Economics on Seismic Rehabilitation of Existing Low-rise Building in Korea

J. S. Byeon
Hyundai Insurance Research Center, Korea

SUMMARY
This paper describes a cost-benefit analysis for seismic rehabilitation of existing buildings, and it is one of a research series of seismic mitigation project for low-rise buildings, supervised by the National Emergency Management Agency of Korea.
In order to measure the economical efficiency of seismic rehabilitation, three common structure types of buildings below 5-story in Korea are selected; a masonry structure of multi-family house, a reinforced concrete structure of multi-family house, and a reinforced concrete structure of neighborhood facility.
For those buildings, the cost-benefit analysis is performed to calculate the B/C ratio, with the construction cost of retrofitting as "Cost" and the difference of expected loss between before-retrofitting building and after-retrofitting building as "Benefit".
Those expected losses are estimated using a new component-based loss estimation methodology, which is based on Capacity Spectrum Method. Assemblies of the component fragilities are used to approximate the loss of the entire structure and each component's loss is defined by the exceeding probability of fragility curve multiply by the repair/replacement cost, with different levels of damage state. For estimating an accurate loss, the repair/replacement cost refers to Korea material price handbook 2011 and actual construction cost in practice is used.
As a result, seismic rehabilitation is cost effective for all three buildings, which are even located in relatively low-mid frequent earthquake area.

Keywords: cost-benefit analysis, fragility curve, repair/replacement cost, economical efficiency

1. INTRODUCTION

In Korea, a seismic design code was first established in 1988, and the code has been continuously revised with respect to story and/or size of the building. After 2005, if the building is over 3-story or the total building floor area is greater than 1,000 m^2, the building is mandatory to reflect the earthquake-resistance design. In other words, the buildings were built before 1988 or below 5-story buildings were built after 1988, they were not constructed by any seismic design code. Especially low-rise masonry buildings mostly belongs to those non-earthquake resistance building and they are the most vulnerable to earthquake. And even if the building is not a masonry structure, the low-rise building is generally weak to earthquake due to their short-period of building characteristics and lack of ductility.

This paper describes a cost-benefit analysis for seismic rehabilitation of existing buildings, and it is one of a research series of seismic mitigation project for low-rise buildings, supervised by the National Emergency Management Agency of Korea (NEMA). Among the NEMA project, many research topics are already dealt with many researchers such as evaluation of seismic performance and seismic retrofit design, etc. However the topic of an economics on seismic rehabilitation is especially a quiet new research field in Korea.

The aim of economics on seismic rehabilitation study is promoting retrofitting of the existing buildings. And the result of the cost-benefit analysis will show the benefit as a monetary, with the construction cost of retrofitting as "Cost" and the difference of expected loss between before-retrofitting building and after- retrofitting building as "Benefit".

Expected losses are estimated using a new component-based loss estimation methodology, which is based on Capacity Spectrum Method. Assemblies of the component fragilities are used to approximate the loss of the entire structure and each component's loss is defined by the exceeding probability of fragility curve multiply by the replacement cost, with different levels of damage state. For estimating an accurate loss, the repair/replacement cost refers to Korea material price handbook 2011(Korea Construction Association, 2011) and actual construction cost in practice is used.

2. SELECTED BUILDING TYPES AND REHABILITATION COST

In order to measure the economical efficiency of seismic rehabilitation, three common structure types of buildings below 5-story in Korea are selected; a masonry structure of multi-family house, a reinforced concrete structure of multi-family house, and a reinforced concrete structure of neighborhood facility.

According to HAZUS's building classification, those buildings are classified as a low-rise unreinforced masonry bearing walls(URML), a mid-rise concrete shear wall(C2M) and a mid-rise concrete frame with unreinforced masonry infill walls(C3M), respectively.

In Korea, a research titled "Development of Seismic Fragility Function for Buildings in Korea" recently conducted by National Disaster Management Institute of Korea (NDMI, 2009)). According to NDMI's building classification, those buildings belong to a low-rise unreinforced masonry bearing walls (URML), a mid-rise concrete shear wall with pilotis (C5L) and a mid-rise concrete frame with unreinforced masonry infill walls (C2L2), respectively.

