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Cost-Performance Criteria for Seismic Retrofitting

by

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ABSTRACT

A methodology to facilitate the decision making process for seismic retrofitting of buildings is presented. To this end, the damage cost to a building is calculated as the sum of direct flows from the capital stock and human capital. Four damage cost functions are considered. These are the replacement or repair cost, loss of contents, human injury and fatality, and economic loss. The damage cost functions are conveniently expressed in terms of a global damage index, D_m, which is a qualitative measure of the building performance after an earthquake.

The Park-Ang damage model was incorporated into the SNAP-2D computer program in order to calculate damage indices for reinforced concrete members. Using the weighting scheme proposed by Bracci, the global damage index for the building structure is evaluated. Henceforth, the cost-performance methodology is implemented for reinforced concrete building prototypes in Puerto Rico. Two classes of building prototypes are considered. Class 1 buildings are older buildings that were properly designed for the time of their construction but may not be adequate by the current standards. Class 2 buildings are buildings that are designed using the current building code regulations. In all cases, steel bracing systems are the retrofitting schemes of choice.

Results from an Input-Output analysis are used to estimate the economic losses for different classes of occupancies. Other factors explicitly considered are the socio-economic status of building population, business density, reconstruction time, and earthquake recurrence rates. The methodology also allows the designer to generate different cost schedules for different clients simultaneously. As the needs of potential clients may vary considerably, the process will address any specific concerns, whether the client is the owner, the business occupant, the government, or the insurance company.

RESUMEN

Se presenta una metodología para facilitar el proceso de decidir si un edificio necesita ser rehabilitado para resistir terremotos. Para este propósito, el costo del daño en un edificio se calcula como la suma del flujo directo de la pérdida del acervo de capital (*capital stock*) y del capital humano. Cuatro funciones de costo de daños son consideradas. Estas son el costo de reemplazo ó reparación, pérdida del contenido, lesiones y pérdidas humanas y económicas. Las funciones de costo de daños son convenientemente expresadas en término del índice de daño, D_m, el cual es una medida cualitativa del comportamiento de un edificio después de un terremoto.

El modelo de Park-Ang se incorporó al programa SNAP-2D para calcular el índice de daño de elementos de concreto reforzado. El índice de daño global para el edificio se evalúa usando el modelo de peso propuesto por Bracci. De esta forma, la metodología de costo-comportamiento se implementó para prototipos de edificios de concreto reforzado para Puerto Rico. Se consideran dos clases de prototipos. La clase 1, que corresponde a edificios viejos que fueron diseñados apropiadamente en el tiempo de su construcción, pero en la actualidad pueden no ser adecuados. La clase 2 correspondiente a edificios diseñados usando los códigos vigentes. La técnica de rehabilitación seleccionada, en todos los casos, es un sistema de riostras de acero.

Resultados de un análisis de insumo-producto (*Input-Output*) son usados para estimar las pérdidas económicas en edificios de usos diferentes. Otros factores considerados

explicitamente son el estatus socio-económico de los inquilinos del edificio, la densidad del negocio, el tiempo de reconstrucción y la razón de recurrencia del terremoto. La metodología tambien permite al diseñador generar diferentes informes de costos para diferentes clientes al mismo tiempo. Según las necesidades potenciales del cliente varíen, el proceso aplicará a cualquier interés específico, independientemente de que el cliente sea el dueño, el ocupante del edificio, el gobierno ó la compañia de seguro.

A Dios, por darme el valor y apoyo espiritual de seguir luchando: Siempre estás ahí.
A mis padres, Dulce María y Luis Antonio: Mami, papi, lo logramos.
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"La vida es como una ola....

... lo importante es permanecer en la cresta"

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List of Symbols

A	Floor Area.
$\mathbf{A}$	Inter-industry technical coefficients matrix.
A_s	Cross sectional area of steel reinforcement (tension).
$A_s^{/}$	Cross sectional area of steel reinforcement (compression).
AIBP	Average income for building population.
a	Gravity acceleration in Donovan's attenuation law (c_m/sec^2) or the depth of Whitney's rectangular stress block.
a, b	Coefficients from the regression analysis equation for the period of reconstruction.
a_{ij}	Technical coefficient matrix.
$\mathbf{B}$	Leontief inverse matrix.
[C]	Damping matrix.
C_C	Loss of contents factor.
C_D	Total damage cost in present worth value.
$C_D(x)$	Damage cost associated with the damage level x.
C_{DI}	Instantaneous damage cost for all possible earthquakes.
C_E	Economic loss factor.
C_{Ec}	Operating expense factor.
C_{Er}	Rent factor.
C_{Eg}	Gross income factor.
C_{Ep}	Payroll factor.
C_H	Human injury and fatality factor.
C_L	Location adjustment factor.
C_{LC}	Life cycle cost for upgrading.
C_R	Replacement or repair cost factor.

C_T	Time adjustment factor.
C_U	Upgrading cost.
C_{hi}	Fatality or injury cost per person unit, $i = 1$ to 4 depending on severity.
C_0	Initial construction cost.
C_1	Building group mean cost.
C_2	Floor area adjustment factor.
C_3	Seismicity/performance objective adjustment factor.
D	Element damage index.
D_m	Global damage index.
dE	Incremental dissipated hysteretic energy.
E	Expense vector.
E[ ]	Expected value.
E_s	Young's modulus of elasticity for steel.
F_y	Yield stress of steel.
$f_S(s)$	Probability density function for seismic intensity distribution.
$f_X(x)$	Probability density function for seismic damage distribution.
f_c'	Compressive strength of concrete.
G	Gross income vector.
[K]	Stiffness matrix.
L	Element length when computing the ultimate rotational capacity or structure design life when computing R_D.
L_p	Length of the plastic hinge.
l/d	Shear span ratio.
[M]	Mass matrix.
M_y	Yield moment.
m	Magnitude on the Richter scale used in Donovan's attenuation law.
N_D	Number of persons per cells.

n_o	Normalized axial stress.
$\mathbf{P}$	Payroll vector.
q	Annual discount rate.
R	Focal distance in kilometers in Donovan's attenuation law.
R_D	Present worth factor = $E(C_D) / C_{DI}$.
R_f	Fatality rate.
s_{max}	Maximum probable seismic intensity for the region.
s_{min}	Minimum seismic intensity of design significant.
T_R	Period of reconstruction.
w_i	Weight assigned to the design earthquake causing C_{di}.
x_i	Output of sector *i*.
x_{ij}	Amount of product of sector *i* absorbed by sector *j*.
y_i	Final demands of sector *i*.
z_i	Total primary inputs of sector *i*.
α_m, α_k	Damping matrix coefficients.
β	Non-negative constant in the element damage index.
$\Gamma(,)$	Incomplete gamma function.
ε_i	Critical damping ratio.
θ_m	Maximum response rotation under an earthquake.
θ_u	Ultimate rotational capacity under monotonic loading.
λ	Number of load cells.
μ_i	Severity factor: $i = 1$ for minor injuries; $i = 2$ for major non-disabling injuries; $i = 3$ for disabling injuries; $i = 4$ for fatalities.
ν	Mean annual occurrence rate of significant earthquakes ($S \leq s_{min}$).
ρ_c	Catastrophe factor.
ρ_d	Site demolition and cleanup factor.
ρ_e	Engineering factor.
ρ_o	Ordinary repair/remodeling factor.

ρ_t	Total repair-to-initial cost factor or longitudinal steel ratio in percent.
ρ_w	Confinement ratio in percent.
Φ_u	Ultimate curvature.
Φ_y	Yield curvature.
ω_c	Content type factor.
ω_i	Importancy factor when calculating the global damage index or circular frequency when computing the damping matrix.

CHAPTER 1

INTRODUCTION

1.1 Justification

The ability to build seismically safe structures has improved substantially in the past three decades. Correlation of data from past earthquake experiences, various laboratory and field experiments and the advancements of numerical computational techniques have revolutionized the way building codes are written. With new building codes being revised constantly, seismic design requirements will continue to evolve on an even faster pace. This should place a greater toll on decision makers regarding seismic retrofitting.

The aging infrastructure in Puerto Rico has been the cause of great concern over the last decade. The ongoing debate has drawn special attention to recent geological studies that place Puerto Rico as the third highest risk seismic zone in the United States and its territories. Consequently, the Puerto Rico building code was amended in 1987 and is being revised again to include stricter guidelines for seismic design and construction. Because of insufficient design loads and ductility details, a large number of older buildings are thought to be inadequate by current standards. The reasoning goes that unless these older buildings are retrofitted, their performance in an earthquake may prove unsatisfactory. The Puerto Rico problems may therefore be of more pressing nature than those of the United States of America.

Evolving seismic code provisions is only one of the reasons that may bring about an upgrading decision. Other reasons include damages from previous earthquakes, changes in building occupancy, and design or construction errors. One should appreciate the balance that would define allowable safety margins within the bounds of acceptable construction costs. Upgrading decision is also tempered by the probabilistic nature of earthquake occurrence. Typical damage cost functions considered are life safety, repair or replacement cost, and loss of content. An equally important, but far less obvious factor is the supply and demand induced contractions associated with the partial or total loss of a building. This study is the first to incorporate such an analysis using the well-known Input-Output (I-O) economic model.

The proposed cost-performance methodology specifically targets the treatment of seismically deficient reinforced concrete buildings in Puerto Rico. Even so, it is equally applicable to other types of structures. Several reinforced concrete building prototypes are tested using the Park-Ang damage model (Park and Ang, 1985). Each building is then retrofitted with steel bracing. The seismic response of structural systems coupled with the response of retrofitted structures will form the basis for cost comparisons.

1.2 Previous Work

Efforts to formulate earthquake loss estimation methodology for buildings are just beginning to gain wide spread recognitions. Except for some early reports from the Applied Technology Council (ATC) and the Federal Emergency Management Agency (FEMA), most of other research in this area were conducted concurrent to this work. The most relevant of these efforts are cited in this section.

The first study on earthquake loss estimation was performed in 1972 by the National Oceanic and Atmospheric Agency (NOAA) for San Francisco (Algermissen et al., 1972). This was followed shortly with about thirty other regional earthquake loss studies, with differences in assumptions and methodologies used (Whitman et. al, 1997). The ATC-13 document was the first attempt to try set national standards (ATC, 1985).

ATC-13 provides damage estimates versus seven levels of earthquake intensities for 78 existing facility classes in California. A damage factor is defined as the ratio of dollar loss to replacement, expressed in percentages. Its estimated values are based on the inputs from 70 senior-level earthquake engineering experts. Each expert was asked to answer a questionnaire, providing a low, best and high estimate of damage factors at Modified Mercalli Intensities (MMI) VI through XII. The low and high estimates were defined to be the 90% probability bounds of the damage factor distribution, while the best estimate was defined as the damage factor most likely to be observed for a given MMI and facility class.

The ATC-21 document, which was published in 1988, presents a field survey methodology to identify the primary structural lateral load resisting system and significant seismic deficiencies in buildings. The methodology is based on visual observations and includes such systems as wood frames, steel moment resisting frames, steel braced frames, reinforced concrete frames, and shear wall structures. The field survey data also provides a scoring system which relates to the probability of each building sustaining life threatening damages during major earthquake. The scoring system begins by specifying a range of seismic intensities to which the surveyed buildings could be subjected. Each building is then assigned a performance modifier based on the type of structure and a performance score with higher numbers meaning better seismic resistance. Using these parameters and according to the seismicity level, a Basic Structural Hazard score (BSH) is established and assigned to each building. High BSH scores reflect a potentially good seismic performance, while low BSH scores reflect a potentially bad seismic performance.

FEMA-156 presents the latest attempt to generate a comprehensive set of costs for the seismic rehabilitation of buildings (FEMA, 1994). Although the results are based on a relatively small sample, they do provide helpful guidelines on this very significant topic. Predefined seismic performance levels, regional seismicity levels, location factors for variations in material and labor costs, inflation factor for future cost of construction, and building class and characteristics are parameters used to determine the retrofitting cost.

In 1989, FEMA published the report from the National Academy of Sciences entitled *Estimating Losses from Future Earthquakes* (Whitman et. al, 1997). The report presented a consensus set of guidelines for conducting loss studies. It systematized the groundwork for a loss methodology structure and provided the momentum for methodology development. Ang and De León (1995a, 1995c) proposed a systematic approach for making cost-effective earthquake design decisions for buildings. Their work inspired in part what is presented here and will be cited in Chapters 2 and 3.

A cooperative agreement between FEMA and the National Institute of Building Sciences has focused on the development of a nationally applicable standard for estimating potential earthquake losses. To that end, a project work group consisting of earthquake experts was created to provide technical oversight. An eighteen-member Project Oversight Committee was also formed to represent user interest in the earthquake community and provide user/client input. The end result is a methodology composed of six major modules:

1. Potential Earth Science Hazards, i.e. Ground Motion/Site Effects, Ground Failure, Tsunami.
2. Inventory, Classification Systems, Data Collection and Handling.
3. Direct Damage, General Building Stock, Essential Facilities, High Loss Facilities, Lifelines.
4. Induced Damage, Flooding, Fire Following, Hazardous Materials Release, Debris.
5. Direct Losses, Economic Losses, Casualties, Shelter.
6. Indirect Losses.

Modules are interdependent and each one is required for a comprehensive loss estimation study.

1.3 Objectives

The principal objectives of this research are the following:

- To create a methodology for evaluating the economic impacts of an earthquake through the loss of building structure, contents, and life safety.
- To identify and to formulate supply and demand induced contractions associated with the partial or total loss of a building.
- To simplify the decision making process for building rehabilitation.
- To quantify parameters for the immediate and practical implementation in Puerto Rico.

The end results will place damage repair costs versus upgrading costs.

1.4 Scope of the Thesis

The next two chapters of this thesis deal with the development of a methodology to evaluate cost-performance criteria for seismic retrofitting. Chapter 4 and Appendix A present tools to implement the methodology developed. Some practical implications are discussed in Chapters 5 and 6. A summary of each chapter follows.

Chapter 2 defines damage cost functions which are used to evaluate the economic impacts of an earthquake. A discussion about the Input-Output analysis is also presented, reviewing basic economic concepts to better understand the methodology. Numerical examples are used to discuss the significance of various coefficients.

Chapter 3 presents the event parameters required to calculate the expected life-cycle costs. Since one cannot predict the occurrence of an earthquake with certainty, an explanation on how to convert the future cost to present worth is given. Also included is a discussion on how to define the design earthquake for Puerto Rico.

Chapter 4 deals with the computational tools which are used to evaluate the dynamic behavior of the prototype buildings. Included are the modifications made to the selected computer program, the elements used, and descriptions of the damage index at the local and global levels.

Chapter 5 presents the decision making process to retrofit and how it may be influenced by occupancy. Reinforced concrete building prototypes are used to further emphasize real life applications.

Finally, a summary and conclusions from this thesis are presented in Chapter 6.

CHAPTER 2

DAMAGE COST FUNCTIONS

2.1 Introduction

The decision to reach certain required level of protection when upgrading an existing building for earthquakes is more than a mere function of the replacement cost versus the repair cost. It should take into consideration both direct and indirect effects from the loss of capital and human stocks. Building related earthquake stocks are shown in Figure 2.1.

The general economic model presented herein calculates the damage cost to a building in the event of an earthquake as the sum of direct flow from the stock of the capital and human capital. It is consistent with the systematic approach proposed by Ang and De León (1994). The factors considered are the replacement or repair cost, C_R, loss of content, C_C, human injury and fatality, C_H, and economic loss, C_E, which become the damage cost functions used in this study.

Damage cost functions are most conveniently expressed in terms of a global damage index, D_m, which is a qualitative measure of the building performance after an earthquake. The damage in this study should be interpreted as a change in the structure, caused by an earthquake, which produce significant degradation in the stiffness of the structure. The Park-Ang damage model is used to calculate damage indices for reinforced concrete members. A description of this model as well as some background information are given in

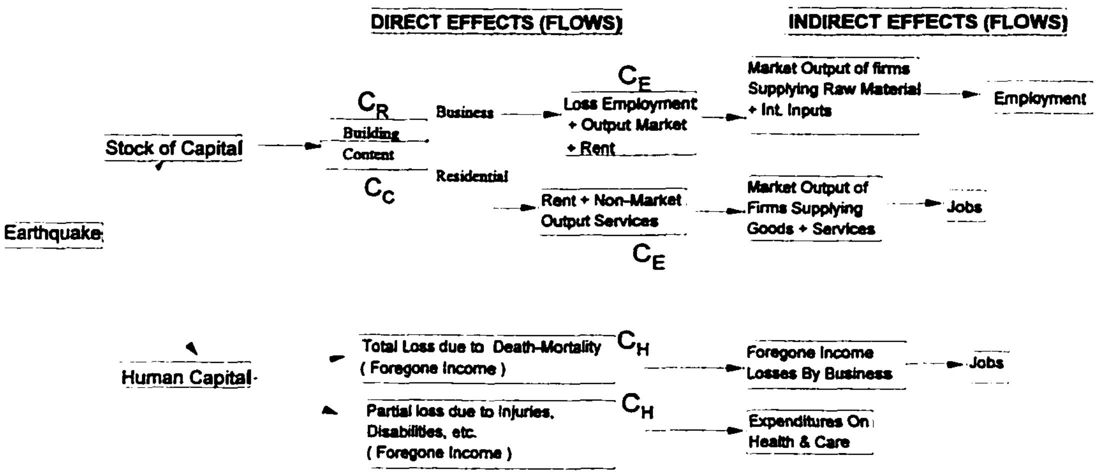


Figure 2.1: Building related earthquake stocks.

Chapter 4. Damage indices at the story levels are then calculated by adding the members' indices, each weighted based on the loads assigned to them. The procedure is extended to the structural level resulting in the aforementioned global damage index.

2.2 Construction Cost Estimating

The process to develop an estimate will be affected by three conditions. These are the information supplied to the estimator, the purpose of the estimate, and the amount of time allowed. Based on these criteria, there are four basic methods of estimates that may be used: the Unit Price, Assemblies or Systems, Square Foot or Cubic Foot, and Order of Magnitude estimates (R.S. Means Repair and Remodeling Estimating Method-RREM, 1997).

Unit Price is the most accurate and detailed of all construction cost estimating procedures. It is also the one procedure that takes the most time to complete. Working drawings and specifications are needed to estimate quantities of materials, equipment, and labor required. In addition, up-to-date and accurate cost information on those items are required to complete the estimate. All construction components are allocated into the 16 master format divisions developed by the Construction Specifications Institute, Inc. (RREM,1997). These divisions provide a standard of uniformity that is widely used in the construction industry for building construction. The relative accuracy of Unit Price procedure for repair and remodeling can be ±10% (RREM,1997).

Assemblies or Systems estimate is a procedure used when only certain parameters of a renovation project are known. These parameters may be as general as the building size, construction type, and basic information on utilities such as heating systems. A Systems estimate is important at the planning stages of a renovation project and shows the way the contractor views the project. Here, the items are reorganized in divisions that reflect the logical and sequential approach to construction. The major difference with respect to Unit Price estimate is that an assembly is a group of unit price items. They are unitary analysis assembled to form a whole unit. The result is twelve items divisions that organize the renovation project into assemblies. Although it does not provide all the details that are inherent to the Unit Price estimates, it is a faster way to develop information on costs. The relative accuracy can be ±15% (RREM,1997).

Square Foot and Cubic Foot estimates are cost estimating procedures used when only the size and proposed use for a renovation project are known. They can be used to estimate the cost of a renovation before the plans or even sketches are available. This will help to identify whether it is economically practical to continue, or to decide the best use for an existing structure. A Square Foot or Cubic Foot estimate is much faster to complete than a Unit Price or a Systems estimate. It also provides a relative accuracy of ±20% (RREM,1997).

The Square Foot estimate is considered the most appropriate for a general study of this type. For example, as an informal phone survey performed by the author revealed the average construction cost for typical reinforced concrete buildings in Puerto Rico is estimated to be around 51 dollars per square feet (550 dollars per square meter). Henceforth, the initial construction cost for a prototype reinforced concrete structure, C_0, is conveniently expressed in floor area units.

Order of Magnitude is the estimate used for planning future renovation projects at its very early stages, in order to decide whether to proceed with renovation. It requires the least amount of time to complete and provides the lowest level of estimate accuracy. An Order of Magnitude estimate for a building entails both its proposed use and the number of units involved such as units in an apartment building and hospital beds. The complexities of remodeling and renovation makes this type of estimate ineffective, unless costs from similar projects are available. The relative accuracy can be ±25% (RREM,1997).

2.3 Buildings and Contents

Repair and refurbishing cost information on buildings damaged during an earthquake is fairly scarce. Park and Wen (1987) used the data on only nine reinforce concrete buildings to calibrate the global damage index of the type used in this study (Chapter 3). Their calibration has placed the limit of repairable damage at $D_m = 0.4$. Correlating the calculated damage indices with the reported cost data from the 1985 Mexico City earthquake, Ang and De León established the repair and the replacement costs as a linear function of the damage index. The same held true for the loss of building contents (Ang and De León, 1995a). Recently, FEMA researchers used the inventory information from California to arrive at the same conclusions (Kircher et al. 1997).

In equation form, the repair cost for a building may be given by:

$$C_R = (1 + \rho_t) C_0 D_m \qquad ; 0 \leq D_m < 0.4 \tag{2.1}$$

where ρ_t is the total repair-to-initial cost factor given by:

$$\rho_t = \rho_o + \rho_d + \rho_e + \rho_c \tag{2.2}$$

For a damage index grater than 0.4, C_R becomes the replacement cost. The replacement cost function will be presented later in this section. Each of the ρ_t components are explained next.

In planning and estimating repair and remodeling projects, many factors may affect the project cost beyond the basic material and labor. Work-schedule coordination between trades frequently becomes difficult, and work-area restrictions can lead to subcontractor quotations with start-up and shut-down costs exceeding the cost of the specified work. The ordinary repair/remodeling factor, ρ_o, represents the cost ordinarily associated with the loss of productivity in any repair and remodeling project. Its major components are described as follows (RREM,1997).

- In actual construction a trade-off produced by cutting and patching can often lead to an economical balance. For example, to remove entire walls rather than create new door and window openings. Substitutions for materials that are no longer manufactured may be expensive. Piping and duct work runs may not be as straight as in new construction, and wiring may have to be snaked through walls and floors. The minimum and maximum percentages to be added to construction costs are 5% and 14%. There are no reasons why this cost component should be any different for earthquakes. Consequently, an average value of 9.5% is used in this study.
- Technics used to protect the non-construction areas from dust and noise might alter the usual construction methods. The minimum and maximum percentages to be added to construction costs are 3% and 15%. Because this cost component is only a function of the remodeling process itself, the average value of 9% should be equally applicable to earthquake environments.
- Shoring and bracing are used, when necessary, to support the building while structural changes are being made. This also includes the allowance for temporary storage of construction materials on above-grade floors. The minimum and maximum percentages to be added to the overall construction costs are 7% and 17%. Shoring and bracing cost component will be highly dependent on the level of damages sustained by the building because of the earthquake. As this is not clearly a normal remodeling environment where the

damages are rarely present, the maximum value of 17% is adopted for this study.

- The movement and material handling restriction that could exist in a project may have a costly influence on the final cost of the repair and remodeling project. Examples of this are low capacity elevators and stairwells, which may be the only access to the upper floors of a multistory building. The minimum and maximum percent to be added to construction costs are 2% and 13%. This cost component will be highly sensitive to the type of damages sustained after an earthquake. For example, elevators may be unavailable or the use of stairwells may be restricted. Consequently, the maximum value of 13% will be used for the movement and material handling.
- The workers would be required to work in limited spaces and this might entail using new equipment which might not be as productive as the traditional one. The minimum and maximum percent to be added to construction costs are 2% and 13%. After an earthquake, the access to many areas may be restricted by debris, displaced components, and shoring. This is specially true when the damages to the building are extensive. Consequently, the maximum value of 13% is selected for this study.
- Protection of existing work from vandalism or possible damage during ongoing construction, will almost always be required. The minimum and maximum percent to be added to construction costs are 4% and 12%. This factor is not

earthquake dependent in most cases. The average value of 8% is used in this study.

Adding all the percentage stated above will result in ρ_o = 70%.

The site demolition and cleanup factor, ρ_d, represents functions that in contrast to conventional work (excavation, site utilities, and pavement) are most crucial to remodeling projects. Demolition in commercial renovation may be divided into three phases. First, the actual dismantling of the existing structures/substructures, including labor and equipment. Second, handling the debris. This includes the transport of material to an on-site container or truck, and may include the installation and rental of a trash chute. Third, hauling the garbage to an approved dump site. According to the Means Repair and Remodeling Cost Data (RRCD, 1998) the cost associated with a demolition of a concrete building is \$ 0.32/ft^3 (\$11.30/m^3). Assuming an average story height of 12 feet, this factor become \$3.84/ft^2 (\$41.33/m^2). Multiplying this value by 0.88 which is the conversion factor for Puerto Rico (National Construction Estimator, 1991) and dividing by the initial construction cost C_0 = \$550/m^2, one can obtain ρ_d = 7% which is the value used in this study.

The engineering factor, ρ_e, represents the cost of inspection and testing required early in planning for any repair and remodeling project. Its values are dependent on the dynamics of how various engineering tools (building plans, visual inspections, and testings) are utilized. Therefore, although this factor is easy to evaluate on a building to building basis, it cannot be reasonably quantified in a global sense. Nevertheless, in lieu of a more exact analysis, an engineering factor of 15% is assumed. Lower ρ_e values of 8-10 percent may be more appropriate when accurate building plans are in hand. However, the difficulty in obtaining such plans is a documented problem for older buildings in Puerto Rico.

The catastrophe factor, ρ_c, refers to the increase in labor and material costs in the aftermath of a natural disaster such as an earthquake. For the same reason that gasoline prices increase during an energy crisis when demand is high and supplies are limited, construction costs may also increase during a catastrophe. Most states have emergency cost freezing laws in place that aim to maintain the prices of the basic products of prime necessity somewhat. However, beyond a short recovery time early on, the effectiveness of these measures is questionable at best. For the most part, state laws are motivated more with providing temporary shelter and food than long term reconstruction needs.

In Puerto Rico, Price Regulation No. 11 (Reglamento de Precios Número 11) from the Department of Consumer Affairs (Departamento de Asuntos del Consumidor-DACO) gives the agency head wide range of powers to freeze prices. However, it also allows for motions to grant exceptions, and the exceptions are often granted. During hurricane Hugo, for example, the cost freeze was in effect for four months while the price of plywood, the main component of most damage wood houses, rose by more than 38%. Assuming similar increases in about half the building materials, a cost increase of about 20% for construction materials is thought reasonable for this study. This is consistent with the newspaper accounts from the most recent hurricanes (Luciano, 1996, Valdivia, 1995, Torres, 1995). Using the average 35/65 labor-to-material ratio, the 20% price increase for materials will give an increase of 13% in overall building costs. As for labor costs, one should consider the scarcity of labor, the likelihood of bringing some in from neighboring areas, the housing for out of area workers, and the emergency overtime work schedule expected in these cases. R.S. Means handbook (RREM, 1997) recommends a minimum of 5% and a maximum of 30% to be added to the construction cost as a result of overtime in everyday remodeling and repair projects. The maximum 30% increase in overall costs due to labor in catastrophes is therefore thought reasonable. Henceforth, adding the material and labor costs together, a ρ_c value of 43% is obtained.

Calculating the ρ_t value for this study:

$$\rho_t = 70\% + 7\% + 15\% + 43\% = 135\% = 1.35$$

and Equation 2.1 can be rewritten as:

$$C_R = 2.35\, C_0 D_m \qquad ; 0 \leq D_m < 0.4 \tag{2.3}$$

As for the replacement costs, the only component of the total repair-to-initial cost factor that prevails is the site demolition and cleanup factor, thus:

$$C_R = (1 + \rho_d)\, C_0 \qquad ; D_m > 0.4 \tag{2.4}$$

or

$$C_R = 1.07\, C_0 \qquad ; D_m > 0.4 \tag{2.5}$$

The loss of contents for a building is a weighted function of the damage index multiplied by the content's value (C_c). This will vary linearly for intermediate (repairable) damage; thus,

$$C_C = \omega_c C_c D_m \tag{2.6}$$

The content type factor, ω_c, is assigned values from 0.5 (Kircher et al., 1997) to 1 (Ang and De León, 1995b). The model assumes that there will never be a total loss of content. For most buildings, and in lieu of an exact analysis, a C_c value of $0.5C_0$ may be reasonable (Kircher et al., 1997, Ang and De León, 1995b). Then at a minimum:

$$C_C = \frac{1}{4} C_0 D_m \tag{2.7}$$

which is the formula used in our examples.

2.4 Human Capital

Any procedure to account for the loss of human capital will be tri-fold. First, the number of people who would be present in the building at the time of an earthquake must be estimated. Next, the percentage of those affected and the cost associated with each death or injury must be quantified.

To estimate the number of people present during an earthquake, the choice was made to adopt the load cell methodology used in specifying the live loads. This is highly desirable for two reasons. First, the number of persons accounted for by the live load model does not significantly deviate in characteristics from that expected during an earthquake. Second, any approximation introduced because of such an adaptation will be far more desirable than going through the scarce and highly questionable data on buildings surveyed after an earthquake. This is specially true for zones of limited seismic activity. For example, except for the peak intensity and some pictorials there is no other information on the last major earthquake in Puerto Rico in 1918.

The existing live load models divide the floor area, A, into a number of load cells, λ. A widely used expression for λ, which is the basis of the ASCE specification for live loads is due to Ellingwood and Culver (1977), where:

$$\lambda = \sqrt{\frac{A-155}{6.3}} \tag{2.8}$$

The number of people, N_D, assigned to each load cell varies with the type of occupancy. Using reported data from various live load surveys, Chalk (1979) generated the means and standard deviations for extraordinary live loads that can be expected over the lifetime of a building. Table 2.1 lists N_D-statistics derived from that study. For the purposes of this investigation, the characteristic design N_D value is calculated at 90 percent fractile assuming a normal distribution. The use of 90% fractile instead of the mean (which is the 50% fractile after all) places a higher priority on the life safety consistent with the well established practices by the building codes (Cornell and Corotis, 1969, Ellingwood, 1977; Chalk, 1979). The number of persons for a building will then simply be $\lambda\ N_D$.

Published literature contains less information on deaths and injuries than that on damages to buildings. The ATC-13 report from the Applied Technology Council (ATC, 1985) is one of those few documents that presents data correlating the damage index and people injuries. This data is reproduced in Table 2.2. The severities of events ranged from

Table 2.1: People load statistics

Occupancy	Mean	Variance	Characteristic Value (N_D)	
			90% Fractile	95% Fractile
Offices	4	2	7.29	8.65
Residential	3	2	6.29	7.65
Hotels	3	1	4.65	5.33
Retail Stores	4	2	7.29	8.65
Schools	4	2	7.29	8.65

the minor injuries, not requiring hospitalization, major injuries to instantaneously dead or mortally wounded.

The ATC-13 data was thought appropriate for this study. Although most of their recordings are from California, other states as well as the Commonwealth of Puerto Rico share similar building codes, quality of construction, health services, emergency services, access road networks, and life styles. The fatality rate, R_f, is therefore defined in such as to correspond to the last column of Table 2.2. Figure 2.2 shows the result of a regression analysis with the damage index as a semi-log function of R_f. In algebraic terms

$$R_f = e^{11.2(D_m - 1.12)} \tag{2.9}$$

The fraction injured is calculated from the fraction dead by multiplying R_f with a severity factor, μ_i. Four casualty severities are defined for the purposes of this investigation. The coefficient for each severity case is calculated from Table 2.2. Severity 1 represents minor injuries, henceforth: $\mu_1 = 30$. Severities 2 and 3 represent major injuries, non-disabling and disabling, respectively. Assuming that one fourth of all serious injuries are disabling, $\mu_2 = 3$ and $\mu_3 = 1$. Severity 4 represents fatality where by definition: $\mu_4 = 1$. The values as defined will apply to those cases in which $D_m \leq 0.8$. For $D_m = 1$, $\mu_1 = 2$, $\mu_2 = 1.5$, $\mu_3 = 0.5$, and $\mu_4 = 1$. For D_m between 0.8 and 1, the values of severities coefficient are linearly interpolated.

