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COMPARISON OF TWO DIFFERENT APPROACHES FOR THE ASSESSMENT OF DIRECT LOSSES THROUGH PERFORMANCE-BASED EARTHQUAKE ENGINEERING

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Abstract

This paper addresses the problem of estimating direct economic losses due to seismic damage in modern buildings that comply with seismic codes. The losses were estimated using analytic methods based on performance based earthquake engineering (PBEE). Two approaches are compared: (1) Repair cost estimation based on damage to the structure, and (2) Repair cost estimation based on a global damage ratio and a building replacement cost. The PBEE methodology could be applied on any type of building in seismic regions.

As a case study, modern school buildings located in areas of high seismicity in Peru were analyzed. The results of the model were obtained through incremental dynamic analysis (IDA). The building's global damage states were defined by evaluating the model's local damage. The local damage states and intervention costs were evaluated for each type of element in the building, taking into account available resources in the area. Structural and non-structural elements of the building were taken into consideration. Finally, the expected loss function was obtained by using the theorem of the total probability.

The results showed that multiplying the percentage of damage by reparation cost to obtain the expected loss can overestimate the losses for all intensities measured. Further studies on the time and costs of different repair procedures considering local workforce and available resources are recommended.

Keywords: Incremental Dynamic Analysis (IDA), Performance Base Earthquake Engineering (PBEE), Repair Cost

1. Introduction

Severe earthquakes generate large direct financial losses due to severe damage or collapse of buildings [1]. Medium-intensity earthquakes can also generate significant losses due to minor damage to structural and non-structural elements in buildings that do not comply with the current seismic norms. To face those losses, regional and local governments resort to financial protection policies, such as registration to insurance policies, creation of emergency funds, and issuance of catastrophe bonds. The implementation of those precautionary measures requires an estimation of the probable losses for different seismic scenarios.

Damage-associated losses can be calculated using two methods. The first one consists in analyzing the levels of local damage to each element of the structure, and assigning them a repair cost according to the level of damage. The total loss in the local damage-based method (LDBM) is the sum of the repair costs for the different elements of the structure [2, 3]. The second method is based on the definition of levels or indexes of global damage (global damage-based method, GDBM) and it assumes that the total loss is proportional to that level of damage. In that case, the total loss is estimated by multiplying the total cost of replacement by the level of damage to the structure [4-8].

This paper compares both methods through the study of a typical reinforced concrete building located in a high-seismicity area. It includes the concepts of global reparability limit and the maximum admissible repair cost. The reparability limit is defined as the level of damage for which repairing the structure is no longer feasible from a technical point of view. This situation can occur when there is global instability or partial collapse of a level. If the structure is damaged beyond this point, it is necessary to demolish it and reconstruct it. In this case, the loss associated to this level of damage is the cost of replacement by a new structure, and not just the sum of the local damage. The maximum admissible repair cost is the maximum reconstruction cost financially feasible considering that it must not be higher than the reconstruction cost.

2. Performance-Based Earthquake Engineering

Performance-based earthquake engineering (PBEE) [9] consists of the design, evaluation, construction, and monitoring of civil projects whose performance under extreme loads matches the needs of their owners, users, and society [10]. PBEE allows verifying the fulfillment of a series of performance objectives; for example, that an important building remains operational after a frequent earthquake, or that the structure remains reparable after a very rare earthquake. Damage estimation can be useful in the development of mitigation, reinforcement, planning measures. Additionally, PBEE also allows estimating the direct financial losses due to repair of the different structural elements damaged by earthquakes. This result can be useful in the elaboration of mitigation actions and financial protection.

In the PBEE probabilistic approach, losses are decision variables related to the level of structural damage. The damage suffered by the structures depends on the structural response for a given intensity level [9]. In this context, the decision variable (whether it is the level of damage or the financial loss in a building) for a given seismic intensity is a random variable whose distribution function is expressed in Eq. (1) [2]. The Eq. (2) is the modification of the Eq. (1) if we have just one decision variable (DV) per damage measure (DM).

$$G\left(dv \mid im\right) = \int_{dm}\int_{edp} G\left(dv \mid dm\right) dG\left(dm \mid edp\right) dG\left(edp \mid im\right) \tag{1}$$

$$G\left(dv \mid im\right) = \int_{edp} G\left(dv \mid edp\right) dG\left(edp \mid im\right) \tag{2}$$

where IM is the intensity measure, EDP is the response of the building measured through a demand parameter, and G(dv|im) is the probability distribution function of variable dv conditioned to a value of variable im. The expected value of the distribution functions is given by Eq. (3).

$$E\left[dv \mid im\right] = \int_{edp} E\left[dv \mid edp\right] dG(edp \mid im) \tag{3}$$

The EDP response conditioned to IM can be obtained through non-linear analysis tools such as incremental dynamic analysis, IDA [11] or through the capacity spectrum method [12]. Results obtained through IDA keep track of the number of times the different local damage states take place in the different groups of elements for each EDP, providing statistics of the results. The capacity spectrum method allows defining the mean of EDP and to assign a variance value through a certain criterion. In both cases, once the mean and variance values have been obtained, it is possible to adjust the distribution functions, using for example a lognormal distribution.