Scheme of the selected buildings is summarized in the table 1.

Table 1. Scheme of the Selected Buildings

Construction type	Occupancy type	Construction year	Story	HAZUS	NDMI
Masonry	Multi-family	1979	2	URML	URML
Reinforced concrete	Multi-family	1985	5	C2M	C5L
Reinforced concrete	Neighborhood facility	1980	5	C3M	C2L2

One of the most important steps to objectively estimate the expected loss is to evaluate building response to earthquake force. Nonlinear pushover analysis is proved to be an effective approach to fulfill this task. It takes into account nonlinear actions in the structure and evaluates building capacity and response step by step, as equivalent lateral earthquake force is applied monotonically on the building. The current state of practice is to use pushover analysis in conjunction with Linearization Method (FEMA 440, 2005) to determine the intensity of a potential earthquake on a given building.

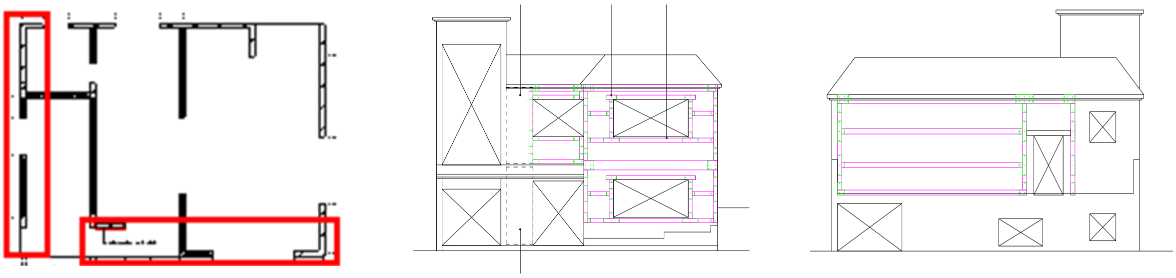
The nonlinear analysis procedure produces two types of information; capacity curve that presents the base shear as a function of deformation of the structure (for example roof displacement); and deformations history of each component at each step of analysis.

By performing PERFORM-3D, a nonlinear structural analysis, the selected buildings have been evaluated the seismic stability and the suitable rehabilitation technique is suggested to meet the current seismic design code. As mentioned earlier, the construction cost of retrofitting is defined as "Cost". Three selected buildings are tested how suggest the rehabilitation technique and how calculate the construction cost.

2.1. Masonry Structure of Multi-family House

Unreinforced masonry building (URM) is one of majority building types in Korea. Most of them are built in 1970's and those old buildings are well known as the most vulnerable to earthquake. Masonry building, in fact, is very difficult modeling into a commercial structural analysis program because of an unpredictable property of masonry. So without any structural analysis, the rehabilitation technique of this building is suggested by expert opinions.

To meet the seismic requirement of the Korea Building Code 2009(KBC, 2009), the following rehabilitation plan are suggested as shown in Fig. 1: (a) Two-side of exterior walls are strengthened as bearing walls, (b) Attach steel plates around the windows, (c) Attach steel plates around the door and the long exterior wall. To doing so, the total construction cost of retrofitting is estimated at 21,260,000 won ($ 18,500 USD), based on Korea material price handbook 2011 and actual construction cost in practice.



