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# SEISMIC EVALUATION OF REINFORCED CONCRETE BUILDINGS IN SAN SALVADOR, EL SALVADOR; CONSIDERING THE LATEST SEISMIC HAZARD ANALYSIS

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**ABSTRACT**

This investigation focuses on the seismic evaluation of low-midrise reinforced concrete buildings in San Salvador, considering the inelastic demand defined by the current seismic design code (NTDS-94). Moreover, the latest Probabilistic Seismic Hazard Assessment (PSHA) for the country, which will be the base for the new seismic code, was used. The implemented methodology was the Probabilistic Based Earthquake Engineering (PBEE) framework, which involves a holistic overview of the performance integrating hazard, structural, and damage analysis. Four simplified framed structures treated as a single degree of freedom systems were studied, two are based on El Salvador seismic standard, and the others are based on Japanese seismic provisions. The above with the intention to compare the influence of the hazard definition and the required capacity specified in each building code on the building's performance. Two approaches were employed to give a solution to the PBEE basic formulation; numerical integration and approximate analytical solution. We calculated the probabilities of limit state exceedance in 50 years in terms of inter-story drift ratios. Based on the results, the probabilities of exceeding the design limit drift imposed by El Salvador's seismic code of 0.015 rad are more than 5% for both Salvadoran SDOF systems (6-story and 10-story buildings) calculated using both approaches. We observed that El Salvador models have higher probabilities of exceeding safety limits than Japanese models. Hence, the influence of the seismic hazard curve and the seismic demand, which in the case of El Salvador depends on the response reduction factor R, was evident. The approximate solution derived more conservative results in the performance of the building models studied.

**Keywords:** PBEE, Reinforced Concrete building, Failure probability.

## 1. INTRODUCTION

El Salvador is located in Central America in a zone of high seismicity. The capital city San Salvador lately presents a tendency to develop vertical urbanization zones, for residential and commercial buildings, due to the lack of space for new horizontal constructions. Reinforced concrete predominates as a structural system preferred for mid-rise and high-rise buildings. In the 1986 earthquake, this construction system exhibited a deficient performance, causing the total collapse of many facilities, and several more were left badly damaged. The latest seismic code has not been updated since 1994. El Salvador's Ministry of Environment and Natural Resources (MARN) is developing technical materials

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that will be the primary inputs and guidance in creating the new seismic design code, including a more complete PSHA. The current seismic code focuses on life safety, leaving in a second perspective the damage control on the structure and the time and cost of rehabilitation. In other countries, however, the performance-based design approach is progressively being adopted. Recently, a second-generation and broader methodology has been developed by the Pacific Earthquake Research Institute (PEER). This methodology establishes the estimation of building performance from a thorough probabilistic overview. The results can be expressed in more tangible parameters (e.g., downtime, monetary losses, casualties, reparation cost) for the governmental authorities, stakeholders, and proprietaries of structures. From this perspective, it is a valuable tool for risk analysis and structural reliability assessment. Considering the above, the performance of San Salvador reinforced concrete buildings designed by the current seismic code against future earthquakes, which can be predicted by the most recent PSHA is still uncertain. The PBEE probabilistic-based method is a convenient alternative to evaluate the safety of structures, based on different limit states in a nondeterministic form. The current research addresses a probabilistic performance assessment for reinforced concrete buildings in San Salvador, following the provisions in the current seismic code. Moreover, we explicitly consider the seismic hazard defined by the latest PSHA.

## 2. METHODOLOGY

### 2.1. PEER Performance-Based Earthquake Engineering Methodology

The Pacific Earthquake Engineering Research Center has established a new and more robust methodology of performance-based earthquake engineering, which is based on four stages: 1) Hazard Analysis, 2) Structural Analysis, 3) Damage Analysis, and 4) Loss Analysis; each of them involves a different key parameter such as Intensity Measure (IM), Engineering Demand Parameter (EDP), Damage Measure (DM) and Decision variable (DV), and inherent uncertainties associated. The methodology can be described by Eq. (1), based on the integration of probabilities related to the stages mentioned above using the total probability theorem.

$$\lambda(DV) = \iiint G\langle DV|DM\rangle|dG\langle DM|EDP\rangle|dG\langle EDP|IM\rangle|d\lambda(IM) \qquad (1)$$

Where $\lambda(DV)$ is the mean annual frequencies of exceedance (MAF) for DV, $\lambda(IM)$ represents the mean annual frequencies of exceedance (MAF) for IM, and $dG\langle A|B\rangle$ means conditional probabilities for the components IM, EDP, DM, and DV, which can be represented by a complementary cumulative distribution function (CCDF).

