

Decision Analysis for Seismic Retrofit Based on Loss Estimation



H. Parvini sani

PhD Student, Dept. of Civil Engineering, Semnan University, Semnan, Iran,
hosseinp@aut.ac.ir

M. Banazadeh

Assistant Professor, Dept. of Civil Engineering, Amirkabir University of Technology, Tehran,
Iran, mbanazadeh@aut.ac.ir

Summary:

This paper presents a discussion of the use of seismic loss estimation for retrofit decision-making considering risk management and expected economic benefit. Three performance measures: Repair cost, Casualties, Downtime is considered for loss estimation. Time-based performance assessments are used for loss estimation with utilizing Performance Assessment Calculation Tool (PACT). Considering two cases of Collapse and No-Collapse for building and using probabilistic framework, Annual Loss (AL) has been estimated. AL within a reasonable relationship is combined with retrofit cost and discount rate to obtain the amount of net losses and minimum time required for the economic feasibility of each retrofit alternative. This method is used for assessing the steel resisting frame that has been retrofitted with three different methods and comparison between the retrofit options considering seismic risk was done. According to this study various retrofit strategies will have reasonable comparability and eases decision process for clients.

Keywords: Decision-Making, Seismic Retrofit, Loss Estimation, Expected Economic Benefit, Risk Management.

1. INTRODUCTION

Current seismic design codes provide guidelines for the design and detailing of structures with the primary goal of preventing global collapse during strong ground motion shaking. However, observations from worldwide earthquakes in the past two decades illustrated the severe economic consequences resulting from earthquakes in highly developed regions of society. These economic consequences can be primarily attributed to: 1-direct economic losses associated with repairing damage within a structure; 2- direct losses associated with injuries and casualties; and 3- indirect losses associated with downtime. Some examples from the United States include the 1994 Northridge (\$17-26 billion), and 1989 Loma Prieta (\$11 billion) earthquakes. In response to these observed losses it has become apparent that seismic design of structures should consider all of these potential consequences and their likelihood of occurrence (Bradley 2009).

Probabilistic seismic risk based on estimation of losses in a building due to earthquake damage is a topic of interest to decision makers and an area of active research. In order to incorporate seismic risk of facilities into a decision making framework, procedures are needed to quantify such risk for stakeholders. Quantification of seismic risk is a difficult task which is subject to inherent variability. One promising approach to the problem, proposed by the Pacific Earthquake Engineering Research (PEER) Center, involves breaking the analysis into separate components associated with ground motion hazard, structural response, damage to components and repair costs.

This paper presents a discussion of the use of seismic loss estimation for retrofit decision-making. Seismic loss estimation methods combine seismic hazard, structural response, damage fragility, and damage consequences to allow quantification of seismic risk (Williams *et al.* 2009, Krawinkler *et al.* 2005). Loss is measured in the forms of direct structural and non-structural repair costs, and although casualties and downtime are considered.

Also, this study makes informed decision about economic feasibility for seismic retrofit. To this end, after estimating Annual Loss (AL), the impact of factors such as discount rate and seismic retrofit cost is studied in the technical-economic justification of seismic retrofit (Bradley 2009). In other words, this paper tries turning existing uncertainty in the earthquake occurrence parameters, structural response and damage models in a logical framework based on principles of seismic risk assessment into decisions parameters.

An outline of the state-of-the-art seismic loss estimation is given with reference to a specific case study of a 5-story steel moment residential building in Tehran. Using the case study structure a full loss assessment is performed and discussion is given to each of the possible outputs for decision making.

