Optimization of Base Isolation Systems Using Low Cost Bearings and Frictional Devices.

by

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B.S. Civil Engineering
Universidad de La Salle, Bogotá – Colombia. 1997

SUBMITTED TO THE DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ENGINEERING IN CIVIL AND ENVIRONMENTAL ENGINEERING AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2001

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ABSTRACT

The concept of seismic isolation is presented as an alternative to be applied for improving the seismic response of the structures at a low cost. A description of the scheme, its development, assessment and potential applications is performed. Different base isolation systems are explained, and divided into two main categories based on the nature of the system's performance. In the first category the performance of the system depends on the materials used in the isolation layer, and represent different kinds of rubber bearings, such as high strength, high damping and synthetic rubber bearings. In the second category, the response depends on the gravity loads and can be found alternatives like frictional pendulum systems - FPS, ball systems and universal linear sliders. The ball system is highlighted as a promising alternative, since combine free rolling and FPS. A performance comparison among the different systems is also executed. In addition, an optimal distribution of the isolators is proposed, based on stiffness, damping and costs considerations.

The analysis of a 2 degree-of-freedom system is performed, in order to introduce the governing equations of the system under dynamic and ground excitation. The interaction between the parameters of the structure and isolation system is explained, as well as the way to obtain the response of the system. Furthermore, an explanation of computer-based analysis is done taking into account the load definition process, the mathematical model, the analysis and the evaluation of the results. Finally, several low cost conceptual schemes are presented as alternatives base isolation systems. Among the options, longitudinal rubber bearings, fiber reinforced bearings, independent story load distribution and local fabrication are proposed as means to spread out even more the technique in future civil engineering projects.

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ACKNOWLEDGMENTS

The continuous support given by my parents Rafael and Esperanza, the unconditional closeness offered by my sisters Sandra and Pilar, and the love offered by my girlfriend Margarita, were fundamental for developing and culminating this project with success. It was remarkable how, without giving importance to the distance, we managed to remain close and devoted to foster our objectives and goals.

In addition, COLFUTURO, a Colombian private organization, whose mission is to contribute to the internationalization and development of Colombia through educational programs, allowed me to remain financially healthy during the process of concluding this interesting endeavor at MIT.

Regarding my classmates, all the M.Eng. 2001 students were particularly important, since they became the basic social and academic network in which I was immerse. High performance structures colleagues let me have a bigger interaction due to our similar schedules and interests, and obviously, due to a higher degree of communication, I especially thank my building rehabilitation's team members Tai-Chieh Wu, Noelle Bachas and John Kelly, because it was possible to share our experiences and learn the best things from each other to apply in our dynamic life projects.

I also have to recognize that the visionary attitude of Professors Jerome J. Connor and Oral Buyukozturk, inspired me to continue doing research on the now emerging field of structural motion control, which for sure is going to be the basis of structural engineering in the coming years; and for which base isolation is just a single piece in a vast puzzle of alternatives to improve the seismic response of structures. Finally, I would like to thank the faculty, and administrative staff with whom I was involved, and got appropriate advices and cooperation when they were required.

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1. INTRODUCTION

Base isolation or seismic isolation is an approach to earthquake-resistant design that is based on the concept of reducing the seismic demand rather than increasing the earthquake resistance capacity of the structure. Capacity is a complex function of strength, stiffness, and deformability given by the structural configuration and material properties. Demand, on the other hand, is controlled by the design motion criteria, such as static base shear and lateral-force distribution relationships, design spectra or time histories. An appropriate application of this concept leads to better performing structures that will remain essentially elastic during large earthquakes.

Many mechanisms have been proposed over the last century to try to achieve the goal of uncoupling the building from the damaging action of an earthquake, for example, rollers, balls, cables, rocking columns or sand interfaces. However, the concept of base isolation has become a practical reality within the last 25 years with the modification of sliding approaches and the development of multilayer elastometric bearings, which are made by vulcanization bonding of sheets of rubber to thin steel reinforcing plates. These bearings are very stiff in the vertical direction and can carry the vertical load of the building but are very flexible horizontally, thus enabling the building to move laterally under strong ground motion.

In practice, the structural engineer has to face a basic dilemma of how to minimize interstory drift and floor accelerations when trying to provide superior seismic resistance of a building. Large interstory drifts cause damage to nonstructural components and to the equipment that interconnects stories. However, interstory drifts can be minimized by stiffening the structure, but leading to amplification of the ground motion, which produces high floor accelerations that can damage sensitive internal equipment (approximately 0.20g[1]). Floor accelerations can be reduced by making the system more flexible, but this leads to large interstory drifts. Therefore, a practical way of reducing simultaneously interstory drift and floor accelerations is using base isolation, see Figure 1.1; the isolation system concentrate the displacements in the isolation level while reducing not only the relative deformations of the structure but also the seismic demand, which is related with the acceleration and the natural period of vibration. Examples of applied base isolation systems in the United States, Japan, Europe and New Zealand are described in reference [1].

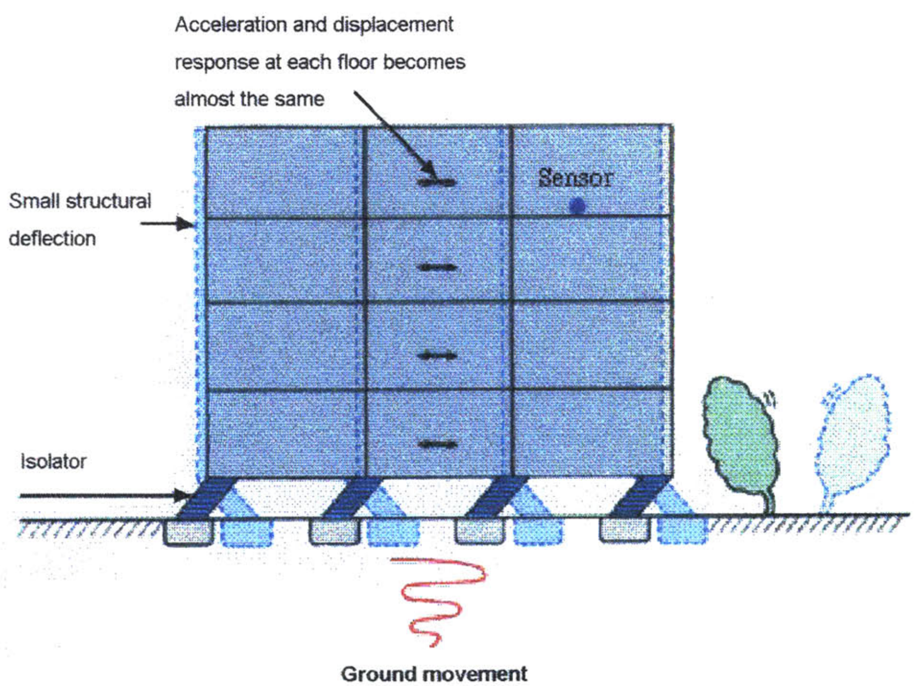


Figure 1.1 – Base isolation scheme.

[1] Comfort limits in humans are exceeded with approximately 0.02g, under serviceability conditions.

2. BASE ISOLATION SYSTEMS

At the present moment there are two basic types of isolation systems: one is typified by the use of elastometric bearings, and the other one by the use of gravity-based systems (sliding and frictional). The concept of base isolation in both cases is founded on the decoupling of the building or structure from the horizontal components of the ground motion by interposing structural elements with low horizontal stiffness between the structure and the foundation. This gives the structure a fundamental period that is much longer than both its fixed-base period and the predominant period of the ground motion. The first dynamic mode of the isolated structure (known as isolation mode) involves deformation only in the isolation system while the structure behaves essentially as a rigid body. The higher modes involve some deformation of the structure, although they contribute little to the earthquake-induced forces. The isolation system does not absorb the earthquake energy, but rather deflects it through the dynamics of the structure; though this effect does not depend on damping, a certain level of damping is required to suppress possible resonance at the isolation period. Figure 2.1 shows a typical elastometric rubber bearing.

Figure 2.1 – Elastometric rubber bearing.

In particular, the gravity-based system works by limiting the transfer of shear across the isolation interface, isolating the structure but without connections (isolation layer – structure). Within this category the Frictional Pendulum System - FPS is found, which use a special interfacial material sliding on a concave stainless steel surface used as restoring mechanism.

2.1 SYSTEMS WITH RUBBER BEARINGS

The highly dense natural rubber, from which the isolators are made, has mechanical properties that make it ideal for a base isolation system. The shear stiffness of this rubber is high for small strains but decreases by a factor of four or five as the strain increases, reaching a minimum value at a shear strain of 50%. For strains greater than 100%, the stiffness begins to increase again, providing a fail-safe action under a very high loading.

The damping follows the same pattern of the stiffness but less dramatically, decreasing from an initial value of 20% to a minimum of 10% and then increasing again. The high initial stiffness is invoked only for wind load design and the large strain response only for fail-safe action. When the requirements of stiffness for serviceability and wind cannot be met, lead plugs are inserted into the bearings, see Figure 2.2, giving not only the additional initial stiffness but also the contribution of damping for the extreme design event due to its yielding. Lead-plug rubber bearings were developed in New Zealand in the 60's. Another approach for providing the required initial stiffness under service loads is bracing the steel plates that hold the rubber bearing; Figure 2.3 shows this technique [2].

Ongoing research on the base isolation concept has improved the effectiveness of the isolators in decreasing the problems of stability, roll-out, failure, or unexpected responses, and strengthens the trend of moving away from add-on mechanical dampers. In addition, the difficulties of manufacturing the isolators have diminished, and now it is possible to find bearings as large as 1.6m in diameter. This combination of increased size with low-modulus rubber has resulted in highly reliable isolation systems. However, fire protection is still a critical issue, since the mechanical properties of the isolators are very vulnerable to high temperatures.

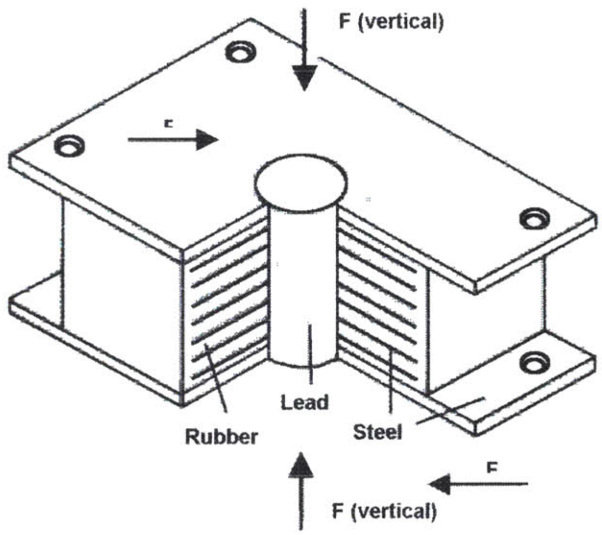


Figure 2.2 – Lead plug rubber bearing.

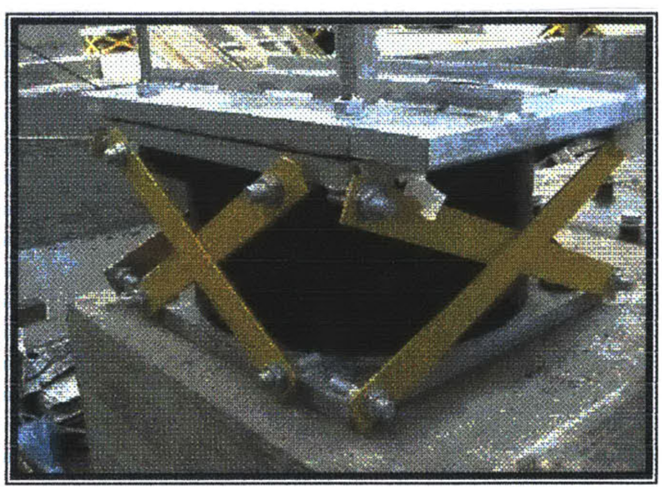


Figure 2.3 - Braced rubber bearing.

The above facts have increased the interest in applying this technology to public housing, schools, and hospitals in developing countries located in high seismic hazardous areas, where the replacement costs due to earthquake damage can be a significant part of the gross national product.

