Fragility of Shear Wall Buildings with Torsional Irregularity

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SUMMARY:
Fragility curves are useful for damage assessment of structures. There are many criteria that affect the reliability of fragility curves such as transitional damage states, plan irregularity and different measures of seismic intensity. Determination of fragility of a shear wall structure is important, especially for installations that have torsional irregularity. In this study fragility curves of a shear wall building with torsional irregularity have been obtained. This building was subjected to synthetic earthquake motions on the AZALEE shaking table under the coordination of CEA (Commissariat à l'Energie Atomique) and Electricité de France (EDF) in Saclay, Paris under the scope of the SMART program.

Maximum inter-story drift values have been used as the damage indicator to obtain the fragility curves and different seismic intensity measures such as PGA, PGV, PGD and CAV have been used. Thirty bi-directional horizontal ground motions have been applied for the time history analyses. These synthetic acceleration sets applied to the structure have different amplitudes in the range of 0.1 to 1 g. Micro modeling approach has been used to obtain reasonably accurate and consistent results with experiments. ANSYS finite element software has been used for the response history analyses.

Fragility curves of shear wall building have been calculated according to pre-established damage indicators. The limits are light, controlled and extended damage indicators. These curves are compared with those of the HAZUS damage states for correlation.

Keywords: Shear Wall Building, Fragility, Torsion, Micro- modeling

1. INTRODUCTION

Calculation of three dimensional seismic effects on buildings involving torsion is a challenge, especially for non – linear behavior under earthquake effects. Modeling these types of buildings requires care to generate acceptable results. In spite of the computational technology and existence of numerical models, there still are deficiencies in modeling because of the assumptions made in the numerical models for material and seismic excitation estimation.

One critical concept is the determination of fragility curves for different structural categories. These statistically-evaluated or empirically-derived curves provide a basis for the assessment of the performance of buildings under different ground motion intensities so that loss estimates can be made. In this study, the fragility curves for shear wall structures with torsional irregularity are examined.

2. FRAGILITY CURVES: DERIVATION

2.1 Literature

For walls two main modeling approaches are used as macro and micro modeling depending on the chosen finite element technology. Micro modeling is a continuum mechanics based approach and uses two or three dimensional solid or shell finite elements.

Non – linear behavior of concrete and steel can be applied in the model on the basis of material constitutive relationships from experimental results (Ile and Reynouard 2003, 2005; Kazaz et al, 2006; Ile et al., 2008; Fischinger and Isakovic, 2000). Micro modeling is suitable for representing the local behavior in the structure. ANSYS, ABAQUS, ADINA and DIANA are sample software packages that include a variety of element and material models in their libraries for micro modeling. Many researchers have used micro modeling approach to simulate the experimental measurements (Kwak and Kim, 2004; Palermo and Vecchio, 2007).

In performing a seismic risk analysis of a structural system, the vulnerability information in the form of fragility curves is a widely practiced approach. Performance – based design is a powerful tool for the assessment of buildings under earthquake effects. In recent decades, the probabilistic approaches have become popular than deterministic approaches for the determination of fragility curves of structures. Shinozuka et al. (2000) developed fragility curves associated with different states of damage of bridges from observations following the 1995 Kobe earthquake event. They introduced the uncertainty and statistical interpretation of randomness through the notation of combined and composite fragility curves.

Ay and Erberik (2008) investigated seismic safety of the low- and mid – rise structures, approximately 75 percent of the total building stock in Turkey, by generating theoretical fragility curves. They used moment resisting reinforced concrete frames with different numbers of stories. The Latin Hypercube Sampling was used for the selection of suitable data for whole population in general and ground motion prediction relationships for near and far-fault effects.

Shear wall building behavior under earthquake effects and its performance are observed from past earthquakes and experimental results. It has been noted that for shear wall buildings there is no collapse under earthquake effects. The inadequate number of research on the performance limits of shear wall buildings indicates conflicting results (Wallace and Moehle, 1992; Moehle, 1996).

