PROBABILISTIC PREDICTION OF RETROFIT COST FOR MASONRY STRUCTURES

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ABSTRACT

A probabilistic model is developed that predicts the retrofit cost for masonry buildings. This model is key in the prioritization of vulnerable structures for seismic retrofit. A database of real data for school buildings in Iran is compiled and the Bayesian regression modeling methodology is employed to establish the model. This modeling approach emphasizes the comprehensive characterization and modeling of epistemic uncertainties. As a result, the model is updated as new data become available. The explanatory functions of the model are selected in accordance with the mechanics of the problem. An important explanatory function is the amount of increase in lateral strength of buildings due to retrofit, which is accounted for in such a model for the first time. The paper presents the data collection, model development, insights obtained from the model, and concludes with a numerical example.

INTRODUCTION

The primary objective of this paper is to make probabilistic prediction of the seismic retrofit cost for masonry structures. In particular, a model is developed to evaluate the cost of retrofitting such structures by adding Shotcrete layers to the exterior of masonry walls. Masonry buildings are among the most common structures in developed and developing countries (Ghorbani et al., 2013). They have caused severe economic and human life losses in recent earthquakes, such as the 2003 Bam earthquake in Iran (Tobita et al., 2007). In particular, they comprise a large number of school buildings in Iran. The long-term goal of this research is the prioritization of school buildings on a national level for seismic retrofit. One of the requirements of the adopted methodology for this purpose (Mahsuli and Haukaas, 2013b) is to have models that predict the construction cost for a desired level of retrofit. This methodology employs reliability sensitivities for the prioritization. The use of reliability methods requires all models, including retrofit cost models, to conform to a specific format, as described by Mahsuli and Haukaas (2013a). One approach to develop probabilistic models with this format is the Bayesian linear regression (Box and Tiao, 1973; Gardoni et al., 2002). This modeling approach relies both on mechanics and on observed data. Explanatory functions of the model as well as the model form are determined based on the mechanics. Thereafter, observed data are employed to carry out a Bayesian regression to determine the probability distribution of the model parameters and the model error. The all-important aspect of this modeling approach is that the model is constantly improved as new data emerge. The developed model is based on real data of retrofit action scheme for school buildings in Iran. In an extensive data-gathering effort, a database from reports on the retrofit plan of 98 schools is compiled. These reports were provided to authors by the State Organization of School Renovation.

Shotcrete is the most common retrofit action currently used for strengthening masonry buildings in Iran (Ghiassi et al., 2011). In this method, as illustrated in Figure 1, a mesh of steel wires is anchored to one or two sides of masonry wall and then it is covered by a thin layer of concrete.

Figure 1. Adding Shotcrete layer to masonry wall

Few studies have addressed retrofit cost models for masonry buildings. Potangaroa (1985) developed a multi-linear regression model for predicting the retrofit cost of unreinforced masonry (URM) buildings. The database that was employed to calibrate the models included 86 buildings in the United States. The variables of the model were the total floor area, building age, design level and number of floors among which the total floor area was the most significant variable. The next attempt was models in first edition of FEMA 156 (FEMA, 1988) in which models was based on the data for 614 buildings which contain 199 URM buildings. In second version of FEMA 156 (FEMA, 1994) the data were increased to 2,088 in which 643 samples were associated with URM buildings. These models were introduced in three levels according to different performance levels. The third-level model was the finest which was developed by using regression and predicted retrofit cost for a single building. The variables of the model were total floor area, building age, number of floors, seismicity, occupancy class, building group and occupancy condition during seismic retrofit. Hopkins and Stuart (2003) introduced a model that evaluates retrofit cost based on damage ratio of original and retrofitted building. In recent years, Jafarzadeh et al. (2014) developed regression models for retrofit cost of masonry buildings in Iran. Their database consisted of 183 confined masonry school buildings. They used the floor area, seismic weight, diaphragm type and mortar quality as model variables with the floor area as the most significant one.

The limitations of abovementioned studies and improvements made in this paper are as follows:

1) The modeling approach employs classical regression and yields deterministic models. In contrast, the models in the present study employs Bayesian regression and yields probabilistic models that account for the model uncertainty and are amenable for use in reliability analysis.
2) Some studies neglect the type of retrofit action in the model. In contrast, the present study focuses on the retrofit cost due to the use of Shotcrete. Ongoing research addresses other retrofit actions, such as the use of fiber reinforced polymers.
3) No studies, to the best knowledge of authors, include the amount of increase in lateral strength of the building due to retrofit. This variable is, however, crucial when using this model in the aforesaid prioritization methodology. That is, the models must predict the retrofit cost for any given amount of increase in the strength. This is addressed in this study.

