Fragility Analysis of Reinforced Concrete Buildings' Performance under a Suite of Earthquakes

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ABSTRACT

Current building design has a life-safety performance focus when it comes to responding to an emergency, code compliance does not lead to reoccupancy and functionality. Earthquake events in New Zealand and Japan have shown that including functional recovery in the design is key for improving the resilience of communities; that is, their ability to return to their everyday lives. Functional Recovery is a performance state less than original functionality, but sufficient for re-occupancy and temporary provision of lifeline services. This paper seeks to explore the performance of an archetypal 3-story reinforced concrete building designed following ACI 318 guidelines for reinforced concrete frames. The building is subjected to a vast library of earthquake motions recorded in California. Maximum inter-story drifts and maximum displacement at the top story are used as performance measures to determine the condition of the building. Based on these, 3 limit states are calculated: prompt occupancy, repairable loss of functionality and collapse risk. Fragility curves are constructed for the probability of exceeding the limits established by the code. The curves resulting from this study, in the form of exceedance probability against pseudo-acceleration spectrum, will serve to conduct trade studies between stiffness and deformation capacity based on the performance limits.

Keywords: Performance Based Engineering, Earthquakes, Drifts, Fragility Curves, Functional Recovery

INTRODUCTION

Building codes seek to ensure evacuation during earthquakes and other hazards; and even though preserving human lives is the main priority, this focus does not satisfy communities' needs after events. When looking at the current state of the built environment, (FEMA, 2018) noted that at least 20% of code compliant buildings in the US would be unfit to be reoccupied after a disaster. Moreover, at least another 15% would be economically unrepairable. The study carried out from 2012 to 2018 consisted of creating almost 2000 archetypes that would represent code-complying steel and reinforced concrete structures found in areas of high seismic risk. FEMA then used their PACT tool to simulate damages. It is worth noting that the tool is based on probability distributions and that results are not deterministic.

Another problem in the design process is the many assumptions that must be made when analyzing structures. (Papadopoulos & Fragiadakis, 2011) mention that traditional linear analysis is less robust than nonlinear analysis; however, nowadays the latter is being applied more often due to the increase of computational capacity and the adoption of performance-based criteria. The authors describe two different methods, one which is the Concentrated Plasticity Approach; also mentioned by (Haselton, Liel, Deierlein, Dean, & Chou, 2011). This method consists of assigning greater rigidity to the ends of beams and columns around joints. This is because structures will usually accumulate more stress in these areas, hence the non-linearity. Haselton et al. go on to describe the choice of 30 different archetypal buildings that will best represent reinforced concrete buildings in areas of high seismic activity in the United States. Their study seeks to simulate damages; namely, the collapse mechanism of code-complying structures and the probability of collapsing given a ground motion of certain magnitude. They found that non-linear analysis can and should be used to evaluate response to earthquake events.

The archetypal building on which the current study is based on takes characteristics from Haselton et al.: bay lengths, story heights, rotational and shear springs at joints, plastic rotation capacity, post-capping rotation capacity, maximum to yield moment ratio and a degradation parameter. The model is run on SAP2000, a widely used modelling software that allows users to design their structures and determine the analysis methods. Other lesser-known, research-focused tools developed by NHERI Sim Centre were explored, but were ruled out due to inefficiency.

The goal of the model is to output enough data for a statistical analysis that will produce fragility curves. As explained in (Krawlinker & Lignos, 2009), fragility curves are cumulative distribution functions that show a building's probability of damage. The curves have earthquake intensity on the *x*-axis, be

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it in some scale like Richter or Mercalli, or in the form of peak ground acceleration. When conditioned to some intensity, the curves will yield the probability that the building presents some damage. A scheme of the result can be seen in *Figure 1*.