The IM selected was Peak Ground Acceleration (PGA), the EDP inter-story drift ratio (IDR) and the DM was also selected in terms of design limits of IDR. The last stage, Decision variable is not considered in this research. Whit the above, Eq. (1) can be reduced as follows.

$$\lambda(DM) = \int G\langle DM|IDR\rangle|dG\langle IDR|PGA\rangle|d\lambda(PGA) \qquad (2)$$

### 2.2. Analytical approximation by Cornell formulation

Eq. (2) could be solved by the analytical approximation of three components: hazard, demand, and capacity. First, we assumed the approximation of the seismic hazard curve with Eq. (3).

$$\lambda(PGA) = \mathrm{k}_0(PGA)^{-k} \qquad (3)$$

Where $k_0$ and $k$ are coefficients from a regression analysis of the seismic hazard curve in logarithmic scale. Then, the demand defined in terms of the mean $\overline{IDR}$ can be predicted approximately by Eq. (4), which comes from the mean curve of a set of responses in the levels of PGA of interest.

$$\overline{IDR} = a(PGA)^b \qquad (4)$$

Where $a$ and $b$ are constants from regression analysis for the mean curve. Finally, the annual probability of performance level not being met or $\lambda(DM)$ could also be expressed as follows.

$$P_f = \lambda(DM) = \lambda(PGA^{DM}) \exp\left[\frac{1}{2}\frac{k^2}{b^2}\left(\beta^2_{(IDR|PGA)} + \beta^2_C\right)\right] \qquad (5)$$

$$PGA^{DM} = \left(\frac{DM}{a}\right)^{\frac{1}{b}} \qquad (6)$$

Where $\beta_{(IDR|PGA)}$ represent the dispersion of IDR, calculated as a standard deviation. and $\beta_c$ is the dispersion of the capacity ratios. The above expressions are found in multiple references. First proposed by (Cornell, 1996), and a similar approach is stated as an analytical formulation of seismic demand hazard in (Lu et al., 2012).

## 3. DATA

For the First step, hazard analysis, approximated seismic hazard curves for El Salvador and Japan were derived. The first one is based on the Seismic Hazard Map for PGA (g) of El Salvador; for a return period of 475 years, taken from the latest PSHA from (Mixco, 2021). For Japan, the seismic hazard curve approximation was taken from (NAGAE et al., 2006) and is based on (Architectural Institute of Japan, 2015). Both are compared in Figure 1(a).

We use Incremental Dynamic Analysis (IDA) (Vamvatsikos & Cornell, 2002) for the structural analysis phase. Four Model buildings were considered, a pair of six-story and ten-story facilities simplified as a single degree of freedom systems (SDOF) defined by El Salvador's seismic code and Japanese provisions. Specifically, the yielding strength coefficient $c_y$ was taken from the inelastic response spectrum of El Salvador, and for Japanese models, a constant value of 0.3 was considered. Takeda model was adopted (Takeda, 1970) to evaluate the nonlinear properties; the tri-linear capacity curves are shown in Figure 1(b).

