STRUCTURAL PERFORMANCE FACTORS AND BUILDING DAMAGE FOLLOWING THE 19 SEPTEMBER 2017 PUEBLA, MEXICO EARTHQUAKE

Ezra Jampole, PhD, PE[1]; Jeffrey Hunt, PhD, PE[2]
Exponent
New York, New York[1]; Irvine, California[2], USA

Abstract

The 19 September 2017 Puebla, Mexico Earthquake caused binary damage to structures in Mexico City: similar structures in similar locations experienced either little to no damage or catastrophic collapse. This study draws on observations from over 700 buildings near ground motion recording stations in Mexico City to identify the relationship between ground motion intensity, building age, and structural performance factors that drive behavior and contribute to damage during earthquakes, such as: height, vertical and plan irregularities, pounding potential, location in a block of buildings, and the presence of a short column. A multinomial logistic regression model is created to assist in risk assessments based on structural performance factors and earthquake intensity. Additionally, structure performance factors are assessed through numerical modeling, including a block of concrete frame buildings with masonry infill. It is found that, in the absence of detailed information, e.g. design drawings, the presence of structural performance factors provides a strong indication of expected behavior during an earthquake of a given intensity.

Introduction

The 19 September 2017 M7.1 Puebla, Mexico Earthquake caused damage throughout the Mexico City Lakebed and Transition Zones, but only to a subset of structures. Many seemingly similar structures subjected to the same earthquake intensity as measured by peak ground acceleration had very different damage conditions. This study uses a large dataset from post-earthquake reconnaissance documenting building properties and vulnerabilities to identify their influence on the probability of different damage conditions for a given earthquake shaking intensity using multinomial logistic regression. Numerical modeling of a block of buildings provides insight into the role of features such as building location in a block and pounding between structures on response quantities, from which damage state could be inferred.

Data Set

Building information and damage condition was collected on 713 buildings in Mexico City after the September 19, 2017 earthquake (Weiser et al. 2018), including: damage state, approximate age, number of stories and floor plan, the presence of structural performance factors (soft-story, short column, vertical irregularity, plan irregularity, potential slope stability issues, pounding potential), location within a block of buildings, building type and use, and evidence of retrofits. Buildings were mainly observed in clusters around ground motion recording stations that measured a variety of shaking intensities. The damage states were defined as: DS-0 = no damage; DS-1 = minor damage; DS-2 = moderate (structural) damage; DS-3 = severe damage; and DS-4 = collapse or partial collapse. The reader is referred to Weiser et al. (2018) for a full description of the data set.

Damage Prediction Model

A damage prediction model was developed to predict the damage state in the concrete frame buildings with masonry infill, which is the construction type for 543 buildings in the data set. The following parameters are used in the prediction model: retrofit (Yes/No); building is at the end of a row (Yes/No); site location (Lakebed/Transition/Firm Zone); average spectral acceleration for periods from 1 to 3 seconds; ground motion duration as measured by D5-75; the number of structural performance factors present); construction date (Pre-1985/Post-1985/Unknown); height (1-3/4-9/10+ stories above ground; and the period ratio, which is a derived metric for how close the building period is to the peak spectral acceleration. The period of concrete frame buildings with masonry infill was estimated using Crowley and Pinho (2006), where: $T_{estimate}$ = 0.55*height, assuming 3.6m/story. Period ratio, is calculated as:

$$Tratio = \left| \frac{T@Peak\ S_a}{(T@Peak\ S_a - T_{estimate})} \right| \tag{1}$$

A binomial logistic regression is created to predict the probability of a building being damaged, regardless of the damage state:

$$P(damage|X) = \frac{e^{\beta_0 + \beta_1 X_1 + \cdots + \beta_p X_p}}{1 + e^{\beta_0 + \beta_1 X_1 + \cdots + \beta_p X_p}} \tag{2}$$

where P(X) is the probability of any damage state, β's are regression coefficients, and X's are the values for building properties and ground motion intensities. X values for binary indicators are Yes = 1; No = 0. A multinomial logistic regression is then created to predict the probability of a damage condition:

$$P(Y = k|X, damage) = \frac{e^{\beta_{0k} + \beta_{1k} X_1 + \cdots + \beta_{pk} X_p}}{\sum_{i=1}^{K} e^{\beta_{0i} + \beta_{1i} X_1 + \cdots + \beta_{pi} X_i}} \tag{3}$$

where Y is the outcome, k's are outcomes (damage states), K is the number of outcomes, β_{pi}'s are regression coefficients corresponding to each variable (X_0 to X_p) and damage state (i = 1 to K), and X's are variable values. The probability of seeing a damage given a set of X's is therefore Eq. (2) times Eq. (3). Case-controlled sampling is used to correct the intercepts, $\hat{\beta}_0$ to $\hat{\beta}_{0^*}$, to account for differences in the rate of observing a damage state, $\tilde{\pi}$, and an estimate of the real rate of the damage state, π:

$$\hat{\beta}_{0^*} = \hat{\beta}_0 + \log\frac{\pi}{1-\pi} - \log\frac{\tilde{\pi}}{1-\tilde{\pi}} \tag{4}$$

In the absence of available data on the total number of damaged buildings, order of magnitude, estimated real rates of seeing each damage state are made based on available literature and using engineering judgement. McDonnell reported 3,000 damaged buildings in Mexico City three days after the earthquake (McDonnell et al. 2017). Their threshold for damage is unknown, but it is assumed that this roughly corresponds to the number of moderately damaged buildings. Galvis reported the collapse of 46 buildings in Mexico City (Galvis et al. 2017). We make the following additional assumptions:

- The number of severely damaged buildings in the population is of the order of magnitude between the number of moderately damaged and collapsed buildings: 300.
- The number of lightly damaged buildings is an order of magnitude greater than the McDonnell report of number of damaged buildings immediately after the earthquake: 30,000 buildings.
- An order of magnitude estimate of the total number of buildings is one million.

Based on assumptions of the total population sizes and the data set, Table 1 shows the estimated and observed rates for each damage state, and used for correcting the intercept values in the regression models with Eq. (4).

Table 2 shows the regression coefficients and p-value for predicting the probability of damage using binomial logistic regression with the list ground motion intensity and building property parameters. Table 3 shows the regression coefficients and p-value for predicting the probability of each damage state (given damage has occurred) using multinomial logistic regression. A two-sided Wald test is used to determine statistical significance, where a p-value < 0.05 is considered significant.

Table 1. Estimated and Data Set Rate of Damage Conditions

Condition	*Estimate Rate*	*Observed Rate*
Any Damage	3.2E-02	2.6E-01
DS - 1: Minor | Damage	9.0E-01	6.6E-01
DS - 2: Moderate | Damage	9.0E-02	1.4E-01
DS - 3: Severe | Damage	9.0E-03	1.1E-01
DS - 4: Collapse | Damage	1.5E-03	9.1E-02

Table 2. Regression Coefficients and P-Value for Probability of Damage Model

Variable Name	*Variable*	*Regression Coefficient*	*p-value*
Intercept	-	-24.56	-
Retrofit? - Yes	X_1	-14.45	0.9866
End Building? - Yes	X_2	0.14	0.5696
Lakebed Zone? - Yes	X_3	14.34	0.9873
Transition Zone? - Yes	X_4	16.58	0.9854
Sa average from 1 to 3 seconds [g]	X_5	12.55	0.0019
D5-75 [s]	X_6	0.08	0.0001
Number of Performance Factors	X_7	0.50	0.0000
Period ratio	X_8	0.14	0.0080
Unknown Construction Date	X_9	0.60	0.0356
Built after 1985	X_{10}	0.59	0.0817
Height 10 stories +	X_{11}	19.70	0.9906
Height 4-9 stories	X_{12}	0.43	0.1356