There are two approaches to estimate the global damage. The first one is based on measuring the damage through a loss ratio LR_{ds} obtained from the local damage to elements through a proper aggregation method [8, 13]. The sub-index ds denotes that the ratio is associated to a damage state. In the second approach, different damage states are defined as a function of the displacement of the building's top level [14].

In the first approach, the local damage state (for example: without damage, localized, minor, moderate, severe, and irreparable) can be characterized by the local damage curve that links local damage states with a certain local demand parameter. For instance, the parameter for reinforced concrete beams can be the cross-section curvature [11]; in isolated partitions, it can be the ground acceleration or the distortion of walls in its plane [15].

In the second approach, the global damage state is obtained from sectioning the capacity curve (base shear vs. roof lateral displacement) of the structure through the push-over method, in displacement intervals corresponding to the states of damage: immediate occupancy (IO), damage control (DC), life safety (LS), and collapse prevention (CP) [14].

3. Estimation of direct losses using local damage-based method, LDBM

Direct financial losses are the sum of the repair costs for each group of elements. Repair costs are estimated from the unit repair costs of the different structural and non-structural elements, based on their local damage level. Repair costs include material, labor, and general costs.

The distribution's mean and variance G(dv|edp) are calculated for each EDP; those functions are then used to adjust a beta distribution [16], since the loss value is limited by zero and the replacement cost. If the EDP is higher than the reparability limit of the structure, or if the average repair cost is higher than the maximum admissible cost, the function can be modeled as a Dirac delta function taking the unit value as the replacement value for the structure. In summary the method used to obtain the G(dv|edp) function is as follows:

1) Calculate EDP_{lim}.

$$EDP_{lim}=\min[EDP_i, EDP_m] \tag{4}$$

where EDP_i is the response value associated to the structure instability, and EDP_m is the structure response parameter associated to the maximum admissible repair cost. The repair cost for an EDP higher than the EDP_{lim} is the building replacement cost. This EDP_i is defined by observing the IDA median and the damage matrices.

2) G(dv|edp) is characterized by a beta distribution probability function. Variable v is the ratio between the repair cost and the replacement cost, and ranges from 0 to 1 when EDP is lower than EDP_{lim}. When EDP is higher than EDP_{lim}, the function is a Dirac delta $\delta(x=1)$.

The Eq. (5) shows the distribution functions dv|im obtained through the discretized Eq. (2) by Riemman sum:

$$G\left(dv\,|\,im\right)=\sum_{i=1}^{N}\left(\frac{G\left(dv\,|\,edp\right)\cdot g(edp)_i+G\left(dv\,|\,edp\right)\cdot g(edp)_{i+1}}{2}\right)\cdot \Delta EDP\cdot g\left(edp\,|\,im\right) \tag{5}$$

The expected value and variance of G(dv|im) represent the expected value and variance of the financial loss for a given intensity.

4. Estimation of direct losses using global damage-based method, GDBM

The global damage state is generally associated to the repair cost required to bring the structure back to its pre-event conditions. It is often expressed as a percentage of the total replacement cost [4]. Global damage states can be found in the structure capacity curve, which is obtained through a push-over analysis by sectioning it according to the roof displacement [14]. Global damage can also be quantified through the LR_{ds} index, obtained from the number of elements showing a present local damage level [8].

To determine the global damage indices for each log and intensity level, a damage percentage is calculated for each of the considered damage states. The result of this approach is a value of damage percentage for each damage state, LR_{ds}. Probable losses are calculated from Eq. (6) [8].

$$E\left[LossRatio\,|\,IM=im\right]=\sum_{ds=0}^{nDS}\left(P\left[DS=ds\,|\,IM=im\right]LR_{ds}\right) \tag{6}$$

Where P[DS=ds|IM=im] is the probability of exceedance of a given damage state for a level of intensity. Global damage can also be defined from drifts [13]. IDA method [11] provides the required data to calculate the probability of how many logs exceed a given performance value (inter-story drift) linked to a global damage state.

5. Case study

A case study of typical modular two- and three-level school buildings was used to compare LDBM and GDBM. Those structures were built in Peru, following the guidelines of the seismic-resistant norm from 1997. Nowadays, there is a large interest in estimating the seismic losses for those essential buildings, and therefore there are several studies that have researched this case both empirically [5] and numerically [6, 7].

The buildings feature a structural system based on reinforced concrete frames and confined masonry; the plan is rectangular, and the staircase is structurally separated from the building. Masonry infill walls are correctly isolated from the building, which eliminates the problem of short columns effect. Fig. 1 shows the typical plan. Only the longitudinal direction of the structure was analyzed, since it is the more flexible direction and thus the one that would present the largest damage.