Table 2.2: Injury and death

Damage	Fraction Injured		Fraction Dead
	Minor	Serious	
0	0	0	0
0.05	3/100,000	1/250,000	1/1,000,000
0.05	3/10,000	1/25,000	1/100,000
0.20	3/1,000	1/2,500	1/10,000
0.45	3/100	1/250	1/1,000
0.80	3/10	1/25	1/100
1	2/5	2/5	1/5

Once the number of people affected is estimated, the loss of human capital factor, C_H, can be calculated as follows:

$$C_H = R_f(\lambda N_D) \sum_{i=1}^{4} \mu_i C_{hi} \tag{2.10}$$

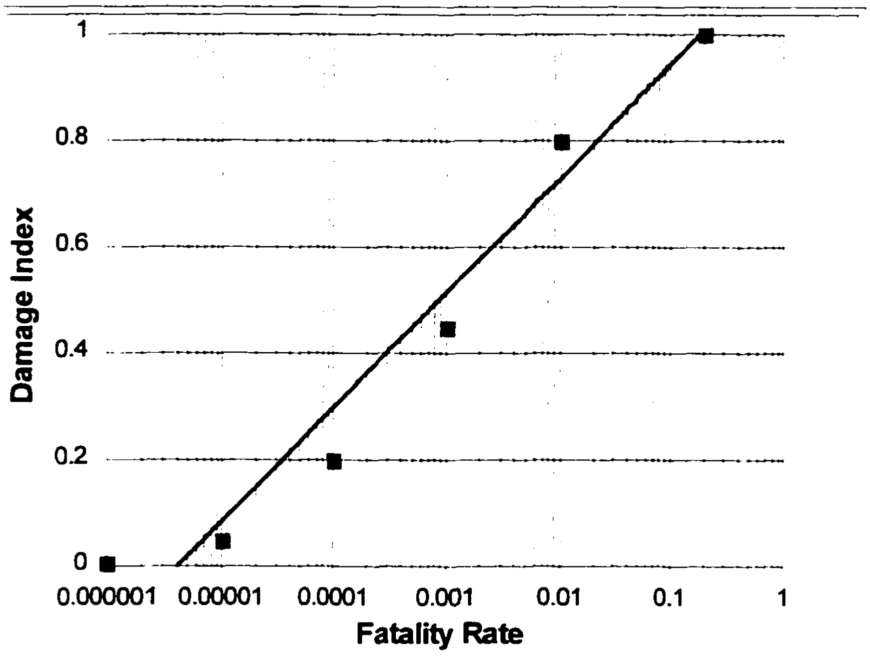


Figure 2.2: Fatality rate using data from ATC-13

where C_{h_i} is the fatality or injuries cost per person unit. There are several factors involved in estimating C_{h_i}. These factors will be discussed as they apply to Puerto Rico but could be easily adjusted for any other area.

From the data furnished by the Corporación del Fondo del Seguro del Estado and Junta de Planificación de Puerto Rico (Corporación del Fondo del Seguro del Estado, 1997):

$$C_{h1} = \$200$$

$$C_{h2} = \$3{,}742$$

These values are based on the average cost of emergency treatment and the hospitalization for non-disabling injuries, respectively. C_{h2} in particular was calculated by dividing the

$76,900,000 paid in non-disabilitating injuries for the year 1997 by the number of people (20,550) affected.

The calculation for C_{h3} is far more complicated because it involves possible costs of retraining as well as pay cut over the years remaining in service. In a generic approach, it may be beneficial to set C_{h3} as a weighted function of C_{h4}. It is not unusual to set $C_{h3} = C_{h4}$ (Ang and De León, 1995a). However, because our data indicates that less than 40 percent of accident related disabilities are what may be considered total disabilities (Corporación del Fondo del Seguro del Estado,1994), it was decided to set $C_{h3} = 0.4\, C_{h4}$

The cost of a human fatality, C_{h4}, is based on the average income of the people most likely to populate the building at the time of an earthquake and their age. In equation form,

$$C_{h4} = (\,\textit{average income of building population}\,)\,(\,\textit{average work years left}\,) \qquad \textbf{(2.11)}$$

In the case of residential building, the average income should be taken as the gross per capita income, because the family is a sample of the population (workers and non-workers). The Social Security Administration recognizes a retirement age of 65. The latest Census Bureau data indicates a median age of 35 years for Puerto Rico (Census of Population, 1990). Thus, taking the gross per capita income of 8,119 dollars (Puerto Rico Planning Board, 1997), for residential buildings:

$$C_{h4} = \$8{,}119\,(\,65 - 35\,) = \$243{,}570$$

For occupancies other than residential, the population may be much less varied. In manufacturing, for example, there are very few visitors from outside. The average salary of the employees and their average age minus the retirement age should then be inserted into Equation 2.11 resulting in much higher costs than those of residential. For services, on the other hand, the employees will be treated as in manufacturing while the general population may represent the customers. For example, if you have a 4 to 1 customer to worker ratio, the average income of building population (AIBP) can be calculated as:

$$AIBP = 0.8\,(\mathit{gross\ per\ capita\ income}) + 0.2\,(\mathit{average\ worker\ salary\ for\ the\ business})$$

Other variations to the model may be considered on a case to case basis.

2.5 Economic Loss

The methodology that will be used to measure the economic impacts of an earthquake is the Input-Output (I-O) analysis. The I-O model was originally designed by Nobel prize laureate Wassily Leontief in 1941. It is part of the family of econometric models widely used in natural resources. The advantage of this type of model is that one can specify the constraints of an economic system and then measure the impacts given those constraints. The problem studied here is how the availability of the capital stock affected by an earthquake can alter the output or valued added for the economy.

The I-O model has already been used with some success to calculate the economic impacts of an earthquake in the San Juan metropolitan area (Zalacaín, 1985). However, this is the first time that an Input-Output model is used to calculate the economic loss associated with one building. The model uses a direct plus an indirect requirement matrix, called the Leontief inverse matrix, to relate the gross output of an economic sector to the sector output available for the final consumption.

In order to evaluate the economic loss factor, four distinct components are identified. These are rent, operating expenses excluding rent and payroll, the payroll, and gross income. The rent factor, C_{Er}, is the main component considered for residential buildings. The operating expense factor, C_{Ee}, is calculated by setting a row vector **E** based on the intake from different economic sectors and multiplying it by the appropriate column in the Leontief inverse matrix **B**. The payroll factor, C_{Ep}, is calculated much the same way, because it is considered as an expense. In fact, the row vector for the payroll component, **P**, is set up here by using the same weight scale as in **E**. The gross income factor, C_{Eg}, on the other hand, is calculated by first seeking an income vector, **G**, and then having it multiplied by the appropriate row from the **B** matrix. In general the expense, payroll, and gross income vectors will be obtained by getting the total amount of money corresponding to expenses, payroll, and gross income from the client, and then multiplying these amounts by the respective unit vector. The discussion on how to obtain this unit vector will be presented later on section 2.9. Then, the gross income, expense, and payroll vectors will have as row or columns as economic sectors:

$$G = \begin{Bmatrix} g_1 \\ g_2 \\ \vdots \\ g_n \end{Bmatrix} \qquad E^t = \begin{Bmatrix} e_1 \\ e_2 \\ \vdots \\ e_n \end{Bmatrix} \qquad P^t = \begin{Bmatrix} p_1 \\ p_2 \\ \vdots \\ p_n \end{Bmatrix} \qquad \textbf{(2.12)}$$

Assuming a business occupant to be from the economic sector k, the following equation are obtained:

$$C_{Ee} = \sum_{i=1}^{n} e_i\, b_{ik}$$

$$C_{Ep} = \sum_{i=1}^{n} p_i\, b_{ik} \qquad \textbf{(2.13)}$$

$$C_{Eg} = \sum_{j=1}^{n} b_{kj}\, g_j$$

where n is the number of economic sectors.

The economic loss factor is shown to be a quadratic function of damage index. The initial observation was based on the cost data from the 1985 Mexico City earthquake (Ang and De León, 1995b). It was further verified by the FEMA researchers based on the California information inventory (Kircher, et al., 1997). The fact is that most buildings reporting 20% in damages will continue to function near full capacity as some activities can always be relocated to other areas. Even at 40% damages, it has been pointed out that operation can continue with relocation of some functions, while the repair process is in progress (ATC-13, 1985).

In equation form:

$$C_E = (C_{Er} + C_{Ee} + C_{Ep} + C_{Eg})\, T_R\, D_m^2 \qquad \textbf{(2.14)}$$

where T_R is the period of reconstruction or relocation. To calculate the total economic loss factor for the building, one will only need to sum the C_E's for all the building tenants.

The remainder of this chapter focuses on the basic definitions and qualification of terms significant to the proper use of Equation 2.13. Coverage will include a review of the I-O analysis since it may not be well known to many engineers. The chapter concludes with a numerical example on how the total damage cost of a building can be evaluated for an earthquake event in Puerto Rico.

2.6 Input-Output Analysis

Input-Output analysis is a method of systematically quantifying the mutual interrelations among the various sectors of a complex economic system (Leontief, 1986). In practical terms, the economic system to which it is applied may be as large as a nation or even the entire world economy, or as small as the economy of a metropolitan area or even a single enterprise. In all instances the approach is essentially the same.

The structure of each sector's production process is represented by an approximately defined vector of structural coefficients that describe in quantitative terms the relationship between the inputs it absorbs and the output it produces. The interdependence among the sectors of the given economy is described by a set of linear equations expressing the balances between the total input and the aggregate output of each commodity and service produced and used in one or several periods of time. The technical structure of the entire system can accordingly be represented concisely by the matrix of technical Input-Output coefficients of all its sectors. This matrix is well known by economists as the Input-Output matrix, Input-Output table, or transaction matrix.

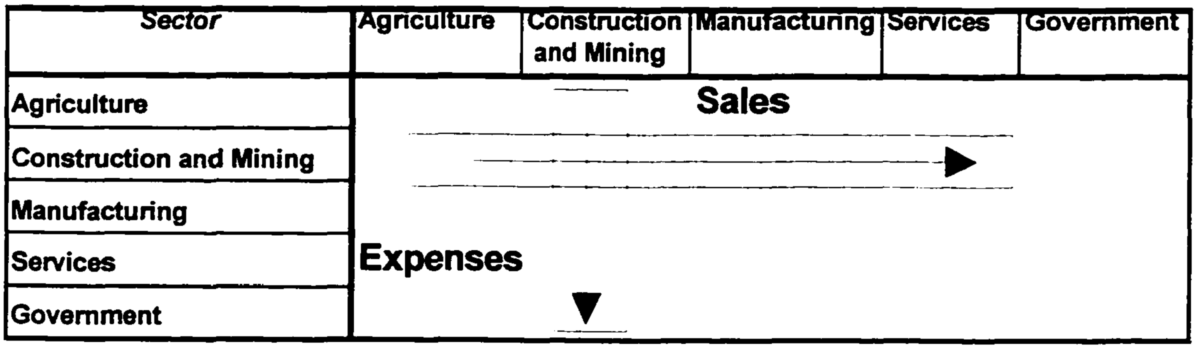
The I-O matrix has three major components: intermediate demands, final demand and value added. The intermediate demands represent buying and selling transactions occurred during each industry's productive process and the origin of the goods and services consumed. This becomes one of the focal points in this study. The final demand, integrated by personal and government consumption, investment and nets import, shows the final use of the goods and services produced. The value added are the charges for the productions of goods and services, which includes employment compensations, companies benefits, depreciation (capital consumption), paid net interest, subsidies, and indirect contributions. These charges need to be subtracted from the total production.

Table 2.3 represents the Puerto Rico local transaction's matrix, grouped in five sectors, for the period between 1986 and 1987 as presented by Puerto Rico Planning Board (1987). Just the intermediate demand is shown. That is because of the stated purpose to identify the local impact or how the reductions in the output of some sectors may affect the overall economy. The quantities shown in this table are in thousands of dollars. Any subsequent reference to the I-O matrix shall be interpreted as the one in its condensed form.

2.7 Input-Output Matrix

An Input-Output matrix describes the flow of goods and services among all the individual sectors of a national economy over a stated period of time, say, a year. To prepare this matrix the economy is divided into a number of sectors (industries) based usually on a census of production and other national statistical classifications (Connor, 1975). In Puerto Rico, this matrix consists of 94 sectors which can be contained in five group sectors for an easy understanding of the system (Table 2.3). All the sectors defining the economy are shown in rows and columns. The matrix is square because it has as many columns as rows.

Figure 2.3 shows a schematic sketch of an I-O matrix. Here, a row represents the products and services sold by the group sector named for that row (output-total sales). A column, represents the current products and services delivered to a certain group sector by all group sectors (input-total expenses). In short, the cells in this matrix describe all transactions among all local sectors of a given economy in certain period of time.



Sector	Agriculture	Construction and Mining	Manufacturing	Services	Government
Agriculture					
Construction and Mining					
Manufacturing					
Services					
Government					

Figure 2.3: Input-Output Matrix

Because of the inter-relationship between different sectors of an economy, a change in the final demand for the products of one sector causes ramifications throughout the system which change not only the outputs of that sector but also those of most or perhaps all of the other sectors of the economy. One of the main aims of the Input-Output analysis is to study these changes.

In the I-O example of Table 2.3, the sectors representing the Puerto Rico accounting system with their total annual output from a 1986-1987 survey are Agricultural ($369,989,000), Construction and Mining ($488,561,000), Manufacturing ($4,396,062,000), Services ($9,159,261,000), and Government ($228,251,000). The rest of the rows of the table illustrate, in the same way, the allocation of outputs from other sectors.

The figures entered in each column of the table describe the input structure of the corresponding sector. To produce an output amount of $369,989,000, Agriculture absorbed $8,936,000 of its own products, $2,201,000 from Construction and Mining, expended $110,958,000 on manufactured goods, $22,848,000 on Services, and pay out $1,782,000 to the Government. Adding all the expenses results in the total local intermediate consumption. Then, to obtain the local production for a sector, the imports and the value added have to be combined to the total local intermediate consumption. The last four lines of Table 2.3 quantify these terms.

The final demand for the products of a sector generates indirect as well as direct income effects on the economy as a whole. The relationship between the initial spending and the total effect generated by the spending is known as the impact of the sector on the economy as a whole (Connor, 1975). The local production for each sector will be used to define the technical coefficients for the I-O model adopted in this study. The general procedure is discussed in the next section.

2.8 Technical Coefficients

To generate an I-O mode some assumptions related to the behavior of its components have to be made. First, each industry produces its own characteristic product and not another kind of product (Puerto Rico Planning Board, 1984). For example, the plastic industries just produce plastics products. Second, each product is uniform: all the plastics products are the

Table 2.3: Local transactions matrix for 1986-1987 (in thousands of dollars)

Sectors	Intermediate Demand					
	Agriculture	Const. & Mining	Manufac.	Services	Government	**Total**
Agriculture	8,936	9,312	331,826	14,263	5,652	369,989
Construction & Mining	2,201	32,478	184,177	258,074	11,631	488,561
Manufac.	110,958	436,054	2,757,828	865,990	225,232	4,396,062
Services	22,848	542,773	3,354,688	4,434,576	804,376	9,159,261
Government	1,782	4,464	36,127	178,165	7,713	228,251
Total Local Intermediate Consumption	146,725	1,025,081	6,664,646	5,751,068	1,054,604	14,642,124
Imports	86,397	665,813	7,075,747	1,499,215	220,952	9,548,124
Value Added	415,479	445,767	9,509,995	12,788,867	3,124,267	26,284,375
Local Production	648,601	2,135,661	23,250,388	20,039,150	4,399,823	50,474,623

same. Finally, in any period of time each input contribute to the production in a fixed ratio, which is independent of the level of production. For example, if we have previously estimated that the furniture industries absorb 10 tons of wood and 50 tons of steel to produces 100 chairs, it will need 0.1 tons of carbon and 0.5 tons of steel per chair, no matter how many chairs it builds in a determined period of time.

The quantity of the output of sector *i* absorbed by sector *j* per unit of its total output is the technical coefficient a_{ij}. That is the input coefficient of product of sector *i* into sector *j*. A technical coefficient can be obtained through the transaction matrix for all the sectors. Let the national economy be subdivided into $n + 1$ sectors; *n* industries, that is, producing sectors and the $n + 1^{th}$ final demand sectors. The physical output of sector *i* is usually represented by x_i while the symbol x_{ij} stands for the amount of the product of sector *i* absorbed, as its input, by the sector *j*. Then:

$$a_{ij} = \frac{x_{ij}}{x_j} \tag{2.15}$$

The quantity of the product of sector *i* delivered to the final demand sector x_{in+1} is usually identified in short as y_i.

A complete set of the input coefficients of all sectors of a given economy arranged in the form of a rectangular table, corresponding to the Input-Output table of the same economy, is called the *structural matrix* of that economy (Leontief, 1985). This matrix can tell the quantity of input required by each industry to produce the value of one dollar of product in any given industry. In other words, if we visualize a matrix with suppliers in the rows and buyers in the columns, the structural matrix can identity the needs of the buyers from the suppliers to exhibit the value of one dollar of their products. To clarify, let us suppose an economy with only five sectors, which are defined in Table 2.4. These sectors are Agriculture, Construction and Mining, Manufacturing, Services, and Government, with x_1, x_2, x_3, x_4, and x_5, representing the total outputs respectively. The final demands for these sectors are represented by y_1, y_2, y_3, y_4, and y_5, respectively while x_{11}, x_{12}, x_{13}, x_{14}, and x_{15}, are used to illustrate the internal flows within the economy. Notice that the final demand refers to the total value of goods and services consumed by the economic sectors during a stated period of time, and it is distributed between personal consumption, the investments, the exports and the government consumption. The final demand together with the intermediate demand constitutes the local production per industry. Total primary inputs are represented by z_1, z_2, z_3, z_4, and z_5. These quantities are called primary because they are not part of the output of current production. The primary inputs address payments in the form of imports, indirect taxes, subsidies, wages, salaries, profits and interests, corresponding to the rows of imports and value added in Table 2.3.

Thus, the various flows in this system may be represented by the following system of linear equations:

$$\begin{aligned} x_1 &= x_{11} + x_{12} + x_{13} + x_{14} + x_{15} + y_1 \\ x_2 &= x_{21} + x_{22} + x_{23} + x_{24} + x_{25} + y_2 \\ x_3 &= x_{31} + x_{32} + x_{33} + x_{34} + x_{35} + y_3 \\ x_4 &= x_{41} + x_{42} + x_{43} + x_{44} + x_{45} + y_4 \\ x_5 &= x_{51} + x_{52} + x_{53} + x_{54} + x_{55} + y_5 \end{aligned} \qquad \textbf{(2.16)}$$

Table 2.4: Commodity flows by sector of origin and destination

Inputs	Agriculture	Const. & Mining	Manufact.	Services	Government	Total Final Demand	Total Output
Agriculture	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	y_1	x_1
Const. & Mining	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	y_2	x_2
Manufact..	x_{31}	x_{32}	x_{33}	x_{34}	x_{35}	y_3	x_3
Services	x_{41}	x_{42}	x_{43}	x_{44}	x_{45}	y_4	x_4
Government	x_{51}	x_{52}	x_{53}	x_{54}	x_{55}	y_5	x_5
All Inputs Primary	z_1	z_2	z_3	z_4	z_5		
Total Inputs	x_1	x_2	x_3	x_4	x_5		

The inter-industry technical coefficients are given as symbols in Table 2.5, which in Input-Output terminology is usually referred as the **A** matrix. Where, as explained above, the technical coefficients are calculated by dividing each figures in the columns by the corresponding column totals or total inputs, therefore from Table 2.4 and Table 2.5:

$$a_{11} = \frac{x_{11}}{x_1} \quad a_{12} = \frac{x_{12}}{x_1} \quad a_{13} = \frac{x_{13}}{x_3} \quad a_{21} = \frac{x_{21}}{x_1} \ldots. \qquad \textbf{(2.17)}$$

Table 2.5: Inter-industry technical coefficients in symbolic form (A matrix)

Sector	Agriculture	Const. & Mining	Manufact.	Services	Government
Agriculture	a_{11}	a_{12}	a_{13}	a_{14}	a_{15}
Const. & Mining	a_{21}	a_{22}	a_{23}	a_{24}	a_{25}
Manufact.	a_{31}	a_{32}	a_{33}	a_{34}	a_{35}
Services	a_{41}	a_{42}	a_{43}	a_{44}	a_{45}
Government	a_{51}	a_{52}	a_{53}	a_{54}	a_{55}

Then, solving Equation 2.17 for the x_{ij}'s and substituting in Equation 2.16, the following system is obtained:

$$\begin{aligned}
x_1 &= a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + a_{14}x_4 + a_{15}x_5 + y_1 \\
x_2 &= a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + a_{24}x_4 + a_{25}x_5 + y_2 \\
x_3 &= a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + a_{34}x_4 + a_{35}x_5 + y_3 \\
x_4 &= a_{41}x_1 + a_{42}x_2 + a_{43}x_3 + a_{44}x_4 + a_{45}x_5 + y_4 \\
x_5 &= a_{51}x_1 + a_{52}x_2 + a_{53}x_3 + a_{54}x_4 + a_{55}x_5 + y_5
\end{aligned} \qquad \textbf{(2.18)}$$

Moving the x_i to the left-hand side and re-grouping:

$$\begin{aligned}
(1-a_{11})x_1 - a_{12}x_2 - a_{13}x_3 - a_{14}x_4 - a_{15}x_5 &= y_1 \\
-a_{21}x_1 + (1-a_{22})x_2 - a_{23}x_3 - a_{24}x_4 - a_{25}x_5 &= y_2 \\
-a_{31}x_1 - a_{32}x_2 + (1-a_{33})x_3 - a_{34}x_4 - a_{35}x_5 &= y_3 \\
-a_{41}x_1 - a_{42}x_2 - a_{43}x_3 + (1-a_{44})x_4 - a_{45}x_5 &= y_4 \\
-a_{51}x_1 - a_{52}x_2 - a_{53}x_3 - a_{54}x_4 + (1-a_{55})x_5 &= y_5
\end{aligned} \qquad \textbf{(2.19)}$$

This equation system can be written in matrix form as:

$$\begin{bmatrix} (1-a_{11}) & -a_{12} & -a_{13} & -a_{14} & -a_{15} \\ -a_{21} & (1-a_{22}) & -a_{23} & -a_{24} & -a_{25} \\ -a_{31} & -a_{32} & (1-a_{33}) & -a_{34} & -a_{35} \\ -a_{41} & -a_{42} & -a_{43} & (1-a_{44}) & -a_{45} \\ -a_{51} & -a_{52} & -a_{53} & -a_{54} & (1-a_{55} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \\ y_5 \end{bmatrix} \qquad \textbf{(2.20)}$$

or using matrix algebra notation, the whole system may be written in abbreviated matrix form:

$$(I - A)x = y \qquad \textbf{(2.21)}$$

Now in Input-Output analysis the vector of *y*'s, i.e., vectors of final demand, is usually assumed to be given, and the problem is to determine the vector of outputs, i.e., the *x*'s. Thus, the solution to Equation 2.21 above is:

$$x = (I - A)^{-1} y \qquad \textbf{(2.22)}$$

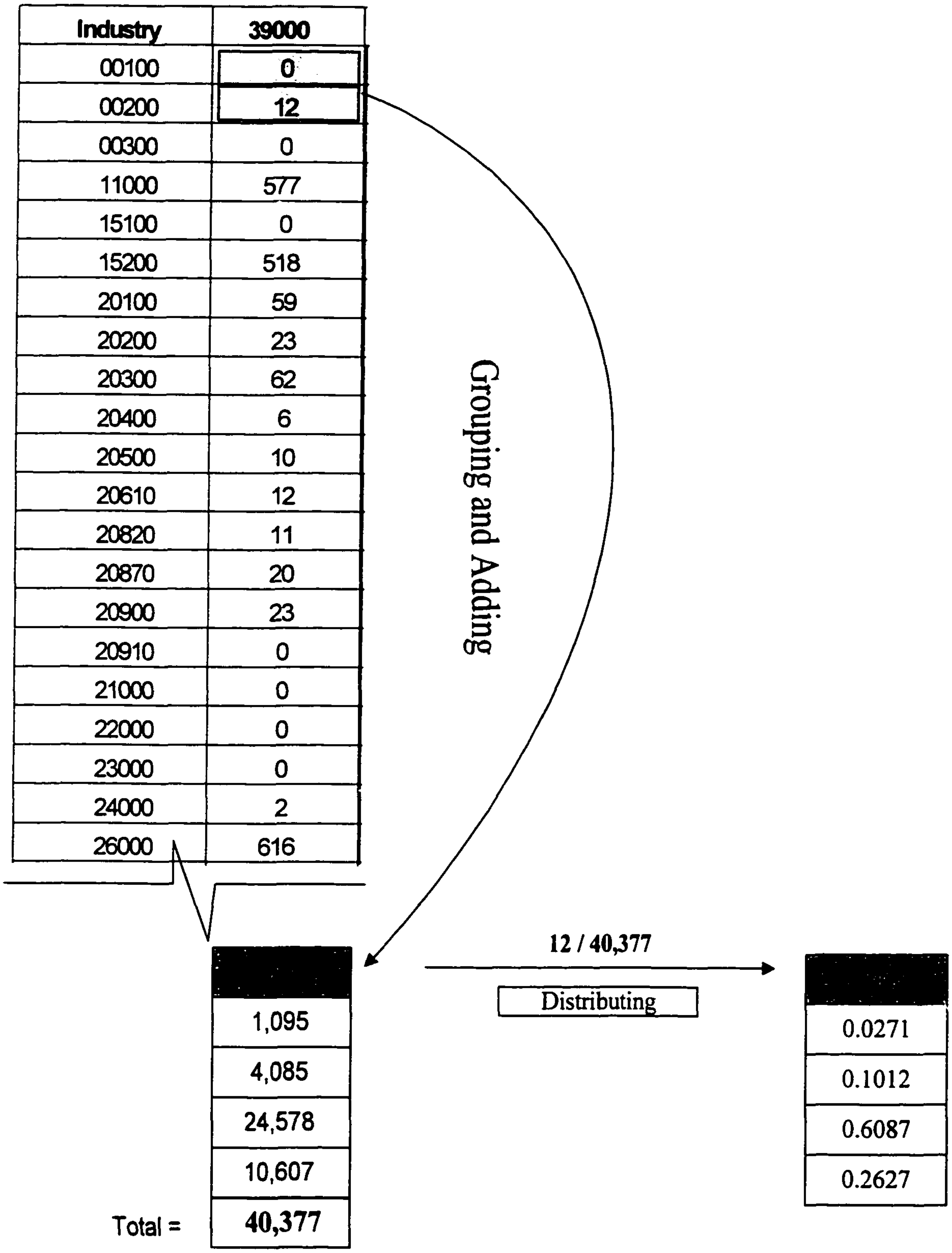
Where $(I - \mathbf{A})^{-1}$ is the inverse of the matrix $(I - \mathbf{A})$, or the Leontief inverse matrix, **B**. The problem then is to determine the **B** matrix. Finally, the **B** matrix in a general term will be equal to:

$$[B] = \begin{bmatrix} (1-a_{11}) & -a_{12} & \dots & -a_{1n} \\ -a_{21} & (1-a_{22}) & \dots & -a_{2n} \\ \vdots & \vdots & & \vdots \\ -a_{n1} & -a_{n2} & \dots & (1-a_{nn}) \end{bmatrix}^{-1} = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2n} \\ \vdots & \vdots & & \vdots \\ b_{n1} & b_{n2} & \dots & b_{nn} \end{bmatrix}$$

The Input-Output data for Puerto Rico is available through the Puerto Rico Planning Board. The most recent **A** matrix from the 1986-87 Puerto Rican Survey was generated for the purposes of this study and is presented in Appendix A. Also included is the corresponding **B** matrix which is needed to solve Equation 2.22.

2.9 Weighting Vectors

The Puerto Rico economy, as stated above, is grouped in five sectors. Each group comprehends the union of the sectors which principal activity is similar. This mean, sectors that the final product is the same. Thus, the weighting vector has five elements. This weighting vector is established with the intake from the ninety-four different economic sectors adding each contribution from the Input-Output matrix and distributing it among the corresponding economic sectors. This is shown in Figure 2.4, where the values are in thousands of dollars. In the same figure, the industries classified as 00100 and 00200 are grouped in the agricultural sector (industry 3900). Adding the corresponding contribution, here, will result in $12,000. This amount, is then divided by the total sales for that sector, which is $40,377,000, resulting in 0.003. Thus, this number represents the weighting value for the agricultural sector. A similar procedure is followed for the remaining four sectors and for both the sales and the expenses. These vectors are presented in Appendix B, where each column represents Agricultural, Construction and Mining, Manufacturing, Services, and Government, respectively.



Industry	39000
00100	0
00200	12
00300	0
11000	577
15100	0
15200	518
20100	59
20200	23
20300	62
20400	6
20500	10
20610	12
20820	11
20870	20
20900	23
20910	0
21000	0
22000	0
23000	0
24000	2
26000	616

	1,095
	4,085
	24,578
	10,607
Total =	40,377

0.0271
0.1012
0.6087
0.2627

Figure 2.4: Generation of the weighting vectors

2.10 Numerical Example

The numerical example presented in this section is used to clarify further the methodology by which different cost damage functions are quantified. It should also help demonstrate the ripple effects of economic loss as calculated through I-O matrix. A two-story building with 20,000 ft^2 in floor area is selected. Different occupancy types considered are both floors residential, first floor commercial and second floor residential, both floors commercial, and both floors manufacturing.

- **Building and Content Cost**

From the floor area, it is possible to estimate the initial cost of the building, as follow:

$$C_0 = (51)(20000) = \$1{,}020{,}000$$

Using Equations 2.3 and 2.7 the repair and content cost are obtained:

$$C_R = (2.35)(1{,}020{,}000)D_m = 2{,}397{,}000D_m$$

$$C_C = (\frac{1}{4})(1{,}020{,}000) = 255{,}000D_m$$

- **Cost of Human Capital**

For this particular building, using the Equation 2.8, the number of cells is set as follows:

$$\lambda = \sqrt{\frac{20000-155}{6.3}} = 56.125$$

The following C_{h-l} values are used:

$C_{h-l} = \$243,570$ for residential, based on an AIBP = \$8,119

$C_{h-l} = \$360,390$ for businesses, based on an AIBP = \$12,013

$C_{h-l} = \$474,240$ for manufacturing, based on an AIBP = \$15,808

assuming an average of 30 work years left for building populations in all cases.