2. LOSS ESTIMATION METHOD

2.1. PEER framework formula

According to damages induced from earthquakes, clients are faced with the decision of whether or not to retrofit existing structures in order to lower their potential losses that needs respecting associated risk. In response to perceived insufficiencies of risk assessment methodologies performance-based guidelines have been developed to consider quantitative measures which can be used to objectively assess seismic performance in terms of a decision variable (DV) which is used for considering economic standpoint of clients. One of key developments of Pacific Earthquake Engineering Research (PEER) Center was the development of the PEER framework formula considering all potential uncertainty in estimation of the DV. PEER framework formula expressed as follows (Krawinkler *et al.* 2005):

$$\lambda[DV] = \iiint G(DV|DM)dG(DM|EDP)dG(EDP|IM)d\lambda(IM) .dEDP.dDM \quad (2.1)$$

where terms $\lambda[X]$, $G(X|Y)$, DV, DM, EDP and IM represent, the Mean Annual Frequency (MAF) of exceeding X, the Complementary Cumulative Distribution Function (CCDF) of X conditioned on Y, Decision Variable, Damage measure, Engineering Demand Parameter and Intensity Measure, respectively. Eq. 2.1. domains are:

2.1.1. Hazard Analysis

Intensity measures are quantities that describe the magnitude (M) of ground motion characteristics that significantly affect the upstream variables of the performance assessment approach. In the context of Equation 1, this implies evaluation of the Mean Annual Frequency (MAF) of IMs through seismic hazard analysis. $S_a(T_1, 5\%)$ is indeed the best choice from simplicity and accuracy standpoints (Bozorgnia and Bertero 2004).

2.1.2 Structural Analysis

The amount of demand induced in structure and nonstructural component is represented by term $G(EDP|IM)$ in Equation 1. Once identified, they can be computed from different procedures such as by, the now widely employed, incremental dynamic analysis (IDA) procedure (Vamvatsikos and Cornell 2002), which accounts for record-to record uncertainty that attributed to the aleatory nature of earthquake hazard. In this procedure, the soil–foundation–structure system is subjected to a ground motion whose intensity is incremented after each inelastic dynamic analysis. The result is a curve that shows the EDP plotted against the IM used to control the increment of the ground motion. IDAs can be carried out for a sufficiently large number of ground motions to perform statistical evaluation of the results.

2.1.3. Damage and Loss Analysis

According to uncertainty in damage extent at a specific response level term $G(\text{DM}|\text{EDP})$ is used. To estimate the damage in structural elements, a relationship between relevant EDPs and different levels of damage, referred to here as Damage Measures (DM) is required. The damage analysis methodology used in this paper is based on ATC-58 (ATC-58 2011). The state of damage in structural and nonstructural components is estimated using response vector comprised of peak floor acceleration (PFA) and interstory drift (θ_{\max}) for each story, that is of order $2n+1$ (n represent for number of stories) all developed from IDA results. According to ATC-58, the methodology uses the concept of performance groups (PGs) that account for damage state (DS) of individual components of frame. Because of uncertainties in number of people and facilities and their location (when earthquake occurs) term $G(\text{DV}|\text{DM})$ is used.

After an earthquake, the repair cost will not be the only “loss” suffered by building stakeholder and a variety of factors can affect the consequences of a decision as a Decision Variable (DV), assuredly considering as many factors as possible in the decision-making process will cause the most precise results. For decisions regarding the effects of seismic events on buildings, these consequences include mortality as well as direct and indirect economic losses (Ellingwood and Wen 2005). The challenge lies in incorporating these factors and their consequences, given a particular course of action, into a measurable quantity that can be used to define success or failure. Addressing this challenge is crucial as any decision is ultimately judged on the consequences of its outcome (Williams *et al.* 2009). In this study, three performance measure as DV is considered here:

- 1- repair cost (defined as the cost of repairing or replacing damaged buildings, and their contents).
- 2- casualties (defined as deaths and serious injuries that would normally require hospitalization).
- 3- downtime (defined as the period of time between the occurrence of a seismic event and the completion of the building repair effort. There are various factors that can affect building downtime: building inspection, damage assessment, finance planning, architect/engineering consultations, a possible competitive bidding process, and the repair effort needed to return a building back to its undamaged state.

A probabilistic mapping between a structural response parameter and the level of damage in a particular component may be referred to as a fragility function. Fragility functions associate a relevant EDP with the probability of exceeding a certain level of damage. The best source of information for the development of fragility functions is laboratory test (Fema-461), analytical research, and observations from past earthquakes, engineering judgment or combination of them in which damage states are documented as a function of the EDP that has the largest influence on the extent of damage. Example family of fragility curves for special steel moment frames is depicted in Fig. 2.1.A. The monetary value of repair cost is calculated utilizing cost functions. A sample cost function considering uncertainty is represented in Fig. 2.1.B.

