CHAPTER

17

EVALUATING EARTHQUAKE RETROFITTING MEASURES FOR SCHOOLS: A COST-BENEFIT ANALYSIS

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Abstract: Based on a cost-benefit approach for evaluating seismic mitigation options for apartment buildings in Istanbul, Turkey, this paper presents a demonstration study for a hypothetical vulnerable school building. A probabilistic cost-benefit analysis provides a useful framework for assessing seismic mitigation measures, taking into consideration limited resources and social costs. The hypothetical school is analysed over a variety of time-horizons to determine the break-even point for investments for several seismic retrofitting options.

Introduction

In Smyth *et al.* (2004), a simple cost-benefit analysis was performed to evaluate seismic retrofitting measures of an apartment building in Istanbul, Turkey. The study combined probabilistic seismic hazard estimates, sophisticated structural analysis techniques and economic cost-benefit principles to select the best of three retrofitting options proposed by local contractors. Actual cost estimates for the retrofitting measures, in addition to the direct dollar losses due to a potential collapse, were considered. In addition, to translate all of the losses into one common metric, the dollar cost of human lives lost in the event of a structural collapse was also considered.

While the approach is promising for apartment structures, its potential application to school buildings is even greater. This is simply because in many regions schools are designed using similar building methods, with similar geometries. Therefore, it would not be necessary to perform a detailed analysis for each individual structure. Rather, a probabilistic structure could be considered to represent a class of school structure type. Given the demonstration nature of this study, a deterministic and hypothetical school structure will be considered. The results of this analysis should not be used to draw major conclusions for practice; the presentation of the methodology in the context of schools is the purpose of this paper.

The structure to be considered

A prototype school model was developed based on rough descriptions, photographs and other qualitative information (Figure 17.1).

Figure 17.1. Typical school structures in Mexico

(a) School in Guerrero (b) School in Mexicali
(Photos courtesy of Brian Tucker, GeoHazards International)


(a)

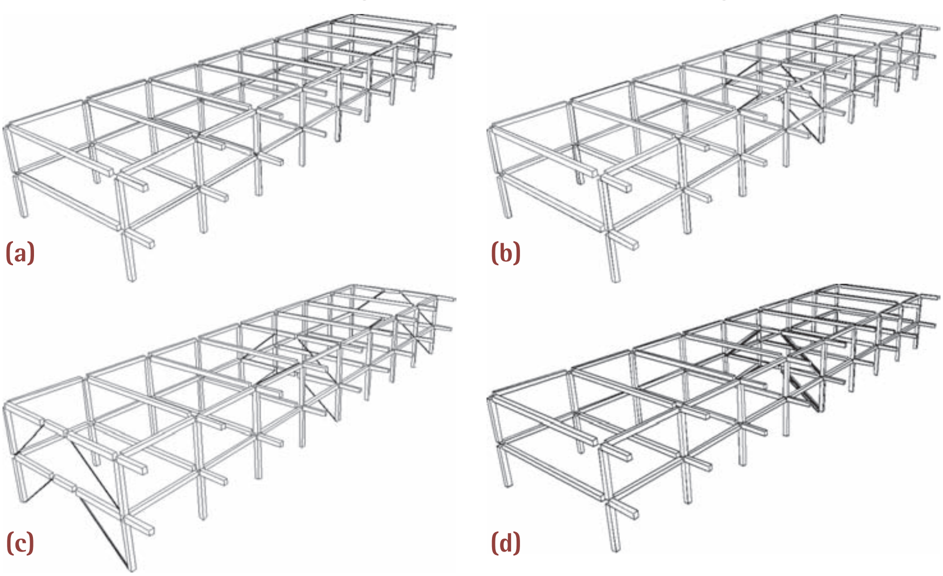

(b)

This structural model consists of a two-storey building with a footprint of 10 m × 40 m and a storey height of 3 m. The structure, the frame of which is shown in Figure 17.2(a), is divided into eight bays with a width of 5 m in the long direction and one bay with a width of 10 m in the short direction. A 2 m cantilevered slab on each floor acts as an access corridor for the different classrooms.