The vulnerability analysis of buildings under three dimensional seismic effects is another topic of current interest. The main problem of these types of buildings is the assessment criteria, corresponding to damage indexes. Jeong and Elnashai (2006a, 2006b) proposed a new three dimensional damage index which takes into account the bidirectional and torsional response effects. The main purpose in their study is to estimate three dimensional damage capacity indexes, namely the global response of the structure under earthquake effects by way of simple frame systems. Aziminejad and Moghadam (2009), investigate the different configurations of centers of stiffness and strength to generate the fragility curves. By the way, the fragility functions for shear walls in terms of demand parameters related to damage proposed by Gulec et al. (2010). In this study, only the results of the non linear time history analysis and damage states specified by SMART 2008 and HAZUS 2003 MH MR-1 were taken into account.

2.2 Fragility Curves

One of the main objectives of this study was to obtain the fragility curves for this structural type to develop the behavior of shear wall buildings under different seismic excitations with torsion effects. The thresholds are given in Table 2.1 and Table 2.2 according to the SMART- 2008 (RAPPORT DM2S, 2009) and HAZUS 2003 MH MR-1 damage indicators, respectively. SMART-2008 damage states were defined by the project team. HAZUS 2003 damage states, which are developed for shear wall buildings, were used just to see the correlation and comparison of the SMART-2008 results with the defined damage states by the SMART-2008 project team.

Maximum inter-story drifts were used as a damage indicator. To investigate the local effects of the damage, the fragility curves were calculated at specified points shown in Figure 3.1. These damage levels are used as the criteria for the fragility analysis. H is the story height and equals to 1.2 m.

Table 2-1 Damage levels defined for maximum inter-story drifts (SMART 2008, RAPPORT DM2S, 2009)

Damage Levels	Drift Ratio
Light Damage	H/400 = 3
Controlled Damage	H/200 = 6
Extended Damage	H/100 =12

Table 2-2 HAZUS Average Inter-Story Drift Ratio of Structural Damage States (HAZUS-MH MR1 2003)

Damage Levels	Slight	Moderate	Extensive	Complete
Drift Angle	0.003	0.005	0.015	0.040
Drift (H=1200 mm)	3.6	6	18	48

Thirty bi- directionally applied time – history analyses were performed for the fragility analysis. According to the results of the fragility analysis, the log – normal distribution was assumed for the distribution of the structural response indicators and then the fragility curves were obtained according to median capacity, A_m and standard deviation, β of this distribution.

The probability of failure P_f of a structure or component conditioned on seismic ground motion level "a" is expressed by fragility curves as given in Equation (2.1).

$$\mathrm{P_f} \equiv \mathrm{P}(Failure|\mathrm{a}) = \mathrm{P}(\mathrm{A} < a) \tag{2.1}$$

Failure occurs if the actual capacity of the structure is inferior to the seismic demand, that is the given ground motion level "a". The failure probability conditioned on ground motion parameter "a" given by the cumulative distribution function of capacity A and *is* calculated from Equation (2.2).

$$\mathrm{P_f} = \Phi\left(\frac{\ln(\mathrm{a}) - \mathrm{A_m}}{\beta}\right) \tag{2.2}$$

To obtain the fragility curves from the probability density functions, we need to define the acceptable median capacity and standard deviations for the limit states defined in Table 2.1 and Table 2.2 under different seismic excitations. One of the methods used to determine the median capacity and the standard deviation is the regression analysis.