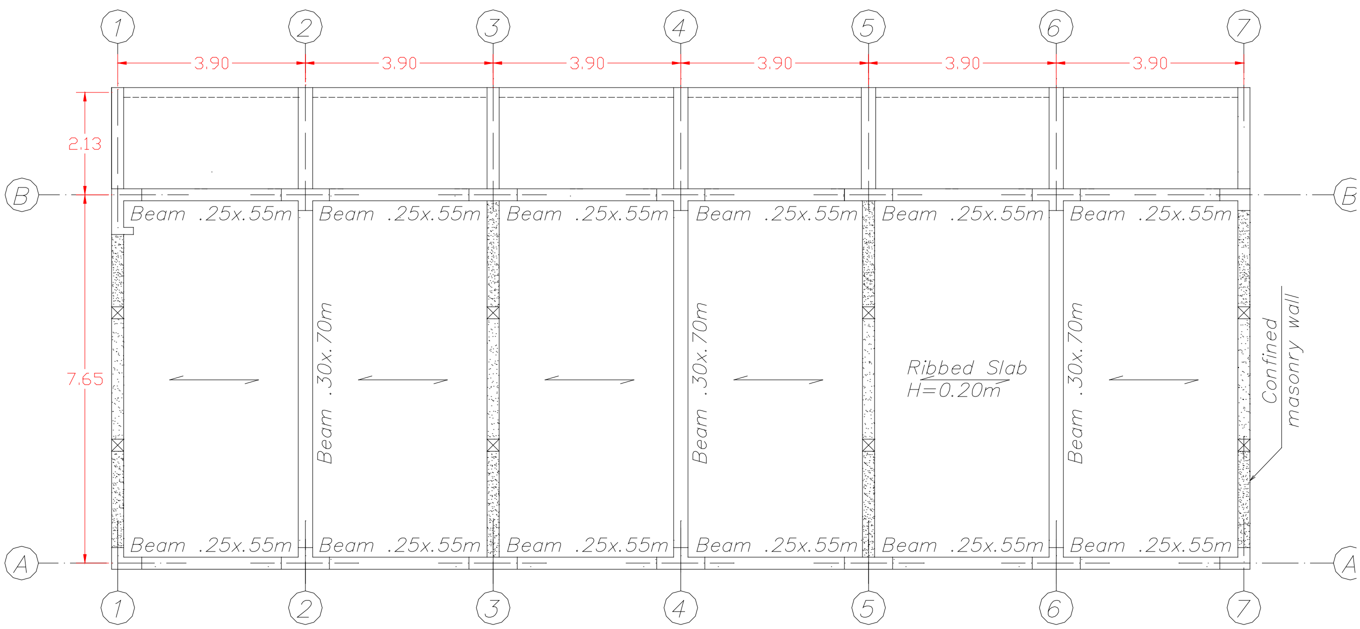


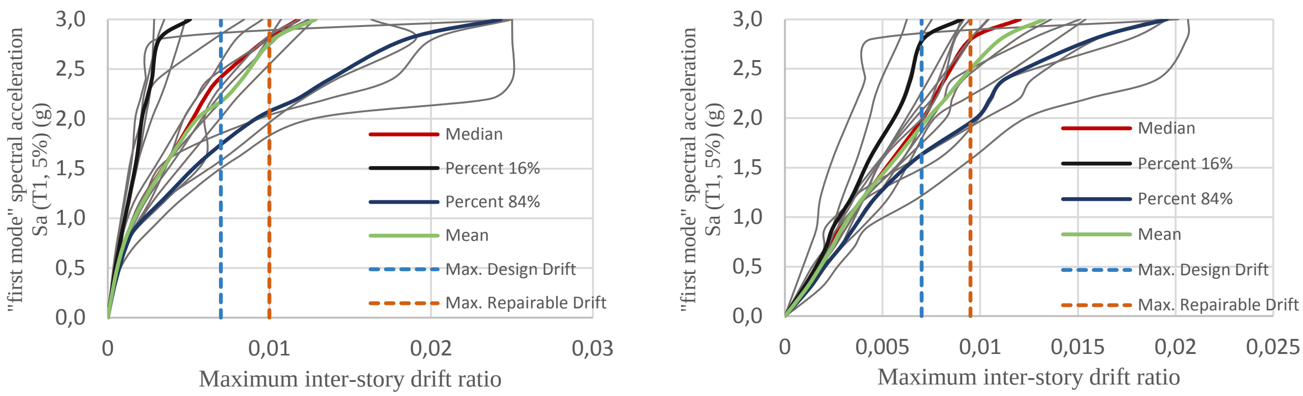
Fig. 1 – Layout of the structural system in the building under study [7]

School buildings were modeled taking into account the non-linear properties of the structural elements. The non-linear behavior were represented through plastic hinges in the extremes of the elements. Constitutive models from Park et al. [17] were used for concrete, and those from Park & Pauley [18] were used for the reinforcement steel. Interaction diagrams were considered on columns, to take into account the moment–axial load relationship. The confined masonry on the transversal side was modeled through shear panels with properties taken from tests on traditional confined walls [19]. The masonry infill walls on the longitudinal side of the buildings were taken into account by means of a distributed load over the beams, since they are correctly isolated from the frames through seismic isolation joints. The non-linear dynamic analyses were performed using the software Perform 3D [20].

