Estimation of Financial Added Value for Retrofitted Buildings

M. R. Zolfaghari
Associate Professor, KN Toosi University of Technology, Tehran, Iran

Sh. Mahboubi
MSc Student, KN Toosi University of Technology, Tehran, Iran

E. Peyghaleh
PhD Candidate, KN Toosi University of Technology, Tehran, Iran

SUMMARY:
Damaged caused by many large earthquakes in the recent years have made the necessary justification for retrofitting measures of existing buildings in many countries. Structural retrofitting aims in reduction of building vulnerability and improvement in the financial value for existing buildings. In this study nonlinear static analyses are performed on a selection of typical Iranian low to mid-rise reinforced concrete buildings using a selection of 15 strong ground motion records. Target displacements for these buildings are estimated using capacity-demand method. Based on the methodology proposed by HAZUS, fragility curves are estimated for these buildings before and after retrofitting measures. Damage curve are then associated to each building using fragility curves. Following a risk assessment procedure, probabilistic economic losses are estimated for each building before and after retrofitting process.

Keywords: Retrofitting, Seismic Risk, Financial Loss

1. INTRODUCION

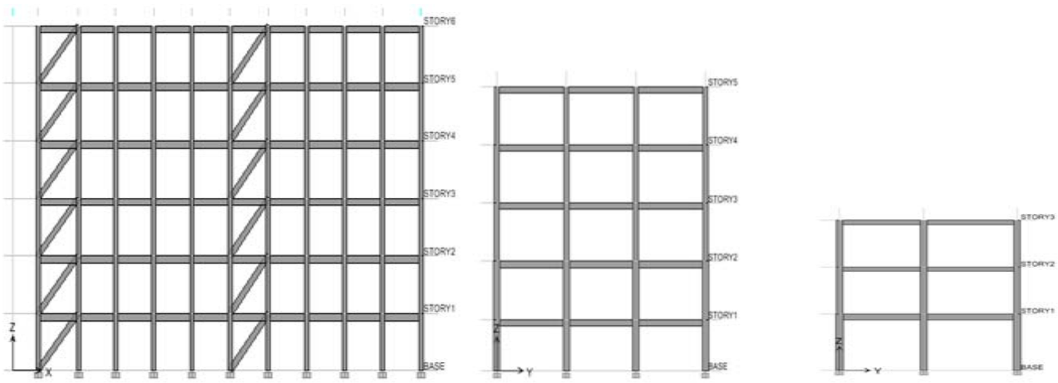
Earthquake hazards are among natural phenomena causing loss of human life and socio-economic consequences. During the past decades seismic design codes have been improved significantly resulting life safety as well as minimizing economic losses due to earthquake. For existing building stock, retrofitting is a framework to improve seismic performance which is an effective approach for reducing seismic losses. Due to considerable cost of retrofitting, it seems hard for decision makers and building owners to determine on what level the retrofitting should be performed and whether from cost/benefit points of view, the process can be justified. The process of loss estimation modelling consists of four major steps: identification of seismic hazard, structural analysis, estimation of building vulnerability and loss assessment. Seismic hazard can be classified as probabilistic or deterministic. Peak ground acceleration (PGA) or peak ground velocity (PGV) may be used as seismic hazard agent. To determine building response to a given seismic hazard, structural analyses are performed and usually nonlinear static analyses are employed to assess push over curves. Vulnerability assessments include developing fragility curves and estimating building damage states. Fragility curves represent probability that specific building damage states exceed under a certain hazard level. Loss estimation model provides probabilistic losses that a building may suffer as the result of regional seismic hazard and building vulnerability. Comparison on the probabilistic losses obtained in this way for buildings before and after retrofitting process can be used as measures indicating added value for the building as the result of retrofitting process. This paper explains the basic for such assessment for sample building types in Tehran, Iran.