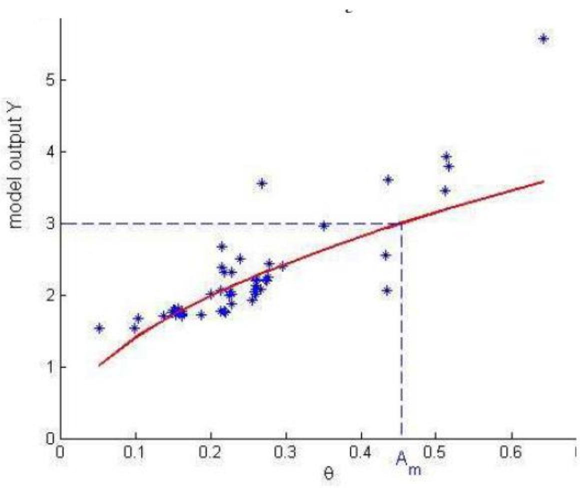


Figure 2-1 Regression analyses for model output Y (SMART 2008 Phase 2 Report, 2009).

To obtain the least error, the method of least squares is applied to the data in this study. Following regression analyses the needed median seismic capacity, A_m and log-standard deviation, β can be evaluated. For the evaluation of A_m, Y_{crit} value can be used as shown in Equation (2.4).

$$\ln(\mathrm{A_m}) = \frac{\ln(\mathrm{Y_{crit}}) - \alpha}{\mathrm{b}} \tag{2.4}$$

In Equation 2.7, Y_{crit} values were defined in the SMART 2008 Phase-2 report (RAPPORT DM2S, 2009) as damage levels which were given in Table 2.1.

3. MODEL BUILDING AND SPECIFICATIONS
3.1. Geometry, Material Properties, Shaking Table and Additional Loadings

The model building, is a 1/4 scale trapezoidal-plan, three-story reinforced concrete structure. It is composed of three walls forming a U shape, a column and a beam. The height of the floor levels are, accordingly, 1.25 m, 2.45m, and 3.65 m from the basement. The thickness of the slab is 10 cm. The geometrical details of column beam and walls are shown in Figure 3.1 and given in Table 3.1.

Table 3-1 Dimension of Structural Elements

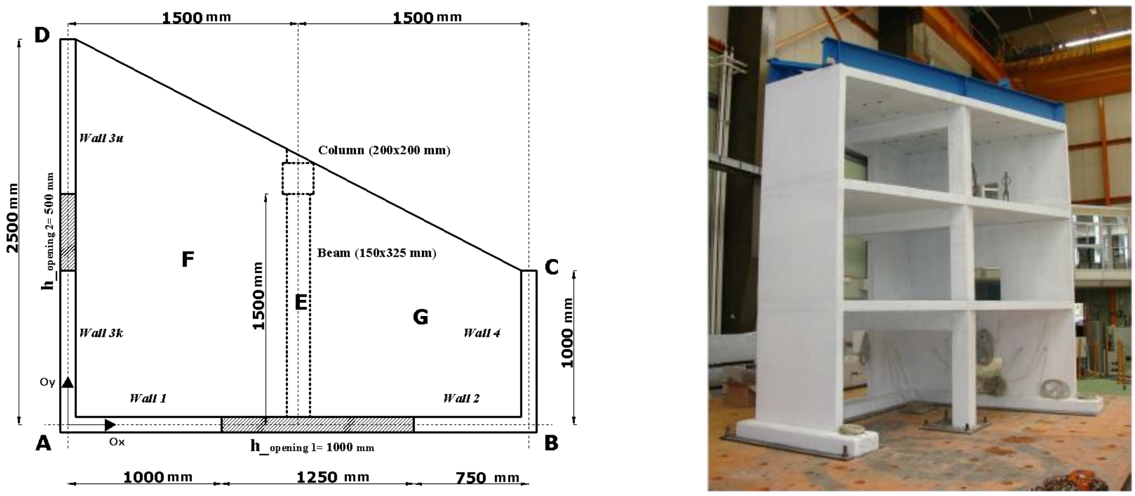
	Length (m)	Thickness (m)	Height (m)
Wall (#V01+#V02)	3.1	0.1	3.65
Wall #V03	2.55	0.1	3.65
Wall #V04	1.05	0.1	3.65
Beam	1.45	0.15	0.325
Column	3.8	0.2	0.2

Compressive and tensile strength of the concrete, elasticity modulus of concrete and Poisson’s ratio are given in Table 3.2.