Having defined these quantities, the cost associated with the human capital is obtained using Equations 2.10, resulting in an exponential function of the damage index:

$$
\begin{aligned}
C_H &= R_f(56.125)(6)[(30)(200)+(3)(3,742)+(1)(97,428)+(1)(243,570)] \\
&= (120,631,932)\,e^{11.2(D_m-1.12)} \rightarrow \textit{For Residential } (N_D = 6) \\
C_H &= R_f(56.125)(7)[(30)(200)+(3)(3,742)+(1)(144,156)+(1)(360,390)] \\
&= (204,991,175)\,e^{11.2(D_m-1.12)} \rightarrow \textit{For Business } (N_D = 7) \\
C_H &= R_f(56.125)(7)[(30)(200)+(3)(3,742)+(1)(189,696)+(1)(474,240)] \\
&= (267,611,521)\cdot e^{11.2(D_m-1.12)} \rightarrow \textit{For Manufacturing } (N_D = 7)
\end{aligned}
$$

- **Economic Cost**

In the case of residential (apartments building) the economic loss is estimated from the loss of rental during the reconstruction or repair period. Informal call to Realtors Agencies reveal an average rent \$19.20 per ft^2 per year. Consequently, for a maximum reconstruction period of T_R years, the economic loss factor becomes:

$$C_E = C_{Er} A\, T_R\, D_m^2 = 19.2 A\, T_R\, D_m^2$$

To calculate the economic cost, for business and factory, the I-O vectors described in section 2.5 have to be generated for each occupancy type. These vectors were obtained from the data surveyed at the Mayagüez area. Only the gross income, expenses, and payroll from the selected economic sectors were required. Each amount was multiplied by the corresponding unit vector as discussed in section 2.5 The results are shown in Table 2.6. An average yearly rent equal to that of residential is assumed, although typical values are higher for businesses and lower for factories.

Thus, using the vectors shown in Table 2.6, the **B** matrix illustrated on Table A.2, and performing the calculation indicated by Equations 2.13 and 2.14 the economic loss factor for business occupancy type is as follows:

$$\begin{aligned}
C_{Er} &= 19.2 \\
C_{Ee} &= [0.1557\,(0.0020369) + 1.207\,(0.0176692) + 8.803\,(0.0691864) \\
&\quad + 59.18\,(1.3056254) + 4.313\,(0.0117788)] = 77.95 \\
C_{Ep} &= [0.0941\,(0.0020369) + 0.7294\,(0.0176692) + 5.321\,(0.0691864) \\
&\quad + 35.77\,(1.3056254) + 2.607\,(0.0117788)] = 47.11 \\
C_{Eg} &= [0.6261\,(0.0866464) + 9.185\,(0.3830911) + 83.16\,(0.2190238) \\
&\quad + 63.74\,(1.3056254) + 16.36\,(0.2514715)] = 109.12
\end{aligned}$$

Then, the total economy cost becomes,

$$C_E = 253.38\,\mathrm{T_R}\,A\,D_m^2 \quad \Rightarrow \text{For business}$$

Identical procedure can be used to obtain the economic loss factor for the factory occupancy type resulting in the following equation:

$$C_E = 68.71\,\mathrm{T_R}\,A\,D_m^2 \quad \Rightarrow \text{For Factory}$$

Table 2.6: Economic vectors ($/sq. ft)

Classification[1]	Business - *(7300)*			Factory - *(3900)*		
Sector	**G**	**E^t**	**P^t**	**G**	**E^t**	**P^t**
Agriculture	0.6261	0.1557	0.0941	1.250	0.0233	0.0086
Mining and Construction	9.185	1.207	0.7294	0.7281	2.102	0.7780
Manufacturing	83.16	8.803	5.321	19.08	7.838	2.901
Services	63.74	59.18	35.77	5.235	47.16	17.46
Government	16.36	4.313	2.607	0.9389	20.35	7.534
Total Amount[2]	173	73.66	44.52	27.23	77.48	28.68

1. The SIC numbers are given in brackets.
2. From the cost survey in the Mayagüez area.

●Total Damage Cost

Figures 2.5 and 2.6 show the effects of changing the occupancy type for the prototype building. The computation is based on the addition of the building and content cost, the economic cost, and the human capital cost, yielding the following equation:

$$C_d = C_R + C_C + C_E + C_H \tag{2.22}$$

The total damage cost is evaluated in a deterministic fashion, varying the damage index from 0.2 to 0.5. Although, a building is assumed lost at 0.4 damage index, most of the damage cost functions would vary up to a damage index of 1. This is illustrated here by showing the change in total damage cost from 0.4 to 0.5 damage indices. Notice how a change in the reconstruction period alters the cost associated to the different occupancies.

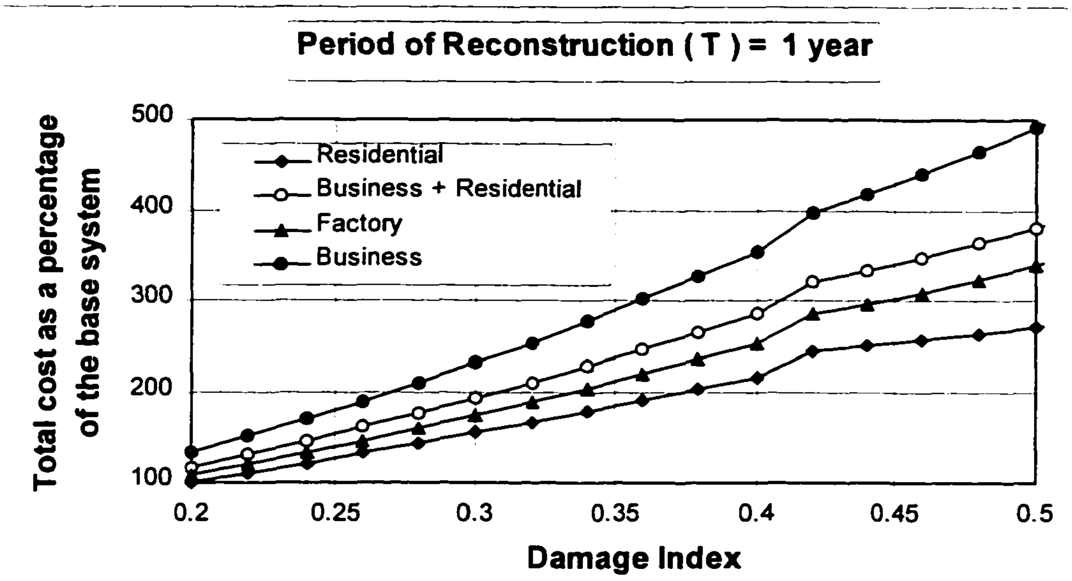


Figure 2.5: Total cost for different occupancies type with constant reconstruction period of 1 year.

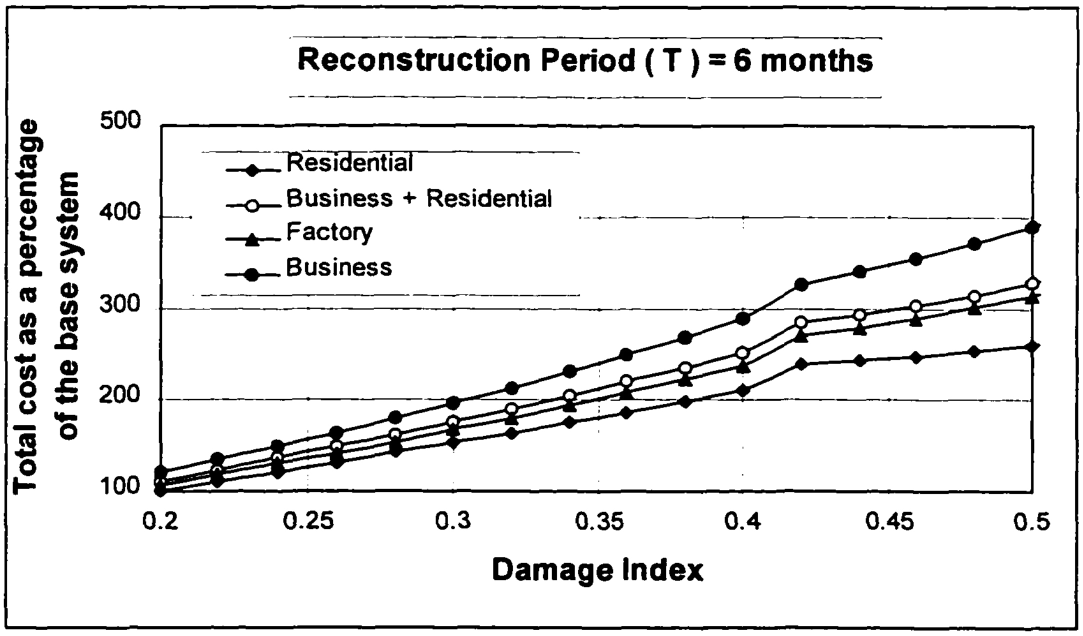


Figure 2.6: Total cost for different occupancies type with constant reconstruction period of 6 months.

CHAPTER 3

EVENT PARAMETERS

3.1 Introduction

When upgrading an existing building for earthquakes, the decision making process is influenced by a perceived loss of property, which may or may not materialize, as well as the immediate cost to attain what aims to be an optimal level of safety. Because of the uncertainties in predicting earthquake occurrences, the life-cycle cost for upgrading is highly probabilistic in nature. Its expected value includes the present day upgrading expenses and the potential cost for damages from all future earthquakes that may occur over the remaining life of the structure.

In the previous chapter, the method by which the damage cost functions for an event earthquake may be evaluated was discussed. It is often convenient to express the design seismic intensity from a finite collection of event earthquakes, although a continuous function may be possible. The likelihood of occurrence for any event earthquake can then be used to assign weight to its probable damage costs.

If the cumulative distribution function of seismic intensities is known, the expected damage costs for the design earthquake can be formulated. Because the expected damage costs as presented pertains to the future occurrences of earthquakes, it should also be evaluated for the present worth. Assuming C_U to be the present day upgrading cost for the building, the expected life-cycle cost function for upgrading $E[C_{LC}]$ can be written as,

$$E[C_{LC}] = C_U + E[C_D] \tag{3.1}$$

where the total damage cost in present day value is denoted by C_D.

In this chapter we should look at event parameters that will help quantify the terms in Equation 3.1 for Puerto Rico. Only a knowledge of damage cost functions presented in Chapter 2 is assumed.

3.2 Retrofitting Cost, C_U

For purposes of this investigation, the retrofitting costs for reinforced concrete structures will be calculated using FEMA-156. Sponsored by the Federal Emergency Management Agency, FEMA-156 is a summary report on typical costs for seismic rehabilitation of existing buildings. The report was compiled using some computerized database containing 2088 data points, each point representing the rehabilitation cost for one building (FEMA, 1994). The cost information is based on the actual practices in the Unites States and its territories, including two rehabilitation projects in Puerto Rico, and is converted to 1993 Missouri dollars.

Three major options for a typical cost estimation process are presented. Which option to use depends on the user need and the availability of information. Fifteen different building types are arranged into eight groups. Seismic performance objectives considered are *life safety*, *damage control*, and *immediate occupancy*. Four regional seismicity levels (low, moderate, high, or very high), variations in material and labor costs from location to location, and inflation effects on future cost of construction are some other factors that may be included. The requirements for each of three cost estimation option are explained below.

- **Option 1:** This option requires the identification of the type of structure to be retrofitted, floor area, and the time of construction. It is recommended only for a very general discussion on the potential seismic retrofitting costs of large building inventories.
- **Option 2:** All that is required in Option 1 plus the seismicity of the location and the desired performance objectives.
- **Option 3:** All that is required in Option 2 plus the age of the building, number of stories, type of occupancy, and occupancy conditions (vacant or in use during rehabilitation).

Although generally the most accurate, problems with the existing database may cause Option 3 to yield inconsistent results. It is therefore recommended to verify the consistency of Option 3 through comparison with results obtained from Option 2. For the type of investigation proposed herein, Option 2 was also shown to be the most appropriate (Piñero, 1998).

FEMA-156 recommends the following equation for an Option 2 retrofitting cost estimate:

$$C_U = C_1 C_2 C_3 C_L C_T \qquad \textbf{(3.2)}$$

where:

C_U = Typical Seismic Retrofitting Cost for a Building ($/sq. ft.).

C_1 = Building Group Mean Cost. It is estimated at $18.00 /sq. ft. for concrete frames with or without shear walls.

C_2 = Floor Area Adjustment Factor. Table 3.1 which is adopted from FEMA-156 lists C_2 values for concrete frames with or without shear walls.

C_3 = Seismicity/Performance Objective Adjustment Factor. FEMA recommended C_3 values are 0.70 for life safety, 0.85 for damage control, and 1.40 for immediate occupancy. This numbers represent mean low, moderate, and high cost retrofitting options respectively. A low retrofitting cost for steel bracing is assumed (Piñero, 1998).

C_L = Location Adjustment Factor. This factor converts Missouri dollars on which the costs in FEMA-156 are based to that of any other locality. For Puerto Rico a C_L value of 0.91 is assumed (National Construction Estimator, 1991).

C_T = Time Adjustment Factor. This factor converts 1993 dollar values from the time of FEMA study to the current costs of seismic retrofitting. C_T value is set equal to $(1 + i)^n$, where "i" is the average discount rate and "n" is the number of years between 1993 and the date for which the costs are estimated. The average discount rate from January 1993 to

January 1997 is 4.37%, so the current costs would be obtained by multiplying the calculated 1993 costs by a factor of 1.19 (Piñero,1998).

Table 3.1: Floor area adjustment factor (C_2)

Building Size	**Area (sq.ft)**	**Area Adjustment Factor, C_2**
Small	less than 10,000	1.09
Medium	10,000 - 49,999	1.06
Large	50,000 - 99,999	1.01
Very Large	100,000 or more	0.84

The estimated seismic retrofitting costs for reinforced concrete buildings in Puerto Rico would be those presented in Table 3.2. The listing is based on Equation 3.2 and presents the cost as a function of the building size and the performance objective. These estimated costs do not take into consideration non-structural costs like architectural finishes, and electrical and mechanical upgrades to the building.

Table 3.2: Typical seismic retrofitting costs in 1998 Puerto Rico dollars

Area (sq. ft)	**Seismic Retrofitting Cost ($/sq. ft)**		
	Type of Retrofitting Investment		
	Low	**Moderate**	**High**
less than 10,000	14.9	18.1	29.8
10,000 - 49,999	14.5	17.6	28.9
50,000 - 99,999	13.8	16.7	27.6
100,000 or larger	11.5	13.9	22.9

3.3 Reconstruction Period, T_R

The reconstruction period, T_R, refers to the elapse time after an earthquake which takes to restore a facility to its operational state. It is dependent on the extent of structural damage, the importance of the facility in post-earthquake recovery, the availability of labor and resources such as construction material and equipment, and the speed by which building permits are issued. Also critical are the failures of various lifeline systems that include sanitary, energy (electricity and gas), transportation (highway, railway, sea and air), and communication (telephone, telegraph, radio and television). Depending on the extent of damage to equipment and on-site utilities, the availability of replacement parts and related services may also be considered.

The ATC-13 of 1985 presents a methodology on how to establish a function restoration curve. Experts' opinions were sought through rounds of questionnaires. A Project Engineering Panel (PEP) was formed to discuss and control information feedback between rounds. The following guidelines were established:

1. The damage state of the facility represents both the state of direct damage and service lifeline damage to the facility.
2. Vast resources are available for the reconstruction. Therefore, reconstruction/repair would follow ordinary non-emergency construction schedules and would be based upon existing plans.
3. The time it takes to restore function at a facility includes restoration of all factors critical to that facility (structures, equipment, and on-site utilities).

For their familiarity with each of the 35 facility types considered, individual experts were rated and assigned different weights. The statistics of time-to-restore functions at 30%, 60%, and 100% of capacity were established accordingly.

For purposes of this investigation, it was assumed that all facilities will cease to function until the rehabilitation is completed. Using the ATC-13 data on time-to-full restoration of functions, the following general expression is obtained (Appendix C):

$$T_R = a\,D_m^{\,b} \tag{3.3}$$

where *a* and *b* are regression coefficients whose values are listed in Table 3.3 for different types of facilities.

Table 3.3: Regression coefficients for reconstruction period (in days)

Facility	***a***	***b***	**Mean Squared Difference**
Residential	328.1	0.9772	0.9261
Agricultural	215.3	0.6602	0.9881
Mining	844.1	0.8616	0.9228
Construction	390.0	0.6065	0.9791
Manufacturing	807.2	0.6915	0.9883
Services			
General	779.4	0.6351	0.9889
Parking Facilities	267.77	0.9747	0.9839
.**Government**	577.85	0.6858	0.9840

Unless evaluating the rent component of the economic factor, C_{Er}, the T_R values calculated from Equation 3.3 shall not exceed one year. That is the time frame considered severe enough for most businesses to move to temporary or alternate locations.

Figure 3.1 illustrates the same example as the previous chapter, but now using the power equations obtained above for the restoration time, T_R. Once again the influence of the restoration time shows its importance changing the cost associated with different occupancies. Figure 3.2 shows the effects of the aforementioned one year limit on T_R values. Note that the residential costs are not influenced.

3.4 Design Earthquake

A building code has to meet two major objectives when dealing with earthquakes. Those are the usual life safety standards and the need to minimize the long term cost-benefit ratio of earthquake protection. It would clearly be economically unpractical to set the level of earthquake-resistant design so high that the most remote scenarios are covered.

Puerto Rico is located in a zone of high seismicity. The last major earthquake on the island occurred at the Mona Channel (west coast) in 1918, killing 116 people and causing more than four million dollars in damages. The 1918 earthquake was 7.3 on the Richter scale. Unfortunately, there are no recorded acceleration data on this or any other earthquake prior to 1975. Historically, it was assumed that Puerto Rico ground motions have comparable characteristics to California ground motions (Housner, 1973). This assumption has never been verified. The current Puerto Rico seismic regulations Building Code are

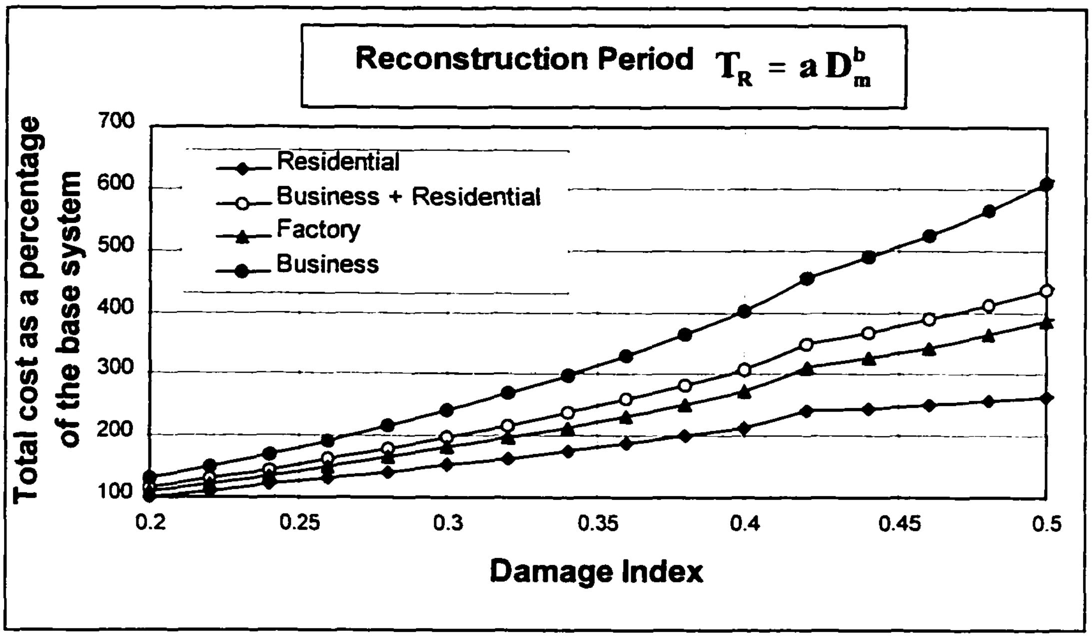


Figure 3.1: Total cost for different occupancies type with variable reconstruction period with one year moratorium on all but residential.

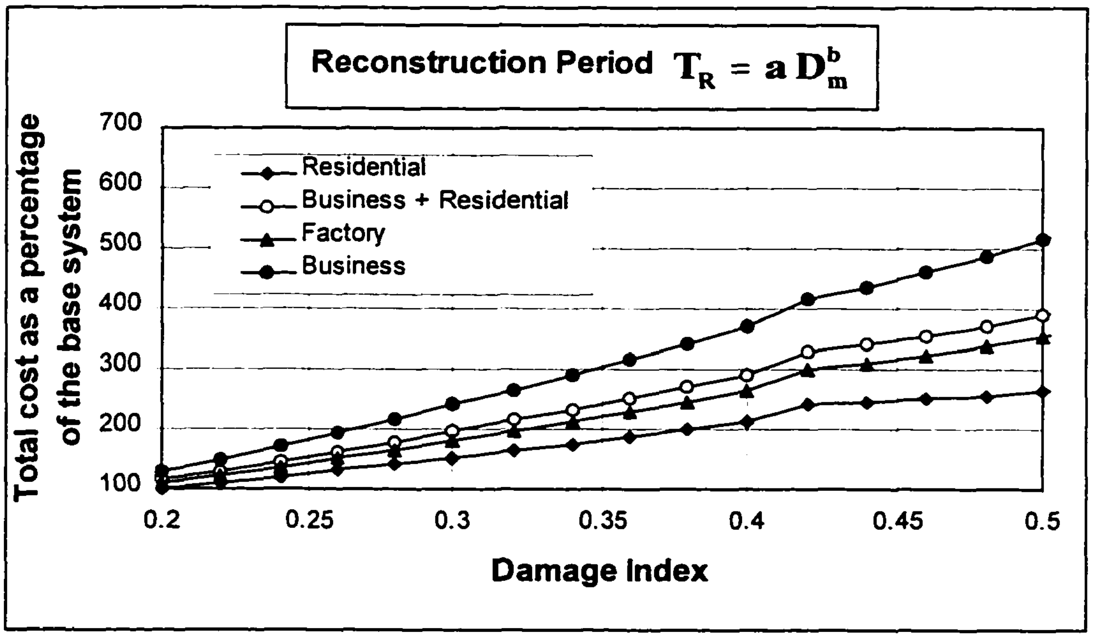


Figure 3.2: Total cost for different occupancies type with variable reconstruction period without one year moratorium.

based on the Tehachapi earthquake, which occurred on the White Wolf fault in 1952. The magnitude of the event was 7.7 on the Richter scale. The recorded ground accelerations were at Taft, approximately 25 miles from the causative fault, and also at Hollywood, approximately 65 miles from the causative fault. Both places are in California.

Given the uncertainties inherent to the current regulations, it is not surprising to note that efforts are under way to remedy the situation. Researchers at UPR-Mayagüez have been working over the last four years to come up with a more rationale earthquake design philosophy. Although this research is not yet completed, the framework is in place for an earthquake recurrence model (Maldonado and Martínez-Cruzado, to be published).

Figure 3.3 shows the seismic fault zones established for the region. Using the well-known Gutenberg-Richter relationship, a periodic table of earthquake design levels is produced. This is presented in Table 3.4, where for each zone the minimum magnitudes expected to have a 50%, 10%, 5%, and 2% probability of exceedance in fifty years are shown.

Donovan's attenuation law is used to calculate the peak ground acceleration associated with those earthquake levels. In equation form,

$$a = 1320(R + 25)^{-1.52} e^{0.58m} \qquad \textbf{(3.4)}$$

where a is the acceleration in cm/sec^2, R is the focal distance in Km, and m is the magnitude on the Richter scale. For purposes of this investigation, the recorded accelerogram from the Taft earthquake is adjusted for each of the four design levels presented in Table 3.4. The design Peak Ground Acceleration (PGA) at every level is the maximum PGA calculated at different faults zones using a minimum fault distance of 12 Km. The last row in Table 3.4 lists design PGA values at different levels. The most critical fault zones were at the northwest, north, or northeast of the island, corresponding to Puerto Rican Trench I, Puerto Rican Trench II, and Puerto Rican Trench III.

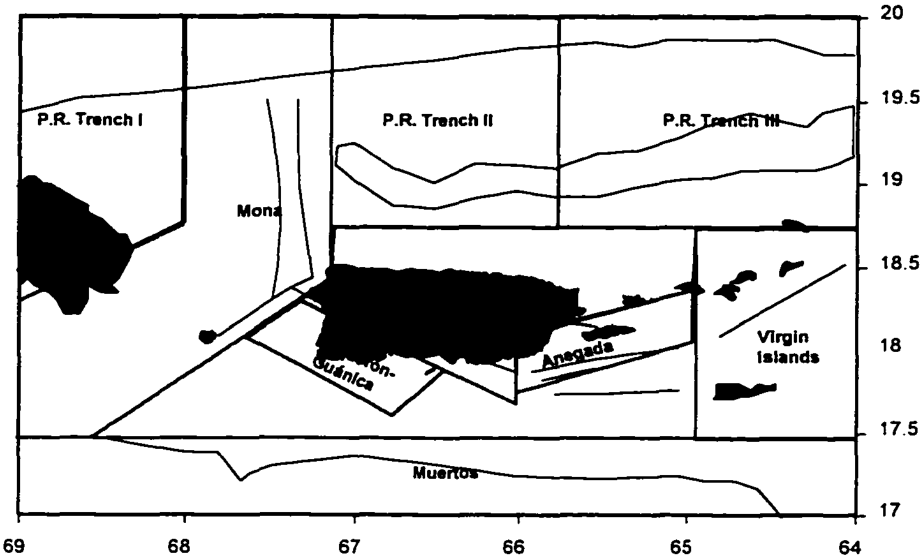


Figure 3.3: Selected seismic fault zones in the Puerto Rico region (Adopted from Maldonado and Martínez-Cruzado, to be published).

3.5 Expected Damage Cost

The methodology by which the damage cost for an event earthquake may be evaluated was discussed in Chapter 2. Let $C_d(x)$ represent damage cost associated with the damage level x. Assuming that x is statically independent from the earthquake intensity, s, the instantaneous damage cost for all possible earthquakes can be formulated as (De León, 1996):

$$C_{DI} = \int_{s_{\min}}^{s_{\max}} \left[\int_{0}^{\infty} C_d(x) f_X(x)\, dx \right] f_S(s)\, ds \tag{3.5}$$

Table 3.4: Magnitudes for earthquake types for Puerto Rico per 50 years[1]

Zone	50%	10%	5%	2%
PR Trench I	6.00	6.67	6.92	7.23
PR Trench II	6.58	7.27	7.50	7.74
PR Trench III	6.12	6.71	6.93	7.20
GSPRFZ[2]	5.01	5.52	5.71	5.94
Boquerón	5.46	5.99	6.16	6.34
Anegada	5.22	5.71	5.89	6.13
Mona	6.13	6.72	6.92	7.16
Muertos	5.17	5.73	5.94	6.21
GNPRFZ[3]	5.28	5.80	5.98	6.19
Virgin Islands	5.20	5.73	5.94	6.20
Design PGA[4]	0.220	0.286	0.312	0.347

1.Adopted from Maldonado and Martínez-Cruzado (to be published).
2.Great Southern Puerto Rico Fault Zone.
3.Great Northern Puerto Fault Zone.
4. Maximum value calculated for a focal distance of 12 Km.

where:

$s_{\min}$ = minimum seismic intensity of design significance,

$s_{\max}$ = maximum probable seismic intensity for the region,

$f_X(x)$ = probability density function for seismic damage distribution, and,

$f_S(s)$ = probability density function for seismic intensity distribution.

Damage costs calculated from Equation 3.5 will correspond to seismic activities sometime in the future. To convert that value into its expected present day worth, $E(C_D)$, certain simplifying assumptions are made. Chief among those, earthquake occurrences follow a Poisson distribution and sustained damages are repaired before the next earthquake takes place. Let R_D denote the $E(C_D)/C_{DI}$ ratio. Then (Ang and De León, 1995b):

$$R_D = \sum_{n=1}^{\infty} \left[\sum_{k=1}^{n} \frac{\Gamma(k,\alpha L)}{\Gamma(k,\nu L)} \left(\frac{\nu}{\alpha}\right)^k \right] \frac{(\nu L)^n}{n!} e^{-\nu L} \qquad \textbf{(3.6)}$$

where:

$\alpha = \nu + \ln(1 + q)$

ν = mean annual occurrence rate of significant earthquake ($S \geq s_{\min}$)

L = design life of structure

q = annual discount rate

$\Gamma(k, \alpha L)$ = incomplete gamma function = $\int_0^{\alpha L} e^{-u} u^{k-1} du$

Figure 3.4 depicts a graphical presentation of the above equation, assuming a building life span of 50 years.

It is not always possible to use Equation 3.5 when calculating C_{DI}. The seismic damage distribution, $f_X(x)$, depends on the particular characteristics of the structure and the ground motion which would make it difficult to be represented analytically. The earthquake intensity distribution, $f_S(s)$, is an unknown for all but the most active seismic regions. Consequently, the following more simplified alternative is proposed:

$$C_{DI} = \sum_{i=1}^{n} w_i C_{di} \qquad \textbf{(3.7)}$$

where w_i is the weight assigned to the design earthquake causing C_{di}. Only those intensities that are accounted for by Equation 3.6 are considered. Thus, for each one of the probability of exceedance the weights becomes,

$$w_1 = \frac{50\% - 10\%}{50\%} = \frac{0.40}{0.5}$$

$$w_2 = \frac{10\% - 5\%}{50\%} = \frac{0.05}{0.5}$$

$$w_3 = \frac{5\% - 2\%}{50\%} = \frac{0.03}{0.5}$$

$$w_4 = \frac{0.02}{0.5}$$

The data from Table 3.4 is used to specialize Equation 3.7 for Puerto Rico. It will be easy to show that:

$$C_{DI} = \frac{0.40}{0.50} C_{d,0.220} + \frac{0.05}{0.50} C_{d,0.286} + \frac{0.03}{0.50} C_{d,0.312} + \frac{0.02}{0.50} C_{d,0.347} \qquad \textbf{(3.8)}$$

where $C_{d,0.220}$, for example, represents the damage cost to the building caused by a design earthquake of 0.220 PGA. Because there is a 50% chance of having an earthquake of 0.220 GPA or more in 50 years, an earthquake recurrence period of $\nu = \frac{0.5}{50} = 0.01$ is assumed.

Using 4.37% discount rate for Puerto Rico, a R_D value of 0.21 is obtained (Figure 3.4). Consequently:

$$\begin{aligned} E[C_D] = {} & 168\times10^{-3} C_{d,0.220} + 210\times10^{-4} C_{d,0.286} + \\ & 126\times10^{-4} C_{d,0.312} + 840\times10^{-5} C_{d,0.347} \end{aligned} \qquad \textbf{(3.9)}$$

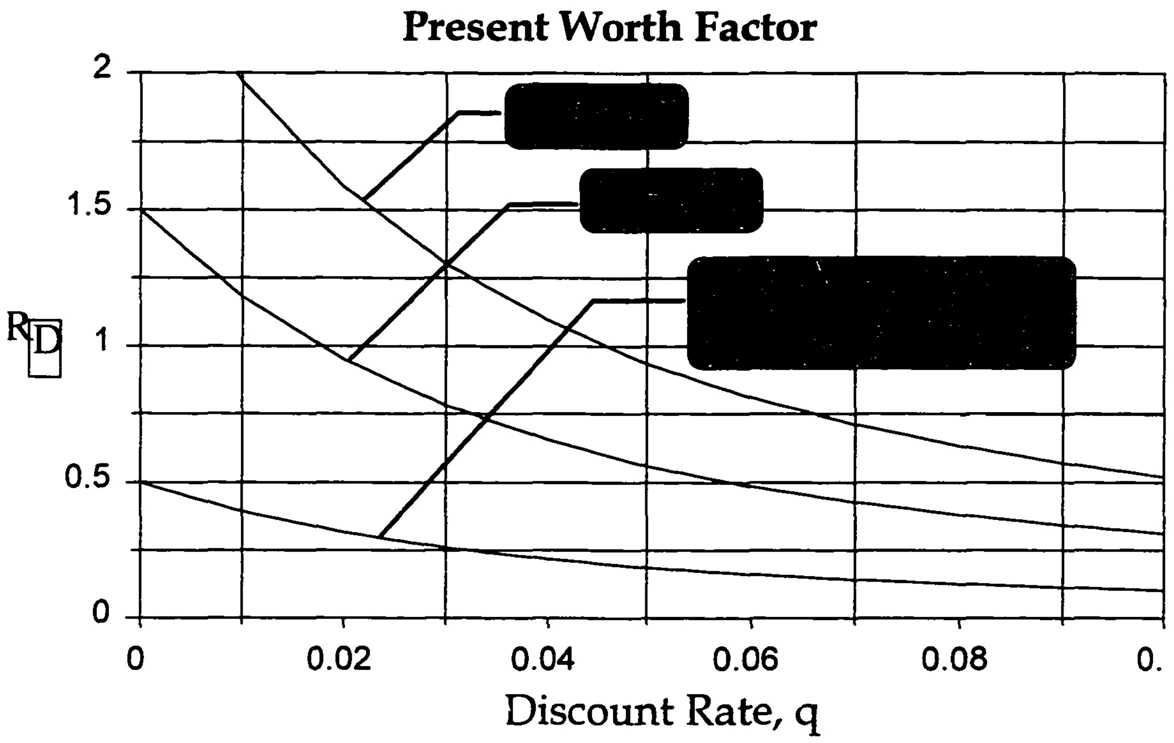


Figure 3.4: Present worth factor for Puerto Rico.

