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Seismic vulnerability and risk assessment of urban habitat in Southern European cities

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The hybrid methodology for seismic vulnerability assessment

- Developed because reliable statistical data for seismic damage were quite limited and typically corresponded to a very small number of intensities
- The initial database included ≈6000 buildings from eastern part of Thessaloniki ↔ ≈50% of building stock (after 1978 earthquake), sampling density of 1:2
  - First (and so far only in Greece) with reliable data in terms of economic damage index, i.e.

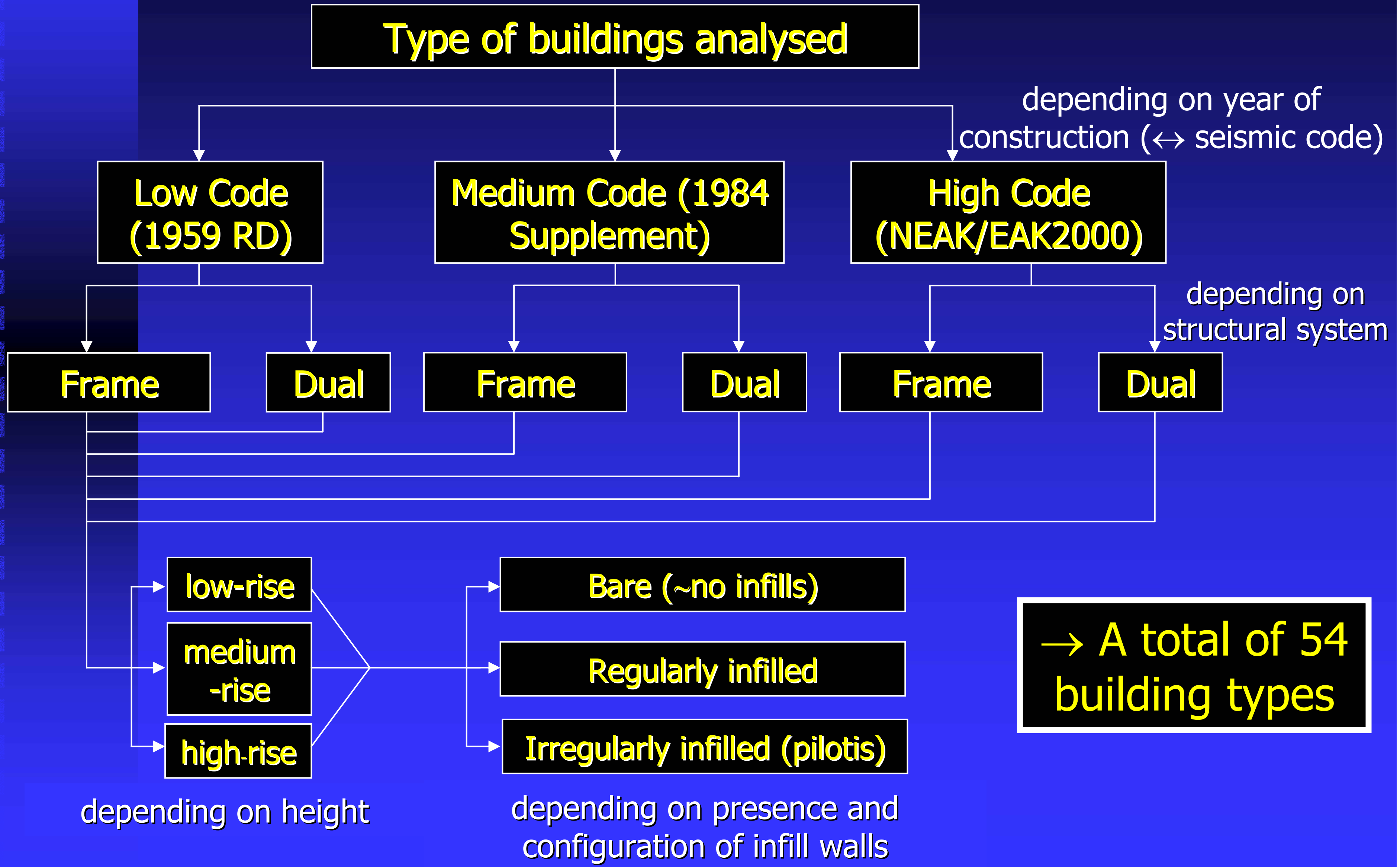
    repair cost / replacement cost

- Good quality data for Thessaloniki (1978) correspond to a single intensity (I ≈ 6.5)
- Analytical generation of damage data preferred to importing data from abroad (…)
- Purely analytical approaches (e.g. HAZUS) should be avoided! (typically - but not consistently - they overestimate cost of damage)
- Focus of this presentation:
  - time-history based version of the method, applied for ≈all common R/C building types
  - pushover analysis-based version for URM buildings
  - new fragility curves, based on rigorous procedure (lognormal CDFs)
  - pilot loss scenario for Thessaloniki

Model building types and design levels for R/C building analysis

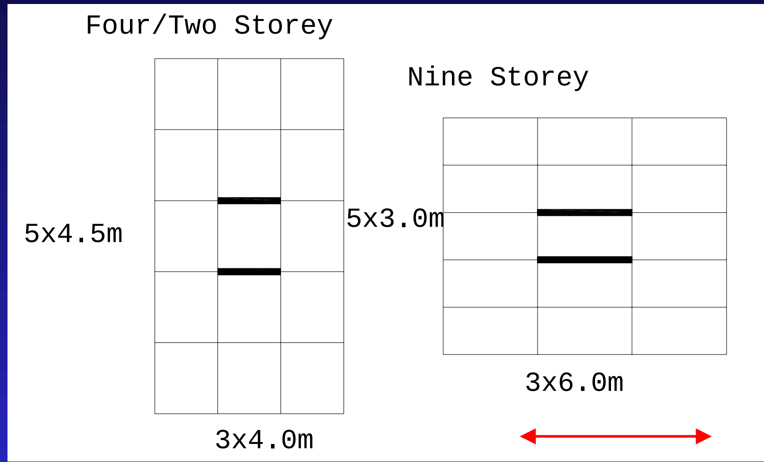
	Reinforced concrete structures	*Height class*	*Number of storeys*	*Height (m)*	*Code Level*
RC1	Concrete moment frames	Low-rise Mid-rise High-rise	2 4 9	7.5 13.5 28.5	RD'59, NEAK*
RC3	Concrete frames with unreinforced masonry infill walls				
3.1	Regularly infilled frames	Low-rise Mid-rise High-rise	2 4 9	7.5 13.5 28.5	RD'59, NEAK*
3.2	Irregularly frames (pilotis)	Low-rise Mid-rise High-rise	2 4 9	7.5 13.5 28.5	RD'59, NEAK*
RC4	RC Dual systems (RC frames and walls)				
4.1	Bare systems	Low-rise Mid-rise High-rise	2 4 9	7.5 13.5 28.5	RD'59, NEAK
4.2	Regularly infilled dual systems	Low-rise Mid-rise High-rise	2 4 9	7.5 13.5 28.5	
4.3	Irregularly infilled dual systems (pilotis)	Low-rise Mid-rise High-rise	2 4 9	7.5 13.5 28.5	RD'59, NEAK