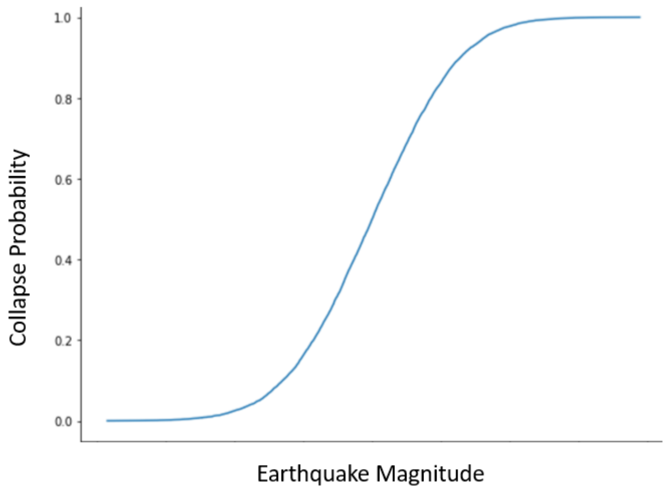

Figure 1. Typical Fragility Curve

Further into their paper, Krawlinker & Lignos define collapse capacity as *"the ground motion intensity at which the structure experiences dynamic instability*", where dynamic instability is the point at which drifts increase arbitrarily without an increase in the intensity of the ground motion. They go on to explain that enough data will allow to build the plot by statistically estimating the collapse capacity of every intensity and subsequently the cumulative probability of collapse.

All the aforementioned concepts will be the foundation for the current study and the procedure to get these curves will be thoroughly explained. The purpose of this study is to define three different performance states and produce fragility curves for re-ocuppancy, repairability and collapse risk.

METHOD

BUILDING THE ARCHETYPE

The archetypal building to be analysed is designed according to (Haselton, Liel, Deierlein, Dean, & Chou, 2011):

- Frame Material: Reinforced Concrete (4000psi)
- Bay Length: 6 metres
- Number of Bays: 3
- First Story Height: 4.6 metres
- Other Stories' Height: 4 metres
- Number of Stories: 3

The cross sections of beams and columns are shown in figures 2 and 3 respectively, these were designed to comply with ACI 318 and following the guidelines on (NIST, 2016). In the case of the SAP2000 model, hinges at the ends of beams and columns are used to simulate concentrated plasticity (Surana, n.d). An image of the setup can be seen in figure 4. Further assumptions include a rigid diaphragm and fixated nodes at the ground level.