Equation 3.1 can now be used to calculate the expected life cycle cost for retrofitting, which will be used in the Chapter 5 in a general example.

CHAPTER 4

COMPUTATIONAL TOOLS

4.1 Introduction

The aging infrastructure is a world wide problem. It has forced engineers to continually face difficult retrofitting and repair decisions. In recent years, a number of research projects have focused on the idea of a damage index to qualify the response of structures. The proposed methodologies are still being debated for their merits. However, practical implementations in seismic design area have already been started. The damage index is now universally recognized as an important tool in planning for earthquakes as well as any post-earthquake assessments.

In Chapter 2, damage indices were used to predict the likely costs of a future earthquake for a building. They are also important in assessing building vulnerability to aftershocks, enabling authorities to conclude whether or not a building is safe to enter immediately after an earthquake. In the long run, damage indices may also be used as an aid in deciding whether to repair or demolish a damaged structure (Williams and Sexsmith, 1995).

The modern seismic design philosophy adopted by the Structural Engineers Association of California states that a structure should withstand a minor earthquake without any damage, a moderate earthquake with no structural damage (although non-structural damage is acceptable), and a severe earthquake without structural collapse (Allahabadi, 1987). The rational applications of this philosophy depend on our ability to quantify and assess damages.

In the next chapter, we should introduce building prototypes to evaluate the proposed damage cost model for Puerto Rico. The computational tools presented in this chapter will be used to assess the seismic performances of those prototypes.

4.2 Method of Analysis

Current practice in the earthquake resistant design of reinforced concrete structures relies on the energy dissipation through inelastic cyclic deformation. There are many computer programs for the nonlinear analysis of building structures that may be used for such purposes. Examples include IDARC-2D (Inelastic Damage Analysis of Reinforced Concrete), DRAIN-2DX (Dynamic Response of Inelastic 2-Dimensional Structures), SARFC (Seismic Analysis of Reinforced Concrete Frames), and SNAP-2D (Structural Nonlinear Analysis Program). What program to use will depend on the overall modeling needs of the individual user.

SNAP-2D computer program was selected for this study. The decision was based on its performance, its extensive library of elements, and the ease by which it can be adopted for both steel and reinforced concrete members (Piñero, 1998). The program is an outgrowth of the DRAIN-2DX. It was developed in the University of Michigan, Ann Arbor (Xia and Hanson, 1990).

Five types of analysis can be performed using the SNAP-2D. These are static analysis, dynamic analysis using event-to-event scheme, dynamic analysis using iteration scheme, dynamic analysis using Euler scheme, and response spectrum analysis. The dynamic analysis using event-to-event scheme, where each event corresponds to a significant change in stiffness, was adopted for this study because of its simplicity and reliability (Prakash and Powell, 1993).

A pre-processor for the SNAP-2D computer program was specially developed by the author to simplify the creation of input files. Then, the Park-Ang damage model was included into the program to habilitate the damage computation. The viscous damping matrix of the system is then generated as a linear combination of mass and stiffness matrices. That is

$$[C] = \alpha_m [M] + \alpha_k [K] \tag{4.1}$$

where the proportionality coefficients α_m and α_k are calculated from one of the three options specified by the user. These are:

a) Mass proportional damping.
b) Stiffness proportional damping.
c) Rayleigh damping.

In the mass proportional damping option, $\alpha_k = 0$, and

$$\alpha_m = 2 \varepsilon_i \omega_i \tag{4.2}$$

were ε_i and ω_i are the critical damping ratio and the circular frequency for the mode "*i*".

Similarly, $\alpha_m = 0$ for the stiffness proportional damping, and

$$\alpha_k = \frac{2\varepsilon_i}{\omega_i} \tag{4.3}$$

In the Rayleigh damping approach, both α_m and α_k coefficients can have non-zero values. In general:

$$\alpha_m = \frac{2\varepsilon_i\omega_i\omega_j^2 - 2\varepsilon_j\omega_j\omega_i^2}{\omega_j^2 - \omega_i^2} \tag{4.4}$$

$$\alpha_k = \frac{2\varepsilon_j\omega_j - 2\varepsilon_i\omega_i}{\omega_j^2 - \omega_i^2} \tag{4.5}$$

Notice, that "*i*"and "*j*" correspond to the frequency for two selected modes of vibration, which typically are the first two. If the damping ratio is the same for the two modes considered, $\varepsilon_i = \varepsilon_j = \varepsilon$, the following simplifications are obtained from Equations 4.4 and 4.5, respectively:

$$\alpha_m = \frac{2\varepsilon\omega_i\omega_j}{\omega_i + \omega_j} \tag{4.6}$$

$$\alpha_k = \frac{2\varepsilon}{\omega_i + \omega_j} \tag{4.7}$$

The choices of proportionality coefficients greatly influence the outcome of an SNAP-2D dynamic analysis. While the many sources of damping have been identified qualitatively, questions on the viscous damping values to be used in dynamic analysis abound. It is important to realize that many suggested values are intended for the elastic analyses of structures. In such cases, sources other than pure viscous damping (such as hysteretic damping) are introduced as equivalent viscous damping. This results in larger damping values than those really associated with material viscosity. While the validity of such practices is debatable, hysteretic damping is already accounted for in the present study through the inelastic response of structural members. Recommended values of viscous damping for reinforced concrete vary from 2 to 10 percent, depending on the level of deformation and strain induced in the structure (Pincheira, 1992). For purposes of this investigation, the Rayleigh damping option is utilized with an assumed damping ratio of 5 percent.

4.3 Elements Library

The SNAP-2D elements library is presented below:

- Truss element which buckles elastically in compression, or yield in compression without buckling (Type 01).
- Beam-Column element with bilinear behavior in flexure including effect of axial forces but not considering stiffness or strength degradation (Type 02).
- R/C beam element with bilinear behavior in flexure and including stiffness degradation, strength degradation and pinching effects (Type 03).
- Semi-rigid connection element (Type 04).
- Beam element with bilinear behavior in flexure and including stiffness degradation (Type 05).
- Shear-link element (Type 06).

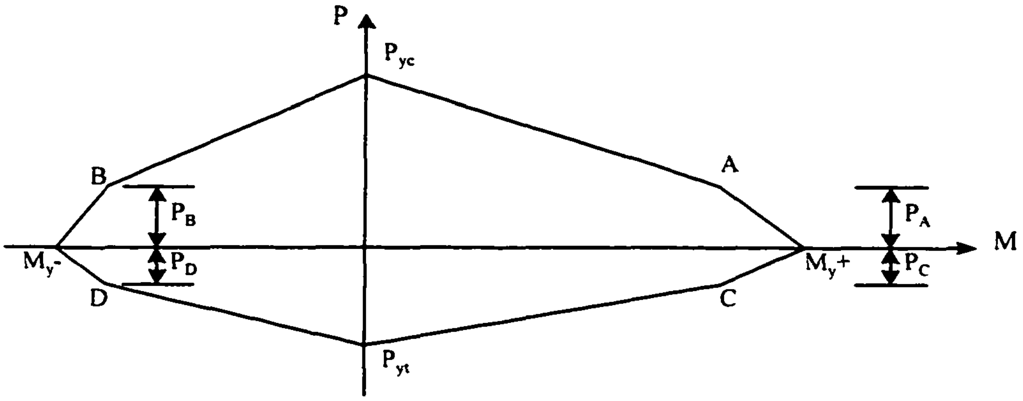
- ADAS element (Type 07).
- Truss element with an improved cyclic buckling model that incorporates a new criterion for fracture life (Type 08).
- Truss element (Type 09; Jain's Model).
- R/C beam-column element with tri-linear behavior in flexure and stiffness degradation during cyclic loading (Type 10).
- Damping element (Type 11; Shear type).
- Damping element (Type 12; Truss type).
- Friction element (Type 13; Truss type).

The friction element 13 is not part of the basic SNAP-2D element library. It was added by the author for purposes of this investigation (Appendix D).

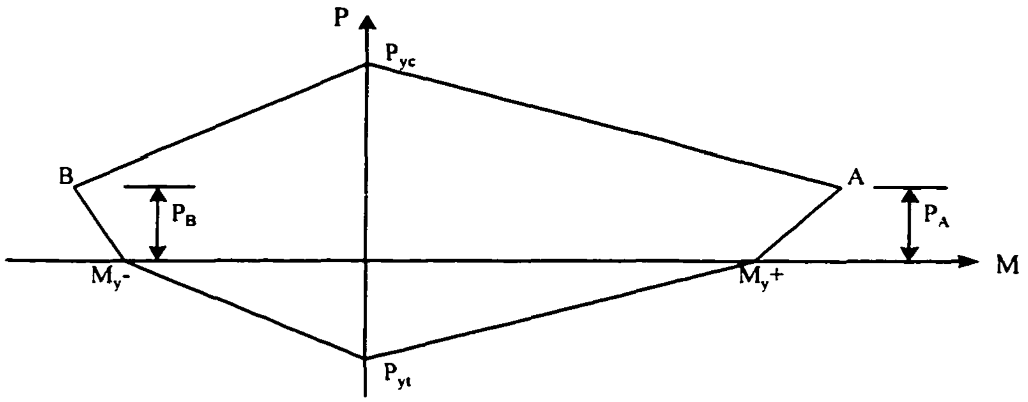
Elements 1, 2, 3, 6, 7, 9 were used by Piñero to model the building prototypes for his study. Much of the discussions related to those prototypes are available elsewhere (Piñero, 1998). For the special cases considered herein, only elements 2, 9, and 13 were utilized.

Element 2 was selected to model both reinforced concrete and steel beam-columns. There are three yield interaction surfaces available for this element. Figure 4.1 shows those surfaces used for reinforced concrete and steel members. Shear deformation as well as the strain hardening effects are also possible with this element.

Bracing members were modeled using the element type 9 and element type 13. Element 9 is the Jain's model which considers the energy dissipation in the post-buckling range (Jain, 1978). The hysteretic model proposed by Jain is reproduced in Figure 4.2. To use this element, one should provide the control points to the hysteretic curve (Piñero, 1998). Element 13 is a friction type truss element. The constitutive relationship is shown in Figure 4.3. This element is an approximation of the model first proposed by Kuhlmann (1989). The elements are designed with a buckling capacity near the friction capacity.



(A) Steel I-Beam Type



(B) R/C Type

Figure 4.1: Cross section yield interaction surfaces for element

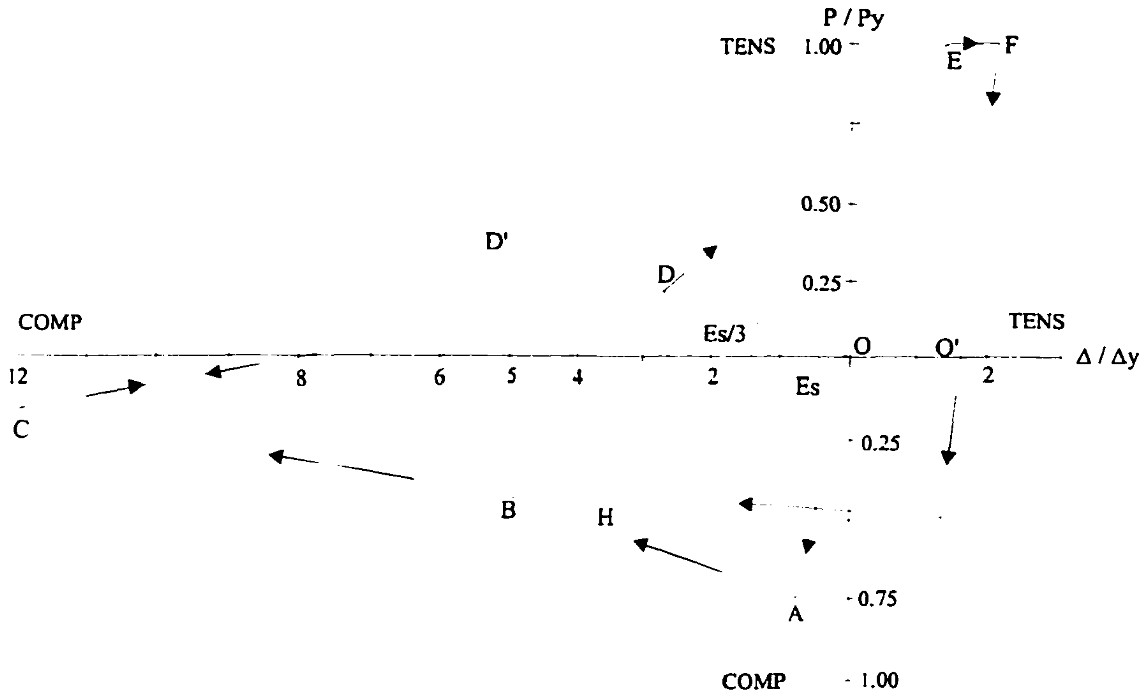


Figure 4.2: Jain hysteretic model.

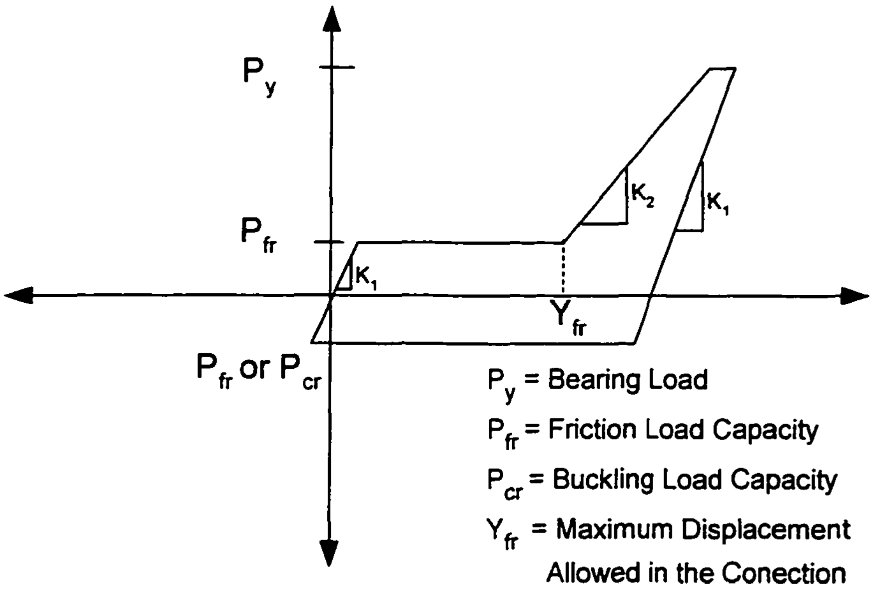


Figure 4.3: Friction type truss element.

4.4 Element Damage Model

The Park-Ang damage model was selected for this project. This is the cumulative damage index model most widely used and universally accepted for reinforced concrete structures. The model formulates the potential damage of a reinforced concrete member as a function of the maximum deformation and the absorbed hysteretic energy. A linear combination of damages caused by excessive deformation and those contributed by repeated cyclic loading effects are assumed. There are several forms of this model. The form utilized herein is as follows:

$$D = \frac{\theta_m}{\theta_u} + \frac{\beta}{M_y \theta_u} \int dE \qquad \textbf{(4.8)}$$

where:

θ_m = maximum response rotation under an earthquake.

θ_u = ultimate rotational capacity under monotonic loading.

M_y = calculated moment yield strength.

dE = incremental dissipated hysteretic energy.

β = non-negative constant.

In programming the Park-Ang damage model into the SNAP-2D computer program, the information on θ_u and β were added to the input line on element data (Appendix E). Moment yield strength, M_y, was already inputted. The loading history parameters θ_m and dE are calculated by the program itself.

The ultimate rotation capacity, θ_u, is calculated using the following general expression which may be found in many standard text books (Pauly and Priestley, 1992):

$$\theta_u = \frac{\phi_y L}{3} + \frac{L_p}{L}(\phi_u - \phi_y)(L - 0.5L_p) \tag{4.9}$$

L_p is the length of the plastic hinge taken at 9 percent of the member length, L. That is $L_p = 0.09$ L. ϕ_y, and ϕ_u are the yield and the ultimate curvature of the member. A method for calculating these curvatures as well as the yield and the ultimate moments are given in Appendix F.

The β parameter considers the effect of cyclic loadings on structural damage. To evaluate this parameter, a large set of cyclic test data on reinforced concrete beams and columns were selected (Park, 1985). For each test, the load-deformation curve was traced up to the failure point. Then, using Equation 4.8 at the point of failure and with **D** = 1.0, the corresponding β value was evaluated. Through trial and error, the minimum variance values of β were determined in such a way that the standard deviation of **D** is minimized and the mean value of **D** is close to unity. The results yielded the following (Park,1985),

$$\beta = (-0.447 + 0.073\ l/d + 0.24 n_0 + 0.314\ \rho_t\ )\ 0.7^{\rho_w} \tag{4.10}$$

in which,

l/d = shear span ratio (replaced by 1.7 if $l/d < 1.7$).

n_0 = normalized axial stress = $\dfrac{N}{bdf'_c}$ (replaced by 0.2 if $n_0 < 0.2$)

ρ_t = longitudinal steel ratio in percent (replaced by 0.75% if ρ_t <0.75%) , and

ρ_w = confinement ratio in percent.

The dissipated hysteretic energy is calculated through the enclosed area of the hysteretic loops. A hysteretic loop is defined as the load path described on a load-displacement diagram when the structural element undergoes a complete load process. That includes loading, unloading, and reloading in both directions. For example, the dissipated hysteretic energy in Figure 4.4 corresponds to the area under lines **OABA.**

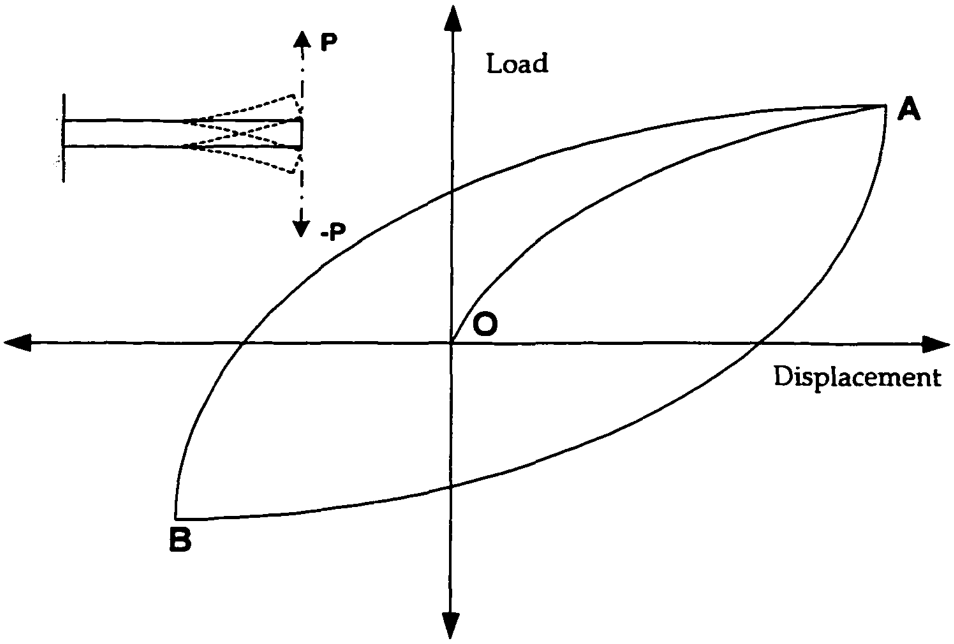


Figure 4.4: Dissipated hysteretic energy

4.5 Global Damage Index

In the aftermath of an earthquake, the global damage state of any structure will depend on both the distribution and severity of localized damages. A direct approach will try to evaluate the overall performance from the characteristic changes observed at the system level. However, if damages are assessed at the substructure or member levels, a procedure is needed to translate such data into a global damage index.

The approach most widely used is to take an average of the local indices, weighted by the local energy absorptions (Williams and Sexsmith, 1995). Thus, for a single story:

$$D_{story} = \frac{\sum D_i E_i}{\sum E_i} \tag{4.11}$$

where D_i and E_i are the recorded damage index and the energy absorbed by the element *i*. In a similar fashion, the global damage index is calculated from the story indices. Because the model assigns higher weights to the elements that absorb larger amounts of energy, the locations and functions of the damaged elements are not explicitly considered. Consequently, it would be quite possible to have a situation in which such an index would significantly misrepresent the overall damage state of the structure. For example, if all the beams from the fourth floor, in a 5-story building collapsed, the global damage index will be high, indicating collapse of the building which is not necessarily true.

A new and growing area in the field of structural reliability involves the assessment of damages from changes in modal parameters during an earthquake. The existing methodologies could be entirely based on the building natural frequencies, yielding information about the overall damage state, or it may involve the use of mode shapes to locate damages. Of this latter type, we have the softening indices which associate changes in the first few natural frequencies of the building to the damage level it has endured.

Damaged structures usually exhibit reductions in their natural frequencies due to stiffness degradations. This simple observation has been the focal point for some researchers in recent years. Roufaiel and Meyer (Williams and Sexsmith, 1995) were pioneers in this direction. Although they had concentrated on only the fundamental mode, they came out with a correlation for a simple global damage index:

$$D_{global} = \frac{\delta_m - \delta_y}{\delta_f - \delta_y} = \frac{14.2\delta_y\left(\sqrt{\frac{f_{und}}{f_{dam}}} - 1\right)}{\delta_f - \delta_y} \tag{4.12}$$

where f_{und} and f_{dam} are the fundamental frequencies of the structure, before and after it is damaged. As the structure suffers more damages throughout its response time history, the fundamental period changes. These changes can be tracked as shown in Figure 4.5. It shows the response of the Millikan Library, in Pasadena, California, during the San Fernando earthquake of 1971 (DiPasquale et. al, 1989). Consequently, a number of different softening indices can be formulated in terms of the three periods indicated on the same figure. These are the maximum softening, D_{ms}, the plastic softening, D_{ps}, and the final softening, D_{fs}.

In equation form:

$$D_{ms} = 1 - \frac{T_{und}}{T_m}; \quad D_{ps} = 1 - \frac{T^2_{dam}}{T^2_m}; \quad D_{fs} = 1 - \frac{T^2_{und}}{T^2_{dam}} \tag{4.13}$$

where T_m, is the maximum period developed by the structure. Of these indices, the maximum softening is considered the best indicator of the global damage state (William, 1995). Miyamura (William, 1995) has shown that the maximum softening provides a reliable estimate of whether or not yielding has occurred within the structure. Nevertheless, a drawback of the softening indices is that they provide very little information on the distribution of damages within the structure.

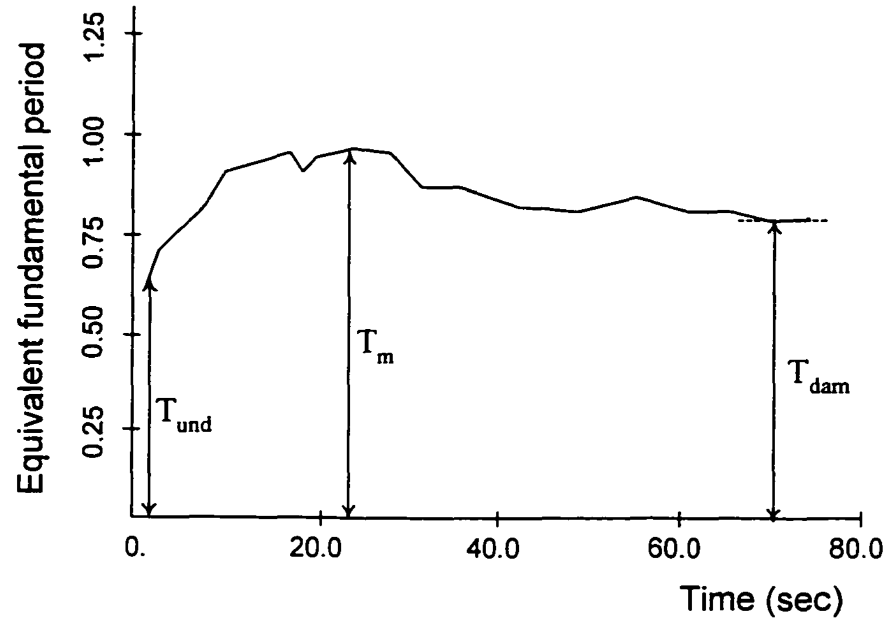


Figure 4.5: Evolution of equivalent fundamental period for Millikan Library

In an attempt to improve on the maximum softening index approach, the model was extended by Mork to include the second mode (William, 1995). Two new damages parameters were defined as:

$$D_1 = 1 - \sqrt{\frac{k_{1,m}}{k_{1,und}}}\ ; \quad D_2 = 1 - \sqrt{\frac{k_{2,m}}{k_{2,und}}} \tag{4.14}$$

where k_i ; $i = 1, 2$, values are the spring constants for a two degree of freedom system having two equal masses and giving the same first and second periods as the actual structure. Thus,

k_1 and D_1 may be assumed to represent the lower part of the structure and k_2 and D_2 the upper part.

The use of softening damage indices presents a promising method of assessing the global damage state of structures. However, since it provides no information on the damage distributions, further studies are required to realize its implementation in design. A more practical procedure to calculate the global damage indices is proposed by Bracci et al. (1989). At the story level, they combine the element damage indices using the weighting schemes given by:

$$D_{story} = \frac{\sum_{i=1}^{N} \omega_i \, (D_i)^{m+1}}{\sum_{i=1}^{N} \omega_i \, (D_i)^{m}} \qquad \textbf{(4.15)}$$

where:

i = element number.

m = weighting factor controller for elements at the story level.

ω_i = importance factor for element i.

N = number of elements in a floor.

The importance factor should satisfy the condition $\sum_{i=1}^{N} \omega_i = 1$, so that the damage index **D** is always normalized. Similar equation may be used at the global level, only now element numbers will be replaced by story numbers.

The idea of assigning importance to the members and story levels is suggested in assessing the quality of damage (Bertero et al, 1976). Sound engineering practice would dictate assigning heavier weights to columns than to beams. Likewise, lower story levels may be considered of greater importance than the upper levels. The weighting procedure devised by Bracci et al. satisfies both of these requirements. In equation form, at story level:

$$\omega_i = \frac{(\textit{gravity loads tributary to element } i)}{(\textit{total gravity loads at the story level})} \tag{4.16}$$

and at global level:

$$\omega_i = \frac{(\textit{gravity loads tributary to story level } i)}{(\textit{total gravity loads for the building})} \tag{4.17}$$

Assuming $m = 1$, one can modify Equation 4.15 to obtain:

$$D_{story/global} = \frac{\sum_{i=1}^{N} \omega_i \, (D_i)^2}{\sum_{i=1}^{N} \omega_i \, (D_i)} \tag{4.18}$$

which is the expression used in the present study to evaluate damage indices for building prototypes. The global damage index was designated D_m in Chapter 2.

To evaluate various seismic performance levels for a building, Park and Wen calibrated their damage index from the data on nine reinforced concrete buildings (Park and Wen, 1987). The buildings were among those that were moderately or severely damaged during the 1971 San Fernando and the 1978 Miyagiken-Oki earthquakes. The performance limits recommended by their study and adopted herein are for immediate occupancy, $D_m \leq 0.2$, damage control, $0.2 < D_m \leq 0.3$, life safety, $0.3 < D_m \leq 0.4$, and collapse, $D_m \geq 0.4$.

CHAPTER 5

PRACTICAL IMPLEMENTATIONS

5.1 Introduction

The general concerns about the seismic deficiencies of some reinforced concrete buildings with insufficient design loads and weak requirements on detailing were discussed in Chapter 1. It is very important to find out how those buildings will behave during an earthquake and, even more so, what types of economic losses will be endured. Our aim in this chapter is to establish a mechanism to evaluate such buildings. Two classes of buildings are considered. Class 1 buildings are those designed using the 1968 Puerto Rico Building Code which is considered very weak in its seismic regulations. Class 2 buildings represent modern types designed after the 1987 revision of the Puerto Rico code.

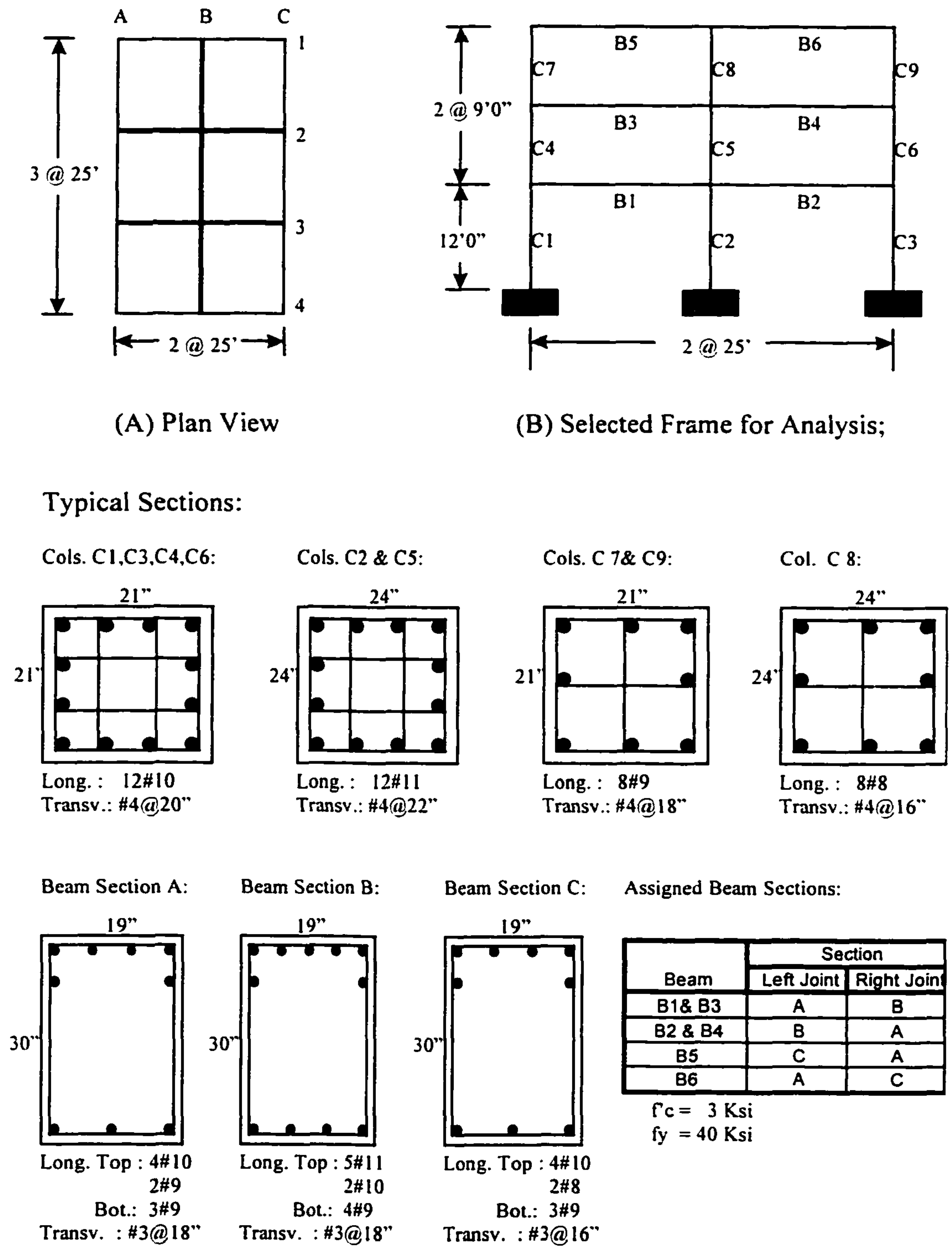
5.2 Selection of Prototypes

The major cities of Puerto Rico (San Juan, Arecibo, Ponce, and Mayagüez) were surveyed through visual inspections to establish building prototypes for the island. The four prototypes selected are buildings of two, three, five and seven stories. The design loads correspond to the 1968 and1987 Puerto Rico Building Codes. Members were designed using the 1968 and 1989 manuals of the American Concrete Institute (ACI). The portal method was employed as a preliminary analysis to estimate the dimensions of the members. A more exact structural analysis was then employed using a linear-elastic analysis program. Once the final dimensions and properties for the members were obtained, the SNAP-2D computer program was used to analyze the buildings and to assess their damage states. Both the El Centro and the Taft earthquakes were used. The former because it was considered as an extraordinary ground motion for Puerto Rico and the later because it is one of two ground motions included in the Puerto Rico Building Code. The analysis were performed by Piñero (1998). Piñero tested different bracing systems as retrofitting technics, with different schemes. The author added another system: the Concenctric-X bracing with Friction connections.