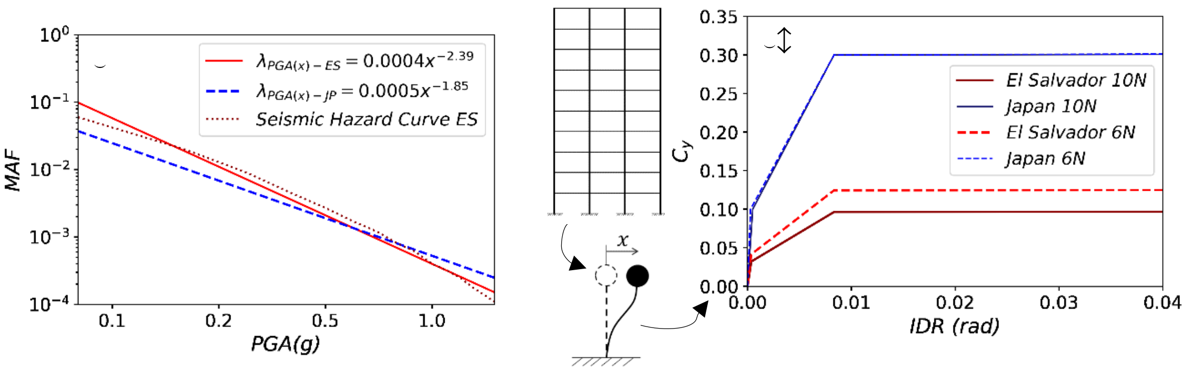


Figure 1. (a) Approximation of seismic hazard curves of El Salvador, Japan, and real hazard curve of El Salvador (MAF= Mean annual rate of exceedance). (b) SDOF model representation and Capacity curves.

Figure 2 shows the response spectrum of the selected waves for the analysis, corresponding to 40 Inland earthquakes recorded in site class D, with magnitudes from 6.5 to 6.9Mw and source-to-site distances from 13 to 40km (Medina & Krawinkler, 2004). In the damage analysis stage, we defined the ultimate deformation capacity fragility curve to evaluate safety limit states based on the research of (NAGAE et al., 2006), and (Architectural Institute of Japan, 2015) experimental results of calculated to ultimate deformation ratios. The median of the ratios was 1.41, and the equivalent dispersion 0.39.

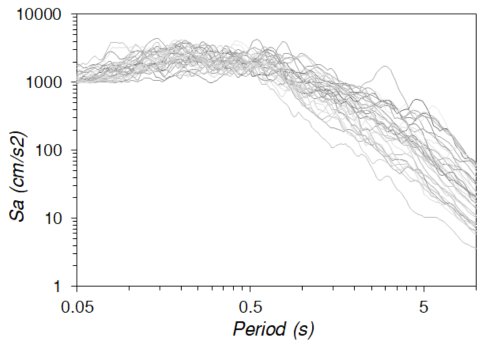


Figure 2. Acceleration response spectrum of the selected 40 Inland earthquakes scaled at $PGA = 1g$.

## 4. RESULTS AND DISCUSSION

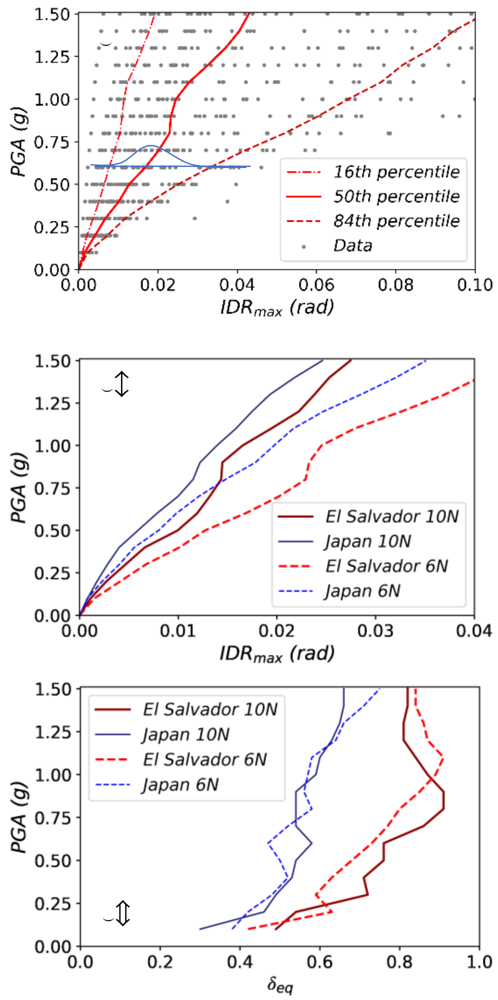


Figure 3. (a) 16th, 50th, and 84th percentiles of seismic responses for El Salvador 6-story building. (b) Median curve comparison. (c) Equivalent dispersion comparison.

