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Earthquake Induced Damage Estimation In Steel Buildings

Gustavo Cortés-Areizaga, Eng.
Graduate Research Asssistant, University of Puerto Rico, Mayagüez, PR, USA, gcortes.dde@gmail.com

Ricardo López-Rodríguez, PhD
Professor, University of Puerto Rico, Mayagüez, PR, USA, rilopez@uprm.edu

Ali Saffar, PhD
Professor, University of Puerto Rico, Mayagüez, PR, USA, asaffar@uprm.edu

Abstract
This work presents a method for estimating the expected damage caused by an earthquake on steel buildings in Puerto Rico. Since Puerto Rico is located between a series of tectonic faults, buildings could suffer the damages caused by a major earthquake. The objective of this research is to develop the information needed for insurance companies to estimate the earthquake damage of steel buildings in a simple and practical way. Steel buildings typically found in Puerto Rico have been analyzed, considering their response to many acceleration time histories and the statistical data recorded. With this data, curves which indicate the probability of a certain damage to occur, were created. A cost per square foot has been assigned to each damage state; this cost is then multiplied by the probability of damage for each damage state and the final cost for the total damage is obtained.

Keywords
Earthquake, Damage Estimation, Steel Buildings, Non-linear Dynamic Analysis, Fragility Curves

1. Introduction

Puerto Rico is bounded by many faults; the two principal faults are the Great Northern Puerto Rico Fault Zone and the Great Southern Puerto Rico Fault Zone. Throughout our history, many earthquakes have affected Puerto Rico in the past. The purpose of this research is to estimate the structural damages a given building will suffer due to an earthquake. The building will be subjected to economical losses caused by different events and situations. These may include losses by: damaged contents, removing debris, business interruption, renting alternative space, and moving to a new location, as a few examples. It is also possible that many other disasters following the earthquake may occur, including land sliding, tsunamis, and flooding, as the most common disasters after an earthquake. All those possible disasters following an earthquake will generate additional damage to the structures, sometimes even worse than the ones caused by the earthquake itself.

On the other hand, economic losses caused by earthquakes to the structural elements (force resisting elements) and to the non-structural elements are usually called direct losses; while other losses like those mentioned before are called indirect losses. The emphasis of this paper is given on calculating the direct losses to the structural elements of steel buildings.

2. Methodology

The methodology necessary to create the fragility curves and to link these fragility curves to monetary losses is presented in this paper.

Different building categories must be considered in order to take into account different structural behaviors. A first division was made depending on the buildings' occupancy. This is important because the code's requirements depend on the building occupancy. The categories in this division are: Commercial & Offices Buildings, Industrial Buildings, and Storage Buildings. Having in mind that buildings behave different depending on its height, a second division based on the number of stories was considered. The categories for the second subdivision are: buildings of three or less stories (low-rise buildings), buildings having four to seven stories (mid-rise buildings), and buildings having eight or more stories (high-rise buildings).

The most important step in order to estimate the damage induced to the buildings is to create a mathematical model of the different buildings, and to analyze them. This was done with the help of the computer software Ram Performance 2D. Once the building is modeled, a nonlinear dynamic analysis is performed, and the building's response parameters are found.

