The Development of a Selection Criteria Model for the type of Seismic Retrofitting Scheme Applicable to Philippine Buildings

by

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ABSTRACT

The Philippine Archipelago lies in a highly sensitive position in the Asian continent, named the Pacific "Ring of Fire" and it is one of the most seismically active and disaster prone areas in the world. In the Philippines, where a percentage of the buildings are structurally out of date, seismic retrofitting is of utmost importance.

This study presents an overview of various rehabilitation strategies such as Seismic Isolation, Passive Energy Dissipation and Active Systems. An analysis of the rehabilitation process given by the Federal Emergency Management Agency is presented. The most significant factor affecting the modifications is the level of seismic activity in the Philippines. The direct implication of such a level of seismicity is directly seen in that the third phase of the rehabilitation process is Systematic Rehabilitation. Another direct effect is in the method of component analysis for the Philippine setting, which calls for the use of nonlinear analysis methodologies. This rehabilitation process was modified to provide a selection criteria model that was suited to meet the Philippine setting.

Thesis Supervisor: Jerome J. Connor
Title: Professor of Civil and Environmental Engineering

"Always bear in mind that your own resolution to succeed is more important than any other."
Abraham Lincoln

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"Our greatest fear is not that we are inadequate, but that we are powerful beyond measure. It is our light, not our darkness, that frightens us. We ask ourselves, who am I to be brilliant, gorgeous, handsome, talented, and fabulous? Actually, who are you not to be? You are a child of God. Your playing small does not serve the world. There is nothing enlightened about shrinking so that other people won't feel insecure around you. We were born to make manifest the glory of God within us. It is not just in some; it is in everyone. And, as we let our own light shine, we unconsciously give other people permission to do the same. As we are liberated from our fear, our presence automatically liberates others."

– Marianne Williamson

Dedicated to Jose V. R. Angeles Jr.

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Chapter 1: The Philippine Setting

Seismic retrofitting concerns the rehabilitation or modification of existing structures to fortify them against earthquake activity and failure. Seismic safety is a pressing issue in today's society. This is particularly so, since many of the buildings standing today are products of the past. In previous years, design strategies and technologies available to the present generation were inexistent. Today, with technology, people are better able to assess the safety of a structure. With this in mind, many of the old buildings are structurally inadequate. Since it is important to preserve buildings, not only because of historical significance but also because of economic reasons, retrofitting is what the population has turned to. This is a compromise that many people have found acceptable to both those who want to preserve the building and those who are charged with safeguarding the lives of the building's users.

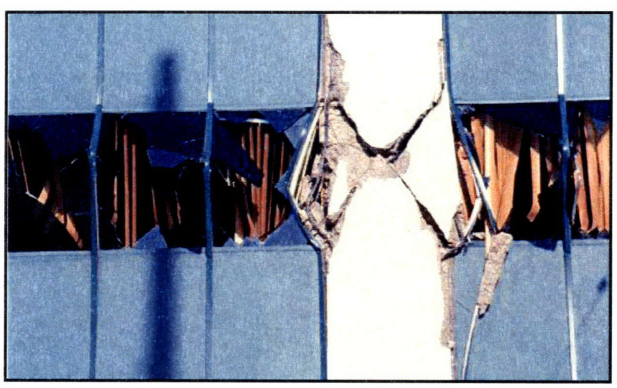

Figure 1. Earthquake of Structural Integrity[1]

In the Philippines, where a percentage of the buildings are structurally deficient, seismic retrofitting is of utmost importance. Since 1990, the total number of deaths due to natural calamities in the Asia Pacific region has exceeded 200,000.[2] In every calamity, it is for certain that there is damage to property. This is the reason behind this study. The study is dedicated to developing a selection criteria model for the type of seismic retrofitting scheme applicable to a given building in the Philippines.

The Philippines

The Philippines constitutes an archipelago of 7,107 islands with a total land area of approximately 300,000 square kilometers (116,000 sq mi). Its location is between 116° 40' and 126° 34' E. longitude, and 4° 40' and 21° 10' N. latitude. It is bound by the Philippine Sea on the east, on the South China Sea the west, and the Celebes Sea on the south.

Figure 2. Political Map of the Philippines[3]

The Philippine Archipelago lies in a highly sensitive position in the Asian continent, named the Pacific "Ring of Fire" and it is one of the most seismically active and disaster prone areas in the world. Dangerous natural hazards such as typhoons, landslides, earthquakes, tsunamis and volcanic eruptions occur very frequently, leading to life losses, homeless people and large damages. In the last decade, the Philippines has suffered severely from natural disasters. In 1990 the Philippines was hit by the most damaging earthquake that devastated a wide area in Luzon, and reached a magnitude of 7.9 on the Richter scale.

Table 1. Destructive Earthquakes in the Philippines[3]

Date	Magnitude	Location
02 Aug 1968	Ms7.3	Casiguran
17 Mar 1973	Ms7.0	Ragay Gulf
17Aug 1976	Ms7.9	Moro Gulf
17 Aug 1983	Ms6.5	Laoag
08 Feb 1990	Ms6.8	Bohol
14 Jun 1990	Ms7.1	Panay
16 Jul 1990	Ms7.9	Luzon
15 Nov 1994	Ms7.1	Mindoro
27 May 1996	Ms5.6	Bohol
07 Jun 1999	Ms5.1	Bayugan
06 Mar 2002	Ms6.8	Palimbang
15 Feb 2003	Ms6.2	Masbate

Table 1 presents a record of the most destructive earthquakes that have hit the Philippines. The Philippine Fault System is a major strike-slip fault structure that traverses the entire length of the archipelago and characterized the country seismic risk between a M8 and M9. The historic records of the Philippines show an impressive record of earthquakes ranging from M5 to M7.8, within a 650-km range from the capital city.

Table 2. Typical Earthquake Activity in the Philippines[3]

Date-Time (Local Time)	Epicenter (Latitude, Longitude)	Depth (km)	Magnitude	Location
18 Nov 2007 - 12:17PM	09.78°N, 124.53°E	21	3.7	Guindulman Bohol
10 Nov 2007 - 04:25 AM	18.84°N, 120.81°E	12	4.6	Laoag City
10 Nov 2007 - 03:31 AM	19.04°N, 120.75°E	13	2.8	Laoag City
10 Nov 2007 - 01:32 AM	18.69°N, 120.98°E	20	2.5	Laoag City
09 Nov 2007 - 07:24 PM	09.82°N, 125.37°E	34	2.4	Surigao City
07 Nov 2007 - 12:12 PM	09.76°N, 124.54°E	24	4.8	Anda (Bohol)
07 Nov 2007 - 08:47 AM	13.40°N, 121.99°E	29	2.5	Boac (Marinduque)
06 Nov 2007 - 09:38 PM	13.25°N, 121.80°E	27	2.5	Boac (Marinduque)
02 Nov 2007 - 08:47 AM	12.51°N, 124.52°E	31	3.0	Catarman (N. Samar)
01 Nov 2007 - 09:55 AM	12.44°N, 123.62°E	17	2.8	Masbate (Masbate)

As can be seen from Table 2, minor earthquakes occur in the Philippines daily. Earthquakes range from the smallest of tremors, those which cannot be felt to the most destructive of earthquakes as presented on the previous page. The Philippine Institute of Volcanology and Seismology has a vast seismic monitoring network scattered around the archipelago which takes seismic activity readings daily.

The Seismic Hazard Map of the Philippines shows the peak accelerations (m/s^2) with a 10% probability of exceedance in 50 years.

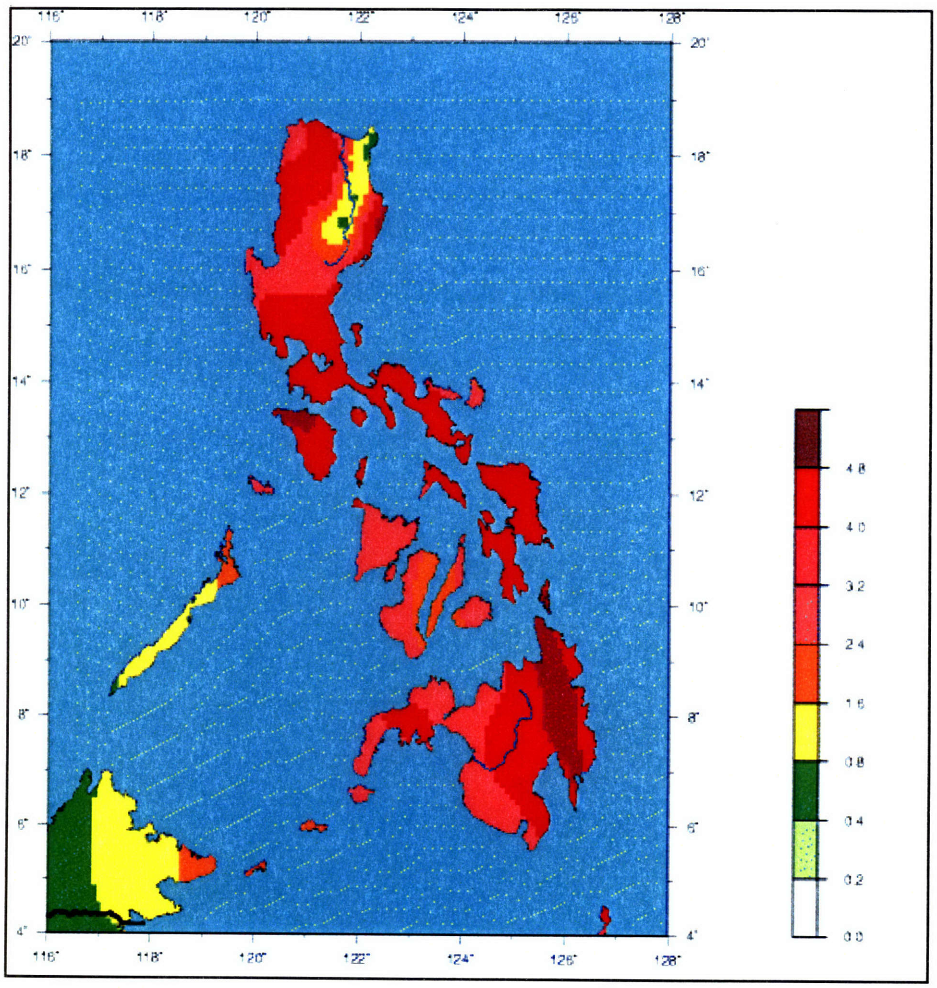

Figure 3. Seismic Hazard Map of the Philippines[3]

The Earthquake Density Map below shows the number of earthquakes per year of magnitude 5 and greater at all depths. The major tectonic boundaries are outlined with the subduction zones in the outer boundary lines of the Philippine plates (purple), and transform faults going through the Philippine plates (green).