Consequently, because the level of damage was very low for both classes of two-story buildings (Piñero, 1998), they were not considered for retrofitting. Figures 5.1 through 5.6 show geometric and section properties for the remaining prototypes.

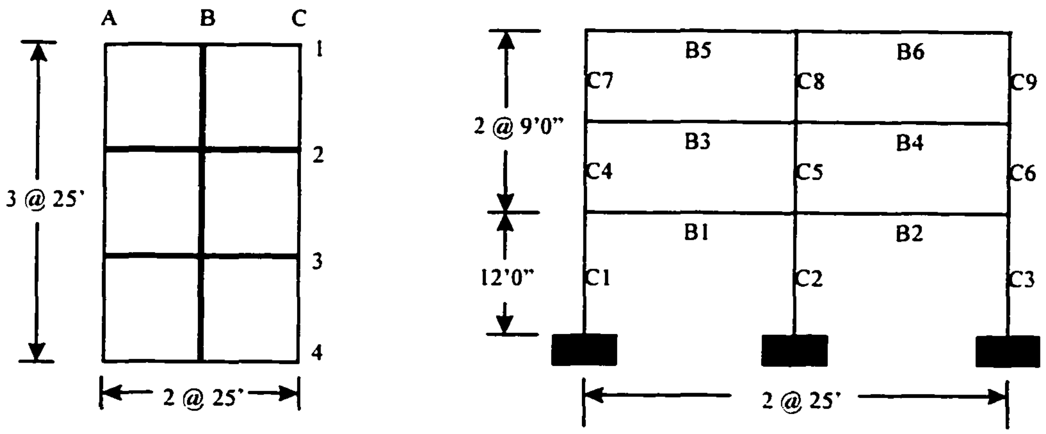
5.3 Selection of the Retrofitting Scheme

The steel bracing system best suited for retrofitting reinforced concrete in Puerto Rico is the concentric X-bracing, with a SR = 3 (Piñero, 1998). The SR is the ratio of the lateral stiffness of the retrofitting system to the lateral story stiffness of the original unretrofitted structure. The decision was based on a series of computer runs using the SNAP-2D program. All prototypes were retrofitted for different schemes in the manner suggested in Figure 5.7 and were subjected to 1.0 El Centro. System evaluations were based on performance, ease of construction, and economy.



Beam	Section	
	Left Joint	Right Join
B1& B3	A	B
B2 & B4	B	A
B5	C	A
B6	A	C

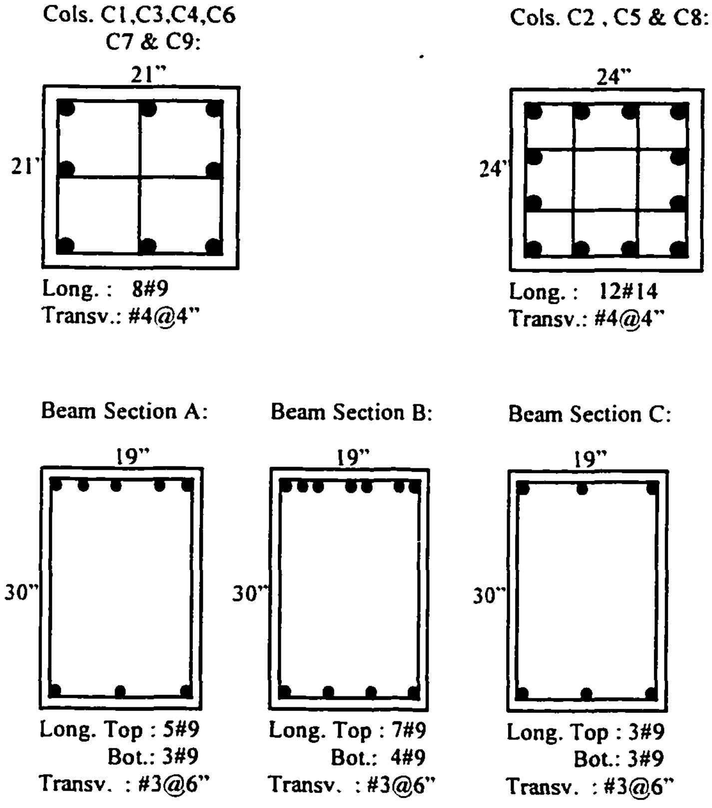
Figure 5.1: Three-story R/C building prototype (1968).



(A) Plan View

(B) Selected Frame for Analysis;

Typical Sections:



Cols. C1,C3,C4,C6
C7 & C9:

Long. : 8#9
Transv.: #4@4"

Cols. C2 , C5 & C8:

Long. : 12#14
Transv.: #4@4"

Beam Section A:

Long. Top : 5#9
Bot.: 3#9
Transv. : #3@6"

Beam Section B:

Long. Top : 7#9
Bot.: 4#9
Transv. : #3@6"

Beam Section C:

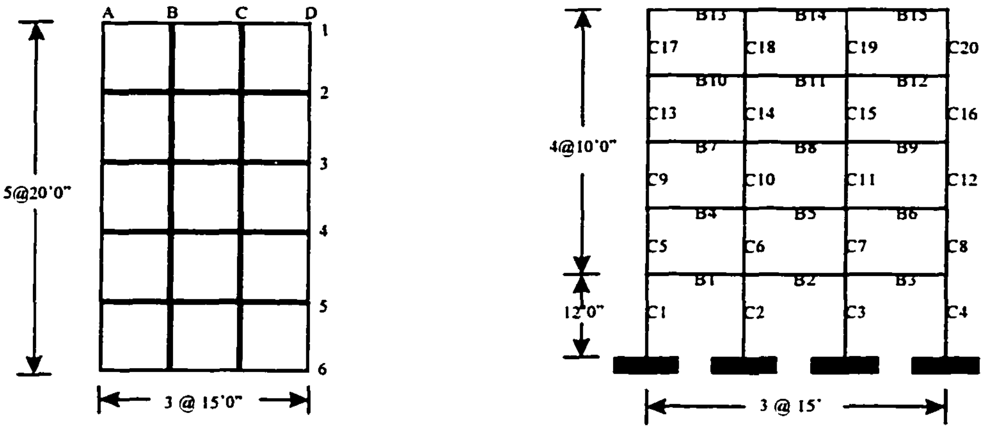
Long. Top : 3#9
Bot.: 3#9
Transv. : #3@6"

Assigned Beam Sections:

Beam	Section	
	Left Joint	Right Join
B1& B3	A	B
B2 & B4	B	A
B5	C	A
B6	A	C

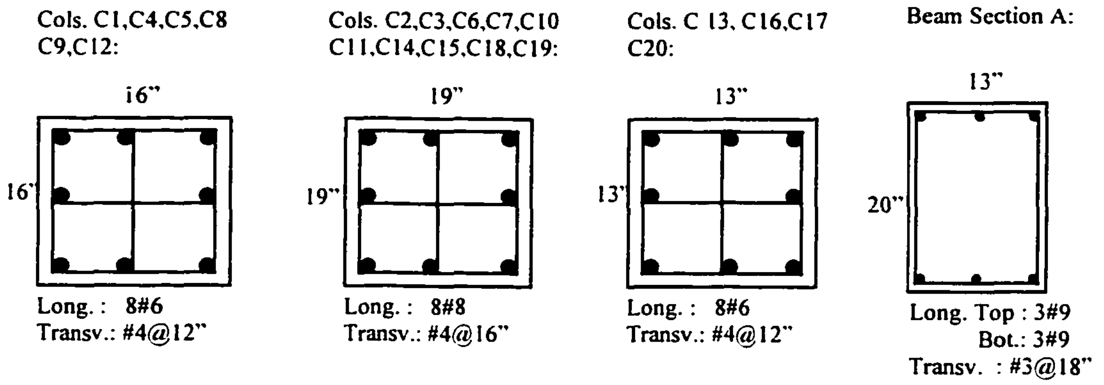
f'c = 3 Ksi
fy = 40 Ksi

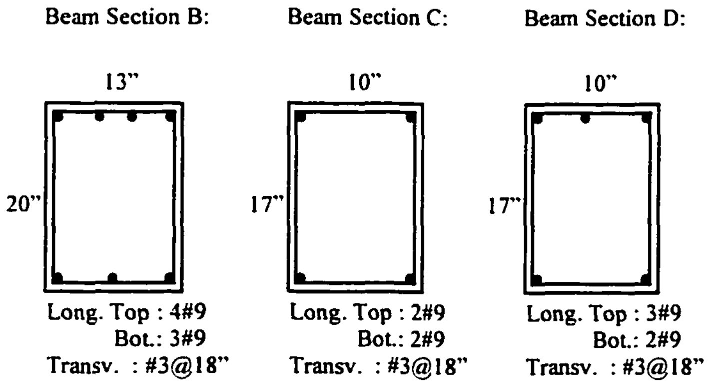
Figure 5.2: Three-story R/C building prototype (1987).



(A) Plan View (B) Selected Frame for Analysis;

Typical Sections:



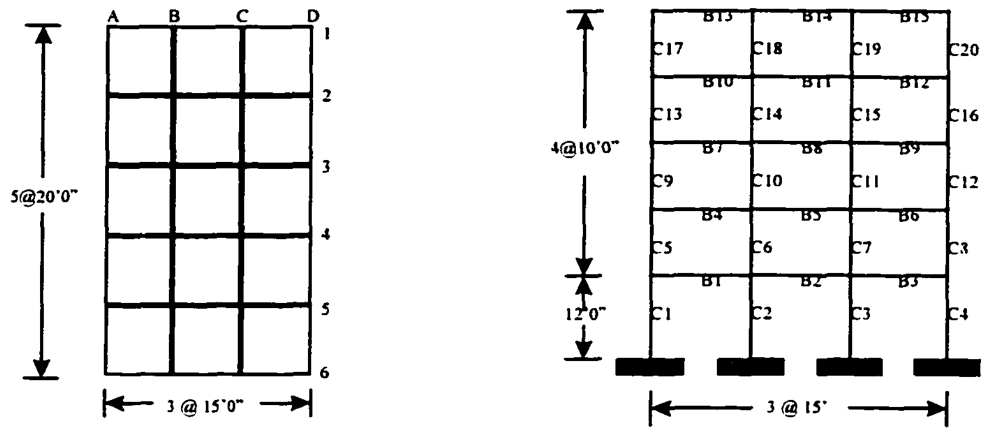


Assigned Beam Sections:

Beam	Section	
	Left Joint	Right Joint
B1,B4,B7	A	B
B2,B5,B8,	B	B
B3,B6,B9	B	A
B10,B13	C	D
B11,B14	D	D
B12,B15	D	C

f'_c = 3 Ksi
f_y = 40 Ksi

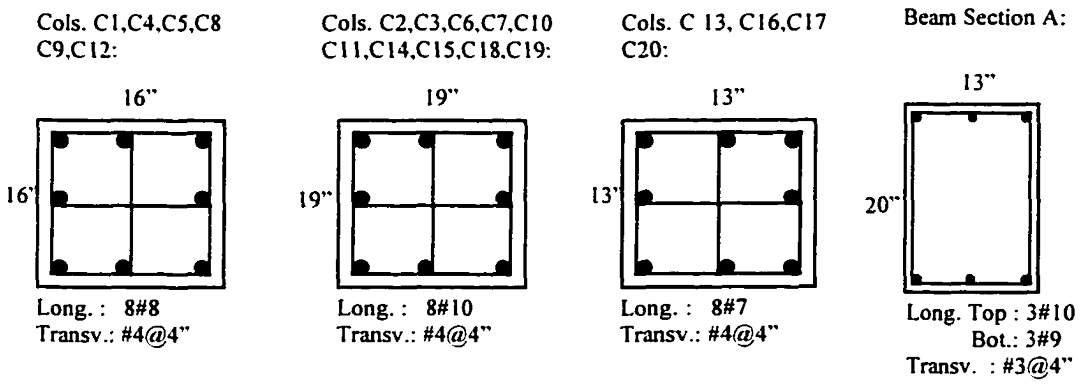
Figure 5.3: Five-story R/C building prototype (1968).

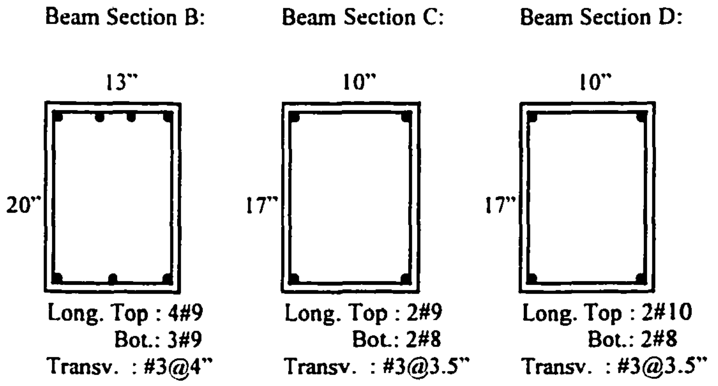


(A) Plan View

(B) Selected Frame for Analysis;

Typical Sections:



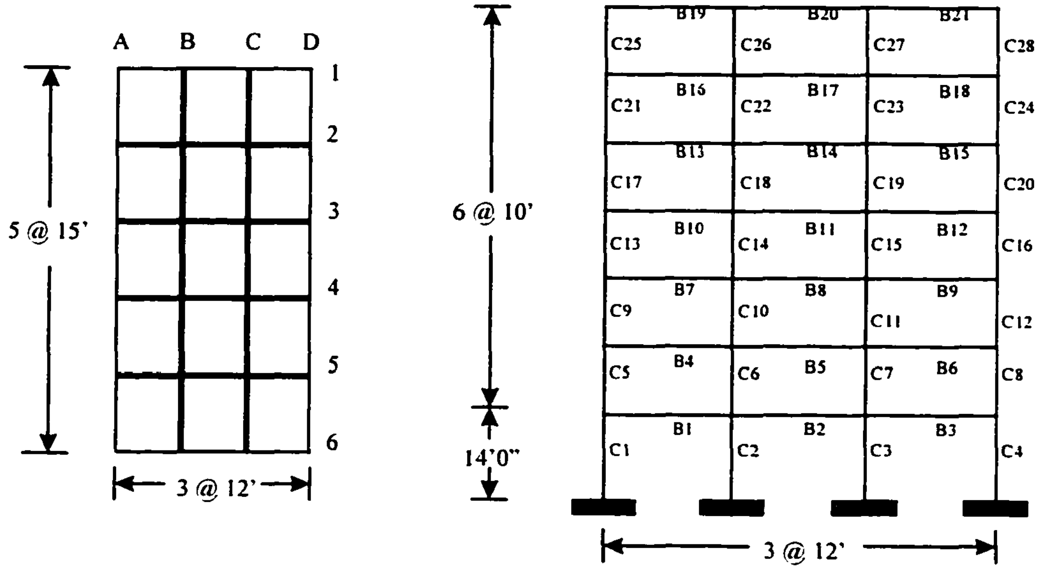


Assigned Beam Sections:

Beam	Section	
	Left Joint	Right Joint
B1,B4,B7	A	B
B2,B5,B8,	B	B
B3,B6,B9	B	A
B10,B13	C	D
B11,B14	D	D
B12,B15	D	C

f'_c = 3 Ksi
f_y = 40 Ksi

Figure 5.4: Five-story R/C building prototype (1987).



(A) Plan View

(B) Selected Frame for Analysis;

Typical Sections:

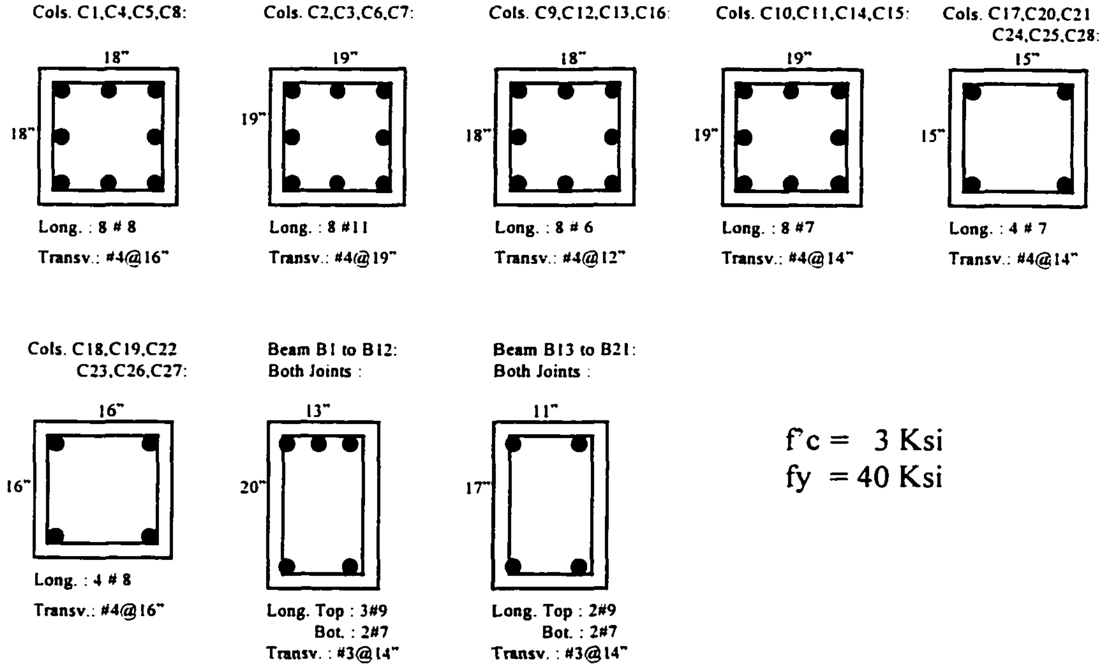
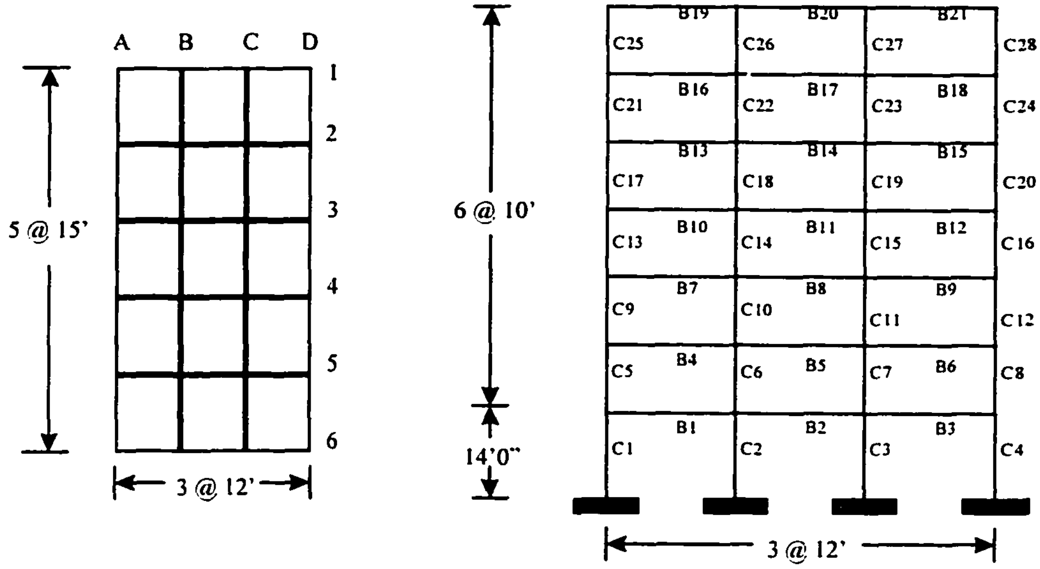


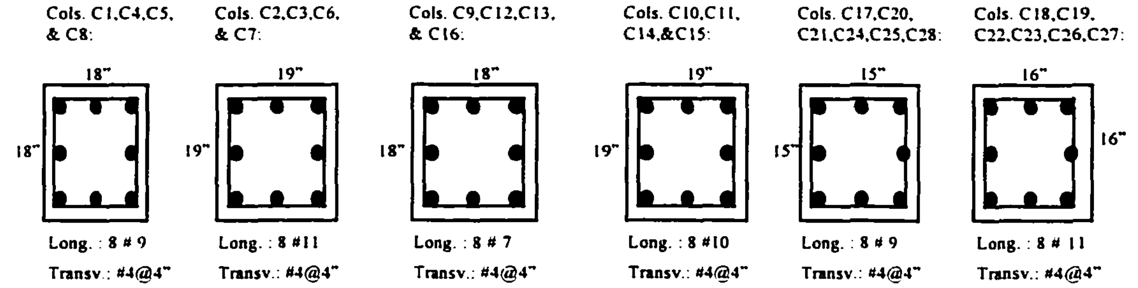
Figure 5.5: Seven-story R/C building prototype (1968).

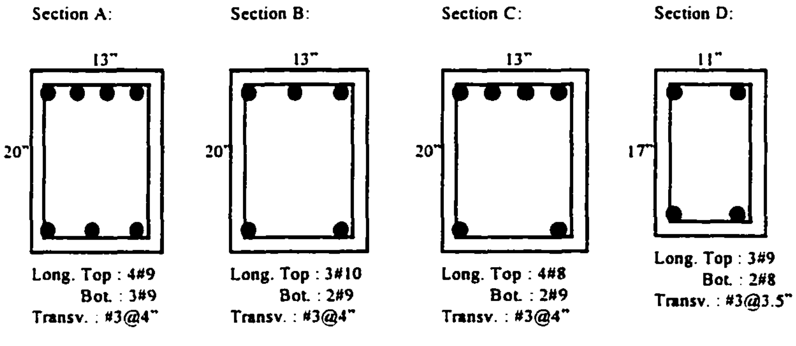


(A) Plan View

(B) Selected Frame for Analysis;

Typical Sections:





Assigned Beam Sections:

Beam	Section	
	Left Joint	Right Joi
B1, B4	A	B
B2, B5	B	B
B3, B6	B	A
B7, B10	B	C
B8, B11	C	C
B9, B12	C	B
B13, B14, B1	D	D

fy = 40 Ksi
f'c = 3 Ksi

Figure 5.6: Seven-story R/C building prototype (1987).

Table 5.1 presents global damage indices for Class 1 retrofitted building prototypes. As shown, the concentric-X bracing system produced the lowest damage index in most cases. It is also easier to construct and the required bracing member areas are smaller than all other options, specially ADAS (Piñero, 1998). Finally, different schemes of concentric-X steel bracing were studied to find out which ones perform the best. Different schemes examined are shown in Figures 5.8 to 5.10. The best schemes were found to be: scheme #2 for the three story building, scheme #3 for the five story building, and scheme #2 for the seven story building. The Jain's brace element was used throughout as it exhibited performance levels similar to friction-type bracing element, yet it is simpler to construct.

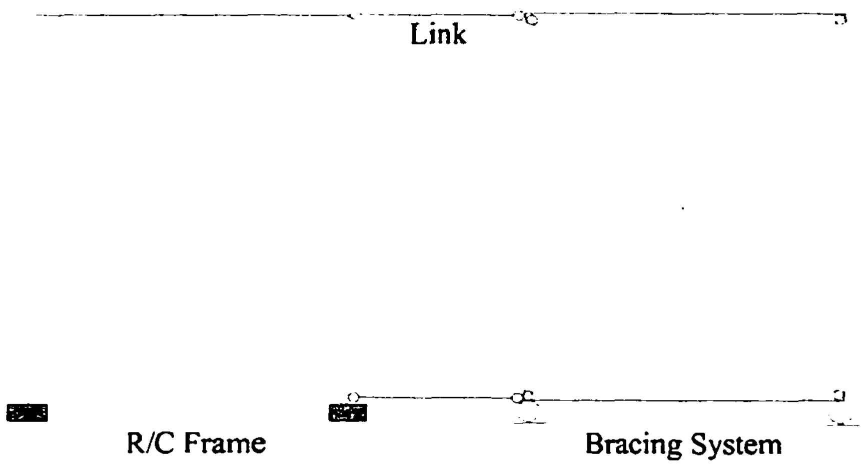
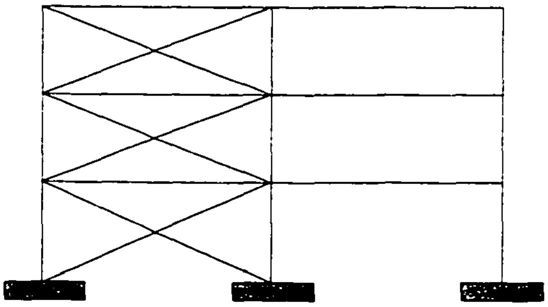


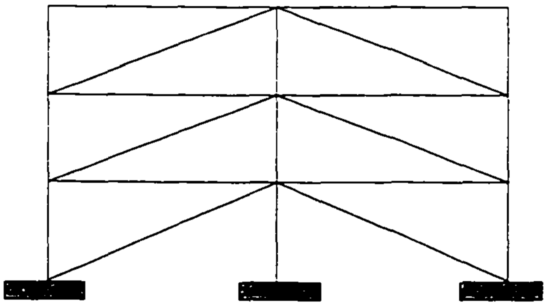
Figure 5.7: Approximate modeling of retrofitting system.

Table 5.1: Global damage indexes for building prototypes using different steel bracing systems.

Retrofitting System	1968 design, El-Centro		
	3-story	*5-story*	*7-story*
Inverted-Y with ADAS	0.20	0.13	0.66
Eccenc-K	0.21	0.20	0.40
Conc-K	0.17	0.16	0.44
Conc-X (with post buckling Truss Element)	0.16	0.22	0.31
Conc-X (with Friction Brace Element)	0.16	0.14	0.32

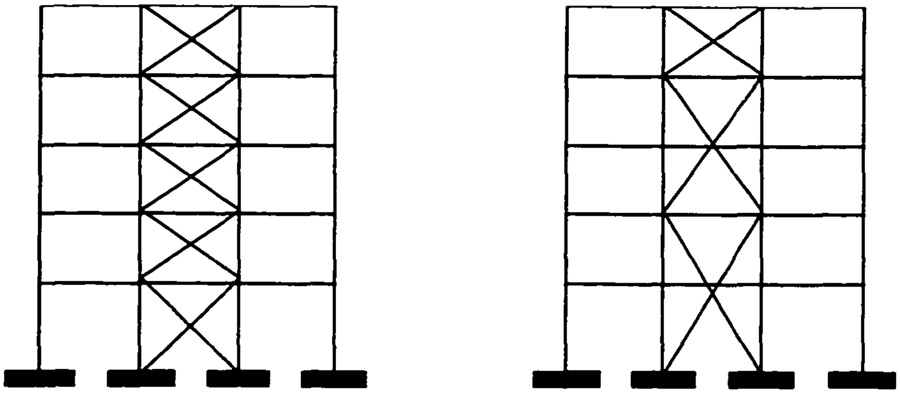


A) Scheme #1



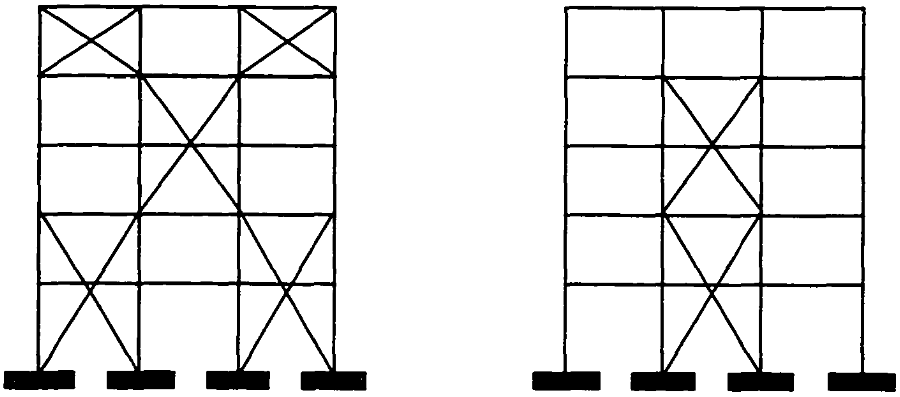
B) Scheme #2

Figure 5.8: Concentric-X steel bracing schemes for the three story R/C building prototype.



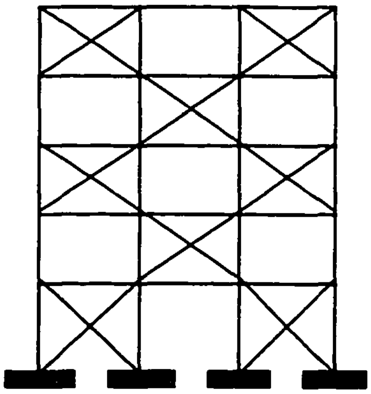
A) Scheme # 1

B) Scheme # 2



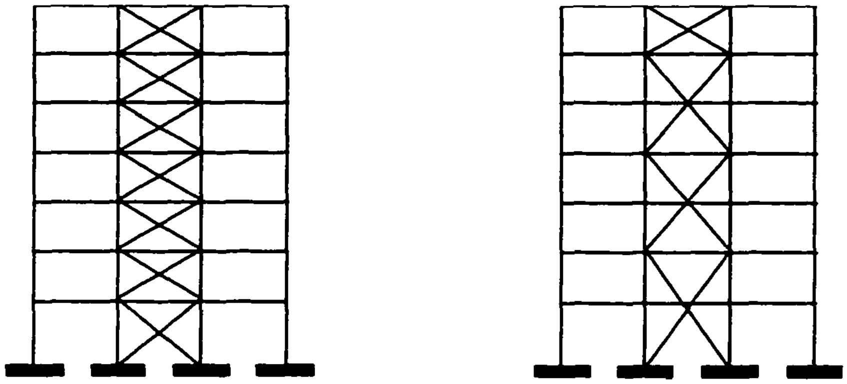
C) Scheme # 3

D) Scheme # 4

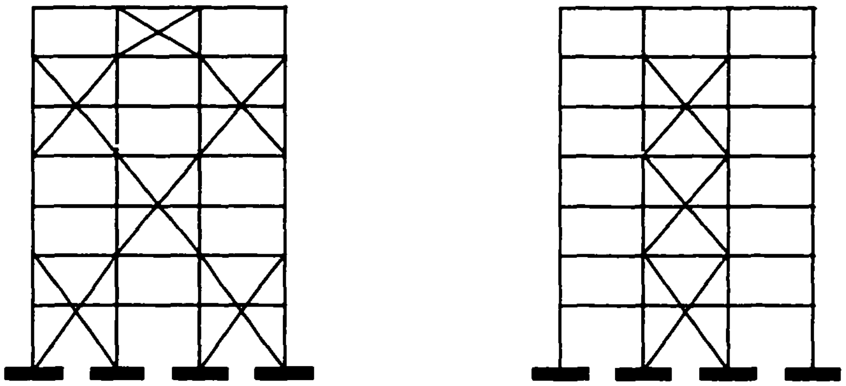


E) Scheme # 5

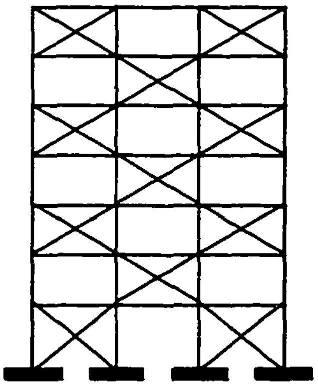
Figure 5.9: Concentric-X steel bracing schemes for the five-story R/C building prototype.