Table 3. Regression Coefficients and P-Value for Severity of Damage Model

Variable Name	*Regression Coefficient*				*p-value*			
	DS -1	*DS - 2*	*DS - 3*	*DS - 4*	*DS -1*	*DS - 2*	*DS - 3*	*DS - 4*
Intercept	-18.84	-20.46	-31.94	-33.51	-	-	-	-
Retrofit? - Yes	-6.45	-14.93	-12.53	-13.61	0.7884	0.0000	0.0361	0.0000
End Building? - Yes	-0.05	-0.50	0.92	1.18	0.8674	0.4161	0.0988	0.0632
Lakebed Zone? - Yes	13.11	11.48	14.40	7.19	0.0000	0.0000	0.0000	0.0135
Transition Zone? - Yes	14.62	13.55	18.29	15.62	0.0000	0.0000	0.0000	0.0000
Sa average from 1-3 seconds [g]	9.17	14.46	18.92	44.64	0.0337	0.1002	0.0900	0.0058
D5-75 [s]	0.08	0.01	0.11	0.15	0.0002	0.8350	0.0886	0.0483
Number of Performance Factors	0.52	0.40	0.62	0.11	0.0001	0.1623	0.0340	0.7347
Period ratio	0.14	0.15	0.14	0.15	0.0089	0.0070	0.0097	0.0089
Unknown Construction Date	0.82	-0.25	0.21	0.73	0.0086	0.7180	0.8096	0.3753
Built after 1985	0.92	-1.05	0.52	-0.17	0.0134	0.3325	0.4406	0.8501
Height 10 stories +	22.08	23.43	25.37	24.12	0.0000	0.0000	0.0000	0.0000
Height 4-9 stories	-0.20	1.18	2.80	2.41	0.5367	0.0859	0.0109	0.0079

Figure 1 shows regression curves as a function of Sa avg. for a base case of an unretrofit building that is in the middle of a block in the Transition Zone, has a D5-75 = 15 seconds, two structural performance factors, a period ratio = 1, was built before 1985, and is 4-9 stories; and then steps through the parameter space in various directions, as indicated in the legend. DS 1 and 2 are lumped, and DS 3 and 4 are lumped to improve the clarity of the results. Figure 2 and Figure 3 show additional regression curves with alternative intensity measures: Period Ratio and D5-75.

The following observations are made from reviewing regression model results presented in the figures:

- Post-1985 buildings were more vulnerable to lighter damage than pre-1985 buildings in the transition zone, but did not pass the significance test at higher damage states. Particularly vulnerable pre-1985 buildings may have already been knocked down in the 1985 earthquake. Increased damage may also speak to construction quality and building code enforcement issues. The statistical significance of "Unknown Construction Date" highlights the importance and difficulty in assessing the age of a building without detailed knowledge of local construction practice. There is likely correlation between buildings in this category and construction type and real age.
- 4-9 story buildings are significantly more likely to have heavy damage than 1-3 story buildings, because of the period of the soil relative to the period of the taller structures.
- The number of performance factors has a significant effect on building performance in the Transition Zone. At 0.25g, the probability of heavy damage is significantly greater when a building has two or four structural performance factors.
- While it does not pass the significance test, end buildings appear to be more vulnerable than middle of the block buildings. At low intensities, the probability of a lower damage condition is similar but the probability of heavy damage is relatively much higher. When the intensity is higher, the probability of heavy damage in end buildings is only moderately greater than middle of the block buildings. Intuition and engineering judgement suggest that end buildings are more vulnerable than middle of the block buildings because they may serve as a fuse in the row of buildings and irregularities. This will be further investigated with numerical modeling.
- Light/moderate damage can begin at low intensities. The probability of seeing heavier damage increases significantly at Sa avg above 0.25g in the Transition Zone. Significant duration plays a large role in earthquake intensity in both the Transition Zone and Lakebed Zone. The significant duration ranged from 20-40s in Lakebed Zone sites. A combination of long significant duration and high Sa avg is required to induce heavy damage in the Lakebed Zone.
- Retrofits were significant and effective.
- Period ratio has a large effect on both light and heavy damage predictions. There is a steep increase in the probability of damage as it increases because of resonance in the structures.

It is important to note that ground motion intensity does not occur in a vacuum: period ratio, Sa avg, significant duration, and the soil site are all related, which is reflected in the p-values. The reader is encouraged to plot the regression models themselves to further assess the influence of the various earthquake intensity and building factors on damage state probabilities.

