TOWARDS A RESILIENT DESIGN AND RETROFIT OF SCHOOLS IN MEXICO

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Abstract

The paper deals with the generation of practical recommendations for design and retrofit of schools in Mexico on the basis of modern resiliency ideas and the application of well-known risk and reliability criteria and tools.

The formulation balances traditional and recent techniques to protect human life and to provide the grounds for an easy and fast recovery after the earthquake. Uncertainty on the seismic load effects and the structure resistance is considered and the likelihood of typical limit states are pondered from the perspective of the life-cycle.

Governing limit state, selected among resistance or serviceability (inter-story drift) modes, is used to appraise the school failure probability and Monte Carlo Simulation techniques are implemented to calculate it. The target failure probability is considered as an upper limit for the school failure probability and it is used as a safety control variable.

For existent schools, several alternative retrofit schemes are proposed and assessed in order to select the most appropriate to achieve the above described goals. The life-cycle perspective involves the challenge to predict the load maximum effects due to all the seismic events provoking a serious damage or failure to the structure within the school life-cycle. In this sense, the expected life-cycle cost is used as a cost control variable.

By having two control variables, the space for optimal decision is bounded and the objectives may be achieved.

A curve of the initial cost is drawn, for design and retrofit, to devise the cost of reliability, i.e., the cost of the school building as a function of the reliability index, for a given seismic intensity. The expected life-cycle cost is also expressed conditional to a given seismic intensity. These expected life-cycle cost is composed by the school initial cost and the present value of the expected future costs for a typical structural system. The future costs include the potential failure consequences as: fatalities, loss of the structure and contents and the loss related to the business interruption or the building substitution. And the fatalities cost is estimated based on the *human capital approach* as proposed by late Prof. Rosenblueth.

Among the alternatives, special consideration is given to those that may drive to a rapid recovery (easy access to damaged components, quick repair or components substitution, etc.) to restore the school activities within a short time and under reasonable costs.

Keywords: optimal repair, seismic hazard, school reliability, resilience, expected life-cycle cost

1. Introduction

Mexico´s National Development Plan, 2007-2012, acknowledged that one of the principal deficiencies in the national education system was the unequal physical conditions of the infrastructure. Schools buildings degradation is due to old construction, adverse local climate and seismic exposure, an intensive use, and the lack of an adequate maintenance, so these tasks were pointed as strategic to establish a preventive approach for guidelines and repair criteria.

National programs as "Escuelas de calidad" and "Escuelas al cien" were implemented as a response of those tasks and, in 2013, the National Statistics and Geography Institute [1] revealed that 23 percent the school buildings didn´t accomplish the minimum construction regulations.

Standards for new structures have been developed [2] but nowadays repair criteria and guidelines have not been as well developed as the standards for new structures. As a result, engineers lack of quantitative criteria to select the optimal upgrading works and to decide the conditions for which a damaged building has to be demolished or repaired from the life-cycle point of view.

Due to an earthquake in Mexico in 2017 [3], several schools were damaged.

Several works have been published, like the assessment of retrofit methods for reinforced concrete columns [4], the guidelines by FEMA for seismic retrofit of existing buildings [5], and some others resorting on life-cycle cost [6].

Recently, the retrofit by using fiber-reinforced polymer composites [7], and the use of numerical tools like the combination of the First-Order Reliability Method (FORM), response surfaces, the saturated design and the central composite design sampling schemes [8], and the evolutıonary support vector machıne [9] have been proposed as innovative techniques.

Specific cost/benefit analysis [10] and schemes for retrofit of schools have been presented in Spain [11] and Mexico [12].

2. Formulation

2.1 General procedure

The building failure probability is considered as the failure of the critical frame, and the frame failure probability is defined here as the probability that a load effect, or load combination effect, exceeds the resistance of a number of critical structural members, that is the frame limit state G_f is somehow exceeded [13].

$$P_f = P(G_f < 0) \tag{1}$$

Where G_f represents the event for which the acting stresses exceed the resistant stresses for a combination of structural members that causes the global frame instability. The loads include typical code dead and live loads, local seismic effects and their combination.