(a) Strengthen wall (b) Add steel plate (c) Add steel plate

Figure 1. Retrofitting plan for masonry structure of multi-family house

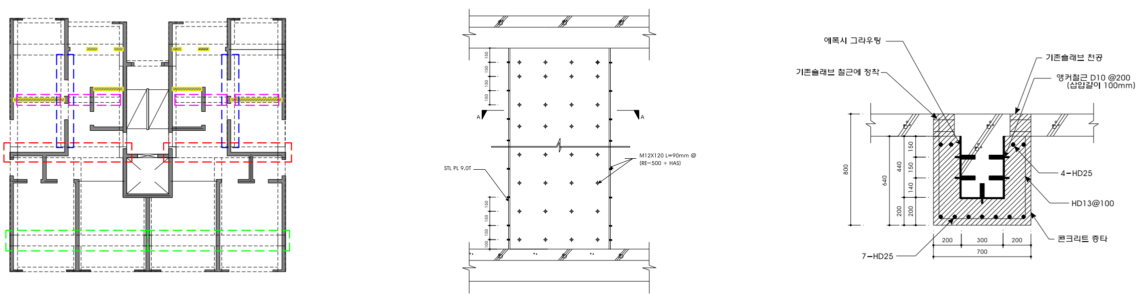
2.2. Reinforced Concrete Structure of Multi-family House

This building is also common structure type for multi-family residence in Korea. In 1980’s, Korea government strongly recommended to build this type of buildings for efficient of land use. The first floor of the building has usually open space, called “pilotis”, and it is reserved as parking space. However due to the insufficient of vertical members, this type of building is weak to the lateral force such as an earthquake.

Seismic performance of the building is evaluated by the current seismic design level (Life Safety) with FEMA 440 Linearization Method. Followings are assumed for the evaluation: Site coefficient as 0.176, site soil class as Sc (very dense soil and soft rock), damping ratio as 5%, and period of the building as 0.541 second.

As a result, the transition story is found between first and second floor. And to meet the KBC 2009 building code, many beams and some bearing walls at second floor and the core area at first floor are needed to strengthen. Other floor does not need any additional reinforcements.

Location of the reinforcing steel plate of the beams and walls, and structural drawing for increasing size of the beam are shown in Fig. 2. The total retrofitting cost is estimated at 28,590,000 won ($ 24,900 USD).



(a) Add steel plate(wall) (b) Add steel plate(beam) (c) Enlarge Beam

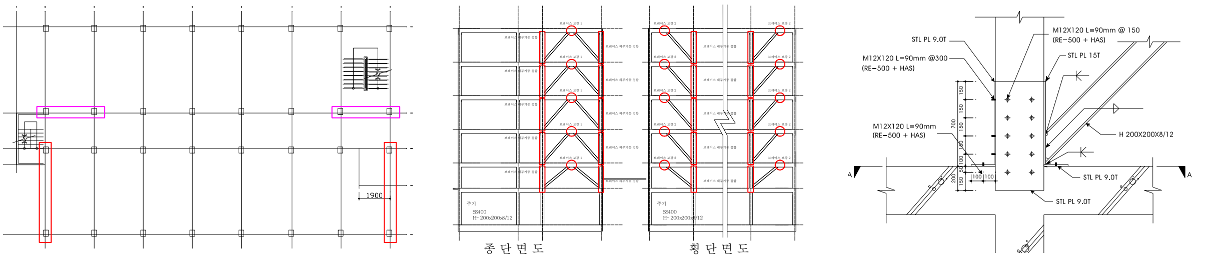
Figure 2. Retrofitting plan for reinforced concrete structure of multi-family house

2.3. Reinforced Concrete Structure of Neighborhood Facility

For the occupancy point of view, small offices and shops belong to this type of building in Korea.

Similar to a reinforced concrete structure of multi-family house, this building is evaluated the seismic performance by the current seismic design level (Life Safety) with FEMA 440 Linearization Method. Following assumptions are used for the evaluation: site coefficient as 0.176, site soil class as Sc (very dense soil and soft rock), damping ratio as 5%, and period of the building as 0.5426 second.

According to a result, the rehabilitation plan is suggested as shown in Fig. 3. Frames strengthened with 15-steel braced members and columns strengthened with steel plates is needed to meet the KBC 2009 building code. Total retrofitting cost is estimated at 50,400,000 won ($ 43,800 USD).



(a) Add Bracing (b) Add Bracing (c) Add steel plate

Figure 3. Retrofitting plan for reinforced concrete structure of neighborhood facility

3. EARTHQUAKE LOSS ESTIMATION METHODOLOGY

In chapter 2, we estimate the construction cost of retrofitting as "Cost" for three different buildings. The purpose of this paper is measuring the economical efficiency of seismic rehabilitation and now we need to calculate “Benefit”. Benefit is defined by the difference of expected loss between before-retrofitting building and after-retrofitting building. Expected loss is a result of the loss estimation methodology.