To mimic possible poor design practice in developing countries, no lateral loads such as seismic loading were considered in the design. The structure was designed for gravity loads, which include the weight of the structural elements (beams and columns), the weight of the slab, and permanent elements estimated at about 2.50 kN/m^2. A live load of about 1.91 kN/m^2 was also considered. These loads are applied on both storeys to allow for the typical practice of constructing additional floors. The material is assumed to be reinforced concrete of average quality with a concrete compressive strength of 20 684 kN/m^2 and a yield strength of 413 686 kN/m^2 for the steel. The mass of each of the elements is considered, and additional masses are added on each floor to simulate the slabs. The Eurocode 1999 is used for dimensioning the steel reinforcement with the appropriate safety factors for loads and materials. As designed, the structure is vulnerable; it is capable of appropriate standard service loads but unfit to sustain any strong loads other than gravity.

Figure 17.2. Model of the structural frame for the original and retrofitted structures

(a) Original structure (b) First steel bracing option
(c) Second steel bracing option (d) Reinforced-concrete bracing retrofit



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While this design is appropriate for highlighting in general terms the effectiveness of retrofitting and the economic analysis methodology, should a study of this type be completed for actual school buildings, a survey of designs and materials used in existing structures must be carried out to model these buildings more accurately. The three retrofitting measures considered are shown in Figures 17.2(b) to 17.2(d). The first involves the addition of light steel bracing at the central bay to stiffen the weak axis of the structure. The second is a more aggressive steel bracing retrofit that also braces the end walls. Finally, a more substantial reinforced-concrete bracing alternative is considered. This reinforced concrete option – while somewhat more labour intensive – is assumed to be cheaper than the second option simply because steel shapes are not always readily available in rural regions in developing countries.

Note that in developing countries, it is not uncommon to find that a substandard structural analysis was undertaken prior to a building's construction, and that little if any quality control was carried out in the manufacturing of materials. It is also typical to find evidence of poor construction practices – *e.g.* insufficient cover for the rebar or insufficient spacing between the steel reinforcement bars – in collapsed buildings after earthquakes (EERI, 2000). From this perspective, the design carried out in this paper is sound; the cover for the rebar is no less than 5 cm and the spacing is consistent with the Eurocode 1999 norm. This model is designed with the help of the software package SAP2000 v.7.40, which is a standard tool for structural calculations. The dynamic analysis was also undertaken using this software.

Fragility analysis

The fragility of a given structure is defined as the probability that for a given ground motion shaking level (peak ground acceleration), the structural response will exceed a given threshold level corresponding to a particular damage level. The structural response is probabilistic in terms of peak ground acceleration (PGA) because the structural response deformations will, in general, be different for different ground motion time histories with the same PGA. For each of the structural configurations, the fragility curves are shown in Figure 17.3. Four damage levels E_i are considered: slight, moderate, major and total collapse. These damage levels are defined by inter-storey drift ratios in accordance with the HAZUS99-SR2 Technical Manual. Note that retrofit strengthening has the effect of pushing the fragility curves to the right, *i.e.* for the same PGA value, the probability of exceeding a given damage state is lower.