There are numerous opportunities to improve the regression models, including:

- correcting estimates of the total number of buildings in each damage state and in the total population;
- adding interaction between each of the structural performance factors, i.e. assessing the influence of a soft-story combined with a short column;
- assessing the intensity measures and performance factors that influence damage probability for other building types.

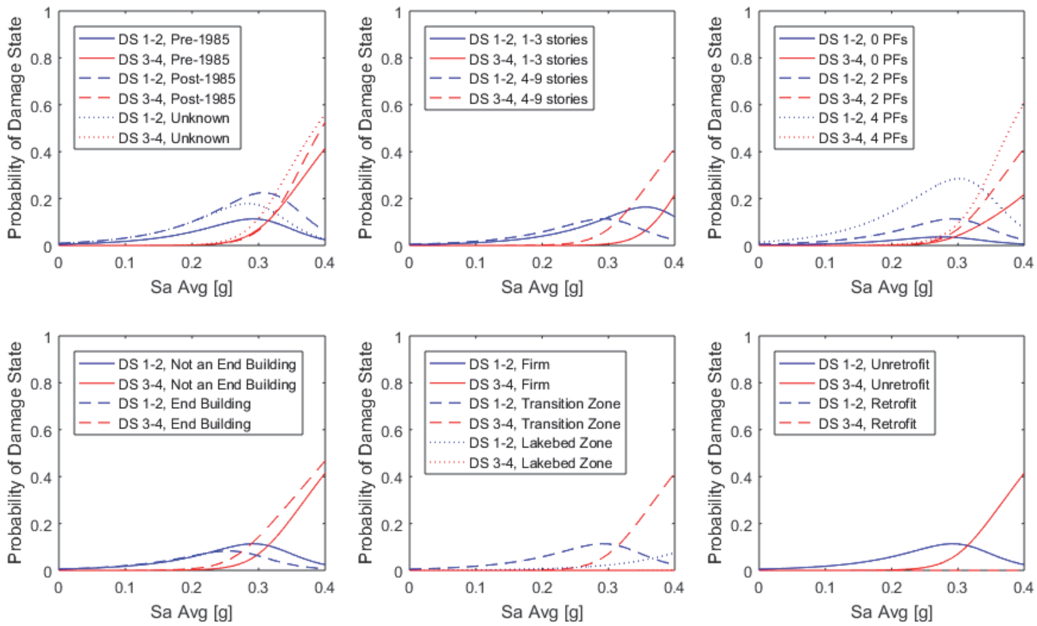

Figure 1. Regression curves for base case: Unretrofit building; Not an end building; Transition Zone; D5-75 = 15 seconds; Number of performance factors = 2; Period ratio = 1; Pre-1985; 4-9 stories.

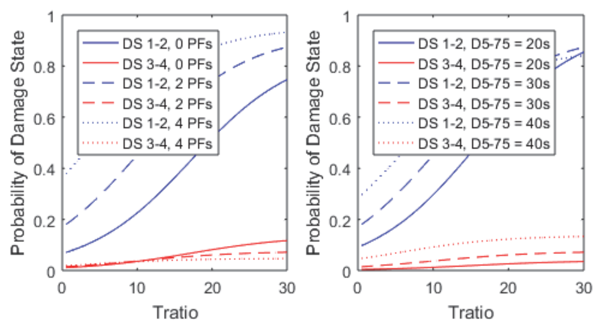

Figure 2. Regression curves for base case: Unretrofit building; Not an end building; Lakebed Zone; D5-75 = 30 seconds; Number of performance factors = 2; Sa Avg. = 0.4g; Pre-1985; 4-9 stories.