2.1.1 High strength rubber bearings

Base isolation systems that use High Strength Rubber Bearings – HSR, jointly developed in by Takenaka Corporation[2] and Bridgestone Corporation[3], have carbon mixed within the rubber, which greatly increases the compressive strength and tensile strength. This enables the isolators to well withstand the tensional "pull-out forces" working on the column bases due to overturning effects during an earthquake. Thus, it is now possible to construct base isolated super high-rise structures (between 80 - 150 meters tall).

By using this base isolation system with HSR, the input of the seismic motion into the building is reduced between ½ to ¼, this means there is hardly any damage requiring repair to the building, or any household valuables or equipment falling over; also panic during the earthquake can be prevented, so a super high-rise apartment where there is a higher level of safety and feeling of security with regard to earthquakes can be realized.

2.1.2 High damping rubber bearings

A damping function is indispensable for a seismic isolation system and this has required up to now a separate mechanism. If this function could be added to

[2] Takenaka Corporation is Japan's oldest architecture, engineering and construction firm with more than 100 years of experience [3].

[3] Bridgestone Corporation is a Japanese firm that started in 1931 making tires in the island of Kyushu [4].

rubber, it would be a great advantage from the standpoints of building design and construction. However, in trying to give to the rubber material a large attainability (damping ability), creep characteristics and temperature dependency become worse. The effect of creep yields large local stress and strain inside the rubber causing the tilting of the structure. Temperature and velocity dependent properties change the stiffness and damping of the rubber over temperature and frequency ranges.

Fortunately, current research has resulted in the achievement of a highly functional high-damping rubber bearing with low-creep and low temperature dependency. The characteristics of this rubber bearing are not only its high-damping effect (approximately 15%) for large earthquakes, but also for small and medium size displacements. In addition, super plastic rubber with even higher damping capacity than high damping rubber is being developed (approximately 40%). This material exhibits a stress and strain behavior very similar to rubber but with the advantage of the damping required for reducing the swaying of skyscrapers due to earthquakes and strong winds. Figure 2.4 shows a cross-section of the high damping rubber bearings [4].

2.1.3 Synthetic Rubber bearings

Ethylene-propylene rubber - EPR, is a random copolymer of ethylene and propylene. This is a rubbery non-crystalline material commonly used for toughening of other polymers, and that now can be used for isolation bearings. EPR possess excellent resistance to ozone, sunlight, and weathering, has good flexibility at low temperatures, good electrical insulation properties, and behaves adequately under shear deformations. It is used in the manufacture of tires, hoses, auto parts, coated fabrics, electrical insulation, and isolation bearings. Ongoing research and improvements in the characteristics of this synthetic rubber will have an impact in lowering the costs of natural rubber bearings.

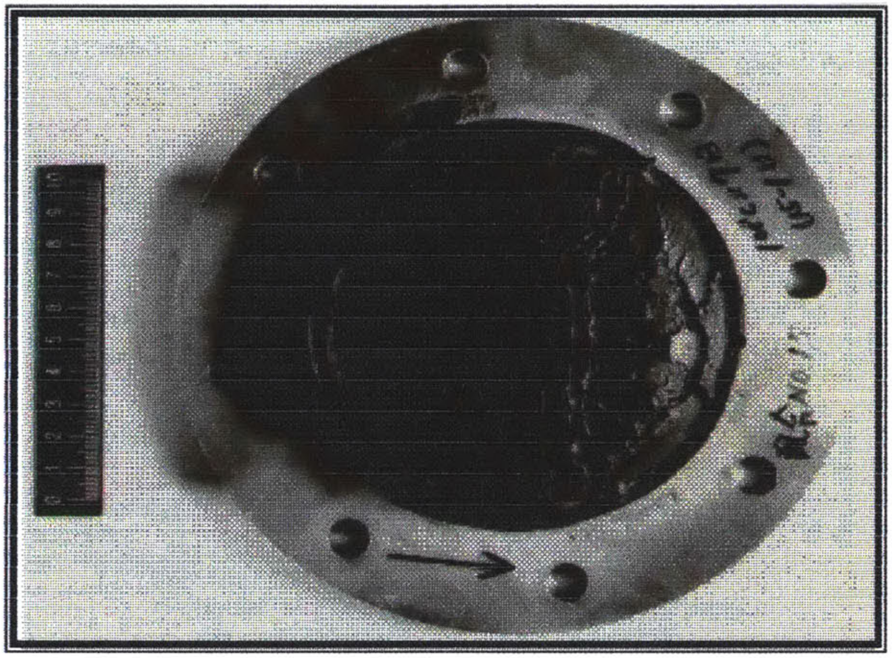


Figure 2.4 – Cross-section of a high-damping rubber bearing.

2.2 GRAVITY-BASED SYSTEMS

These types of systems have been proposed as seismic isolation because of their inherent simplicity, their relatively low cost, and the fact that no more than friction force is transmitted to the superstructure. However, they present problems such as excessive drift and lack of fail-safe constraints, mainly due to their force-deflection characteristics, which show no resistance once the sliding threshold has been overcome. In addition, they may produce a very low effective frequency because of the magnitude of the input excitation, leading to extremely large relative displacements. Figure 2.5 shows a conventional sliding support.

Some observations have pointed out that small masonry buildings cannot be isolated cost-effectively using elastometric rubber bearings, while using sliding systems leads to a more economical alternative among the earthquake-resistance solutions [5].

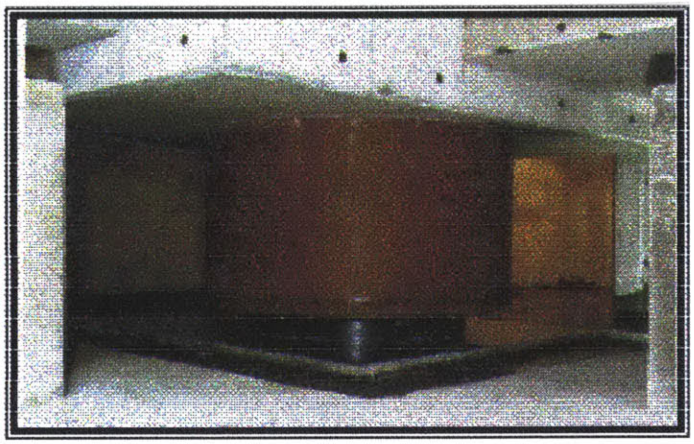


Figure 2.5 – Conventional sliding support.

2.2.1 Frictional Pendulum Systems – FPS

Coulomb friction has proven to be a simple and reliable mean of vibration isolation and energy dissipation in earthquake engineering applications. Frictional forces developed at the interphase of two sliding materials are well understood at the present time in their functional dependency with contact pressure and sliding velocity.

Among the seismic isolation devices based on friction as means of energy dissipation, a remarkable kind is the Frictional Pendulum system – FPS [5]. This system makes use of spherically shaped stainless steel surface and a lentil-shaped articulated slider covered by a Teflon-based high bearing capacity composite material, having a movement of one part of the bearing with respect to others resembling a pendulum motion in the presence of friction, see Figure 2.6. The lateral force needed to induce a lateral displacement of the building-bearing system depends primarily upon the curvature of the spherical sliding surface, and the vertical load on the bearing. The lateral force is proportional to the vertical load, a property that minimizes adverse torsional motions in structures with asymmetric mass distribution.

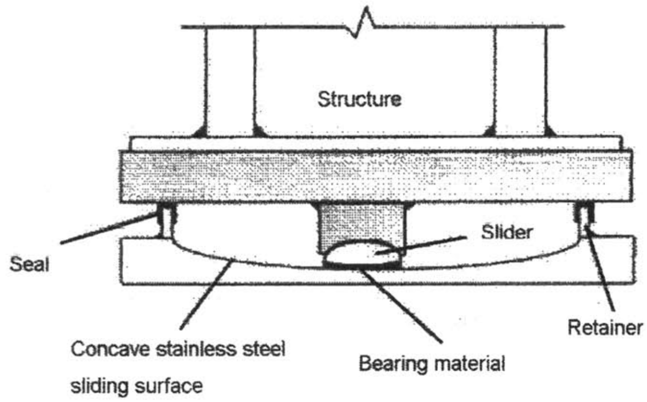


Figure 2.6 – Section of a typical FPS.

One of the most relevant features of the FPS is that residual displacements in the isolation are reduced due to the self-centering action induced by the concave spherical surface. These residual displacements are an important drawback of other sliders in general.

2.2.2 Ball system as low cost base isolation

In the traditional seismic-resistant design, it is assumed that every structural member has enough strength to resist seismic force and enough ductility to absorb seismic energy. When this design philosophy is adopted, experience shows that the structures absorb plenty of energy and that plastic deformation of some structural members is very large. Moreover, it is very difficult to repair and reinforce the structures after an earthquake, and it always results in serious damages to indoor devices.

Multistory brick masonry structures are a major structural form in developing countries, but at the same time are the most vulnerable buildings. Every seismic attack in the past has shown that the seismic performance of these structures is very bad, and that the cost for reinforcing and repairing is very high; see Figure 2.7. Thus, it is necessary for masonry structures to adopt seismic isolation in high earthquake intensity regions. However, laminated rubber bearings are expensive if designed for ordinary structures in developing countries.

Again, it is known that the best technique of isolation is to disconnect the structure from the ground completely when an earthquake occurs. In general, rolling friction is so small that the inertia force of the superstructure is inevitably small, and base isolation by a ball system can be an example of the concept. See basic scheme of ball system without restoring property in Figure 2.8.

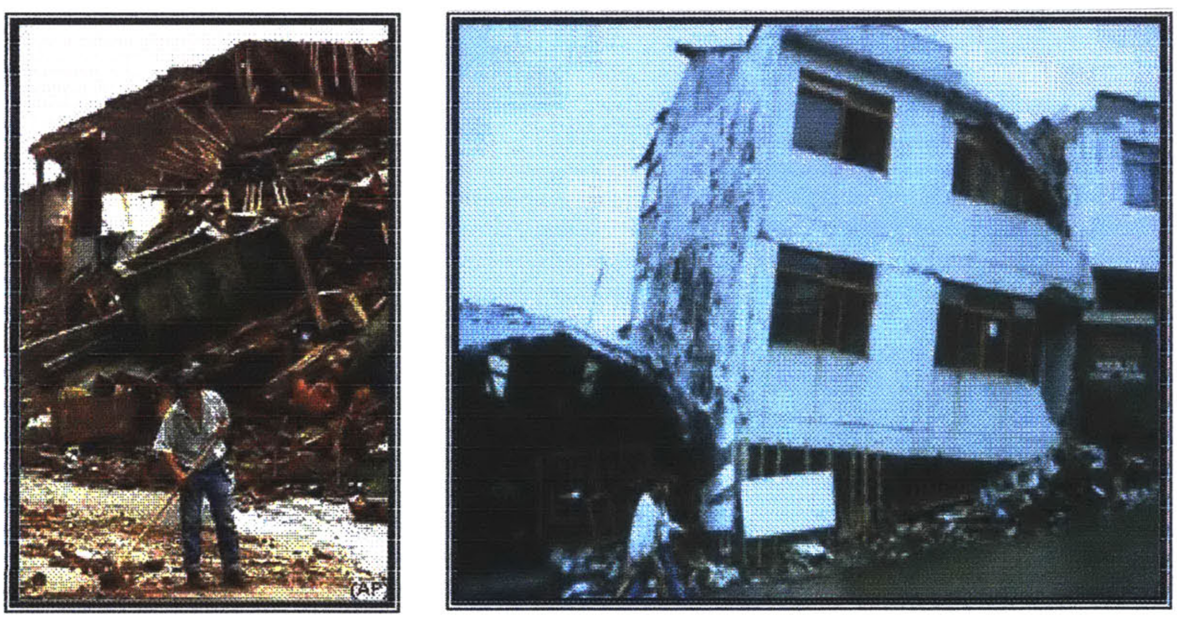


Figure 2.7 – Collapsed unreinforced masonry buildings in Colombia, after the earthquake of Armenia and Pereira on January 25th, 1999.