The frame failure probability is calculated as follows:

a) The unconditional (total) failure probability P_{fT} is obtained through the convolution of conditional failure probabilities for a given scenario with seismic intensities "a_i" and the respective occurrence probabilities of those intensities [14].

$$P_{fT} = \int_a P[G_f < 0 \mid a] P(a) da \tag{2}$$

b) The global frame failure is characterized by the individual failure of a number "n" of critical members, which are acknowledged through a series of preliminary frame response analyses (under the scenario a_i) by sequentially eliminating the most stressed members until a global instability is reached.

c) When the critical members are identified, the frame failure probability might be expressed by the product of the conditional frame failure probability given the failure of those critical members and the probability that those critical members fail, assuming that these failure events are independent.

$$P_f(G_{fai}) = P(G_f | a_i) = P(G_{sai} \leq 0 | F_1 \cap F_2 \cap \ldots \cap F_n) P(F_1 \cap F_2 \cap \ldots \cap F_n) \quad (3)$$

Where $F_1 \cap F_2 \cap \ldots \cap F_n$ constitutes the failure of the set "*s*" of *n* members, which induces the global frame failure.

d) To identify the critical member´s group, it is observed that the *n* critical members trend to fail in a sequential way [15]. Consequently, for the loading combination "a_i" scenario, the first members that would fail are those with the largest working ratio, those members would be removed in the next analysis, and, again, a new group of members would be selected, those with the maximum working ratios, and so on, until the occurrence of global frame instability for the "a_i" scenario . The failure probability of each member is calculated based on the maximum acting and resisting forces (bending moment, if the member is a beam), the calculation of the failure probability will be explained further later.

e) Once the set is complete, the first factor in Eq. (3) is 1.0 and the system failure probability is the second factor. This second factor might be expressed through the above described sequential process, as:

$$P(F_1 \cap F_2 \cap \ldots \cap F_n) = P[F_1 \cap F_2 \cap \ldots \cap F_n | (F_a \cap F_b) P(F_a \cap F_b)] \quad (4)$$

$$P[(F_1 \cap F_2 \cap \ldots \cap F_n) | (F_a \cap F_b)] P(F_a \cap F_b) = P[F_1 \cap F_2 \cap \ldots \cap F_n | (F_c \cap F_d)]\ P(F_c \cap F_d) P(F_a \cap F_b)] \quad (5)$$

f) For the last unconditional probabilities, it might be assumed that the individual failures of members are independent. Therefore, the failure probability of this group might be obtained through the product of the individual failure probabilities. The mean acting force is taken as the maximum stresses at the critical member (with working ratio closest to 1), as a result of the nonlinear response frame analysis, and the mean resistance is the one calculated for the respective member.

If the critical failure mode is bending, the limit state corresponds to:

$$G_i = 1 - M^i_{act} / M^i_r \quad (6)$$

Where M_{act}^i and M_r^i are the acting and resisting moment of member *i*.
If the critical failure mode is shear, the limit state corresponds to:

$$G_i = 1 - V^i_{act} / V^i_r \quad (7)$$

Where V_{act}^i and V_r^i are the acting and resisting shear of member *i*.

If the critical failure mode is the inter-story drift, the limit state corresponds to:

$$G_i = \Delta^i_{allow} - \Delta^i_{act} \quad (8)$$

Where Δ_{allow}^i and Δ_{act}^i are the allowable and acting inter-story drift for member *i*.
If the limit state corresponds to the critical combination of axial load and bending moment simultaneously occurring at a member:

$$G_i = 1 - (P^i_{act} / P^i_r + M^i_{act} / M^i_r) \quad (9)$$

Where P_{act}^i is the acting axial load and P_r^i is the resistant axial force, for the most critical combination of axial loads and moments occurring simultaneously at all columns in the building. For the columns, the resistant point (P_r^i , M_r^i) is obtained through the interaction diagram: the demand point (P_{act}^i , M_{act}^i) is located into the diagram and the line joining the origin to this demand point is extended to intercept the curve of the diagram. The intersection point is the resistant point.

g) For simplicity, the same uncertainty will be considered only on the acting axial load and bending moment [16] and also the same uncertainty will be taken for the resisting moment and resisting axial force. The 4 variables will be considered here as lognormal [17, 18].

