic protection strategy with major buildings and bridges being supported either on lead-rubber bearings, natural rubber bearings, or single-concave sliding bearings. Following the 1994 Northridge, California and the 1995 Kobe, Japan earthquakes, seismic isolation enjoyed increasing acceptance world-wide for the seismic protection of civil structures.

ACKNOWLEDGEMENTS

While preparing this note, I benefited from the input and feedback from Professors James M. Kelly, Michael C. Constantinou, James L. Beck, and Ian G. Buckle. I gratefully acknowledge their advice together with the information that they offered. The assistance of Dr Ian Aiken for preparing electronic files of older slides together with offering valuable information, and that of Dr Mehrdad Aghagholizadeh with the electronic management of this manuscript is also gratefully acknowledged.

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How to cite this article: Makris N. Seismic isolation: Early history. *Earthquake Engng Struct Dyn*. 2018;1–16. https://doi.org/10.1002/eqe.3124