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DEVELOPMENT OF FRAGILITY CURVES FOR MEDIUM RISE REINFORCED CONCRETE SHEAR WALL RESIDENTIAL BUILDINGS IN PUERTO RICO.

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Keywords: Fragility Curves, Concrete Shear Wall Structures, Residential Building, Insurance Companies.

Abstract. Puerto Rico is situated in an earthquake prone region. Because of the imminent risk of being affected by a strong earthquake, it is important to study the damage vulnerability of existing structures in the Island. This study is directed to medium rise concrete residential buildings in Puerto Rico. Most of multistory residential buildings in Puerto Rico are reinforced concrete structures with lateral resisting system composed by shear walls oriented in both directions. The lack of local earthquake vulnerability curves for Puerto Rico and the fact that local construction practice differs from that in USA motivates the author to look at the development of reliable fragilities curves based on typical buildings properties and selection of ground motions based on local geology characteristics and past worldwide earthquakes scaled to different peak ground acceleration to obtain a wide range of maximum accelerations. The analytical models are two-dimensional and are analyzed using the nonlinear dynamic time history method considering both flexural and shear nonlinear behavior for shear walls. Algan's formulation (1982) and HAZUS drift limits were used to calculate the expected damage of the models. Damage of the structures is quantified based on the inter-story drift ratio of the structure. The damage states considered were: Minor, Moderate, Substantial and Major, for Algan and Slight, Moderate, Extensive and Complete for Hazus. With this information, lognormal functions expressed in the form of two parameters (log-median and log-standard deviation) were fitted and fragility curves developed as a function of PGA. A set of four fragility curves, one for each damage state is developed for each scenario studied. These curves are useful tools for the insurance companies in Puerto Rico in order to improve their risk assessments.

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1 INTRODUCTION

Puerto Rico is situated in an earthquake prone region, lying within a seismic active zone that presents a wide variety of seismic fault zones. It is located in the northeastern margin of the Caribbean Plate where it collides with the North American Plate while moving eastward with respect to the North American Plate (Irizarry 1999). It has been 89 years since the last major earthquake hit the island in 1918. The last strong earthquake felt in Puerto Rico occurred in August 4, 1946 to the northeast of the Dominican Republic having a surface magnitude of 7.8 (Irizarry 1999). According to official data, one hundred and sixteen people died in the 1918 event, while the economic loss was calculated at four million dollars, two times the annual budget for the whole island at the time.

Most of multistory residential buildings in Puerto Rico are reinforced concrete structures with lateral resisting system composed by shear walls oriented in both directions. Because of the imminent risk of being affected by a strong earthquake, it is important to study the behavior and damage vulnerability of these structures. This is of particular importance to the insurance companies in Puerto Rico in order to improve their risk assessments.

The lack of local earthquake vulnerability curves for Puerto Rico and the fact that construction practice for residential building in Puerto Rico differs from that in USA motivates the author to look at the development of reliable analytical fragility curves based on typical buildings properties and selection of ground motions based on local geology characteristics and past worldwide earthquakes.

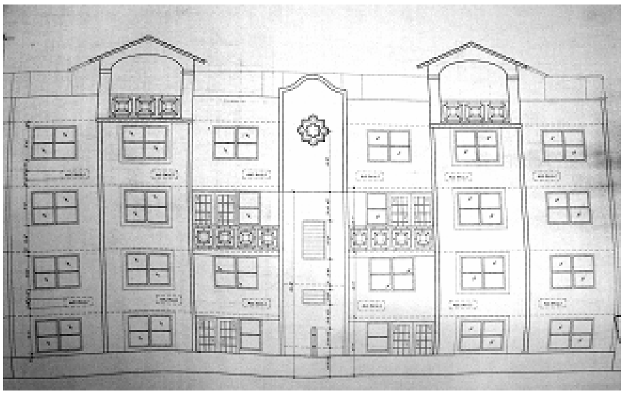


Figure 1. Example of a Front Elevation of a Multistory Building

2 DEFINITION OF ANALYTICAL MODELS

Multistory residential plans were collected from the Regulations and Permits Administration in Puerto Rico, San Juan office. A total of 13 plans were used in this investigation. Figure 1 and Figure 2 present an example of the front elevation and plan view of the building collected. The plans shows a common lateral resisting system. All models present reinforced concrete shear walls oriented in both direction as the main system to resist earthquake loads, thus this system was chosen as representative of the multistory residential buildings in this investigation. Due to the variability of structural parameters, real structures were modeled in both directions instead of creation of prototypes models. A total of 26 models were obtained from plans.