A limitation in this study and others mentioned above is that predicting construction cost according to historical data is error-prone because of the dynamic nature of economy and human action (Ogunlana, 1989). Thus, Skitmore (1991) suggests that accuracy of cost modeling should be considered in term of bias and consistency. Bias is the difference between averages of actual bid values, while consistency is the variation around average. This is addressed by ongoing research.

DATA COLLECTION

To compile a database for regression analysis, 98 school retrofit projects are employed. The reports for these projects were made available to authors by the State Organization of School Renovation. The latter organization is the client of these projects, which are conducted by consulting engineering companies. These reports include the vulnerability assessment, retrofit plan, and the associated estimates of the construction cost. Each report includes three sections: 1) Qualitative vulnerability assessment, 2) Quantitative vulnerability assessment, and 3) Seismic retrofit design and cost estimates.

The client reviewed each section of the report in accordance the Iranian Retrofit Code No. 360 (Deputy of Technical Affairs, 2014). Upon approval of the section, the consulting company proceeded with the next one. In the final section of the report, three candidate retrofit actions were investigated and one was opted for as the final retrofit action according to technical and financial considerations. This step-wise review process ensures adequate reliability for the reports. This, in turns, yields a robust database for the modeling in this paper. In 58 of these reports, the consulting company recommended Shotcrete as the final retrofit action for masonry buildings. The database for modeling in this paper is extracted from these reports.

The authors extracted the data needed for modeling from the mass of information in each report. These data are selected based on the mechanics of the problem, i.e., they are the parameters that are deemed to have the most influence on the retrofit cost of masonry structures. In general, the extracted data are in three broad categories as tabulated in Table 1: 1) Building properties, which represent the current state of the building structure; 2) Retrofit action properties, which represent the mechanical and physical features of the retrofit action, such as the amount of increase in the lateral strength; 3) Cost estimates, which include the retrofit construction cost and the building value. The retrofit construction cost is evaluated by the consulting engineers in accordance with the Iranian Construction Cost Index. This includes the cost of material and labor. Other cost factors, such as overheads, variations in market conditions, geographical location and height adjustments are excluded from the retrofit cost. The costs are adjusted for inflation to Persian calendar year 1388.

Table 1. Extracted data items

Category	Description	Formula
Building properties	Height of the building	H
	Footprint area	A
	Number of stories	N
	Year of construction	T
	Plan irregularity	I_{PI}
	Vertical irregularity	I_{VI}
	Pounding	I_P
	Soil Type	S
	Vertical cross section area of entire walls	A_W
	Height of the typical masonry walls used in the building	H_W
	Width of the typical masonry walls used in the building	B_W
	Horizontal length of the walls of the buildings	L_W
Retrofit action properties	Shear strength of the Shotcrete	V
	Width of the Shotcrete layer	B
	Horizontal length of the retrofitted walls	L
Cost values	Building value	C
	Retrofit construction cost	C_R

MODEL DEVELOPMENT

This section describes the process of developing the retrofit cost model with the Bayesian linear regression approach. The general model form in this approach is

$$y = \theta_0 \cdot h_0 + \theta_1 \cdot h_1 + \cdots + \theta_k \cdot h_k + \varepsilon \qquad (1)$$

where y = model response, θ_i = model parameters, h_i = explanatory functions and ε = model error. The θ-parameters are random variables whose distribution is obtained from the Bayesian linear regression analysis.

The model error is a normal random variable with a zero mean and a standard deviation of σ_ε. The latter is another random variable whose properties are given by the Bayesian regression. In contrast, the explanatory functions of the model are determined by the mechanics of the problem. These are the variable combinations that are expected to affect the seismic retrofit cost. The explanatory functions that are initially considered are shown in Table 2.

Table 2. Initial explanatory functions

Explanatory function	Description	Formula
h_0	Intercept	1
h_1	Height of the building (m)	H
h_2	Footprint area (m^2)	A
h_3	Number of stories	N
h_4	Code level	α
h_5	Plan irregularity	I_{PI}
h_6	Vertical irregularity	I_{VI}
h_7	Pounding	I_P
h_8	Soil Type	S
h_9	Relative wall	A_W/A
h_{10}	Height to width ratio of the typical masonry walls used in the building	H_W/B_W
h_{11}	Shear strength of the Shotcrete (ton/m)	V
h_{12}	Width of the Shotcrete layer (cm)	B
h_{13}	Retrofitted walls ratio	L/L_W
h_{14}	Building value per unit area (IRR)	C/A