h) Commonly, for seismic environments, the coefficient of variation (*CV*) of 1/3 has been used for loading effects [19], the axial load and the bending moment, so for this work, they would be assumed as *CV* =0.3. Also, the resisting axial force and bending moment are considered to have a *CV* = 0.15, and the expected values of P_{act} and M_{act} will be considered as the structural responses corresponding to the spectral pseudo-accelerations scenario, which are taken as mean values of the demand.

i) As the structure is located on a seismic zone and this condition dominates the structural design, then that demand is used to calculate Pf (Eq. 1). The estimation for the seismic hazard is performed by following a current Design Manual [20], which recommends calculating the rock seismic intensity through the uniform hazard spectra.

j) Next, the expected life-cycle cost $E(C_L)$ is considered for all the alternative repair schemes. The expected life-cycle cost is expressed in terms of the repair cost C_U (which is deterministic and obtained from conventional unit cost techniques) and the expected failure costs $E(C_D)$ [21, 22] for a given seismic intensity.

$$E(C_L | a) = (C_u | a) + E(C_D | a) \quad (11)$$

The expected failure cost includes not only the material building loss, but also the failure consequences, as the economic loss due to school activities moved to other facilities, during the building repair/reconstruction, potential fatalities, injuries to occupants and the loss of contents, current repair practices and current costs in México are used.

k) Finally, the optimal recommendation is associated with the scheme that corresponds to the minimum expected life-cycle cost.

2.2 Failure probability for a member calculation

The failure probability, $P(M_{act}>M_r)$, under a seismic scenario a_i may be obtained by assuming that both, the acting and the resisting moments are lognormal and the corresponding coefficients of variation are: CV_{Mact} = 0.3 CV_{Mr} = 0.15 as it is before explained.

If the resisting moment, which is calculated from conventional design formulas without safety factors, is considered to be the median of the resistant variable $\mathcal{M}_r$ and if the acting moment obtained from conventional response analyses without loading factors, is considered to be the median of the acting force

$\mathcal{M}_{act}$, the failure probability, $P(M_{act}>M_r)$, conditional to a seismic scenario a_i may be obtained

$$P(M_{act}>M_r) = 1- \phi \{[(\ln(\mathcal{M}_r)-\ln(\mathcal{M}_{act},)]/\sqrt{(CV^2_{Mr}+CV^2_{Mact})}\} \quad (12)$$

Where:

$$\mathcal{M}_r=E(M_r)/\sqrt{(1+CV^2_r)} \quad (13)$$

And:

$$\mathcal{M}_{act}=E(M_{act})/\sqrt{(1+CV^2_{act})} \quad (14)$$

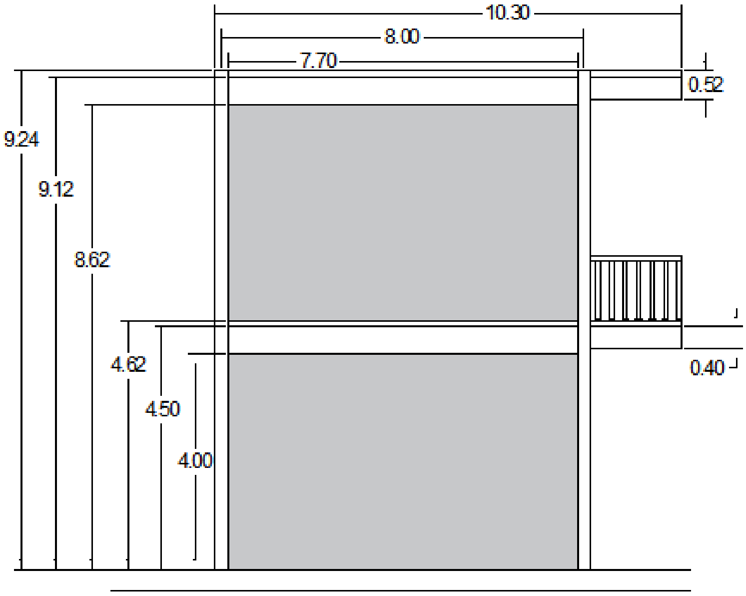
The response analysis is repeated for all intensities a_i and:

$$P_f = \sum_1{}^n P(M_{act}>M_r | a_i)P(a_i) \quad (15)$$

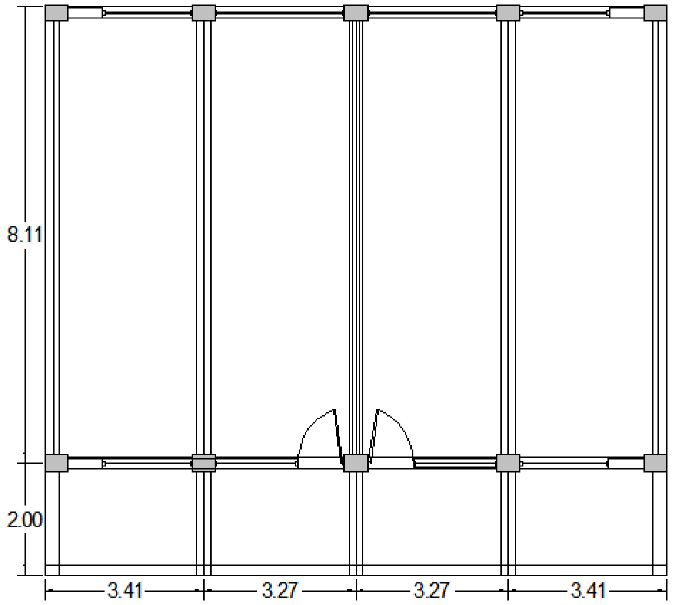
3 Illustration

3.1 School description

The elementary school “Benito Juárez” is located in Tlaltizapan, Morelos. Tlaltizapan is about 197.2 km from Mexico City and 30 km from Cuernavaca main city of the Morelos state. This school has 4 buildings with the same distribution and structural characteristics, which consist on a 2 stories structure with 4 bays in one direction and 1 in the other one, with a cantilever hallway on the second floor. The structural type consists of a concrete frames-masonry dual system, with walls of 10 cm thickness; the foundation is a concrete spread footing. The materials properties are: concrete strength 200 kg/cm^2, reinforcement steel yielding stress 4,200 kg/cm^2 and the masonry compression capacity is 14.99 *kg/cm*^{2}. The school live load is 245 *kg/cm*^{2} [23]. As all the buildings have the same size and structural characteristics, for this work only one building was analyzed.



a) Elevation view (dimensions in m)



b)Plan view (dimensions in m)

Fig. 1 Elevation a) and plan b) views of the considered building.

The rectangular columns cross-section is 50 x 30 cm, the principal beams have a 60 x 30 cm cross-section, and the secondary beams a 40 x 30 cm cross-section. The walls are made of hollow bricks with a compression strength of 14.99 *kg/cm*^{2} with two 5/16” bars every 8 cm.

3.2 Seismic hazard

The estimation of the Tlatizapan seismic hazard is performed by following the Design Manual [20], which recommends to calculate the rock seismic intensity through the uniform hazard spectra. In this work, 3 hazard spectra were used: the one obtained from the design manual as the maximum, the second one as the 90% of the maximum and the third one as the 80% of the maximum. These alternative spectra are chosen to obtain the earthquake occurrence probabilities (0.1, 0.2 and 0.7 for original, 90% and 80% spectra) from a previous work which includes the seismic hazard of Mexico City [24].

