SERIES
8-9 February 2012, Istanbul
Seismic Engineering Research Infrastructures for European Synergies
University of Patras • European Commission • Framework Programme 7
İstanbul Teknik Üniversitesi 1773
International Workshop "Role of research infrastructures in seismic rehabilitation"

"Structural Vulnerability Functions and the Comparison of the Observed Damages of RC Buildings After Major Turkish Earthquakes"

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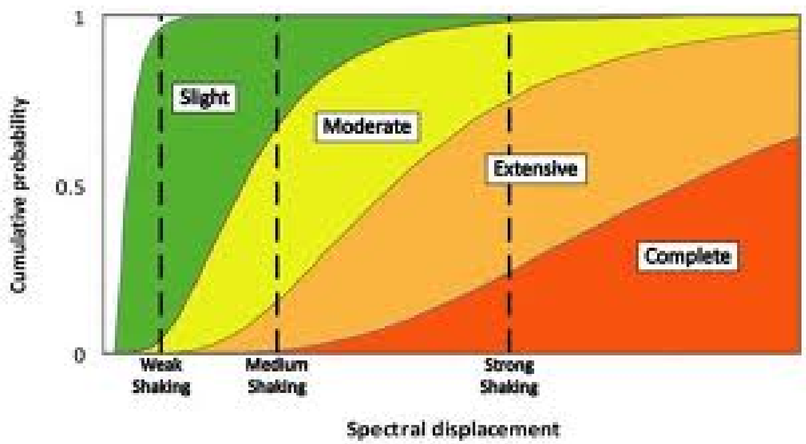
What is a Fragility Function?

- ➔ Fragility functions (*vulnerability curves*) relate the probability of exceedence of multiple damage states to a parameter of ground motion severity.
- ➔ They can be regarded as a graphical representation of seismic risk.



$$P[D/GMP]=\Phi((\ln(GMP)-\mu/\sigma)$$

↓

The conditional probability of a structure to reach or exceed a specific damade state, D, given the GMP.

- ✘ Seismic risk assessments were carried out on populations of buildings to identify the urban areas most likely to undergo large life and economic losses during an earthquake.
- ➔ Seismic risk assessments are important in the mitigation of losses under future seismic events.

Purpose of the Study

➔ Seismic damages to buildings during the recent major earthquakes of Turkey has emphasized the need for risk assessment of existing Turkish building stock to estimate the potential damage from future events.

➔ Destructive earthquakes within the last decades proved that structures, especially those constructed prior to the 1975 earthquake code, have experienced severe damages and partial or even total collapse.

➔ Damage to Turkish existing buildings mainly depends on;

- poor structural material quality,
- inadequate reinforcement detailing,
- lack of confinement zones,
- heavy and large-span cantilevers,
- indirect supporting that prevents the formation of regular structural frames.

Purpose of the Study

- ➔ Buildings have to be sufficient to resist the moderate/major earthquakes that typify the seismicity of our region with an acceptable degree of damage.

- ➔ 'Acceptable' damage varies according to the importance of the buildings, their use and the severity of the ground motion.

- ➔ Typically multiple performance criteria need to be satisfied.

  - ✓ Prediction tools (*vulnerability curves)* are required that will allow the seismic risk assessment of populations of buildings to be carried out within a performance framework.

Categorization of Vulnerability Curves

(*Rosetto T, Elnashai A. 2003*)

Category	Characteristics	
Empirical vulnerability curve	Feature	Based on post-earthquake survey Most realistic
	Limitation	Highly specific to a particular seismo-tectonic, geotechnical and built environment The observational data used tend to be scarce and highly clustered in the low-damage, low-ground-motion severity range Include errors in building damage classification Damage due to multiple earthquakes may be aggregated
	Sample ref.	*(Orsini G., 1999)*
Judgmental vulnerability curve	Feature	Based on expert opinion The curves can be easily made to include all the factors
	Limitation	The reliability of the curves depends on the individual experience of the experts consulted A consideration of local structural types, typical configurations, detailing and materials inherent in the expert vulnerability predictions
	Sample Ref.	*(ATC-13, 1985)*
Analytical vulnerability curve	Feature	Based on damage distributions simulated from the analyses Reduced bias and increased reliability of the vulnerability estimate for different structures
	Limitation	Substantial computational effort involved and limitations in modeling capabilities The choices of the analysis method, idealization, seismic hazard, and damage models influence the derived curves and have been seen to cause significant discrepancies in seismic risk assessments
	Sample Ref.	*(Mosalam et.al, 1997; Reinhorn et.al., 2001; Chryssanthopoulos et.al., 2000)*
Hybrid vulnerability curve	Feature	Compensate for the scarcity of observational data, subjectivity of judgmental data, and modeling deficiencies of analytical procedures Modification of analytical or judgment based relationships with observational data and experimental results
	Limitation	The consideration of multiple data sources is necessary for the correct determination of vulnerability curve reliability
	Sample Ref.	*(Kappos et.al., 1995)*