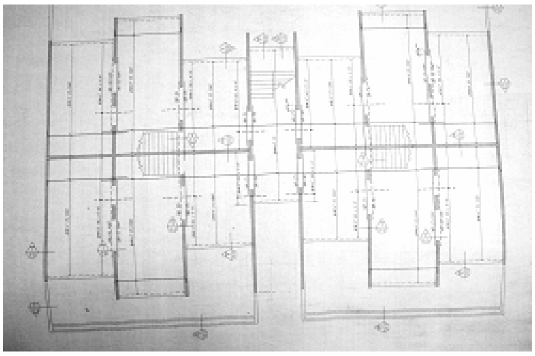


Figure 2. Example of a Plan View of a Multistory Building

The analytical models are two-dimensional. Figure 3 shows an example of a three story wall model studied. Walls are considered as cantilever walls with a common lateral degree of freedom at each level. All models have the same material properties, the concrete strength f'_c=3 ksi, modulus of elasticity E=3200 ksi, Shear modulus G=1200 ksi, and reinforcing bars yield strength f_y=60 ksi.

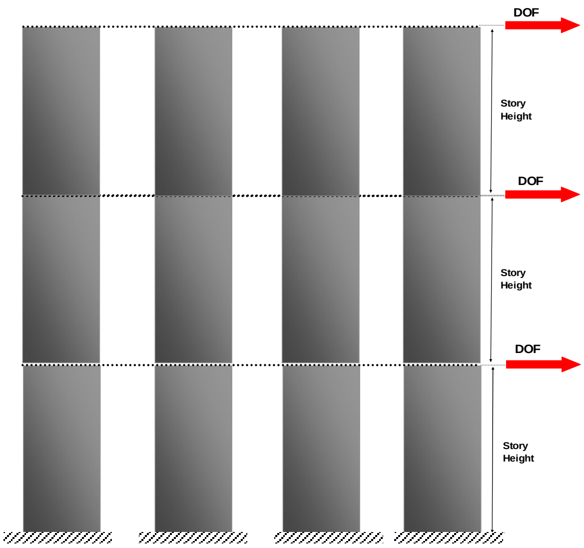


Figure 3. Example of a Multistory Reinforced Concrete Shear Wall Model

Description of multistory reinforced concrete shear wall models analyzed in this investigation is summarized in Table 1. The first column indicates the models, the second column shows the number of stories of each model: models from 3 stories to 10 stories were analyzed; next the wall to floor area ratio of the models is shown: a range of percentages from 0.3% to 6.7% are found. The fourth column describes the orientation of the models studied, direction 1 refers to north-south direction of the building and direction 2 refers to east west direction of the building. The fifth column corresponds to the story height, common height ranges from 8 to 9.5 ft. The last column contains the tributary weight that corresponds to each model.

MODEL	Number of Stories	Wall (%)	Direction	Story Height (in)	W(kip)
1	8	2.3	1	113	160
2	8	1.0	2	113	580
3	8	5.4	1	105	140
4	8	1.7	2	105	435
5	4	2.8	1	102	200
6	4	0.3	2	102	340
7	7	5.6	1	96	85
8	7	1.1	2	96	135
9	6	2.2	1	96	320
10	6	0.7	2	96	150
11	10	4.3	1	101	36
12	10	1.2	2	101	494
13	5	3.1	1	106	280
14	5	0.5	2	106	412
15	3	5.3	1	96	163
16	3	1.3	2	96	133
17	3	5.6	1	96	184
18	3	1.2	2	96	147
19	4	2.2	1	104	26
20	4	6.7	2	104	32
21	4	4.5	1	104	110
22	4	2.5	2	104	40
23	3	3.9	1	101	195
24	3	1.4	2	101	88
25	4	2.7	1	101	315
26	4	0.7	2	101	272

Direction 1 = Walls oriented in north-south direction
Direction 2= Walls oriented in east-west direction

Table 1. Description of Multistory Shear Wall Models

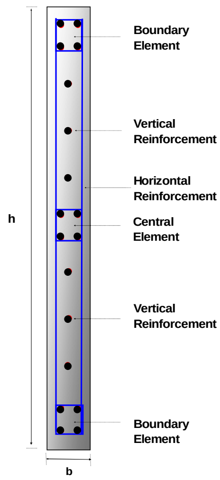


Figure 4. Cross Section Sketch of Multistory Shear Wall Models

A sketch explaining the walls section reinforcement and geometry is presented in Figure 4. Four types of reinforcement are shown: horizontal and vertical wall reinforcement that applies for all walls, and in some cases boundaries elements and also central element were found. The cross section reinforcement of all of the models is presented in Table 2. The cross sections of all of the models were analyzed to obtain their flexural and shear properties.

Model No.	Section No.	Vertical Reinforcement	No. Layer Vertical Reinforcement	Boundary Element	No. Layer Boundary Element	Center Element	No. Layer Center Element	Horizontal Reinforcement	No. Layer Horizontal Reinforcement
1	1	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	2	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	3	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	4	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
2	1	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	2	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	3	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	4	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	5	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	6	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	7	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	8	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	9	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	10	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
	11	#5@12	2	N/A	N/A	N/A	N/A	#5@12	2
3	1	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
	2	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
	3	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
	4	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
	5	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
	6	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
	7	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
	8	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
4	1	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
	2	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
	3	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
	4	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
	5	#3@12	2	N/A	N/A	N/A	N/A	#3@12	2
5	1	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	2	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	3	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	4	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	5	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
6	1	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
7	1	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	2	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	3	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	4	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	5	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
8	1	#4@12	2	18#9 @ 6"	9	10#6 @6	5.00	#4@12	2
9	1	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	2	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	3	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	4	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	5	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
10	1	#4@12	2	10#5 @ 6	5	10#5 @ 6	5.00	#4@12	2