A large part of moving the frontier of performance-based earthquake engineering (PBEE) forward is making both the tools and the methodologies accessible. This has become the focus of numerous recent efforts, for example ATC-58 includes the performance assessment calculation tool (PACT) that allows anyone interested to use off-the-shelf software to compute probabilistic loss estimates. For estimating repair cost, PACT (PACT 2007) software is used. PACT will automatically develop the necessary performance groups based on input of key building descriptive data including: Number of stories, typical story height, typical E-W and N-W building dimension, occupancy of each floor. PACT also contains component fragilities for each damage state and consequence functions for performance measures.

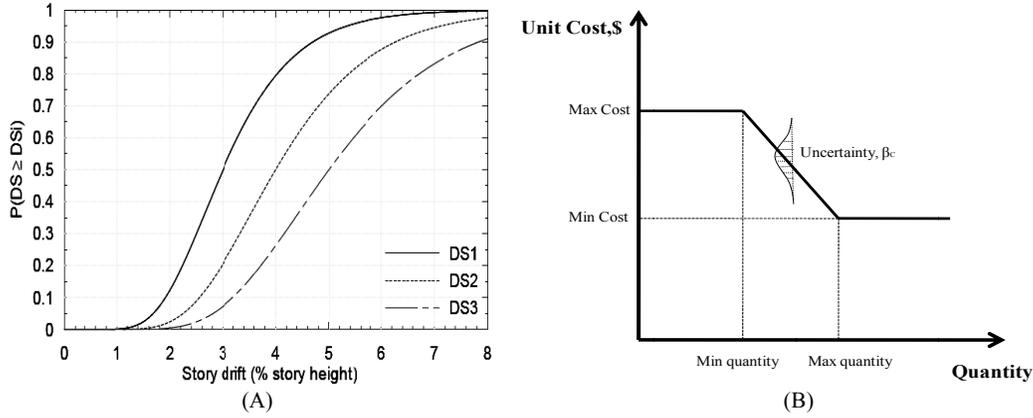


Figure 2.1. A) Family of fragility curves for special steel moment frames, B) Sample cost function considering uncertainty (ATC-58 2011).

Casualty and downtime are considered as a total collapse of structure, so a monetary value for them should be based on social judgment and importance of life loss, and downtime in IRAN. In this study, a cumulative density function is assumed a median cost equal to 3 times the high repair cost (repair cost for most severe damage state resulted from all components) with coefficient of variation equal to 0.4.

2.2. Estimating Final Loss

It should be noted that precise quantification of performance measure is impossible so probabilistic framework should be utilized. According to probability theorem, final loss can be obtained from Equation 2 considering the two probable cases: 1- Collapse (CO) 2- No-collapse (NC):

$$G(\$Loss \geq L | IM) = G(\$RepairCost \geq L | IM \& NC) \times P(NC | IM) + G(\$Loss \geq L | CO) \times P(CO | IM) \quad (2.2)$$

$$*P(CO | IM) = 1 - P(NC | IM) \quad (2.3)$$

In Eq.2, $G(\$RepairCost \geq L | IM \& NC)$ denotes repair cost for NC condition and conditioned on IM, $P(NC | IM)$ is the probability of NC case conditioned on IM which obtained from IDA results (collapse fragility), term $G(\$Loss \geq L | CO)$ represent total cost greater than or equal to L for downtime and casualty conditioned on CO case and finally result of equation is $G(\$Loss \geq L | IM)$ that specifies building total loss for three performance measure greater than or equal to L.