6. Seismic analysis using PBEE

6.1 Analysis of EDP

IDA was performed using 14 records [21-23] scaled to 12 intensities. These records are representative of the Peruvian and Chilean coastal regions. The selection criterion was based on similarities regarding intensity and shape of pseudo-acceleration spectrums. The pseudo-acceleration of the fundamental period with 5% damping $S_a(T_1)$ was taken equal to the intensity marker as recommended by different guidelines and studies [24, 25]. The global demand parameter (EDP) is the maximum inter-story drift ratio. Fig. 2 shows the set of 14 IDA curves for the analyzed buildings. Additionally, it shows the mean, median, and the 16th and 84th percentiles of these curves, as well as the maximum inter-story drift values allowed by the Peruvian Seismic Building Code E-030 [26], and the maximum drift to allow reparability of these buildings, EDP_i.

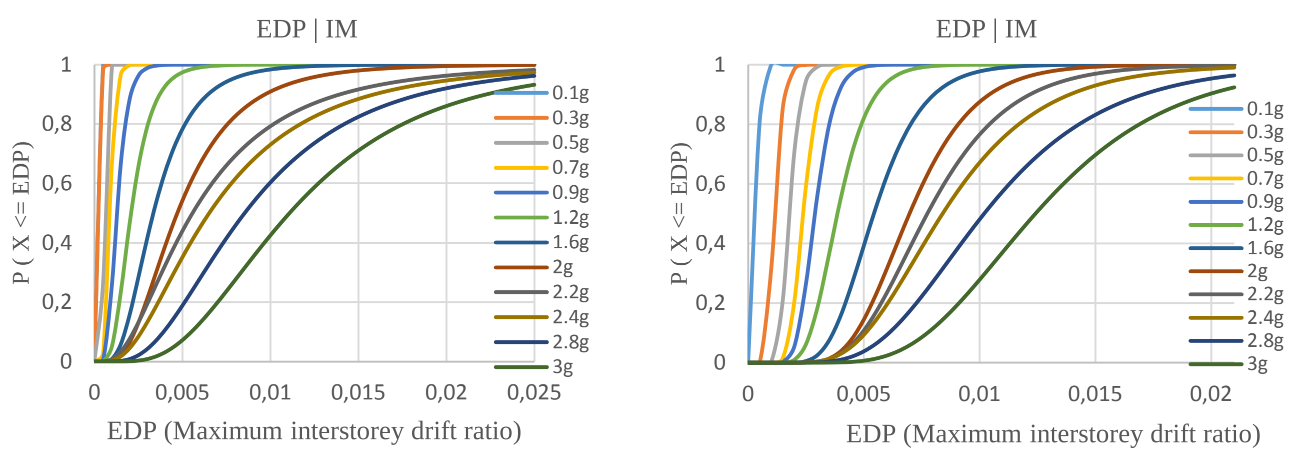


(a) (b)

Fig. 2 – IDA curves for school buildings with (a) two levels, and (b) three levels

The average EDP for structural instability (slope below 20% in the IDA median curve) is 0.01 for 2-story buildings, and 0.0095 for 3-story buildings. In both buildings, the associated intensity level is around 2.7g. The maximum inter-story drift in the Peruvian Seismic-Resistant Norm, equal to 0.007, corresponds to intensity values of 2.4g and 2g, respectively.

The EDP mean and variance were calculated for each seismic intensity. These statistic values were used to adjust the lognormal function G(edp|im) (Fig. 3). Fig. 3 shows that the probability of reaching an EDP equal to 0.009, corresponding to building instability, is very low for intensities below 1.6g. For an intensity of 2.4g, the probability of reaching the instability value is around 55%.



(a) (b)

Fig. 3 – Distribution function EDP|IM for school buildings with (a) two levels, and (b) three levels

6.2 Analysis of local damage

The analysis of damage took into account both structural and non-structural elements, so it is necessary to separate them in groups and to define a demand parameter (EDP) for each of them. This allows evaluating local damage and the corresponding losses through the definition of local damage states.

In beams and columns, two zones of plastic hinges were defined, and local damage states were established. The damage states (localized, minor, major, and severe) were determined from the sectioning of the moment–

curvature diagram of the cross-sections [27]. The irreparable damage state was established as the point when the linear deformation of the concrete reaches the equivalent of the 80% of the compression strength of concrete [28].