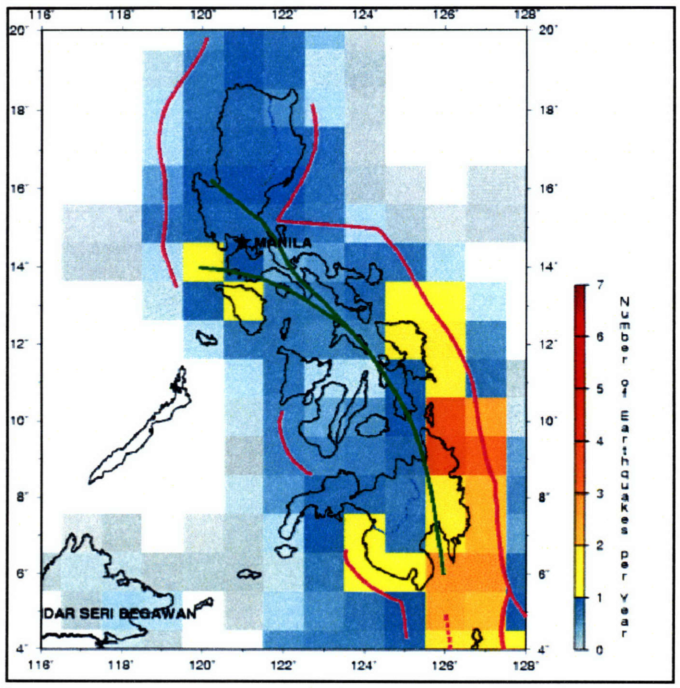

Figure 4. Earthquake Density Map of the Philippines[3]

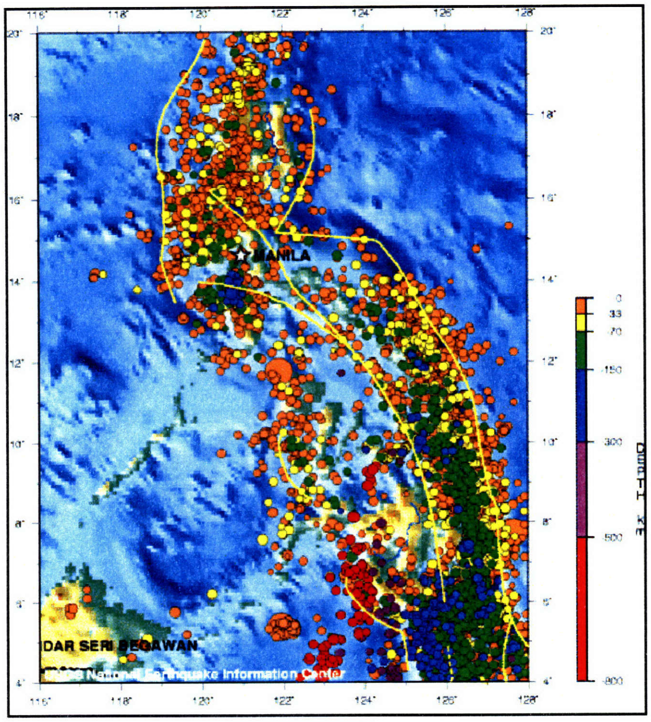

Figure 5. Seismicity Map of the Philippines[3]

The Seismicity Map of the Philippines above shows the concentrations of earthquake prone zones in the country. The location of the earthquakes, as can be seen above, is quite dispersed and occurs at several depths.

Governing Code

The governing code in the Philippines is the National Structural Code of the Philippines (NSCP). In terms of concrete and steel design, this code is patterned after several American codes. For concrete in particular, provisions in the NSCP are adopted from the American Concrete Institute

(ACI 318-99). The NSCP also adopted provisions from the American Society of Civil Engineers and from the American Institute of Steel Construction.

Being the principal structural code of the Philippines, the NSCP details the characteristic design guidelines for loads and materials. The design code however, does not detail any form of rehabilitation for existing buildings. It goes so far as to specify conditions for maintenance, additions, alterations or repairs, but does not state guidelines for the retrofitting structures. Hence, designers have needed to make use of the Federal Emergency Management Agency's publications.

Retrofitting in the Philippines – Past and Present Trends

Since the Philippines is an active seismic country, the buildings are designed in accordance to the National Structural Code of the Philippines' Seismic criteria. Although they are designed following the code's guidelines, most of the buildings in the Philippines are old and outdated. Hence, retrofitting is something that should seriously be considered by the people.

Traditional small structures under frequent seismic disturbances are expected to remain in the elastic range. This doesn't mean that under major earthquake conditions the structure will respond elastically. Even if the structure realizes certain structural and non-structural damages, it relies on its ductility to prevent cataclysmic failure from occurring. The evolution of design criteria from the traditional structure to modern-day structures gives way to the actual dynamic nature of environmental disturbances. This advancement has led to the concepts of structural protection. The retrofitting of buildings is a form of structural protection. Retrofitting buildings for seismic design can take three general forms: Seismic Isolation, Passive Energy Dissipation and Active Systems.

Chapter 2: Scope and Limitations

The scope of this thesis is to develop a selection criteria model for the type of seismic retrofitting scheme that may be applied to a building in the Philippines. This paper will present various retrofitting schemes which can be used for seismic strengthening of buildings namely Seismic Isolation, Passive Energy Dissipation, and Active Systems. Given these retrofitting schemes, a form of selection criteria model is developed based on applicability to the Philippine setting. The primary reference of this paper is the Federal Emergency Management Agency's publications for the National Earthquake Hazards Reduction Program's guidelines for seismic rehabilitation, which is not a code. Together with this primary reference, the National Structural Code of the Philippines was used in order to adapt certain principles attained from FEMA to the Philippine setting. As mentioned in the Chapter 1, the National Structural Code of the Philippines does not address the issue of rehabilitation in terms of processes and analysis and neither does the National Building Code of the Philippines. Thus, there is no formal form of rehabilitation protocol as recognized by the country.

Due to time constraints and availability of information, this paper has set limitations in analysis. This paper develops the selection criteria for one particular type of structure, buildings. The paper does not concern itself with new structures but with existing structures. In a building, one can consider both structural and nonstructural components. However, for the purpose of this paper, the study will focus only on the structural components of the building, more specifically on the structural components of the superstructure part of the building. This paper will concentrate on one material commonly used in the design of buildings in the Philippines:

concrete. This research was undergone particularly with the intent to be made applicable to the Philippines. Hence, the selection criteria model is based on the one prepared by FEMA and is adjusted to the Philippine setting. Certain factors such as rehabilitation methods which may be applicable to the United States of America do not necessarily apply to the Philippines. This then led to the development of a rehabilitation process flowchart which caters to the Philippines. Lastly, this paper does not have an analytical model to assess the effectiveness of the selection criteria presented. Further studies to evaluate the selection criteria model are presented in the recommendations section of this paper.

The main objective of this study is to develop a selection criteria model for the type of seismic retrofitting scheme applicable to Philippine buildings. This study presents a modified rehabilitation process flowchart. The flowchart presented in FEMA 273 was modified after careful review of the considerations that were taken into account during the formulation of FEMA 273. The recommendations presented at the end of this study are given in order to promote a new method for assessing the retrofitting scheme used for seismic rehabilitation of buildings in the Philippines.

Chapter 3: Retrofitting Schemes

Seismic Isolation

The objective of seismic isolation systems is to decouple the building structure from the damaging components of the earthquake input motion. An example is to prevent the superstructure of the building from absorbing the earthquake energy. The entire superstructure must be supported on discrete isolators whose dynamic characteristics are chosen to uncouple the ground motion. Some isolators are also designed to add substantial damping. Displacement and yielding are concentrated at the level of the isolation devices, thus the superstructure behaves very much like a rigid body.