Loss curves conditioned on IM are integrated with hazard curves to outcome exceeding probability for various $S_a(T_1, 5\%)$ values as presented in Eq. 2.4:

$$\lambda(\$Loss \geq L) = \int_{IM=0}^{IM=\infty} G(\$Loss \geq L | IM). d\lambda(IM) \quad (2.4)$$

Annual loss (AL) can be extracted from product of various loss values and their corresponding $\lambda(\$Loss \geq L)$ and integrating over full range of loss values. AL is a seismic performance measure which is particularly useful for decision makers as it contains information on the seismic performance of a structure over a range of different levels of ground motion intensity within a single number. In essence, the annualized loss for repair costs represents the premium that one should be willing to pay for an insurance policy. The annual loss (AL) is also a valuable result for property stakeholders, which accounts for the frequency and severity of various seismic events.

2.3. Application of EAL for Retrofit Decision Making

Net value of expected loss over time accounting for the discount rate is computed by (Bradley 2009):

$$E_L = \frac{(1-e^{-\lambda t})}{\lambda} AL + C_R \quad (2.5)$$

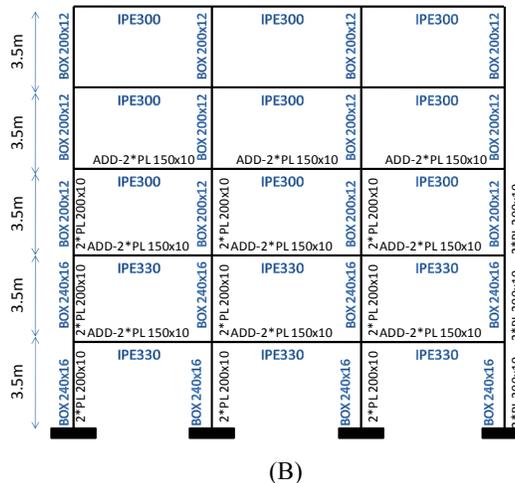
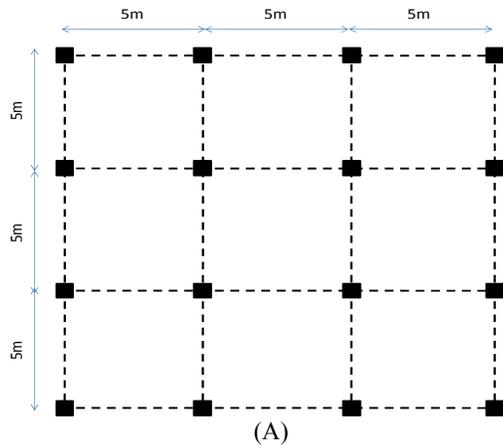
Where λ is the discount rate; t is the time in years; and C_R is the retrofit cost. Then by equating Eq.2.5 for the as-is structure ($C_R = 0$) and retrofitted structure, the time after which the retrofit is economically feasible can be found by:

$$t_{cr} = \frac{-1}{\lambda} \ln \left(1 - \frac{\lambda C_R}{1-\alpha AL} \right) \quad (2.6)$$

Where α is a parameter indicating the reduction in the AL due to the retrofit.

3. CASE STUDY STRUCTURE

Case Study was performed on the 5-story perimeter steel resisting frame that is located Tehran downtown. The frame has excessive drift at floor 3, 4 concerning Iranian code of practice for seismic resistant design of buildings. According to Fig. 3.1, three alternatives for retrofitting is introduced.