2. METHODOLOGY

Various methods are proposed and used to evaluate seismic response of structures. Earthquake engineers are interested to determine the displacement demand when structures deform beyond elastic range. Nonlinear static analysis is often employed for this purpose. In this paper, nonlinear static and pushover analyses were performed to determine target displacement in two performance levels; life safety and collapse prevention. By employing pushover curves and determination of target displacements, vulnerable elements in each structure were defined and retrofitting procedures based on FEMA were performed. A selection of 15 strong ground motion records were used to assess performance point before and after retrofitting procedure. To define performance points for each structure, Capacity-Spectrum Method (CSM-ATC-40) and coefficient method (FEM-356) were employed. Based on CSM method, the capacity curve of each structure and demand spectra need to be converted to ADRS spectra (spectral acceleration vs. spectral displacement) to determine performance points. Using the results from these analyses and based on methodology proposed by HAZUS, four structural damage states for each building were defined and fragility curves were estimated for all sample buildings. The four damages stages are: slight, moderate, extensive and complete damage. Using these fragility curves and based on the HAZUS and FEMA-351 loss estimation methodology, damage curves were estimated for these building in two stages; before and after retrofitting process. Construction costs for similar buildings in Iran are used to estimate the repair or replacement cost.

3. PILOT STUDY

Reinforced Concrete structures represent a significant portion of residential and commercial buildings in many countries in the middle east and in particular Iran. In order to estimate added financial value for building after retrofitting process and to study the effects of retrofitting on building response, three reinforced concrete buildings were modeled in this study. The buildings are; a three-story building with moment resisting frames, a five-story building with shear walls and a six-story building with shear walls. All buildings are located on soil class D (III according to Iranian design code). Figure 1 shows the structural frames for these buildings.



(c) (b) (a)

Figure1. Sample structures: a) 3-story building, b) 5-story building c) 6-story building.

3.1. Seismic Hazard

Every structural analysis method requires some forms of definition for earthquake demand. In equivalent static analysis, lateral forces are calculated by determining spectral acceleration at fundamental period of structure. In Capacity-Spectrum Method, seismic response of structure is evaluated by using nonlinear static analysis and a selection of strong ground motion records. These records indicate many features of earthquake such as; intensity, depth, source distance, fault rupture types and site conditions. For this study, a selection of 15 strong ground motion records was used. This set contains ground motion records on soil type B, C and D with magnitude ranges of 6-7.5 and source-to-distance up to 70km. Table 1 shows more details for these records. These records were scaled to PGA value ranging from 0.25-1.5g in increments of 0.25g before being converted to acceleration spectra curves.

Table 1. Strong ground motions records

No.	Earthquake	(M)	PGA(g)	Distance (km)	Soil condition	Source
1	Big bear	6.4	0.089	45.51	C	CDMG
2	Cape Mendocino	7.1	0.59	53.34	C	CDMG
3	Chichi, Taiwan	7.6	0.364	40.47	C	CWB
4	Coalinga	6.4	0.227	30.06	C	CDMG
5	Erzincan,Turkey	6.9	0.248	8.97	C	
6	Imperial Valley	7	0.313	12.99	C	USGS
7	Kobe	6.9	0.243	45.97	D	CUE
8	Kobe	6.9	0.611	13.12	D	CEU
9	Kocaeli, Turkey	7.4	0.152	5.31	B	ERD
10	Lander	7.3	0.104	59.68	C	CDMG
11	Loma Prieta	6.9	0.216	47.9	C	USGS
12	Nahanni,Canada	6.8	0.978	6.8		
13	Northridge	6.7	0.568	40.68	B	CDMG
14	Northridge	6.7	0.357	29.72	C	USC
15	Tabas, Iran	7.4	0.836	55.24	C	

3.2. Definition of Performance Point or Structural Response

There are several methods to evaluate structural response. CSM is the most extensively used type of nonlinear static analysis due to its ability to provide rapid assessment of the relationship between capacity and demand. Several versions of Capacity-Spectrum Methods are used for investigating the effect of earthquake on structural response. One of these methods is the method used in ATC-40 to define performance point of structures. In this paper, performance points were defined by utilizing this method. According to Capacity-Spectrum method, it is necessary to plot capacity diagrams for each building first. The capacity curves, represented as pushover curves here, are expressed in terms of base shear versus top roof displacement of structure. These curves were estimated by pushover analysis for each structure (ATC-40,1996) .

The second component of capacity spectrum method is demand spectra. Demand spectra are derived from strong ground motion records and expressed in terms of spectral acceleration versus period. In order to define performance point, capacity curves and demand spectra must be represented in ADRS format that is a plot of spectral acceleration versus spectral displacement. Table 2 shows equations presented by ATC-40 for converting capacity and demand spectra to ADRS format. Finally by intersecting capacity and demand spectra, performance point of structure is obtained. This process is shown in figure 2 (ATC-40, 1996).