The technique of seismic isolation is now frequently used in many parts of the world. A seismic isolation system is typically placed at the foundation of a structure. By means of its flexibility and energy absorption capability, the isolation system partially reflects and partially absorbs some of the earthquake input energy before this energy can be transmitted to the structure. The net effect is a reduction of energy dissipation demand on the structural system, resulting in an increase in its life span. The kinds of seismic isolation techniques are: Elastomeric Bearings, Lead Rubber Bearings, Combined Elastomeric and Sliding Bearings, Sliding Friction Pendulum Systems and Sliding Bearings with Restoring Force.

The design of the isolation system depends on many factors, including the period of the fixed-base structure, the period of the isolated structure, the dynamic characteristics of the soil at the site, the shape of the input response spectrum, and the force-deformation relationship for the particular isolation device. The most important requirements for an isolation system concern flexibility, energy dissipation, and rigidity under low-level loading. In terms of flexibility, a structural isolation system generally consists of a set of flexible support elements that are proportioned such that the period of vibration of the structure is reasonably greater than the period of the excitation. When considering the rigidity under low-level lateral loads, increasing the lateral flexibility provides an effective solution for high-level seismic excitation. This may work differently for other lateral loads such as wind. Lastly, energy dissipation or absorption relates to the means of damping. For example, high damping natural rubber has a dissipation capacity about four times the conventional value.

The protection of structures from earthquakes using base isolation is generally suitable for the following conditions: the subsoil doesn't produce a prevalence of long period ground motion, the structure is fairly nothing with sufficiently high column load, the site permits horizontal displacements at the base of the order of 200 mm or more and the lateral loads due to wind are less than approximately 10% of the weight of the structure.

The benefits resulting from base isolation are attributed primarily to a reduction in spectral demand due to a longer period. Additional benefits may come from a further reduction in the spectral demand attained by supplemental damping provided by high-damped rubber components or lead cores in the isolation units. In particular, rubber bearings are relatively easy to manufacture, have no moving parts, are unaffected by time, and are very resistant to environmental degradation.

The application of seismic isolation as a retrofitting technique can be seen in the San Francisco City Hall project that was retrofitted in 1994. It made use of 530 lead rubber isolators. The cost was approximately $105 million. This amount may be cheaper than any other method of retrofitting buildings for seismic design. In the Philippines in particular, it is necessary to consider the cost of the materials and equipment in selecting the type of retrofitting technique to employ. Although seismic isolation may be labor intensive, labor is cheap in the Philippines. Another thing to consider is the construction process for the seismic isolators. Since the Philippines is an earthquake zone, it is necessary to investigate how the construction process will go.[4]

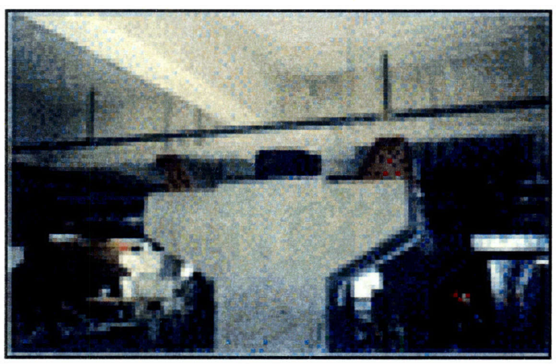

Figure 6. San Francisco City Hall Seismic Isolation System[5]

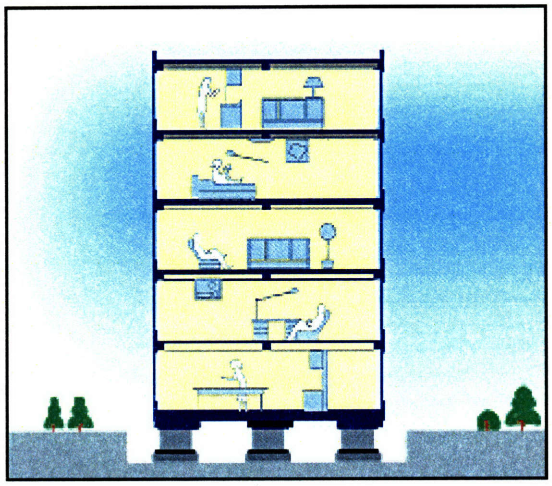

Figure 7. San Francisco City Hall Seismic Isolation Principle[5]

Passive Energy Dissipation

Passive energy dissipation or motion control's goal is to establish a distribution of structural stiffness that produces a set displacement profile. This displacement profile is the pre-determined allowable displacement limit. Hence, these devices are used to limit damaging deformations in structural components. Passive mechanisms require no external energy. These mechanisms come in various forms such as viscous, friction, tuned mass, and liquid sloshing dampers. The degree to which these mechanisms are effective depend on the inherent properties of the basic structure, the properties of the mechanisms themselves and the connecting elements, the characteristics of the ground motion and the limit state being investigated.[6] Passive damping removes energy from the response and therefore cannot cause the response to become unstable. In fact, adding discrete damping devices to the distributed passive damping will improve the response profile.[7]

Viscous fluid dampers are another form of passive energy dissipation mechanisms that are commonly used as seismic protection of structures.[7] The fluid in the damper, however, is usually of relatively low viscosity; hence, its name stems from the macroscopic behavior of the damper which is the same as that of an ideal linear or nonlinear viscous dashpot. There is an alternative to viscous fluid dampers, viscoelastic fluid dampers, which provide stiffness in addition to damping. A major reason for the relatively rapid pace of implementation of viscous fluid dampers is their long history of successful application in the military.

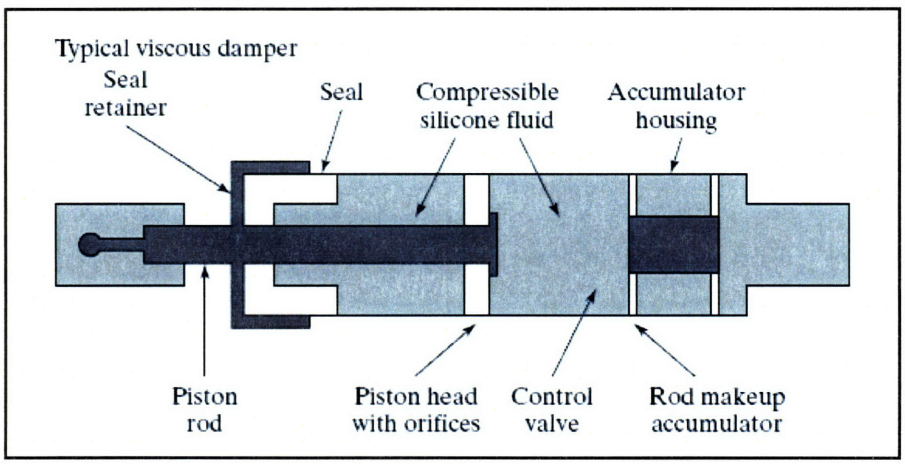

Figure 8. Schematic Diagram of a Viscous Damper[7]

Friction damping is when the damping force acts in phase with the deformation rate and has constant magnitude. Friction dampers dissipate energy by sliding friction between the two solid bodies.

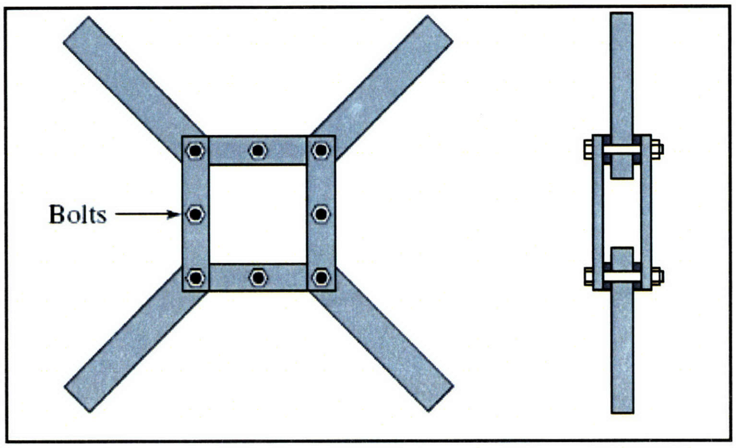

Figure 9. Friction Base Damper[7]

Figure 9 presents a friction base damper with a cross-bracing scheme. At the connection where the bolts meet the plate, friction pads were placed.

Another passive energy dissipating device is the tuned mass damper. The mechanism is made up of a mass, a spring, and a damper. This is attached to a structure in order to reduce the dynamic response of the structure. The damper is "tuned" because its frequency is set to a particular value such that when the frequency is excited, the damper will resonate out of phase with the movement of the structure, thereby dissipating the energy on the structure.

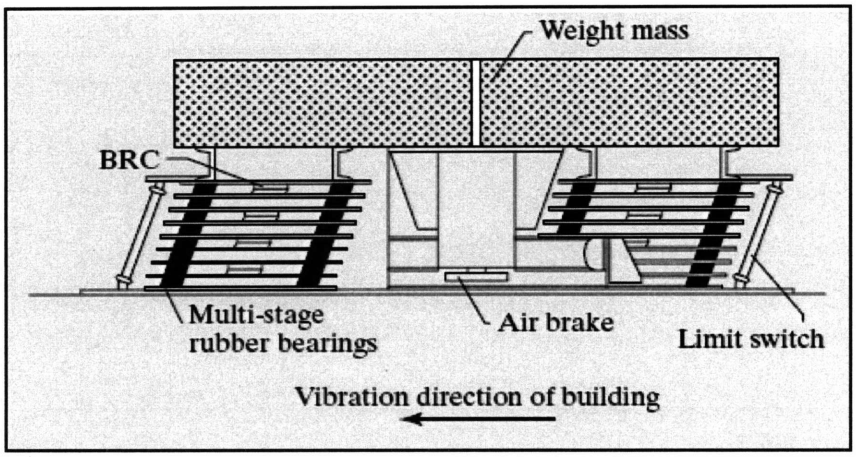

Figure 10. Tuned Mass Damper Assembly[7]

A liquid sloshing damper dissipates energy through liquid sloshing and wave breaking of the free surface. The energy dissipating device consists of a container partially filled with a liquid. The container can come in a vast array of geometries such as rectangular or circular shapes. The containers can also be filled with internal devices like moving spheres, suspended particles and many other that interact with the motion of the liquid. The liquid begins a sloshing motion when the system experiences an excitation, which is accompanied by waves at the free surface. This type of dampers is suitable for suppressing relatively low frequency motion.