In the late 1980’s, an earthquake loss estimation methodology was first developed in U.S. and now it is used worldwide, especially for the government and insurance purpose.

One of the first systematic attempts to quantify building vulnerability to earthquakes came from the Applied Technology Council in a report to the Seismic Safety Commission of the State of California, ATC-13 (1985). ATC-13 essentially derived damage functions by asking experts to estimate the expected percentage of damage that would result to a typical building of a specific construction type were that being subjected to a given MMI. Based on their personal knowledge and experience, the experts responded to a formal questionnaire with their best estimates of damage ratios.

A second major effort to develop a methodology for vulnerability assessment was undertaken by the National Institute of Building Sciences (NIBS), and funded by FEMA (1999). The result, HAZUS, was released in 1997 as risk assessment interactive software. In HAZUS, spectral displacements and spectral accelerations replaced MMI as the measure of seismic intensity. The focus shifted from ground motion to the individual building’s response to ground motion. This objective measure of earthquake intensity allowed for finer gradations in estimating the potential damage to a structure. However, the HAZUS study continues to rely on expert opinion and engineering judgment to estimate the state of damage that would result from a given spectral displacement and acceleration. While HAZUS represent a significant advance, the difficulties surrounding reliance on expert opinion remain.

Considering the shortcomings of both ATC-13 and HAZUS methodologies, a new objective technique has been developed (Byeon, 2000) and it revised in this paper. It is a component based methodology and those components include columns, beams, partitions, etc. A criterion for selecting each component was that one should be able to obtain an individual function describing damageability of each component. These individual damage functions were developed by combining the data obtained from the experimental studies conducted at various universities and research organizations in a probabilistic manner.

A proposed component-based earthquake loss estimation methodology proceeded as following steps.

3.1. Determine the Performance Point from Capacity Spectrum Method

By performing a nonlinear analysis, the seismic capacity spectrums are developed for three selected buildings. The demand spectrum is also constructed with specific site information such as site coefficient, soil condition, etc. Based on Capacity Spectrum Method, an intersection of the capacity spectrum and the demand spectrum is a performance point that approximates the response of the structure.

In the table 2, the spectral displacement and the spectral acceleration of the before-retrofitting (existing) buildings are calculated by CSM, except the masonry structure of multi-family. As stated earlier, the difficulty of the capturing their material property, the intersection point of masonry building is calculated by approximation. And for the after-retrofitting buildings, new spectral displacements are also calculated by performing CSM, and it usually shorter than before-retrofitting buildings due to the additional lateral strength. Life Safety performance level is assumed for all computational structural analysis.

Table 2. Performance Point of the Before- and After-Retrofitting Buildings

Building Type	Spectral Displacement (cm)	Spectral Acceleration.(g)	New Spectral Displacement(cm)	Performance Level
Masonry Structure of Multi-family House	3.700(assumed)	N/A	0.930(assumed)	N/A
Reinforced Concrete Structure of Multi-family House	1.439	0.280	0.360	Life Safety
Reinforced Concrete Structure of Neighborhood Facility	3.270	0.204	0.818	Life Safety

3.2. Calculate the Exceedence Probability at Given Spectral Displacement

Building damage functions are in the form of lognormal fragility curves that relate the probability of being in, or exceeding, a building damage state to for a given spectral displacement. Each fragility curve is defined by a median value of the spectral displacement that corresponds to the threshold of the damage state and by the variability associated with that damage state.