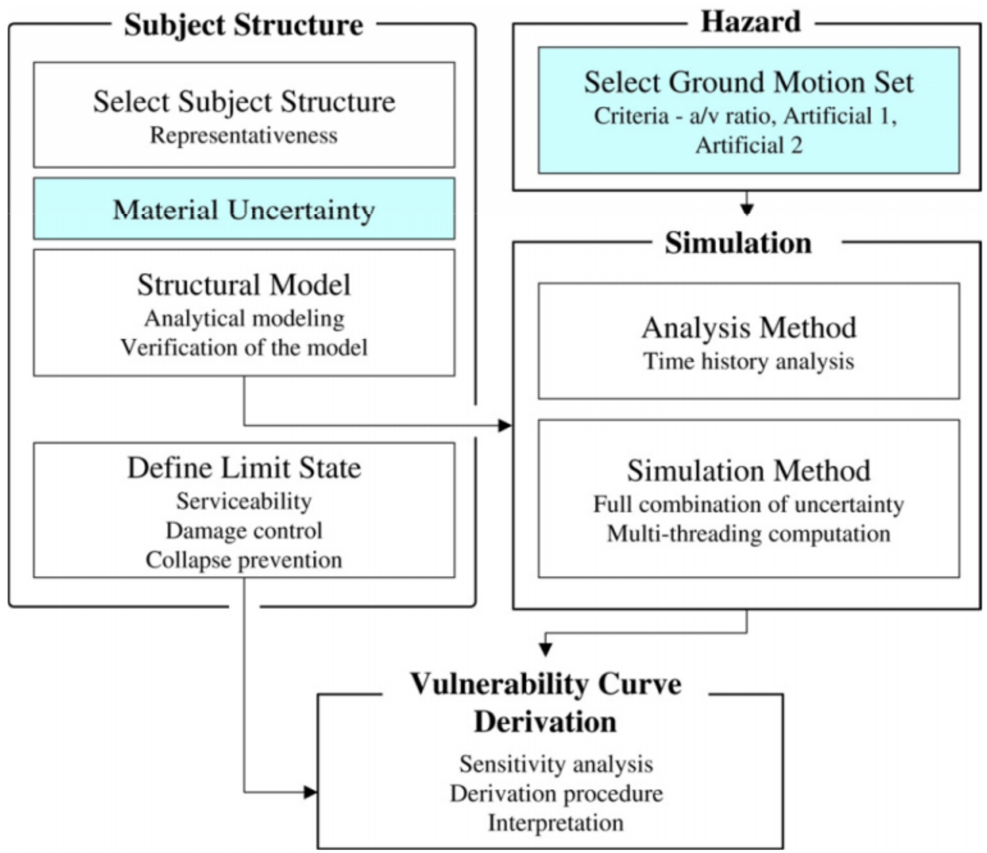
Derivation of Analytical Vulnerability Functions

➔ Vulnerability functions exhibit considerable variability depending on the approaches used in their derivation.

☞ The factors that influence the vulnerability functions are;

- input ground motion sets,
- severity indices of ground motions,
- performance limit states,
- source of structural damage data,
- structural modeling method,
- analysis platform characteristics,
- analysis method.

«Flow chart for the derivation of analytical vulnerability curves»



Summary of Some Existing Curve Characteristics

(*Rosetto T, Elnashai A. 2003*)

Source	Type[a]	Country	Structural unit	Curve Function[b]	GMP[c]	Damage scale
Spence et al.	E	S.Europe	Pre-code MRF	Normal	PSI[g]	MSK
Orsini	E	Italy	Apartments	Normal	PSI[g]	MSK
Yamazaki	E	Japan	Pre-, old- and new-code MRF	Lognormal	PGV	AIJ
Miyakoshi	E	Japan	Pre-, old- and new-code MRF	Lognormal	PGV	Property loss
ATC-13	J	USA	Bare/infilled MRF, various heights and codes considered	Lognormal	MMI	ATC-13.
Onose	A	Japan	Low/mid-rise MRF	Lognormal	PGA	Ductility
Singhal et al.	A	USA	Low-, mid- and High-rise MRF	Lognormal	$Sa_{5\%}(T_{elastic})$	Park and Ang
Mosalam et.al	A	USA	Low-rise MRF	$(1-\alpha exp^{\beta})$	PGA	ISD (%)
Mosalam et.al	A	USA	Low-rise Infilled MRF	$(1-\alpha exp^{\beta})$	PGA	ISD (%)

[a] Type of vulnerability curve: Empirical (E), Analytical (A), Judgement (J).
[b] Cumulative distribution function or equation defining the vulnerability curve shape.
[c] Ground motion parameter used by the curves.

Steps of the Study

➔ ***Step-I:*** Nonlinear dynamic analyses are carried out

- 17 low- and mid-rise RC frame structures,
  - ✓ Seismic zone-1 ; local soil class Z2
  - ✓ Comparatively symmetric; regular structural system
  - ✓ *moderately damaged*
- DRAIN-2DX (Prakash et. al., 1993)
- non-structural infill walls are also introduced within the planar structural models.

➔ ***Step-II:*** To compare the structural responses with the code limits and existing shear force carrying capacities

➔ ***Step-III:*** Comparison of the observed damage with a damage indice (*Di Pasquale and Çakmak, 1987*)

➔ ***Step-IV:*** To compare the results in order to investigate the applicability of recently proposed fragility functions

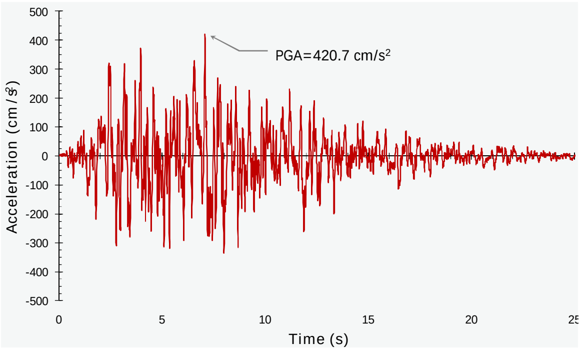
Earthquake Ensemble

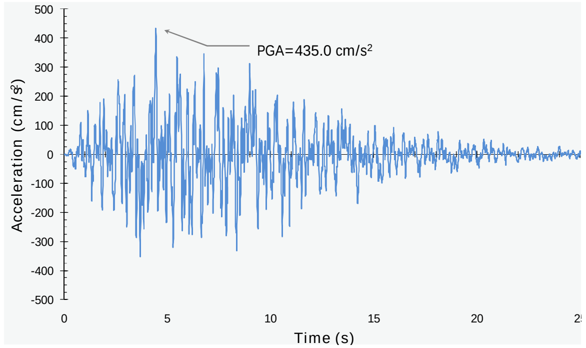
SUNY-ESL ☞ TARSCTHS (*Papageorgiou et al., 2000*)

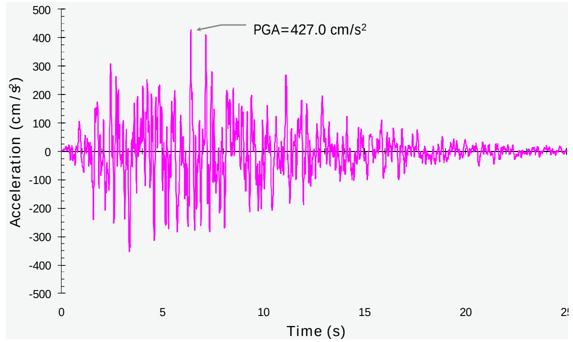
- 7 simulated motions
- each with a duration of 25 seconds
- effective ground acceleration of A_0=0.40g for seismic zone-1
- local soil class of *Z*2 with characteristic periods of T_A=0.15s and T_B=0.40s;