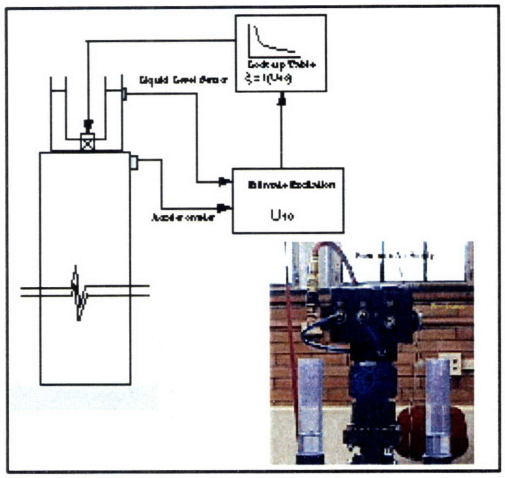

Figure 11. Liquid Sloshing Damper Configuration[8]

Active Systems

Active systems act differently from passive energy dissipation mechanisms. As opposed to passive energy dissipation mechanisms, active systems have the ability to determine the present state of the structure, decide on a set of actions that will change such state to suit desired conditions, and enact functions in a controlled manner and in a short period of time. This means that these systems can accommodate unforeseen occurrences by performing actions that meet performance requirements.

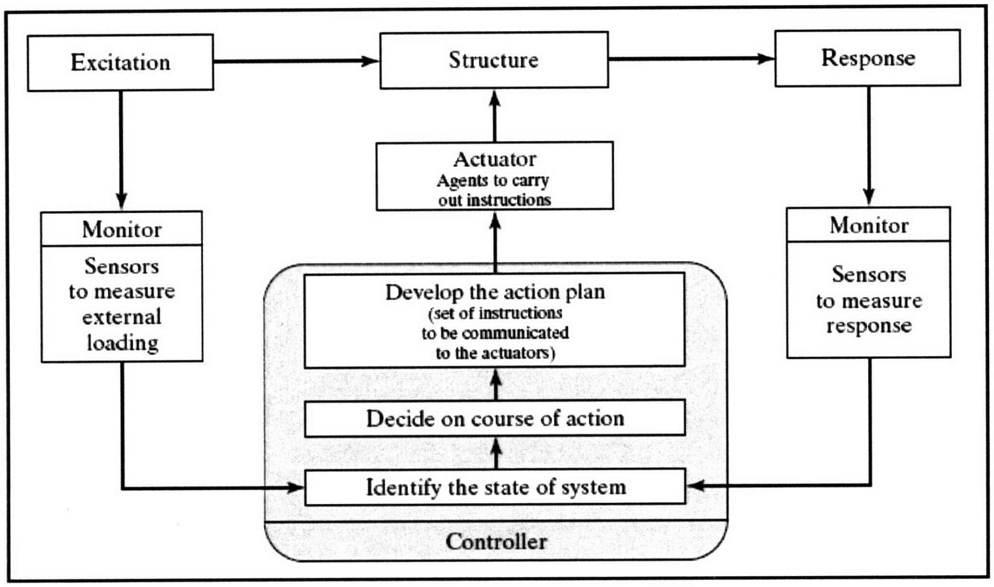

Figure 12. Diagram of an Active System[7]

The figure above presents the diagram of an active system which is basically made up of three main components, namely the monitor, controller, and actuator. The monitor is used to measure the external loading as well as the response. Hence, it performs the data acquisition part of the system. The actuator is tasked with carrying out the instructions given by the controller. Lastly, the controller identifies the state of the system, decides on the course of action, and develops the action plan.

Essentially, the physical system reacts to a certain loading which is read by the sensors. The sensors then send the information through a transmission channel to a modeling and analysis system which provides both visualization and archival and access proponents. After which, the decision-making process commences from which stems the action. This action is performed on the physical system. This is modeled in the figure below.

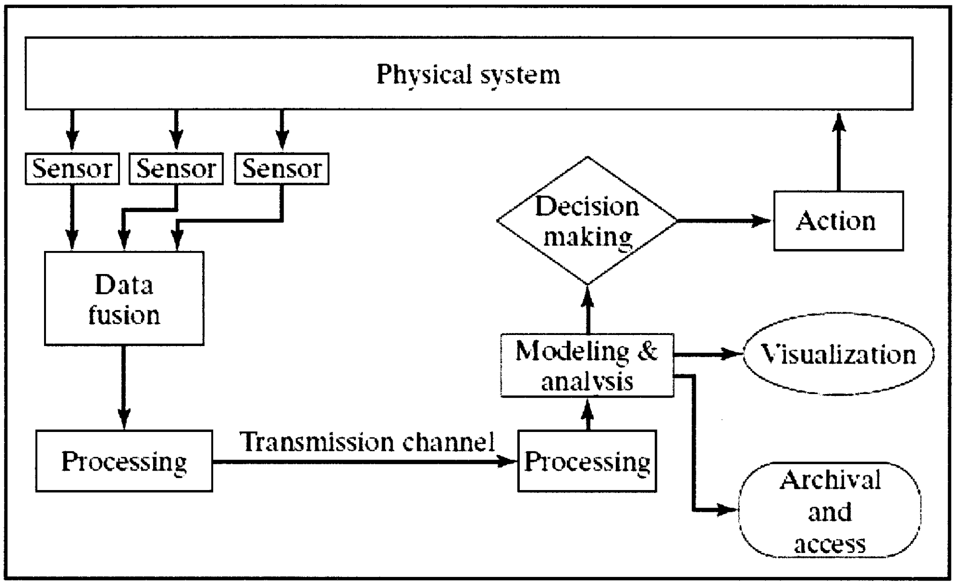

Figure 13. Active System Information Processing Elements[7]

Chapter 4: Selection Criteria Model

Pre-selection Procedure

Building Performance Levels

Seismic rehabilitation intention is essentially the beginning of the retrofitting process. Every structure is assessed differently and hence intentions vary depending on the use of the building, the age of the structure, the significance of the structure, so on and so forth.

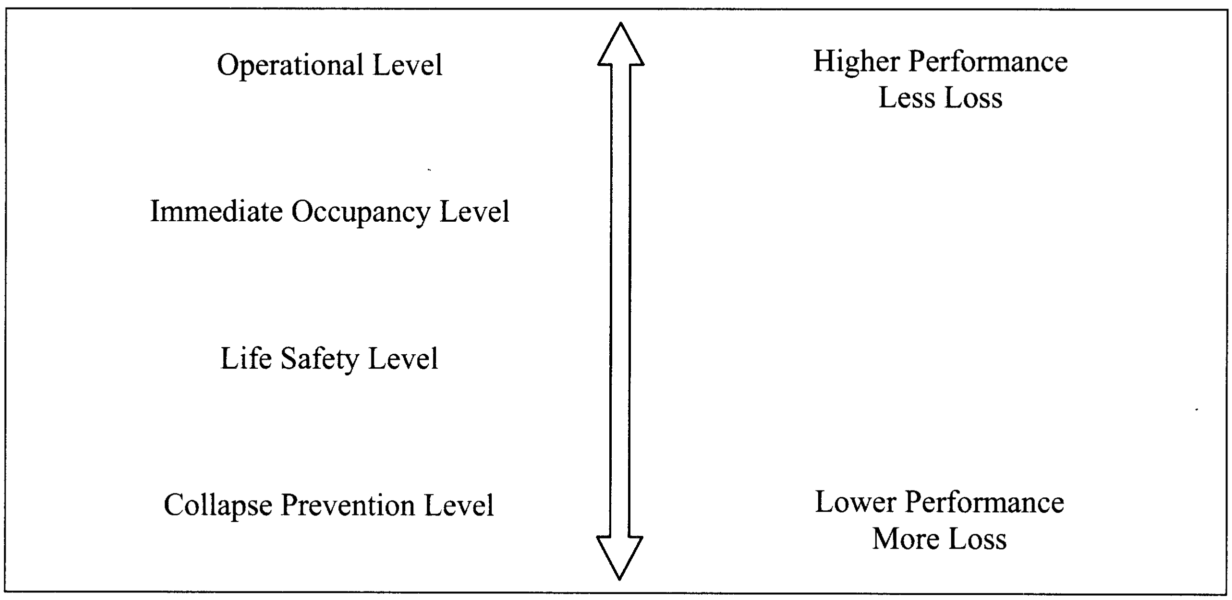

Figure 14. Building Performance Level[9]

Figure 14 presents the building performance spectra which encompasses various rehabilitation intentions. At the Operational level (1-A), the building is expected to sustain minimal or no damage to its structural and nonstructural components. While at the Immediate Occupancy level

(1-B), the building is required to sustain minimal or no damage to its structural components and minor damages to its nonstructural components. The third level, Life Safety level (3-C), is when the building experiences extensive damage to structural and nonstructural components. Lastly, at the Collapse Prevention level (5-E), buildings pose significant hazard to life safety resulting from failure of nonstructural components. As can be seen, the operational level requires higher performance from the structure which is directly related to lesser losses. Looking at the level of collapse prevention, although requires lower performance from the structure, there is a higher degree of loss. The levels of immediate occupancy and life safety show a compromise between degree of performance and loss.