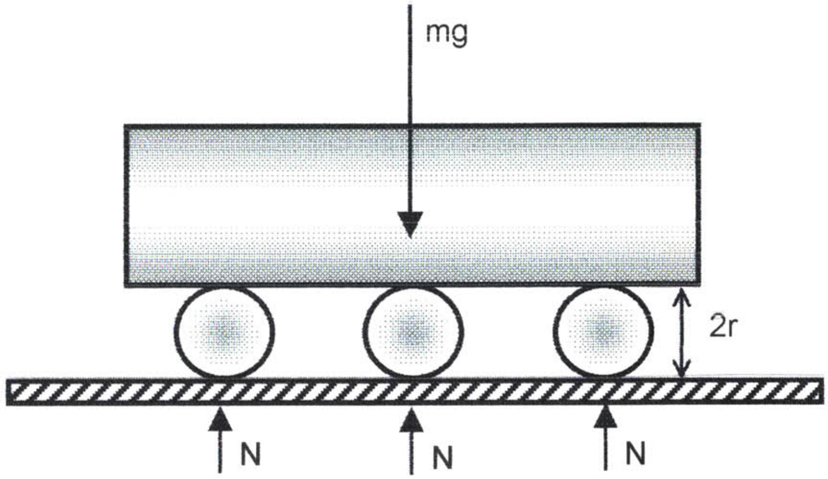


Figure 2.8 – Ball system without restoring property.

If steel balls are in contact with steel plates, and steel balls and plates are well finished and clean, the rolling friction coefficients are very small (between 0.05 – 0.5 mm), which when combined with an appropriate sphere's radius produce a small maximum acceleration of the mass' structure. Therefore, base isolation by a ball system seems to be very effective; even though it presents an obvious defect related with the displacement control, which in turn, can be controlled through a concave rolling surface as FPS.

According to the above notion, combining the advantages of free rolling and FPS, base isolation with ball system and restoring properties becomes an alternative for cheap seismic isolation [6]. Figure 2.9 shows schematically the concept.

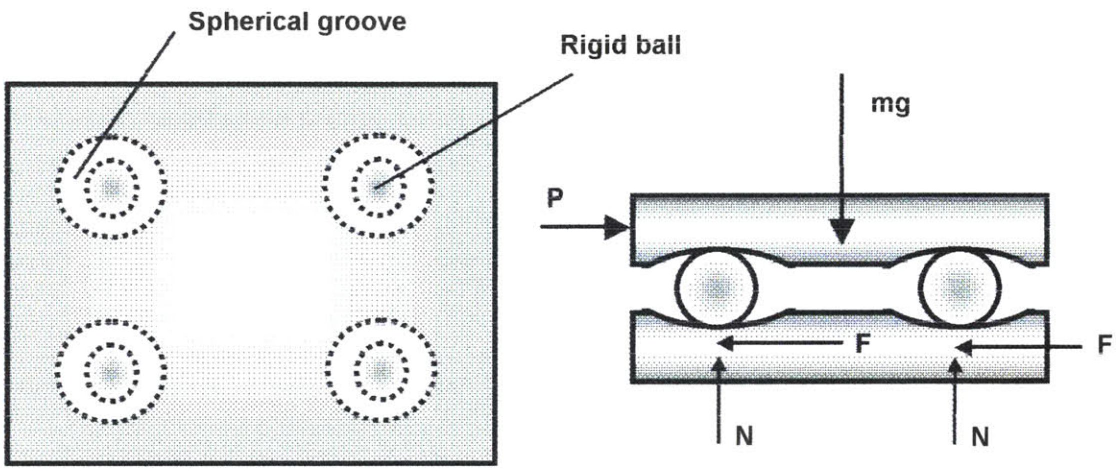


Figure 2.9 – Ball system with restoring property.

2.2.3 Universal linear slider

The Universal Linear Slider – ULS has slide blocks that contain bearings on a rail, which when incorporated in parallel crosses produce a base isolation system in all lateral directions. Regarding the capacity of the system, support per unit load ranges from a few tons to a maximum 4,000 tons. ULS also have a maximum pull-out resistance of 1,600 tons developed through the mutually locked superior and inferior rails, enabling them to be used in a wide range of buildings. Figure 2.10 illustrates the universal linear slider mechanism [3].

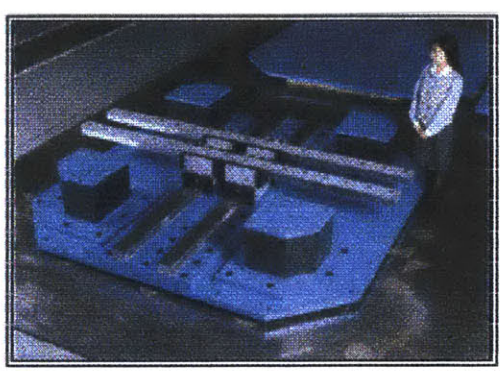


Figure 2.10 – Universal Linear Slider – ULS.

The ULS has grooves on two steel plates that are one-directional, but by arranging them perpendicularly so that they intersect each other, and coupled with bearing movement, sliding can be done in any horizontal direction. This makes it difficult for the shaking of the foundation (underlying steel plates) to be conveyed to the building (overlying steel plates). In order to control the movement of the structure under service and design loads, additional devices such as steel rods and hydraulic dampers have to be installed.

2.3 PERFORMANCE COMPARISON (NRB, HSR, ULS)

Knowing the characteristics of the Natural Rubber Bearings, High Strength Rubber Bearings and Universal Linear sliders, it is possible to establish not only a comparison of the characteristics of each system but also their applicability in different types of structures; see the summary in Table 2.1.

	PARAMETER	NATURAL RUBBER BEARINGS NRB	HIGH STRENGTH RUBBER BEARINGS HSR	UNIVERSAL LINEAR SLIDER ULS
	Size of equipment	Diameter: ~ 1.5m	Diameter: ~ 1.5m	Area: 3m x 3m
	Load supported	~ 1,400 tons/unit	~ 2,000 tons/unit	~ 4,000 tons/unit
	Pull-out resistance force	~ 0 tons/unit	~ 600 tons/unit	~ 1,600 tons/unit
	Natural period	2 to 3 seconds	4 to 6 seconds	up to 10 seconds
	Usable life (years)	60 years	60 years	100 years
	Aspect ratio (H/W)	Maximum 3	Maximum 6	Maximum 6
	Height of structure	Maximum 60m	Maximum 150m	Maximum 150m
Application	**Detached house**	Not applicable	Not applicable	Applicable
	Low/medium-rise building	Suitable	Suitable	Suitable
	High-rise building	Hard to apply	Suitable	Suitable
	Pencil building	Hard to apply	Applicable	Applicable
	Megastructure	Hard to apply	Applicable	Suitable
	Dome	Not applicable	Hard to apply	Applicable
	Man-made foundation	Not applicable	Applicable	Applicable
	Soft foundation	Not applicable	Applicable	Suitable

Scale: Suitable, Applicable, Hard to Apply, Not applicable.

Table 2.1 – Comparison between NRB, HSR and ULS.

2.4 DISTRIBUTION OF BASE ISOLATION SYSTEMS

Taking advantage of the properties of the systems discussed above, there is an alternative that combines the sliding bearing with elastometric rubber bearings, providing a lock-up mechanism to avoid large horizontal displacements. Nonetheless, the application of the hybrid system is limited by the height of the structure to be isolated, as well as the aspect ratio.

The above limitation is due to the pull-out effect on the isolators, see Figure 2.11, caused by the overturning moment due to service or design loads, such as wind or earthquake. At the present moment, as discussed in heading 2.1.1 and in Table 2.1, the range for the highest base-isolated buildings in the world has increased and varies between 80m to 150m, mainly due to the newly developed rubber bearings with carbon content that well withstand pull-out forces. This has challenged the engineering community, which had accepted the concept to be applicable only to low-rise buildings up to 10 stories.

Consequently, a combined rubber and frictional pendulum system can be selected for decreasing the costs of implementation and obtaining a good performance of the system relative to the type of structure. The frictional pendulum system minimizes the seismic demand produced by the active fault, and the rubber bearing system minimizes the excitation of higher modes of vibration in the earthquake-resistant system of the building or structure caused by the starting and stopping of the frictional system. Both systems are completely compatible, and also, torsional effects can be controlled by the stiffness of the lead plug rubber bearings when located strategically far enough from the center of mass and center of rigidity of the building. The schematic location is shown in Figure 2.12.

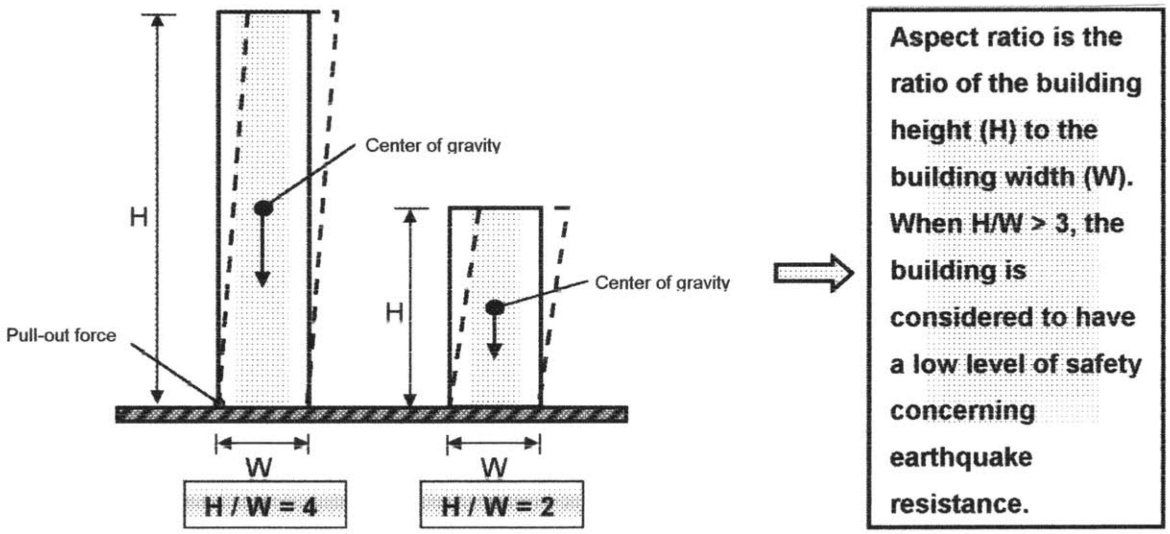


Figure 2.11 – Pull-out forces in high-rise base-isolated buildings.

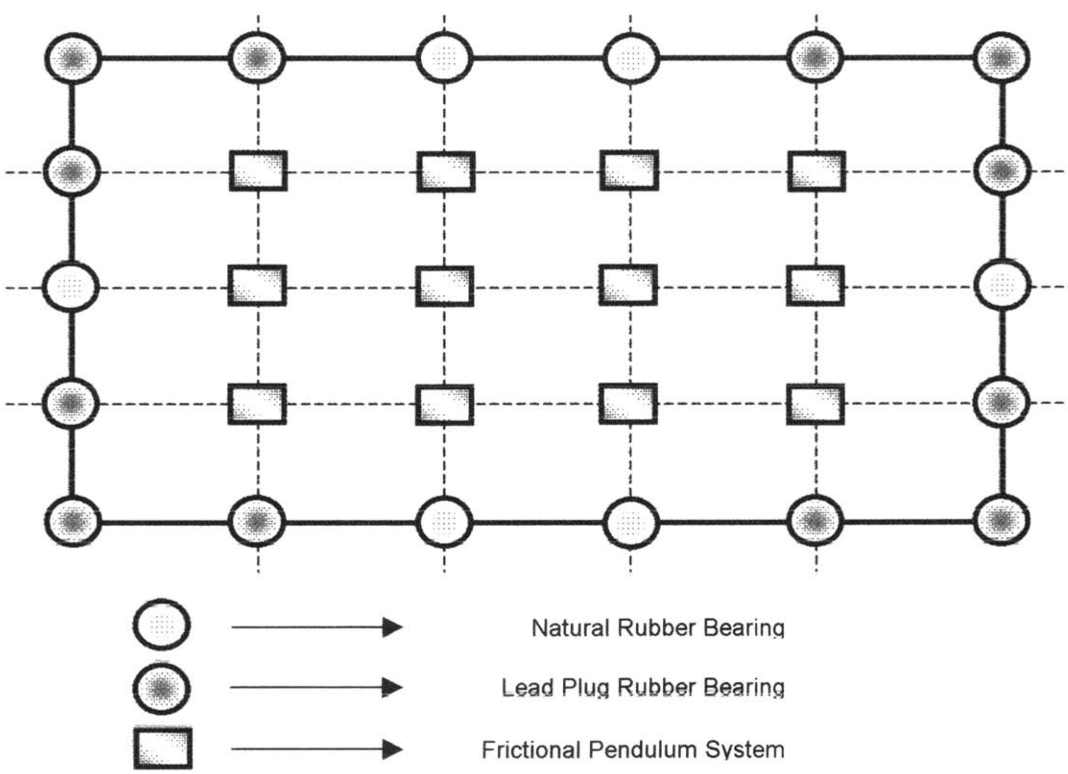


Figure 2.12 – Preferred location of isolators in the hybrid system.