Table 2. Cross Sections Reinforcement of Multistory Shear Wall Models

3 SEISMIC GROUND MOTION

In the absence of past strong earthquake records in the region, five earthquakes were used in this study, two artificial earthquakes created by Irizarri(1999) and modified by Montejo (2004) for Mayagüez and Ponce city and surroundings, based on the geotectonic characteristic of Puerto Rico, and three past earthquake records widely used by researchers. Those are: Imperial Valley, Northridge an San Salvador earthquakes. These earthquake ground motions were normalized to different peak ground acceleration values (PGA) from 0.1g to 1.5g.

4 NONLINEAR ANALYSIS AND DAMAGE STATE STIMATION

A nonlinear time history analysis of all models subjected to each of the earthquake ground motions was carried out. using LARZ code (Saiidi and Sozen, 1979). Numerical models used by Larz and adopted in this investigation to analyze the buildings are: The wall were modeled by wall elements developed by López (1988). The assumptions made are also explained. The model has one translational DOF at each floor and one rotational DOF at each joint. The structures represented in LARZ are planar reinforced concrete structures with the supports fixed, subjected to a uniaxial base motion acceleration or displacement or to a lateral story-force distribution. The model is characterized by the geometry, moment-curvature relationships of each element, and nonlinear shear properties of wall elements. Nonlinear behavior of shear wall is defined by both flexure defined by Takeda's rules and shear contribution defined by Hoedajanto (1983).

Model No.	Section No.	Vertical Reinforcement	No. Layer Vertical Reinforcement	Boundary Element	No. Layer Boundary Element	Center Element	No. Layer Center Element	Horizontal Reinforcement	No. Layer Horizontal Reinforcement
11	1	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	2	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	3	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	4	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	5	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	6	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	7	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	8	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	9	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	10	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	11	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	12	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	13	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	14	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	15	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	16	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
12	1	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	2	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	3	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	4	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	5	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
13	1	#3@11	2	6#6 @ 6	3	N/A	N/A	#3@11	2
	2	#3@11	2	6#6 @ 6	3	N/A	N/A	#3@11	2
	3	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	4	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	5	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	6	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
14	1	#3@11	2	6#6 @ 6	3	N/A	N/A	#3@11	2
	2	#3@11	2	4#6 @ 6	2	N/A	N/A	#3@11	2
	3	#3@11	2	4#6 @ 6	2	N/A	N/A	#3@11	2
	4	#3@11	2	6#6 @ 6	3	N/A	N/A	#3@11	2
	5	#3@11	2	6#6 @ 6	3	N/A	N/A	#3@11	2
15	1	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	2	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	3	#4@12	1	10#5 @ 6"	5	N/A	N/A	#4@12	1
	4	#4@12	1	10#5 @ 6"	6	N/A	N/A	#4@12	1
	5	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	6	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	7	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	8	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	9	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
16	1	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	2	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	3	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
17	1	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	2	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	3	#4@12	1	10#5 @ 6	5	N/A	N/A	#4@12	1
	4	#4@12	1	10#5 @ 6	6	N/A	N/A	#4@12	1
	5	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	6	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	7	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	8	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	9	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	10	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
18	1	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	2	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
	3	#4@12	2	N/A	N/A	N/A	N/A	#4@12	2
19	1	#4@15	1	N/A	N/A	N/A	N/A	#4@15	1
	2	#4@15	1	N/A	N/A	N/A	N/A	#4@15	1
	3	#4@15	1	N/A	N/A	N/A	N/A	#4@15	1
	4	#4@15	1	N/A	N/A	N/A	N/A	#4@15	1
20	1	#4@15	1	N/A	N/A	N/A	N/A	#4@15	1

Table 2. Continuation

Model No.	Section No.	Vertical Reinforcement	No. Layer Vertical Reinforcement	Boundary Element	No. Layer Boundary Element	Center Element	No. Layer Center Element	Horizontal Reinforcement	No. Layer Horizontal Reinforcement
21	1	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	2	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	3	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	4	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	5	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	6	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	7	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	8	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	9	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
22	1	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	2	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	3	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
23	1	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	2	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	3	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	4	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	5	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	6	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	7	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	8	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	9	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	10	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	11	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	12	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	13	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	14	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
24	1	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
	2	#4@12	1	N/A	N/A	N/A	N/A	#4@12	1
25	1	#3@8	1	N/A	N/A	N/A	N/A	#3@8	1
	2	#3@8	1	N/A	N/A	N/A	N/A	#3@8	1
	3	#3@8	1	N/A	N/A	N/A	N/A	#3@8	1
	4	#3@8	1	N/A	N/A	N/A	N/A	#3@8	1
	5	#3@8	1	N/A	N/A	N/A	N/A	#3@8	1
	6	#3@8	1	N/A	N/A	N/A	N/A	#3@8	1
	7	#3@8	1	N/A	N/A	N/A	N/A	#3@8	1
	8	#3@8	1	N/A	N/A	N/A	N/A	#3@8	1
	9	#3@8	1	N/A	N/A	N/A	N/A	#3@8	1
	10	#3@8	1	N/A	N/A	N/A	N/A	#3@8	1
	11	#3@8	1	N/A	N/A	N/A	N/A	#3@8	1
26	1	#3@12	2	8#5 @ 6	4	N/A	N/A	#3@12	2
	2	#3@12	2	8#5 @ 6	4	N/A	N/A	#3@12	2
	3	#3@12	2	8#5 @ 6	4	N/A	N/A	#3@12	2