In masonry structural walls, the local damage curve was defined in terms of the maximum inter-story drift on the direction perpendicular to the plane of the wall reached during the analysis. Each structural wall has a unique damage state according to Tu et al [29]. It is worth remembering that the structural walls are located in the direction perpendicular to the analysis.

In non-structural walls or partitions, the local damage curve was defined in terms of the maximum inter-story drift in the direction longitudinal to the wall's plane [15]. Two types of partitions of different heights were analyzed, since they presented different damage states; the higher partitions show more damage since they are also slenderer.

Losses on doors and windows happen when the building reaches a global damage state of "life safety", which represents the complete replacement of the building.

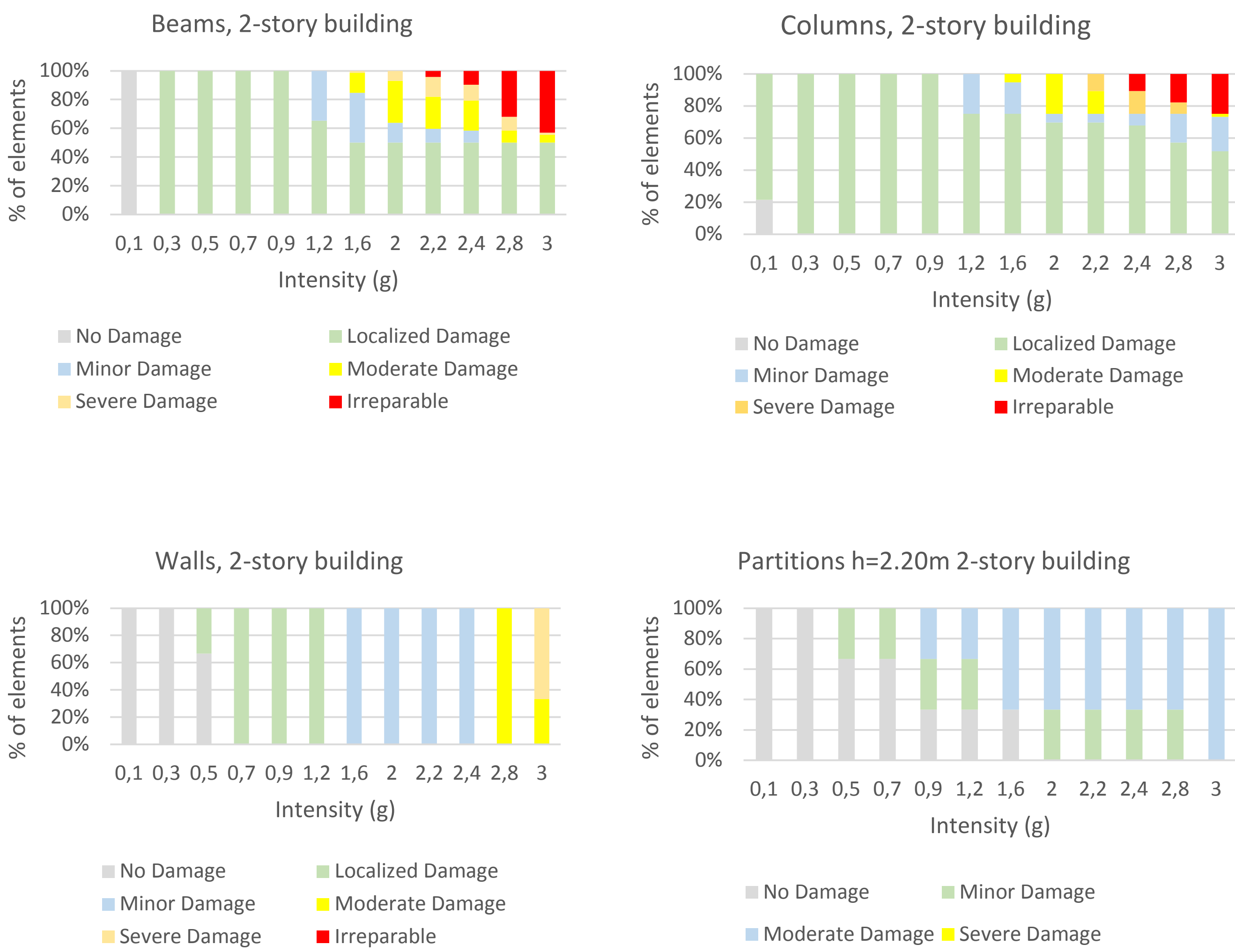


Fig. 4 – Evolution of local damage in some elements of the 2-story school building for Arequipa's earthquake on August 15, 2001

For illustration purposes, Fig. 4 shows the relative frequency of occurrence of the different damage states on structure's elements in the 2-story building, for different intensities. Notice that for 0.9g, beams show only localized damage, while columns present both minor damage (10%) and localized damage (90%). For 2.2g, 50% of the beams present localized damage, but 5% of the beams are already irreparable. For that same intensity level, columns have only reached a moderate damage level (25%). For 2.5g (corresponding to global instability), 10% of the beams have reached the irreparable state, while columns only present severe damage (10%), moderate damage (5%) and localized damage (75%). The failure mechanism in both school buildings is the strong column weak beam one. In other words, the plastic hinges form first on the beams and then on the columns. In the case of walls and partitions, 30% of the partitions show severe damage for a 0.9g intensity.