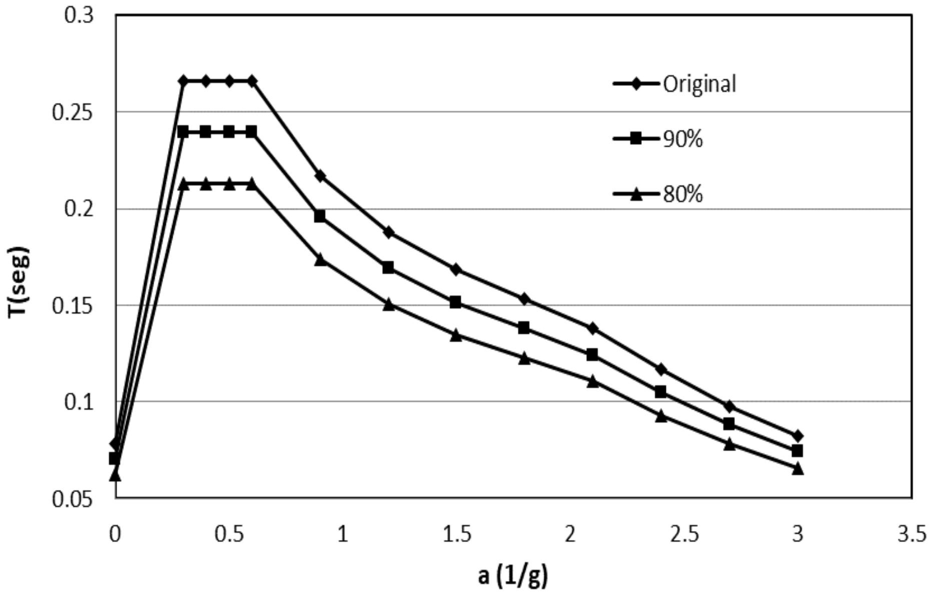


Fig. 2 Uniform hazard spectra.

3.3 Cost estimation

The repair cost C_u was estimated for each element as if it would be demolished and rebuilt throughout a classical unit cost analysis. The cost of failure consequences C_D, for the elementary school "Benito Juárez", was calculated as follows:

$$C_D = C_C + C_e + C_{in} + C_f \quad (16)$$

Where:

C_C is the cost of the building content, C_e is the cost of functionality loss, C_{in} the injury cost, and C_f the fatality cost.
The estimation of contents loss considers the number of desks with chairs, computers, screens, projection equipment and, lab equipment. Typical costs are included from Mexican school suppliers (https://todooficina.com/equipamiento/).
Injury cost is obtained using a rate of 0.0168/m^2 obtained by De León in previous works [21], and by obtaining the current average cost for an injury from the Mexican Institute of Health (IMSS, 2018).

The cost of fatalities was calculated through the remaining productive lifetime of an individual, 52 years, the average annual income for Mexico and the number of fatalities assessed per m^2 [21] with:

$$N_D = 45.48+5.53A^2 \quad (17)$$

Where N_d is the number of deaths and A the building total plan area. Each one of these costs was calculated for different scenarios.

3.4 Structural response

Resistant bending moments and resistant forces, axial and shear, were calculated for the columns and beams according to the current design code. For the principal beams resistant shear is 11.45 ton and resistant bending moment is 33.65 ton-m, for the secondary beams resistant shear is 9.23 ton and resistant bending moment
is 11.25 ton-m. The results for the columns are in Table 1.

Table 1. Resistant forces and bending moments for columns

M (ton-m)	***P (ton)***
0.00	*467.94*
28.43	*304.40*
49.40	*118.28*
47.91	*71.70*
44.94	*21.28*
37.82	*-22.65*

The frame system with brick walls was modeled in the following way:
Typical FEM method with bar elements and equivalent diagonals to represent the walls were used for the analysis. Three potential failure modes were assessed: axial force, shear capacity and bending resistance for both directions.

3.4.1 Preliminary analyses

A series of preliminary analyses were performed to calculate the columns and beams shear forces and bending moments for the 3 previously mentioned seismic demands. These preliminary analyses allowed identifying the governing failure mode. Some of the results are shown in Table 2.

Table 2. Sample of shear forces and bending moments for the seismic demands.

Beam	***Node A***	***Max M_z (ton-m)***	***Max M_y (ton-m)***	***Max F_z (ton)***	***Max F_y (ton)***
58	*39*	*40.12*	*2.00*	-	*7.67*

60	*37*	*40.12*	*1.13*		*4.46*
59	*38*	*39.78*	-		*4.56*
64	*43*	*39.78*	-		- *4.94*
63	*42*	*39.10*	*1.45*		- *8.41*
65	*44*	*39.10*	*4.16*		- *1.44*
48	*27*	*24.54*	*11.18*		
50	*29*	*24.54*	*4.66*	- *0.00*	

3.4.2 Failure probability

From the simulated responses, the probability failure for each element was calculated with the procedure described above. Table 3 shows a sample of these results.