Table2. Equations use to convert capacity and demand spectra to ADRS format (ATC-40, 1996)

Diagram	Converting Equation	
Capacity Curve	$S_a = \frac{V/W}{\alpha_1}$	$S_d = \frac{\Delta_{roof}}{\phi_{roof,1} PF_1}$
Demand Spectra	$S_d = \frac{T^2}{4\pi^2} S_a g$	

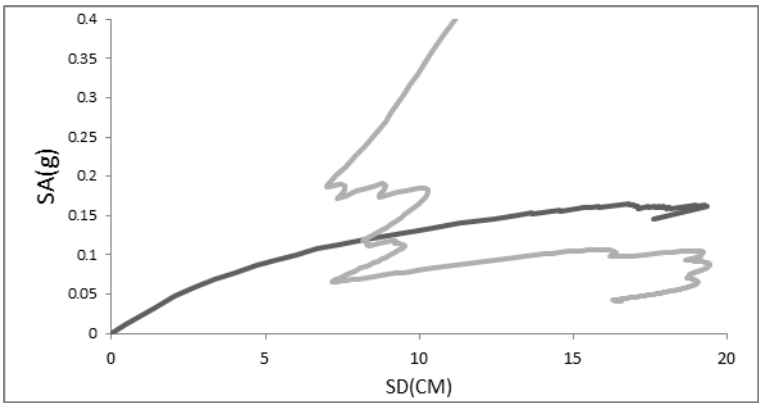


Figure 2. Intersection of capacity and demand spectra

3.3. Structural Damage Limit States

Building codes set life safety as the main objective in seismic design but to maintain damage caused by earthquake hazard it is necessary to estimate social and economic loss due to seismic hazard. For this purpose the relationship between damage levels and behavior of building must be defined. In most design codes, drift ratio and displacement measures are used as indication of buildings behavior and functionality. Therefore damage criteria can be described based on displacement values. Performance based design is also a methodology that describe design objectives in terms of performance levels. In most building codes, performance levels are defined according to qualitative approach. The three important structural performance levels in seismic design codes are immediate occupancy, life safety and collapse prevention. HAZUS damage functions have two basic component; capacity curves and fragility curves. Capacity curves indicate the nonlinear behavior of structures and defined by structural analyses. Each fragility curve has four structural damage states; slight, moderate, extensive and complete. These threshold values of damage states are defined according to capacity diagram. Each capacity curve is described by two control points; (1) yield capacity that represents the lateral strength of building and accounts for design strength in seismic design codes and (2) ultimate capacity which represents maximum strength of building and it is assumed that a building can deform beyond its ultimate point without loss of stability and its structural systems provide no additional resistance to lateral earthquake forces. In HAZUS, there are certain parameters which define yield points and ultimate point (HAZUS-MH-2003).

In this study, structural damage limit states were defined according to drift and strength values upon examining the behavior of structures. Behavior of structure can be identified according to characteristics that are visible on capacity curves. These characteristic include sudden changes in stiffness, changes in material properties and strength level. Damage limit states were described in terms of spectral displacement and were defined as follows:

- Slight structural damage state: The first yield point of structure and first significant change in slope of capacity diagram.
- Moderate structural damage state: The yield point that is calculated as the point equivalent to elasto-plastic system which energy absorption are equivalent to that of a real system.
- Extensive structural damage state: The average value between moderate and complete limit states.
- Complete structural damage state: the ultimate point of capacity curve (Frankie, T. M. 2010).

These threshold values were derived by averaging over all capacity curves. Figure 3 displays an example of capacity curve with the average damage limit states values for the five-story building.

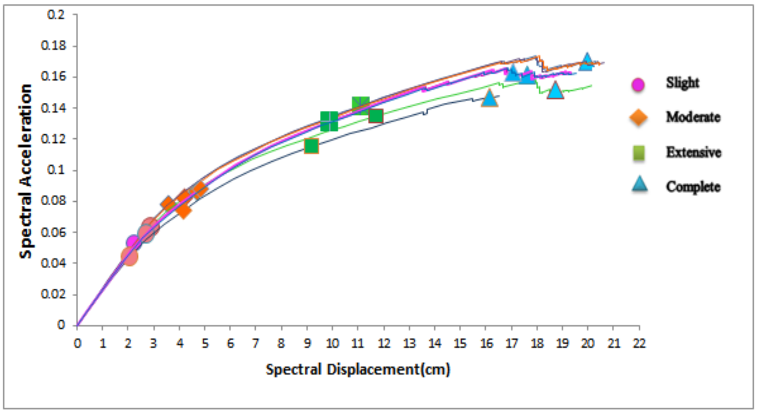


Figure 3. Limit state threshold values plotted and averaged for a set of curves.