The conditional probability of being in, or exceeding, a particular damage state, *ds*, given the spectral displacement, S_d, is defined by the function as Eqs 1.:

$$P[ds|S_d] = \Phi\left[\frac{1}{\beta_{ds}}\ln\left(\frac{S_d}{S_{d,ds}}\right)\right] \quad (1)$$

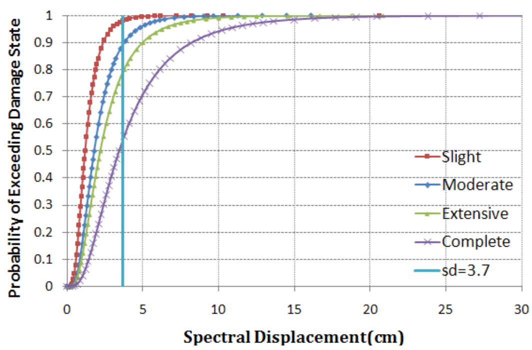
Here, $\bar{S}_{d,ds}$ is the median value of spectral displacement at which the building reaches the threshold of the damage state, d_s, β_{ds} is the standard deviation of the natural logarithm of spectral displacement of damage state, d_s, and Φ is the standard normal cumulative distribution function.

For all building types in Korea including selected buildings, the median ($\bar{S}_{d,ds}$) and lognormal standard deviation (β_{ds}) are recently developed by NDMI (2009) and they are used in this study. Their parameters are listed in the table 3.

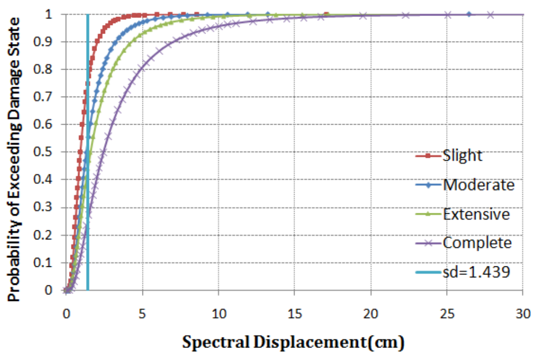
Table 3. Fragility Curve Parameter of Selected Buildings

Building Type	Slight		Moderate		Extensive		Complete	
	med	beta	med	beta	med	beta	med	beta
Masonry Structure of Multi-family House (URML, pre-code)	1.2	0.54	1.8	0.58	2.2	0.64	3.45	0.68
Reinforced Concrete Structure of Multi-family House (C5L, pre-code)	0.911	0.63	1.3	0.71	1.58	0.78	2.43	0.83
Reinforced Concrete Structure of Neighborhood Facility (C2L2, pre-code)	0.956	0.5	1.37	0.6	2.23	0.82	4.84	0.83

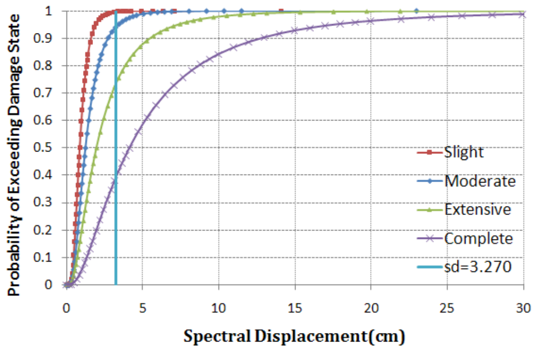
Figure 4 shows the fragility curves of 5 different damage states for three selected buildings. And it describes how to get the cumulative probabilities and the discrete probabilities of the given spectral displacement. For the before- and after-retrofitting buildings, the corresponding probabilities of each damage state of selected buildings are listed in table 4, 5, 6 respectively.



(a) URML, pre-code



(b) C5L, pre-code



(c) C2L2, pre-code

Figure 4. Fragility Curves for Selected Buildings

Table 4. Exceedence Probabilities of URML (pre-code)

Damage states	Before-Retrofitting Building		After-Retrofitting Building	
	Cumulative Prob.	Discrete Prob.	Cumulative Prob.	Discrete Prob.
None	1.0000	0.0185	1.0000	0.6851
Slight	0.9815	0.0885	0.3149	0.1894
Moderate	0.8929	0.1012	0.1255	0.0376
Extensive	0.7917	0.2507	0.0879	0.0615
Complete	0.5410	0.5410	0.0264	0.0264
Total		1.0000		1.0000

Table 5. Exceedence Probabilities of C5L (pre-code)