	Building Performance Levels			
	Collapse Prevention Level	**Life Safety Level**	**Immediate Occupancy Level**	**Operational Level**
Overall Damage	Severe	Moderate	Light	Very Light
General	Little residual stiffness and strength, but load-bearing columns and walls function. Large permanent drifts. Some exits blocked. Infills and unbraced parapets failed or at incipient failure. Building is near collapse.	Some residual strength and stiffness left in all stories. Gravity-load-bearing elements function. No out-of-plane failure of walls or tipping of parapets. Some permanent drift. Damage to partitions. Building may be beyond economical repair.	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. Elevators can be restarted. Fire protection operable.	No permanent drift; structure substantially retains original strength and stiffness. Minor cracking of facades, partitions, and ceilings as well as structural elements. All systems important to normal operation are functional.
Nonstructural components	Extensive damage.	Falling hazards mitigated but many architectural, mechanical, and electrical systems are damaged.	Equipment and contents are generally secure, but may not operate due to mechanical failure or lack of utilities.	Negligible damage occurs. Power and other utilities are available, possibly from standby sources.
Comparison with performance intended for buildings designed, under the *NEHRP Provisions*, for the Design Earthquake	Significantly more damage and greater risk.	Somewhat more damage and slightly higher risk.	Much less damage and lower risk.	Much less damage and lower risk.

Figure 15. Damage Control and Building Performance Levels[9]

Each of the building performance levels shown above is made up of structural and nonstructural performance levels. Structural performance levels describe the damage state limits of the structural systems. Correspondingly, nonstructural performance levels describe the damage state limits of the nonstructural systems.

Looking particularly at the structural performance levels and ranges, FEMA lists three for the former and two for the latter. They are categorized according to the following:

Table 3. Structural Performance Levels and Ranges

S-1	Immediate Occupancy Performance Level
S-2	Damage Control Performance Range (extends between Life Safety and Immediate Occupancy Performance Levels)
S-3	Life Safety Performance Level
S-4	Limited Safety Performance Range (extends between Life Safety and Collapse Prevention Performance Levels)
S-5	Collapse Prevention Performance Level

Each level defines the post-earthquake damage state of the building. Table 4 presents the levels and their corresponding damage states.

Table 4. Overview of Structural Performance Levels

States	Immediate Occupancy Performance Level (S-1)	Life Safety Performance Level (S-3)	Collapse Prevention Performance Level (S-5)
Post-Earthquake Damage State	Very Limited	Significant Damage but a margin against either partial or total structural collapse remains.	On the verge of experiencing partial or total collapse.
Structural Elements and Components	Basic Vertical- and Lateral-force-resisting systems retain most of their pre-earthquake strength and stiffness.	Some structural components are severely damaged, however no large falling debris hazards.	Significant degradation in the stiffness and strength of the lateral-force resisting system, large permanent lateral deformation, and degradation in vertical-load-carrying capacity. However, significant gravity-load-resisting system components must be able to carry their loads.
Risk of Life	Very Low	Low	Significant due to falling hazards from structural debris.

More specifically, FEMA 273 outlines the structural performance levels and damage both for vertical and horizontal elements, as can be seen in the succeeding figures.

Elements	Type	Structural Performance Levels: Collapse Prevention S-5	Life Safety S-3	Immediate Occupancy S-1
Concrete Frames	Primary	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Extensive damage to beams. Spalling of cover and shear cracking (< 1/8" width) for ductile columns. Minor spalling in nonductile columns. Joint cracks < 1/8" wide.	Minor hairline cracking. Limited yielding possible at a few locations. No crushing (strains below 0.003).
	Secondary	Extensive spalling in columns (limited shortening) and beams. Severe joint damage. Some reinforcing buckled.	Extensive cracking and hinge formation in ductile elements. Limited cracking and/or splice failure in some nonductile columns. Severe damage in short columns.	Minor spalling in a few places in ductile columns and beams. Flexural cracking in beams and columns. Shear cracking in joints < 1/16" width.
	Drift	4% transient or permanent	2% transient; 1% permanent	1% transient; negligible permanent
Concrete Walls	Primary	Major flexural and shear cracks and voids. Sliding at joints. Extensive crushing and buckling of reinforcement. Failure around openings. Severe boundary element damage. Coupling beams shattered and virtually disintegrated.	Some boundary element distress, including limited buckling of reinforcement. Some sliding at joints. Damage around openings. Some crushing and flexural cracking. Coupling beams: extensive shear and flexural cracks; some crushing, but concrete generally remains in place.	Minor hairline cracking of walls, < 1/16" wide. Coupling beams experience cracking < 1/8" width.
	Secondary	Panels shattered and virtually disintegrated.	Major flexural and shear cracks. Sliding at joints. Extensive crushing. Failure around openings. Severe boundary element damage. Coupling beams shattered and virtually disintegrated.	Minor hairline cracking of walls. Some evidence of sliding at construction joints. Coupling beams experience cracks < 1/8" width. Minor spalling.
	Drift	2% transient or permanent	1% transient; 0.5% permanent	0.5% transient; negligible permanent

Figure 16. Structural Performance Levels and Damage - Vertical Elements[9]

Element	Performance Levels: Collapse Prevention S-5	Life Safety S-3	Immediate Occupancy S-1
Concrete Diaphragms	Extensive crushing and observable offset across many cracks.	Extensive cracking (< 1/4" width). Local crushing and spalling.	Distributed hairline cracking. Some minor cracks of larger size (< 1/8" width).

Figure 17. Structural Performance Levels and Damage - Horizontal Elements[9]

FEMA has a final designation of S-6, which means that structural performance is not considered. This simply means that the only factors being improved on are the nonstructural aspects of the building. Ranges are used to allow for specialized levels which are building-specific. The Damage Control Performance range (S-2) entails a damage state which is less than that of the Life Safety Performance level but more than that of the Immediate Occupancy Performance level. On the other hand, the Limited Safety Performance range defines the section between the Life Safety Performance level and the Collapse Prevention Performance level.

On the other hand, FEMA also presents four nonstructural performance levels. These are listed in Table 5.

Table 5. Nonstructural Performance Levels

N-A	Operational Performance Level
N-B	Immediate Occupancy Performance Level
N-C	Life Safety Performance Level
N-D	Hazards Reduced Performance Level

Likewise, there is an N-E rating which corresponds to when only structural improvements are covered.

After finding the proper building performance levels needed for the building, the Rehabilitation Objective arises. In sight of that objective, the minimal requirement is referred to as the Basic Safety Objective. This objective enlists only two criteria which must be satisfied. The first is the Life Safety Performance Level. At this level, both structural and nonstructural components meet the requirements for Basic Safety Earthquake 1 (BSE-1). BSE-1 is the lesser of the ground shaking at a site for 10%/50 year earthquake or two-thirds of the Maximum Considered Earthquake at the site. The second is the Collapse Prevention Performance Level which is when the stronger shaking occurs less frequently as defined in the Basic Earthquake 2 (BSE-2). BSE-2 is the Maximum Considered Earthquake at the site. This criteria is so because the level of safety it provides is at par with what the present provisions of the United States of America's seismic code. Since the Philippines' codes are patterned after that of North America's, these criteria can be adopted with modifications for earthquake impact severity.

There are two fundamental rehabilitation methods. Those methods are the Simplified and Systematic methods. Simplified rehabilitation has the primary objective of reducing seismic risk efficiently where possible and appropriate by seeking Limited Objectives. Limited Objectives are those which fail to satisfy the Basic Safety Objective. These objectives should be permissible under the following conditions: (1) The rehabilitation measures do not create a structural irregularity or make an existing structural irregularity more severe; (2) The rehabilitation measures do not result in a reduction in the capability of the structure to resist lateral forces or deformations; (3) The rehabilitation measures do not result in an increase in the seismic forces to any component that does not have adequate capacity to resist these forces, unless this component's behavior is still acceptable considering overall structural performance; (4) All new or rehabilitated structural elements are detailed and connected to the existing structure; (5) An unsafe condition is not created or made more severe by the rehabilitation measures; and (6) Locally adopted and enforced building regulations do not preclude such rehabilitation.[9]

The Systematic Method on the other hand, concentrates on the nonlinear behavior of the structure. This method is virtually applicable to all types of structures and involves detailed analysis of each component of the building.

Given such classifications, the rehabilitation process can be concretized in Figure 15.[9] The succeeding sections are dedicated to modifying the process to account for changes to adhere to the Philippine setting.