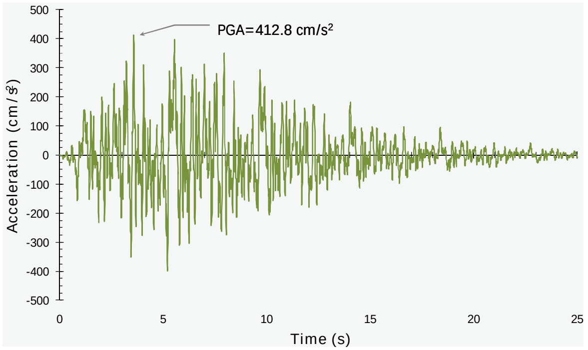
are generated compatible with the design spectrum defined in the TERDC, which has a probability of exceedance of 10% within 50 years.

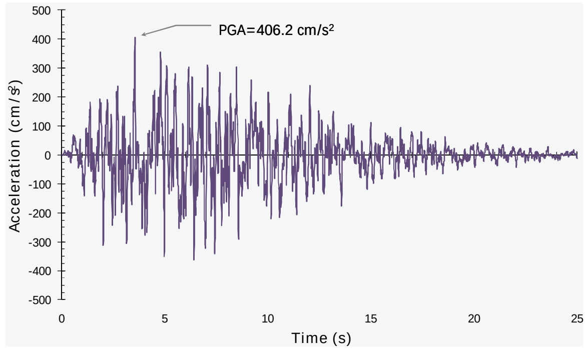
Earthquake Ensemble

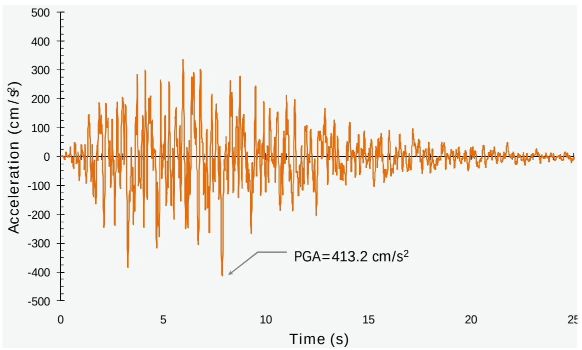


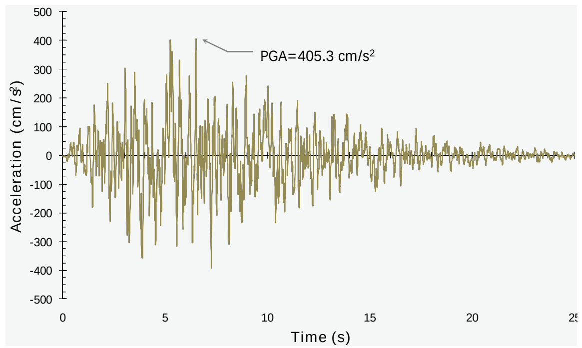




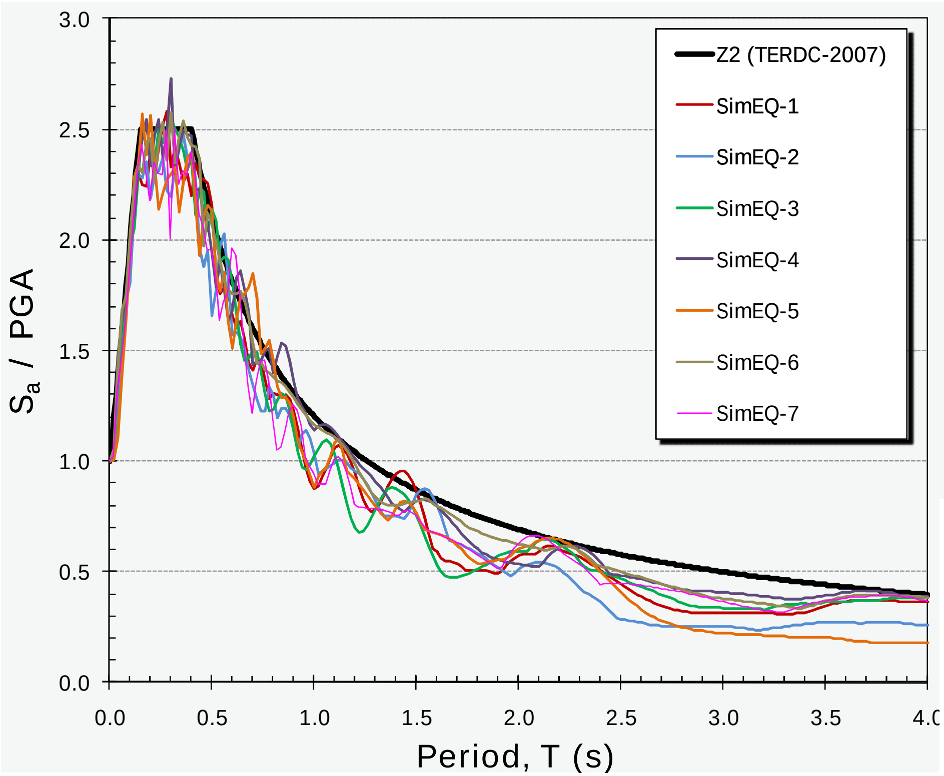




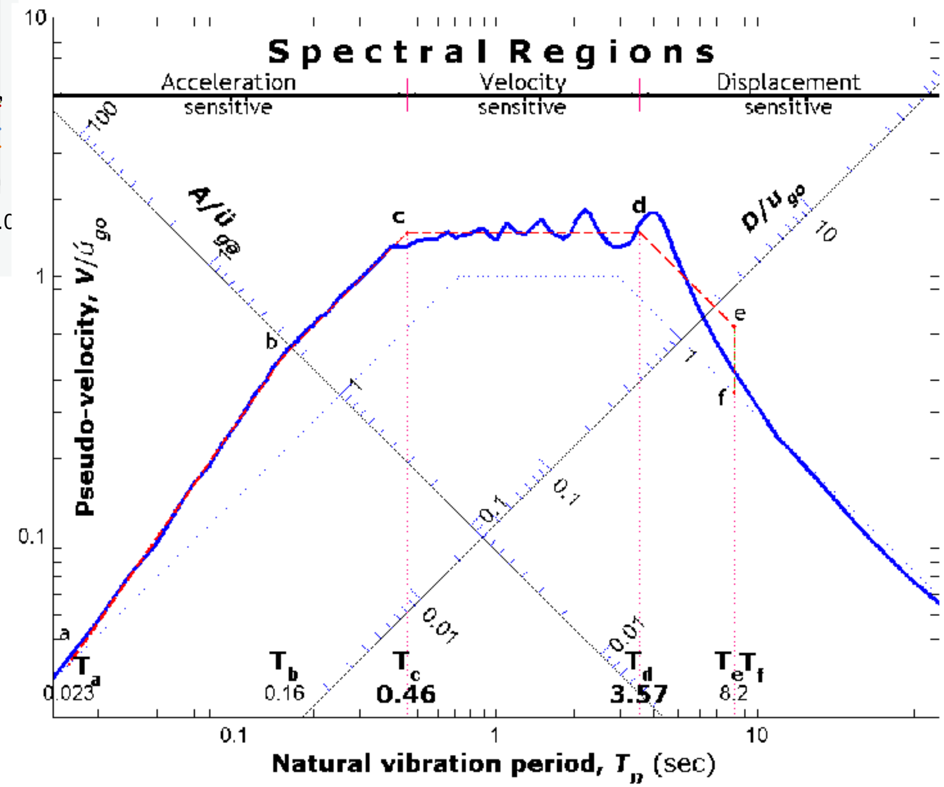




Earthquake Ensemble



«Elastic Response Spectra of Ground Motions and Design Spectra in TERDC-2007»



«Tripartite Elastic Response Spectra of the Earthquake Ensemble»

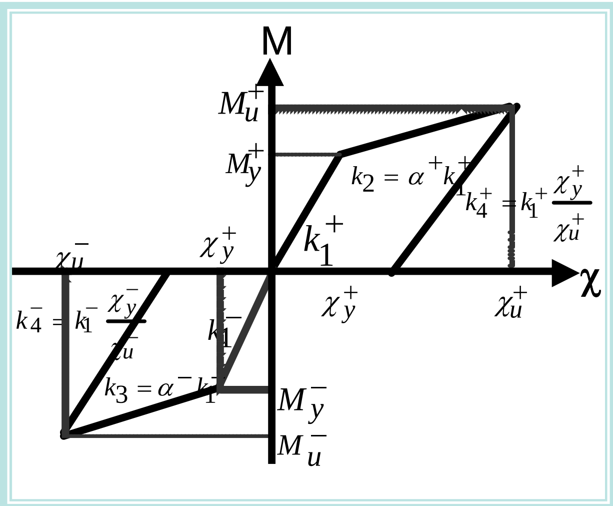
Step I: Structural Properties of the Building Stock

➔ Most of the damaged buildings in Turkey are observed to be designed brittle, weak in stiffness and strength and poor in material qualities due to the lack of proper amount of engineering service during the design and site-control stages.

Code Name	Direction	No of Stories	h_{Total} (m)	f_{ck} (MPa)	W (kN)	$T_{1(x\text{-}x/y\text{-}y)}$ (s)
GUL	y-y	4	12.00	14.0	17100.0	0.469
L11	x-x / y-y	3	8.25	16.0	3950.7	0.324 / 0.351
P01	x-x / y-y	6	14.5	16.5	10750.7	0.502/0.544
P06	x-x / y-y	6	13.75	13.3	8104.4	0.442/0.445
P20	x-x / y-y	3	8.85	8.6	7676.8	0.439/0.319