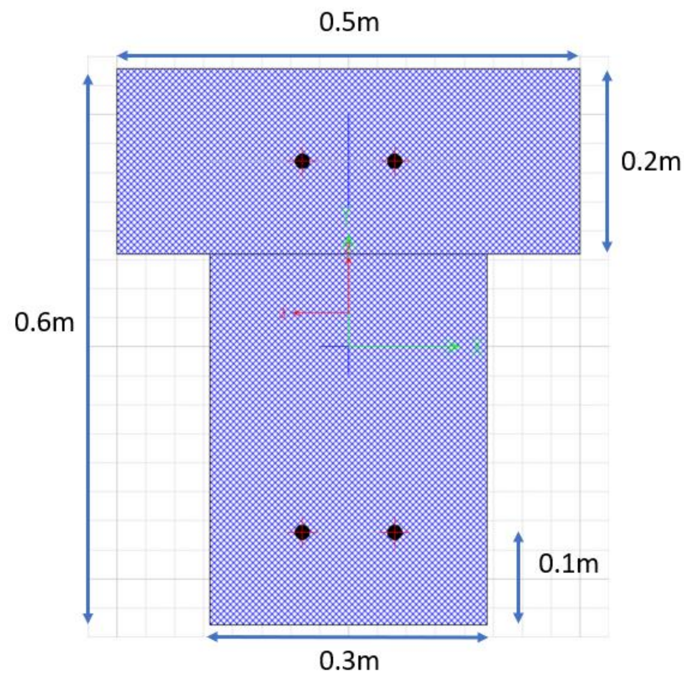

Figure 2. Cross Section of Beam

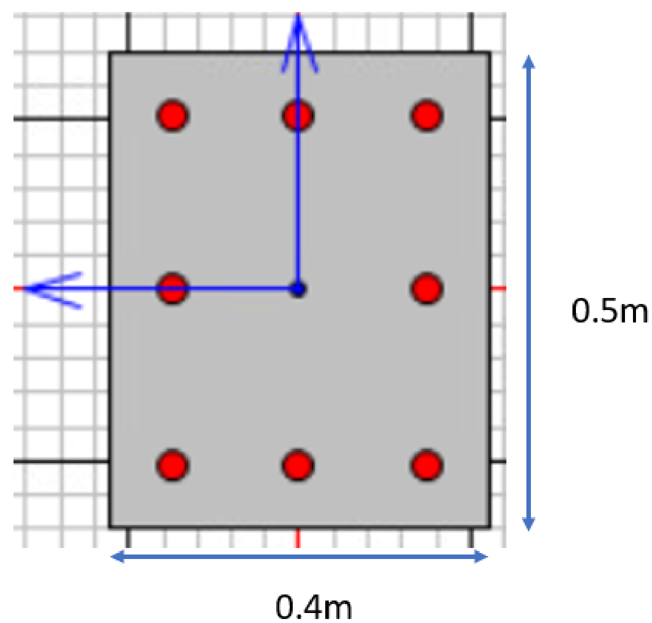

Figure 3. Cross Section of Column

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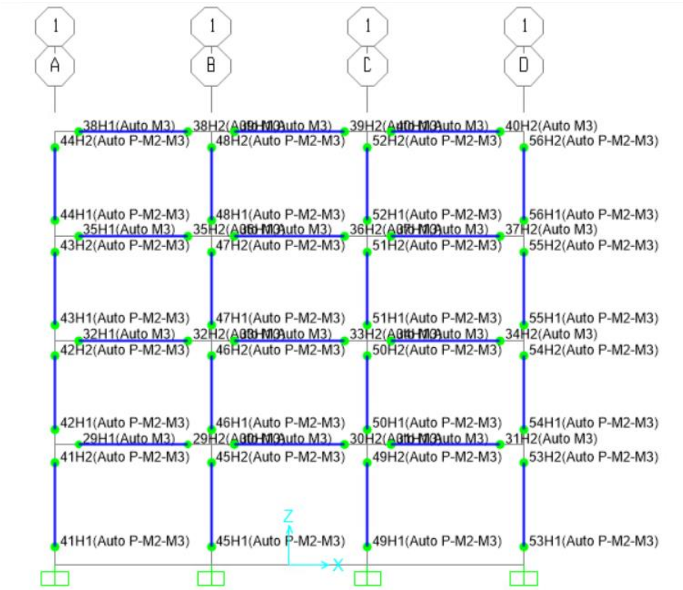

Figure 4. Complete Scheme of SAP2000 Model, labels are for every hinge placed

COMPUTATIONAL MODEL

To carry out the analysis, a sufficiently large earthquake library is necessary. A total of 60 files containing motions recorded in Los Angeles were obtained. The files describe an acceleration against time plot, the acceleration being in a single direction (horizontal). The files have varying durations and peak ground accelerations, that is to analyze all possible scenarios. A typical plot will look like Figure 5. The data must be cleaned of null entries and formatted correctly for SAP2000 to read it. Every ground motion can be amplified by a factor to increase or decrease its intensity.

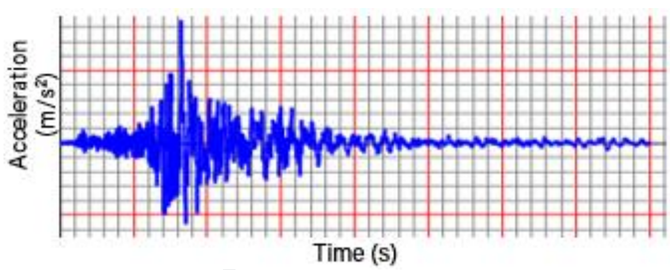

Figure 5. Typical Ground Motion Plot

A Time History Analysis is carried out on the platform to obtain the maximum displacement, be it left or rightwards, of the building's stories. This is a simulation of the building's motion when subjected to the accelerations of the earthquake; it considers its dead weight and nonlinearity. The software displays displacements at every point in time, allowing to always see the building's performance and not only at its most critical state. With this information, the inter-story drifts are calculated.

Inter-story drifts are the relative drift between a story and the one directly beneath it, given by the equation

$$\frac{\mathrm{D_n} - \mathrm{D_{n-1}}}{\mathrm{H_n}}$$

Where D_i represents the story of some drift and H_i is the height from a story to the one beneath it. Drifts serve as the performance measure used in this study. *"Interstory drift […] is an important engineering demand parameter and indicator of structural performance."* (Skolnik & Wallace, 2010). Its importance is also taken into account by the code: ASCE 7 determines a maximum allowable drift of 2% for this archetype (SkyCiv, 2021). Moreover, "for 0.5% residual drift, there is a negligible chance that the structure would need to be demolished. Re-alignment for residual drifts less than 0.5% is expected to be difficult and unnecessary" (Alameida et al., 2013). Taking that into account, the current study will judge the health of a building by the following parameters:

- H_1 (IDEAL): No drifts and up to 0.5%
- H_2 (REOCCUPIABLE): Drifts from 0.5% to 2%
- H_3 (DAMAGED): Drifts greater than 2%

These health states will be important for the mathematical analysis of the archetype, which is based on probability. It turns out that the way a building will react when faced with an earthquake is non-deterministic. First, the moment at which an earthquake occurs is random, and so are the ground accelerations at every point in time. Because of many factors like the live load at some moment, changes in built environment, and soil composition; at any point in time the building is different. Therefore, it is impossible to know beforehand how a building will perform.

MATHEMATICAL MODEL

A fragility function is defined as "a mathematical function that expresses the probability that some undesirable event occurs as a function of some measure of environmental excitation" (Potter, 2018). In the case of this study, it is a cumulative distribution function that expresses cumulative probability as a function of peak ground acceleration in gravities (g). When conditioned to a specific peak ground acceleration, this function yields the probability of presenting damage. This is particularly useful in building design as admissible boundaries can be determined; for example, that the probability of attaining certain damage after an earthquake with some peak ground acceleration doesn't exceed some percentage.

This study follows procedures from *A Beginners Guide to Fragility, Vulnerability, and Risk* and from *Creating Fragility Functions for Performance-Based Earthquake Engineering*, both by Keith Potter. The author explains a variety of methods and the most suitable must be selected. This study seeks to make three fragility curves: from the ideal state to the two other states, and from the reoccupiable state to the damaged state.

The computational model was run for 60 sample earthquakes with peak ground accelerations ranging from 0.1g to 1.3g. Although it was possible, the results obtained from

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SAP2000 did not record the actual ground acceleration at which the maximum drift happened; so Potter's method B was more suitable. This method is suggested for data that is bounded: at least one run did not fail (attain the damage being studied), at least one did, and peak excitations are known for all the runs. This method suggests that a lognormal distribution is set to be made from the values, and that the median and logarithmic standard deviation values must be optimized to make them the most likely to produce the data. In other words, since it is known that the distribution should be lognormal, solve for the median and logarithmic standard deviation. Again, the probability of a specimen failing is given by the lognormal distribution; namely by:

$$p_i = \Phi\left(\frac{ln(r_i/\theta)}{\beta}\right)$$

Where Φ is the normal cumulative distribution function, r_i is the excitation level, θ is the median and β is the logarithmic standard deviation. From there, specimens are grouped by their peak ground acceleration; within those groups each specimen either fails or doesn't, yielding a binomial distribution. The product of all binomial distributions, where p_i is the probability for every peak ground acceleration i gives the likelihood; the values for θ and β that maximize this are the ones that will be taken.

Computing these values on a Python solver was not straightforward as the method had difficulties converging; however, after going through several educated guesses of initial values, the values for the fragility curves that denote the probability of going from H_1 to H_2 (Curve 1) and from H_1 to H_3 (Curve 2) were obtained:

- Curve 1: $\theta = 0.44791569$,
  $\beta = 0.31070075$

- Curve 2: $\theta = 1.50545199$,
  $\beta = 0.32777167$

Obtaining values for the other curve (from H_2 to H_3) demanded a different procedure. SAP2000 runs all models from their initial, undamaged state. It is possible to set initial story displacements, but it wasn't accurate since starting at preset values would be opposite to the non-deterministic nature of story displacement. In that case, it was deemed more valuable to analyze the entire time history of the runs that reached the damaged state (which were only 2 of the 60). The runs were divided into equally large time slots and every timeslot served as a specimen. The focus was on the timeslots that transitioned from H_2 to H_3. Naturally, this procedure has an inherent limitation: by dividing into timesteps, the influence of events in past timeslots is disregarded and that is not necessarily true. Moreover, the data was no longer fit to be used for method B as there were only two different ground accelerations and very few failed. Instead, Potter's method C was deemed more suitable (Potter, 2007). In this case, few data are input in empirically found equations, and with the aid of tables and the assumption that $\beta = 0.4$, the value of θ is determined, giving:

- Curve 3: $\theta = 1.4$,
  $\beta = 0.4$

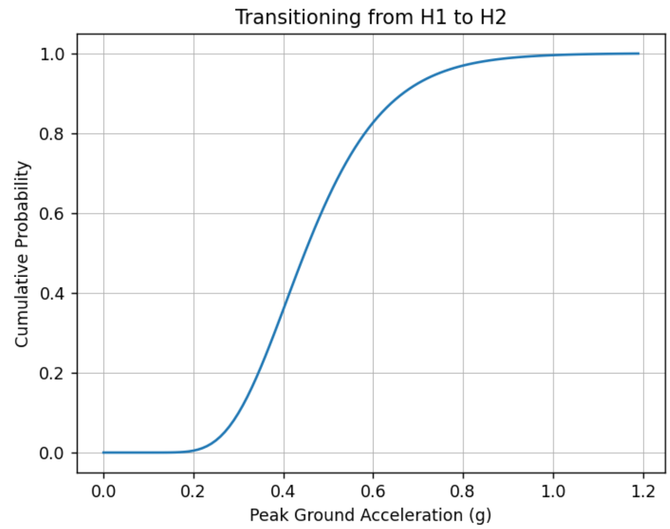

Figure 6. Fragility Curve 1

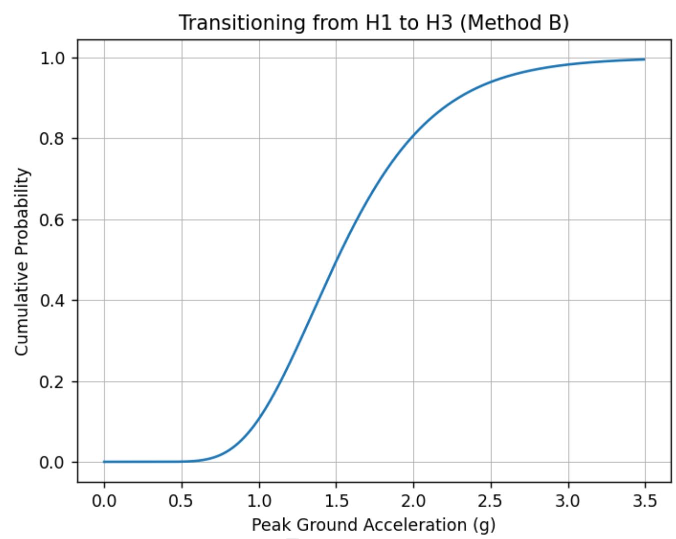

Figure 7. Fragility Curve 2

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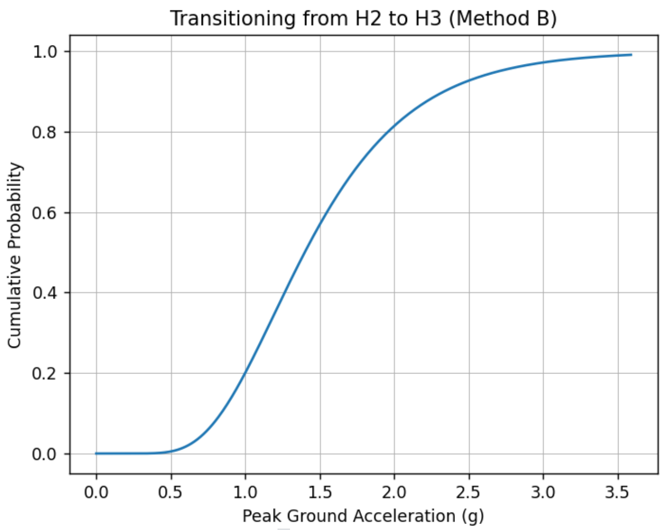

Figure 8. Fragility Curve 3

The curves look similar at first sight, but the scale on the horizontal axis is different. One final step is necessary. These curves are fed into a Python program that runs Poisson Processes. A Poisson Process is a mathematical model in which events with a known average rate of occurrence happen with their time of occurrence being Poisson Distributed. It is well known that earthquakes are one of such events, and the average rate of occurrence was easily determined with the USGS database for earthquakes near Los Angeles in the last 120 years. The program will have earthquakes of different peak intensities occurring at random moments, and using the Fragility Curves, will determine the state of the building after every earthquake.

The model seeks to find the time in years that it takes to go to H_2 and subsequently to H_3, assuming that no repair will be carried out. For that, it is necessary to determine the likelihood of going into a different health state after some ground motion; that calls for a transition matrix, where the probability of going from H_i to H_k is given by the matrix's element in the *i*th row and *k*th column. These matrices must be defined for every possible earthquake.