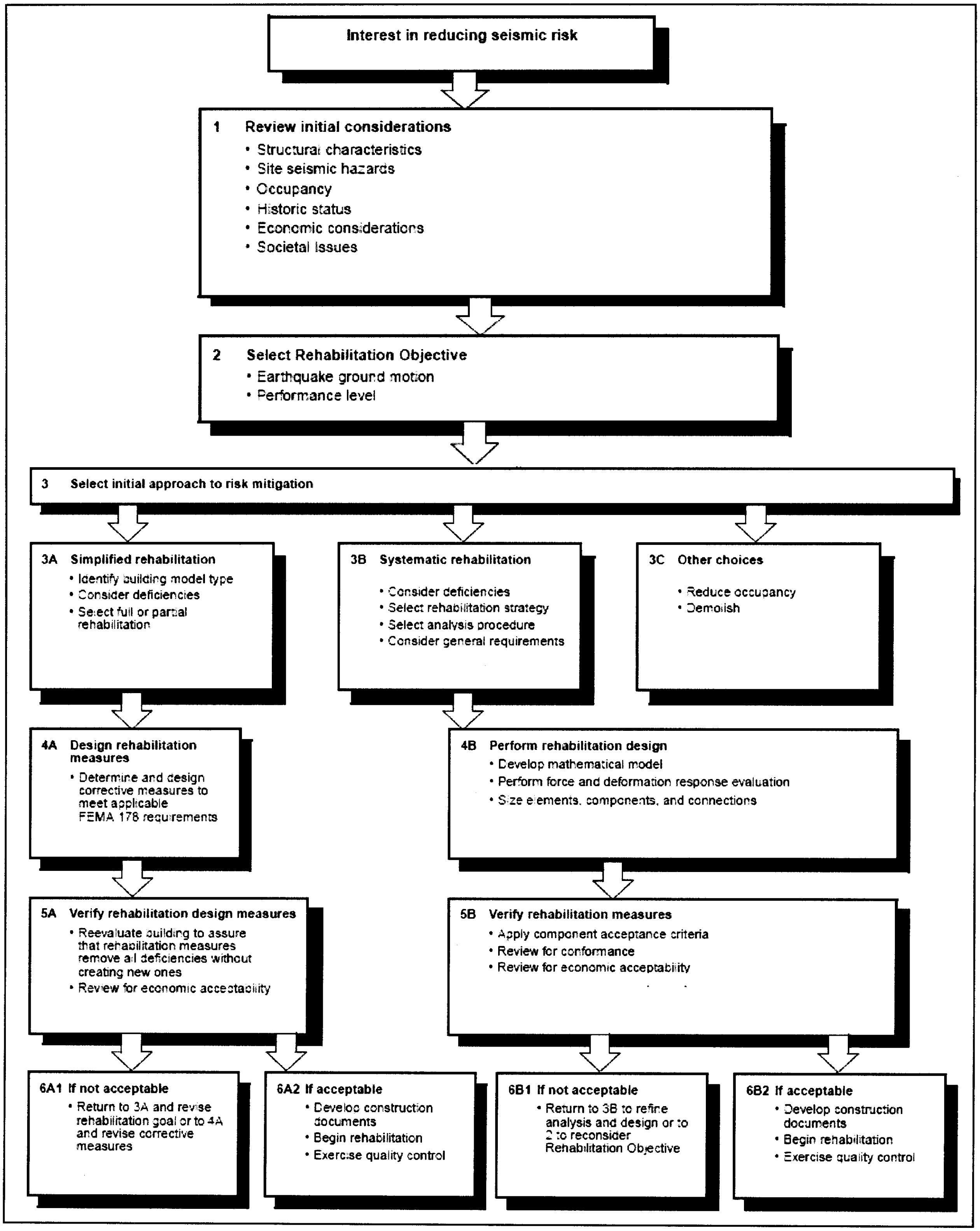

Figure 18. Rehabilitation Process Flowchart[9]

Review Initial Considerations

At this stage, an assessment of the present conditions of the existing structure takes place. This is where, as can be seen in Figure 15, factors such as structural characteristics, site seismic hazards, occupancy, historic status, economic considerations and societal issues are diligently examined. Each of these factors is crucial to the formulation of the Rehabilitation Objective since they reflect the interest in reducing seismic risk and the extent to which this interest is going to be carried out.

Also, an evaluation of the existing structure's present seismic resistance system should be made. A review methodology can be patterned after FEMA 178.

Select Rehabilitation Objective

Earthquake ground motion is site-specific. Depending on the location of the building, the Rehabilitation Objective may modify. This is where seismic hazard is considered. Response spectra are used to characterize the seismic effects on a building. The NSCP discusses in detail the seismic mapping of the Philippines, where it shows the response spectra for Seismic Zone 2 and 4. The Philippines is primarily made up of those two zones. The objective is also affected by the performance level determined for the building. In essence, this marks the commencement of the actual rehabilitation movement.

The previous step, the review of initial considerations, can be classified as stating the problem. The establishment of the Rehabilitation Objective is the hypothesis which is about to be tested.

Table 6 shows a matrix of Earthquake Hazard levels and Building performance levels. It shows a broad range for which the Rehabilitation Objective can be carried out.

		Building Performance Levels			
		Operational Performance Level (1-A)	Immediate Occupancy Performance Level (1-B)	Life Safety Performance Level (3-C)	Collapse Prevention Performance Level (5-E)
Earthquake Hazard Level	50%/50 year	a	b	c	d
	20%/50 year	e	f	g	h
	BSE-1 (~10%/50 year)	i	j	k	l
	BSE-2 (~2%/50 year)	m	n	o	p

k + p = BSO
k + p + any of a, e, i, m; or b, f, j, or n = Enhanced Objectives
o = Enhanced Objective
k alone or p alone = Limited Objectives
c, g, d, h = Limited Objectives

Figure 19. Rehabilitation Objectives[9]

As mentioned earlier, Limited Objectives are those which fail to satisfy the Basic Safety Objective. There are also Enhanced Objectives which provide performance far exceeding those stipulated under the Basic Safety Objective. Enhanced Objectives can be achieved in two ways:

directly and indirectly. They can be achieved directly by designing for BSE-1 and BSE-2. Enhanced Objectives are achieved indirectly by designing for an objective that provides better performance than the Basic Safety Objective.

Select Initial Approach to Risk Mitigation

Uncertainties are a part of everyday life and more often than not, seismic hazards come without warning. This is where managing such uncertainties via risk mitigation comes into play. Selecting an approach to address this issue allows for careful consideration of the value of life and the safety measures that should be employed to safeguard it.

From this stems the two rehabilitation methods discussed earlier. For the Philippine model, the Simplified method is out of the question because this method is suited only for buildings in locations of low or moderate seismic activity. The Philippines, being in the ring of fire, is in a region of high seismicity and therefore requires the Systematic rehabilitation method.

If rehabilitation is an option which shows no promise in terms of objective satisfaction, then other options such as reducing occupancy or demolition can be explored.

Perform Rehabilitation Design

After considering the deficiencies of the building, selecting the rehabilitation strategy and analysis procedure, as well as considering the general requirements for buildings, the rehabilitation design can begin.

The first phase in the design process is to develop mathematical model for stiffness and strength. There are several design software programs with the capability to do simulations of buildings.

The second phase is when force and deformation response evaluations are performed. Two general procedures are considered, linear and nonlinear. As FEMA 273 specifies, the linear analysis procedures, whether static or dynamic, cannot be used as rehabilitation strategies incorporating the use of supplemental energy dissipations systems and some types of seismic isolation systems.[9] For the purpose of this paper, since the focus is on retrofitting schemes involving seismic isolation, passive energy dissipation and active systems, the appropriate analysis procedure would be the nonlinear analysis.

Just as there are two linear methods, there are also two nonlinear methods, namely the Nonlinear Static Procedure (NSP) and the Nonlinear Dynamic Procedure (NDP). The NSP is appropriate for buildings without significant higher node response. It should not be used unless comprehensive knowledge of the structure has been obtained. The NDP on the other hand, is suitable for any structure provided: (1) The NDP is not recommended for use with wood frame structures; (2) The NDP should not be utilized unless comprehensive knowledge of the structure has been obtained; and (3) The analysis and design should be subject to review by an independent third-party professional engineer with substantial experience in seismic design and nonlinear procedures.[9]

These nonlinear procedures then lead to the use of rehabilitation strategies. This is where the need for structural redundancy is established and where engineers make use of the various retrofitting schemes discussed in Chapter 3.