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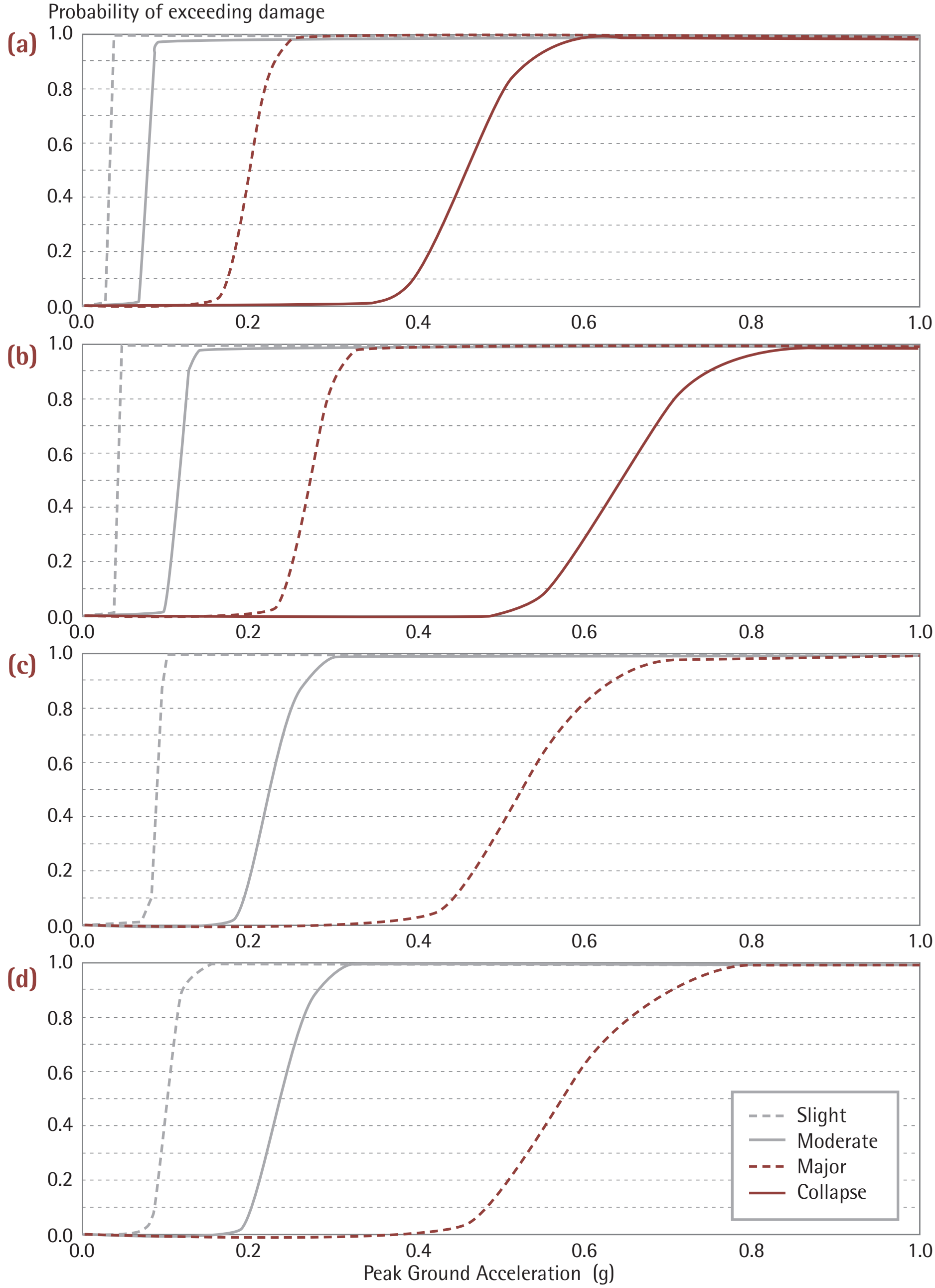
Figure 17.3. Derived fragility curves for the four structural configurations

(a) Original structure (b) First steel bracing option
(c) Second steel bracing option (d) Reinforced-concrete bracing retrofit



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Loss estimation procedure

In order to perform a basic cost-benefit analysis, the expected losses for arbitrary time horizons must be computed. The basic equation to calculate the present value of losses using a real (social) discount rate *d* is:

Total loss in present value for a given time horizon *T** (in years) =

$$\sum_{T=1}^{T^*}\sum_{i=1}^{4}\int_{a_{min}}^{a_{max}} [\hat{R}(a+da,T)-\hat{R}(a,T)]\; P(E_i \text{ only} \mid a)\,\frac{C_i^D}{(1+d)^{T-1}}\,da$$

where

$\hat{R}(a,T)$ = the probability of exceeding the PGA value *a*, given that no earthquake has occurred in the previous years

= (the probability of exceeding the PGA value *a* in year *T*) x (the probability that no earthquake has occurred in the previous (*T-1)* years)

= $R(a)\times e^{-R(a_{min})(T-1)}$

$e^{-R(a_{min})(T-1)}$ is the probability that no earthquake has occurred in the previous (*T-1*) years, assuming a Poisson distribution of earthquake occurrence. The term a_{min} denotes the lower limit of PGAs considered, so if this value is not exceeded, then a (significant) earthquake will not have occurred. In this study, the lower limit a_{min} is set equal to 1% of *g*. The annual hazard curve *R*(*a*) was the same as that used in Smyth *et al*. (2004). This information is region-specific and requires the input of seismological experts.

The additional probability in the above expression is:

$P(E_i \text{ only} \mid a)$ = the probability of only event E_i occurring for a given PGA value *a*. This probability is needed so that damage levels which are lower than (or fall within the set of) more severe damage levels will not be counted twice. This expression is easily related to fragility curves.