Implementation of hybrid procedure
Inelastic analysis phase

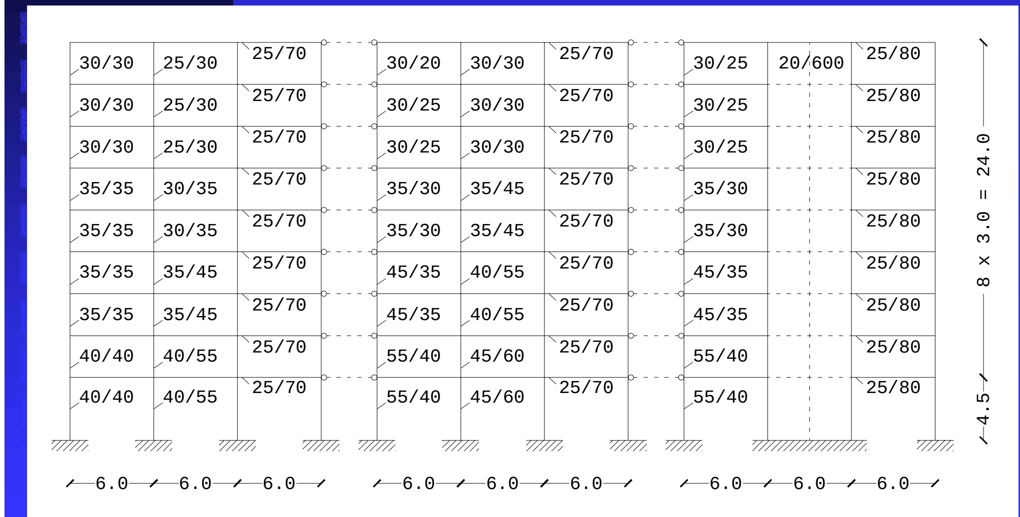


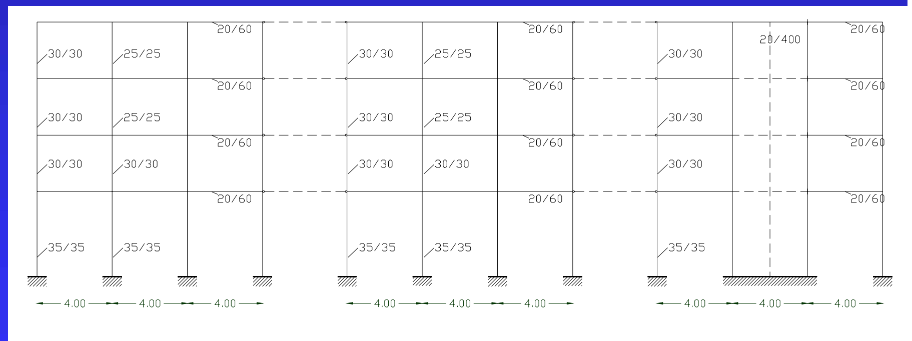
Examples of R/C structures analysed

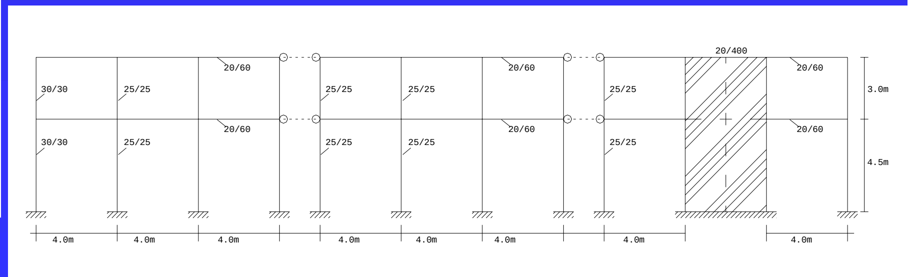
Typical dual structures designed to old codes