Table 3. Sample of failure probabilities for single elements. Original demand

Member	***E(M$_r$)***	***E(M$_{act}$)***	***Acting mean***	***Acting median***	***Resisting mean***	***Resisting median***	***β***	***P_f***
58	*44.3*	*40.12*	*38.43*	*36.81*	*43.44*	*42.60*	*0.41*	*3.42E-01*
60	*44.3*	*40.12*	*38.43*	*36.81*	*43.44*	*42.60*	*0.41*	*3.42E-01*
59	*44.3*	*39.78*	*38.10*	*36.50*	*43.44*	*42.60*	*0.43*	*3.34E-01*
64	*44.3*	*39.78*	*38.10*	*36.50*	*43.44*	*42.60*	*0.43*	*3.34E-01*
63	*44.3*	*39.1*	*37.45*	*35.87*	*43.44*	*42.60*	*0.48*	*3.16E-01*
65	*44.3*	*39.1*	*37.45*	*35.87*	*43.44*	*42.60*	*0.48*	*3.16E-01*
48	*44.3*	*24.548*	*23.51*	*22.52*	*43.44*	*42.60*	*1.77*	*3.85E-02*
50	*44.3*	*24.548*	*23.51*	*22.52*	*43.44*	*42.60*	*1.77*	*3.85E-02*
53	*44.3*	*23.494*	*22.50*	*21.55*	*43.44*	*42.60*	*1.89*	*2.94E-02*

The failure probability for the groups is calculated in the following way:
Once the group of members with the highest G_i is removed, the analysis is repeated of the structure with the remaining members and the corresponding failure probabilities are calculated for this condition, and so on, until global frame instability occurs. For this case, 4 iterations were performed before global instability took place, Table 4 presents the 4 groups of members that were removed in successive 4 iterations. For the 2nd. iteration, and after members 71, 12, 9 and 4 were removed, a new response analysis was performed and a new member failure probabilities were calculated. Table 5 shows a small sample of this new member failure probabilities.

Table 4. Removed members

Iteration	*Members*
1	*71, 12, 9, 4*
2	*15, 14, 7, 6*
3	*16, 3, 1, 8*
4	*5, 51, 47, 56*

Table 5. Small sample of new member failure probabilities after removing some members. Iteration 2

Member	*$E(M_r)$*	*$E(M_{act})$*	*Acting mean*	*Acting median*	*Resisting mean*	*Resisting median*	*β*	*P_f*
15	*32,33*	*31,82*	*30,47*	*29,19*	*31,97*	*31,62*	*0,24*	*0,91*
14	*32,33*	*31,82*	*30,47*	*29,19*	*31,97*	*31,62*	*0,24*	*0,91*
7	*32,33*	*31,19*	*29,87*	*28,61*	*31,97*	*31,62*	*0,30*	*0,88*
6	*32,33*	*31,19*	*29,87*	*28,61*	*31,97*	*31,62*	*0,30*	*0,88*
16	*32,33*	*30,79*	*29,50*	*28,25*	*31,97*	*31,62*	*0,34*	*0,87*
13	*32,33*	*30,79*	*29,50*	*28,25*	*31,97*	*31,62*	*0,34*	*0,87*

Once it is known what elements would cause a global instability, the cost for repairing and damage cost were calculated for each repair strategy.

4 Modeling and analysis of repairs

From a previous work [25], the damaged conditions of the structure is modeled by reducing the cross area and inertia moment of the damaged members. Then, the structure failure probability is calculated and the retrofit strategies are modeled to calculate the new failure probability and the corresponding retrofit costs.
The next step is the proposal of 3 repair methods for the removed members in order to obtain a probability failure smaller than 0.01 for those members. For this work the repair methods used were: 1) incorporating reinforcement steel, by making grooves with the help of a mechanical saw, by cleaning the area where the drilling was performed, by incorporating the required steel into the groove and, finally, by filling the groove with an epoxy that ensures proper adhesion between the existing concrete and the placed steel. 2) Making a pike that starts at the bottom of the member until it reaches above the hoop and allow to add the required steel to the existing steel pair, cover these with concrete 3) Adding steel elements in order to form an exo-skeleton for the critical members.

For each repair method, the structural analysis was performed again and the failure probabilities are calculated for the selected members. See Table 6, as an example, for the 1st. repair alternative.