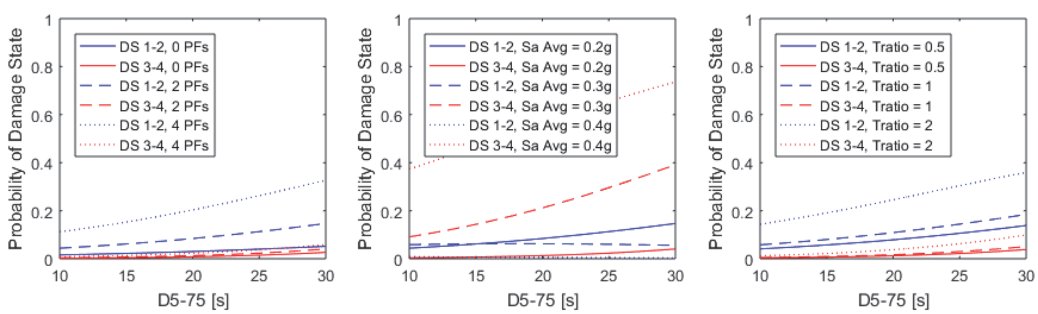

Figure 3. Regression curves for base case: Unretrofit building; End building; Transition Zone; Number of performance factors = 2; Period Ratio = 1; Sa Avg. = 0.2g; Pre-1985; 4-9 stories.

Analysis Model Description

The regression model has highlighted that the number of structural performance factors can affect the expected damage state of a building after an earthquake. To illustrate the influence of specific building vulnerabilities, an OpenSees model of four concrete frame buildings with masonry infill, inspired by the buildings in Mexico City shown in Figure 4, was created. Figure 5 shows a schematic diagram of the model and labels the buildings. The buildings are spaced 5 centimeters apart. Buildings 1 and 4 are six stories, and buildings 2 and 3 are eight stories. Each building is modeled after Gunay and Mosalam (2010). Masonry infill contributing to the building stiffness is included in the directions perpendicular to the street. Infill is not included in bays where there are large openings because it will not significantly contribute to the lateral resisting system. For the corner building 3, the infill is thus in perpendicular directions, and for the other buildings, the infill is on parallel faces, and abutting adjacent buildings. A Hertz contact model is used to account for pounding between the buildings at the floor levels (Muthukumar and DesRoches 2006). The building is subjected to simultaneous bidirectional application of orthogonal horizontal components of the SCT2 recording from the 2017 Puebla, Mexico Earthquake.

Figure 4. Exemplar damaged block of buildings in Mexico City.

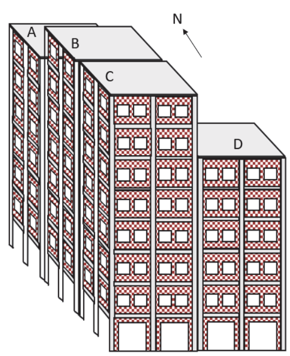

Figure 5. Schematic diagram of building block model.

Analysis Results

Figure 6 and Figure 7 show the displacement response histories for each building. The following observations are made regarding interaction and behavior of the block of buildings:

- In the North/South direction, Buildings A and B and are more flexible than building D because of the masonry infill oriented in the North/South direction in Building D in both exterior walls. The opposite is true in the East/West direction, where Building D is more flexible. Building C has solid infill walls at only its exterior North and East faces, which initially yields intermediate flexibility in both directions.

- Building B contacts Building C in the North/South direction beginning at 76 seconds, then oscillates between Buildings A and C until 107 seconds. Building C begins oscillating about a residual displacement of about 2 cm after it collides with Building B at 83 seconds. This contact occurs at a time in which the buildings were out-of-phase towards each other, at a high velocity. The contact knocks out some infill in the first story the East/West direction, which is reflected in period elongation in Building B in the East/West direction at 83 seconds.
- In the East/West direction, Building A maintains its short period through the response history because is no significant contact in the North/South direction that results in out-of-plane infill losses. None of the buildings have a permanent residual displacement in the East/West direction.