direction of interest

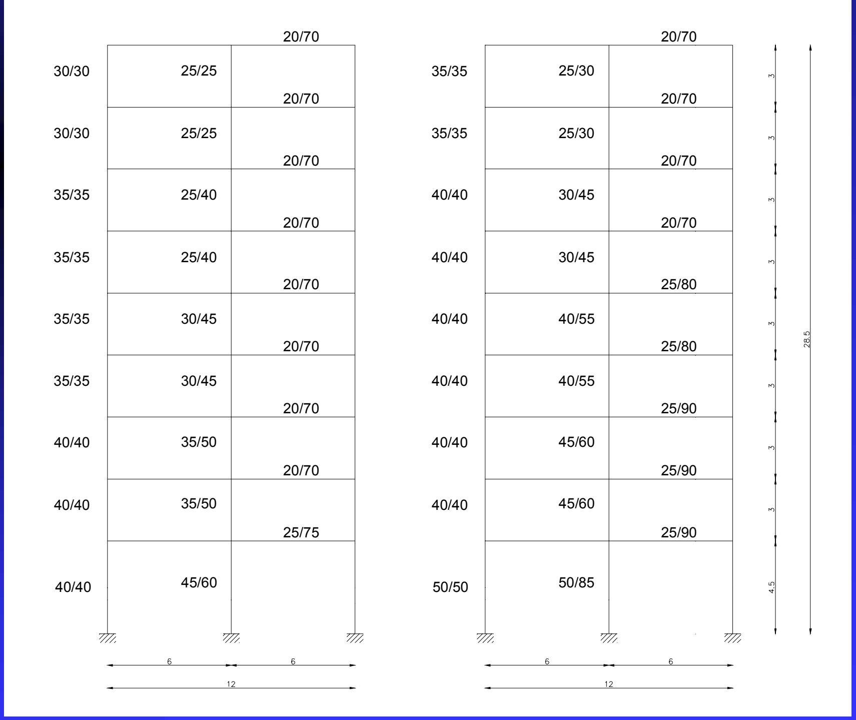


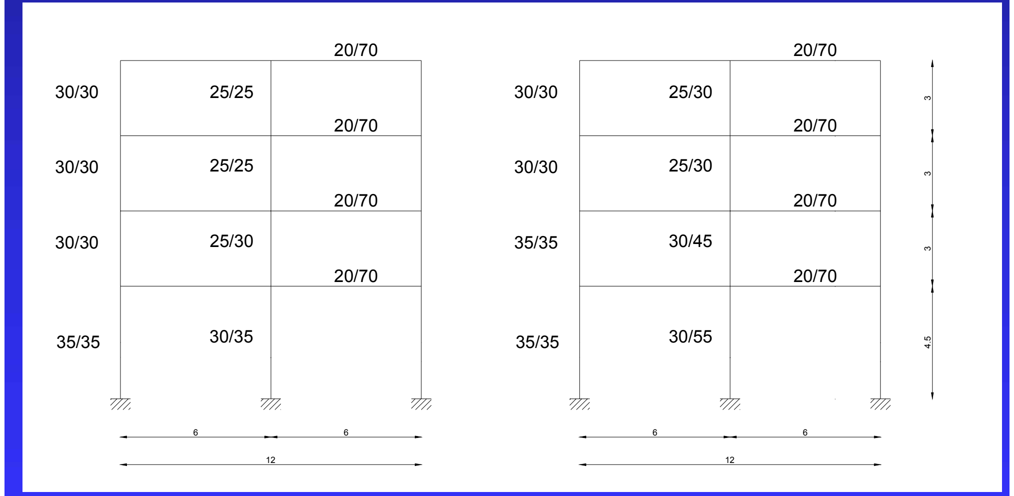




Examples of R/C structures analysed (contnd.)