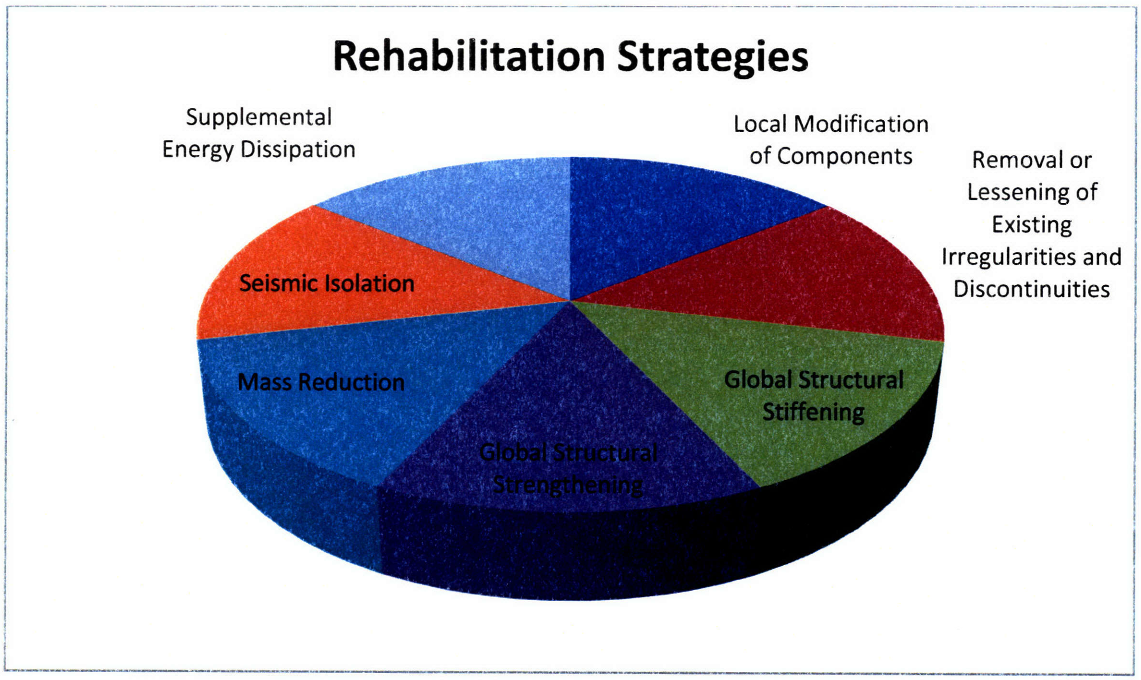

Figure 20. Rehabilitation Strategies[9]

Figure 20 shows the different rehabilitation strategies that can be used on a building. Local modification of components means upgrading them with substantial strength and stiffness. This basically entails taking local corrective measures. Another strategy that can be seen in Figure 20 is the removal or lessening of existing irregularities and discontinuities. Irregularities and discontinuities can cause undesirable building performance under earthquakes. Considering the nonlinear analysis done on the structure, irregularities are spotted by examining the distribution of structural displacements and inelastic deformation demands. Removal of discontinuities can have both a positive and negative impact on the building. Its positive impact means lessening the components that add to irregularities, while a negative impact would be the aesthetics of the building after such a removal.

There is also global structural stiffening which considers bracings and shear walls to increase the lateral strength of the building. The fourth is global structural strengthening which concerns itself with the lateral force resisting system. Another area that may aid in the seismic rehabilitation of the building is mass reduction. Adding stiffness would be a much easier method for seismic rehabilitation to perform, but one cannot deny the effect of mass reduction on the amount of deformation the building experiences. Lastly, there are the retrofitting schemes discussed in Chapter 3: seismic isolation, passive energy dissipation, and activity systems. As was mentioned earlier, these retrofitting schemes can be employed under certain parameters that make each scheme more suitable to protect the structure against seismic activity.

The next step would be to size elements, components and connections. From the results of the nonlinear static or dynamic analyses used through the mathematical models, the sizes of the newly rehabilitated structural components can be determined.

Verify Rehabilitation Measures

At this point, the rehabilitation design is compared against the component acceptance criteria. FEMA 273 lists the various acceptance criteria for structural members and can be seen in the following figures.

			Modeling Parameters[3]			Acceptance Criteria[3]				
						Plastic Rotation Angle, radians				
						Component Type				
			Plastic Rotation Angle, radians		Residual Strength Ratio	Primary			Secondary	
						Performance Level				
Conditions			a	b	c	IO	LS	CP	LS	CP
i. Beams controlled by flexure[1]										
$\frac{\rho - \rho'}{\rho_{bal}}$	Trans. Reinf.[2]	$\frac{V}{b_w d \sqrt{f'_c}}$								
≤ 0.0	C	≤ 3	0.025	0.05	0.2	0.005	0.02	0.025	0.02	0.05
≤ 0.0	C	≥ 6	0.02	0.04	0.2	0.005	0.01	0.02	0.02	0.04
≥ 0.5	C	≤ 3	0.02	0.03	0.2	0.005	0.01	0.02	0.02	0.03
≥ 0.5	C	≥ 6	0.015	0.02	0.2	0.005	0.005	0.015	0.015	0.02
≤ 0.0	NC	≤ 3	0.02	0.03	0.2	0.005	0.01	0.02	0.02	0.03
≤ 0.0	NC	≥ 6	0.01	0.015	0.2	0.0	0.005	0.01	0.01	0.015
≥ 0.5	NC	≤ 3	0.01	0.015	0.2	0.005	0.01	0.01	0.01	0.015
≥ 0.5	NC	≥ 6	0.005	0.01	0.2	0.0	0.005	0.005	0.005	0.01
ii. Beams controlled by shear[1]										
Stirrup spacing ≤ d/2			0.0	0.02	0.2	0.0	0.0	0.0	0.01	0.02
Stirrup spacing > d/2			0.0	0.01	0.2	0.0	0.0	0.0	0.005	0.01
iii. Beams controlled by inadequate development or splicing along the span[1]										
Stirrup spacing ≤ d/2			0.0	0.02	0.0	0.0	0.0	0.0	0.01	0.02
Stirrup spacing > d/2			0.0	0.01	0.0	0.0	0.0	0.0	0.005	0.01
iv. Beams controlled by inadequate embedment into beam-column joint[1]										
			0.015	0.03	0.2	0.01	0.01	0.015	0.02	0.03

1. When more than one of the conditions i, ii, iii, and iv occurs for a given component, use the minimum appropriate numerical value from the table.
2. Under the heading "Transverse Reinforcement," "C" and "NC" are abbreviations for conforming and nonconforming details, respectively. A component is conforming if, within the flexural plastic region, closed stirrups are spaced at ≤ d/3, and if, for components of moderate and high ductility demand, the strength provided by the stirrups (V_s) is at least three-fourths of the design shear. Otherwise, the component is considered nonconforming.
3. Linear interpolation between values listed in the table is permitted.

Figure 21. Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures - RC Beams[9]

Conditions			Modeling Parameters[4] Plastic Rotation Angle, radians a	Modeling Parameters[4] Plastic Rotation Angle, radians b	Residual Strength Ratio c	Acceptance Criteria[4] Plastic Rotation Angle, radians Component Type Primary Performance Level IO	Primary LS	Primary CP	Secondary LS	Secondary CP
i. Columns controlled by flexure[1]										
$\frac{P}{A_g f'_c}$	Trans. Reinf.[2]	$\frac{V}{b_w d \sqrt{f'_c}}$								
≤ 0.1	C	≤ 3	0.02	0.03	0.2	0.005	0.01	0.02	0.015	0.03
≤ 0.1	C	≥ 6	0.016	0.025	0.2	0.005	0.01	0.016	0.01	0.025
≥ 0.4	C	≤ 3	0.016	0.025	0.2	0.0	0.005	0.016	0.010	0.025
≥ 0.4	C	≥ 6	0.01	0.015	0.2	0.0	0.005	0.01	0.01	0.015
≤ 0.1	NC	≤ 3	0.01	0.015	0.2	0.005	0.005	0.01	0.005	0.015
≤ 0.1	NC	≥ 6	0.006	0.005	–	0.005	0.005	0.006	0.005	0.005
≥ 0.4	NC	≤ 3	0.006	0.005	–	0.0	0.0	0.006	0.0	0.005
≥ 0.4	NC	≥ 6	0.0	0.0	–	0.0	0.0	0.0	0.0	0.0
ii. Columns controlled by shear[1,3]										
Hoop spacing ≤ $d/2$, or $\frac{P}{A_g f'_c} \le 0.1$			0.0	0.016	0.2	0.0	0.0	0.0	0.01	0.016
Other cases			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
iii. Columns controlled by inadequate development or splicing along the clear height[1,3]										
Hoop spacing ≤ $d/2$			0.01	0.02	0.4	1	1	1	0.01	0.02
Hoop spacing > $d/2$			0.0	0.01	0.2	1	1	1	0.005	0.01
iv. Columns with axial loads exceeding $0.70P_o$[1,3]										
Conforming reinforcement over the entire length			0.015	0.025	0.02	0.0	0.005	0.001	0.01	0.02
All other cases			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

1. When more than one of the conditions i, ii, iii, and iv occurs for a given component, use the minimum appropriate numerical value from the table.
2. Under the heading "Transverse Reinforcement," "C" and "NC" are abbreviations for conforming and nonconforming details, respectively. A component is conforming if, within the flexural plastic hinge region, closed hoops are spaced at ≤ $d/3$, and if, for components of moderate and high ductility demand, the strength provided by the stirrups (V_s) is at least three-fourths of the design shear. Otherwise, the component is considered nonconforming.
3. To qualify, hoops must not be lap spliced in the cover concrete, and hoops must have hooks embedded in the core or other details to ensure that hoops will be adequately anchored following spalling of cover concrete.
4. Linear interpolation between values listed in the table is permitted.