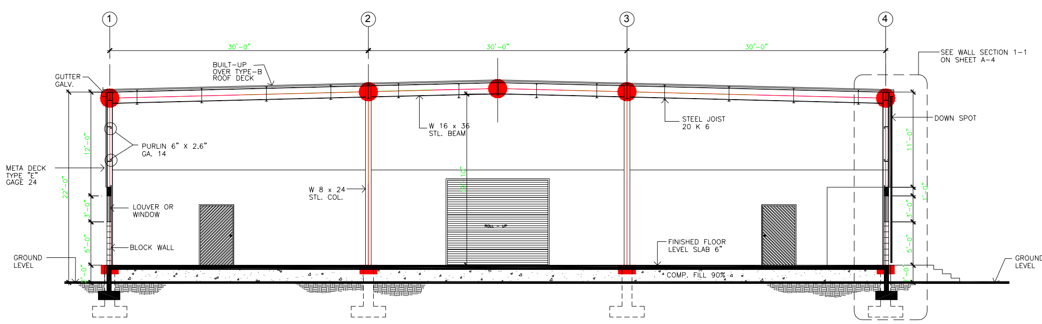

Figure 1: Industrial Building As Taken From Designers Plans

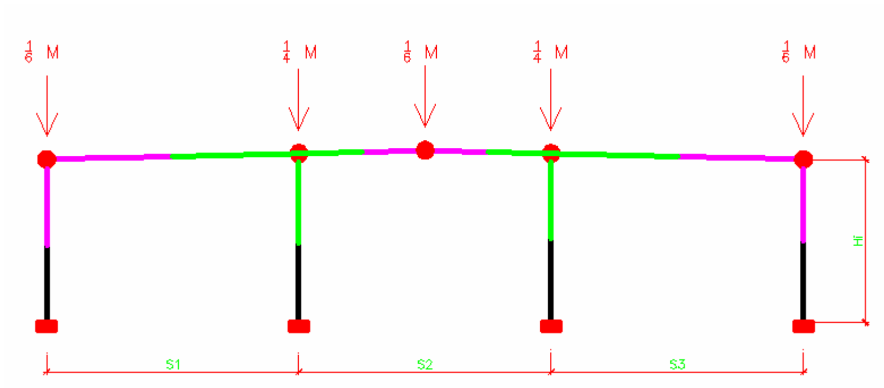

Figure 2: Model Idealization for the Industrial Building shown in Figure 1.

Five earthquake records were used as ground motions. Records from past earthquakes that occurred in San Salvador, California, and two artificial earthquakes (Irizarry 1999) created for Puerto Rico were used. Figure 1 presents the acceleration record for the artificial earthquake expected in Mayagüez.

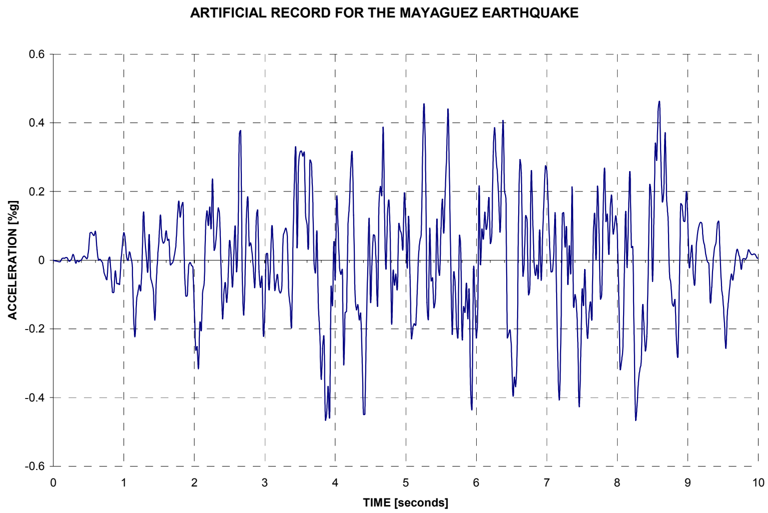

Figure 3: Artificial Record for the Mayagüez Earthquake

From the ground motion records applied to the structure, the peak inter-story drift (δ_i) is found and used as the response parameter. Inter-story drift has been selected as the response parameter because it is an excellent parameter for judging the ability of a structure to resist P-Δ instability and collapse. Inter-story drift is also closely related to plastic rotation demand, or drift angle demand, on individual beam-column connection assemblies, and is therefore a good predictor of the performance of beams, columns and connections. The peak inter-story drift represents the maximum displacement of one floor relative to any adjacent floor divided by the story height.

2.1 Damage State Definition

Although damage occurs as a continuous function, intervals are made so that a procedure can be followed. Table 1 presents the damage states used, and its values. It has been taken from reference FEMA-351.

Table 1: Damage States

Damage State (DS)	Inter-story drift (δ)
Slight Damage (SD)	≥ 0.010
Moderate Damage (MD)	≥ 0.015
Extensive Damage (ED)	≥ 0.025
Complete Damage (CD)	≥ 0.040

Once the maximum inter-story drift values are obtained, each value is classified in one of the damage state categories.