Amongst the variables in Table 2, some requires further elaboration as follows:

- Code level, α, is analogues to the building code level in FEMA-NIBS (2012) that is determined based on the year of construction. The year of construction identifies if the building is built prior to the appearance of seismic codes, denoted by α=1, or designed according to non-ductile provisions, denoted by α=2, or modern provisions, denoted by α=3.
- Plan irregularity, I_{PI}, is unity if the building has a non-rectangular plan and zero otherwise.
- Vertical irregularity, I_{VI}, is unity if there is a change in the building plan along its height and zero otherwise.
- Pounding, I_P, is unity if there is insufficient separation with adjacent buildings and zero otherwise.
- Soil type, S, is the class of ground in Iranian Seismic Code, Standard No.2800 (BHRC, 2014). From rock to soft soil, S ranges from 1 to 4, which correspond to Ground Type I to IV in Standard No.2800 (BHRC, 2014), respectively. Type I corresponds to S=1 and Type IV to S=4.
- "Relative wall" is a dimensionless variable that is defined as the ratio of the horizontal cross sectional area of walls to the footprint area of the building. This variable is employed by the Iranian Seismic Code as a measure of the lateral strength of unreinforced masonry structures.
- "Height to width ratio" is another dimensionless variable that is used as a measure of wall stability and out-of-plane strength in the Iranian Retrofit Code No. 360 (Deputy of Technical Affairs, 2014).
- Shear strength of Shotcrete is the strength of one meter of Shotcrete layer, and is doubled if Shotcrete is applied on both sides of a wall.

Retrofit cost is influenced by the location of building because the construction cost is not equal in different provinces of the country. Therefore, the response of the model, y, is considered as C_R/C, i.e., the ratio of the retrofit cost to the building value, which eliminates the location-dependency of the cost.

46 candidate model forms are established. For this purpose, various combinations of the explanatory functions in Table 2, including linear, multiplicative, fractional, exponential, and logarithmic, are formed. For each model form, a Bayesian linear regression is conducted to determine the properties of the model parameters and the model error. Thereafter, the quality of the model prediction as well as the normality and the homoscedasticity of the residuals are examined. The models with poor prediction, with heteroscedasticity of residuals, and with non-normal residuals are eliminated. Amongst the remaining models forms, the one with the lowest mean-value for the standard deviation of model error, σ_ε, and the lowest coefficients of variation (CoV) of θ-parameters is selected as the best candidate. Next, in a stepwise model reduction in accordance with Gardoni et al. (2002), the explanatory variable whose associated θ-parameter has the highest CoV is considered as inconclusive and is eliminated. Thereafter, the regression analysis is carried out again. This process continues until the CoV values of all remaining model parameters are within an acceptable

range. In this process, the mean of σ_ε increased from 0.045 to 0.051, which is insignificant and hence satisfactory. These two steps yield the following model:

$$\sqrt{C_R / C} = \theta_1 \cdot (C / A) + \theta_2 \cdot (L / L_W) + \theta_3 \cdot B + \theta_4 \cdot \ln(V) + \theta_5 \cdot \exp(A_W / A) + \theta_6 \cdot \exp(V \cdot L / L_W) + \varepsilon \qquad (2)$$

The square root function on the left-hand side is used to avoid heteroscedasticity of the residuals. It also ensures that the model does not produce negative values for cost. Table 3 presents the second moments of the model parameters and model error. According to this table, there are no high correlations between the θ-parameters. A high correlation between the θ-parameters would necessitate expressing one θ as linear function of the other, which is not the case for the model in Eq. (2).

Figure 2 shows the model predictions against the observed data in order to assess the quality of the model. The points are reasonably close to the 45°-line, and the coefficient of determination, R, is 0.684, both of which indicate a satisfactory prediction. Finally, the normality of the model residuals, as a basic requirement of the linear regression models, is assessed in Figure 2. The figure shows only a slight deviation of the residuals from the normal distribution, which shows that the model is acceptable in this regard.