Table 3-2 Materials characteristics

f_{cj} (MPa)	f_{tj} (MPa)	E_c (MPa)	ν_c	ν_s
30	2.4	32000	0.2	0.3

Additional loads on the first, second and third floor levels are given as 11.60 t, 12.00 t and 10.25 t, respectively. The average density of the reinforced concrete of the structure was taken 2460 kg/ m^3 as given in the SMART 2008 Phase 2 report (RAPPORT DM2S, 2009).
In this study, shaking table effects are not considered due to uncertainties in its mechanics according to the SMART 2008 Phase 2 report (RAPPORT DM2S, 2009).

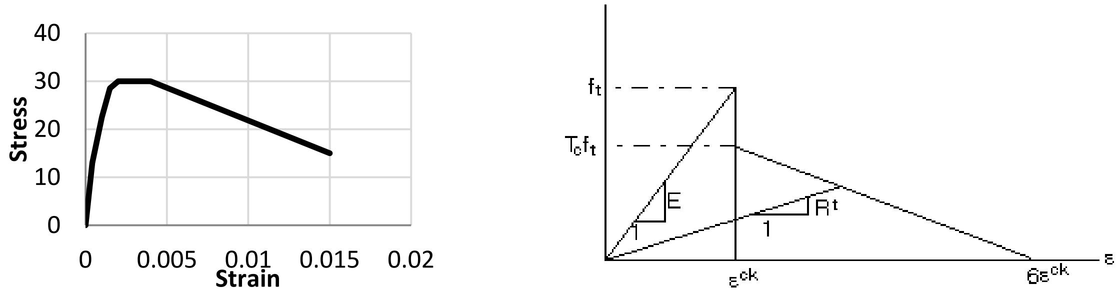


(a) (b)

Figure 3-1 Plan drawing of the SMART-2008 Specimen and the locations where results have to be computed

3.2. Numerical Model

Three–dimensional–modeling approach was chosen for analyzing the specimen. ANSYS v12.1 was used for the finite element platform. The element type chosen for this purpose is SOLID 65 (3-D Reinforced concrete element). Smeared modeling was preferred for the definition of the reinforcement in the model. The CONCRETE material type and multi-linear kinematic hardening models were used in the numeric model as given in the Figure 3.2 (ANSYS v12 User Manual). For CONCRETE material type open shear transfer coefficient, 0.2 and closed shear transfer coefficient, 0.8, are used. The uniaxial cracking stress is 2.4 MPa.



(a) (b)

Figure 3-2 MKIN Stress- Strain Relationship (a), Strength of Cracked Condition (b)

The model developed for this study consists of 28740 concrete elements and 5282 mass types. The model has 43179 nodes for stress calculations.

Shaking table and foundation were not modeled and basement was assumed as fixed supported (RAPPORT DM2S, 2009) (Figure 3.3). Seismic excitations were applied at basement level bi-directionally in the analytical model.

The given figures of the model (Figure 3.3) were chosen for their real constant change. In other words, different colors in the model represent the change in the reinforcement ratios in concrete elements. 74 real constants were defined in the model for the reasonably accurate simulation of the real structure with smeared modeling approach of the reinforcement.