Table 2. Continuation

Algan's formulation (1982) and HAZUS drift limits were used to calculate the expected damage of the models. From the analysis, the damage parameters are obtained and damage of the structures is quantified based on the inter-story drift ratio of the structure for HAZUS methodology and both drift ratio and tangential deviation for walls for Algan metohodology The damage states considered were: Minor, Moderate, Substantial and Major, for Algan and Slight, Moderate, Extensive and Complete for Hazus.

1.1 Algans Formulation

Algan (1982) presented a formulation to estimate the damage of a reinforced concrete building using the drift index and percentage of walls in each story. The damage index of each story of a reinforced concrete frame without walls is directly the drift index. In the case of the walls, the damage index is given by the difference of the drift index angle for that story and the joint rotation at the bottom floor level. The structural walls are considered as isolated cantilever beams for the selection of a damage index. The parameters related to damage of structural walls are presented in Figure 5.

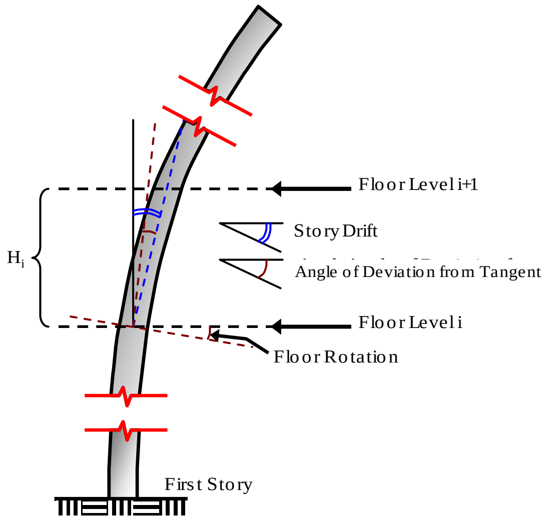


Figure 5. Parameters related to damage of structural walls.

The damage index for a story for shear wall models T_i is given by equation 1:

$$T_i = R_i - \frac{Z_{i+1} - Z_{i-1}}{h_i + h_{i-1}} \tag{1}$$

where:

T_i is the wall damage index , Z_i is the displacement at level i, Z_{i+1} is the displacement at level i+1, Z_{i-1} is the displacement at level i-1, h_i is the height of story i, and h_{i-1} is the height of story i-1.

After the damage index is calculated, the damage state that goes from 0 to 1 is determined. The scale of damage that estimates the damage condition of the building is given in Table 3.

Algan damage state ($U_{B,i}$)	0.05	None (no repair)
	0.35	Minor (minor or no repair)
	0.55	Moderate (some repair)
	0.75	Substantial (a lot of repair)
	1	Major (demolition and rebuilding)

Table 3. Damage State (Algan 1982)

The damage state ($U_{B,i}$) for structural reinforced concrete members is a simple linear form given by equation 2:

$$U_{B,i} = \frac{2}{3}\left(T_i\right) - \frac{1}{3} \tag{2}$$

1.2 HAZUS Formulation

HAZUS assumes that building damage varies from "None" to "complete" as a continuous function of building deformation. The definition of HAZUS limit states for Concrete Shear Wall is described below:

Slight Structural Damage: Diagonal hairline cracks on most concrete shear wall surfaces; Minor concrete spalling at few locations.

Moderate Structural Damage: Most shear wall surfaces exhibit diagonal cracks; some shear walls have exceeded yield capacity indicated by larger diagonal cracks and concrete spalling at wall ends.

Extensive Structural Damage: Most concrete shear walls have exceeded their yield capacities; some walls have exceeded their ultimate capacities indicated by large, through-the-wall diagonal cracks, extensive spalling around the cracks and visible buckled wall reinforcement or rotation of narrow walls with inadequate foundations. Partial collapse may occur due to failure of nonductile columns not designed to resist lateral loads.

Complete Structural Damage: Structure has collapsed or is in imminent danger of collapse due to failure of most of the shear walls and failure of some critical beams or columns.

Hazus damage state are based on the drift index for different grades of design. Moderate Code was used , as recommended by López *et al*. (2001). Table 4 presents the interstory drift ratio limits for each damage state proposed by HAZUS-MH MR1 (2003) for medium rise reinforced concrete shear wall structures.