Table 6. Small sample of new member failure probabilities after repair (1st. alternative)

Member	*E(Mr)*	*E(Mact)*	*Acting mean*	*Acting medium*	*Resisting mean*	*Resisting medium*	*β*	P_f
71	83,25	32,44	31,08	29,77	82,33	81,42	3,00	0,0013
12	83,25	32,20	30,84	29,54	82,33	81,42	3,02	0,0013
9	37,84	13,59	13,01	12,47	37,42	37,01	3,24	0,0006
4	37,84	13,50	12,93	12,38	37,42	37,01	3,26	0,0005
15	83,25	31,82	30,47	29,19	82,33	81,42	3,06	0,0011
14	83,25	31,82	30,47	29,19	82,33	81,42	3,06	0,0011
7	83,25	31,19	29,87	28,61	82,33	81,42	3,12	0,0009
6	83,25	31,19	29,87	28,61	82,33	81,42	3,12	0,0009
16	83,25	30,79	29,50	28,25	82,33	81,42	3,16	0,0008
13	83,25	30,79	29,50	28,25	82,33	81,42	3,16	0,0008
1	37,84	13,25	12,69	12,16	37,42	37,01	3,32	0,0005
8	37,84	13,13	12,58	12,05	37,42	37,01	3,35	0,0004

Once the analyses for the 3 repair alternatives were performed, the failure probabilities and expected life-cycle costs were calculated. See table 7.

Table 7. Costs (USD) associated to each repair alternative

Repair alternative: / *Cost*	*1*	*2*	*3*
C_r	$19,838.42	$37,871.00	$79,353.79
C_c	$2,679.26	$2,679.26	$2,679.26
C_e	$7,650.63	$7,650.63	$7,650.63
C_{in}	$488.58	$488.58	$488.58
C_f	$14,496,969.05	$14,496,969.05	$14,496,969.05
Total Cost	$14,507,787.53	$14,507,787.53	$14,507,787.53
$E(C_D)$	$14,507.79	$14,507.79	$14,507.79
$E(L_C)$	$34,346.21	$52,378.79	$93,861.58

The optimal repair strategy corresponds, then, to the 1st. one. See fig. 3.

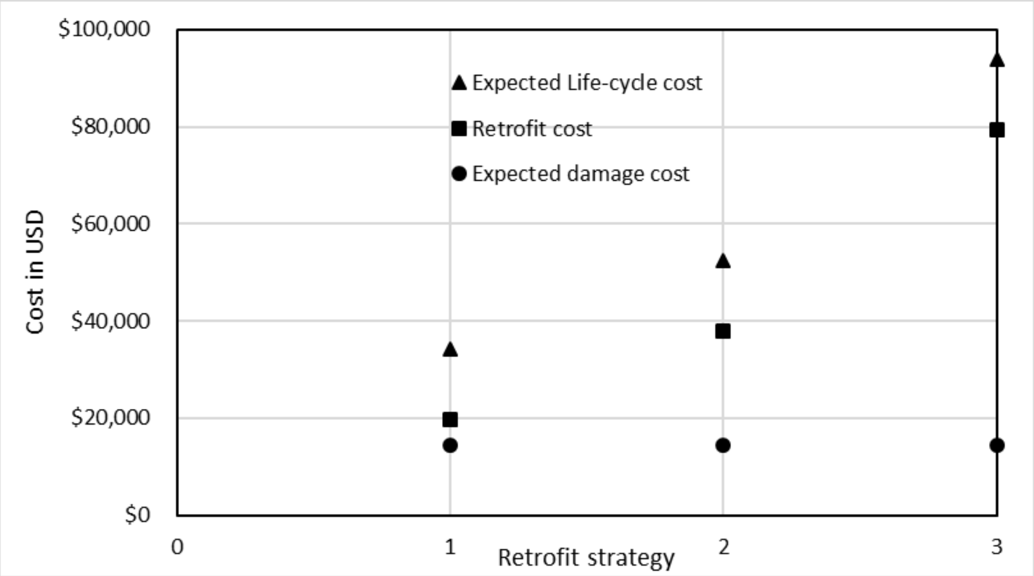


Fig. 3 Retrofit cost, expected damage cost and expected life-cycle cost per repair strategy

5 Conclusions and recommendations

A systematic reliability-based procedure to identify the optimal retrofit for buildings damaged by earthquakes was proposed and applied to a school in Mexico. The procedure compares the cost-effective performance of alternative retrofit techniques from the life-cycle point of view.

For the considered reinforced concrete building, the retrofit strategy of rebar added, by making grooves on the concrete and the filling with an epoxy, was the optimal strategy.

The study may be extended to consider a catalog of buildings, all types of typical damages and more retrofit alternatives in order to generate practical retrofit recommendations for the buildings inventory in a whole seismic region.

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