Typical frame structures designed to old codes

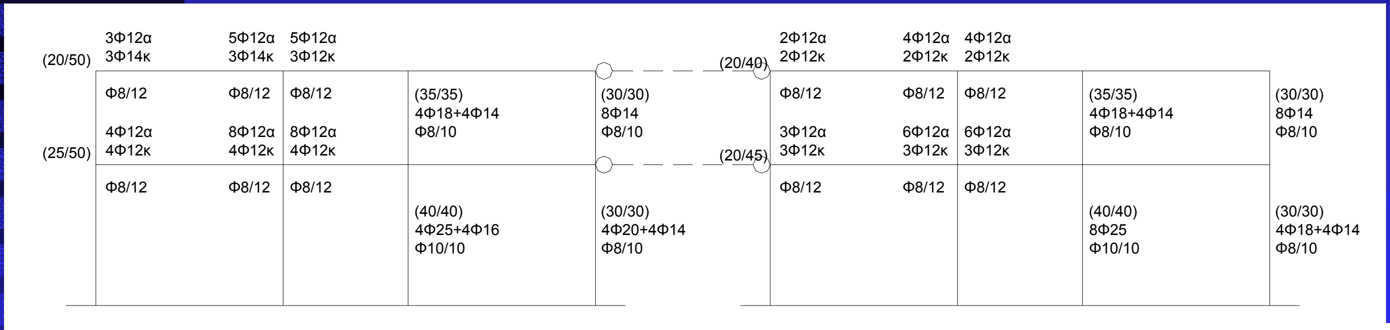


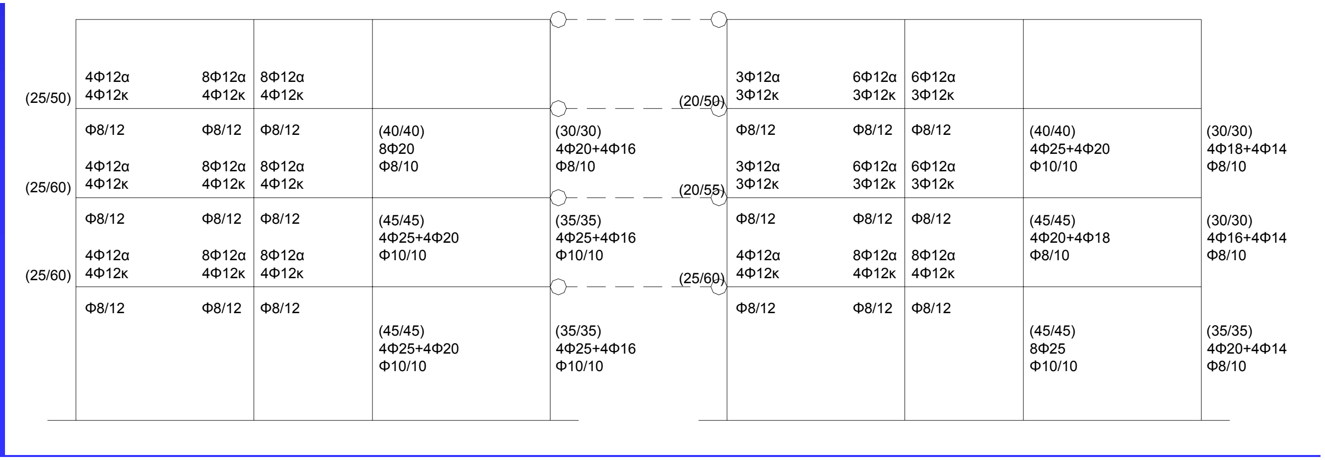


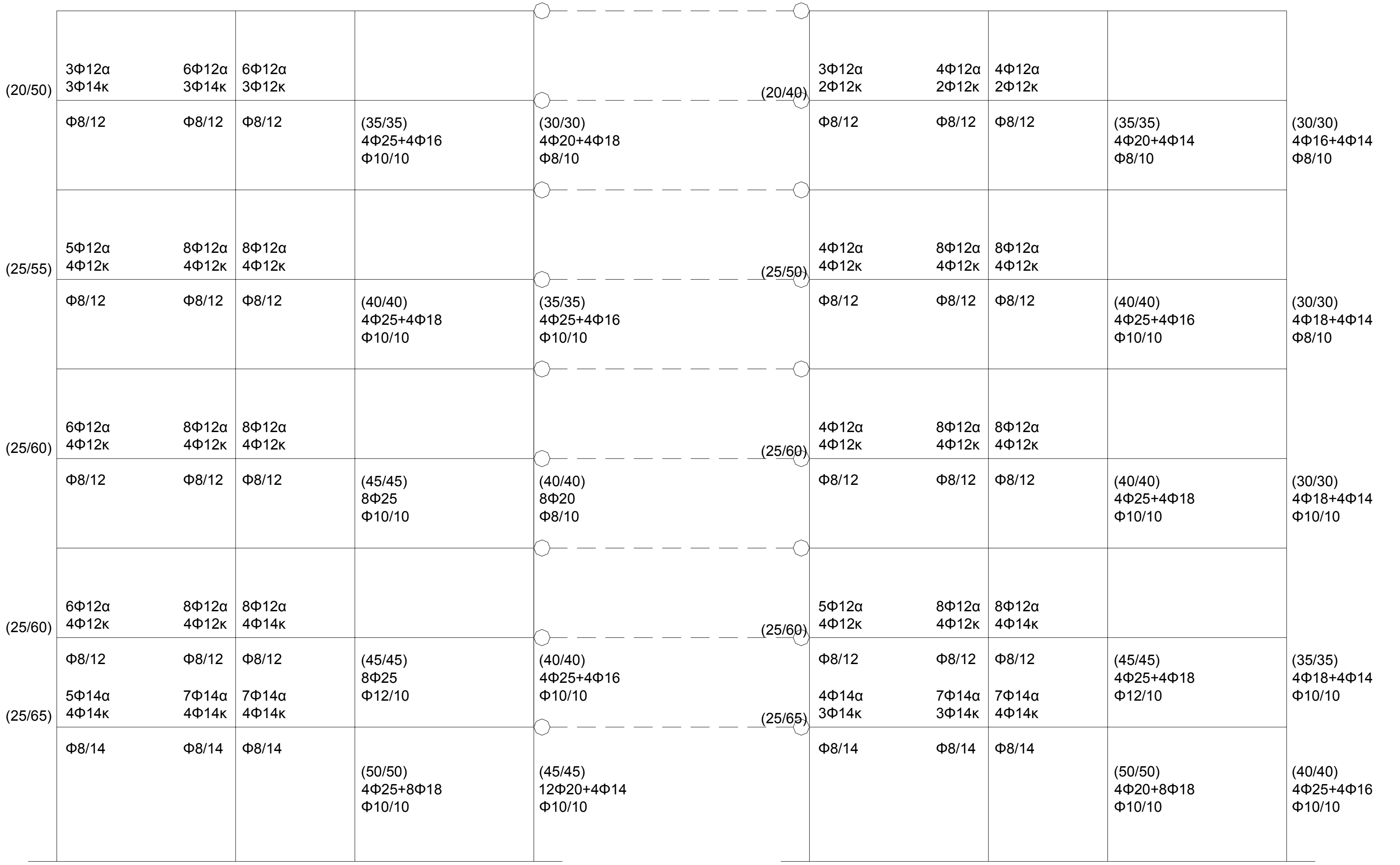
Examples of R/C structures analysed (contnd.)

Typical structures designed to modern codes (NEAK/EAK2000)

- dual structures have the same configuration as those designed to old codes
- frame structures are slightly different, i.e. more realistic (3 spans instead of two)







(20/50)
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(35/35) 4Φ25+4Φ16 Φ10/10
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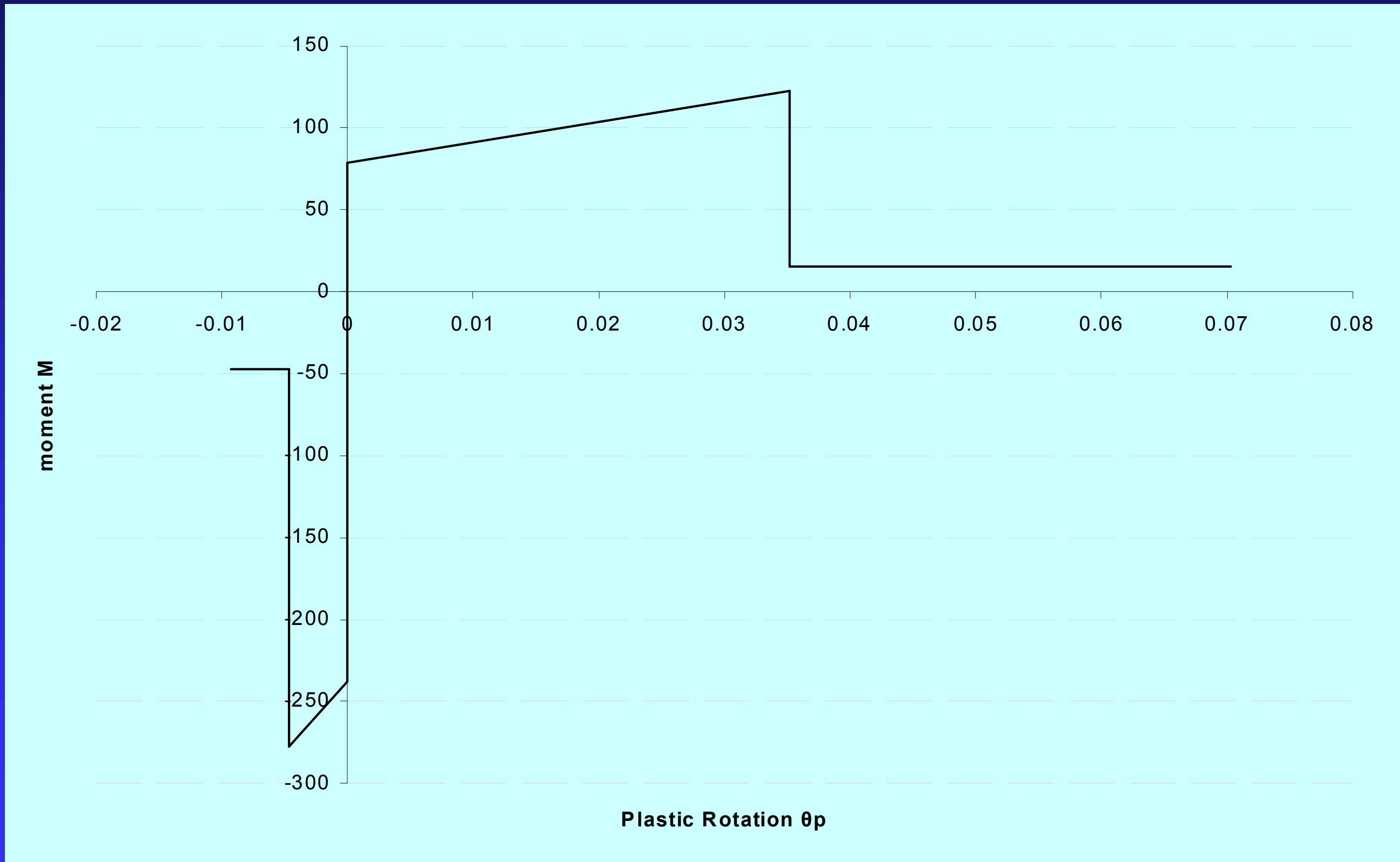
(50/50) 4Φ20+8Φ18 Φ10/10
(40/40) 4Φ25+4Φ16 Φ10/10