6.3 Relationship of approaches for the description of global damage

For validation purposes and to verify consistency of the results Table 1 shows the descriptions of damage obtained in this study and the ones associated to damage states defined by ATC-40 [12]. Inter-story drifts, intensities, and percentage of damaged elements on Table 1 are an average of the results obtained on all the analyzed logs. These results are in agreement with the descriptions of damage states by ATC-40 for buildings featuring non-ductile reinforced concrete frames. The structure becomes irreparable when it reaches the "Life Safety" damage state, and global instability of the structure takes place when it reaches the "Collapse Prevention" damage state.

Table 1 – Descriptions and drifts associated to damage states for the school building

Damage State	**Description of damage obtained in this study**	**Description ATC- 40**
Immediate Occupation (IO)	70% of the beams show localized damage; the structure is considered to present minor global damage.	Very limited flexural and shear cracking with no spalling. No permanent horizontal offset in columns. No permanent deflection in beams. Gravity capacity maintained.
Damage Control (DC)	20% of the beams have reached moderate damage, or more than 20% of the columns show moderate damage; the structure is considered to present moderate damage.	Limited flexural and shear cracking with little or no spalling. No permanent horizontal offset in columns. No permanent deflection in beams. Gravity capacity maintained.
Life Safety (LS)	25% of the beams show irreparable damage, or 80% of the first level columns present severe damage. The structure has possibly reached global irreparable damage state.	Hinges have formed in the lower portions of the building (columns) Permanent horizontal offset approaching 2.0 interstory drift. Spalling around hinge region and beam column joint. Flexural cracking in hinge region in beams. Permanent vertical deflection.
Collapse Prevention (CP)	40% of the beams show irreparable damage, or 80% of the first level columns present irreparable damage. The structure is completely damaged.	Hinges have formed in the lower portions of the building causing significant spalling above and below beam column joints and pulverizing of concrete within the core (columns). Extensive spalling around hinge regions and beam column joint. Permanent deflections in beams.

6.4 Analysis of global damage and losses

The direct losses on the building under analysis due to the effect of earthquakes were estimated using the PBEE approach and the LDBM and GDBM methods. The type of repair intervention to perform according to the level of local damage on different elements was determined by LDBM. Unit costs for each intervention were based on local supplier information and repair project budgets. Table 2 shows the calculations for reinforced concrete beams and columns.

Table 2 – Descriptions and repair cost for beams and columns

Damage State	Type of implication	Information	Repair Cost
Localized damage	**Repair actions**	Replacement of finishes, paint, and plaster using mixes prepared in situ	Beams: $ 10
	Damage implications	Requires minor repairs and exterior finishes in this area. It should be emphasized that there is no creep in the reinforcement steel. Damage is basically external. Very small cracks.	Columns: $ 15
	Element functionality	Totally functional	
Minor damage	**Repair actions**	Evaluation of cracks and the need to inject epoxy resins (such as Concresive 1380) to restitute the monolithic behavior of structural elements, replace finishes (paint and plaster)	Beams: $ 60
	Damage implications	Some portions of the beam could show concrete cracks. Also, the finishes on the damaged area require repair. It should be emphasized that steel is close to the creep point. Significant cracks on the concrete.	Columns: $ 190
	Element functionality	Partially functional	
Moderate damage	**Repair actions**	Evaluation of cracks and the need to inject epoxy resins (such as Concresive 1380) to restitute the monolithic behavior of structural elements, coating should be replaced with structural repair mortar (such as Master Emaco S488CI), replace finishes (paint and plaster)	Beams: $ 170
	Damage implications	Some portions of the beam could show concrete cracks and spalling of the coating. Also, the finishes on the damaged area require repair. It should be emphasized that steel has reached the creep point on the affected areas and therefore it must be replaced. It should also be noted that the steel to be replaced is the upper one, inside the slab.	Columns: $ 360
	Element functionality	Partially functional	
Severe damage	**Repair actions**	Replacement of spalled concrete using structural repair mortar (such as Master Emaco S488CI)	Beams: $ 270
	Damage implications	The damaged area shows concrete spalling and exposure of reinforcement steel. Therefore, the section has lost its coating. It should be emphasized that steel has reached the creep point on the affected areas and therefore it must be replaced. It should also be noted that both the upper and lower steel must be replaced.	Columns: $580
	Element functionality	Not functional	
Irreparable damage	**Repair actions**	Use concrete with bonding primer (such as Master ADH - ex concresive 1090) to reconstruct the structural element	Beams: $ 270
	Damage implications	The damaged area must be completely demolished and the beam must be reconstructed. It should be emphasized that steel has reached the creep point on the affected areas and therefore it must be replaced. It should be noted that the beam is fully damaged.	Columns: $ 580
	Element functionality	Not functional.	