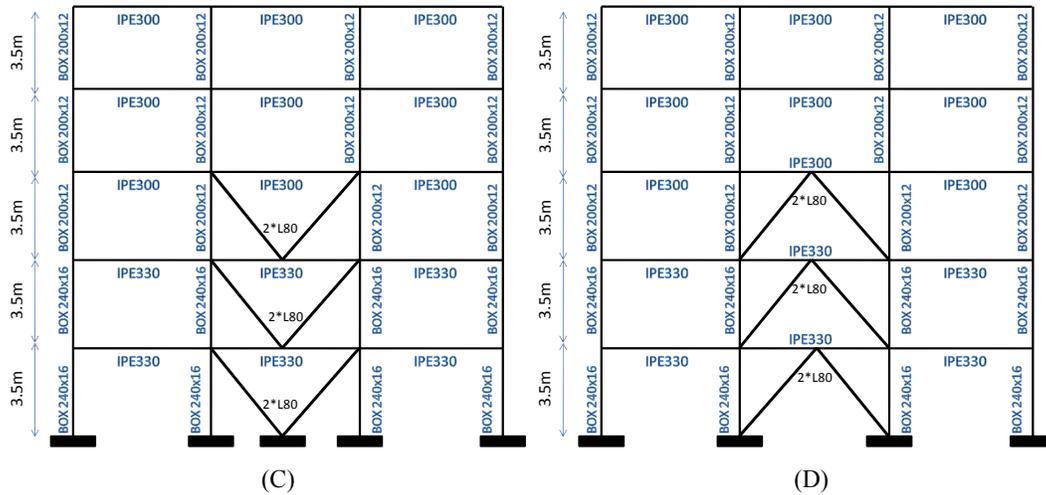


Figure 3.1. A) Plan of case study, B) Alternative-1 of retrofit, C) Alternative-2 of retrofit, D) Alternative-3 of retrofit

3.1. Modeling Details

Concerning the symmetry in plan, the structures are modeled in two-dimensional format in OpenSees (OpenSees 2006) software. Nonlinear beam-column elements with concentrated plastic hinges in two ends, connected by an elastic element, are adopted for modeling the frames. The nonlinear behavior in plastic hinges is modeled implementing rotational springs (with stiffness and strength deterioration). Cyclic moment-rotation of steel beams and columns are represented by Lignos and Krawinkler (2007) which focuses on development of a steel component database that can serve as the basis for validation and improvement of analytical models that explicitly model deterioration in structural steel components and can be used in collapse assessment of steel moment resisting frames. Also, in order to consider the cyclic deterioration, the modified model suggested by Ibarra and co-workers have been used (Ibarra and Krawinkler 2005). In this model, cyclic deterioration parameter is accounted for deterioration criterion by using energy dissipation. The definition of plastic hinges has been performed using Joint2D-5spr element (Altoontash 2004) in OpenSees with panel zone modeled following suggestion (Gupta and Krawinkler 1999). Column base uplift, as expectable in a braced frame, has been accounted for through definition of zero-tension spring elements at the column-foundation interface.

Besides, braces are modeled with distributed inelasticity and fiber discretization of the cross section. The brace member is subdivided into two inelastic beam-column elements. An initial camber displacement of 0.08% of the brace length should be specified at brace midspan. The inelastic response of each element is monitored at five integration points (Uriz *et al.* 2008).

3.2. Ground Motions

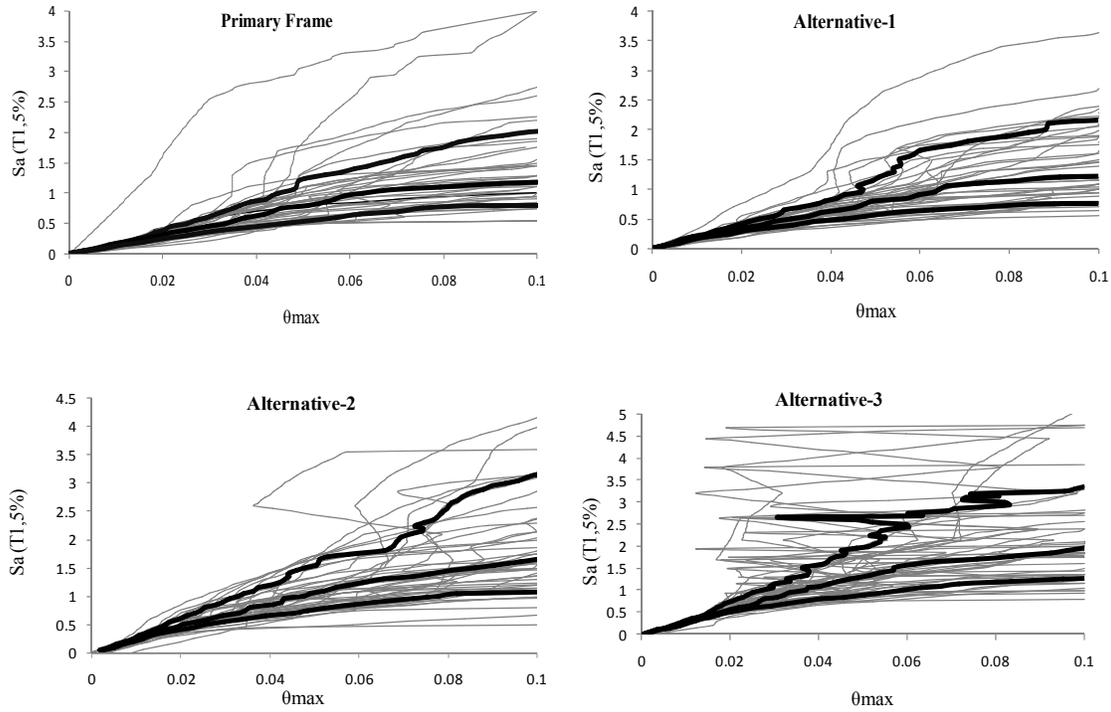
To reflect variability in ground motion, we drew on a set of horizontal-component pairs of 22 far field ground-motion time histories compiled by FEMA P695 (FEMA P695 2009).