2.2 Fragility Curves Generation

Having identified each of the inter-story drifts in one of the damage states allows counting the number of occurrence for each damage state for a certain building. Ninety one (91) buildings were analyzed, each of them subjected to the five earthquakes aforementioned. Each of the five earthquakes was scaled from 0.1g to 1.0g, with intervals of 0.1g, resulting in a total of 10 records for each earthquake, or 50 records total. Figure 4 shows the frequency distribution obtained for the entire population of buildings plotted for each of the PGA values.

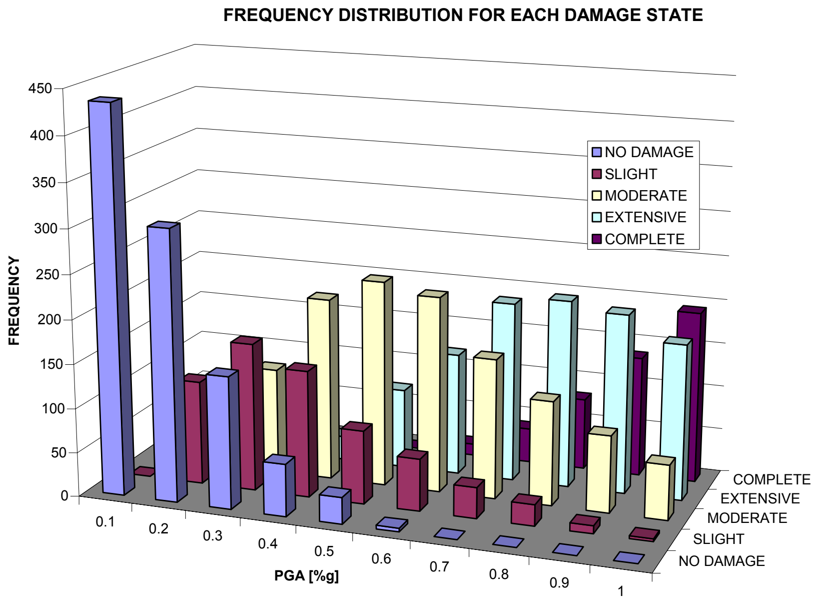

Figure 4: Frequency Distribution for All Damage States.

Fragility curves give the probability of being in or exceeding a certain damage state. The fragility curves were created in the form of a two parameter log normal cumulative distribution. The lognormal distribution has a probability density function:

$$f(x \mid \mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\left(\frac{(Ln(x)-\mu)^2}{2\sigma^2}\right)} \qquad \textbf{(1)}$$

Where:

x = is the value at which you evaluate the function
μ = is the mean value of the PGA and,
σ = is the log-standard deviation of the drift values.

The cumulative lognormal distribution is obtained by integration of the area below the density function; it is shown in Equation 2. After implementing Equation 2 to each of the four damage states to all buildings analyzed the fragility curves shown in Figure 5 are obtained.

$$f(x \mid \mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^x \frac{e^{-\left(\frac{(Ln(x)-\mu)^2}{2\sigma^2}\right)}}{t} dt \qquad \textbf{(2)}$$