Incremental dynamic analysis was performed to characterize the responses in different seismic intensity levels. The range of PGA applied varies from 0.1g to 1.5g. For each building, 600 points conformed the IDA curves. We applied counted statistics to the results to get the 16th, 50th and 84th percentile (see Figure 3(a)), then we made a comparison between the medians of all models (see Figure 3(b)) as well as the equivalent dispersion (Figure 3(c)).

A lower slope was identified in the median curves for Salvadoran building models, which means higher story drifts are achieved for the same level of PGA. This pattern is related to the structure's capacity. In the case of El Salvador, it mainly depends on the response reduction factor (R). Additionally, the equivalent dispersions were higher for Salvadoran models, disregarding the buildings' height.

Four safety limit drifts were studied, 0.01, 0.015, 0.02, and 0.03rad; the second one corresponds to the design limit drift indicated in the seismic code of El Salvador. Following the first approach, numerical integration, we calculated the hazard curve of IDR (figure 4 (a)). We then derived the mean annual rate of exceedance of the above limit drifts (figure 4(b)). Comparing the hazard curves of IDR, we observe that the displacement demand will be more significant for El Salvador building models. Additionally, as the slope of descending in Japan's curve is steeper, the mean annual exceedance rate decays more rapidly in higher drifts, contrary to El Salvador's 6-story and 10-story models. The return period, which is the inverse of the MAF of the established limit drifts, is lower for the SDOF system of El Salvador, implying that the limit drifts will be exceeded more frequently. Additionally, we applied the approximate procedure, obtaining the relationship of PGA and mean IDR from the results of IDA as shown in Figure 5(a), and with Eq. (5), we calculate the mean annual rate of exceedance of the safety limit drifts (Figure 5(b)).

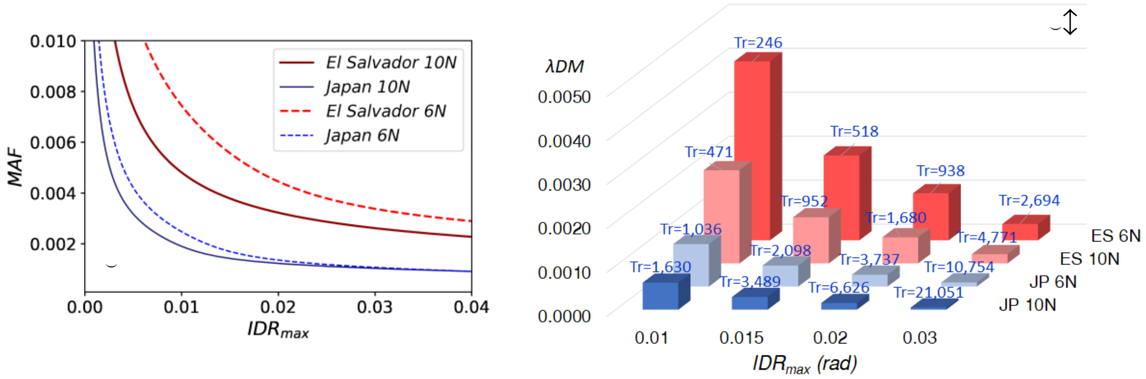


Figure 4. (a) Hazard curve of IDR for all buildings (b) Annual failure probability and return periods given limit states of 0.01, 0.015, 0.02, and 0.03, calculated with numerical integration.