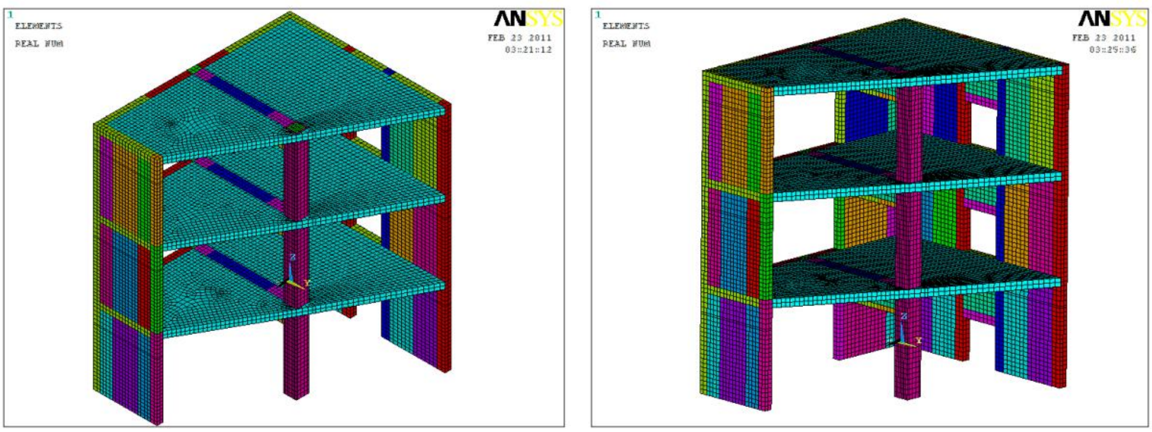


Figure 3-3 Representations of the model building

Model structure is validated by the experimental results which were provided by the SMART-2008 project team in terms of the displacement responses and acceleration responses at specified points. The relationship between the ground motion intensity and the damage investigated in Yakut and Yılmaz (2008) study. The results of the validation can be obtained from the Akansel et al (2010) and Nazirzadeh et al (2011) studies.

4. RESULTS AND DISCUSSION

Damage indicators for the fragility analysis are given as maximum inter-story drift results from the time-history analyses and different seismic intensity measures such as PGA, PGV, PGD and CAV have been used as seismic ground motion indicators. PGA is a basic measure of earthquake potential however it is not reliable all time. For instance, earthquakes with a very large PGA could not produce appreciable structural damage, while earthquakes with a very low PGA could produce an unexpectedly high level of destruction. Thus, the other parameters such as the PGV seem to be another representative measure of earthquake intensity. PGV is directly related with the energy demand. CAV is also used because of this reason. In this study, all this seismic indicators were investigated separately.

Regression analyses done for both X and Y directions for seismic ground motion indicators (SGMI) and maximum inter-story drift (MISD) results were obtained from time history analyses on points A, B, C, D, E, F and G (Figure 3.1-a) with respect to the given damage indicators . In this study, only point E will be demonstrated due to better correlation coefficients with respect to the calculated responses. In Figure 4.1, regression analysis results for Point E under PGA seismic ground motion intensity are displayed for both x and y direction maximum inter story drift results.

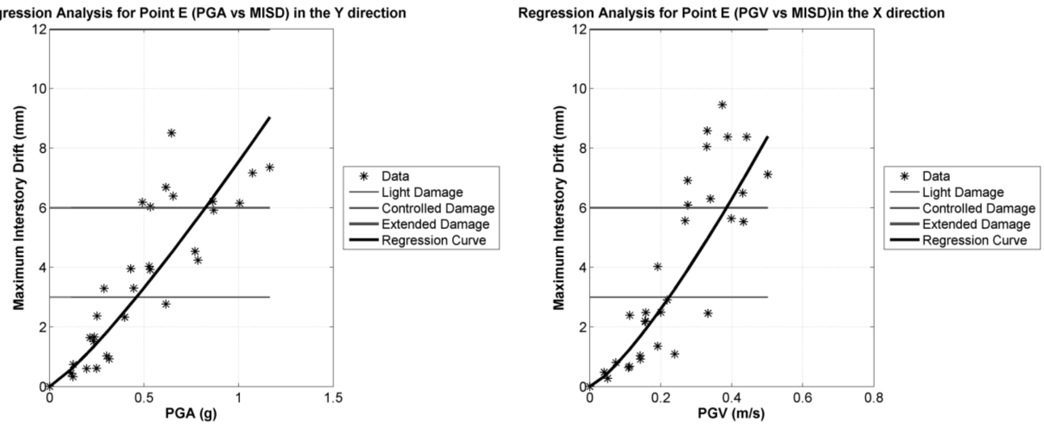


Figure 4-1 Regression Analysis for Point E

The correlation coefficients for regression curves are shown in Table 4-1 and the probabilities of the data exceeding the damage levels are given in Table 4-2 for both SMART 08 and HAZUS damage states. According to this information, it can be observed that only the A_m, seismic median capacities, which represent the fifty percent probability of exceedence, changed as shown in Table 4.3.