P21	x-x / y-y	4	12.1	10.0	6382.8	0.532/0.490
P23	x-x / y-y	3	8.7	8.3	3872.7	0.356/0.379
P24	x-x / y-y	5	11.00	11.4	7859.3	0.196 / 0.519
P25	x-x / y-y	4	11.05	12.0	5890.4	0.539/0.557
P30	x-x / y-y	3	8.55	11.9	4009.2	0.302 / 0.285
P48	x-x / y-y	3	8.10	9.4	3556.9	0.393 / 0.421
P51	x-x / y-y	4	12.25	13.1	5731.8	0.527 / 0.496
P79	x-x / y-y	6	13.75	11.5	8104.4	0.451/0.454
SE05	x-x / y-y	5	14.25	8.2	10587.2	0.921/0.604
SL07	x-x / y-y	5	15.3	11.7	7383.9	0.855/0.545
YDB	x-x / y-y	2	5.60	12	4594	0.222/0.233
VKB	x-x / y-y	3	7.95	12	5789	0.467/0.384

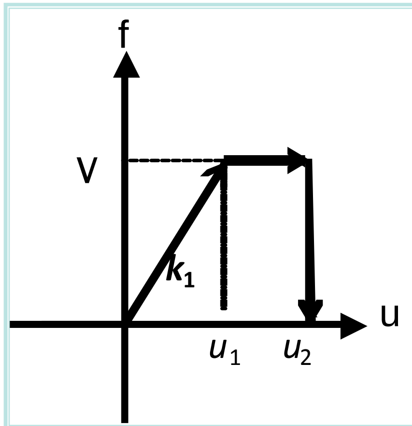
Step I: Analytical Modeling of the Structural Systems (Cont.)

- Buildings are modeled utilizing **DRAIN-2DX** program (*Prakash et al. 1993*), the modified version by *Ascheim (2005)* is preferred, which is capable of handling the stiffness degradation.



"Hysteretic model for non-linear behaviour of RC elements"

- Element type-7 for stiffness-degrading elements and type-9 for the non-structural walls are assigned.



"Hysteresis for non-linear behaviour of infill walls"

$$a_w = 0.175 r_w \left(H \left(\frac{E_w t \sin 2\theta}{4 E_c I_c h_w} \right)^{1/4} \right)^{-0.4}$$

«Wall model by: Al-Chaar ve Lamb (2002) and TEDRC (2007)»

Step I: Nonlinear Dynamic Analyses Results (Cont.)