C_i^D = The losses associated with damage state *i* are summarised in Table 17.1.

Table 17.1. Losses associated with damage state *i*

Damage level		Cost (C_1^D)	Comments
E_1	Slight damage	$C_1^D=(s_1\times S)+(0\times V)$	$0\% \leq s_1 \leq s_2 \leq 100\%$ (s_1 = 1%)
E_2	Moderate damage	$C_2^D=(s_2\times S)+(0\times V)$	$0\% \leq s_1 \leq s_2 \leq 100\%$ (s_2 = 10%)
E_3	Major damage	$C_3^D=(s_3\times S)+(0\times V)$	s_3 = 100%
E_4	Total collapse	$C_4^D=(s_4\times S)+(N_L\times V)$	s_4 = 100%

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Results of the economic cost-benefit analysis

In order to perform a cost-benefit analysis, realistic estimates of the costs of the retrofitting measures as well as the losses C_i^D for each damage state must be established. As this is not a real building, assumed values were selected without the usual consultation with local experts. The replacement cost of the entire structure is assumed to be S = USD 160 000, and the costs of each retrofit C_i^M are:

- Retrofit 1: Steel bracing in 1 bay C_i^M = USD 8 000.
- Retrofit 2: Steel bracing in 3 bays C_2^M = USD 20 000.
- Retrofit 3: Reinforced-concrete bracing C_3^M = USD 13 000.

The social discount rate is assumed to be 3% (Weinstein *et al.*, 1996). The fact that children would typically only occupy a school for one-third of the day (eight hours) was also factored into the calculation. Therefore in the loss calculations above, the assumed number of lives lost N_L is actually one-third of the number of actual lives lost in the event of collapse. The net present value is the benefit minus the certain cost of retrofit. The benefit is simply the difference in expected losses with and without mitigation.

Table 17.2 illustrates the cost-benefit analysis results for an assumed value of human life V = USD 400 000, and an assumption that 15 lives would be lost if collapse occurred. The table lists net present values for different retrofitting decisions. Negative values indicate

Table 17.2. Expected net present value with 15 fatalities and V = USD 400 000 (NPV(5))*

Alternative (A_i) Time horizon	i=1 Steel bracing 1 (USD)	i=2 Steel bracing 2 (USD)	i=3 Reinforced-concrete bracing (USD)
1	-3 110	-11 899	-4 794
2	1 366	-4 480	2 719
3	5 466	2 313	9 600
4	9 221	8 535	15 903
5	12 661	14 234	21 674
6	15 810	19 452	26 959
7	18 694	24 231	31 799
8	21 335	28 607	36 232
9	23 754	32 615	40 291
10	25 969	36 285	44 009
25	43 620	65 531	73 632
50	49 344	75 016	83 238

* Negative values (unshaded) indicate economically undesirable choices for the given time-horizon, while positive values (shaded) indicate economically desirable choices.

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economically undesirable choices for the given time-horizon, while positive values indicate an economically desirable choice. Note that the second steel bracing retrofitting option only "breaks even" after three years of hazard exposure. The reinforced-concrete bracing option, which is about as effective as the more expensive three-bay steel bracing option, naturally hits its break-even point sooner. In all cases, the break-even point occurs rather quickly simply because the retrofitting options are inexpensive relative to the potential loss of life due to collapse.

From this hypothetical and simplistic example one can begin to appreciate the types of decision-making information that the cost-benefit approach yields. For other combinations of parameters, costs, etc., the conclusions would change. This also permits analysts to perform sensitivity analyses to test the robustness of decisions.

Conclusions and further work

As mentioned at the outset, in order for this approach to be applied to a particular stock of school buildings, more careful modelling of the particular construction type is required. To apply this approach to an ensemble of different structures of the same type, some randomness also needs to be introduced in the structural model. This will have the effect of making the fragility curves ascend more gradually because of the increased uncertainty. The authors are currently working on a framework to introduce randomness to capture material, geometric and workmanship uncertainties.

Another limitation of this demonstration study is that only direct losses are considered. In the case of a school building, the obvious disruption caused by a building collapse and time required to rebuild should be considered. The modular framework presented here can easily accommodate estimation of indirect losses.

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