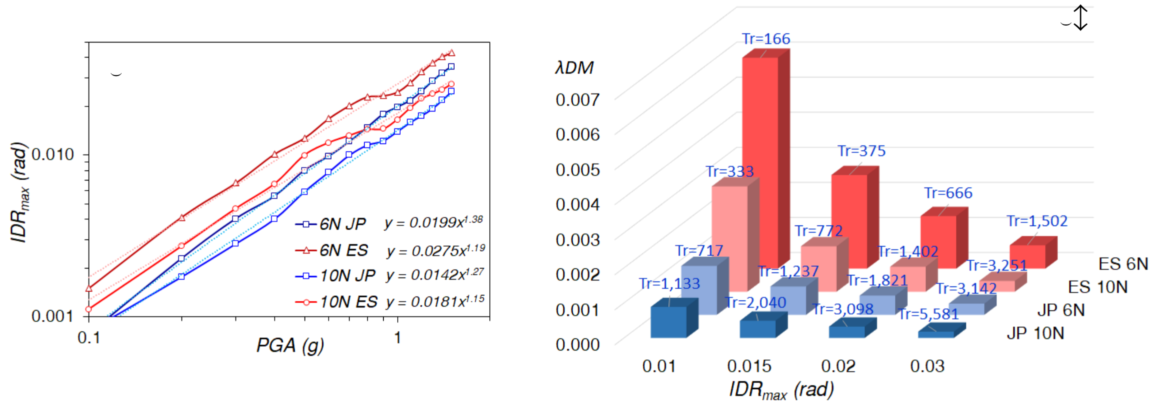


Figure 5. (a) Regression analysis on IDA results (b) Annual failure probability and return periods given for limit states of 0.01, 0.015, 0.02, and 0.03, calculated using Cornell formulation.

For a better representation, we transformed the MAF into probabilities of exceedance safety limit drifts in 50 years, assuming a poison process (Figure 6). Higher POE were obtained for El Salvador systems compared to those from Japan using both calculation approaches. From the results, and considering El Salvador's design allowable drift, the probabilities of the studied country-based structures not meeting this requirement are high (more than 5%). Nevertheless, considering the limit state defined by a drift of 0.03 rad, which could represent the onset of collapse, the probabilities are below 2%, except for the response of the 6-story building based on Cornell formulation. Comparing both methods, higher POE were found with the approximate solution, varying from 1.2 to 4.5 times the numerical integration results.

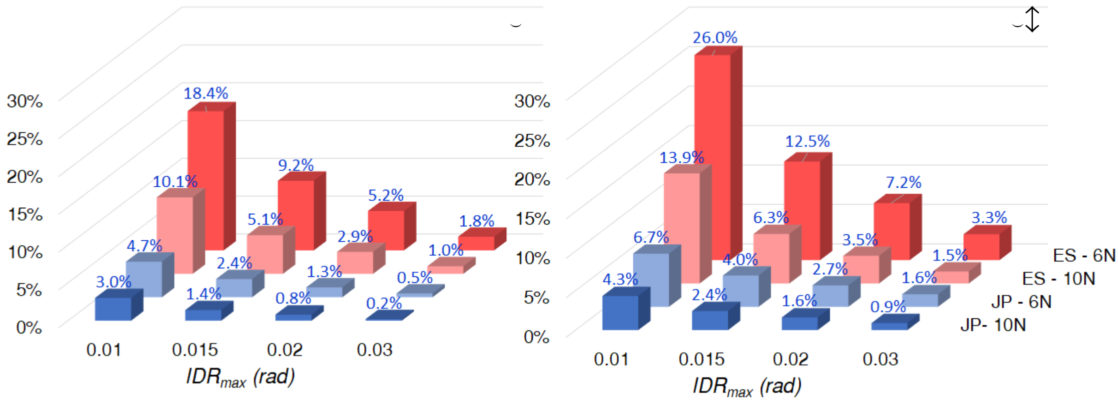


Figure 6. (a) probabilities of exceedance IDR in 50 years calculated using numerical integration (b) probabilities of exceedance IDR in 50 years calculated using Cornell formulation.

## 5. CONCLUSIONS

We used the latest study of seismic hazard in El Salvador and the current seismic code to define the building models' capacity for evaluating the performance of El Salvador buildings in a probabilistic approach. Moreover, Japanese building models were used considering the seismic hazard of Japan and the capacity specified in the codes to compare the seismic responses.

The probability of exceedance limit states was higher for El Salvador buildings considering the 40 Inland waves using both calculation approaches, numerical integration, and analytical solution.

The capacity of El Salvador buildings is directly related to the response modification factor R, which made the seismic coefficient small compared to Japan. Reconsideration in the definition of this factor is needed in the future seismic code to have more reliable buildings.

The results obtained using the approximate solution proposed by Cornell are more conservative. Nevertheless, this method is more practical and still reliable.

In this study, we applied the incremental dynamic analysis outcome to the Cornell method, specifically to obtain the mean IDR and the uncertainties. Another simplified approach, such as the capacity spectrum method, could be studied to reduce the calculation time and effort.

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