HAZUS drift limits for Moderate Code Design Level for Mid-Rise Reinforced Concrete Shear Wall buildings	Slight	0.003
	Moderate	0.005
	Extensive	0.015
	Complete	0.040

Table 4. HAZUS Average Inter-Story Drift Ratio of Structural Damage States (HAZUS-MH MR1 2003)

5 FRAGILITY CURVES

Fragility curves are Lognormal functions that describe the probability of reaching, or exceeding, structural and nonstructural damage states, given deterministic (median) estimate of spectral response, for example spectral displacement. These curves take into account the variability and uncertainty associated with capacity curve properties, damage states and ground shaking (Kircher *et al.* 1997). These curves are useful tools for the insurance companies in Puerto Rico in order to improve their risk assessments.

6 DEVELOPMENT OF FRAGILITY CURVES

After the whole population of 26 multistory models was subjected to the five earthquake records defined earlier, the number of models that reached of exceeded each damage state for each earthquake record was counted and the results presented in “Cumulative damage-state occurrence” tables For each peak ground acceleration considered a sample size of 130 is obtained.

Values of damage state occurrence using Algan limit states are presented in Table 5. The third row of the table shows that for a peak ground acceleration of 0.3g, a total of 16 building shows at least Minor damages and only 9 models present damage greater than Moderate damage state. Even at high peak ground acceleration, 1g, most of the buildings remain with almost no damage, only 55 buildings; around 42% of the whole sample reach or exceed Moderate damage state.

PGA	None	Minor	Moderate	Substantial	Major
0.1	130	4	2	2	1
0.2	130	5	4	4	3
0.3	130	16	9	7	5
0.4	130	32	11	9	7
0.5	130	42	23	13	11
0.6	130	53	33	23	14
0.7	130	54	39	31	23
0.8	130	61	47	37	26
0.9	130	64	54	46	34
1	130	72	55	51	44
1.1	130	78	61	54	49
1.2	130	86	65	58	55
1.3	130	90	72	63	60
1.4	130	90	77	65	60
1.5	130	96	82	71	62

Table 5. Cumulative damage-state occurrence using Algan limits state: All Earthquakes for Multistory Reinforced Concrete Shear Walls

Values of damage state occurrence using HAZUS limit states for multistory shear wall models are presented in Table 6. For the whole sample of 130 models the table shows that for a peak ground acceleration of 0.3g, a total of 39 building shows at least Slight damages and only 17 models present damage greater than Moderate damage state.

PGA	No Damage	Slight	Moderate	Extensive	Complete
0	130	0	0	0	0
0.1	130	5	4	1	0
0.2	130	17	5	4	1
0.3	130	39	17	5	2
0.4	130	54	34	9	2
0.5	130	64	46	12	4
0.6	130	68	53	15	4
0.7	130	77	55	24	6
0.8	130	87	62	28	7
0.9	130	93	66	37	9
1	130	99	76	46	10
1.1	130	101	84	51	13
1.2	130	102	88	55	15
1.3	130	102	94	60	18
1.4	130	102	95	61	17
1.5	130	104	97	64	21

Table 6. Cumulative damage-state occurrence using HAZUS limits state: All Earthquakes for Multistory Reinforced Concrete Shear Walls

Next, the input data damage-state probability was calculated by dividing the number of data points that are in or exceed a particular damage state by the number of data points of the whole sample as proposed by Shinozuka (2001). This value represents the cumulative distribution functions of each damage state, thus data point for fragility curves generation. With this information lognormal functions expressed in the form of two parameters (log-median and log-standard deviation) were fitted and fragility curves developed.

The cumulative distribution function obtained using Algan limit is summarized in Table 7. For example at 0.3g there is a 7% probability of reaching or exceeding Moderate damage state. These values are data point of the fragility curves. Figure 6 plots the input data points and the lognormal function fitted for Minor, Moderate, Substantial and Major damage. The log-median and log-standard deviation obtained. The set of fragility curves as a function of PGA proposed for this population is plotted in Figure 7.

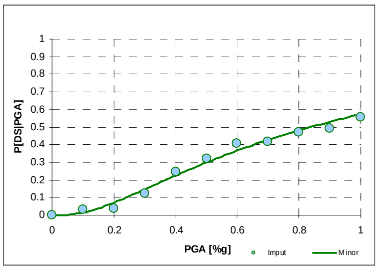
PGA	None	Minor	Moderate	Substantial	Major
0.1	1.00	0.03	0.02	0.02	0.01
0.2	1.00	0.04	0.03	0.03	0.02
0.3	1.00	0.12	0.07	0.05	0.04
0.4	1.00	0.25	0.08	0.07	0.05
0.5	1.00	0.32	0.18	0.10	0.08
0.6	1.00	0.41	0.25	0.18	0.11
0.7	1.00	0.42	0.30	0.24	0.18
0.8	1.00	0.47	0.36	0.28	0.20
0.9	1.00	0.49	0.42	0.35	0.26
1	1.00	0.55	0.42	0.39	0.34
1.1	1.00	0.60	0.47	0.42	0.38
1.2	1.00	0.66	0.50	0.45	0.42
1.3	1.00	0.69	0.55	0.48	0.46
1.4	1.00	0.69	0.59	0.50	0.46
1.5	1.00	0.74	0.63	0.55	0.48