A) Scheme # 1 B) Scheme # 2



C) Scheme # 3 D) Scheme # 4



E) Scheme # 5

Figure 5.10: Concentric-X steel bracing schemes for the seven-story R/C building prototype.

5.4 The Decision Making Process

The decision on whether or not to retrofit may be based on the following general equation:

$$E(C_{LC})_{unretrofitted} > E(C_{LC})_{retrofitted}$$
$$E(C_D)_U > E(C_D)_R + C_U \qquad \textbf{(5.1)}$$

From the above equation, if the cost associated with the damage on the unretrofitted structure exceeds the cost related to the damage on the retrofitted structure plus the retrofitting cost, the reinforced concrete building most be rehabilitated. For illustration purposes, the six prototype buildings were evaluated using Equation 5.1. The non-linear dynamic analysis was performed using the SNAP-2D computer program. Tables 5.2, 5.3 and 5.4 show the damage states reached by those prototypes at the four different earthquake intensity levels.

Table 5.2: Global damage indices for three story building prototypes

Factored Intensity for Taft Earthquake[1]	**1968 Code**		**1987 Code**	
	Unretrofitted	**Retrofitted**	**Unretrofitted**	**Retrofitted**
1.94 (2%)	0.4265	0.1823	0.2220	0.0882
1.73 (5%)	0.3949	0.1626	0.1826	0.0801
1.59 (10%)	0.3598	0.1494	0.1717	0.0735
1.22 (50%)	0.3539	0.1146	0.1552	0.0565

[1] Numbers in parentheses represent recurrence rates for Puerto Rico.

Table 5.3: Global damage indices for five story building prototypes

Factored Intensity for Taft Earthquake[1]	1968 Code		1987 Code	
	Unretrofitted	Retrofitted	Unretrofitted	Retrofitted
1.94 (2%)	0.2583	0.1286	0.2397	0.1286
1.73 (5%)	0.2404	0.1124	0.2303	0.1124
1.59 (10%)	0.2345	0.1035	0.2148	0.0766
1.22 (50%)	0.2012	0.0831	0.1683	0.0588

1. Numbers in parentheses represent recurrence rates for Puerto Rico.

Table 5.4: Global damage indices for seven story building prototypes

Factored Intensity for Taft Earthquake[1]	1968 Code		1987 Code	
	Unretrofitted	Retrofitted	Unretrofitted	Retrofitted
1.94 (2%)	0.5585	0.3408	0.2625	0.2382
1.73 (5%)	0.5307	0.3157	0.2414	0.2260
1.59 (10%)	0.4976	0.2985	0.2308	0.2095
1.22 (50%)	0.4406	0.2768	0.1840	0.1609

1. Numbers in parentheses represent recurrence rates for Puerto Rico.

Afterward, the economic model is fed using the damages previously calculated. The associated economic losses are presented in Tables 5.5 through Tables 5.16. These tables provide guidelines on what types of damage costs may be expected for different types of occupancies and earthquake intensities.

Table 5.5: Damage costs in US dollars for three story building prototypes

(1968 design - T_R = 1 year)

Damage Cost - Retrofitted Structure				***Taft by***	**Damage Cost - Unretrofitted Structure**			
D_M	Residential	Business	Factory		D_M	Residential	Business	Factory
0.115	172,176	276,913	195,657	**1.22**	0.354	545,446	1,548,374	776,519
0.149	224,685	402,508	264,277	**1.59**	0.360	555,423	1,592,482	794,981
0.163	244,668	455,272	291,512	**1.73**	0.400	618,417	1,877,658	914,797
0.182	274,578	539,291	333,436	**1.94**	0.426	714,119	2,180,247	1,066,284

Table 5.6: Damage costs in US dollars for three story building prototypes

(1968 design - T_R from Table 3.3)

Damage Cost - Retrofitted Structure				***Taft by***	**Damage Cost - Unretrofitted Structure**			
D_M	Residential	Business	Factory		D_M	Residential	Business	Factory
0.115	172,122	229,020	184,471	**1.22**	0.354	545,055	1,651,432	793,041
0.149	224,596	338,599	249,007	**1.59**	0.360	555,023	1,710,949	814,764
0.163	244,565	408,992	275,021	**1.73**	0.400	617,956	2,107,763	958,435
0.182	274,450	491,316	315,607	**1.94**	0.426	713,607	2,529,966	1,066,284

Table 5.7: Damage costs in US dollars for three story building prototypes

(1987 design - $T_R = 1$ year)

Damage Cost - Retrofitted Structure				*Taft by*	Damage Cost - Unretrofitted Structure			
D_M	Residential	Business	Factory		D_M	Residential	Business	Factory
0.056	84,904	110,589	91,006	**1.22**	0.222	335,262	727,958	422,780
0.074	110,401	153,663	120,370	**1.59**	0.183	275,034	540,620	334,087
0.080	120,337	171,686	132,084	**1.73**	0.172	258,471	493,297	310,686
0.088	132,472	194,635	146,595	**1.94**	0.155	233,460	425,344	276,161

Table 5.8: Damage costs in US dollars for three story building prototypes

(1987 design - T_R from Table 3.3)

Damage Cost - Retrofitted Structure				*Taft by*	Damage Cost - Unretrofitted Structure			
D_M	Residential	Business	Factory		D_M	Residential	Business	Factory
0.057	84,890	94,014	87,258	**1.22**	0.222	335,081	658,087	404,601
0.074	110,378	128,290	114,579	**1.59**	0.183	274,906	468,058	316,243
0.080	120,310	142,702	125,444	**1.73**	0.172	258,356	422,649	293,497
0.088	132,439	161,175	138,896	**1.94**	0.155	233,365	359,357	260,325

Table 5.9: Damage costs in US dollars for five story building prototypes

(1968 design - T_R = 1 year)

Damage Cost - Retrofitted Structure			*Taft by*	Damage Cost - Unretrofitted Structure		
D_M	Residential	Business		D_M	Residential	Business
0.083	249,193	432,366	**1.22**	0.222	605,250	1,677,324
0.104	310,412	594,319	**1.59**	0.183	706,789	2,163,385
0.112	337,146	671,904	**1.73**	0.172	724,866	2,255,757
0.129	385,860	823,942	**1.94**	0.201	779,904	2,547,579

Table 5.10: Damage costs in US dollars for five story building prototypes

(1968 design - T_R from Table 3.3)

Damage Cost - Retrofitted Structure			*Taft by*	Damage Cost - Unretrofitted Structure		
D_M	Residential	Business		D_M	Residential	Business
0.083	249,095	330,152	**1.22**	0.222	604,743	1,432,610
0.104	310,263	454,386	**1.59**	0.183	706,126	1,945,442
0.112	336,973	515,950	**1.73**	0.172	724,174	2,047,356
0.129	385,636	640,580	**1.94**	0.201	779,122	2,378,032

Table 5.11: Damage costs in US dollars for five story building prototypes

(1987 design - T_R = 1 year)

Damage Cost - Retrofitted Structure			*Taft by*	Damage Cost - Unretrofitted Structure		
D_M	Residential	Business		D_M	Residential	Business
0.0598	176,365	268,286	1.22	0.168	505,566	1,255,673
0.0766	229,703	385,407	1.59	0.215	646,628	1,868,608
0.112	337,148	671,904	1.73	0.230	693,938	2,098,779
0.129	385,860	823,943	1.94	0.240	722,719	2,244,699

Table 5.12: Damage costs in US dollars for five story building prototypes

(1987 Design - T_R from Table 3.3)

Damage Cost - Retrofitted Structure			*Taft by*	Damage Cost - Unretrofitted Structure		
D_M	Residential	Business		D_M	Residential	Business
0.0588	176,315	209,185	1.22	0.168	505,198	1,022,566
0.0766	229,619	295,119	1.59	0.215	646,059	1,629,573
0.112	336,974	515,950	1.73	0.230	693,296	1,874,978
0.129	385,636	640,580	1.94	0.240	722,031	2,035,084

Table 5.13: Damage costs in US dollars for seven story building prototypes

(1968 design - $T_R = 1$ year)

Damage Cost - Retrofitted Structure			*Taft by*	Damage Cost - Unretrofitted Structure		
D_M	Residential	Business		D_M	Residential	Business
0.277	704,371	3,093,082	**1.22**	0.441	1,199,196	7,275,702
0.298	761,534	3,540,185	**1.59**	0.498	1,265,838	9,041,388
0.316	807,346	3,916,220	**1.73**	0.531	1,323,828	10,192,193
0.341	875,207	4,496,779	**1.94**	0.558	1,389,325	11,239,886

Table 5.14: Damage costs in US dollars for seven story building prototypes

(1968 design - T_R from Table 3.3)

Damage Cost - Retrofitted Structure			*Taft by*	Damage Cost - Unretrofitted Structure		
D_M	Residential	Business		D_M	Residential	Business
0.277	703,338	2,960,600	**1.22**	0.441	1,197,097	8,898,816
0.298	760,365	3,514,660	**1.59**	0.498	1,263,390	11,896,709
0.316	806,066	3,998,941	**1.73**	0.531	1,321,194	13,941,408
0.341	873,763	4,780,770	**1.94**	0.558	1,386,548	15,848,861

Table 5.15: Damage costs in US dollars for seven story building prototypes

(1987 design - $T_R = 1$ year)

Damage Cost - Retrofitted Structure			*Taft by*	Damage Cost - Unretrofitted Structure		
D_M	Residential	Business		D_M	Residential	Business
0.161	406,369	1,213,580	**1.22**	0.184	465,026	1,519,975
0.210	530,192	1,897,847	**1.59**	0.231	584,928	2,245,038
0.226	572,465	2,163,635	**1.73**	0.241	612,283	2,428,508
0.238	603,964	2,372,020	**1.94**	0.262	667,019	2,814,989

Table 5.16: Damage costs in US dollars for seven story building prototypes

(1987 design - T_R from Table 3.3)

Damage Cost - Retrofitted Structure			*Taft by*	Damage Cost - Unretrofitted Structure		
D_M	Residential	Business		D_M	Residential	Business
0.161	405,970	947,059	**1.22**	0.184	464,518	1,234,193
0.210	529,552	1,612,850	**1.59**	0.231	584,169	1,982,315
0.226	572,734	1,893,946	**1.73**	0.241	611,463	2,185,229
0.238	603,163	2,122,212	**1.94**	0.262	666,074	2,628,774

The calculated damage costs are then used to obtain the life cycle costs for the buildings prototypes using Equation 5.1. For example, if we were to consider the Class 1 three story residential building and use T_R equal to 1:

$$E(C_{LC})_R = 0.21\,((\frac{0.4}{0.5})(172{,}176) + (\frac{0.05}{0.5})(224{,}685) + (\frac{0.03}{0.5})(224{,}668) +$$

$$(\frac{0.02}{0.5})(274{,}578)) + (3\,(3{,}750)(14.5)) = \$\,201{,}906$$

and

$$E(C_{LC})_U = 0.21\,((\frac{0.4}{0.5})(545{,}446) + (\frac{0.05}{0.5})(555{,}423) + (\frac{0.03}{0.5})(618{,}417) +$$

$$(\frac{0.02}{0.5})(714{,}119)) = \$\,117{,}089$$

Therefore, one need not retrofit this building for residential use.

Life cycle cost analysis for different prototypes are shown in Tables 5.17 to 5.19, where the values are rounded for simplification. As shown, for the three story building prototypes, only Class 1 with business occupancy type should be rehabilitated. The same holds true for the seven story building prototypes. The five story buildings appeared to be economically sound for the occupancies types considered.

Notice that in the case of five and seven-story buildings, the results for manufacturing type occupancy were not included. That is because these building sizes were not considered practical for a factory. The life cycle cost analysis provides the designer with a decision making toolset that can be implemented to fit any or all possible design situations.

Consider if you were the owner of the Class 1 three story building prototype. If your main interest in the building is the rent income, then you should be advised not to retrofit. However, if you run a business of the type presented in Table 5.17, then it will make sense for you to retrofit.

Table 5.17: Life cycle cost comparisons for three story building prototypes.

Design	**Occupancy**	**Unretrofitted Costs in US Dollars**		**Retrofitted Costs in US Dollars**		***Decision to Retrofit***	
		T_R = 1 Year	**T_R from Table 3.3**	**T_R = 1 Year**	**T_R from Table 3.3**	**T_R = 1**	**T_R from Table 3.3**
1968	Residential	117,000	117,000	202,000	202,000	No	No
	Business	336,000	361,000	228,000	218,000	Yes	Yes
	Factory	168,000	171,000	208,000	206,000	No	No
1987	Residential	67,000	67,000	182,000	182,000	No	No
	Business	143,000	129,000	189,000	185,000	No	No
	Factory	84,000	81,000	184,000	183,000	No	No

Another interesting case could involve insurance companies. Having insured an economically viable business that runs through a seismically deficient rented building, there may be some need to present incentives to the building owners to retrofit. These incentives could be in the form of discounted insurance premiums.

Table 5.18: Life cycle cost comparisons for five story building prototypes.

Design	**Occupancy**	**Unretrofitted Costs in US Dollars**		**Retrofitted Costs in US Dollars**		***Decision to Retrofit***	
		T_R = 1 Year	**T_R from Table 3.3**	**T_R = 1 Year**	**T_R from Table 3.3**	**T_R = 1**	**T_R from table 3.3**
1968	Residential	132,000	132,000	382,000	382,000	No	No
	Business	377,000	327,000	427,000	403,000	No	No
1987	Residential	113,000	113,000	368,000	368,000	No	No
	Business	296,000	247,000	395,000	378,000	No	No

Table 5.19: Life cycle cost comparisons for seven story building prototypes.

Design	**Occupancy**	**Unretrofitted Costs in US Dollars**		**Retrofitted Costs in US Dollars**		***Decision to Retrofit***	
		T_R = 1 Year	**T_R from Table 3.3**	**T_R = 1 Year**	**T_R from Table 3.3**	**T_R = 1**	**T_R from Table 3.3**
1968	Residential	256,000	256,000	426,000	426,000	No	No
	Business	1,635,000	2,054,000	955,000	936,000	Yes	Yes
1987	Residential	104,000	104,000	366,000	366,000	No	No
	Business	357,000	299,000	565,000	509,000	No	No

Since the life cycle cost methodology was implemented for Puerto Rico, where the recurrence rates for significant earthquakes are low, it was thought interesting to investigate a somewhat different scenario. Increasing the R_D value from 0.21 to 0.7, then all Class 2 three story building prototypes would require retrofitting while they did not before. This is shown in Figures 5.11-5.13. Figures 5.14 and 5.15 show similar patterns for Class 2 five story building prototypes.

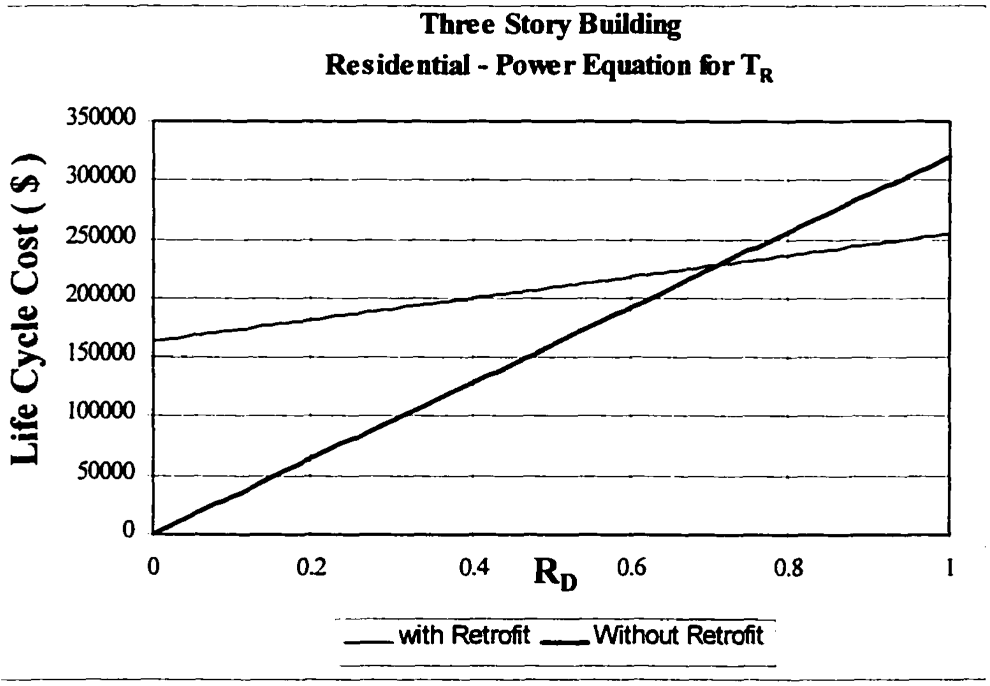


Figure 5.11: Variation of the cycle cost with R_D for a 1987 residential three story building.

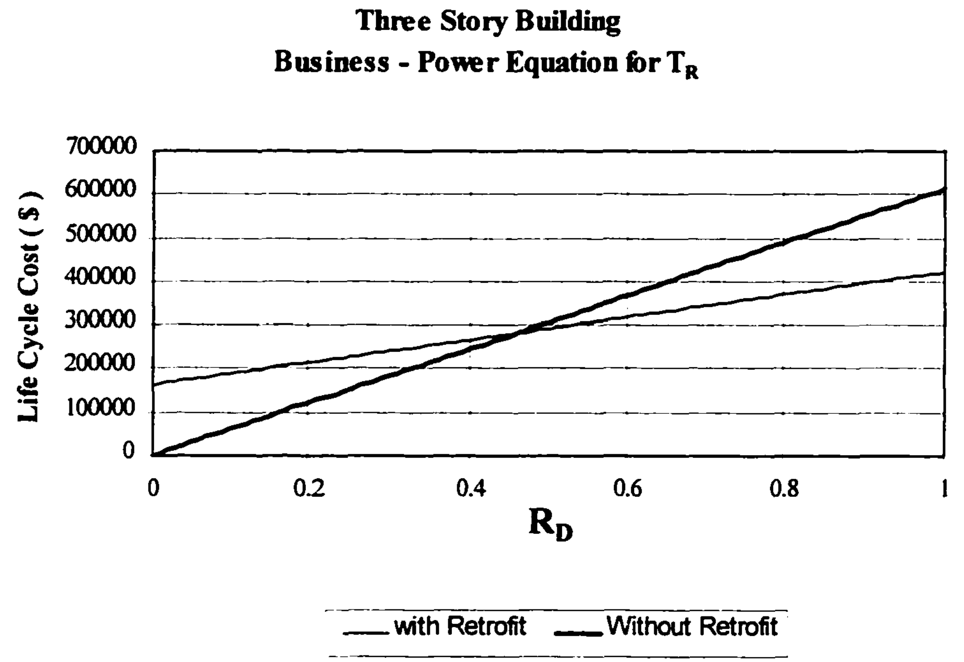


Figure 5.12: Variation of the life cycle cost with R_D for a 1987 business three story building.

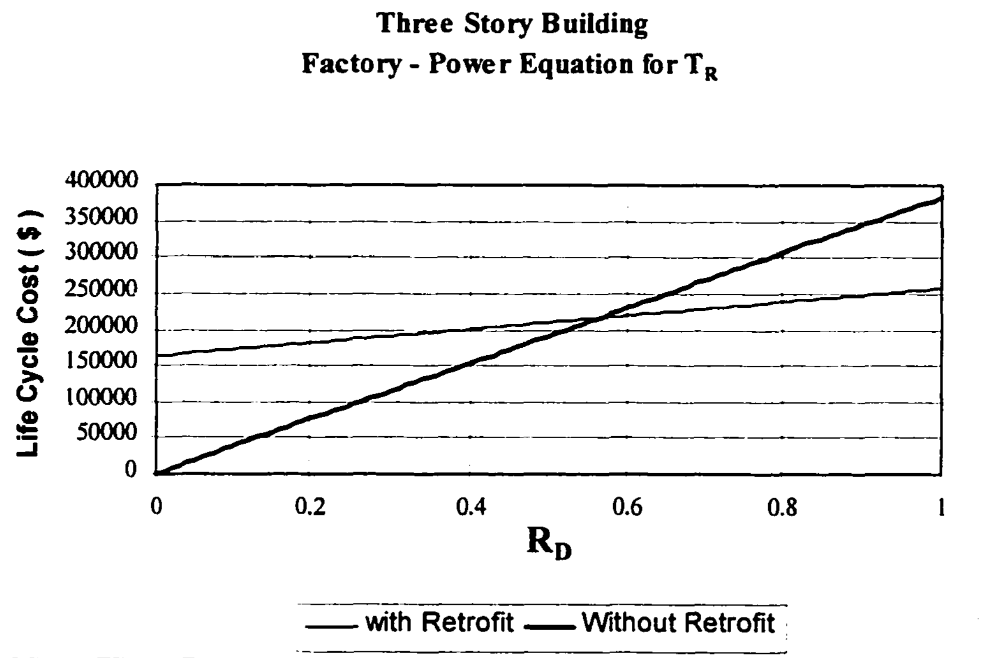


Figure 5.13: Variation of the life cycle cost with RD for a 1987 factory three story building.

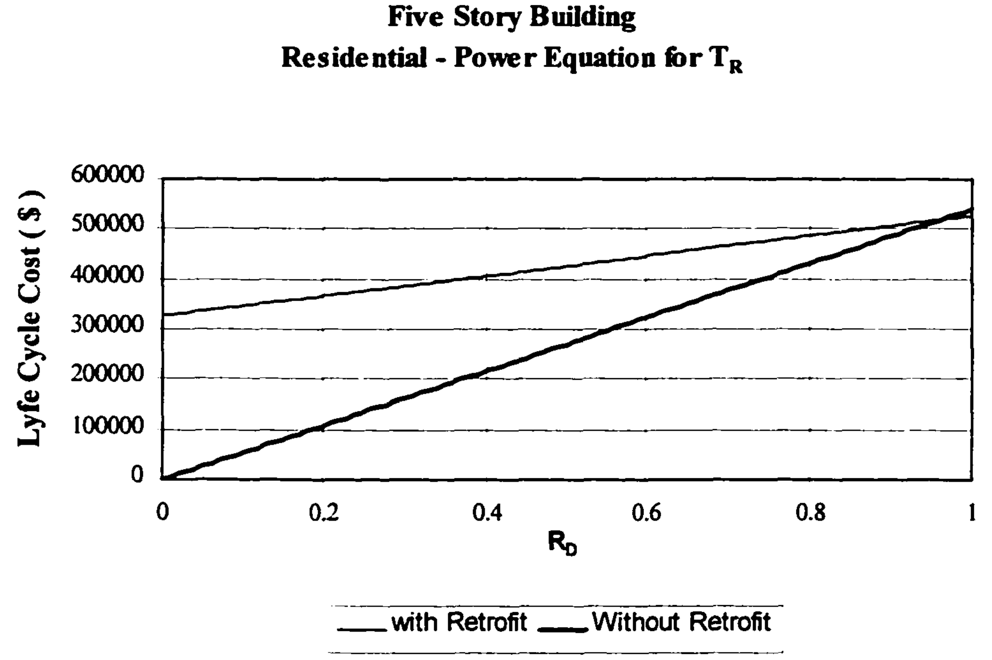


Figure 5.14: Variation of the life cycle cost with R_D for a 1987 residential five story building.

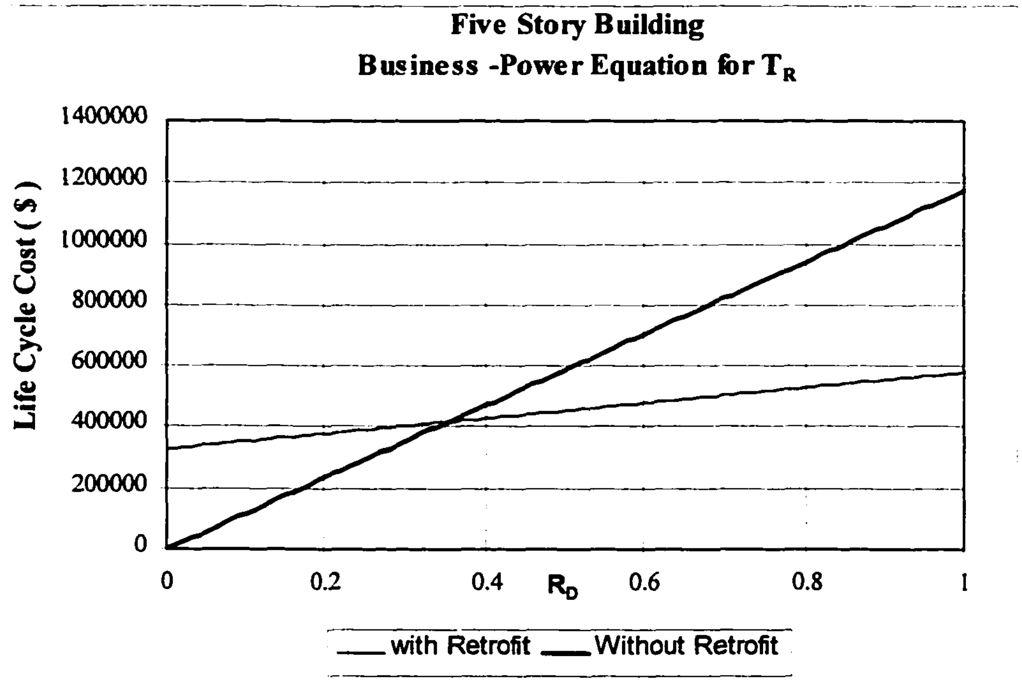


Figure 5.15: Variation of the life cycle cost with R_D for a 1987 business five story building.

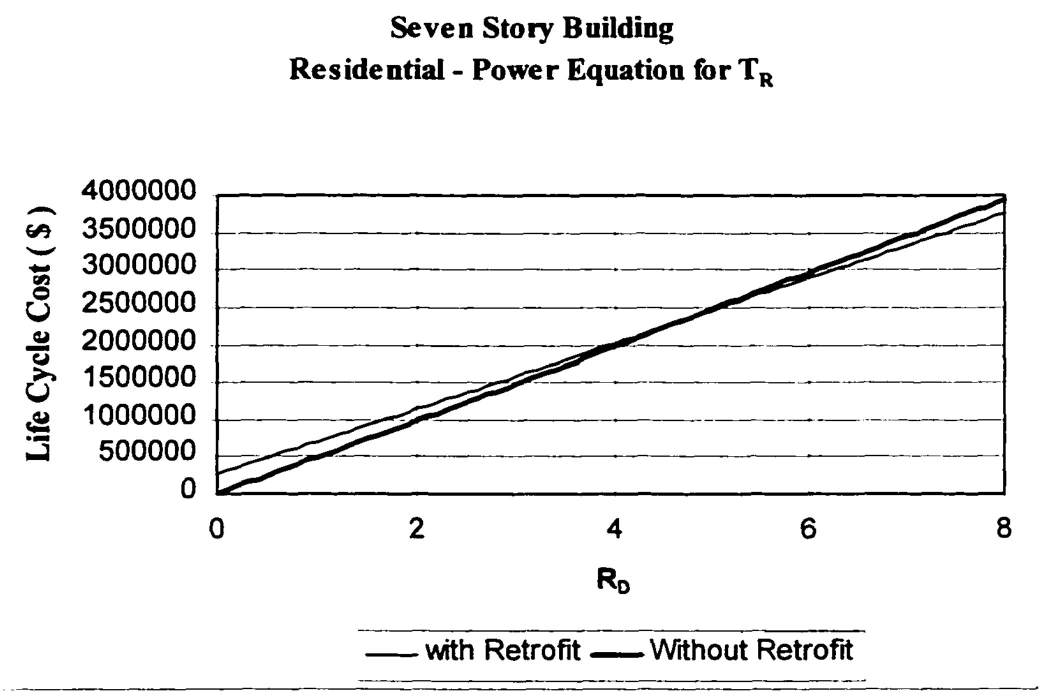


Figure 5.16: Variation of the life cycle cost with R_D for a 1987 residential seven story building.

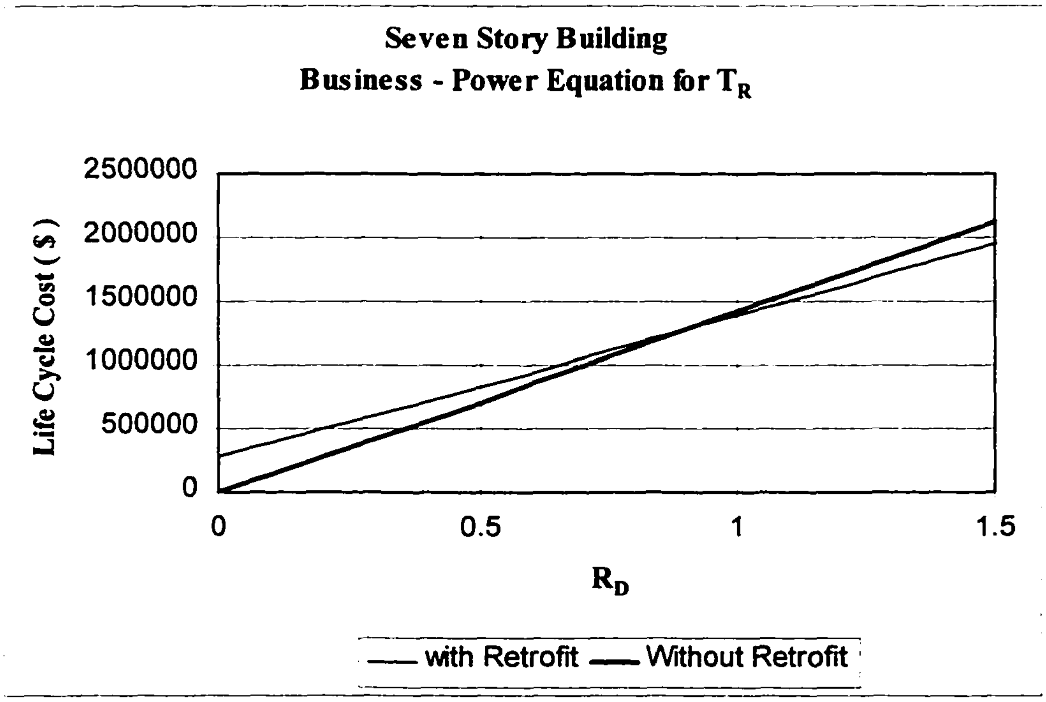


Figure 5.17: Variation of the life cycle cost with R_D for a 1987 business seven story building.