Code Name	*W* (kN)	$u_{top(x\text{-}x)}$	$u_{top(y\text{-}y)}$	$V_{base(x\text{-}x)}$ (kN)	$V_{base(y\text{-}y)}$ (kN)	$V_{r(x\text{-}x)}$ (kN)	$V_{r(y\text{-}y)}$ (kN)	$M_{0(x\text{-}x)}$ (kNm)	$M_{0(y\text{-}y)}$ (kNm)
GUL	17100.0	-	0.124	-	1649.4	-	742.62	-	19574.1
L11	3950.7	0.131	0.101	234.5	242.4	253.05	290.07	2966.4	3695.3
P01	10750.7	0.126	0.139	1206.3	1239.8	n/a	n/a	19080.4	17809.6
P06	8104.4	0.099	0.098	1059.2	1004.8	n/a	n/a	12875.3	12279.9
P20	7676.8	0.124	0.076	733.3	1034.8	n/a	n/a	6889.7	10174.1
P21	6382.8	0.166	0.146	636.2	527.9	n/a	n/a	5515.7	6359.1
P23	3872.7	0.102	0.117	310	315	n/a	n/a	3539.8	3333.9
P24	7859.3	0.031	0.15	380.8	335.7	376.94	408.35	5077.6	6370.4
P25	5890.4	0.152	0.16	428.8	374.1	n/a	n/a	5345.2	4976.1
P30	4009.2	0.066	0.063	32.3	35.2	218.33	218.33	24451.9	5766.9
P48	3556.9	0.11	0.143	205.2	144.4	129.78	129.78	3233.7	2404.8
P51	5731.8	0.147	0.142	429.9	512.3	511.26	455.70	5094.2	5918.8
P79	8104.4	0.104	0.103	957.8	930.4	n/a	n/a	12133	11781.3
SE05	10587.2	0.238	0.175	543	807.7	n/a	n/a	6142.6	9882.3
SL07	7383.9	0.195	0.145	223.8	367.1	n/a	n/a	4499.1	7791.9

Step I: Nonlinear Dynamic Analyses Results (Cont.)

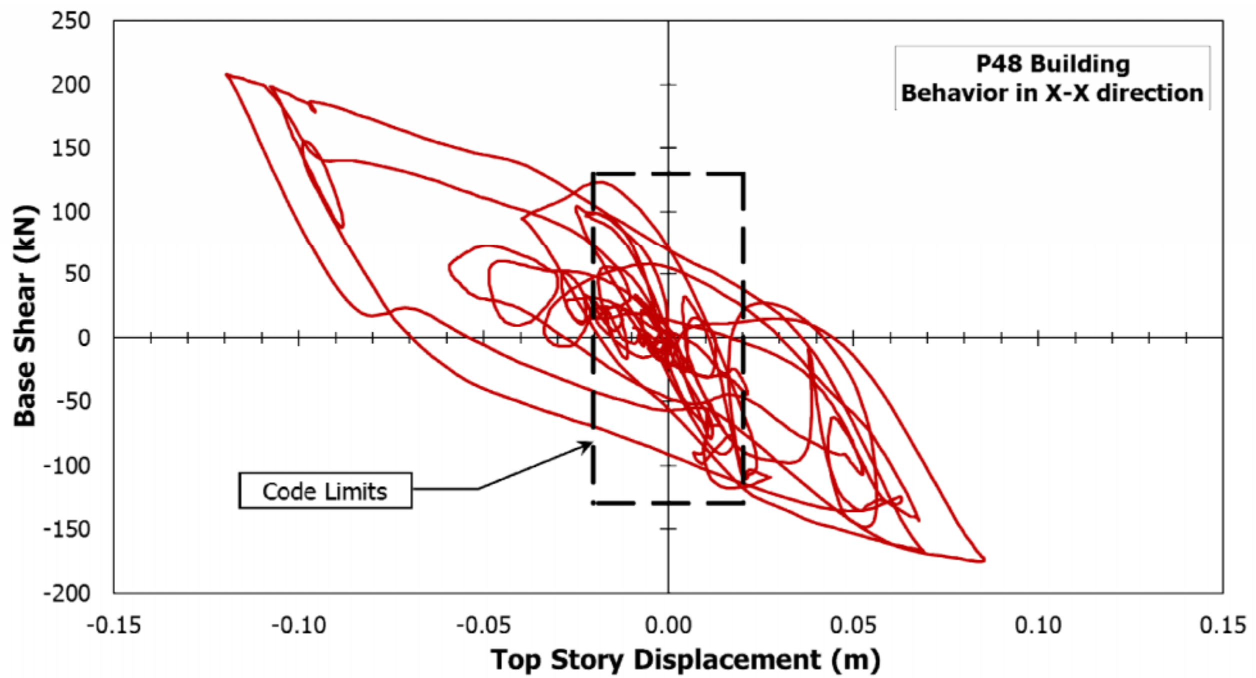
Code Name	h_{Total} (m)	Stories	h_{story}	Δ_i (x-x)	Δ_i (y-y)	Δ_i/h_{story} (x-x)	Δ_i/h_{story} (y-y)
GUL	12.00	3	3.0	-	0.011	-	0.004
		2	3.0	-	0.053	-	0.018
		1	3.0	-	0.029	-	0.010
		ZK	3.0	-	0.041	-	0.014
L11	8.25	2	2.75	0.019	0.006	0.007	0.002
		1	2.75	0.053	0.048	0.019	0.017
		ZK	2.75	0.062	0.053	0.023	0.019
P01	14.5	4	2.9	0.005	0.008	0.002	0.003
		3	2.9	0.012	0.018	0.004	0.006
		2	2.9	0.024	0.032	0.008	0.011
		1	2.9	0.036	0.038	0.012	0.013
		ZK	2.9	0.036	0.034	0.012	0.012
		BK	2.9	0.02	0.019	0.007	0.007
P06	13.75	4	2.75	0.028	0.027	0.010	0.010
		3	2.75	0.012	0.011	0.004	0.004
		2	2.75	0.021	0.021	0.008	0.008
		1	2.75	0.032	0.034	0.012	0.012
		ZK	2.75	0.036	0.035	0.013	0.013
		BK	2.75	0.0	0.0	0.000	0.000
P20	8.85	2	2.95	0.018	0.017	0.006	0.006
		1	2.95	0.05	0.031	0.017	0.011
		ZK	2.95	0.059	0.035	0.020	0.012
P21	12.1	3	2.8	0.029	0.028	0.010	0.010
		2	2.8	0.054	0.047	0.019	0.017
		1	2.9	0.06	0.057	0.021	0.020
		ZK	3.6	0.027	0.028	0.008	0.008

Step I: Nonlinear Dynamic Analyses Results (Cont.)