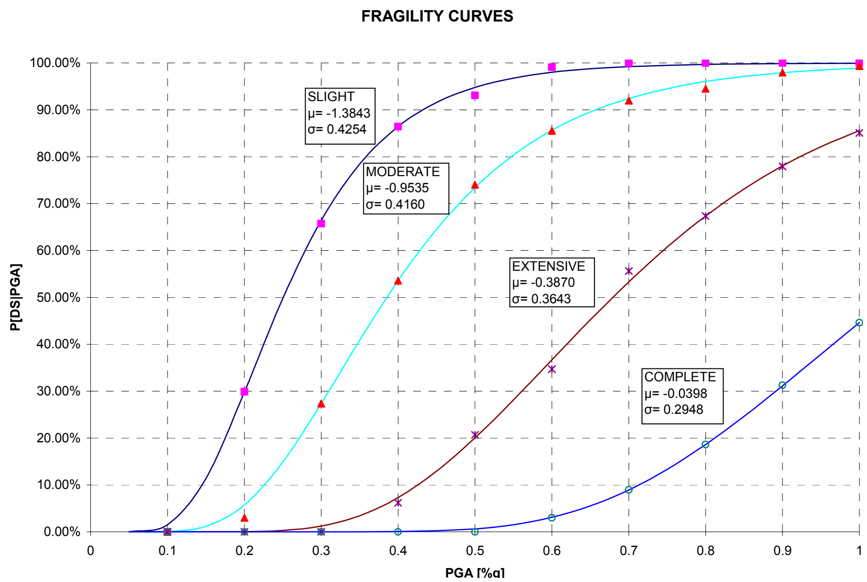

Figure 5: Fragility Curves for all buildings analyzed.

2.3 Simplified Method

This method pretends to estimate the expected damage on a building in a simple way. It can be used to get an initial descriptive estimate of how much damage is expected. The idea of the method is that a linear regression can be plotted for the maximum drift vs. PGA ordinates of the average taken from all model variations for each building type.

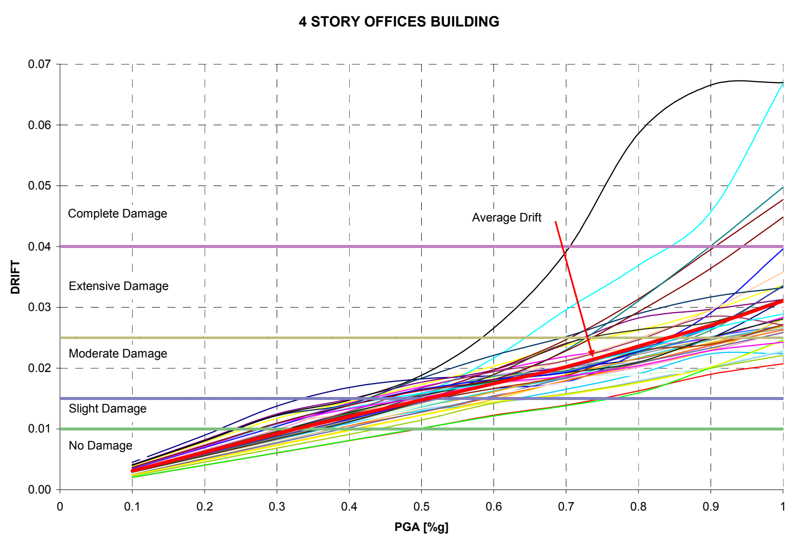

Figure 6: Drift vs. PGA for the 12 models

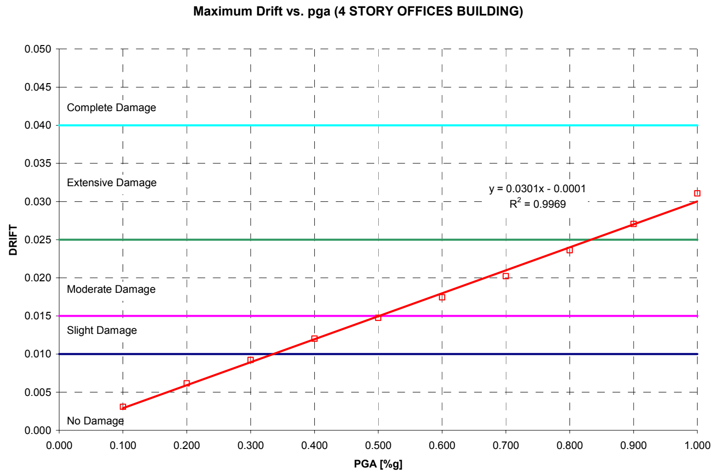

Figure 7: Linear Regression

From the linear regression the equation of the line is:

$$Drift = 0.0301(pga) - 0.0001 \quad \textbf{(3)}$$

If we have a four stories building located in a place where the expected PGA value is 0.6g we would get,

$$Drift = 0.0301(0.6) - 0.0001 = 0.01796 \quad \textbf{(4)}$$

According to the damage states previously defined in Table 1, a drift value of 0.01796 would cause moderate damage to the building. If the analyzed building used Pre-Northridge connections, this amount of drift would cause that as many as 25% of the connections on any floor level experience fracture. If Post-Northridge connections were used in the building, only moderate amounts of yielding and distortion of some column panel zones and minor buckling of some girders is expected (FEMA-351 2000).