3.3. IDA Outcomes

Fig. 3.2. represent IDA curves for frames that median S_a values for fractile IDAs (16%, 50% & 84%) are highlighted in it and summarized S_a for each limit state (Immediate Occupancy (IO) & Collapse Prevention (CP)) are shown in Table 3.1.

Table 3.1. Summarized S_a for limit-states IO and CP for frames ($\times g$)

S_a	Primary Frame		Alternative-1		Alternative-2		Alternative-3	
	IO	CP	IO	CP	IO	CP	IO	CP
16%	0.249	0.74	0.31	0.82	0.39	0.94	0.45	1.007
50%	0.315	1.11	0.39	1.34	0.48	1.66	0.55	1.75
84%	0.399	1.807	0.507	2.2	0.59	2.91	0.676	3.04

**Figure 3.2.** IDA curves for frames

3.4. Loss Estimation and Decision-Making

Hence by calculating Eq. 2.2. and integrating over specific hazard curve (Mahdavi Adeli *et al.* 2011), AL is achieved and decision parameters are calculated for primary frame and retrofitted alternatives that are denoted in Table 3.2. In this table $\lambda_{\text{Collapse}}$ is annual probability of collapse, CMR stands for Collapse Margin Ratio (FEMA P695 2009), C_R is the retrofit cost, AL is annual loss and t_{cr} is the time after which the retrofit is economically feasible considering discount rate ($\lambda=7\%$). It can be inferred, alternative-2 is suitable for performing retrofit from economic standpoint, although alternative-1 has lower AL, but because of more retrofit cost, t_{cr} is become 28 years comparing to alternative-1 with $t_{cr}=19$ years.

Table 3.2. Decision parameters for case studies

Cases	Primary	Alternative-1	Alternative-2	Alternative-3
$\lambda_{\text{Collapse}} \times 10^{-4}$	1.03	0.9618	0.8416	1.113
CMR	2.385	2.483	2.837	2.473
C_R (\$USD))	-	14000	10000	10000
AL (\$USD))	2223.1	1083.565	1257.027	1376.487
t_{cr} ($\lambda=7\%$)	-	28 years	19 years	25 years
Best Choice			Alternative-2	

4. CONCLUSIONS

The present study makes informed decision about economic feasibility for seismic retrofit. In essence this paper tries turning existing uncertainty in the earthquake occurrence parameters, structural response and damage models in a logical framework into decisions parameters. Noteworthy results of this paper are:

- 1- According to this study various retrofit strategies will have reasonable comparability and eases decision process for stakeholders with accessible information. The results of methodology make stakeholders and decision-makers to communicate more easily according to expected economic benefits.
- 2- Estimating Annual loss (AL) can be a valuable tool to estimate insurance amount for seismic vulnerability of buildings and assess performance of existing structures.
- 3- Decision maker should estimate AL and mean annual frequency of collapse and also study economic feasibility of retrofit to mitigate seismic risk by trying different alternatives for retrofitting.

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