Table 7. Input data damage-state probability using Algan limit state: All Earthquakes for Multistory Reinforced Concrete Shear Walls

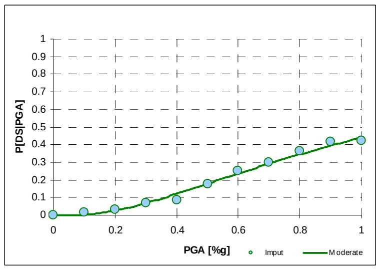
PGA	No Damage	Slight	Moderate	Extensive	Complete
0	1.00	0.00	0.00	0.00	0.00
0.1	1.00	0.04	0.03	0.01	0.00
0.2	1.00	0.13	0.04	0.03	0.01
0.3	1.00	0.30	0.13	0.04	0.02
0.4	1.00	0.42	0.26	0.07	0.02
0.5	1.00	0.49	0.35	0.09	0.03
0.6	1.00	0.52	0.41	0.12	0.03
0.7	1.00	0.59	0.42	0.18	0.05
0.8	1.00	0.67	0.48	0.22	0.05
0.9	1.00	0.72	0.51	0.28	0.07
1	1.00	0.76	0.58	0.35	0.08
1.1	1.00	0.78	0.65	0.39	0.10
1.2	1.00	0.78	0.68	0.42	0.12
1.3	1.00	0.78	0.72	0.46	0.14
1.4	1.00	0.78	0.73	0.47	0.13
1.5	1.00	0.80	0.75	0.49	0.16

Table 8. Input data damage-state probability using HAZUS limits state: All Earthquakes for Multistory Reinforced Concrete Shear Walls

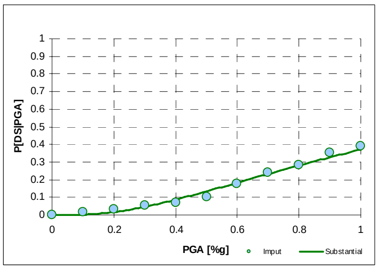
The cumulative distribution function obtained using HAZUS limit is summarized in Table 8. At 0.3g there is a 17% probability of reaching or exceeding Moderate damage state. These values are data point of the fragility curves. Figure 8 plots the input data points and the lognormal function fitted for Slight, moderate, Extensive and Complete damage. The log-median and log-standard deviation obtained. The set of fragility curves as a function of PGA proposed for this population is plotted in Figure 9.



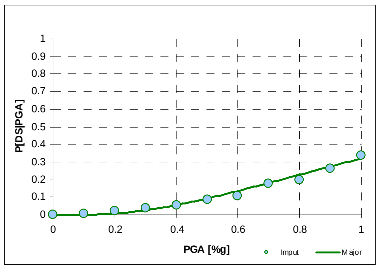
a) Minor Damage



b) Moderate Damage



c) Substantial Damage



d) Major Damage

Figure 6. Damage Fragility curves using Algan limits state for Multistory Reinforced Concrete Shear Walls

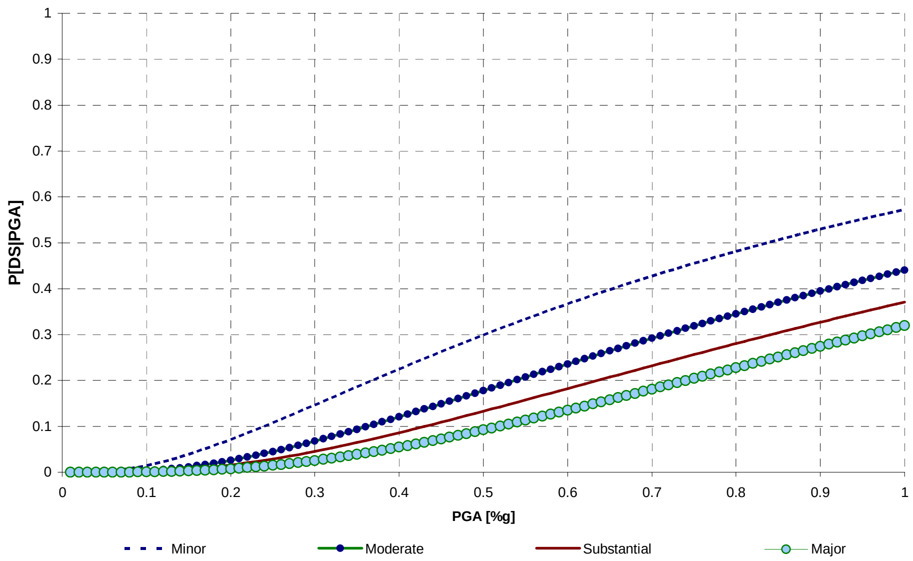
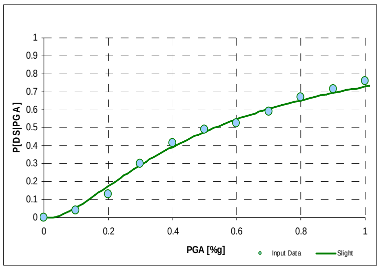
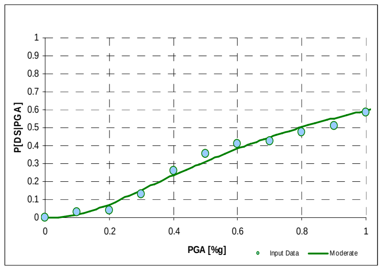