Figure 22. Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures - RC Columns[9]

Conditions			Modeling Parameters[4]			Acceptance Criteria[4]				
						Plastic Rotation Angle, radians				
						Component Type				
						Primary			Secondary	
			Shear Angle, radians		Residual Strength Ratio	Performance Level				
			d	e	c	IO	LS	CP	LS	CP
i. Interior joints										
$\frac{P}{A_g f'_c}$ [2]	Trans. Reinf.[1]	$\frac{V}{V_n}$ [3]								
≤ 0.1	C	≤ 1.2	0.015	0.03	0.2	0.0	0.0	0.0	0.02	0.03
≤ 0.1	C	≥ 1.5	0.015	0.03	0.2	0.0	0.0	0.0	0.015	0.02
≥ 0.4	C	≤ 1.2	0.015	0.025	0.2	0.0	0.0	0.0	0.015	0.025
≥ 0.4	C	≥ 1.5	0.015	0.02	0.2	0.0	0.0	0.0	0.015	0.02
≤ 0.1	NC	≤ 1.2	0.005	0.02	0.2	0.0	0.0	0.0	0.015	0.02
≤ 0.1	NC	≥ 1.5	0.005	0.015	0.2	0.0	0.0	0.0	0.01	0.015
≥ 0.4	NC	≤ 1.2	0.005	0.015	0.2	0.0	0.0	0.0	0.01	0.015
≥ 0.4	NC	≥ 1.5	0.005	0.015	0.2	0.0	0.0	0.0	0.01	0.015
ii. Other joints										
$\frac{P}{A_g f'_c}$ [2]	Trans. Reinf.[1]	$\frac{V}{V_n}$ [3]								
≤ 0.1	C	≤ 1.2	0.01	0.02	0.2	0.0	0.0	0.0	0.015	0.02
≤ 0.1	C	≥ 1.5	0.01	0.015	0.2	0.0	0.0	0.0	0.01	0.015
≥ 0.4	C	≤ 1.2	0.01	0.02	0.2	0.0	0.0	0.0	0.015	0.02
≥ 0.4	C	≥ 1.5	0.01	0.015	0.2	0.0	0.0	0.0	0.01	0.015
≤ 0.1	NC	≤ 1.2	0.005	0.01	0.2	0.0	0.0	0.0	0.005	0.01
≤ 0.1	NC	≥ 1.5	0.005	0.01	0.2	0.0	0.0	0.0	0.005	0.01
≥ 0.4	NC	≤ 1.2	0.0	0.0	–	0.0	0.0	0.0	0.0	0.0
≥ 0.4	NC	≥ 1.5	0.0	0.0	–	0.0	0.0	0.0	0.0	0.0

1. Under the heading "Transverse Reinforcement," "C" and "NC" are abbreviations for conforming and nonconforming details, respectively. A joint is conforming if closed hoops are spaced at $\leq h_c/3$ within the joint. Otherwise, the component is considered nonconforming. Also, to qualify as conforming details under ii, hoops must not be lap spliced in the cover concrete, and must have hooks embedded in the core or other details to ensure that hoops will be adequately anchored following spalling of cover concrete.
2. This is the ratio of the design axial force on the column above the joint to the product of the gross cross-sectional area of the joint and the concrete compressive strength. The design axial force is to be calculated using limit analysis procedures, as described in Chapter 3.
3. This is the ratio of the design shear force to the shear strength for the joint. The design shear force is to be calculated according to Section 6.5.2.3.
4. Linear interpolation between values listed in the table is permitted.

Figure 23. Modeling Parameters and Numerical Acceptance Criteria for Nonlinear Procedures - RC Beam-Column Joints[9]

	Value of γ				
ρ''	Interior joint with transverse beams	Interior joint without transverse beams	Exterior joint with transverse beams	Exterior joint without transverse beams	Knee joint
<0.003	12	10	8	6	4
≥0.003	20	15	15	12	8

ρ'' = volumetric ratio of horizontal confinement reinforcement in the joint; knee joint = self-descriptive—with transverse beams or not.

Figure 24. Joint Strength Calculation[9]

Whether the analysis method is the Nonlinear Static procedure or the Nonlinear Dynamic procedure, Figures 21 through 24 present the allowable limit to inelastic deformations.

The last step would be to review for conformance and for economic acceptability. Given the acceptance criteria, a review of the nonlinear procedure employed would be in order. In terms of economic acceptability, the Philippines' Peso is roughly 42 to 1 of the U.S. Dollar. Given the rehabilitation strategies presented in Chapter 3 and that none of the equipment used to achieve such strategies are manufactured locally, the cost of those equipment will make the most significant impact on the decision-making process.

We can also go so far as to say that the higher the performance required of the structure, the more likely the cost of the structure will increase. It is more likely to do so simply because ensuring the safety of a structure inevitably affects the amount of material and the rehabilitation techniques that will be used.

Philippine Selection Criteria Model

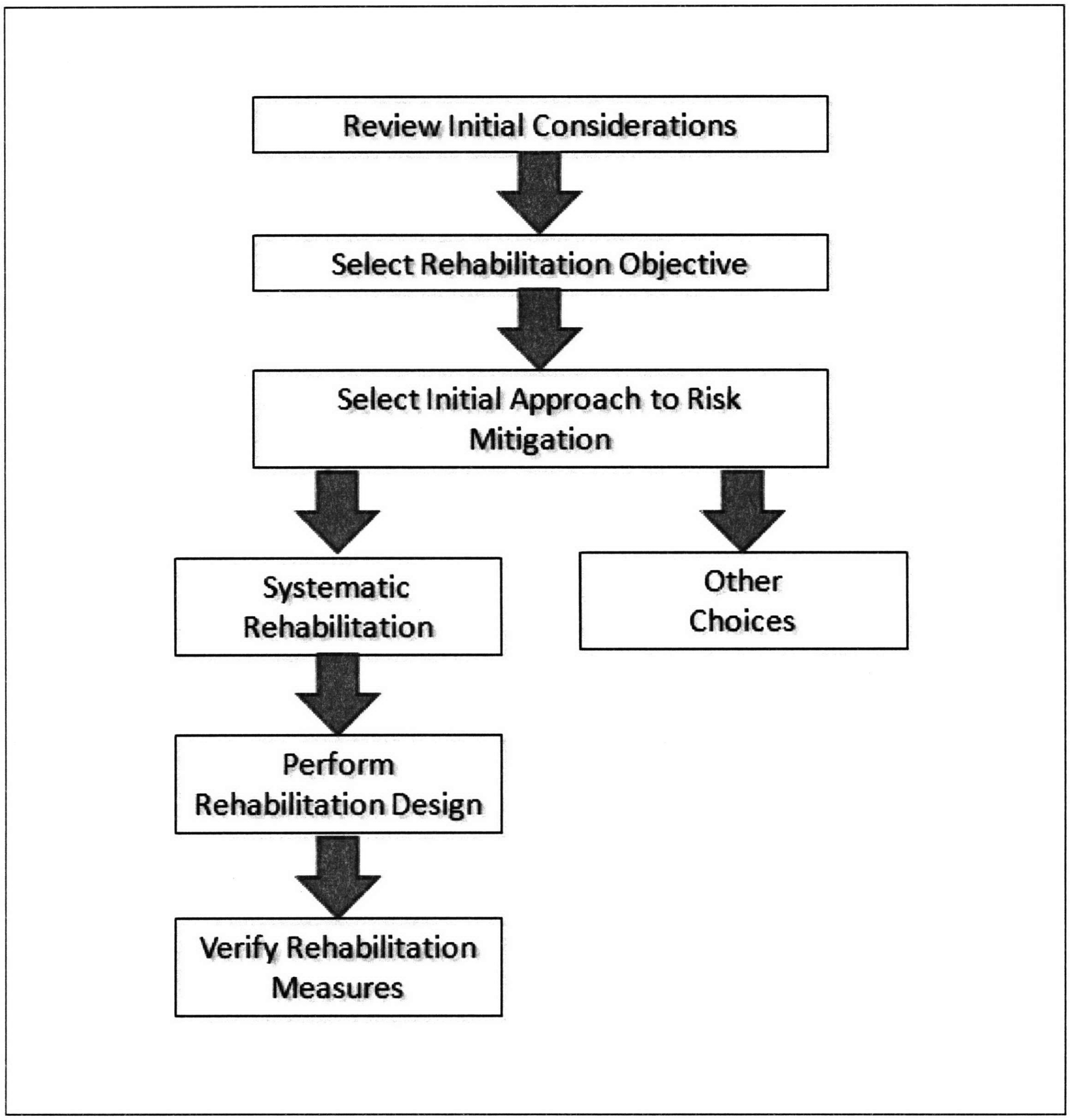

Figure 25. Philippine Selection Criteria Model

The Philippine Selection Criteria Model presented in Figure 25 shows the modification of the rehabilitation process given in FEMA 273. The clear difference is seen in the two phases that take place after risk mitigation. Other choices accounts for reduced occupancy and demolition, just as the process flowchart of FEMA 273 suggests. After verifying the rehabilitation measures and the acceptance criteria has been evaluated the next decision would be whether the rehabilitation scheme is acceptable or not. If it is acceptable, then construction documents are developed and the physical rehabilitation process begins. If it is not acceptable, designers would then have to refine the systematic rehabilitation process in order to satisfy the acceptance criteria.

Conclusion

After deliberating the various parameters presented by FEMA 273, a rehabilitation process has been presented in Figure 25 which is custom-fitted for the Philippine setting. Certain factors that were taken into consideration in the development of the rehabilitation process flowchart by FEMA were not applicable chiefly due to the seismic region to which the Philippines belong. This modified selection criteria model can be adapted into the National Structural Code of the Philippines to provide a certified basis for rehabilitation of buildings in the Philippines.

Recommendations

In line with the study, further analyses of the rehabilitation process should be undertaken. Further analysis would include site testing. Researchers can begin assessing the measurability of the process flowchart by visiting buildings and assessing current site conditions. A team can then be organized to draw from the rehabilitation process flowchart a software script that will allow the users of the software to input various parameters for any given building such as age, material, and others and conclude from it which form of retrofitting, whether it is base isolation, passive energy dissipation or active control, is most appropriate to use.

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