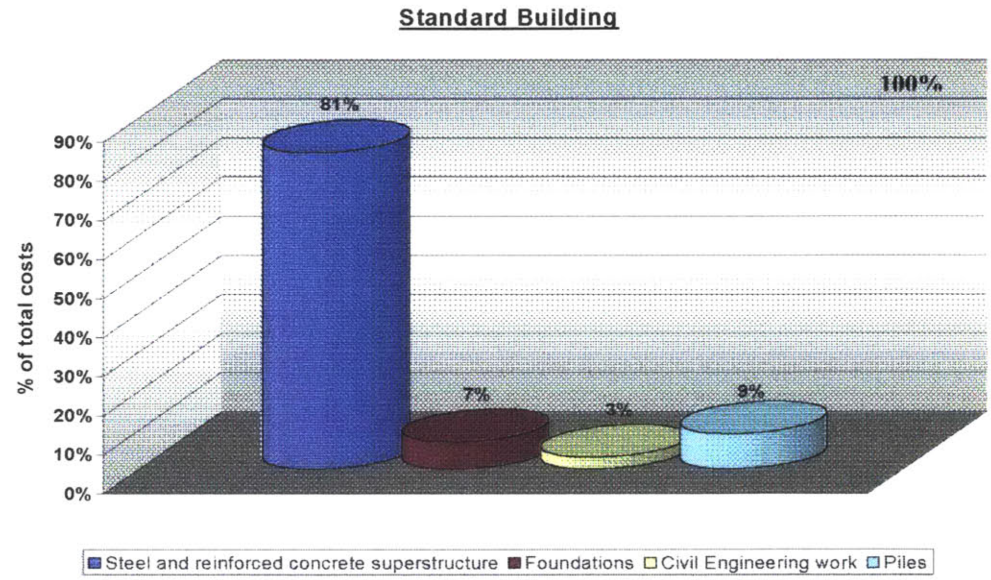
2.4.1 Damping

In order to increase the damping of the isolated structure, additional elements, such as steel energy-absorbing devices, hydraulic dampers or lead plugs within the bearing itself, have to be included. Nevertheless, these added elements induce responses in the higher modes of the structure, being clear that the optimum method of increasing damping is to provide it in the rubber compound itself. Additionally, almost all the types of dampers have mechanical connections and require routine maintenance, except for the internal lead plug and the high-damping rubber bearings, which are also relatively easy to manufacture, are unaffected by time and are very resistant to environmental degradation.

2.4.2 Cost estimate

Regarding the expenses of the isolation system, for most new construction projects the isolation design costs around 5% more when compared with a conventional seismic-resistant code design. However, the design code provides a minimum level of protection against strong ground motion, guaranteeing only that the building will not collapse and that human lives are preserved, but does not protect the building from structural damage, in fact the energy dissipation mechanism is through plastic deformations of the structure. Therefore, when equivalent levels of design performance are compared, an isolated building is always more cost-effective and the premiums if the building requires seismic insurance, will be smaller; also if the life-cycle costs are analyzed, the isolation scheme is again more favorable. Finally, if the market of base isolation systems continues growing and being accepted, the breakdown of the costs for a new base-isolated project compared with a conventional one could be represented schematically as shown in Figure 2.13.

In the case of projects for being retrofitted, base-isolation is again one alternative with important cost-effectiveness properties, since reaches its goal of improving the seismic response of a structure at the lowest costs, when they are compared with the benefits from the response if an important seismic event happens. Chapter four deals with a project for upgrading seismically a historical structure.



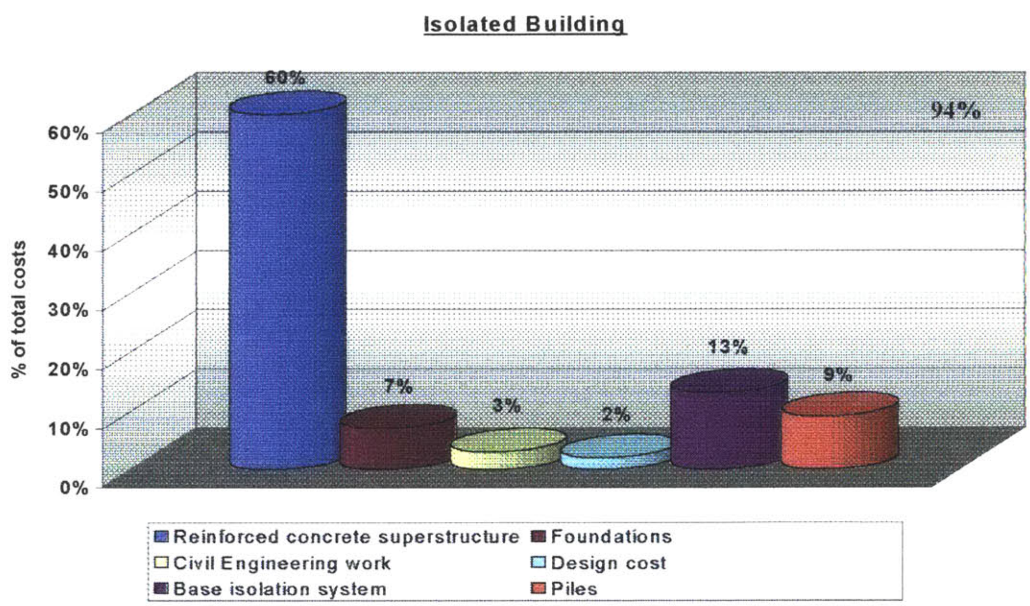


Figure 2.13 - Cost breakdown for conventional and isolated buildings if market of isolation systems continues growing.

3. ANALYSIS OF BASE ISOLATION SYSTEMS

Most isolation systems are nonlinear in their force-deformation relationships, and the nonlinearity is important to be considered in final design. However, a linear analysis for the system would serve to gain insight into the dynamics of base-isolated systems.

Considering a one-story building to be isolated, as shown in Figure 3.1, with its lumped mass is *m*, lateral stiffness *k*, and lateral damping *c*.

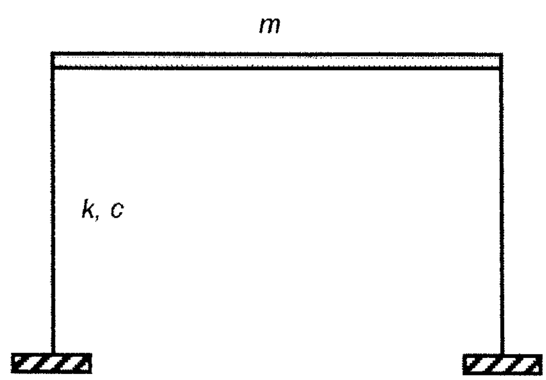


Figure 3.1 - Fixed-base structure.

This model corresponds to a single degree of freedom system – SDOF with natural frequency ω_f, natural period T_f, and damping ratio ξ_f.

$$\omega_f = \sqrt{\frac{k}{m}} \qquad T_f = \frac{2\pi}{\omega_f} \qquad \xi_f = \frac{c}{2m\omega_f} \tag{1}$$

As shown in Figure 3.2, this one-story building is mounted on a base slab of mass m_b, that is supported on a base isolation system with lateral stiffness k_b, and lateral viscous damping c_b. The parameters that characterize the isolated building are the natural frequency ω_b, natural period T_b, and damping ratio ξ_b. For base isolation to be effective in reducing the forces in the building, T_b must be much longer than T_f.

$$\omega_b = \sqrt{\frac{k_b}{m+m_b}} \qquad T_b = \frac{2\pi}{\omega_b} \qquad \xi_b = \frac{c_b}{2(m+m_b)\omega_b} \tag{2}$$

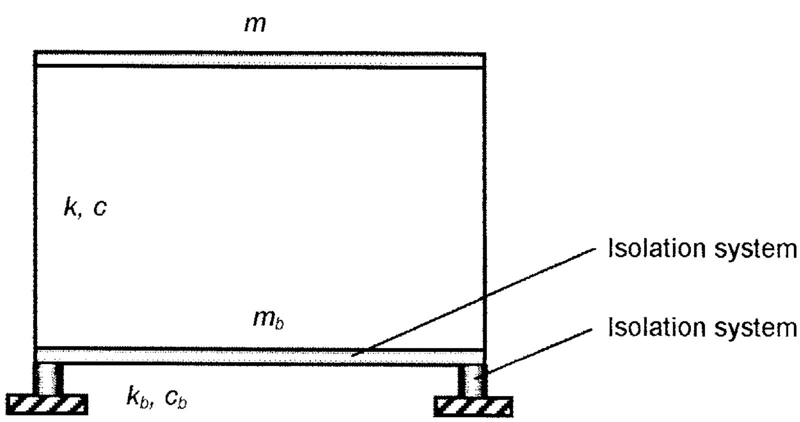


Figure 3.2 – Base-isolated structure.

The above base-isolated structure is a 2DOF system with mass, stiffness and damping matrices denoted by $\underline{m}$, $\underline{k}$ and $\underline{c}$. Due to the differences between the damping in the rubber bearings and the damping in structure, the combined damping of the system is nonclassical. Although, modal analysis is not applicable to nonclassically damped systems, it can provide approximate results, enough to illustrate the behavior of the system.

The natural vibration periods and modes of the system can be determined with the equations of motion of the system [7], defined by the following matrix equation:

$$\underline{m}\ddot{u}+\underline{c}\dot{u}+\underline{k}u=-\underline{m}\ddot{u}_g \qquad (3)$$

The mass and stiffness matrices of the system are:

$$\underline{m}=\begin{bmatrix} m_b & 0 \\ 0 & m \end{bmatrix} \qquad \underline{k}=\begin{bmatrix} k+k_b & -k_b \\ -k_b & k_b \end{bmatrix} \qquad (4)$$

The frequencies can be obtained with the frequency equation, after substituting for $\underline{m}$ and $\underline{k}$ and evaluating the roots of the determinant:

$$\det\left[\underline{k} - \omega_n^2 \underline{m}\right]=0 \qquad (5)$$

The natural modes are determined substituting the frequencies (one at the time) in the previous equation multiplied by ϕ. If one of the elements of the ϕ vector is set equal to 1, the second element of the vector can be calculated.

$$\left[\underline{k} - \omega_n^2 \underline{m}\right]\phi_n=0 \qquad (6)$$

In addition, the earthquake response of the system (for this illustrative 2DOF system) can be estimated by response spectrum analysis, computing the floor displacements and story drifts with the spectral pseudo-displacement and pseudo-acceleration, from the earthquake response spectrum or the design spectrum.

3.1 EFFECTS OF BASE ISOLATION

In order to understand the dynamics of base isolation, we can consider a system whose base slab's mass is 2/3 the building's mass. The fixed-base period is 1/5 the base-isolated period, and the damping of the fixed-base structure is 1/5 of the isolated one. The base shear of the building V_b, and the base displacement u_b can be estimated using a design spectrum.

The schematic natural vibration periods T_n and modes ϕ_n of the system are shown in Figure 3.3.

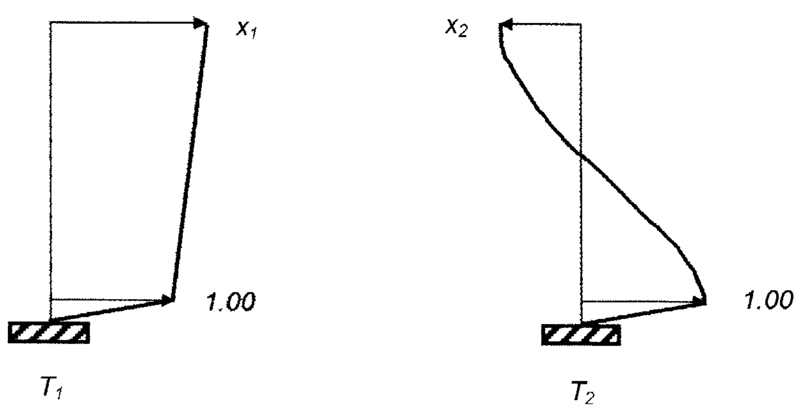


Figure 3.3 – Schematic vibration modes and periods for the 2DOF system.