The seven stories building prototype, illustrated in Figures 5.16 and 5.17, poses a different problem. That is because for R_D values as high as 6, there may be no need to retrofit. Historical data clearly indicates that higher recurrence rates are not real possibilities for most areas including Puerto Rico. An analogous scenario happens with the other occupancy type. Again, this reflects the importance of the recurrence rate of earthquakes.

The result presented here correspond to data surveyed at the Mayagüez region. Nevertheless, having some businesses that double or even triple, those showed in Table 2.6 could be possible. The effect of this, as will be shown, is very important, specially in the regard of the building code. When a building is designed, the occupancy is taken into account to define live loads of the building. However, what kind of business density the buildings will have, is not considered. Table 5.20 shows what is stated above, varying the density from one half, two and three time the economic vectors used on the section 2.6. Thus, looking at the five stories building, which for neither the 1968 nor 1987 codes required retrofitting, when the businesses have two time the C_E's vectors, the building requires retrofitting. In other words, if the business density is higher by a factor of two or greater, the building needs to be rehabilitated. A similar pattern follows the other two prototypes. This brings up the possibility to introduce an economic factor in the codes.

Table 5.20: Decision to retrofit the business buildings when the C_E factor has been increased.

Buildings		Three Story				Five Story				Seven Story			
Factors Time C_E		1	1/2	2	3	1	1/2	2	3	1	1/2	2	3
1968	$T_R = 1$	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
	T_R from Table 3.3	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
1987	$T_R = 1$	No	No	Yes	Yes	No	No	Yes	Yes	No	No	No	No
	T_R from Table 3.3	No	No	No	Yes	No	No	No	Yes	No	No	No	No

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary

This thesis has addressed some of the perceived problems with the aging infrastructure in Puerto Rico. The basic objective was to devise a scheme that will facilitate the decision making process for seismic retrofitting of reinforced concrete structures.

The required level of protection when upgrading an existing building for earthquakes proved to be more than a mere function of the replacement cost versus the repair cost. It includes both direct and indirect effects from the loss of capital and human stocks. The general economic model selected for this study is consistent with the systematic approach proposed by Ang and De León (1995). It calculates the damage cost to a building in the event of an earthquake as the sum of direct flows from the stock of the capital and human capital. The factors considered are the replacement or repair cost, C_R, loss of content, C_C, human injury and fatality factor, C_H, and economic loss, C_E.

The Park-Ang model was used to calculate damage indices for reinforced concrete members. At the story level the component indices were weighted and combined based on the load assigned to each component. The procedure is extended to the structural level resulting in a global damage index, D_m, which is then used to calculate damage cost factors. For the purpose of this investigation, seismic performance levels for buildings were identified as immediate occupancy ($D_m \leq 0.2$), damage control ($0.2 < D_m \leq 0.3$), life safety ($0.3 < D_m \leq 0.4$), and collapse ($D_m \geq 0.4$). Replacement or repair cost factor, C_R, and loss of content factors, C_C, usually are linear functions of the damage index. Loss of human capital factor, C_H, is calculated using human fatality rate, R_f, formulated as an exponential function of the damage index.

The Input-Output model for economy which was originally designed by Leontief (1941) is utilized to calculate the economic loss factor, C_E. The model uses a direct plus an indirect requirement matrix, referred to as Leontief inverse matrix, to relate the gross output of an economic sector to the sector output available for the final consumption. The Leontief inverse matrix for Puerto Rico is available through the Junta de Planificación de Puerto Rico (1990). The five economic sectors considered are agriculture, mining and construction, manufacturing, service, and government.

The expected life-cycle cost function for a retrofitted structure will involve both the damage cost total and the upgrading cost. The latter is calculated using the option 2 model in FEMA-156 and will be in present worth. Assuming that the occurrences of potentially damage inducing earthquakes follows a Poisson process, the damage cost total is also converted to the same base value.

Two classes of R/C buildings are considered. Old buildings that were properly designed at for the time of their construction (Class 1), and buildings that satisfy current building code regulations (Class 2). Four prototype buildings were selected, each of several designs to cover both classes. The concentric-X steel bracing systems found to be the best suited steel bracing systems for Puerto Rico (Piñero,1998), was used as the retrofitting scheme in this study.

6.2 Contributions

The proposed cost-performance methodology presents several contributions to the earthquake loss estimation area which are unique to this study. These contributions are restated as follows.

The definition of the economic loss model and the quantification of terms are unique to this study. They required the evaluation of three cost vectors representing the gross income, the expenses, and the payroll. Since most businesses are reluctant to provide cost information, the very limited data required for this model is an advantage. It is the first time that Input-Output matrix is used to evaluate the total economic loss associated with one single building.

A power equation to calculate the restoration time for different facilities was developed. Although the regression coefficients are based on the data generated elsewhere (ATC-13, 1985), the basic model is new to this study and only here the specialized equations are developed for different occupancies.

The repair or replacement cost function is formulated in terms which may be easily quantified. The total repair-to-initial cost ratio presented is the first to include the catastrophe factor, thought most appropriate for this type of cost analysis.

The load cell concept is used to estimate the number of injuries or casualties in a building, presenting a systematic way to evaluate the loss by breaking the overall cost structure in four basic quantifiable components. These components represents minor injuries, defined as those not requiring hospitalization, major injuries, divided into non-disabling and disabling types, and fatalities.

The application of a basic decision model to a zone of low recurrence rates for earthquakes of significance was performed for the first time combining Ang's present worth model (Ang and De León, 1995b) with a discrete model of costs from weighted earthquakes. The only inputs required are the design earthquake and the recurrence rates and intensities of significant earthquakes for the region.

This is the first study to consider the effects of the occupancy types on the decision making process to retrofit. The economic occupancies, mixed occupancies, business densities, inter-relations with earthquake recurrence rates and intensities are discussed in details. As a result, creating different cost schedules to match a client's specific needs is now possible, whether the client is the owner, the tenant, the government, or the insurance company.

6.3 Conclusions

It is a long held belief that due to insufficient design loads and ductility details, augmented with the recent revisions to the Puerto Rico building code, a large number of older buildings are no longer adequate to withstand a major earthquake. The results of this study contradict that belief. In fact, it now appears that the more conservative ACI specifications of the past are more of a correcting measure than once thought. In cases where rehabilitation was needed, concentric braced frame systems specially X-braced frames proved the most economical. However, this was mostly true for Class 1 buildings. For Class 2 buildings, the seismic performance level would rarely improve enough to justify the upgrading costs.

Other significant conclusions derived from this research are summarized in the following:

- A methodology to measure the economic impacts of an earthquake through partial or total loss of buildings was successfully established. It takes into account the cost to the building structure, loss of contents, human casualties, and economic losses. The corresponding damage cost functions were formulated in terms which are easily quantified. The design examples for Puerto Rico present the practical significance of the proposed methodology.
- The Input-Output analysis has long been recognized as a powerful tool to identify reductions to the supply and demand of a region's economy. Its inclusion to measure the economic losses associated with a single building proved satisfactory.
- Easy-to-use cost schedules can be implemented to simplify the decision making process for seismic rehabilitation of reinforced concrete structure.
- The occupancy types in a building play a crucial role in the determination of damage costs in the aftermath of an earthquake.

- The reconstruction time proved to be a very important parameter in damage cost computations. Smart emergency planning should reduce this time considerably.
- The model indicates the importance of the recurrence rate of significant earthquakes, and not just their intensities. A building that does not require retrofitting in Puerto Rico may do so in California.
- The economic function of a building, referred to herein as business density, is the parameter most critical in making the decision to retrofit. Once again, changing a building's occupancy from a lower business density to a higher one, may present retrofitting needs when it would not otherwise.

6.4 Future Studies

The methodology proposed in this study uses an assumed knowledge of design earthquakes, global damage indices, and periods of reconstruction for building. All this information may not be available in some areas. Even for Puerto Rico where the methodology was successfully implemented, improvements can be made once the current study on design earthquakes is completed. In this sense further researches are recommended to complement the findings of this study.

- The proposed methodology is very sensitive to the design earthquakes selected to perform the cost estimation. That means the more reliable the selection, the more precise the estimates will become. Therefore, it is strongly recommended to complete the current research on a design earthquake for Puerto Rico.

- The number of building prototypes for the island might be increased and improved. The effects of non-structural components such as partitions inside the buildings need also be considered.
- The building prototypes considered for this study were reinforced concrete frame structures. It would be interesting to extend the coverage to include other building types specially shear wall and wood structures that are most common to Puerto Rico.
- The results obtained from the proposed methodology are very sensitive to the calculated damage indices. For the reinforced concrete building prototypes, the Park-Ang damage model was used at the element level. The global damage index was then calculated as a weighted combination of the Park-Ang damage indices using the Bracci model. The future development of some promising new technics such as the softening damage model may provide a more reliable prediction, specially for non-reinforced concrete buildings for which the Park-Ang damage model is not suitable. These types of models also have the advantage of computing the global damage index directly at the structural level which should make for a simpler calibration process. It is therefore a recommendation of this study to promote the advancement of such technics.

- The period of reconstruction was obtained using the construction data for California. A study to investigate any error resulting from applying such data to Puerto Rico is therefore pertinent. It is recommended to establish an expert panel to determine the appropriate periods of reconstruction for Puerto Rico.
- Many times, fires following an earthquake are the most severe cause of damages. This has been a problem well documented in historical events such as the recent earthquake in Kobe, Japan. At the time this study was completed, information to consider the losses associated with fires after the earthquake were just beginning to appear. As a result, one should explore the possibility of adding a new C_F term to the present model so that fire losses can be considered.
- To adopt the proposed methodology to include other natural and man-made hazards, i.e., strong winds and fires. Of course, this will also imply the selection of the most appropriate damage index to quantify the damages associated with the event.
- To perform a sensitivity analysis to identify how the overall loss estimates may be influenced by errors in each of the damage cost functions. This will provide greater understanding of the uncertainties in loss estimates and will identify the parts of the overall process that prove most crucial to such uncertainties.

- Finally, there is a strong need to demonstrate the validity of the elements of the current loss estimation methodology. It is therefore recommended to use future earthquakes in the U.S. and Puerto Rico to test and further modify the damages cost functions established in the present study.

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APPENDIX A

INTER-INDUSTRY ECONOMIC MATRICES FOR PUERTO RICO

The technical coefficients' matrix, **A**, and the Leontief inverse matrix, **B**, for the Puerto Rico accounting system are presented in this appendix. These matrices are based on the latest Planning Board survey of 1986-1987. The explanation on how to obtain these matrices can be found in section 2.8.

Table A.1: Technical coefficients' matrix, A

Sector	Agriculture	Const. & Mining	Manufacturing	Services	Government
Agriculture	0.0137773	0.0043582	0.0142718	0.0007118	0.0012846
Const. & Mining	0.0033935	0.0152004	0.0079215	0.0128785	0.0026435
Manufacturing	0.1710728	0.2040820	0.1186143	0.0432149	0.0511912
Services	0.0352266	0.2540286	0.1442852	0.2212956	0.1828201
Government	0.0027475	0.0020892	0.0015538	0.0088908	0.0017530

Table A.2: Leontief inverse matrix, **B**

Sector	Agriculture	Const. & Mining	Manufacturing	Services	Government
Agriculture	1.0170076	0.0085302	0.0168825	0.0020369	0.0025701
Const. & Mining	0.0062835	1.0225619	0.0121961	0.0176692	0.0065774
Manufacturing	0.2033262	0.2575569	1.1516383	0.0691864	0.0726718
Services	0.0866464	0.3830911	0.2190238	1.3056254	0.2514715
Government	0.0039004	0.0059765	0.0038153	0.0117788	1.0041298

APPENDIX B

ECONOMIC WEIGHTING VECTORS FOR PUERTO RICO

B.1 INTRODUCTION

The industrial coding used in the Input-Output table for Puerto Rico is based on the Standard Industrial Classification Manual (SIC). The SIC is a document prepared by the U.S. office of management and budget. It provides information for classifying establishments or businesses by the type of activity in which they are engaged. In this sense, the industrial code given to each business is based on the product elaborated or on its principal activity. This is with the number in parenthesis shown in the Table B.1. For the sectors presented in this appendix, the SIC number is also included.

The Input-Output tables were classified by 94 industrial sectors and 247 commodities (goods and service). A commodity is defined as merchandise or a service produced by an establishment or business. This can be a single product, as for example fresh bread or a group of similar commodities classified as one commodity, as in the case of apparel that includes men, boys and ladies clothing. The term sector refers to several similar industries classified under the same group. Any industry may have primary and secondary products. Secondary products were transferred from its producing industry, where they represent a secondary product to the industry in which they are the primary products.

B.2 Sales and Expenses Vectors

Sales and expenses vectors are technical coefficients vectors which show the activities between economic sectors. The sale row vectors for a particular economy sector will initially have 93 columns. But, columns corresponding to a particular economy group will be added together, resulting in a sale row vector of 5 columns, which represent Agricultural, Construction and Mining, Manufacturing, Services, and Government sectors. The sale vector is then normalized dividing each component by the total sales of that particular economy sector. This was established in section 2.9. The expense vector is obtained in a similar way. The final vectors are shown in Table B.1.

Table B.1: Sales and expenses vectors for Puerto Rico economy corresponding to the 1987 survey

SECTOR	SALE VECTOR					EXPENSE VECTOR^T				
AGRICULTURAL										
sugar cane (00100)	0.000	0.000	0.998	0.002	0.000	0.000	0.013	0.568	0.419	0.000
Other agricultural, forestry, and fisheries (00200)	0.018	0.003	0.938	0.024	0.017	0.070	0.012	0.817	0.086	0.014
Agricultural services *(00300)*	0.153	0.432	0.081	0.331	0.003	0.023	0.048	0.306	0.621	0.002
MINING										
Mining (11000)	0.000	0.072	0.925	0.003	0.000	0.001	0.012	0.142	0.843	0.002
CONSTRUCTION										
New construction (15100)	0.000	0.000	0.000	1.000	0.000	0.009	0.033	0.445	0.509	0.004
Buildings repair and maintenance (15200)	0.005	0.066	0.312	0.590	0.027	0.012	0.031	0.386	0.567	0.004
MANUFACTURING										
Meat and meat products (20100)	0.003	0.033	0.618	0.234	0.112	0.478	0.005	0.319	0.196	0.003
Milk and milk products (20200)	0.002	0.043	0.341	0.352	0.262	0.567	0.004	0.143	0.286	0.000
Packaged fruit and vegetables products (20300)	0.002	0.083	0.198	0.550	0.167	0.180	0.011	0.356	0.452	0.001
Grains and milled products (20400)	0.607	0.003	0.294	0.054	0.042	0.289	0.065	0.325	0.311	0.010
Bakery and confectionery products (20500)	0.004	0.056	0.138	0.485	0.317	0.000	0.027	0.582	0.389	0.002
Sugar central, Refineries and sweeteners (20610)	0.000	0.005	0.942	0.040	0.013	0.173	0.001	0.380	0.444	0.003
Alcoholic and malts beverages (20820)	0.002	0.034	0.572	0.256	0.136	0.000	0.006	0.539	0.442	0.013
Non-alcoholic beverages (20870)	0.000	0.003	0.943	0.031	0.023	0.000	0.013	0.630	0.355	0.002

Table B.1: Sales and expenses vectors for Puerto Rico economy corresponding to the 1987 survey (Cont.)

SECTOR	SALE VECTOR					EXPENSE VECTOR^T				
Miscellaneous food products (20900)	0.002	0.024	0.544	0.241	0.188	0.391	0.001	0.364	0.244	0.001
Canned cured fish (20910)	0.000	0.000	1.000	0.000	0.000	0.000	0.039	0.486	0.470	0.006
Tobacco products (21000)	0.000	0.000	1.000	0.000	0.000	0.012	0.009	0.575	0.403	0.001
Textiles products (22000)	0.000	0.000	0.639	0.236	0.125	0.000	0.026	0.099	0.868	0.006
Clothing and miscellaneous accessories (23000)	0.010	0.033	0.479	0.326	0.152	0.004	0.022	0.200	0.766	0.008
Wood and wood products (24000)	0.000	0.260	0.606	0.098	0.036	0.002	0.014	0.548	0.433	0.003
Paper and related products (26000)	0.001	0.018	0.753	0.217	0.012	0.001	0.011	0.630	0.313	0.045
Printing and publications (27000)	0.001	0.028	0.319	0.449	0.203	0.002	0.036	0.127	0.817	0.018
Petrochemicals (28100)	0.000	0.005	0.988	0.007	0.000	0.001	0.022	0.438	0.528	0.010
Drugs and pharmaceutical products (28300)	0.001	0.000	0.600	0.227	0.172	0.001	0.023	0.250	0.724	0.002
Other chemical products (28400)	0.151	0.051	0.379	0.390	0.030	0.001	0.011	0.245	0.740	0.003
Petroleum refinery (29100)	0.002	0.053	0.506	0.419	0.020	0.000	0.078	0.721	0.200	0.001
Other petroleum products (29200)	0.005	0.182	0.672	0.124	0.016	0.000	0.214	0.410	0.376	0.000
Plastic and rubber products (30000)	0.001	0.081	0.736	0.174	0.009	0.005	0.056	0.332	0.597	0.011
Leather and leather products (31000)	0.000	0.014	0.833	0.144	0.009	0.001	0.070	0.284	0.624	0.021
Stone, clay, glass, cement and concrete products (32100)	0.000	0.365	0.585	0.025	0.025	0.001	0.114	0.371	0.512	0.003
Primary metal products (33000)	0.000	0.242	0.753	0.005	0.000	0.000	0.000	0.735	0.264	0.002
Fabricated metal products (34000)	0.004	0.234	0.667	0.085	0.009	0.001	0.081	0.358	0.550	0.010
Electrical machinery (35000)	0.002	0.258	0.695	0.038	0.006	0.000	0.023	0.432	0.543	0.002
Non-electrical machinery (36000)	0.000	0.136	0.808	0.055	0.001	0.001	0.018	0.366	0.612	0.002
Transportation equipment (37000)	0.025	0.042	0.465	0.365	0.103	0.001	0.023	0.436	0.522	0.018
Scientist and professional instruments (38000)	0.000	0.254	0.318	0.162	0.265	0.000	0.057	0.252	0.688	0.003
Miscellaneous manufacturing industries (39000)	0.046	0.027	0.701	0.192	0.034	0.000	0.027	0.101	0.609	0.263

Table B.1: Sales and expenses vectors for Puerto Rico economy corresponding to the 1987 survey (Cont.)

SECTOR	SALE VECTOR					EXPENSE VECTOR^T				
TRANSPORTATION										
Taxi and public cars (41100)	0.003	0.087	0.195	0.697	0.018	0.001	0.015	0.207	0.771	0.007
Bus services (41200)	0.000	0.000	0.000	1.000	0.000	0.001	0.010	0.462	0.517	0.011
Trucking and warehousing *(42000)*	0.010	0.115	0.575	0.293	0.006	0.001	0.012	0.230	0.736	0.021
Ocean shipping (44000)	0.009	0.059	0.760	0.152	0.019	0.001	0.046	0.140	0.808	0.006
Air transportation (45000)	0.003	0.057	0.253	0.637	0.049	0.003	0.012	0.100	0.883	0.003
Transportation services (47100)	0.001	0.020	0.024	0.857	0.099	0.001	0.016	0.054	0.451	0.478
Travel agencies (47200)	0.000	0.000	0.111	0.889	0.000	0.003	0.010	0.157	0.821	0.009
COMMUNICATION										
Telephone, telegraph and cable (48100)	0.001	0.059	0.273	0.591	0.075	0.001	0.024	0.128	0.821	0.026
Television and radio stations (48300)	0.000	0.007	0.004	0.981	0.008	0.001	0.004	0.053	0.931	0.011
ELECTRICITY, GAS, WATER AND SALUBRITY										
Electricity and irrigation services (49100)	0.003	0.019	0.394	0.460	0.125	0.001	0.000	0.850	0.143	0.005
Gas and sanitary services (49200)	0.000	0.000	0.436	0.506	0.058	0.003	0.005	0.225	0.762	0.004
Water and sewer services (49400)	0.006	0.034	0.294	0.513	0.153	0.002	0.000	0.154	0.825	0.019
COMMERCE										
Commerce (50000)	0.002	0.072	0.587	0.269	0.070	0.001	0.046	0.088	0.858	0.007
Trucking and warehousing *(42000)*	0.010	0.115	0.575	0.293	0.006	0.001	0.012	0.230	0.736	0.021
Ocean shipping (44000)	0.009	0.059	0.760	0.152	0.019	0.001	0.046	0.140	0.808	0.006
Air transportation (45000)	0.003	0.057	0.253	0.637	0.049	0.003	0.012	0.100	0.883	0.003

Table B.1: Sales and expenses vectors for Puerto Rico economy corresponding to the 1987 survey (Cont.)

SECTOR	SALE VECTOR					EXPENSE VECTOR^T				
Transportation services (47100)	0.001	0.020	0.024	0.857	0.099	0.001	0.016	0.054	0.451	0.478
Travel agencies (47200)	0.000	0.000	0.111	0.889	0.000	0.003	0.010	0.157	0.821	0.009
COMMUNICATION										
Telephone, telegraph and cable (48100)	0.001	0.059	0.273	0.591	0.075	0.001	0.024	0.128	0.821	0.026
Television and radio stations (48300)	0.000	0.007	0.004	0.981	0.008	0.001	0.004	0.053	0.931	0.011
ELECTRICITY, GAS, WATER AND SALUBRITY										
Electricity and irrigation services (49100)	0.003	0.019	0.394	0.460	0.125	0.001	0.000	0.850	0.143	0.005
Gas and sanitary services (49200)	0.000	0.000	0.436	0.506	0.058	0.003	0.005	0.225	0.762	0.004
Water and sewer services (49400)	0.006	0.034	0.294	0.513	0.153	0.002	0.000	0.154	0.825	0.019
BANKS AND OTHER CREDITS AGENCIES										
Commercial banks (61100)	0.003	0.026	0.561	0.234	0.175	0.001	0.052	0.116	0.791	0.040
Mortgage banks and brokers (61200)	0.000	0.438	0.061	0.501	0.000	0.000	0.000	0.042	0.917	0.041
Savings and loan associations (61300)	0.000	0.090	0.135	0.775	0.000	0.001	0.056	0.035	0.893	0.016
Credit cooperatives (61400)	0.000	0.000	0.000	1.000	0.000	0.003	0.021	0.134	0.800	0.043
Stock brokers (61500)	0.000	0.087	0.429	0.484	0.000	0.001	0.000	0.060	0.850	0.089
Personal loan agencies (61600)	0.000	0.000	0.000	1.000	0.000	0.001	0.041	0.069	0.810	0.079
Conditional sales companies (61700)	0.000	0.079	0.253	0.668	0.000	0.005	0.000	0.175	0.801	0.019
Other Credits agencies (61800)	0.000	0.019	0.420	0.508	0.053	0.003	0.007	0.065	0.923	0.002

Table B.1: Sales and expenses vectors for Puerto Rico economy corresponding to the 1987 survey (Cont.)

SECTOR	SALE VECTOR					EXPENSE VECTOR^T				
INSURANCES										
Life, accident, and health insurances (63100)	0.000	0.000	0.000	1.000	0.000	0.001	0.001	0.074	0.918	0.005
Other insurances (63200)	0.003	0.076	0.322	0.571	0.028	0.000	0.000	0.013	0.983	0.004
Adjusters, brokers, and other insurance services (63300)	0.000	0.000	0.000	1.000	0.000	0.002	0.004	0.096	0.884	0.014
REAL STATE										
Real state (65100)	0.002	0.003	0.052	0.809	0.135	0.004	0.105	0.065	0.806	0.020
HOTELS AND GUEST HOUSES										
Tourist hotels (70110)	0.000	0.066	0.220	0.700	0.013	0.007	0.028	0.111	0.852	0.003
Other hotels and guest houses (70120)	0.000	0.000	0.050	0.950	0.000	0.009	0.086	0.093	0.809	0.004
PERSONAL SERVICES										
Laundromats (72100)	0.000	0.000	0.000	0.980	0.020	0.000	0.053	0.306	0.636	0.004
Photography studios (72200)	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.289	0.689	0.022
Beauty parlors and barber shop (72300)	0.000	0.000	0.000	1.000	0.000	0.000	0.043	0.169	0.787	0.001
Funeral homes (72600)	0.000	0.059	0.000	0.873	0.068	0.005	0.011	0.221	0.754	0.010
Shoe repair, bootblacks, and others (72900)	0.000	0.000	0.000	0.000	0.000	0.001	0.020	0.763	0.193	0.023
COMMERCIAL SERVICES										
Publicity (73100)	0.000	0.016	0.615	0.368	0.000	0.002	0.019	0.101	0.864	0.014
Commercial services (73200)	0.005	0.065	0.435	0.368	0.126	0.002	0.012	0.146	0.717	0.123

Table B.1: Sales and expenses vectors for Puerto Rico economy corresponding to the 1987 survey (Cont.)

SECTOR	SALE VECTOR					EXPENSE VECTOR^T				
REPAIR AND RENT AUTOMOBILES, AND PARKING LOT										
Automobile rentals (75100)	0.004	0.050	0.267	0.628	0.051	0.001	0.035	0.150	0.805	0.009
Parking (75200)	0.000	0.000	0.000	1.000	0.000	0.001	0.043	0.049	0.906	0.001
Automobiles repair and miscellaneous (75300)	0.004	0.118	0.429	0.390	0.059	0.001	0.029	0.233	0.590	0.148
RECREATION AND DIVERSION										
Film producers and distributors (78100)	0.000	0.000	0.000	0.991	0.009	0.001	0.016	0.110	0.871	0.002
Movie theaters (78300)	0.000	0.058	0.113	0.810	0.019	0.000	0.021	0.043	0.935	0.000
Producers of public spectacles (78400)	0.000	0.000	0.000	0.982	0.018	0.005	0.006	0.193	0.777	0.019
Race tracks and stables (78500)	0.000	0.000	0.000	1.000	0.000	0.091	0.024	0.305	0.570	0.010
Miscellaneous entertainment (78600)	0.004	0.041	0.190	0.695	0.070	0.003	0.042	0.138	0.811	0.006
MEDICAL SERVICES AND HEALTHCARE										
Physicians and surgeons (80100)	0.000	0.000	0.000	0.504	0.496	0.010	0.036	0.162	0.780	0.012
Dentists (80200)	0.000	0.000	0.000	0.470	0.530	0.000	0.058	0.282	0.621	0.040
Hospitals (80600)	0.000	0.000	0.000	0.438	0.562	0.002	0.006	0.354	0.548	0.090
Medical and dental laboratories (80700)	0.001	0.000	0.075	0.904	0.019	0.001	0.013	0.310	0.662	0.014
Miscellaneous health services (80800)	0.000	0.000	0.557	0.314	0.129	0.001	0.009	0.354	0.626	0.0091
OTHER SERVICES										
Legal services (81100)	0.003	0.148	0.231	0.602	0.015	0.003	0.019	0.151	0.795	0.032
Educational services (81200)	0.000	0.002	0.286	0.658	0.054	0.002	0.064	0.169	0.569	0.197
Engineering and architectural services (81300)	0.003	0.311	0.405	0.255	0.026	0.001	0.018	0.106	0.868	0.007

Table B.1: Sales and expenses vectors for Puerto Rico economy corresponding to the 1987 survey (Cont.)

SECTOR	SALE VECTOR					EXPENSE VECTOR^T				
Accounting and auditing services (81400)	0.003	0.245	0.321	0.427	0.004	0.003	0.011	0.170	0.788	0.028
Non-profit institutions (83000)	0.002	0.047	0.324	0.598	0.029	0.005	0.060	0.315	0.589	0.031
Domestic Services (88000)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
GOVERNMENT										
Commonwealth government (90100)	0.011	0.000	0.128	0.861	0.000	0.007	0.008	0.197	0.779	0.009
Municipal government (90200)	0.000	0.000	0.000	1.000	0.000	0.001	0.030	0.182	0.781	0.005
Federal government (90300)	0.005	0.054	0.254	0.594	0.093	0.002	0.001	0.339	0.658	0.000

APPENDIX C

RECONSTRUCTION TIME

Statistical information on loss of function or restoration time is very limited. The ATC-13 presents statistics of time-to-restore functions at 30%, 60%, and 100% of capacity. For purposes of this study, only the restoration of full capacity is considered. Results from the regression analysis of the ATC-13 data yielded general equations for restoration time as a function of the occupancy types and the damage indices. The data used to generate those equations is presented in this appendix. The social classification numbers used are from the ATC-13. Equal weights are assigned to social functions within an occupancy group.

- **Residential**

Table C.1: Reconstruction time for residential occupancy (in days)

D_m	**Max 100%**
0.005	3
0.05	10
0.2	30
0.45	240
0.8	365
1.0	365

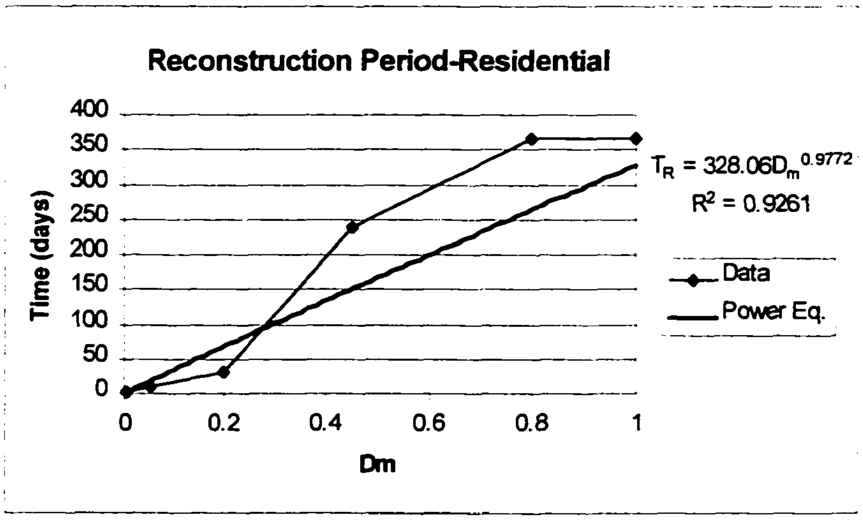


Figure C.1: The result of regression analysis for residential

- **Agriculture**

Table C.2: Reconstruction time for agriculture occupancy (in days)

D_m	Max 100%
0.005	7
0.05	30
0.2	60
0.45	120
0.8	180
1.0	270

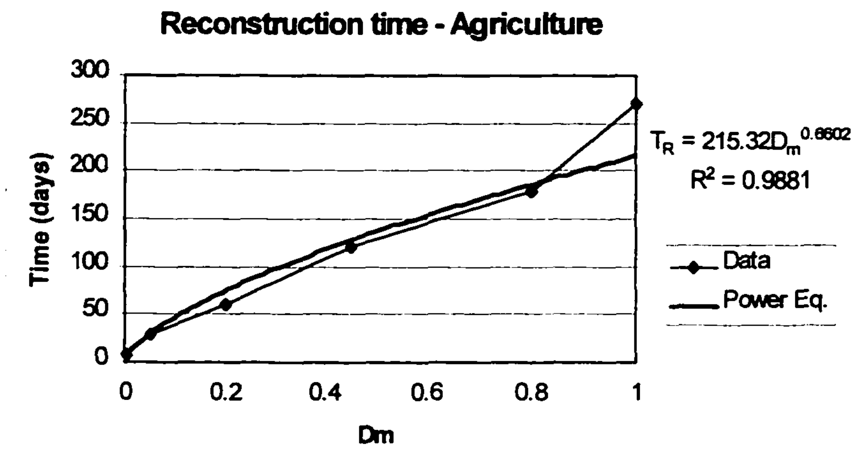


Figure C.2: The result of the regression analysis for agriculture.