The demand parameter EDP was discretized for 40 fixed values of story drifts (ranging from 0.0005 to 0.021) in order to calculate means and variances of the number of damaged elements. For the 2-story building, EDP_i =0.0095 EDP. The repair cost for the EDP_i represents 25% of the building replacement cost. Considering that the maximum admissible repair cost is 100% of the total cost, it is obvious that EDP_m will be higher than EDP_i. For EDP higher than EDP_{lim} = EDP_i the G(dv|edp) distribution functions were modeled using a Dirac delta function. Fig. 5 shows G(dv|edp) functions for a few values of EDP, to visualize the change in functions as EDP increases.

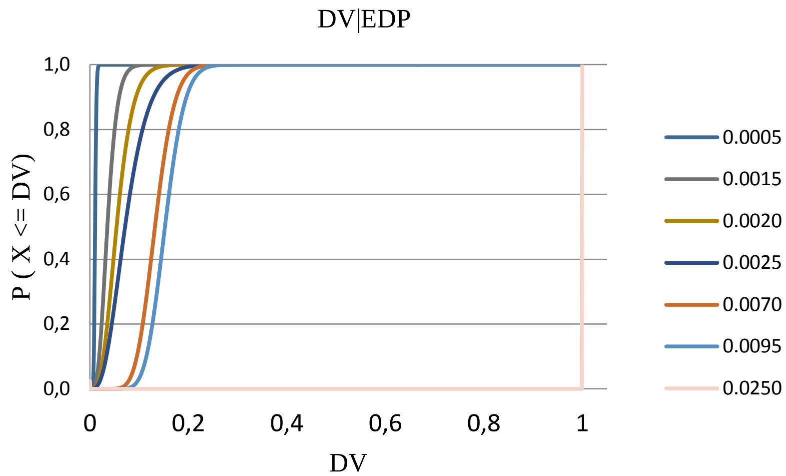
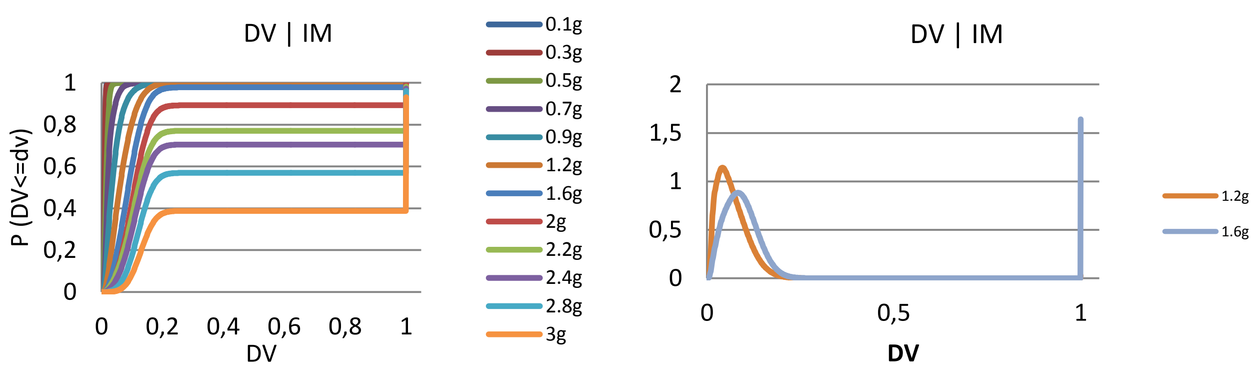


Fig. 5 - DV|EDP distribution functions

Twelve DV|IM distribution functions for each building are obtained by applying Eq. (1) using the data acquired in the analysis of the models. Fig. 6(a) shows the distribution functions for the 2-story building. Notice that for intensities of up to 1.2g, the probability of losses equal to or below 20% is 100%. For intensities between 1.6g and up to 3g, the probability of higher losses ranging from 20% to 99% of the damage values varies from 5% to 58% as the intensity increases. This is due to the fact that EDP values, which determine a replacement cost value, are likely to be exceeded when intensity reaches 1.6g, as shown by the functions EDP|IM (Fig.3).

Fig. 6(b) shows the density functions for the DV|IM distribution functions. These functions illustrate that for low intensities there are no frequency concentrations on the abscissa 1. For intensities starting at 1.6g, mixed distribution functions with frequency concentrations on the abscissa 1 begin to appear. As the intensity increases, so does the frequency concentration at that point, which represents the replacement cost (100% loss).