Code Name	h_{Total} (m)	Stories	h_{story}	Δ_i (x-x)	Δ_i (y-y)	Δ_i/h_{story} (x-x)	Δ_i/h_{story} (y-y)
P23	8.7	2	2.9	0.027	0.032	0.009	0.011
		1	2.9	0.042	0.043	0.014	0.015
		ZK	2.9	0.036	0.043	0.012	0.015
P24	11.00	3	2.75	0.001	0.003	0.000	0.001
		2	2.75	0.007	0.035	0.003	0.013
		1	2.75	0.013	0.054	0.005	0.020
		ZK	2.75	0.012	0.053	0.004	0.019
		BK	2.75	0.0	0.0	0.000	0.000
P25	11.05	3	2.75	0.047	0.043	0.017	0.016
		2	2.75	0.032	0.038	0.012	0.014
		1	2.75	0.053	0.055	0.019	0.020
		ZK	2.8	0.058	0.052	0.021	0.019
P30	8.55	2	2.80	0.01	0.013	0.004	0.005
		1	2.80	0.06	0.056	0.021	0.020
		ZK	2.95	0.004	0.001	0.001	0.000
P48	8.10	2	2.7	0.008	0.041	0.003	0.015
		1	2.7	0.037	0.055	0.014	0.020
		ZK	2.7	0.069	0.051	0.026	0.019
P51	12.25	3	2.75	0.066	0.051	0.024	0.019
		2	2.75	0.016	0.028	0.006	0.010
		1	2.75	0.039	0.041	0.014	0.015
		ZK	4.0	0.091	0.063	0.023	0.016
P79	13.75	4	2.75	0.031	0.029	0.011	0.011
		3	2.75	0.011	0.011	0.004	0.004
		2	2.75	0.021	0.02	0.008	0.007
		1	2.75	0.034	0.035	0.012	0.013
		ZK	2.75	0.04	0.039	0.015	0.014
		BK	2.75	0.0	0.0	0.000	0.000
SE05	14.25	4	2.85	0.06	0.031	0.021	0.011
		3	2.85	0.048	0.033	0.017	0.012
		2	2.85	0.075	0.049	0.026	0.017
		1	2.85	0.079	0.048	0.028	0.017
		ZK	2.85	0.078	0.037	0.027	0.013
SL07	15.3	3	2.8	0.002	0.003	0.001	0.001
		2	3.0	0.041	0.034	0.014	0.011
		1	3.0	0.08	0.05	0.027	0.017
		ZK	3.4	0.098	0.052	0.029	0.015
		BK	3.1	0.0	0.0	0.000	0.000

Step II: To Compare the Structural Responses

➔ The top story displacements (U_{top}) versus base shear (V_b) demands for P48 building in X-X direction under the effect of Sim EQ-4 ground motion ;



- ✓ *In most of the buildings, base shear demands slightly exceed the code limits.*
- ✓ *Besides, for all the buildings, top story displacement significantly exceeds the code limits.*

Step III: Comparison of the observed damage with a damage indice

➔ *Di Pasquale and Çakmak, 1987*

$$\delta_f = 1 - \frac{(T_1)^2}{\left[(T_1)^*\right]^2}$$

✓ *Similar results with the observed damage state of building ensemble.*

Code Name	$T_{1x\text{-}x}$ (s)	$T_{1y\text{-}y}$ (s)	$T_{1x\text{-}x}^*$ (s)	$T_{1y\text{-}y}^*$ (s)	$\delta_{fx\text{-}x}$	$\delta_{fy\text{-}y}$
GUL	-	0.469	-	1.753	-	0.928
L11	0.324	0.351	2.389	2.517	**0.982**	0.981
P01	0.502	0.544	1.7	1.788	0.913	0.907
P06	0.442	0.445	1.233	1.22	**0.871**	0.867
P20	0.439	0.319	1.721	1.248	0.935	0.935
P21	0.532	0.49	2.096	2.075	0.936	0.944
P23	0.356	0.379	1.673	1.729	0.955	0.952
P24	0.196	0.519	0.697	2.166	0.921	0.943
P25	0.539	0.557	2.255	2.61	0.943	0.954
P30	0.302	0.285	1.382	1.244	0.952	0.948
P48	0.393	0.421	2.542	2.899	0.976	0.979
P51	0.527	0.496	2.484	2.085	0.955	0.943
P79	0.451	0.454	1.351	1.298	0.889	0.878
SE05	0.921	0.604	4.136	2.68	0.950	0.949
SL07	0.855	0.545	3.082	2.379	0.923	0.948

Step IV: Comparison of the results with some of the existing vulnerability curves

➔ *Some of the promising functions developed by different researchers depending on many parameters;*

- ✓ *Singhal and Kiremidjian, 1996*
- ✓ *Rosetto and Elnashai, 2003*
- ✓ *Akkar et.al., 2005*
- ✓ *Kırçıl and Polat, 2006*
- ✓ *Ay, Erberik and Akkar, 2006*
- ✓ *Erberik, 2007*
- ✓ *İbrahim and El-Shami, 2011*