Numerical simulations [8] show that in the first mode of vibration, the isolator undergoes deformation while the structure behaves as a rigid body. The second mode involves deformation of the structure as well as in the isolation system. In general the natural period of the base-isolated structure in the second mode is significantly shorter than the fixed-base period by approximately 30%.

Static analysis of the system for forces per mode gives the modal static responses r_n^{st} for response quantity $r(t)$. In particular, for the base shear $V_b(t)$ in the structure and the displacement $u_b(t)$ at the base, the modal static responses of the two modes can be calculated through the modal expansion of the effective earthquake force distribution [7], [9]. From the above, it can be established that the base shear for the second mode is negligible compared to the first mode. This result plus the fact that the natural vibration period of the first mode is much longer than the fixed-base period of the structure reveal the effectiveness of a base isolation system.

The modal damping ratios are determined by the following equations:

$$\xi_n = \frac{C_n}{2M_n\omega_n} \text{ ; where, } \quad M_n = \phi_n^T m \phi_n \quad \text{and} \quad C_n = \phi_n^T c \phi_n \tag{7}$$

In general, the damping for the first mode tends to be similar to the isolation-system damping. Damping in the structure has little influence on modal damping because the structure behaves a rigid body for this mode. In contrast, high damping of the isolation system increases the damping in the second mode.

The peak value of the *n*th-mode contribution $r_n(t)$ to response $r(t)$ is given by the following expression:

$$r_n = r_n^{st} A_n \text{ ; where, } \quad A_n = A(T_n, \xi) \tag{8}$$

A_n is the ordinate of the pseudo-acceleration response (or design) spectrum at period T_n for damping ratio ξ_n. Specializing the above equation for the quantities of interest, base shear V_b in the structure and isolator deformation u_b, gives:

$$V_{bn} = V_{bn}^{st} A_n \qquad u_{bn} = \left(\omega_n^2 u_{bn}^{st}\right) D_n \tag{9}$$

where $D_n = A_n/w_n^2$ is the deformation spectrum ordinate. Combining the modal responses by the SRSS combination rule, the deformation in the isolator and the base shear can be determined. Obviously, the base shear is much larger if the structure is not isolated. Usual relations between shear for the fixed-base and isolated structure are that fixed-base is 4 to 6 times the isolated one. Therefore, the base isolation system reduces the base shear primarily because the natural period of the first mode, providing most of the response, is much longer than the fixed-base period of the structure, leading to a smaller spectral ordinate.

It is important to highlight that the forces in the structure are reduced because of the period shift, depending on the natural period of the fixed-base structure and on the shape of the earthquake design spectrum, which in turn, is defined by the local seismic activity and the way in which the energy is liberated by the active faults. For instance, if $T_b >> T_f$ the structure does not behave as rigidly in the first mode, and the natural period is significantly affected by the flexibility of the structure. In addition, the second mode contribution to the effective earthquake forces is no longer negligible and the first-mode damping is no longer close to the isolation system damping. Also, if the acceleration response spectrum in a particular location contains significant spectral accelerations for long periods of vibration, like in cities with deep deposits of clay such as Mexico City or Bogotá, the application of base isolation becomes ineffective because even by lengthening the period of the structure, the seismic demand is not reduced.

Finally, the behavior and response of the rubber bearings under compression and bending effects can be susceptible to a buckling type of instability similar to that of an ordinary column but dominated by the low-shear stiffness of a bearing [10]. As the isolators experience large lateral displacements, the peak downward load on the isolator will occur at the same time as the peak horizontal displacement, and in combination will be one of the limit states for which the isolator will need to be proportioned. In principle, a complex nonlinear analysis will be needed to predict the bearing behavior under the combination of peak vertical load and maximum horizontal displacement.

4. COMPUTER BASED ANALYSIS

In order to obtain a reasonable design of the base isolation systems under different load scenarios, it is necessary to model mathematically the real structure so that the prediction of its behavior can be achieved efficiently for each iteration.

4.1 LOAD DEFINITION

The static loads have to be defined as close as possible to the real conditions, following when appropriate the recommendations and estimates of the design codes. Regarding the dead load, the self-weight of each structural element can be included in the mathematical model based on its cross sectional area, length and type of material. A representative load for the partition walls should also be included.

For taking into account the dynamic loads, a time history analysis or spectral analysis can be performed using finite-element software. One alternative is the Structural Analysis Program SAP2000. If the time history analysis is chosen, the accelerograms to be used should correspond to characteristic earthquakes produced by the active fault or system of faults that create seismic hazard in the area of interest.

At the present moment, the records can have 200 samples per second, with pre-event times of 5 seconds, post-event time of 10 seconds and channels that coincide with the North - South, East - West and Vertical components. In order to evaluate the response of the structures when subjected to a seismic event with a probability of being exceeded every 450 years, the characteristic record should be scaled to obtain a spectral velocity of approximately 1.2m/s for the fundamental period of the structure. Such scaled records represent the above episode and conserve the frequency content produced when the faults liberate their energy.

4.2 MATHEMATICAL MODEL

As mention before, using the Structural Analysis Program SAP2000, structures can be modeled with finite elements with good accuracy with respect to the real buildings. The columns and the floor grids can be represented by frame elements, which in turn are defined in terms of their cross-sectional geometric properties, dimensions, material characteristics and loads carried, using a general three-dimensional beam-column formulation which can include the effects of biaxial bending, torsion, axial deformation, and biaxial shear deformations. The walls and the concrete slabs of the floors can be modeled as shell elements, which are defined in terms of the thickness, the load supported and the material properties, while the size depends on the aspect ratio (one side cannot be more than 10 times greater the other side). This type of element includes translational and rotational stiffnesses, both in-plane and out-of-plane. A modeled structure that uses the above elements is described in the project “The rehabilitation of Mitchell Hall for seismic upgrade”, [11]. Figure 4.1 shows the referenced 3D-model.

Through the Nllink element in the analysis program [12], it is possible to model the devices for passive control of structures, such as isolator devices like rubber bearings or frictional pendulum systems, and damping devices like viscous dampers. The isolator devices behave as biaxial hysteretic elements that have coupled plasticity properties for the two shear deformations (X-Z and Y-Z), and linear effective stiffness properties for the remaining four deformations. For each shear deformation degree of freedom one can specify independently either linear or non-linear behavior in terms of the elastic spring constants, the yield forces and the ratios of post-yield stiffnesses to elastic stiffnesses. A linear spring relationship applies to the axial deformation, three moment deformations, and to any shear deformation without non-linear properties. All linear degrees of freedom use the corresponding effective stiffness. For modeling Frictional Pendulum Systems, it is possible to define a second type of isolator that has coupled friction properties for the two shear deformations and post-slip stiffness in the shear directions due to the pendulum radii of the slipping surfaces. The frictional forces are directly proportional to the compressive axial force in the element.

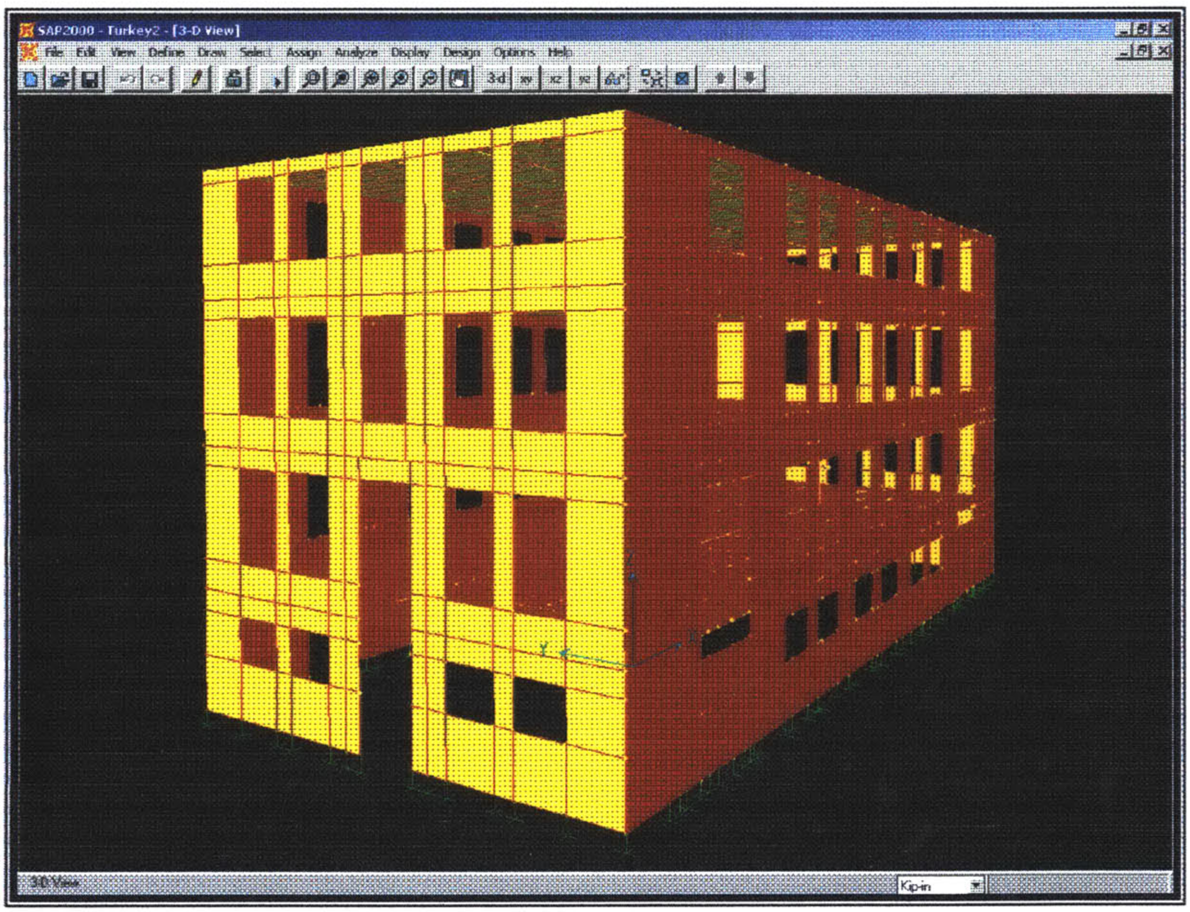


Figure 4.1 - 3D model of the referenced structure in SAP2000 [11].

Finally for modeling the damping devices, it is possible to define the properties based on the Maxwell model of viscoelasticity, having a nonlinear damper in series with a spring, see Figure 4.2.

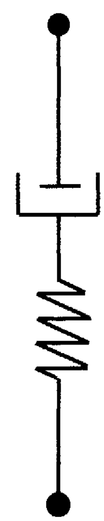


Figure 4.2 – Viscoelastic damper.

The nonlinear force-deformation relation ship is given by:

$$f = k * d_k = c * d_c^{cexp} \tag{10}$$

Where *k* is the spring constant, *c* is the damping coefficient, *cexp* is the damping exponent, d_k is the deformation across the spring, and $\dot{d}_c$ is the deformation rate across the damper. The damping exponent should be positive, and the practical range is between 0.2 and 2.0. The spring and damper deformation account for the total deformation:

$$d = d_k + d_c \tag{11}$$

If pure damping behavior is desired, the effect of the spring can be made negligible by making it sufficiently stiff. The spring stiffness should be large enough so that the characteristic time of the spring-dashpot system, given by $\tau = c / k$

(when *cexp*=1), is an order of magnitude smaller than the size of the load steps. The load steps are the time intervals over which the load is changing. The stiffness should not be made excessively large or else numerical sensitivity may result. An illustrative model with damper and isolator devices is shown in Figure 4.3.