The probabilities of the data exceeding the damage levels according to HAZUS and SMART 2008 damage limits are shown. Controlled damage and moderate damage levels were similar because of having same damage state values and small increase in the slight damage. Extended and extensive damage level probabilities of the data exceeding these levels did not change.

Table 4-1 Correlation coefficients for time history data versus fitted curves

	PGA_x	PGA_y	PGV_x	PGV_y	PGD_x	PGD_y	CAV_x	CAV_y
Point E	0.89	0.91	0.92	0.87	0.86	0.82	0.94	0.97

Table 4-2 The damage levels probabilities

	X Direction			Y Direction		
	LD	CD	ED	LD	CD	ED
Point E (SMART 08 damage levels)	0.55	0.13	0.32	0.45	0.26	0.29
Point E (HAZUS damage levels)	0.55	0.13	0.32	0.52	0.19	0.29
LD = Light Damage; CD = Controlled Damage; ED = Extended Damage						

Table 4-3 A_m –Seismic median capacity coefficients for data

	PGA_x			PGV_x			PGD_x			CAV_x		
	LD-SD	***CD-MD***	***ED-ED***	***LD-SD***	***CD-MD***	***ED-ED***	***LD-SD***	***CD-MD***	***ED-ED***	***LD-SD***	***CD-MD***	***ED-ED***
Point E_X (Smart 08)	0.45	0.8	1.42	0.22	0.39	0.66	0.08	0.14	0.25	7.09	14.91	31.36
Point E_X (HAZUS)	0.52	0.8	2	0.26	0.39	0.91	0.1	0.14	0.34	8.63	14.91	48.43
	PGA_y			PGV_y			PGD_y			CAV_y		
	LD-SD	***CD-MD***	***ED-ED***	***LD-SD***	***CD-MD***	***ED-ED***	***LD-SD***	***CD-MD***	***ED-ED***	***LD-SD***	***CD-MD***	***ED-ED***
Point E_Y (Smart 08)	0.46	0.82	1.48	0.23	0.4	0.7	0.09	0.15	0.26	7.32	15.37	32.27
Point E_Y (HAZUS)	0.54	0.82	2.08	0.27	0.4	0.96	0.1	0.15	0.36	8.89	15.37	49.8

In Figure 4.2, the fragility curves calculated for both SMART 2008 damage states and HAZUS damage states are compared. According to this comparison, the HAZUS damage states give lower probability of failure especially for the extensive damage state. The scatter between the damage states increases when the HAZUS damage states are taken into account.

Controlled damage and moderate damage levels were similar to each other because of having the same damage limit value as 6 mm and the difference between the slight damage and light damage is only 0.6 mm and did not affect the curves.

The fragility curves obtained from the SMART 2008 damage states are more conservative than the HAZUS ones. This difference might be admissible when the SMART 2008 structure was to be designed according to nuclear plant specifications. The biggest difference is in the Extended Damage and Extensive Damage states.

An important point to keep in mind is that HAZUS damage states are defined to represent a large scale of buildings that have no torsional irregularity. However, the fragility curve obtained in this study is only for one structure only. That is considered to be a reason for the difference in the fragility curves corresponding to the Extended and the Extensive damage states.

In Figure 4.2 and 4.3, it can also be observed that fragility curves give low probabilities of failure for Controlled-Moderate and Extended-Extensive damage limits even for high level of ground motion excitations. This means that this type of shear wall building structure behaves well when subjected to earthquakes.