3.4. Fragility Curves Development

Building fragility curves are the main component for damage-based design process and building loss assessment. Fragility curves are cumulative lognormal distribution functions that describe the probability of meeting or exceeding a given damage state. Each fragility curve is defined by median value of the demand parameters that correspond to the threshold of the damage state and by the variability associated with the damage state. The probability of meeting or exceeding a damage state, at a given spectral displacement is defined by the following equation:

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

In this equation $\bar{S}_{d,ds}$ is the median value of spectral displacement when building reaches the threshold of the damage state, *ds*, β_{ds} is the standard deviation of natural logarithm of spectral displacement for damage states, *ds* and Φ is the standard normal cumulative distribution function. According to HAZUS, the total variability of each structural damage state is calculated by combination of three contributors to structural damage variability, β_C,β_D and $\beta_{M(Sds)}$ as follows:

$$\beta_{sd_s} = \sqrt{\left(\mathrm{CONV}\left[\beta_C, \beta_D, \bar{S}_{d,Sd_s}\right]\right)^2 + \beta_{M(Sd_s)}{}^2} \quad (2)$$

According to this equation, standard deviation is dependent on variability of capacity spectrum, β_C, variability of demand spectrum β_D and $\beta_{M(Sd_s)}$that describes the variability in estimating median value of damage limit states. The “CONV” function in this equation indicates the process of convolving probability distribution of demand spectrum and the capacity curves (HAZUS-MH, 2003).

In this study the standard deviation values were defined by using the performance points which are derived from intersection of capacity curves and demand spectra. Following this approach, performance points were divided into four groups; slight damage, moderate damage, extensive damage and complete damage in which each group has a median and a standard deviation. The median values of spectral displacement are the same as threshold values of damage states. So standard deviation values were defined by counting the number of point in each group and using equation 3:

$$\beta_{ds} = \left[\sqrt{\frac{1}{n}\sum_{i=1}^{n}[Ln(sd_i) - \mu\ln(sd_i)]}\right] \quad (3)$$

By calculating standard deviation and using equation 2, fragility curves for all three buildings were developed. This procedure was also performed for the same buildings after retrofitting process. Figure 4, 5 and 6 compare these fragility curves.

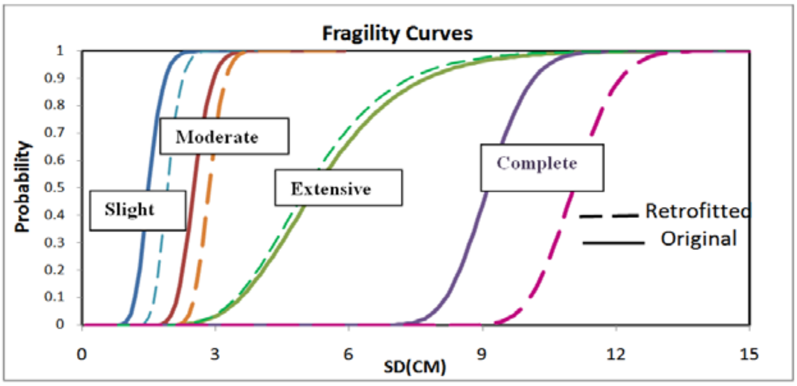


Figure 4. Fragility curves for sample three-story building before and after retrofitting