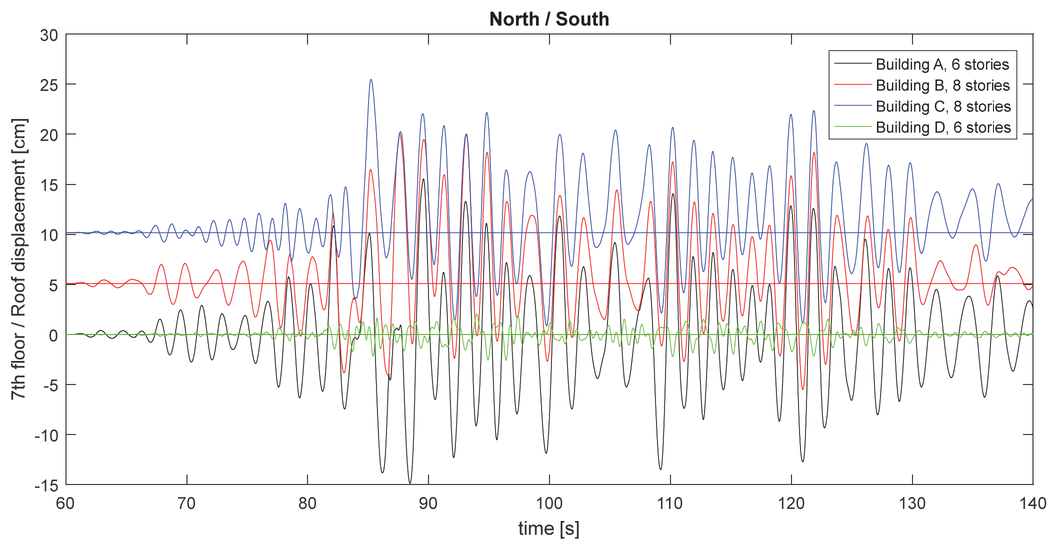

Figure 6. North / South direction top pounding level displacement response histories.

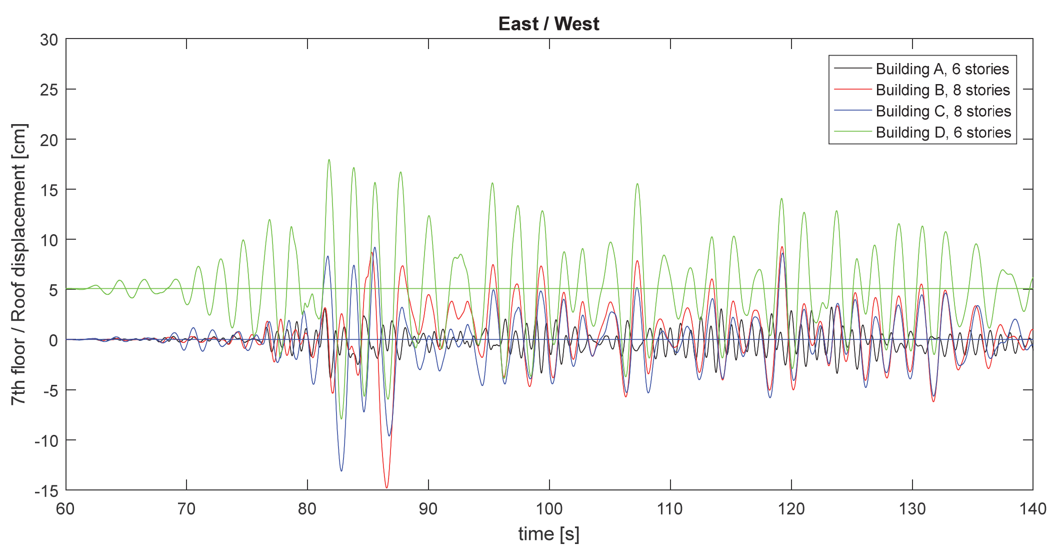

Figure 7. East / West direction top pounding level displacement response histories.

The building block numerical model has demonstrated that a building in the middle of a block may pound against adjacent buildings, but the adjacent buildings restrain its movement. The building at the corner, with pounding potential in orthogonal directions, lack of restraint on one side in each orthogonal direction, and an inherent plan irregularity was the most vulnerable in the block. Based on the infill shed and residual displacement, at least Buildings B and C would be categorized in some damage state. The impact of individual performance factors and block location, as demonstrated in this example and as found in the regression model to influence performance, warrant further evaluation.

Conclusions

In this paper, a preliminary regression model was developed to estimate the probability of observing different damage states in concrete frame buildings with masonry infill based on multiple ground motion intensity measures, using a dataset collected in Mexico City after the 2017 Puebla, Mexico Earthquake. The regression model could be used by insurers to update fragility curves, government agencies to for designing retrofit programs that have the greatest impact in reducing risk, or by building owners interested in their structure's exposure. A numerical model sheds light on how specific structural performance factors can influence building behavior in a typical block.

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