To examine one of the fragility figures, Point E in the X direction and PGA as seismic ground motion indicator was chosen. Figure shows both HAZUS and SMART-2008 fragility curves for specified damage states. For the fragility curves calculated for SMART 2008 damage states, under 0.52 g of PGA, the model has 36.4 % of probability of no damage (above the light damage curve), 45.2 % of light damage (between the light damage and the controlled damage curves), 16.8 % of controlled damage (between the controlled damage and the extended damage curves) and 1.6 % of extended damage (under the extended damage curve).

For the fragility curves calculated for HAZUS damage states, for the same input, the probabilities are 49 % for no damage (above the slight damage curve), 32.64 % or slight damage (between the slight damage and the moderate damage curves), 18.16 % for moderate damage (between the moderate damage and extensive damage curves) and 0.2% for extensive damage (under the extensive damage curve). The influence of damage state limits is observed to be significantly affecting the fragilities.

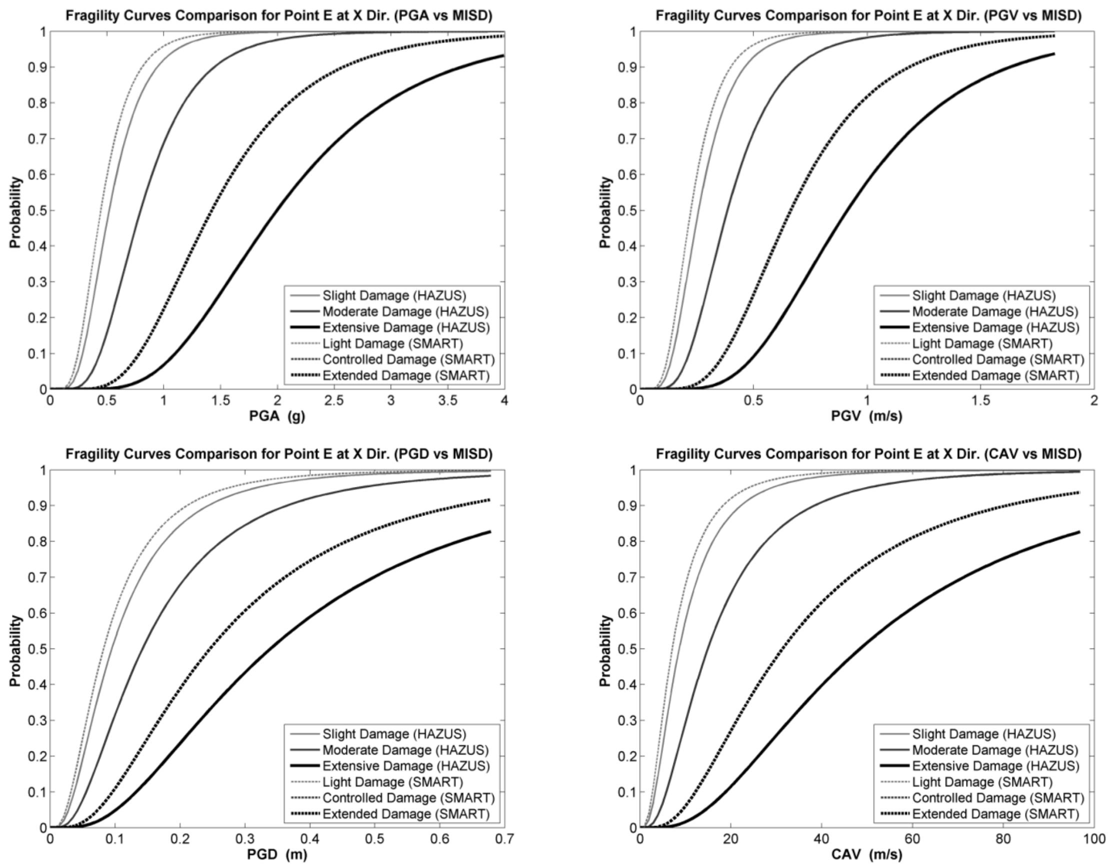


Figure 4-2 Fragility Curves Comparisons of Point E for various seismic motion indicators at X direction