2.4 Loss Functions

Loss Functions are needed to estimate the economic loss. The damage probability of each damage state is multiplied by a relative cost assigned to each one. FEMA-351 defines the structural cost for steel buildings as 20% of the total cost. The relative cost of each damage state depends on the connection used in the building. If a Pre-Northridge connection was used, the costs are much higher. When a Post-Northridge connection is used, the repair cost of slight damage is assumed to be zero on the basis that any incidental damage under this category will not be required to be repaired. For the Moderate and Extensive structural damage the cost of repair is assumed to be 10% and 50% of the structural cost respectively. A 100% of the structural cost will be assumed for the complete structural damage state. Table 2 shows the assigned cost for each damage state for buildings having Pre-Northridge connections. The structural estimated cost per square foot is taken as \$25.00 (\$25.00/ft^2).

Table 2: Pre-Northridge Connections %Cost

	Structural Damage State			
Damage State	Slight	Moderate	Extensive	Complete
Mean Loss Ratio	8%	20%	80%	100%
Mean Loss Rate [$/SF]	$ 2.00	$ 5.00	$ 20.00	$ 25.00

2.5 Loss Functions Estimation from Charts

Charts that indicate the amount of monetary damage are created to simplify the estimation of damages (Figure 8).

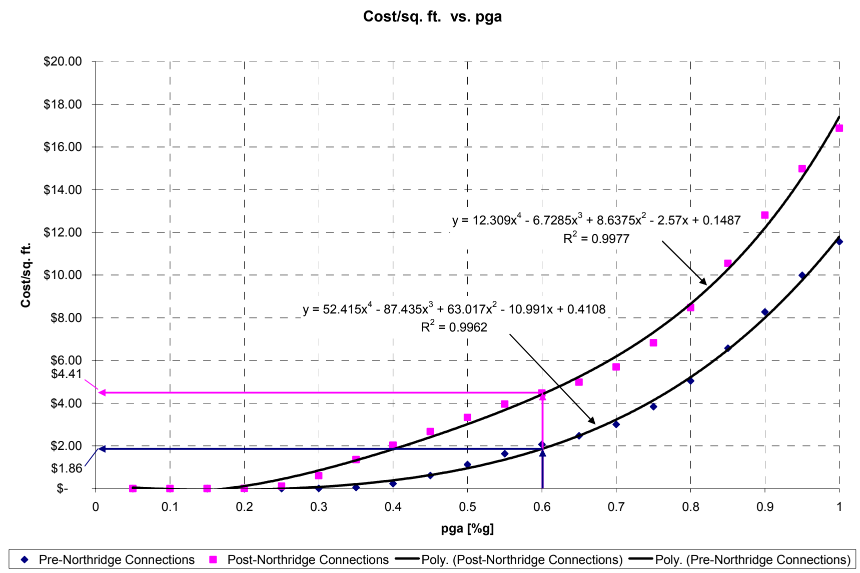

Figure 8: Graph of the cost/sq. ft. vs. PGA

The data obtained for each pair of ordinates has been plotted in Figure 8, a polynomial distribution of fourth degree has been fitted to the data. A polynomial distribution of fourth degree results in a good approximation of the plotted data, for the Pre-Northridge condition the equation is as follows:

$$Cost / Area = 12.30(pga)^4 - 6.7285(pga)^3 + 8.6375(pga)^2 - 2.57(pga) + 0.1487 \qquad \textbf{(5)}$$

For the Post-Northridge condition the equation is:

$$Cost / Area = 52.415(pga)^4 - 87.435(pga)^3 + 63.017(pga)^2 - 10.991(pga) + 0.4108 \qquad \textbf{(6)}$$

For a PGA value of 0.6g, a $2.06 cost per square feet is obtained for the Post-Northridge condition. For the Pre-Northridge condition the cost per square feet is $4.48. In the same manner, using the fourth degree polynomial fit approximation, equations 5 and 6, the values obtained are:

$$Cost / Area = 12.30(0.6)^4 - 6.7285(0.6)^3 + 8.6375(0.6)^2 - 2.57(0.6) + 0.1487 = \$4.41 / ft^2 \qquad \textbf{(7)}$$