Damage states	Before-Retrofitting Building		After-Retrofitting Building	
	Cumulative Prob.	Discrete Prob.	Cumulative Prob.	Discrete Prob.
None	1.0000	0.2340	1.000	0.9299
Slight	0.7660	0.2091	0.071	0.0349
Moderate	0.5569	0.1046	0.0352	0.0063
Extensive	0.4523	0.1884	0.0289	0.0182
Complete	0.2639	0.2639	0.0107	0.0107
Total		1.0000		1.0000

Table 6. Exceedence Probability of C2L2 (pre-code)

Damage states	Before-Retrofitting Building		After-Retrofitting Building	
	Cumulative Prob.	Discrete Prob.	Cumulative Prob.	Discrete Prob.
None	1.0000	0.0030	1.0000	0.5554
Slight	0.9970	0.0545	0.4446	0.2015
Moderate	0.9425	0.2058	0.2432	0.1074
Extensive	0.7368	0.3425	0.1358	0.1032
Complete	0.3943	0.3943	0.0326	0.0326
Total		1.0000		1.0000

3.3. Calculate the Repair/Replacement Cost of Components at Given Damage States

For implementing a new component-based loss estimation methodology, the building divided by structural and non-structural components. Structural component includes column, beam and slab. Non-structural component includes partition, exterior wall, window, ceiling and EMP (electric and mechanic part).

With different levels of damage state, the repair/replacement cost of each component are calculated by using Korea material price handbook 2011(Korea Construction Association, 2011) and actual construction cost in practice.

3.4. Estimate the total Repair/Replacement Cost

For three selected buildings, the repair/replacement cost of each component is listed in the table 7, 8, 9, respectively. And for three selected buildings, the sum of 8-component's repair/replacement cost is listed in the second column of the table 10, 11, 12, respectively.

The total building repair/replacement cost is sum of each component's repair/replacement cost and it assumes as an expect loss of building due to the earthquake.

Table 7. Repair/Replacement Cost of URML (pre-code)

Damage states	Structural Components			Non-Structural Components				
	Column	Beam	Slab	Partition	Ext.Wall	Window	Ceiling	EMP
Slight	-	906,400	453,200	897,750	90,792	435,802	159,341	2,174,536
Moderate	-	2,112,736	1,056,368	3,414,870	476,309	1,307,405	1,171,625	6,523,608
Extensive	-	6,624,960	3,312,480	12,409,470	2,040,725	5,352,538	3,674,216	10,872,680
Complete	-	6,624,960	3,312,480	14,574,330	2,652,523	6,659,942	8,529,430	17,396,288

Table 8. Repair/Replacement Cost of C5L (pre-code)

Damage states	Structural Components			Non-Structural Components				
	Column	Beam	Slab	Partition	Ext.Wall	Window	Ceiling	EMP
Slight	271,040	2,622,400	1,311,200	2,810,640	262,080	1,257,984	678,674	9,261,904
Moderate	1,127,280	6,522,304	3,261,152	10,691,139	1,374,912	3,773,952	4,990,250	27,785,712
Extensive	3,704,870	23,264,640	11,632,320	38,851,075	5,890,752	15,450,624	15,649,424	46,309,520
Complete	6,333,466	23,264,640	11,632,320	45,628,733	7,656,768	19,224,576	36,329,020	74,095,232

Table 9. Repair/Replacement Cost of C2L2 (pre-code)

Damage states	Structural Components			Non-Structural Components				
	Column	Beam	Slab	Partition	Ext.Wall	Window	Ceiling	EMP
Slight	1,056,000	4,642,000	2,321,000	7,567,875	269,880	2,914,704	1,210,613	16,521,300
Moderate	4,392,000	11,562,800	5,781,400	28,786,755	1,415,832	8,744,112	8,901,563	49,563,900
Extensive	10,277,280	41,356,000	20,678,000	87,917,085	6,066,072	35,798,544	27,915,300	82,606,500
Complete	12,337,920	41,356,000	20,678,000	122,859,045	7,884,648	44,542,656	64,803,375	132,170,400

Table 10. Expected Loss of Before- and After-Retrofitting Building (URML, pre-code)