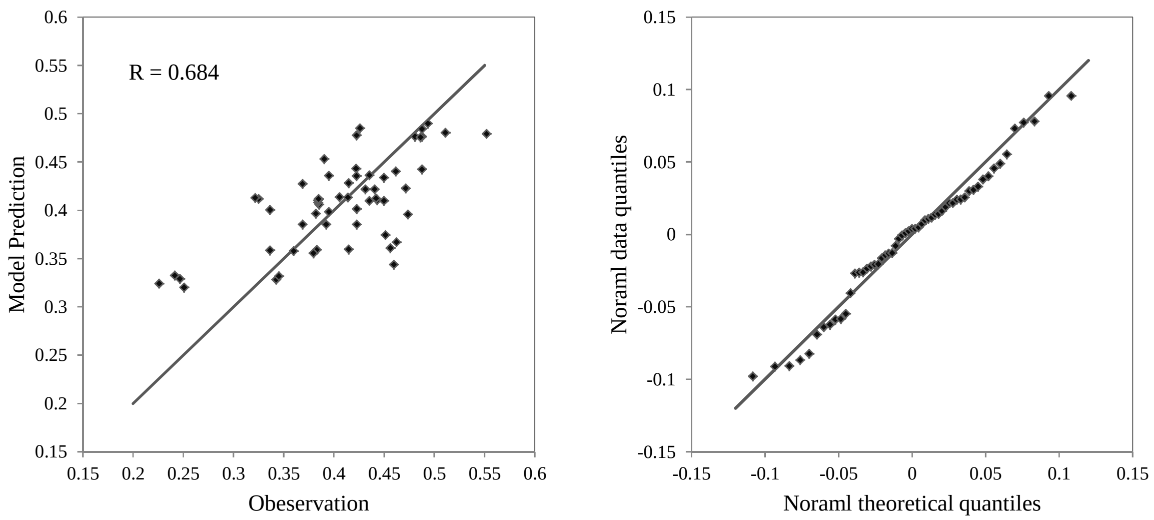

Figure 2. Model prediction versus observation (left) and normality of the residuals (right) for the final retrofit cost model

Table 3. Second moments for the final retrofit cost model

Parameter	Mean	CoV	Correlation coefficient					
			θ_1	θ_2	θ_3	θ_4	θ_5	θ_6
θ_1	$2.22 \cdot 10^{-8}$	0.756	1					
θ_2	0.053	0.533	−0.25	1				
θ_3	0.017	0.372	−0.04	−0.30	1			
θ_4	0.034	0.525	0.01	0.25	−0.19	1		
θ_5	0.225	0.284	−0.65	−0.02	−0.39	−0.51	1	
θ_6	$7.31 \cdot 10^{-8}$	0.533	−0.04	−0.59	0.29	−0.55	0.26	1
σ_ε	0.051	0.102						

DISCUSSION OF THE MODEL

The model form in Eq. (2) reveals a number of insights into the retrofit cost estimation. The parameters that affect the retrofit cost most significantly are the ones that have survived the model reduction process. These include the relative wall, shear strength of Shotcrete, width of Shotcrete layer, retrofitted walls ratio, and building value per unit area. A higher relative wall, A/A_w, indicates that there are more walls in the building. Hence, for a constant L/L_W, it implies that more Shotcrete is needed in retrofitting the building which, in turn, results in a higher retrofit cost. The positive mean-value of θ_5 correctly captures this trend. Furthermore, as expected, the retrofit cost increases by the shear strength of Shotcrete, V, by the width of Shotcrete layer, B, and, by the retrofitted walls ratio, L/L_W. In fact, an increase in the value of these three explanatory functions results in a higher lateral strength of the building, which naturally yields a higher retrofit cost. The negative sign of θ_1 indicates that the ratio of the retrofit cost to the building value decreases as the building value per unit area, C/A, increases. In other words, more valuable buildings cost a smaller fraction of their value to retrofit.

The explanatory functions that are eliminated provide an insight on which parameters are insignificant to the retrofit cost. For instance, the code level is not influential on the retrofit cost, a conclusion that is in agreement with previous studies (Jafarzadeh et al., 2014; Potangaroa, 1985). Moreover, the number of stories or height of the building is also inconclusive for the model. This is explained by the fact that the masonry buildings are typically low-rise. This was pointed out earlier by Jafarzadeh et al. (2014). Also, the height to width ratio of the building walls and different types of irregularity are of small significance to the model, because these parameters have not been employed by the consulting engineers in the process of devising the retrofit plan.

The introduced models can be used to predict the retrofit cost of masonry school buildings in Iran. Any further usage has to be confirmed by studies beforehand. Also, the cost data of the retrofit plans were calculated by the consulting engineers and hence, the final construction cost may vary.