Now, assuming the same four stories building used in Section 2.3, the structural replacement cost can be estimated by multiplying this cost per square feet by the buildings area,

$$Cost = \$4.41 / ft^2 (70{,}000 ft^2) = \$308{,}700.00 \qquad \textbf{(8)}$$

In a similar way, for the Post-Northridge condition,

$$Cost / Area = 52.415(0.6)^4 - 87.435(0.6)^3 + 63.017(0.6)^2 - 10.991(0.6) + 0.4108$$
$$Cost / Area = \$1.86 / ft^2 \quad \textbf{(3)}$$
$$Cost = \$1.86 / ft^2 (70{,}000 ft^2) = \$130{,}200.00 \quad \textbf{(4)}$$

A percent error of 0.23% and 5.7 % is obtained for the Pre-Northridge condition and Post-Northridge condition respectively.

3. Conclusions

This paper presented a method for estimating damages in steel buildings in Puerto Rico. A non-linear dynamic analysis was performed to the 91 models analyzed. Once the nonlinear analysis was performed, the maximum inter-story drift was obtained for each of the earthquake records. With this, analytical fragility curves that describe the probability of damage to the buildings were created.

Fragility curves were created for steel buildings depending (1) on its occupancy, and (2) on the number of stories. Three occupancy classes were considered: offices and commercial buildings, storage buildings and industrial buildings. A fragility curve was created for each of these occupancies. Also, three categories were used for the fragility curves depending on the number of stories: low-rise buildings, mid-rise buildings and high-rise buildings. Finally, a general curve which includes the statistics of all buildings was created. This general curve can give us an idea of the general behavior of steel buildings in Puerto Rico. Furthermore, it can be used to compare the general behaviors of buildings made with different materials.

A simplified method was proposed as a qualitative way of describing the damage. This method serves to get an initial idea of what is the expected damage by using a very simple linear equation. From this linear equation the average maximum drift median value is obtained and classified among the damage states.

Having in mind that the final desired output is to obtain the monetary losses a certain building will suffer should an earthquake occur, plots that relate the cost per square foot of area with the peak ground acceleration [%g] were created. This plots allows to very easily estimate the monetary damage in any steel building subjected to an earthquake with known intensity (PGA). In order to estimate the monetary losses, it is essential to know the cost of the building and what portion of the total building's cost corresponds to the structure. Therefore, the generated plots can be easily changed to consider the specific cost of the building.

From the created fragility curves, the most significant conclusions are summarized below:

- Storage buildings are the most vulnerable, followed by the Industrial buildings and finally by the Commercial buildings.
- An earthquake of 0.1g would not cause damage
- Up to 0.5g the complete damage scenario does not occurs
- Low-Rise buildings are the most vulnerable, followed by High-Rise buildings and by Mid-Rise buildings.

4. Recommendations for Future Work

After reviewing the plans of many steel buildings, it was observed that it is very common to use shear walls in mid-rise and high-rise steel buildings in Puerto Rico. Most of the time when this happens, the shear walls are designed to resists most, if not all, of the earthquake induced forces. This type of mixed buildings was not considered in this research investigation, it will be of much interest since the expected behavior of such combined buildings should be very different to those studied here.

The response parameter used in this thesis was the inter-story drift. The maximum inter-story drift for the building subjected to an intensity x was recorded for each acceleration. However, the analyzed building could reach a maximum drift in a particular story while some other stories do not reach such a high drift. Having in mind that the drift value varies for each story, it will be very interesting to study the building story by story, taking the inter-story drift of every story into account, not only the maximum value.

The fragility curves in this research were calculated using analytical models. It will be helpful to do some experimental work. The beam to column connections could be studied and the rotations causing certain damage could be verified.

If an earthquake occurs, it would bring valuable data that would help in the validation of the analytical models. If such event occurs, it would be very important to conduct a survey and gather the hazard information. With this information, the hazards data could be combined with the existing analytical data using Bayesian methods available.

Acknowledgement

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