(a) (b)

Fig. 6 - (a) G(dv|im) distribution functions, (b) g(dv|im) density functions

7. Comparison and discussion of results

As shown in Fig. 7, Tehrany & Mitchel [13] and Martins et. al [8] methodologies present similar results because they use the IDA method to determine the response of the structure. Also, both methodologies use damage indices derived from a local damage analysis. The damage indices established for the buildings under analysis are: IO=0.20, DC=0.50, LS=0.7, CP=0.8. These damage indices were set based on the evolution of the local loss in elements of the building, and limiting them to 1 when buildings are beyond repair.

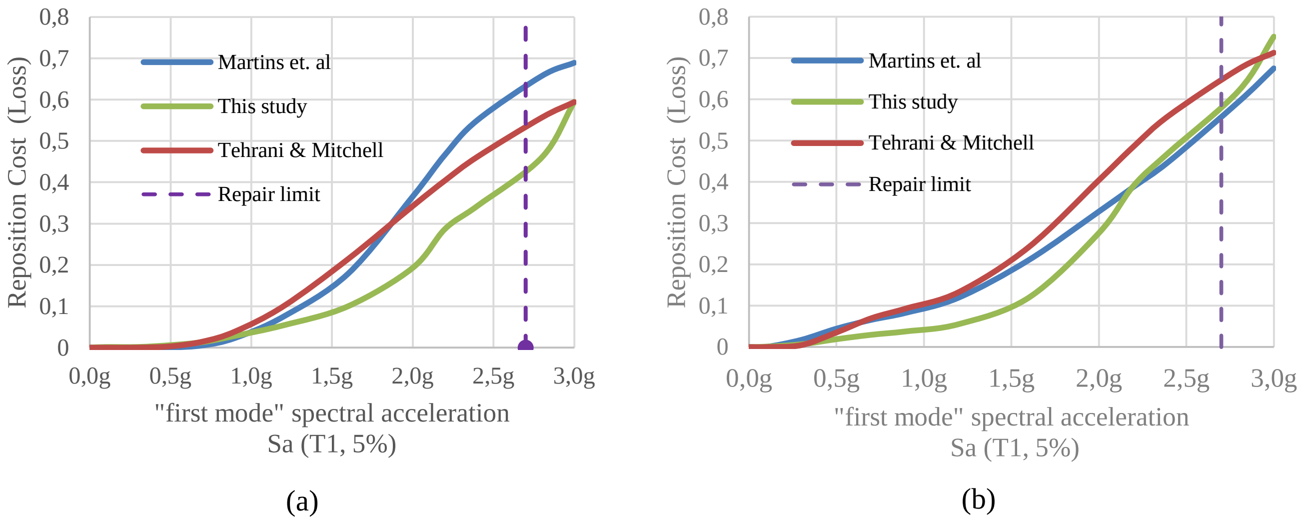


Fig. 7 – Comparison of the results from this study with other methodologies for (a) 2-story building and (b) 3-story building

Fig. 7 shows that in both models, the loss curve is lower when LDBM is used. There are differences in the results for intermediate intensities when comparing GDBM curves with those from this study (LDBM). In the 2-story building there are significant differences, of about 80%, for intensities ranging from 1.5g to 2g. In the 3-story building there are also significant differences, of about 100%, for intensities ranging from 0.7g to 1.6g. It is also worth observing that this difference decreases as the intensity increases. This effect is due to the fact that the probability of reaching the beyond-repair state is significant for higher intensity values, and therefore the loss reaches the total value of the building, which is $280 per square meter. Fig. 2 shows that the maximum intensity for reparability is around 2.7g for both buildings.

6. Conclusions

In this paper, two damage models are compared to compute losses due to seismic action: one that take into account in an explicit manner the damage generated in each one of the structural and non-structural elements, and other that make a generalization of damage based on global performance. For the studied structures, it was observed that take into account the actual local damage based on local behavior for intensities lower than 0.5 g, estimated losses are lower than those obtained when a generalized damage is considered.

The value of reparability limit is associated to two important PBEE concepts: 1) global instability and 2) maximum repair cost. The definition of this value will affect the estimation of losses as function of seismic intensities due to the fact that even if losses for a specific intensity are small, for following intensities losses could increase until reach the total repair cost. The use of the Dirac Delta function concept allows to model this situation in a stochastic approach.

The maximum interstory drift employed as EPD to define the reparability limit value was computed based on the quantification of local damage that occurs in each one of the seismic intensities used in the definition of the IDA curves.

Defining in a proper manner all the local damage states will lead to more reliable results reflecting in a more realistic way probable damages in structures, furthermore, this local damage states may be used to define global damage levels having more control and understanding of the actual damage state of a structure. Assuming a linear relationship between losses and damage might lead to a conservative and unrealistic estimations of losses.

Finally, it is recommended to use experimental studies of structural elements, already carried out all around the world, to associate their performance with those local damages used in this study in order to get a better understanding and definition of them.

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8. Copyrights

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