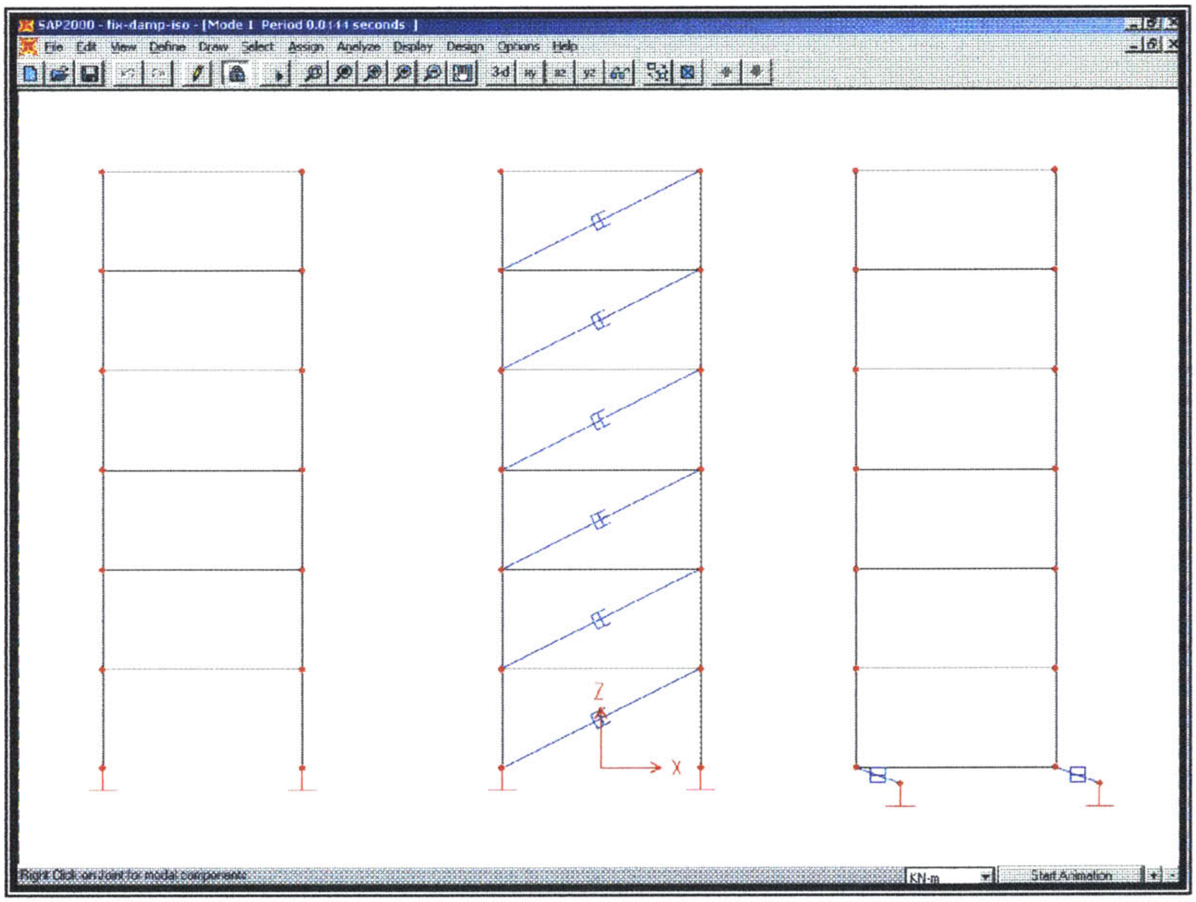


Figure 4.3 – Illustrative model with damper and isolator devices in SAP2000.

4.3 ANALYSIS PHASE

The analysis should be performed with the structure under the dead, live and dynamic loads described above. The loads must be combined with the corresponding modification factors prescribed by design codes in order to obtain the flow of stresses and forces through all structural elements, and isolator or damping devices. The dynamic analysis should be executed defining a representative damping ratio and including enough modes of vibration, so that the analysis accounts for at least 90% mass participation in the X and Y directions. The seismic excitation must be applied in the three global orthogonal directions X, Y and Z, making the necessary combinations. The dynamic analysis to be executed is recommended to include second order effects (P-Δ) and non-linearity to the Nllink elements, such as isolators and dampers.

4.4 EVALUATION OF RESULTS AND DESIGN

As a previous activity of the evaluation of the results, the mass, the expected fundamental period of the structure, the estimated base shear force and the probable wind load should be calculated trough approximate methods, in order to have a reference point for evaluating the SAP-2000 results.

After running the model, it is possible to obtain the maximum stresses and forces through the structural members and through the isolator and damping devices. Also, the maximum displacements, drifts, their locations and the dynamic properties of the structure are obtained. Finally, the design of the elements should be performed based on the strength and deformation requirements.

5. LOW COST CONCEPTUAL SCHEMES

In order to reduce the cost of the isolation systems, it is important to decrease the number of tasks that a single component of the system should perform. For example, high strength rubber bearings – HSR are more expensive than natural rubber bearings - NRB because the former has to provide in addition to the shear deformation capacity, a vertical strength to withstand the weight. The actual mechanism to provide the vertical strength and stiffness is through the use of steel plates and/or the addition of carbon components in the rubber. Therefore, the following strategies to decrease the cost of the isolators are based on the idea of optimizing and alleviating their duty of carrying the vertical loads.

5.1 LONGITUDINAL RUBBER BEARINGS

The idea behind this concept is the distribution of the vertical load in a bigger support surface. Since the isolators commonly used carry the contribution of the load corresponding to their tributary area, as shown in Figure 2.12, the actual load in the device is concentrated. Therefore, if the load can be spread out though a bigger surface, the requirements of vertical stiffness in the isolators are going to decrease.

The concept is an analogy with the raft foundations that support walls or columns. Figure 5.1 shows the scheme. Longitudinal rubber bearings for walls are simply one strip that is wider than the wall distributing the pressure more efficiently. In the case of columns, the rubber bearings are also a longitudinal strip, but now under the connecting beam that joint all columns in a matrix configuration.

The advantage with the longitudinal scheme is the significant reduction in the requirements that the rubber bearings have to meet in order to stand vertical loads. Since the vertical load is uniformly distributed through the matrix, the bearings can be focused to support the lateral deformations, and savings can be done excluding the strict vertical capacity considerations. The application of this concept can be more advantageous if it is designed for new buildings, rather than for retrofitting projects, due to the construction restrictions that buildings impose when they have to remain operational while being retrofitted.

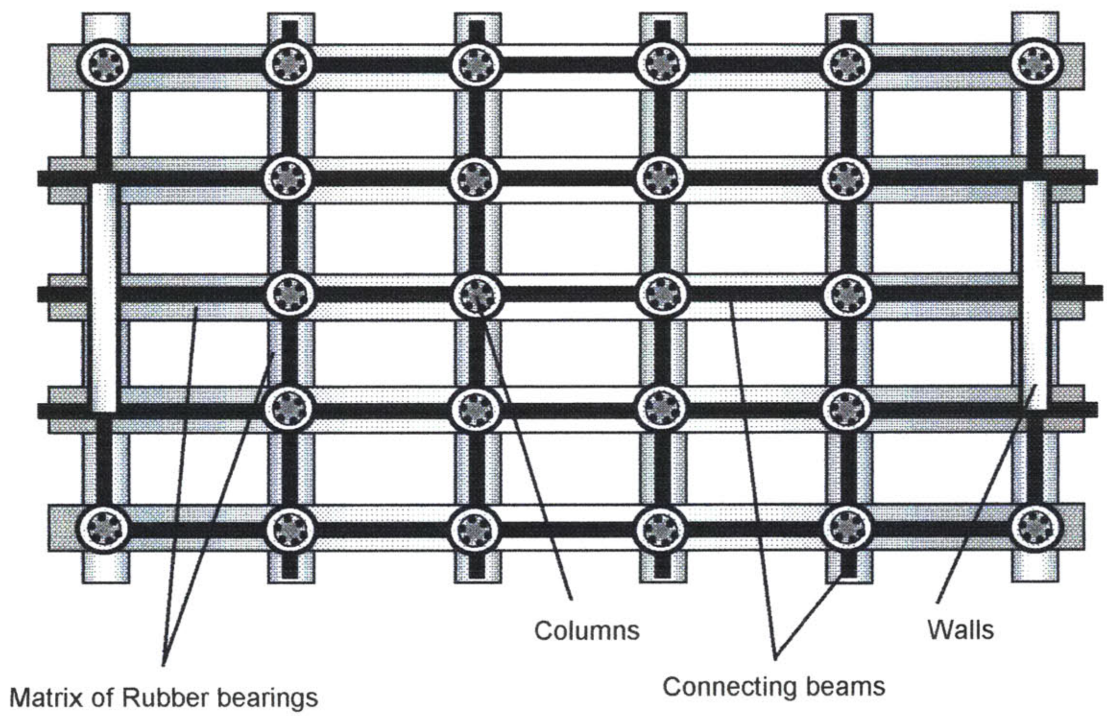


Figure 5.1 – Longitudinal rubber bearings in matrix configuration.

An opportunity of application of the concept is given by buildings designed with reinforced masonry, because the longitudinal rubber bearing can be placed exactly below the walls and the aspect ratios of these buildings usually do not exceed H/W=4. In addition, the scheme can be applied in areas with high seismic risk, where low-income communities are congregated, and where masonry buildings are commonly constructed.

5.1.1 Masonry buildings

In general, shear walls and horizontal diaphragms are the elements in which masonry structures depend for their lateral stability. The characteristic box system, Figure 5.2, does not have a vertical load-carrying frame but depends upon the walls, not only to carry the vertical loads, but also to provide necessary lateral stability.

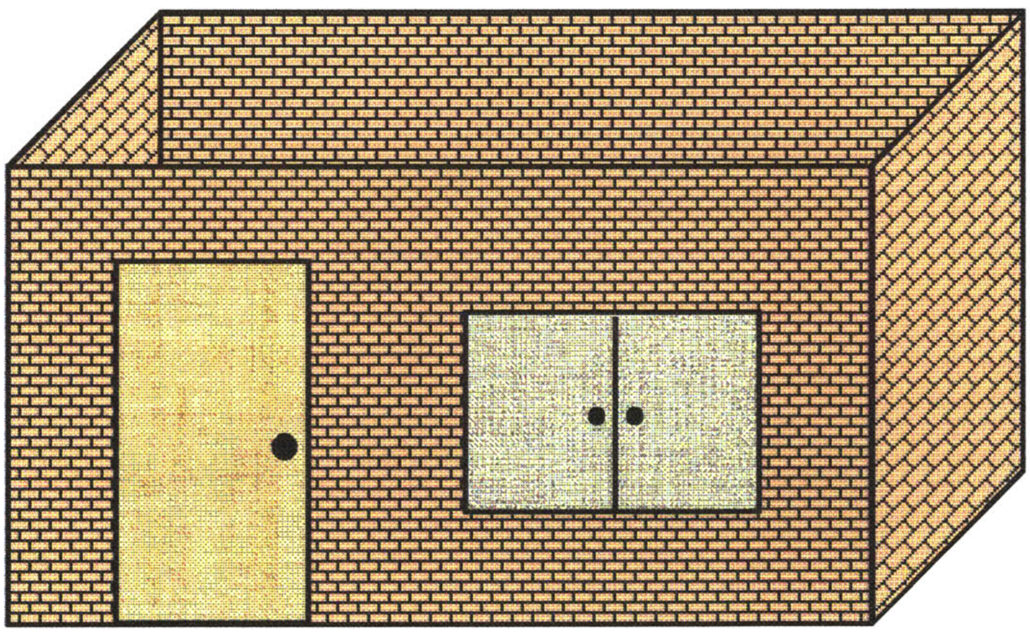


Figure 5.2 – Box-type masonry system.

From the above, it can be seen that there are four essential structural components [13], which comprise the defined box system:

- The walls perpendicular to the direction of the lateral loads.
- The horizontal roof and floor diaphragms.
- The shear walls parallel to the lateral load direction.
- The connections holding the walls and floors together.

It should be noted that although the ground motion can occur in any direction, it becomes a computational convenience to consider the effects of this ground motion as if it were to act only in directions parallel to the perpendicular axes of the masonry building. Therefore, those walls that are perpendicular to the direction of the ground motion must span vertically between the floor diaphragms, and the inertial effect of one-half wall height, both above and below the floor analyzed, is considered to be transferred to the corresponding floor diaphragm.

The diaphragm behaves as a horizontal plate girder, in which the boundary members or chords serve as the girder flanges and the decking functions as the web to carry the flexural shear force. The diaphragm, therefore, spans between the supporting shear walls that are parallel to the direction of the assumed lateral force.