NUMERICAL EXAMPLE

The model is employed to predict the retrofit cost of many buildings with varying amount of increase in the lateral strength. In particular, 100 masonry buildings are selected whose properties are randomly generated according to uniform distributions. Boundaries of these distributions, presented in Table 4, are selected based on typical properties of school buildings in Iran. For each building, a Monte Carlo sampling with 1000 samples is performed to obtain the distribution of the model response, i.e., the retrofit cost normalized to building value. A measure of increase in the lateral strength due to Shotcrete is introduced for each building, as follows:

$$\sim = \frac{V \cdot L}{L_W \cdot B_W \cdot v_{brick}} - 1 \qquad (3)$$

where v_{brick} = shear strength of masonry walls. Other variables are introduced in Table 1. The numerator of the Eq. (3) represents the total shear force that the Shotcrete layer can resist and the denominator represents the same property for masonry walls. The strength of masonry walls is neglected after retrofitting. B_W and v_{brick} are not explanatory functions of the model. These variables are also randomly generated according to uniform distributions with bounds that are described in Table 4.

Figure 3 depicts the scatter diagram of the median as well as the 10^{th} and 90^{th} percentiles of the normalized retrofit cost versus the increase in strength, α. The trend of each scatter diagram is shown by a straight line. As expected, Figure 3 shows that C_R/C increases by lateral strength. Also, the figure also shows a uniform scatter of the model response, which is desirable in a linear regression model.

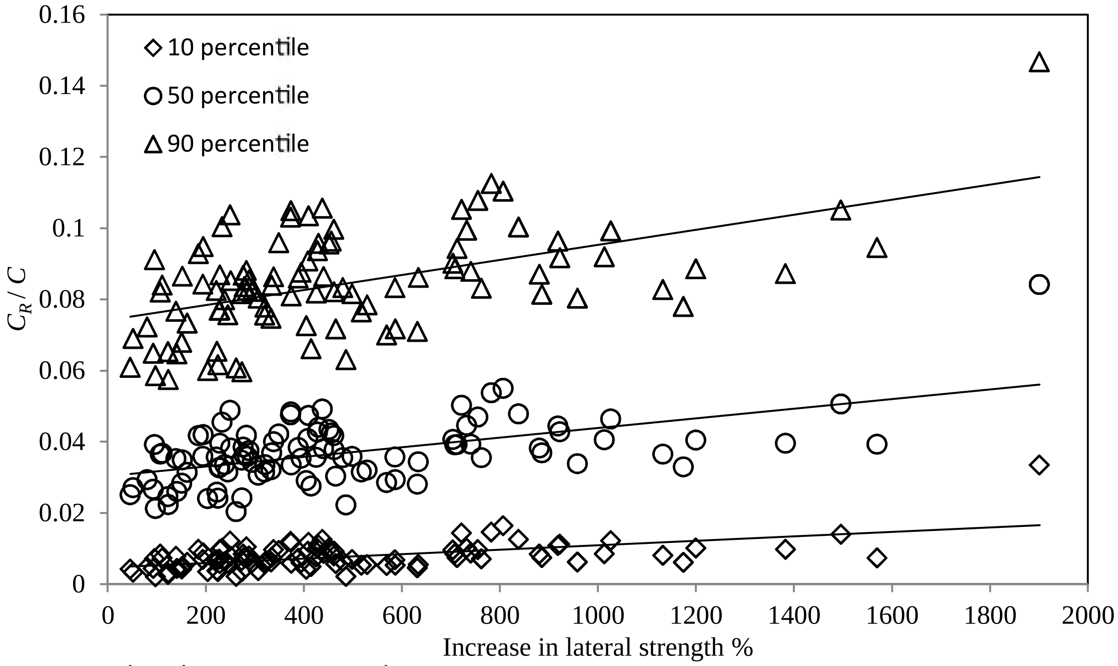

Figure 3. 10th, 50th (median), and 90th percentiles of the normalized retrofit cost in the numerical example

Table 4. Lower and upper bounds of the uniform distribution for the building properties in the numerical example

Building property	Lower bound	Upper bound
C/A (IRR)	1,500,000	3,000,000
L/L_W	0.34	1
B (m)	0.05	.075
V (ton/m)	5	15
A_W/A	0.02	0.11
B_W (m)	0.15	0.4
v_{brick} (ton/m^2)	2	8

CONCLUDING REMARKS

A probabilistic model is put forward for the prediction of retrofit cost for masonry buildings in Iran. The model is developed to evaluate the cost of retrofitting such structures by Shotcrete. A sound database is collected and Bayesian regression is employed to find the properties of model parameters. The explanatory functions of the model are the relative wall, building value per unit area, width of Shotcrete layer, shear strength of Shotcrete and retrofitted walls ratio. The last three variables consider the amount of increases in lateral strength of building due to the retrofit action. That is, the model predicts the retrofit cost given the amount of increase in the lateral strength, which is unprecedented in the literature. It is found that year of construction, soil type, and the height to width ratio of walls and plan irregularity are of less significance in the retrofit cost of masonry structures.

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