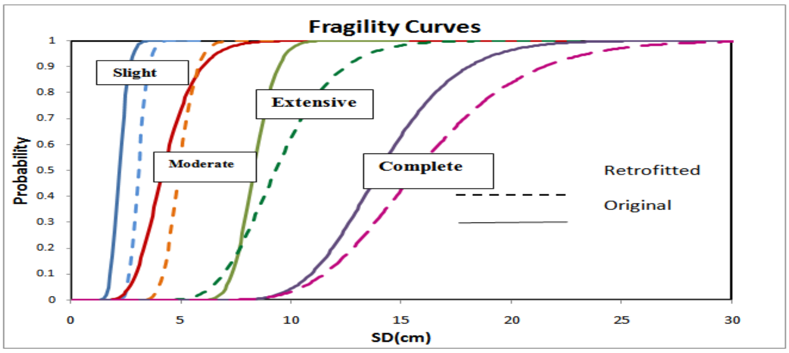


Figure 5. Fragility curves for sample five-story building before and after retrofitting

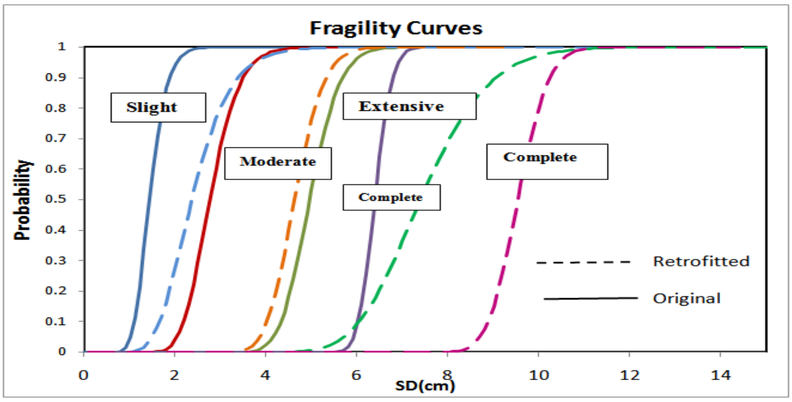


Figure 6. Fragility curves for sample six-story building before and after retrofitting

3.5 Damage Estimation Process

Damage-based design process is in fact on the basis of estimates of building repair costs, downtime and fatalities. Therefore, the relationship between economic and social loss and physical damage states should be defined. In order to estimate the economic losses caused by seismic hazard on structures, level of loss or repair cost for each damage states should be estimated. Earthquake losses have been expressed in various ways. The Applied Technology Council's, ATC-13 introduced damage probability matrices that describe the relationship between physical damage and financial loss. An expression for losses due to earthquake hazard is damage factor, which define the ratio dollar loss to replacement value. Federal emergency management agency, FEMA-351, also used a factor named mean loss ratio. Mean loss ratio express the ratio of repair cost to the total replacement value. To estimate loss due to earthquake, FEMA-351 convert damage to loss by taking the sum over all the losses by all damage states. In this study, FEMA-351 loss estimation methodology has been utilized to evaluated structural losses for buildings before and after retrofitting progress. Figure 7 displays discrete damage state probabilities for five-story structure (FEMA-351, 2000).

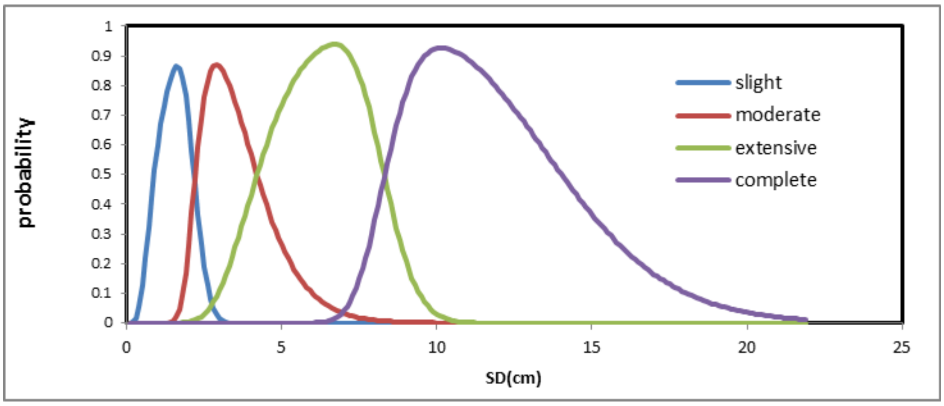


Figure 7. Discrete damage state for five-story building before retrofitting process

By multiplying discrete damage state probabilities by mean structural loss ratio, mean loss ratio curves were constructed. The assumed relationship between damage states and repair cost is represented in Table 3. These values are in the range of damage definitions corresponding to damage ratio presented in ATC-13.