The total horizontal shear force is transferred directly through the diaphragm to the shear walls, based on the adjacent tributary area, or on their relative rigidities. In addition to the diaphragm shear, each shear wall must resist the force produced by its own inertia effect. The sum of the diaphragm shear and the wall shear constitutes the total direct shear force, which must be withstood by the shear-wall materials.

The diaphragm, which supports those side walls normal to the direction of the lateral force, should be adequately tied to the walls in order to prevent the diaphragm form falling away and simply collapsing. Further, the connection must be strong enough to transfer the diaphragm shears to the shear walls, and thus, provide lateral stability to the building.

Finally, if base isolation is applied, all the lateral load-resisting elements in the reinforced masonry design and construction projects can be proportioned according to minimum requirements of strength and serviceability, instead of being the critical issues of the process. Therefore, the construction costs can be decreased significantly.

5.2 RUBBER BEARINGS WITH COMPOSITE PLATES

The use of steel sheets or plates reinforcing the rubber to provide vertical stiffness can be replaced by the use of cheap composite materials; which by turns consist of two or more phases on a macroscopic scale. The mechanical properties [14] are design to be superior to those of the constituent materials acting independently. One of the phases is usually discontinuous, stiffer, and stronger and is called matrix, see Figure 5.3. Sometimes, because of chemical interactions or other processing effects, an additional phase, called interphase, exists between the reinforcement and the matrix. The properties of a composite material depend on the properties of the constituents, geometry, and distribution of the phases.

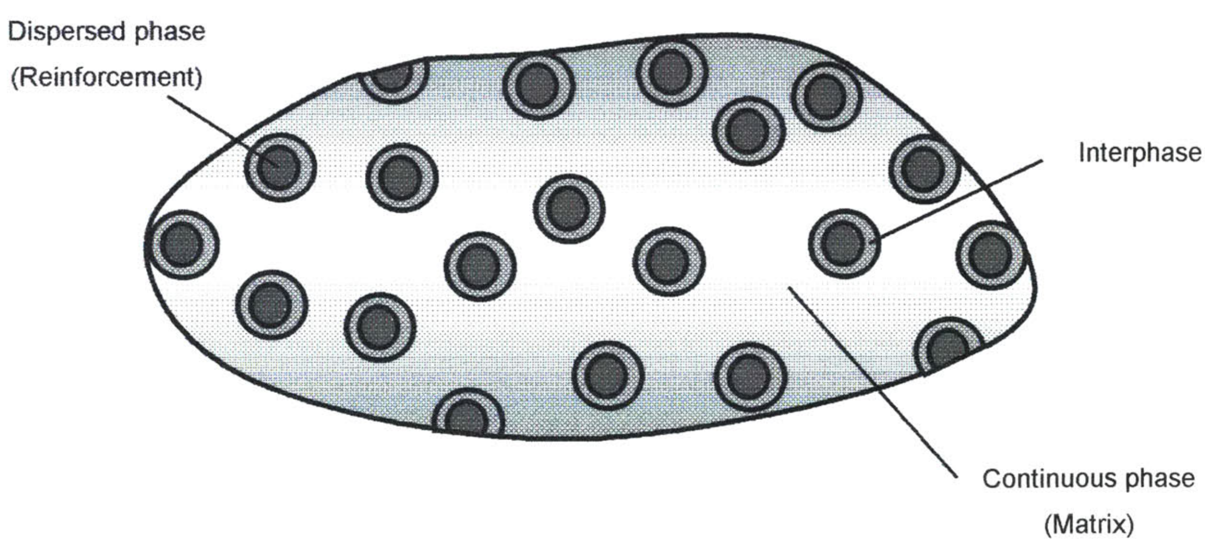


Figure 5.3 – Phases of a composite material.

One of the most important parameters in a composite material is the volume (or weight) fraction of reinforcement or fiber volume ratio. The distribution of the reinforcement determines the homogeneity or uniformity of the material system. The more non-uniform is the reinforcement distribution, the more heterogeneous is the material and the higher is the probability of failure in the weakest areas. The geometry and orientation of the reinforcement affect the anisotropy of the system.

The phases of the composite system have different roles that depend on the type and application of the composite material. In the case of low to medium performance composite materials, the reinforcement, usually in the form of short fibers or particles, provides some stiffening but only local strengthening of the material. The matrix, on the other hand, is the main load-bearing constituent governing the mechanical properties of the material. In the case of high performance structural composites, the usually continuous-fiber reinforcement is the backbone of the material that determines its stiffness and strength in the direction of the fibers. The matrix phase provides protection and support for the sensitive fibers and local stress transfer from one fiber to another. The interphase, although small in size, can play an important role in controlling the failure mechanisms, fracture toughness, and overall stress-strain behavior of the material.

For reinforcing a rubber bearing, the composite material plate should be a multidirectional continuous fiber composite, see Figure 5.4. This type of distribution is the base for considering the material as a quasi-isotropic composite, facilitating the analysis of its elastic behavior and its strength. Another, alternative is just reinforcing the rubber with fibers through its height, but without using defined plates.

The fabrication process is one of the most important steps in the application of composite materials. Structural parts are fabricated with relatively simple tooling. A variety of fabrication methods suitable for several applications are available.

They include autoclave molding; filament winding, pultrusion, and resin transfer molding (RTM). However, this fabrication is still dependent on skilled hand labor with limited automation and standardization, requiring more stringent and extensive quality control procedures.

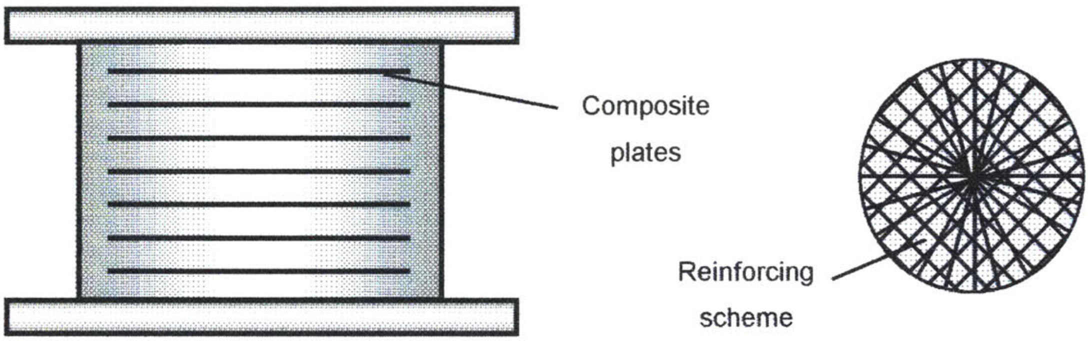


Figure 5.4 – Multidirectional continuous fiber composite.

Composites can operate in hostile environments for long periods of time. In general applications, they have long fatigue lives and are easily maintainable and repaired. However, they suffer from sensitivity to hygrothermal environments. Service-induced damage growth may be internal, requiring sophisticated, nondestructive techniques for its detection and monitoring. Sometimes it is necessary to apply protective coatings against erosion, surface damage, and lightning strike.

With respect to the cost-effectiveness, also from a general application point of view, one of the advantages of composites is the reduction in acquisition and/or life cycle costs. This is obtained through weight savings, lower tooling costs, reduced number of parts, and fewer assembly operations. This advantage is somewhat diluted when one considers the costs of raw materials, fibers and auxiliary materials used in fabrication and assembly with composite materials. Nevertheless, the trend of production costs has a decreasing slope, since the mass production is becoming a reality, and the open market pushes the prices down, while quality is pushed up. In particular, for the fabrication of the rubber bearings' plates, the prices are very competitive, since the overall shape of the plates is not complex, and because their behavior is dominated by the tensile strength, which can be easily provided by carbon-based fibers.

5.3 INDEPENDENT STORY LOAD DISTRIBUTION

The idea behind this concept is trying to transmit in an independent way the vertical load of the building's stories to different sets of rubber bearings, being each set of bearings in charge of different story's vertical loads. Figure 5.5 clarifies schematically the concept.

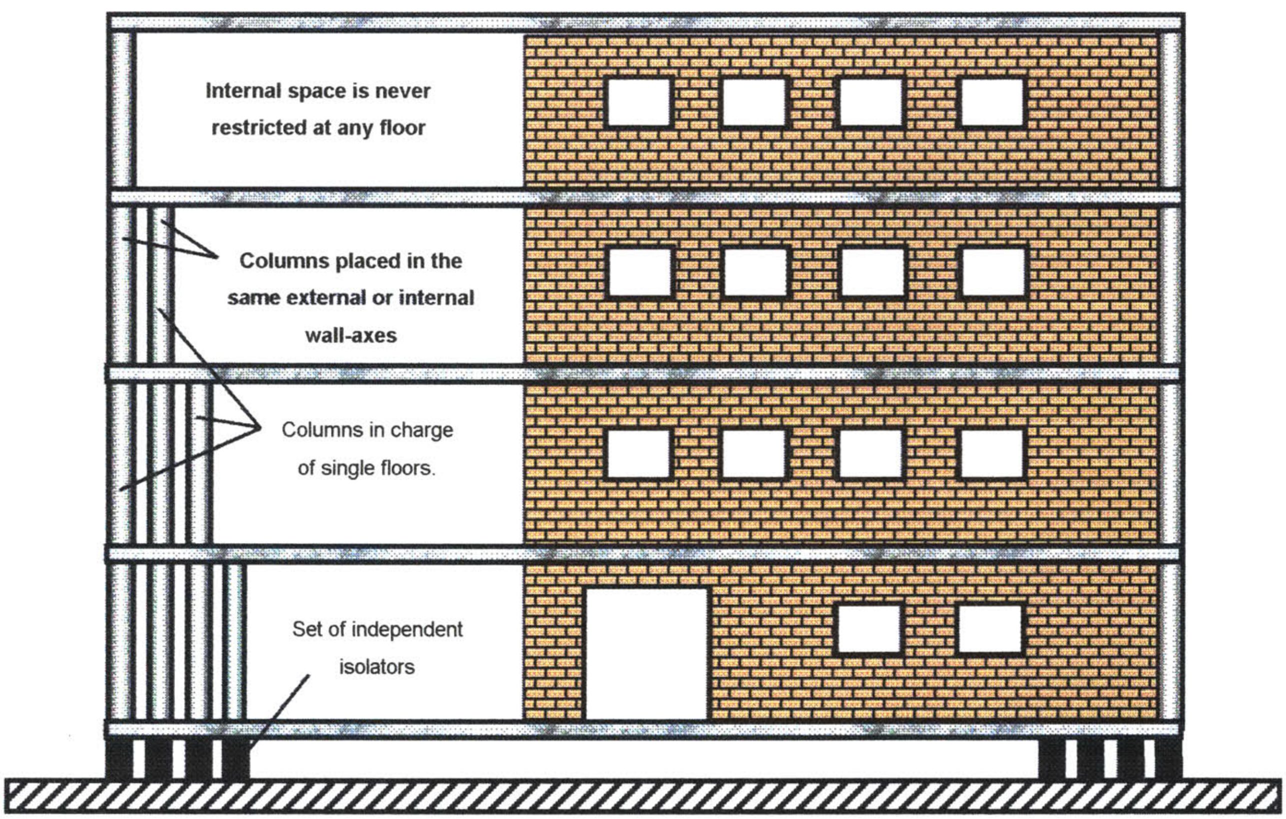


Figure 5.5 – Load distribution to independent sets of isolators.

The plot shows a section of a four-story building with all columns placed in the same plane or longitudinal external axes, such as facades; or in the same internal axes, such as fixed partition walls. Therefore, the interior space is never restricted, in other words, extra room is not required. For having an integrated response of the structure above the isolation layer, all columns must be joined rigidly by the diaphragm so that the performance can be integrated and represented by a mathematical formulation as explained in part 3. In addition, the fact of having the columns joined at each floor level, leads to a reduction in their effective length and the basis for an efficient structural design.

The key aspect for cost reduction is that the transmitted vertical load to each set of isolators represents only the load of each floor, allowing them to withstand less restricted requirements in terms of vertical stiffness and strength. Lastly, columns and nonstructural elements have to have flexible interfacial connection layers, in order to prevent fragile failure of masonry facades, if they are used in the building design.

5.4 LOCAL FABRICATION

If it is intended to apply seismic isolation in developing countries, a strategy to follow in order to decrease the production costs is to utilize local labor force in the fabrication process. Also, if possible it is encouraged to use local materials, lowering even more the mentioned costs. For example, countries of South America are producers of rubber in the forests near the amazons. Cultivation costs are also small and the process can be done in a self-sustainable way.