Damage states	Before-Retrofitting Building			After-Retrofitting Building		
	Sum of Repair cost	Exccedence Probability	Expected Loss	Sum of Repair cost	Exccedence Probability	Expected Loss
Slight	5,117,821	0.0885	453,100	5,117,821	0.1894	969,233
Moderate	16,062,921	0.1012	1,626,357	16,062,921	0.0376	604,184
Extensive	44,287,068	0.2507	11,103,689	44,287,068	0.0615	2,721,729
Complete	59,749,954	0.5410	32,322,993	59,749,954	0.0264	1,580,198
Total			45,506,138			5,875,344

Table 11. Expected Loss of Before- and After-Retrofitting Building (C5L, pre-code)

Damage states	Before-Retrofitting Building			After-Retrofitting Building		
	Sum of Repair cost	Exceedence Probability	Expected Loss	Sum of Repair cost	Exceedence Probability	Expected Loss
Slight	18,475,922	0.2091	3,863,111	18,475,922	0.0349	645,560
Moderate	59,526,701	0.1046	6,225,344	59,526,701	0.0063	374,178
Extensive	160,753,226	0.1884	30,280,746	160,753,226	0.0182	2,929,348
Complete	224,164,754	0.2639	59,165,247	224,164,754	0.0107	2,394,519
Total			99,534,448			6,343,605

Table 12. Expected Loss of Before- and After-Retrofitting Building (C2L2, pre-code)

Damage states	Before-Retrofitting Building			After-Retrofitting Building		
	Sum of Repair cost	Exceedence Probability	Expected Loss	Sum of Repair cost	Exceedence Probability	Expected Loss
Slight	3,395,649	0.0545	1,820,063	33,395,649	0.2015	6,729,223
Moderate	108,924,127	0.2058	22,416,585	108,924,127	0.1074	11,698,451
Extensive	272,531,940	0.3425	93,342,189	272,531,940	0.1032	28,125,296
Complete	395,585,403	0.3943	155,979,324	395,585,403	0.0326	12,896,084
Total			273,558,162			59,449,055

4. ECONOMICS ON SEISMIC REHABILITATION OF EXISTING BUILDING

Expected loss of before- and after-retrofitting is calculated in chapter 3. As stated earlier, the difference of expected loss between before- retrofitting building and after- retrofitting building is "Benefit" and the construction cost of retrofitting is "Cost". As a result, the efficiency of rehabilitation can be represented by B/C ratio. If the ratio is a greater than 1, then it is an efficient. And the bigger B/C is more efficient.

Table 12. Result of Cost Benefit Analysis

Building Type	Expected loss of Before-Retrofit Bldg.	Expected loss of After-Retrofit Bldg.	Benefit	Cost	B/C
Masonry Structure of Multi-family House	45,506,000	5,875,000	39,631,000	21,260,000	1.86
Reinforced Concrete Structure of Multi-family House	99,524,000	6,343,000	93,181,000	28,590,000	3.26
Reinforced Concrete Structure of Neighborhood Facility	273,558,000	59,449,000	214,109,000	50,400,000	4.25

5. CONCLUSION

This paper is a first attempt to study on economics on seismic rehabilitation of existing low-rise buildings in Korea. It describes cost-benefit analysis processes for seismic rehabilitation of three common existing buildings. The aim of economics on seismic rehabilitation study is promoting retrofitting of the existing buildings. And the result of the cost-benefit analysis show the benefit as a monetary, with the construction cost of retrofitting as "Cost" and the difference of expected loss between before- retrofitting building and after- retrofitting building as "Benefit".

Expected losses are estimated using a new component-based loss estimation methodology, which is based on Capacity Spectrum Method. Assemblies of the component fragilities are used to approximate the loss of the entire structure and each component's loss is defined by the exceeding probability of fragility curve multiply by the replacement cost, with different levels of damage state. For estimating an accurate loss, the repair/replacement cost refers to Korea material price handbook 2011 and actual construction cost in practice is used.

As a result, seismic rehabilitation is cost effective for all three selected buildings, which are even located in relatively low-mid frequent earthquake area.

ACKNOWLEDGEMENT

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