- **Mining**

Table C.3: Reconstruction time for mining occupancy (in days)

D_m	Max 100%
0.005	15
0.05	30
0.2	150
0.45	365
0.8	1095
1.0	1095

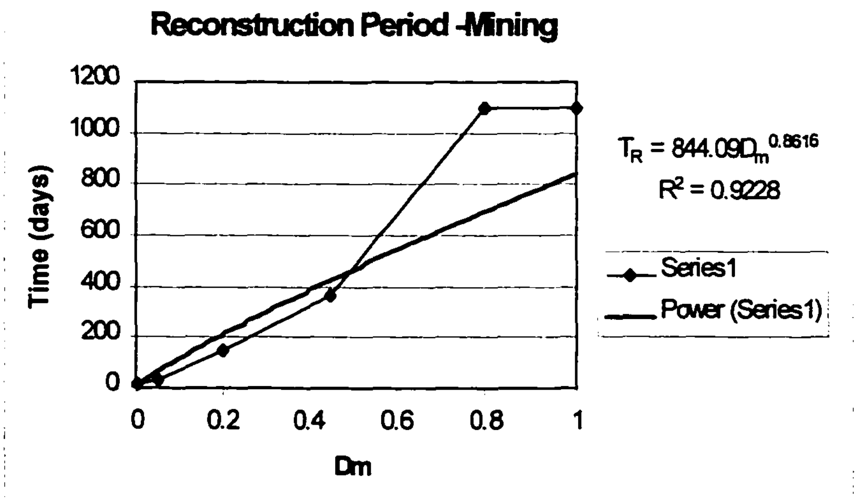


Figure C.3: The result of the regression analysis for mining.

●Services (General)

Table C.4: Restoration time for services - general occupancy (in days)

D_m	Max 100%		
	Social Functions		Average
	4, 5, 6, 7	9	
0.005	30	30	30.0
0.05	90	93	90.6
0.2	300	300	300.0
0.45	500	500	500.0
0.8	730	730	730.0
1.0	730	730	730.0

4. Retail trade.
5. Wholesale trade.
6. Personal and Repair services.
7. Professional, Technical and Business Services.
9. Entertainment and Recreation.

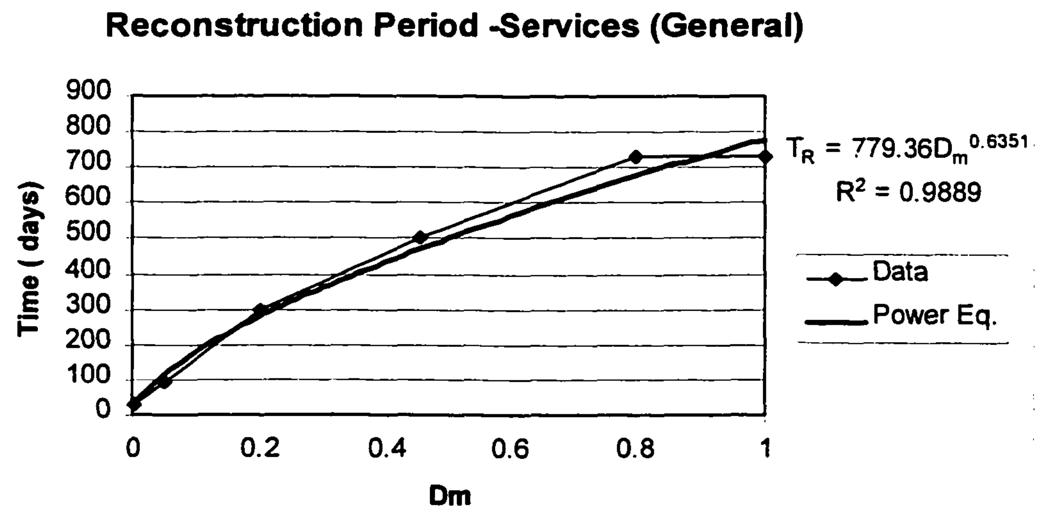


Figure C.4: The result of the regression analysis for services (general).

- **Services (Parking Facilities)**

Table C.5: Reconstruction time for services-parking occupancy (in days)

D_m	Max 100%
0.005	2
0.05	10
0.2	45
0.45	120
0.8	270
1.0	300

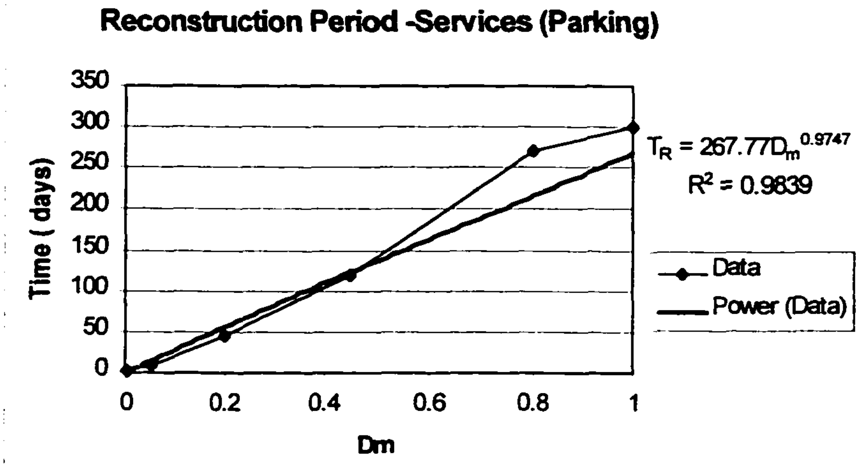


Figure C.5: The result of the regression analysis for services (parking).

- **Construction**

Table C.6: Reconstruction time for construction occupancy (in days)

D_m	Max 100%
0.005	15
0.05	80
0.2	120
0.45	200
0.8	360
1.0	450

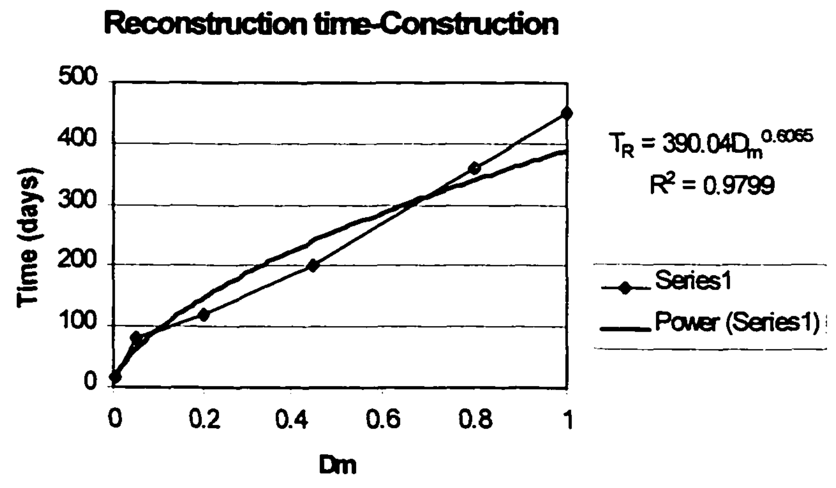


Figure C.6: The result of the regression analysis for construction.

●Manufacturing

Table C.7: Reconstruction time for manufacturing occupancy (in days)

D_m	Max 100%					
	Social Functions					Average
	11, 12	13	14	15	16	
0.005	30	20	30	30	3	23.8
0.05	100	50	100	100	20	78.3
0.2	270	240	270	270	180	250.0
0.45	548	548	548	548	485	537.5
0.8	730	730	730	730	730	730.0
1.0	730	1095	730	730	730	790.8

11. Heavy Fabrication and Assembly.
12. Light Fabrication and Assembly.
13. Food and Drug Processing.
14. Chemicals Processing.
15. Metal and Minerals Processing.
16. High Technology.

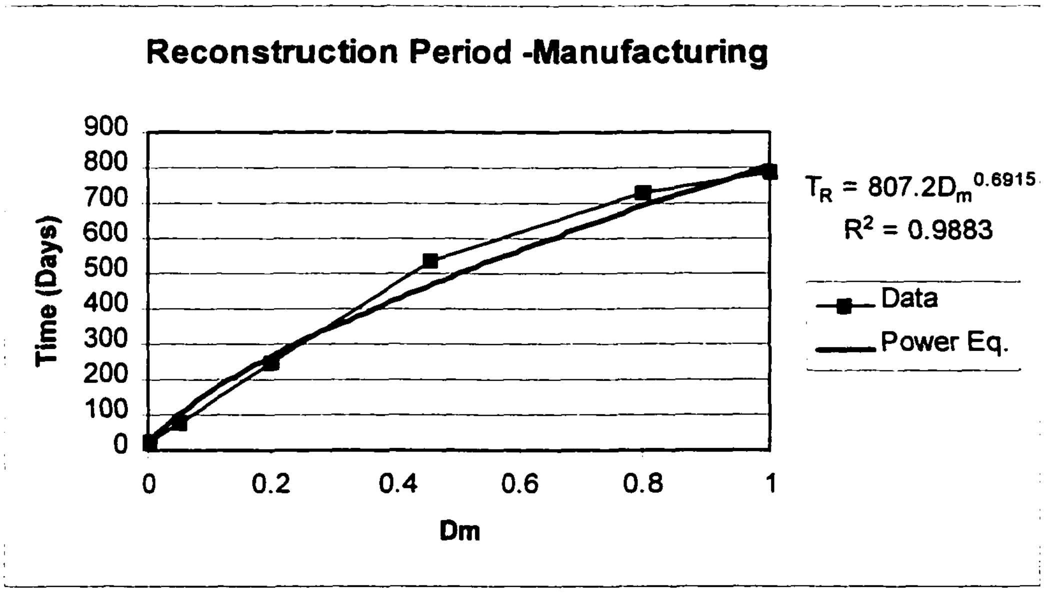


Figure C.7: The result of the regression analysis for manufacturing.

●Government

Table C.8: Reconstruction time for government occupancy (in days)

D_m	Max 100%			
	Social Functions			Average
	22	23	24	
0.005	15	15	20	16.7
0.05	100	60	40	66.7
0.2	270	150	160	193.3
0.45	365	210	270	281.7
0.8	548	365	400	437.7
1.0	1095	455	800	783.3

22. General Services.
23. Emergency Response Services.
24. Education.

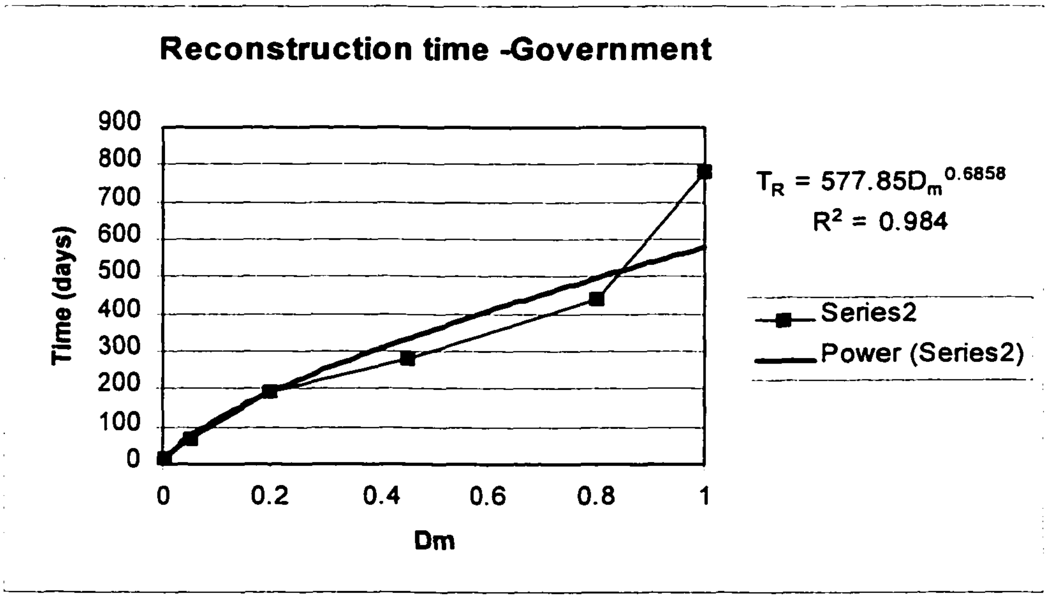


Figure C.8: The result of the regression analysis for government.

APPENDIX D

FRICTION TRUSS ELEMENT

The friction truss element is based on the results from an UPR experimental study (Kuhlmann, 1989). For the cases studied, the friction capacity was shown to be approximately half the yield load capacity for the brace element. Thus, the model proposed here assumes a maximum compressive load (P_{cr}) near the buckling or friction capacity. Then the element have to be designed to afford a buckling load close to the friction load capacity.

The load-displacement model uses straight lines to simplify the relationship between axial force and axial deformation. The complete hysteresis model is represented by four controls points, Cp1, Cp2, Cp3, and Cp4. Cp1 is the point where the load in the brace reaches the friction capacity of the connection. Cp2 depends on the maximum displacement allowed in the connection (VFR). Cp3 corresponds to the bearing load. In Figure D.1, the arrows indicates the path traced at various stages of hysteresis behavior of bracing member, and the number in cycle means the yield code assigned to this path.

The yield code 0 is for the elastic range, where the axial load in the brace element do not exceed the friction load or buckling load (compression). Yield code 1 indicates that the friction range has been reached and the connection has started slipping. In the yield code 2 the axial load in the brace element starts to increase, because the maximum movement allowed in the connection under the constant load P_{fr} has been exceeded. In yield code 3 the bracing member starts to deform in the inelastic range due to the bearing of the plate. Yield code 4 is the unloading path, using same slope as yield code 1. In the yield code 5, the connection is slipping in the other direction.

The followings illustrate the input data format for the friction truss element as programed into the SNAP-2D.

•I.1. CONTROL INFORMATION

Two cards.

I.1(a). FIRST CARD

COLUMNS	DATA
5 :	Element type indicator (= 13 to indicate that group consists of friction truss element).
6 - 10 :	No. of elements in group.
11 - 15 :	Element no. of first element in group. Default = 1.
16 - 25:	Tangent stiffness damping factor, β_0
26 - 35:	Tangent stiffness damping factor, β_T
41 - 80:	Optional group heading.

•I.1(b). SECOND CARD

COLUMNS	DATA
1 - 5:	No. of different element stiffness types.

•I.1(c). STIFFNESS TYPES

COLUMNS	DATA
1 - 5:	No. of different element stiffness types.
6 - 15:	Young's Modulus of elasticity.
16 - 25:	Average cross-sectional area.
26 - 35:	Friction capacity in tension (P_{fr}).
36 - 45:	Bearing Load (P_y).
46 - 55:	Friction capacity in compression (P_{cr}).
56 - 65:	Leave blank.
66 - 75:	Maximum movement allowed to the bolts (VFR)
76 - 85:	Fracture life cycles in terms of standard cycle.

•I.1(e). ELEMENT GENERATION COMMANDS

Add as many cards as needed to generate all elements in group. Cards for the first and last elements must be included.

COLUMNS	DATA
1 - 5:	Element number, or number of first element in a sequential numbered series of elements to be generated by this command.
6 - 10:	Node number at element end *i*.
11 - 15:	Node number at element end *j*.

16 - 20:	Node number increment for element generation. If zero or blank, assumed to be equal to 1.
21 - 25:	Stiffness type number
30:	Geometric stiffness code: a. 0 = ignored. b. 1 = included..
35:	Time history output code a. 0 = not required. b. 1 = required.

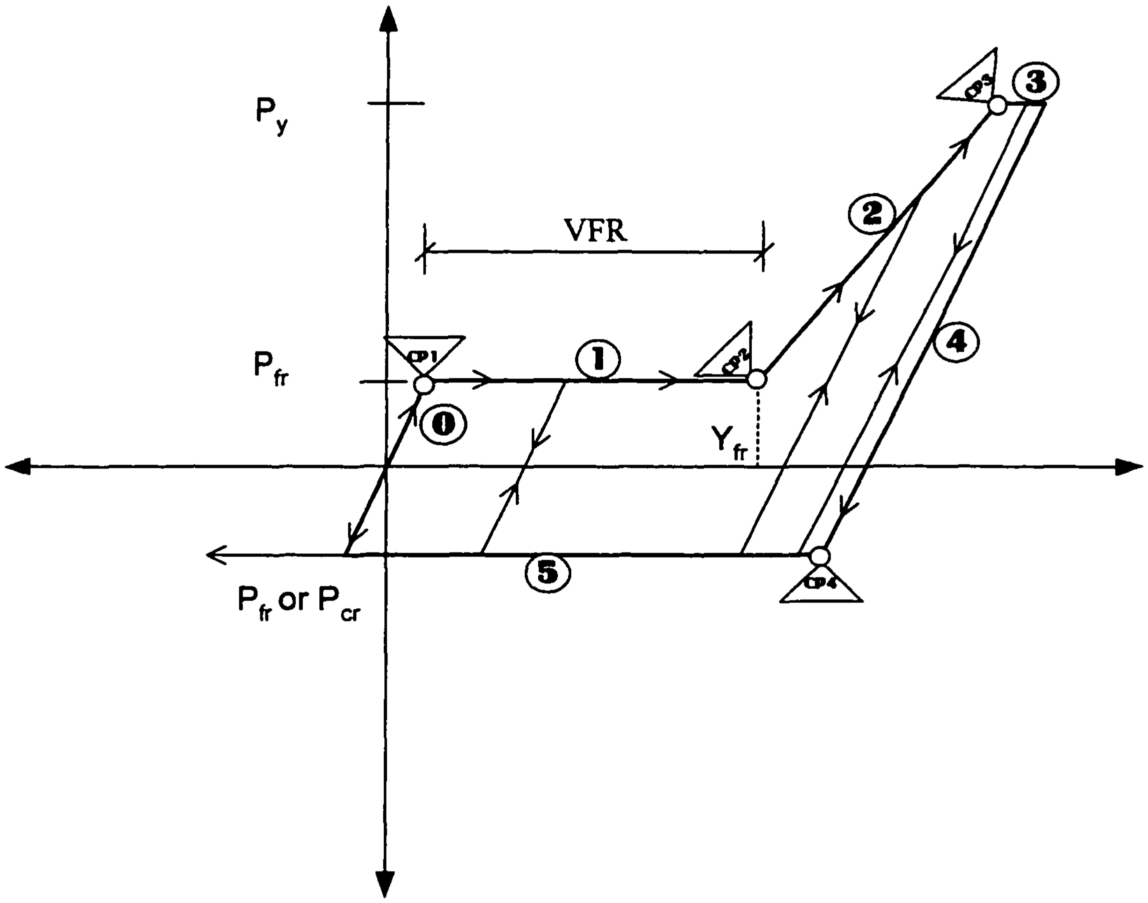


Figure D.1: Load-displacement curve for the friction truss element.

APPENDIX E

MODIFICATIONS TO THE INPUT DATA FILE FOR ELEMENT 2 OF THE SNAP COMPUTER PROGRAM

This appendix describes the modifications made to the SNAP-2D input data file. The information provided herein should be used in conjunction with the SNAP-2D user's guide (1996). The SNAP-2D input data file is divided in control cards. All the new cards needed for the purpose of this study, were added to the end of the existing ones. Just those new cards are presented here. For uniformity the formats of the original Input data have been kept consistent with the SNAP-2D computer program.

•B.1(b). SECOND CARD

COLUMNS	DATA
1 - 5:	No. of different element stiffness types.
6 - 10:	No. of different end eccentricity.
11 - 15:	No. of different yield interaction surfaces for cross sections.
16 - 20:	No. of different fixed end forces patterns.
21 - 25:	No. of different initial element force patterns.
(New) 26 - 30:	No. of different parameter damage calculation. (NDAM)

•B.1(g1). PARAMETERS NEED TO CALCULATE THE DAMAGE INDEX.

This is a totally new card added after **B.1(g)** card. It includes the parameter required to calculate the damage index. Add as many lines as specified by NDAM (omit if NDAM = 0).

COLUMNS	DATA
1 - 9:	Maximum rotation capacity (θ_u)
10 - 18:	Strength degrading parameter (β)

•B.1(h). ELEMENT GENERATION COMMANDS

As many cards as needed to generate all elements in the group. Cards for the first and last elements must be included.

COLUMNS	DATA
1 - 5:	Element number, or number of first element in a sequentially numbered series of elements to be generated by this command.
6 - 10:	No. de number at element end *i*.
11 - 15:	No. de number at element end *j*.
(New) 81 - 82:	Floor's identifier. Each element is assigned to the floor where belongs to.
(New) 83 - 92:	Weighting factor to compute the global damage index. Suggestion: gravity load.
(New) 94 - 95:	Damage parameter type as specified in B.1(g1).

APPENDIX F

MOMENT-CURVATURE RELATIONSHIPS FOR REINFORCED CONCRETE BEAMS

In this appendix, we shall present numerical procedures by which the yield and ultimate moments and curvatures for reinforced concrete sections are evaluated. Figure F.1c shows the stress and strain profiles for a typical section. For the top fiber strain at yield

$$\varepsilon_c = \frac{x\,\varepsilon_s}{d-x} = \frac{x\,F_y}{E_s(d-x)}$$

where x is the position of the neutral axis, and F_y and E_s are the yield stress and modulus of elasticity for steel reinforcement bars, respectively.

The compression force C shown on the idealized stress block (Figure F.1b) consists of two components, C_c and C_s. The main component is in the concrete given by $C_c = 0.85 f_c' B\,\beta_1\,x$ where f_c' is the compressive strength of concrete and β_1 is the ratio of the depth of the Whitney's rectangular stress block, a, to the depth of the neutral axis, x. Its value, subject to a minimum of 0.65, is calculated from: $\beta_1 = 0.85 - 0.05(\frac{f_c' - 4000}{1000})$. C_s is the contributions from the compression steel given by: $C_s = A_s'(f_s' - 0.85 f_c')$ where A_s' is the cross sectional area and f_s' is calculated from the stress-strain profiles as:

$$f_s' = \varepsilon_s' E_s = \frac{\varepsilon_c(x-d')}{x} E_s$$

To satisfy the equilibrium of horizontal forces in Figure F.1b, $T = A_s F_y = C_c + C_s$, which results in the following quadratic equation on x:

$$0.85 f_c' B \beta_1 x^2 - (A_s F_y + A_s' \varepsilon_s E_s + 0.85 A_s' f_c' + 0.85 f_c' B \beta_1) x + \\ (A_s F_y d + A_s' \varepsilon_s E_s d' + 0.85 A_s' f_c' d) = 0$$

Once the position of the neutral axis is found, one can obtain both the yield curvature and the yield moment using the following equations:

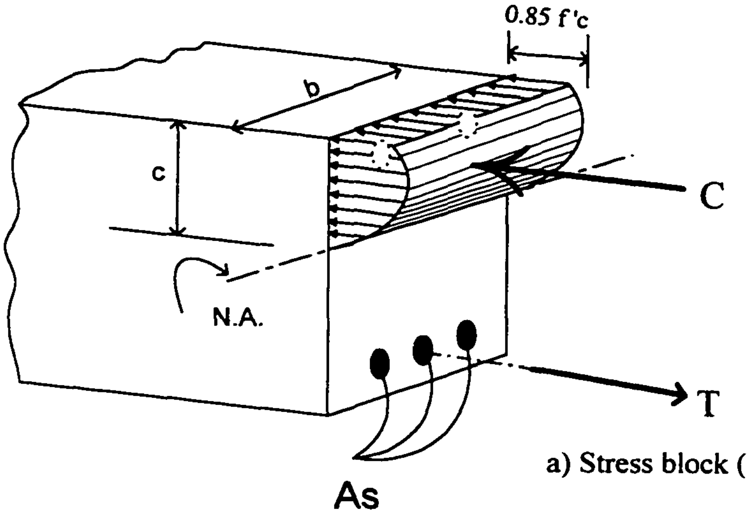
$$\phi_y = \frac{\varepsilon_c}{x}$$

$$M_y = C_c \left(d - \frac{a}{2}\right) + C_s (d - d')$$

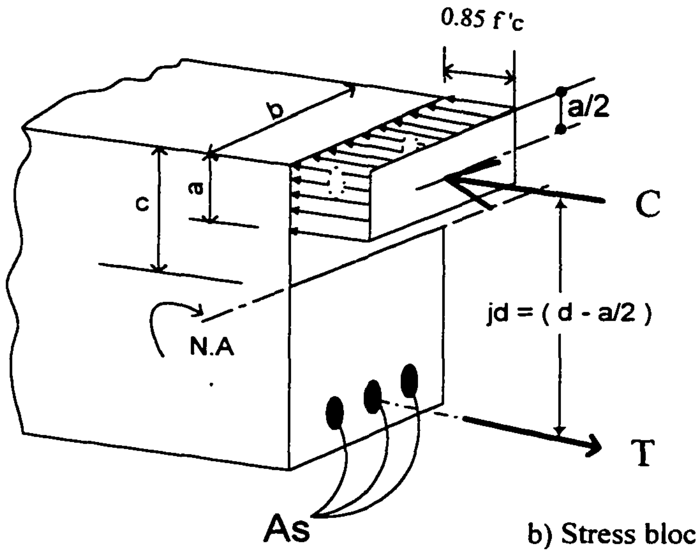
Similar process is followed to evaluate the ultimate curvature. Only now the value of $\varepsilon_c = 0.003$ which is the maximum strain allowed in the concrete is used. This will change the Equation F.1 to:

$$0.85 f_c' B \beta_1 x^2 - (0.85 A_s' f_c' - A_s' \varepsilon_c E_s + A_s F_y) x - A_s' \varepsilon_c E_s d' = 0$$

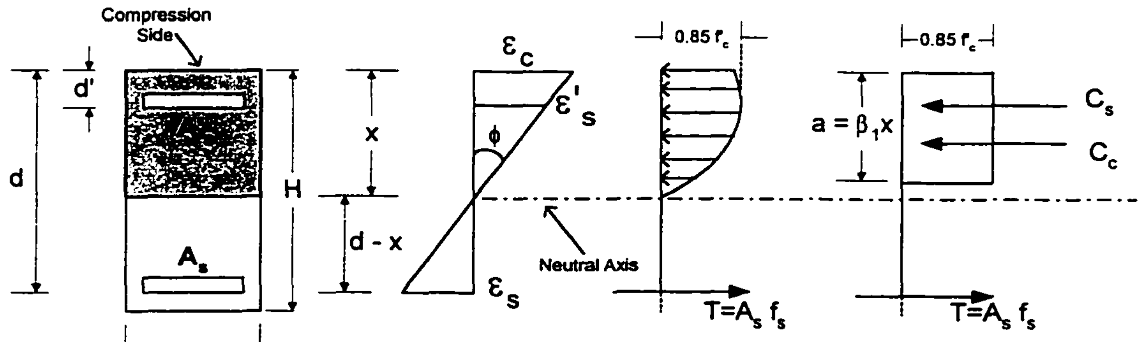
from which the depth of the neutral axis can be obtained.



a) Stress block (Real)



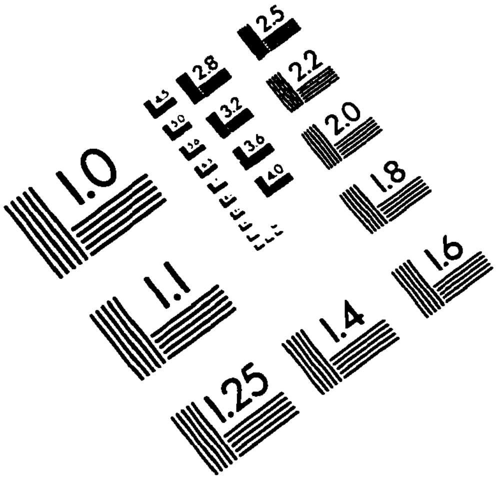
b) Stress block (idealized)

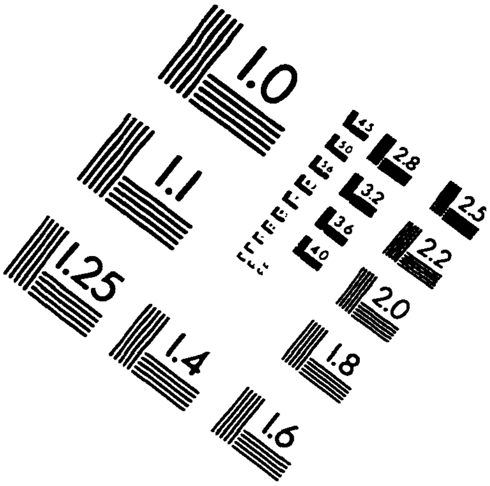


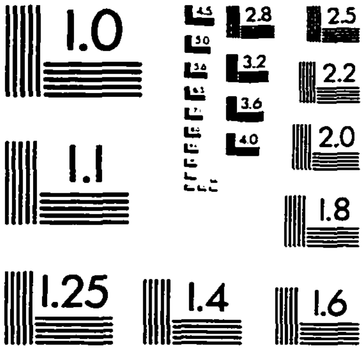
C) Stress-Strain Profiles

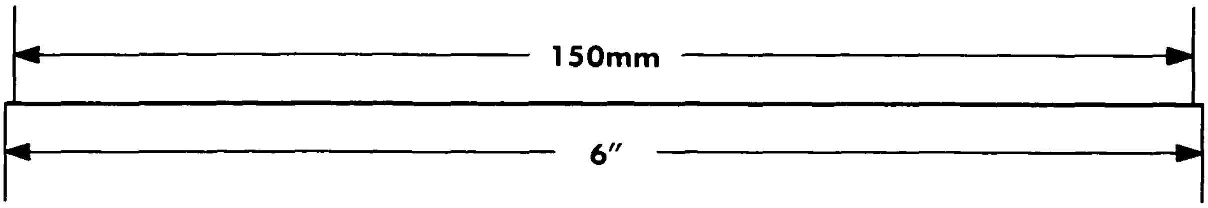
Figure F.1: Typical strain-stress relationship for a concrete section.

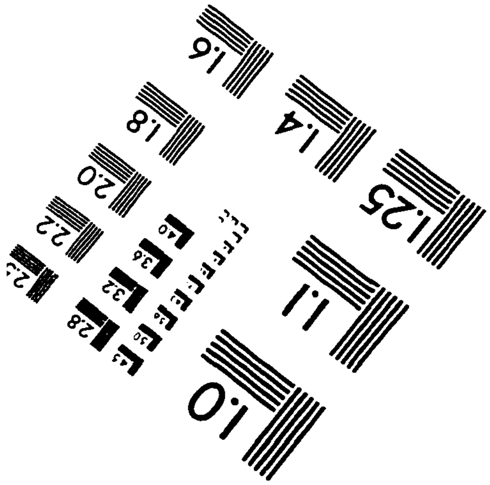
IMAGE EVALUATION
TEST TARGET (QA-3)

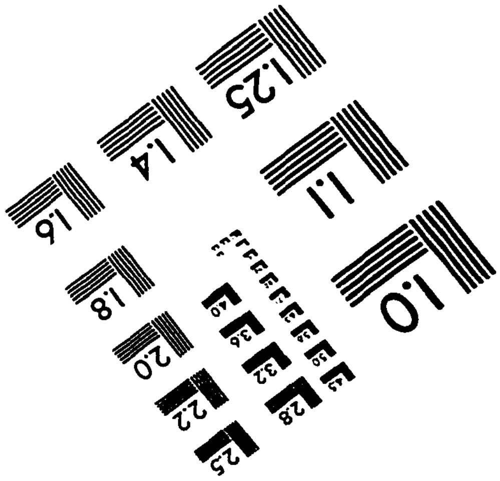












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