Modelling of R/C members:

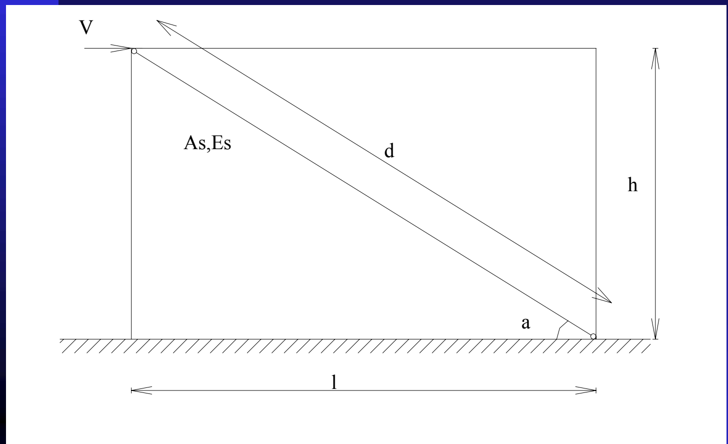
Point hinge approach



moment rotation curve for a beam (SAP 2000)

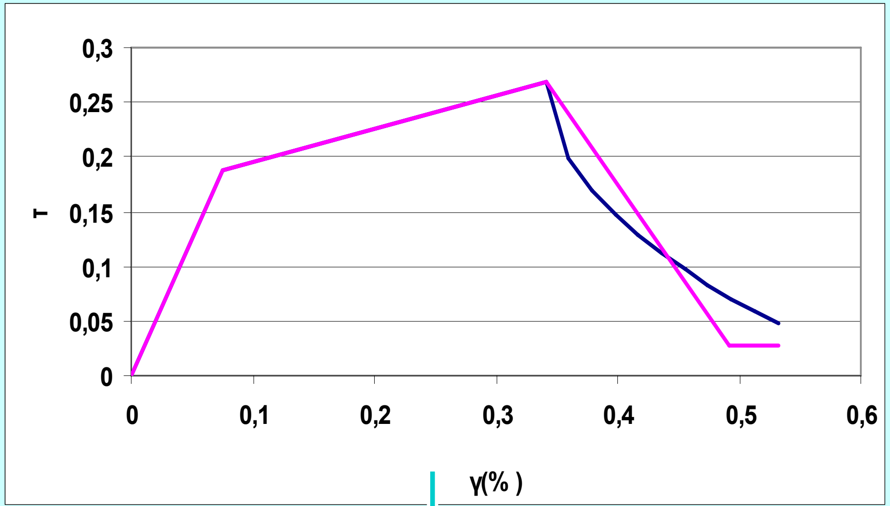
Modelling of infills:

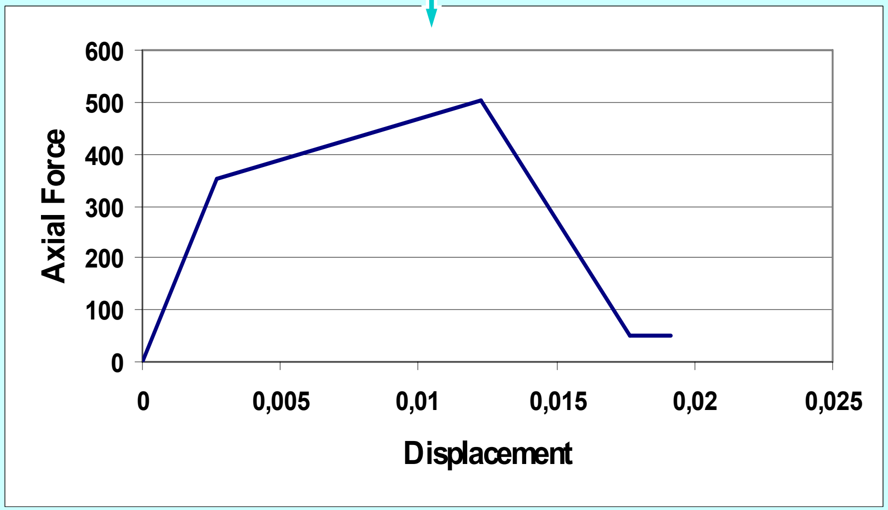
Strut model



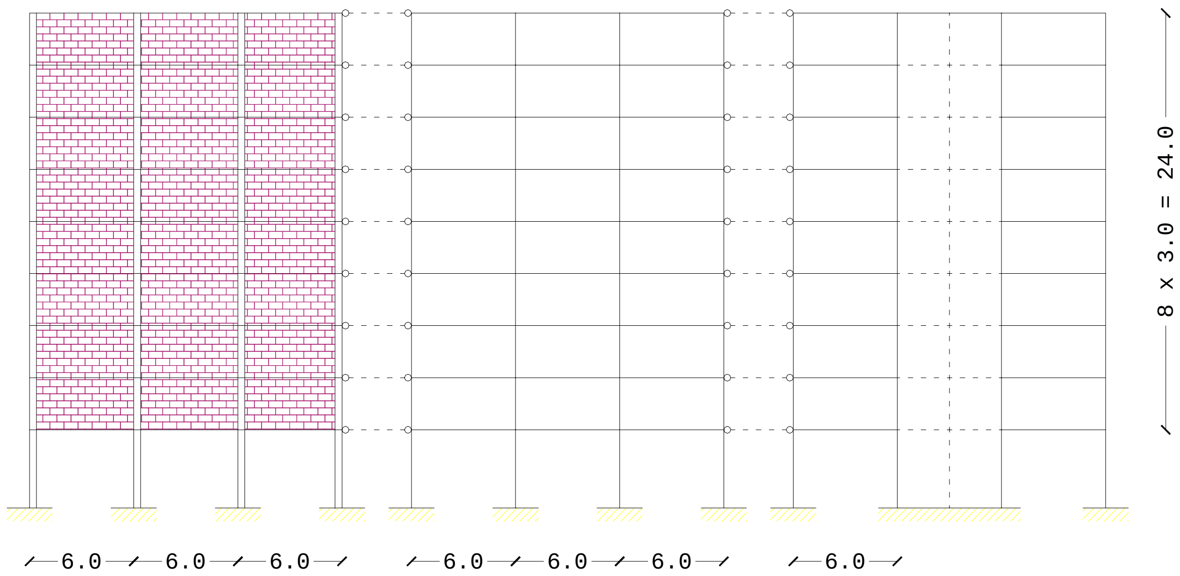
$$E_S \cdot A_S = \frac{G_W \cdot A_W}{\cos^2 a \cdot \sin a}$$

- multilinear version of hysteresis law based on test results (brick masonry)
- no significant axial load
- masonry f_w=1.5 MPa

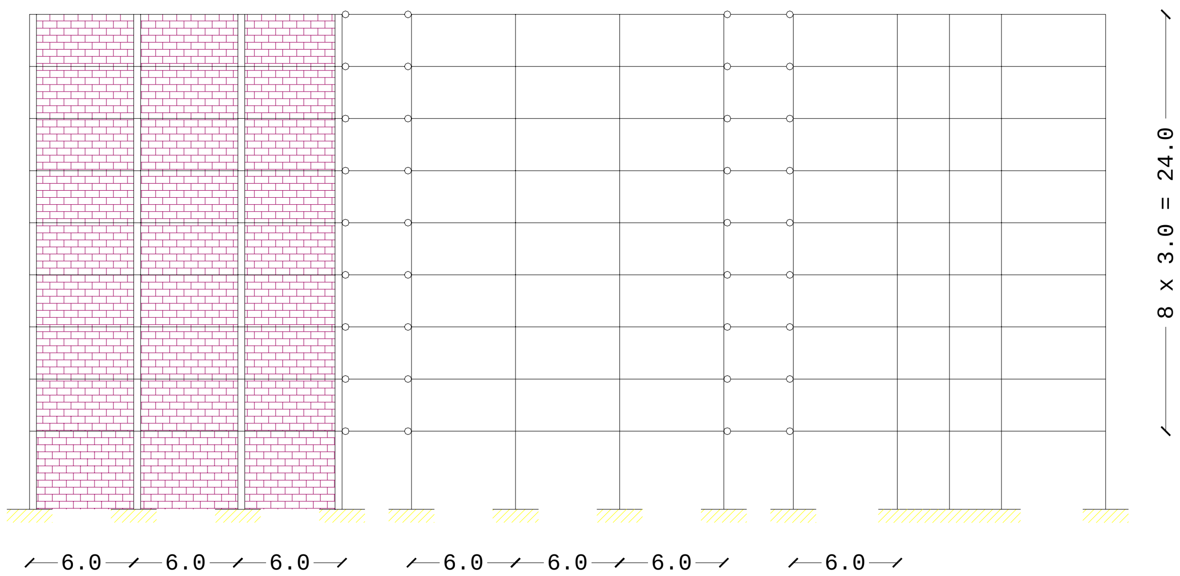




irregularly infilled (RC4.3)



regularly infilled (RC4.2)



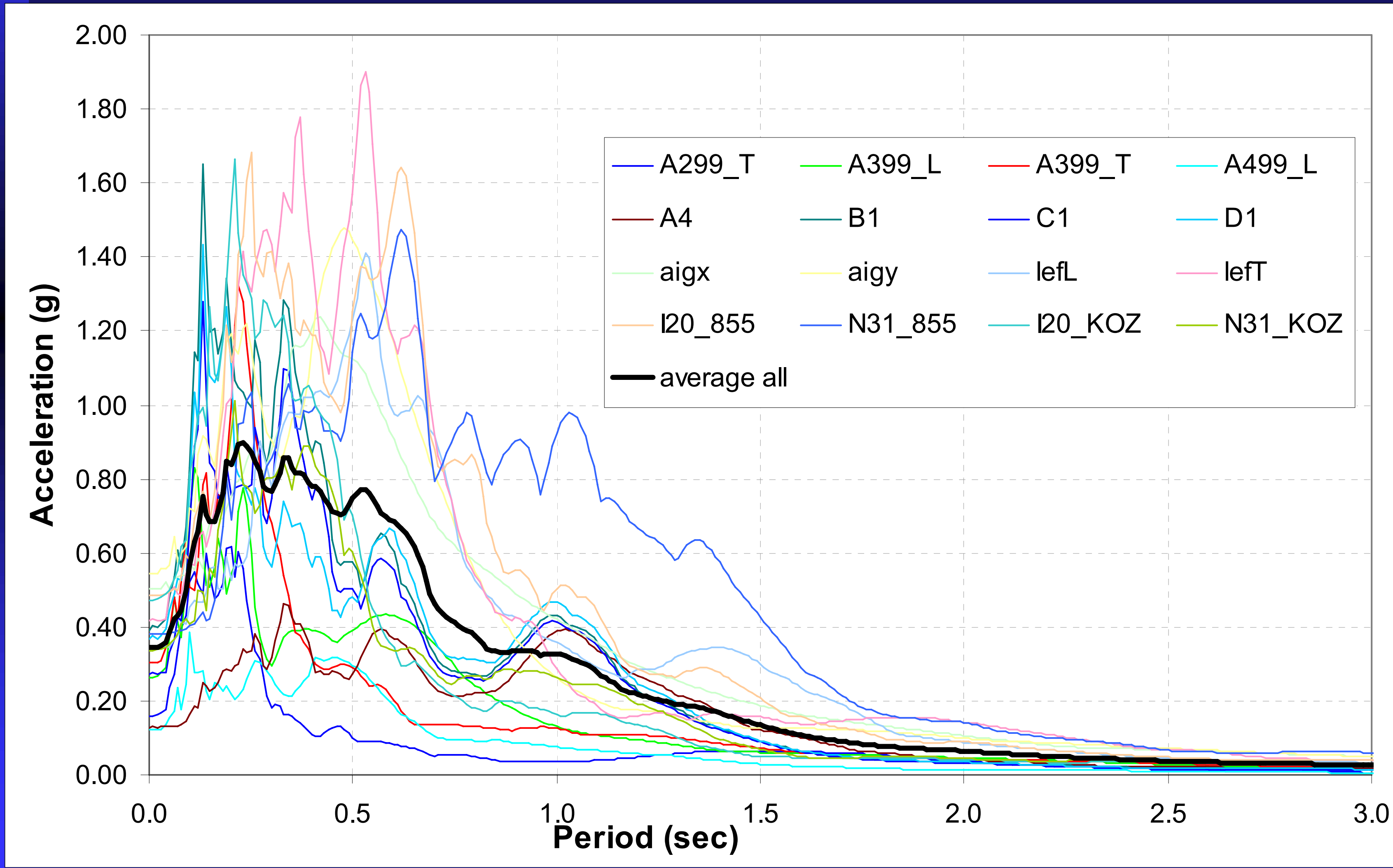
9-Storey dual R/C building with masonry infills