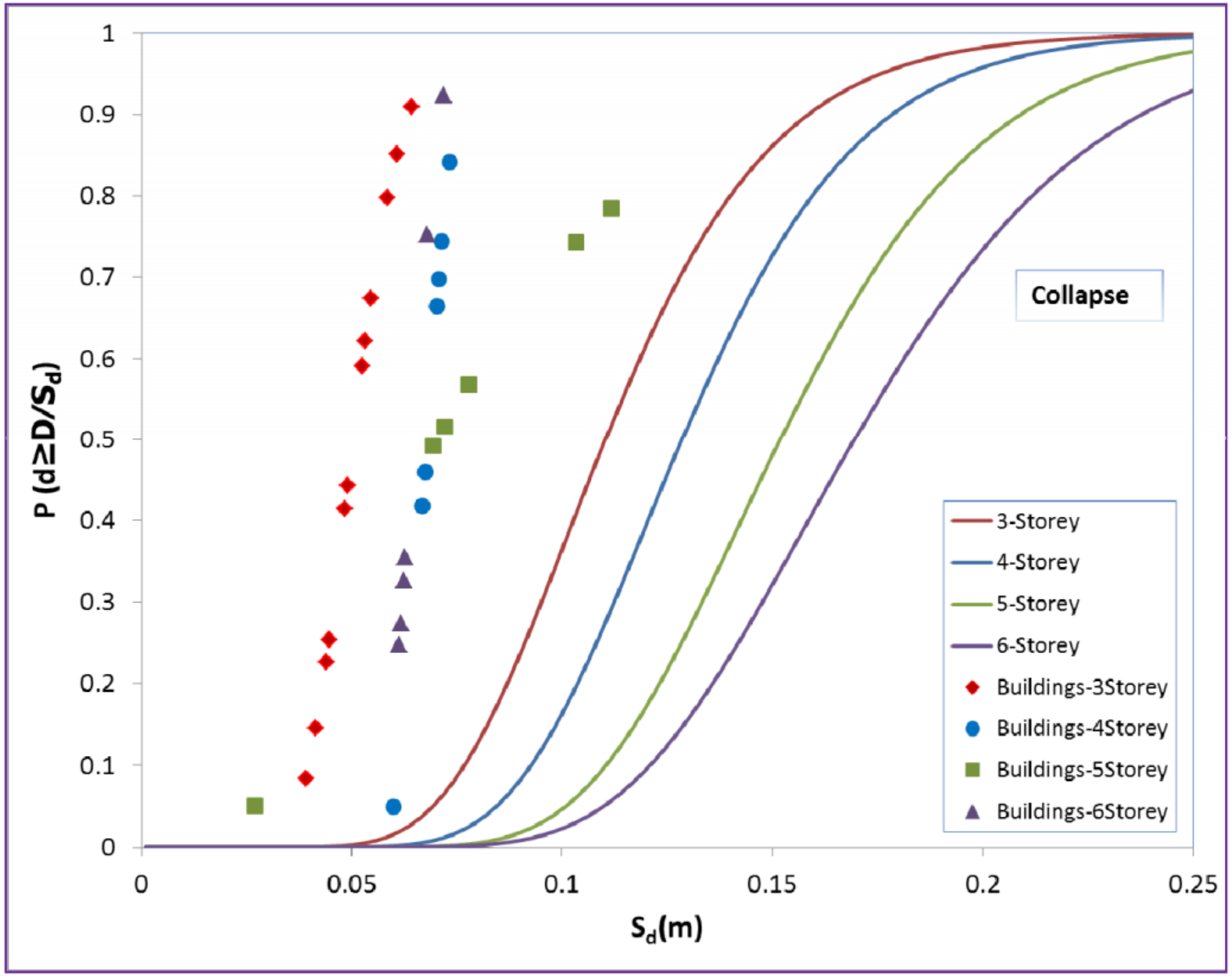
Step IV: Comparison of the results with some of the existing vulnerability curves

➔ *Kırçıl and Polat, 2006*

- *Damage probability of mid-rise concrete frame buildings is investigated*
- *3-, 4-, 5- and 6-storey representative buildings are designed according to 1975 Turkish seismic design code*
- *12 different artificial ground motion records are used*
- *Incremental inelastic dynamic analyses*
- *Yielding and collapse capacities in terms of PGA, S_a, S_d and ISD%*
- *Fragility curves constructed in terms of the same GMPs.*

Step IV: Comparison of the results with some of the existing vulnerability curves