On a building that hasn't yet been affected, given an earthquake of some intensity, there are 3 options: the building stays in its optimal state, it presents drifts between 0.5% and 2% or it presents drifts that exceed 2%. Fragility Curves are functions that have peak ground acceleration as an input and output the probability of presenting some damage, they can be called $f_i(PGA)$ for the three curves. Since buildings that exceed 2% drifts also had to go through drifts between 0.5 and 2% it is correct to assume that the probability of going from H_1 to H_2 and not going over to H_3 is $f_1(PGA) - f_2(PGA)$. The probability of staying in the ideal state would then be

$$1 - [f_1(PGA) - f_2(PGA)] - f_2(PGA) = 1 - f_1(PGA)$$

For the second row of the transition matrix, going back to H_1 is not possible, so that probability is zero. The other entries are given by $1 - f_{3(PGA)}$ and its complement. The final row has two zero entries and 1 as the third, since at H_3 the building can only stay there. The matrix serves as a weighted dice to determine whether the health state changes or not.

RESULTS

ADVANTAGES AND LIMITATIONS

The SAP2000 model was computationally efficient and easy to develop; however, it had certain restrictions to the number of parameters that could be user defined. At first that seemed like a limitation; but following the code in the design of the archetype makes it very likely that parameters which were not user defined still worked for the analysis since they should be very similar to those suggested in the literature.

The sample of 60 earthquakes seems to be statistically significant: the data contain samples of 13 different intensities and the variability in the maximum drifts suggest that the files were not similar among themselves.

The way the data was gathered was also limiting because the complete time-history was not obtained for all samples; nonetheless, Potter's method B was not affected by this. The time history did serve useful in the construction of Curve 3, but assumptions had to be made (see Mathematical Model). Ideally, a longer timeframe for research could allow the investigator to manually change the displacements of the building to match those of a handful of earthquakes and run the same procedure on those damaged buildings.

The Fragility Curves had expected shapes; for example, having Curve 1 reach its peak at 1.1g is consistent with empirical knowledge. Another piece of information that increases the validity is that Curve 3 is always greater of equal than Curve 2, which supports the assumption that the probability of going from H_1 to H_2 is $f_1(PGA) - f_2(PGA)$. To bear in mind is the fact that the optimization process had to handle very complicated equations and the non-convergence at the beginning suggests that there could be better results.

The Poisson Process gives very valuable date as it could be run very efficiently. Over 10,000 simulations suggest very sturdy results, even more if the assumptions also have good validity. Future investigators could include reparations at certain points in time that change the state back to a better one.

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Time to exceed 0.5% Drift (yrs)	0.58647
Time to exceed 2% Drift (yrs)	17.1464
Intensity that induces failure (g)	0.86844

Table 1. Poisson Process Output

DISCUSSION

This statistically robust study shows that the time for some damage to happen is short; only seven months. Moreover, without taking any repair measures the building will be exceeding code drifts in 17 years. Given the lifetime of a building, these values are concerning. The study is suggesting that the code guidelines need improvements aimed at the goal of repair/retrofit for future events.

The methodology is deemed useful because having the ability to simulate buildings' behaviour is very powerful, as data on seismic performance cannot be obtained daily. It also offers a more cost-effective alternative than building frames and testing them; if it is even possible due to size of the buildings.

The methodology could aid authorities in determining which building needs inspection and repair more promptly; it also serves as an indicator of the buildings that can be used as shelter after a disaster and those that can't.

CONCLUSIONS

Recent events worldwide have shown societies the importance of being able to retake everyday life as soon as possible. Current code standards do ensure evacuation from buildings, as these are not due to immediately collapse with any of the tested ground motions. However, buildings do sustain damage after earthquakes that have return periods of less than 100 years. The fact that buildings are not in an ideal state after 7 months is a very worrying figure. This code presents a methodology that easily and quickly produces results that can aid in decision making at the moment of focusing efforts on one place or another.

This study strongly suggests the use of a stochastic performance criteria; for example, the probability of transitioning to H_2 should not exceed certain value when an earthquake of some intensity happens. Finally, the study - while it requires further development- illustrates an available and simple tool to evaluate resilience and work towards the goal of a safer and more resilient built environment

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