Records used and scaling procedure

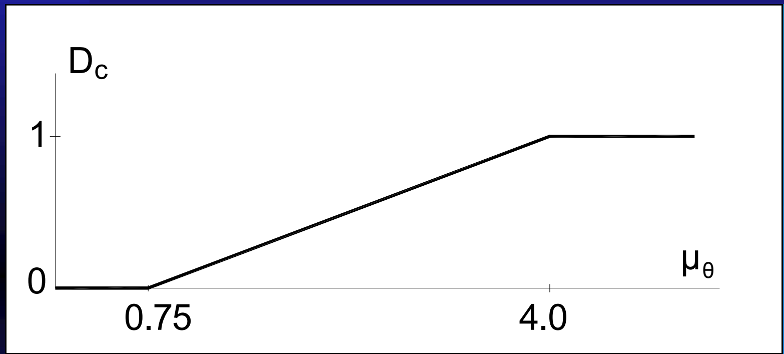
- 8 natural records
  - 2 from the 14/8/03 Lefkada earthquake
  - 2 from the 15/6/95 Aegion earthquake
  - 4 from the 7/9/99 Athens earthquake
- 8 synthetic records
  - 4 from the site-dependent records estimated within the microzonation study of Volos (AUTh Geotechnical Earthquake Engineering Group)
  - 4 records derived for two locations in Thessaloniki based on two different natural records (Kozani '95, Umbro-Marchigiano aftershock)

- **Fairly representative set of records**
- **Different site conditions taken into account**

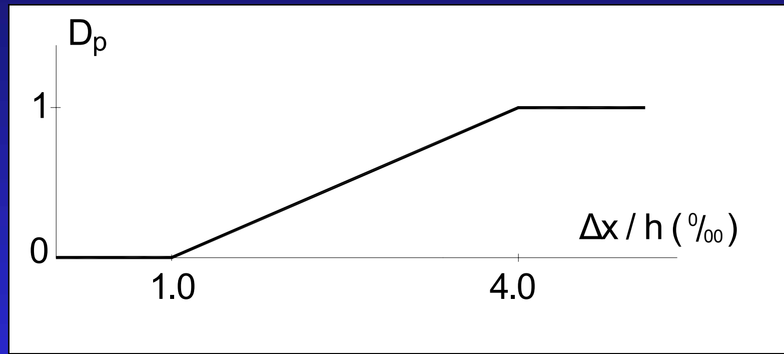
Response spectra of selected records



Method for correlating structural damage index to loss index (Kappos et al., 1998) → crucial stage of the hybrid approach!



model for R/C members



model for masonry infills

$G=G_c + G_p= 0.25D_{cg} + 0.08D_{pg}$ for low/medium-rise buildings (1-6 storeys)

$G=G_c + G_p= 0.30D_{cg} + 0.08D_{pg}$ for high-rise buildings (≥7 storeys)

- cost models based on greek data
- used to translate structural damage predicted by inelastic time-history analysis to loss (repair cost / replacement cost)

Hybrid method – Analysis stage

Correlation with intensity of motions for which damage data exist

- Available damage statistics from past earthquakes are typically available in terms of macroseismic intensity (I).
- To correlate intensity with the PGA of the records used in time-history analysis the Koliopoulos et al. (1998) relationship was used

$$\ln(PGA)=0.74I+0.03, \quad (I \ngtr 9)$$

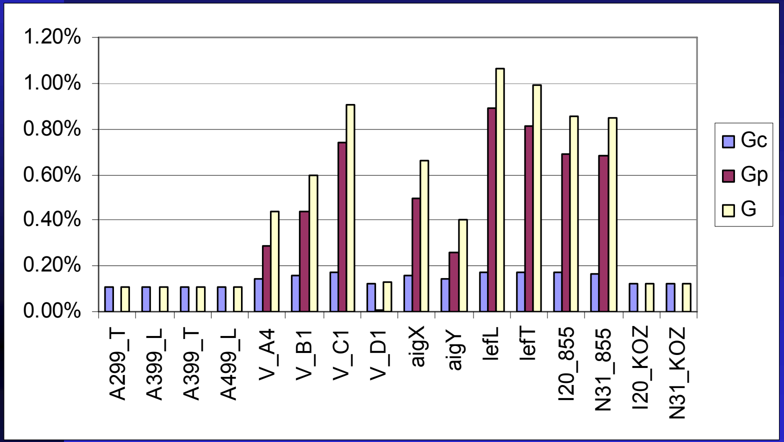
I	PGA (g)
6	0.089
7	0.187
8	0.391
9	0.820