Therefore, the whole process with a good implementation of a quality system not only allows a low cost fabrication process, but also generates employment, training and contributes to the local economy of the regions in which the rubber is going to be produced, and where the labor force is provided. Since the most important scarce production factors like materials and labor are provided in the local economical environment, it is possible to establish relative figures with respect to the United States of the potential savings if the compensation costs of manufacturing are compared among different countries through the uses of indexes. Table 5.1 shows the mentioned indexes for production workers in manufacturing [15]. Samples of 29 countries are analyzed relatively to the United Sates of America in the last 10 years.

Country or area	1991	1992	1993	1994	1995	1996	1997	1998	1999
North America									
United States	100	100	100	100	100	100	100	100	100
Canada	111	107	100	94	94	94	90	84	81
Mexico	12	13	15	15	9	9	10	10	11
Asia and Oceania									
Australia	87	81	76	84	89	95	91	80	83
Hong Kong SAR 1	23	24	26	27	28	29	30	29	28
Israel	56	56	53	54	61	64	66	64	62
Japan	94	102	116	127	139	119	107	98	109
Korea	30	32	34	38	42	46	43	29	35
New Zealand	53	48	48	52	58	61	59	48	48
Singapore	28	31	32	37	43	47	45	42	37
Sri Lanka	3	2	3	3	3	3	3	3	-
Taiwan	28	32	32	33	35	34	32	28	29
Europe									
Austria	116	126	122	128	147	140	120	119	114
Belgium	127	137	130	137	155	147	125	124	119
Denmark	118	126	116	120	140	136	121	122	120
Finland	136	124	101	113	140	132	117	116	110
France	100	109	102	105	116	113	98	98	94
Germany, Former West	145	158	153	158	184	176	152	147	140
Germany, Unified	-	-	148	153	178	171	147	143	136
Greece	45	47	44	46	53	54	50	48	-
Ireland	76	82	72	74	79	79	74	72	71
Italy	118	120	96	94	94	100	96	92	86
Luxembourg	110	119	114	121	136	127	104	100	-
Netherlands	116	125	121	123	140	131	115	113	109
Norway	139	143	122	124	142	142	130	126	125
Portugal	27	32	27	27	31	32	29	29	-
Spain	79	84	70	68	75	76	67	65	63
Sweden	142	153	107	110	125	138	122	118	112
Switzerland	139	144	137	148	170	160	132	131	123
United Kingdom	88	89	75	76	80	80	85	88	86

Table 5.1 – Normalized indexes of hourly compensation costs for production workers in manufacturing relative to the USA.

6. CONCLUSIONS

- Base isolation or seismic isolation is an approach to earthquake-resistant design that is based on the concept of reducing the seismic demand rather than increasing the earthquake resistance capacity of the structure. Basically, the above objective is achieved through the lengthening of the natural period of vibration of the structure, allowing it to be far away from the peak accelerations in the spectral response. In addition, the isolation system concentrates the displacements in the isolation level reducing significantly the relative deformations. The above facts have increased the interest in applying this technology to public housing, schools, and hospitals in developing countries located in high seismic hazardous areas, where the replacement costs due to earthquake damage can be a significant part of the gross national product.

- Structural engineers have to face a basic dilemma of how to minimize interstory drift and floor accelerations when trying to provide superior seismic resistance of a building. Therefore, a selection among the feasible technical solutions has to be done, but within a cost – effectiveness, social and political environment.

- Base isolation systems can be classified in two main categories, depending on the nature of the response. If the system performance depends on the material properties of the isolation system, the category belongs to the rubber bearing systems (high strength, high damping and synthetic rubber bearings). On the other hand, if the system performance depends on the frictional forces produced at the isolator layer, the category belongs to the gravity-based systems (frictional pendulum systems - FPS, ball systems and universal linear sliders).

- Among the mechanical properties of the rubber it is known that the shear stiffness is high for small strains but decreases by a factor of four or five as the strain increases, reaching a minimum value at a shear strain of 50%. For strains greater than 100%, the stiffness begins to increase again, providing a fail-safe action under a very high loading. The damping follows the same pattern of the stiffness but less dramatically, decreasing from an initial value of 20% to a minimum of 10% and then increasing again. The high initial stiffness is invoked only for wind load design and the large strain response only for fail-safe action.

- Base isolation by a ball system seems to be very effective due to combines the advantages of free rolling (friction coefficients are very small and when combined with an appropriate sphere's radius produce an undersized acceleration of the mass' structure) and restoring properties of FPS (concave rolling surface), being a promising alternative for cheap seismic isolation.

- With the state-of-the-art isolator devices, it is possible to design isolation systems with:
  - Diameter of rubber bearings up to 1.6m.
  - Supported load between 1,400 ton/unit to 4,000 ton/unit.
  - Pull-out resistance force up to 1,600 tons/unit.
  - Natural periods in the range of 2 to 10 seconds.
  - Usable life between 60 to 100 years.
  - Application to structures whose height can reach 150m

- There is a base isolation system alternative that combines the sliding bearings with elastometric rubber bearings, providing a lock-up mechanism to avoid large horizontal displacements. The frictional pendulum system minimizes the seismic demand produced by the active fault, and the rubber bearing system minimizes the excitation of higher modes of vibration in the earthquake-resistant system of the structure caused by the starting and stopping of the frictional system. Also, torsional effects can be controlled by the stiffness of the lead plug rubber bearings when located strategically far enough from the center of mass and center of rigidity of the building.

- For most seismic isolation projects, the isolation design for a new construction project costs around 5% more when compared with a conventional seismic-resistant code design. However, the design code provides a minimum level of protection against strong ground motion, guaranteeing only that the building will not collapse and that human lives are preserved, but does not protect the building from structural damage; in fact the energy dissipation mechanism is through plastic deformations of the structure. Therefore, when equivalent levels of design performance are compared, an isolated building is always more cost-effective; also if the life-cycle costs are analyzed, the isolation scheme is again more favorable. In the case of a retrofitting project, when the costs are compared with the benefits from the response of a historical structure if an important seismic event happens, the costs-effectiveness of base isolation is incomparable, since the level of protection given to historical art, architecture and engineering has invaluable significance.

- Most isolation systems are nonlinear in their force-deformation relationships, and the nonlinearity is important to be considered in every final design. Also, due to the differences between the damping in the rubber bearings and the damping in structure, the combined damping of the system is nonclassical.

- From the dynamic analysis of a 2-DOF system that represents a base isolation model, it is established that in the first mode of vibration, the isolator undergoes deformation while the structure behaves as a rigid body; and that the second mode involves deformation of the structure as well as in the isolation system. Also, it can be established that usual relations between shear for the fixed-base and isolated structure are that fixed-base shear is 4 to 6 times the isolated one.

- The applicability of base isolation systems is limited by the local seismic activity and the way in which the energy is liberated by the active faults. For instance, if $T_b >> T_f$ the structure does not behave as a rigid body in the first mode, and the natural period is significantly affected by the flexibility of the structure. In addition, the second mode contribution to the effective earthquake forces is no longer negligible and the first-mode damping is no longer close to the isolation system damping. Also, if the acceleration response spectrum in a particular location contains significant spectral accelerations for long periods of vibration, like in cities with deep deposits of clay such as Mexico City or Bogotá, the application of base isolation becomes ineffective because even lengthening the period of the structure; the seismic demand is not reduced.

- When modeling mathematically a base-isolated structure, static loads have to be defined as close as possible to the real conditions, following when feasible the recommendations and estimates of the design codes. For taking into account the dynamic loads, time history analysis or spectral analysis can be performed. The records for time history analysis have to be scaled so that they can represent a probability of being exceeded at least every 450 years, and that they can produce a spectral velocity of approximately 1.2m/s for the fundamental period of the structure. Such scaled records conserve the frequency content generated when the faults liberate their energy.

- In general, the software available for structural analysis, nowadays provides the option to model passive devices such as rubber bearings, frictional pendulum systems and dampers among other things. Also, the software allows in most of the cases a nonlinear analysis of the structure, including nonlinear material properties especially for the mentioned devices. Lastly, the dynamic analysis should be executed defining a representative damping ratio and including enough modes of vibration, so that the analysis accounts for at least 90% mass participation in the X and Y directions. The seismic excitation must be applied in the three global orthogonal directions X, Y and Z, making the necessary combinations of incidence.

- It is recommended that before running a model with a structural analysis software, the mass, the expected fundamental period of the structure, the estimated base shear force and the probable wind load be calculated trough approximate methods, in order to have a reference point for evaluating and calibrating the software results.

- In order to reduce the cost of the isolation systems, it is important to decrease the number of tasks that a single component of the system should perform. Therefore, the system can be optimized alleviating its duty of carrying the vertical loads.

- Longitudinal rubber bearings are an alternative to reduce costs, since the vertical load can be spread out through a bigger surface when compared with traditional rubber bearings, and the requirements for providing vertical stiffness can be reduced due to the vertical load is uniformly distributed through the bearing matrix that connects columns and walls. Therefore, its performance can be focused to support the lateral deformations. Finally, the above justifies the application of the system in reinforced masonry buildings located in high seismic hazard areas of developing countries.

- Rubber bearings with composite fiber reinforcement or with composite plates reinforcement can be cheaper than steel reinforced rubber bearings because of the trend of decreasing production costs, due to mass production is becoming a reality, and because the open market is pushing the prices down, while quality is being increased. Also, the prices can be very competitive, because the overall shape of the plates is not complex, and because their behavior is dominated by the tensile strength, which can be easily provided by carbon-based fibers. In addition, composites can operate in hostile environments for long periods of time, and in general applications they have long fatigue lives and are easily maintainable and repaired.

- Independent story load distribution is a concept that tries to transmit in an independent way the vertical load of the building's stories to different sets of rubber bearings. The key aspect for cost reduction is that the transmitted vertical load to each set of isolators represents only the load of each floor, allowing them to meet less restricted requirements in terms of vertical stiffness and strength.

- In sum, base isolation could be widely used if an optimal combination of the emerging concepts, such as hybrid systems (FPS + Lead plug rubber bearings), longitudinal rubber bearings, isolators reinforced with composite fibers or plates, independent story load distribution approach, and local fabrication, can be achieved for the projects, through the use of standard devices and methods. In addition, continuous research on materials, and development of the above concepts will lead the most favorable scheme that merge the best characteristics of each concept into single solutions with higher level of performance, response and cost-effectiveness.

- Finally, if it is intended to apply seismic isolation in developing countries, a strategy to follow in order to decrease the production costs is to utilize local labor force in the fabrication process. Also, if possible it is encouraged to use local materials, lowering even more the mentioned costs.

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BIOGRAPHICAL NOTE

Leonardo Augusto, Dueñas Osorio was born in Bogotá D.C., Colombia in 1976. He obtained his Civil Engineer degree at the Universidad de La Salle in Bogotá in March 1997. Subsequently, a master's degree in structural engineering was obtained at the Universidad de Los Andes in Bogotá in September 1998, carrying an investigation related with the dynamic and static behavior of concrete crossties (prestressed and reinforced), for the Colombian railway system. Later on, he studied project management at the Pontificia Universidad Javeriana of Bogotá, executing for the thesis project in June 2000, a simulation to implement the vehicular natural gas in public buses and taxis. At the present moment Leonardo is a candidate for the Master of Engineering degree in High Performance Structures at MIT, being granted with a scholarship-loan by COLFUTURO, a Colombian private organization that contributes to the internationalization of Colombia through graduate academic programs.

In the labor field, Leonardo worked as structural engineer for the Italian consultant – engineering firm SOTECNI S.p.A., for the development of projects related with seismic design of buildings, and with geometric design of railways and highways that incorporate geotechnical, hydraulic and environmental designs. The projects were executed in Colombia and Perú between January 1997 and July 2000. Furthermore, he gained experience in the development and implementation of quality systems according to the International Standards Organization - ISO9000 series for engineering companies. The above interaction allowed Leonardo to improve his written and spoken Italian, English and French, and also, to get practice in SAP200, MS Project, Roadcalac, Autocad and MS Office.

Finally, Leonardo is going to continue his academic formation at the Georgia Institute of Technology, where he has been admitted into the Ph.D. degree program in structural engineering, for doing research on the structural motion control field.