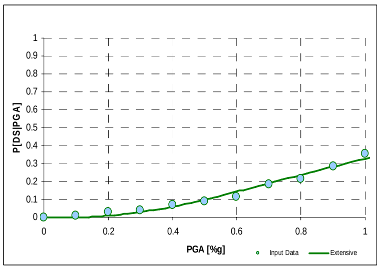
Figure 7. Set of Damage Fragility curves using Algan limits state for Multistory Reinforced Concrete Shear Walls



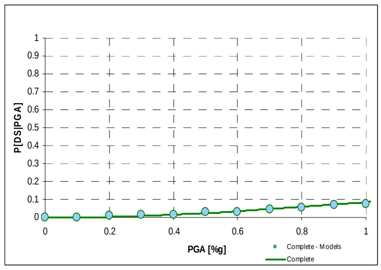
a) Slight Damage



b) Moderate Damage



c) Extensive Damage



d) Complete Damage

Figure 8. Damage Fragility curves using HAZUS limits state for Multistory Reinforced Concrete Shear Walls

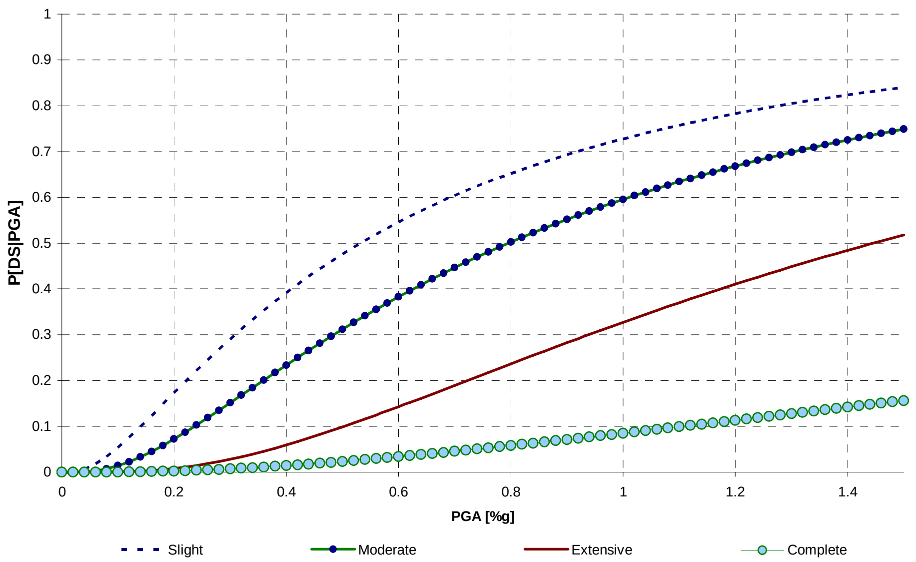


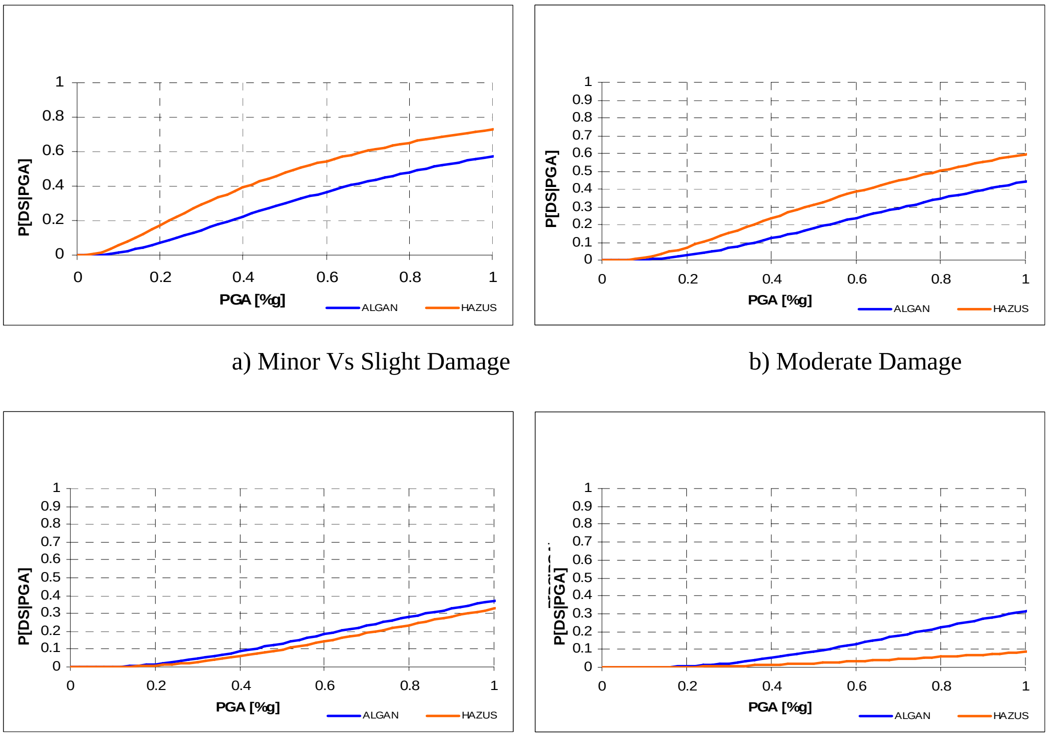
Figure 9. Set of Damage Fragility curves using HAZUS limits state for Multistory Reinforced Concrete Shear Walls