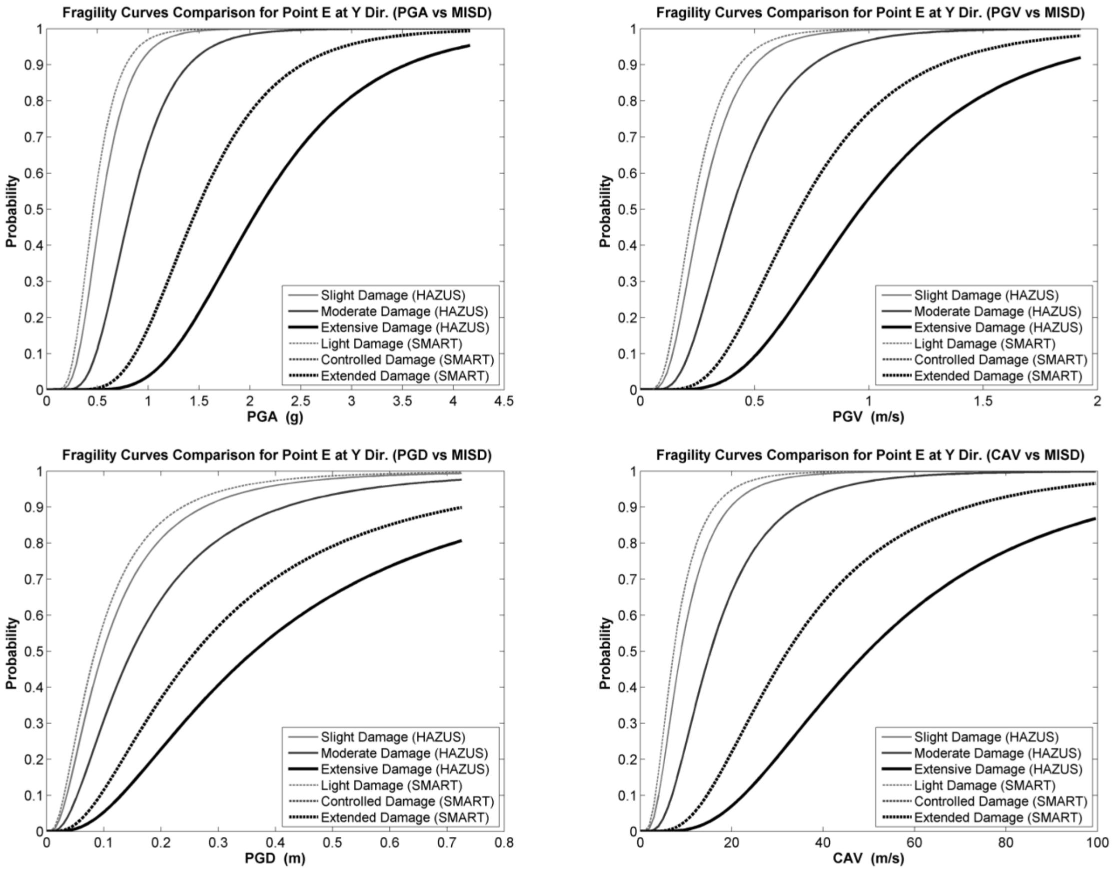


Figure 4-3 Fragility Curves Comparisons of Point E for various seismic motion indicators at Y direction

We counsel against rash extrapolation of these conclusions on the basis of a single model building to the broad class of shear wall type of structures. Our extensive calculations have shown a very good agreement between experiment and theory, supporting the power of the computational approach in obtaining far-reaching generalizations. The model was designed to experience significant coupled translation-torsion during its dynamic response, and the computations captured that well. Interpretation of the drifts in terms of the different damage states according to two different sets of criteria shows acceptable consistency.

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