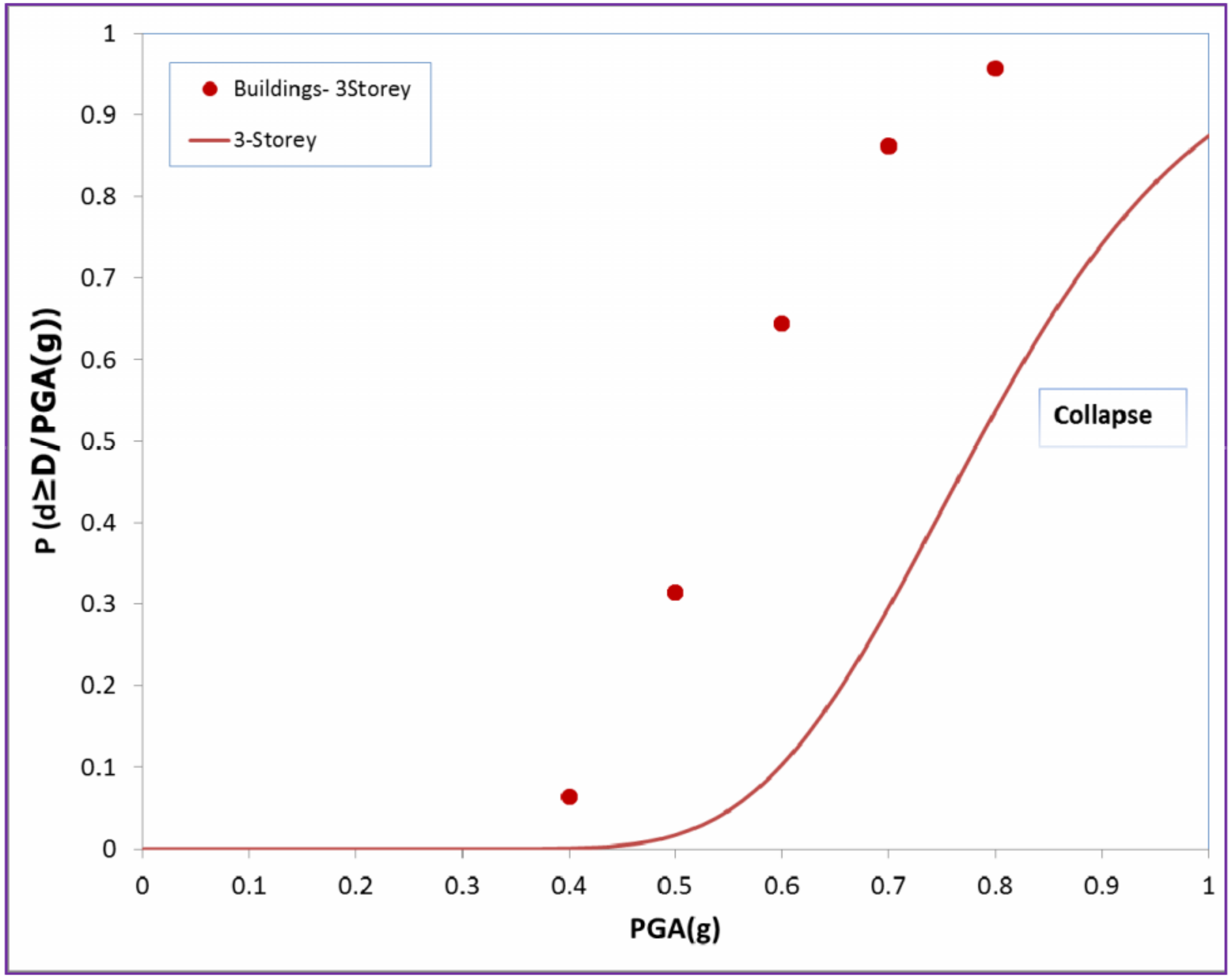
➔ *Kırçıl and Polat, 2006*



✓ *Distribution of the analyses results for each building in the ensemble are significantly differs from the proposed vulnerability functions for buildings.*

Step IV: Comparison of the results with some of the existing vulnerability curves

➔ *Kırçıl and Polat, 2006*



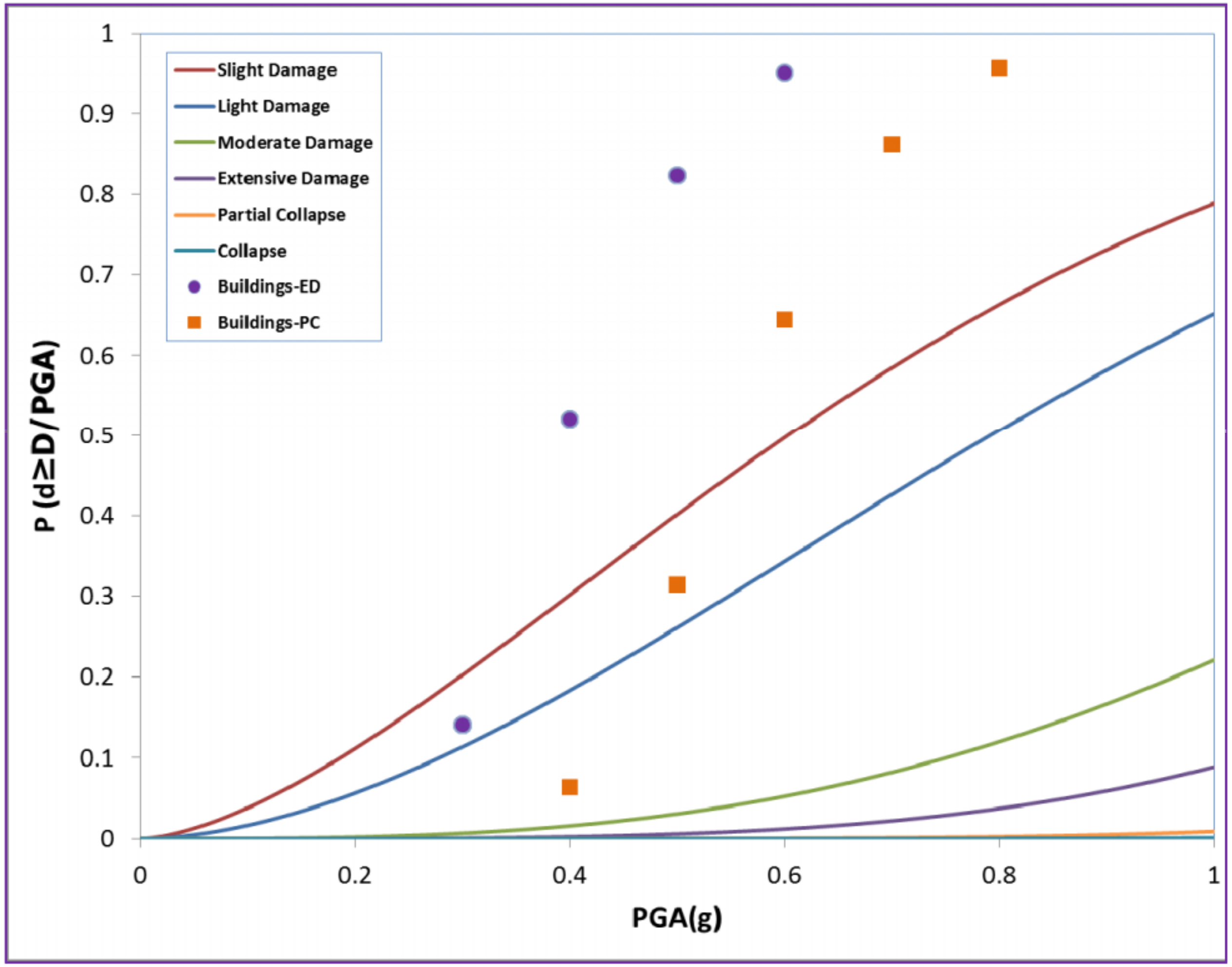
✓ *Distribution of the analyses results are significantly differs from the proposed vulnerability function for 3-storey building.*

Step IV: Comparison of the results with some of the existing vulnerability curves

- *Rosetto and Elnashai, 2003*
  - *Empirical fragility curves for RC buildings*
  - *Derivation of the curves based on 99 post-earthquake damage distributions observed in 19 earthquakes*
  - *Data bank concerns a total of 340000 RC structures*
  - *The observational data are reinterpreted in terms of HRC-scale (Homogenised Reinforced Concrete) which is calibrated experimentally*
  - *The feasibility of using observation-based data for the generation of vulnerability curves for different GMPs is investigated*

Step IV: Comparison of the results with some of the existing vulnerability curves

➔ *Rosetto and Elnashai, 2003*



✓ *Existing structures in Turkey experiences high damages under mid- values of PGA …*

- *Future Work:*
  - *Increasing the number of buildings including new sub-ensembles…*
  - *Try to establish new fragility functions by taking into account different structural parameters…*

THANK YOU FOR YOUR ATTENTION…