Table 3. Mean loss ratio

Damage State			
Slight	Moderate	Extensive	Complete
2%	10%	50%	100%

In order to estimate monetary loss, mean loss ratios must be multiplied by rebuilding cost. Following this method, damage curves were developed for each building before and after retrofitting process. Figure 8, 9 and 10 shows damage curves for three buildings.

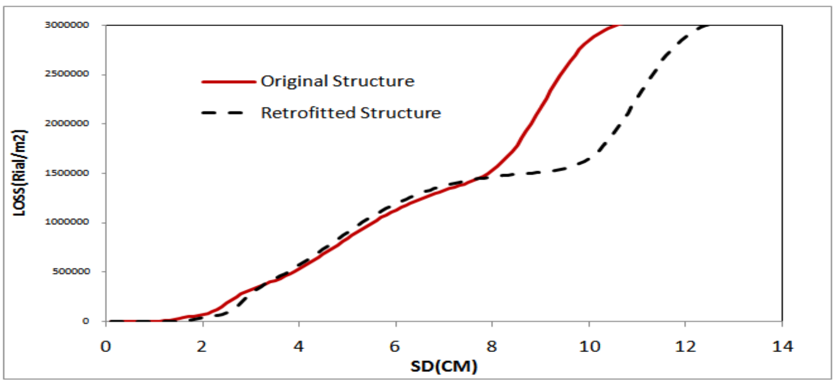


Figure 8. Damage curve for three-story building before and after retrofitting process.

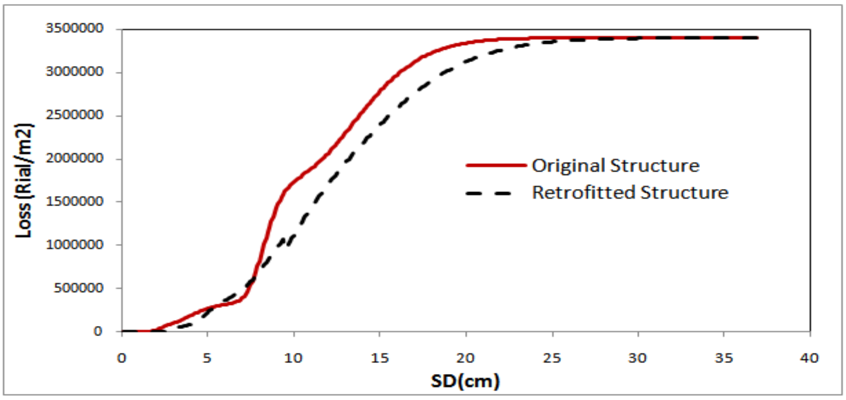


Figure 9. Damage curve for five-story building before and after retrofitting process.

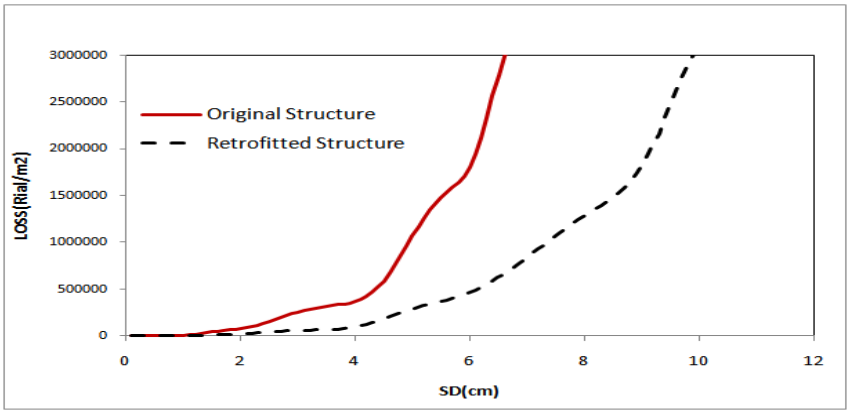


Figure 10.Damagecurve for six-story building before and after retrofitting process.

CONCLUSION

This study has been performed to investigate the effect of retrofitting process on behavior of building and the repair cost. The article presents part of an ongoing study towards assessment of an added value index for retrofitting process which could be used in towards retrofitting justification and cost/benefit analyses.

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