Parameters of the fragility curves (The log-median and log-standard) developed are summarized in Table 9. The first column of the table describes the damage estimation methodology used, the second column defines the damage state and the third and fourth columns are the log-median and log-standard deviation of each models type for each damage state.

Limit State	Damage state	μ_{ln}	σ_{ln}
ALGAN	Minor	-0.18	0.98
	Moderate	0.13	0.90
	Substantial	0.29	0.89
	Major	0.38	0.80
HAZUS	Slight	-0.63	1.04
	Moderate	-0.23	0.95
	Extensive	0.37	0.82
	Complete	1.54	1.12

Table 9. Fragility curve parameters using Algan and HAZUS limit state for Reinforced Multistory Concrete Shear Wall models

7 COMPARISON OF ALGAN AND HAZUS FRAGILITY CURVES



a) Minor Vs Slight Damage b) Moderate Damage

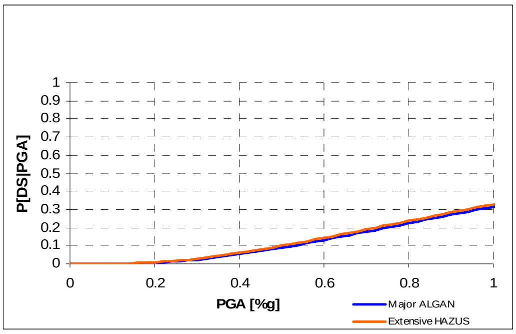
c) Substantial Vs Extensive Damage d) Major Vs Complete Damage

Figure 10. Algan Vs Hazus fragility curves comparisons. Multistory Reinforced Concrete Shear Walls

Figure 10 present comparisons of Algan and Hazus limits. Looking at Sustantial Vs. Extensive damage state, and Major Vs. Complete damage state plots, it can be seen that the biggest difference appears in the Complete damage state. This difference is due to the definitions of damage limits. Algan defines major damage as damage where the structure exhibits such deterioration that may need to be demolished and rebuilt and is based on a maximum drift of 2%. HAZUS defines extensive damage with a drift limits close to 2% also, and considers complete damage or collapse when the structure loses it stability. For moderate code HAZUS assigns a maximum drift of 4% for medium rise reinforced concrete shear wall models.

Figure 11 graphically shows the excellent agreement of Algan Major damage state fragility curves and Hazus Extensive damage state fragility curve for all type of structure studied. Thus there is not a one to one relationship between Algan and Hazus limit states.

Algan fragility curves for Moderate, Substantial and Major damage are very close each other, which seems that the damage threshold that predict Algan for these damage state are almost the same, these behavior seems not be realistic. Having that in mind, it can be said that Hazus limits appears to be more realistic than Algan limits.



e)Mult

Figure 11. Comparisons between Algan's Major damage fragility curves and HAZUS'S Extensive damage fragility curves

8 CONCLUSIONS AND FUTURE WORK

After obtaining a variety of plans of reinforced concrete buildings in Puerto Rico from the Regulations and Permits Administration of Puerto Rico and also from engineering offices, typical structural characteristic of concrete residential building in Puerto Rico were established. The assumed properties for all structures are: Material properties are the same for all cases; usually present a concrete strength of 3 ksi, and reinforcing bars with yield strength of 60 ksi., all multistory residential plans presents reinforced concrete shear walls oriented in both directions as the main system to resist earthquakes load. These buildings present a range of wall to floor area percentages from 0.3% to 6.7% and story height that ranges from 8 to 9.5 ft. A total of 26 models from 3 stories to 10 stories were obtained from plans.

From fragilities curves generated, the following conclusions can be drawn:

- Multistory models have only around 5% of probability of reaching Major damage and 10% probability of reaching or exceeding Moderate damage at PGA of 0.4g using Algan limits and around 5% probability of reaching Extensive damage and 20% probability of reaching or exceeding Moderate damage at PGA of 0.4g using HAZUS limits.
- The low probability of damage, even at high PGA values shows that multistory residential models behave well when submitted to earthquake forces.
- Algan Major fragility curves and Hazus Extensive fragility curves match very well, and
- Hazus limit state appears to be more realistic than Algan limit state

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