Additional analyses carried out for higher intensities (PGA equal to 1.5, 2 καı 4 times that corresponding to I=9) to obtain complete curves for well-detailed structures

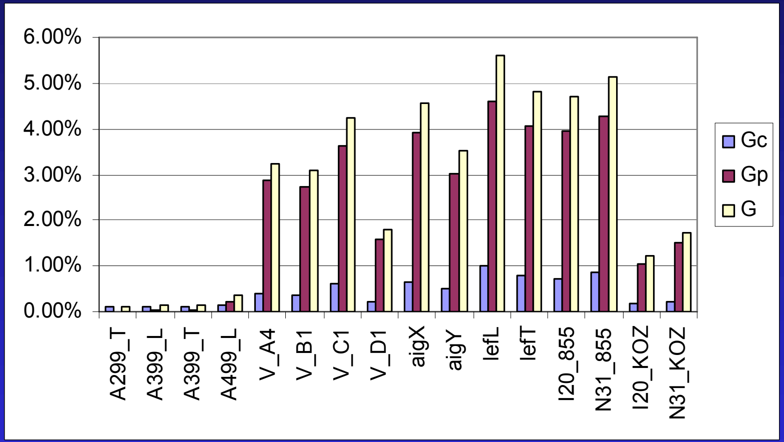
16 records x 7 I x 54 building types = 6048 time-history analyses

Calculated loss indices

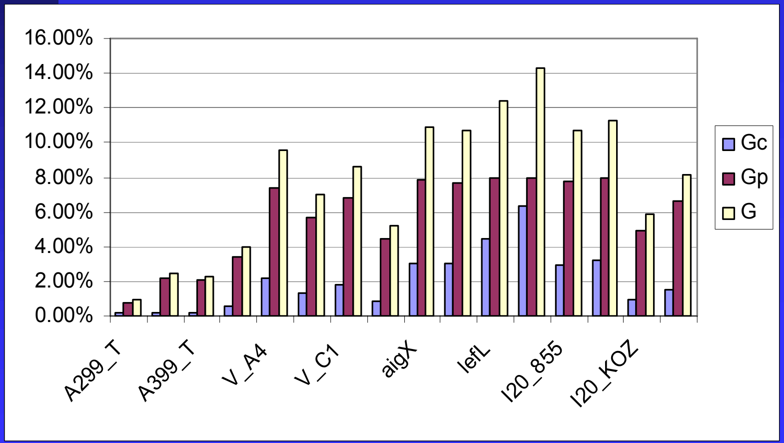
4-storey, regularly infilled dual system, designed to old codes ('Low-code')



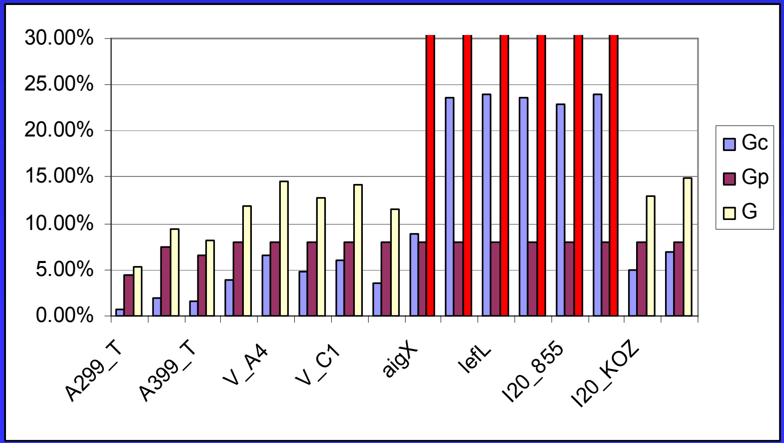
I=6



I=7



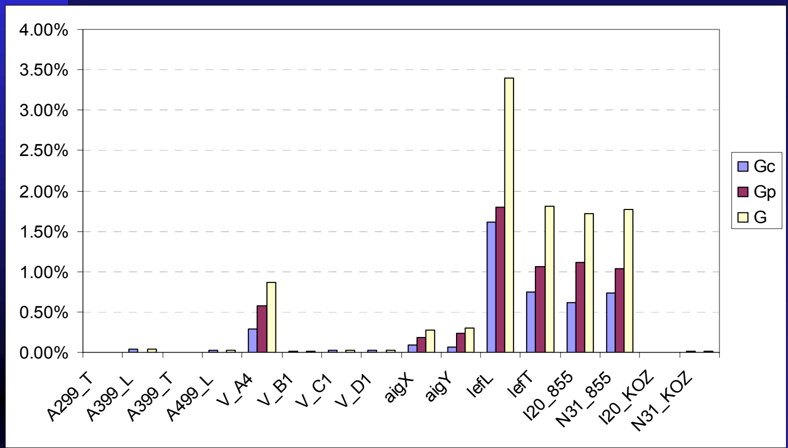
I=8



I=9

Calculated loss indices (contnd.)

RC4.3HL: 9-storey dual system with pilotis, designed to old codes ('Low-code')



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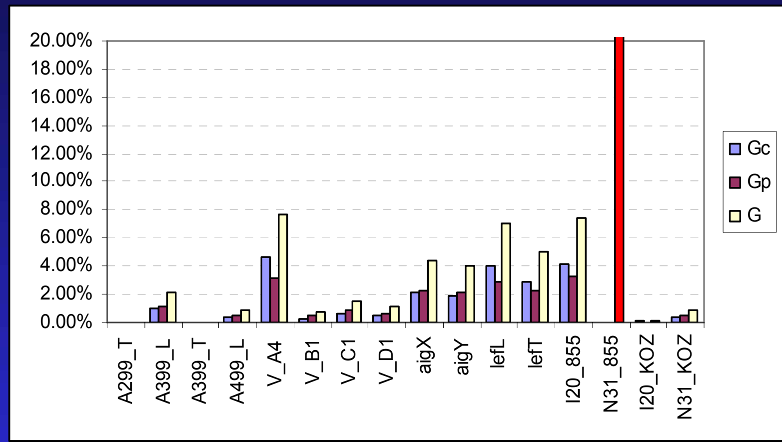

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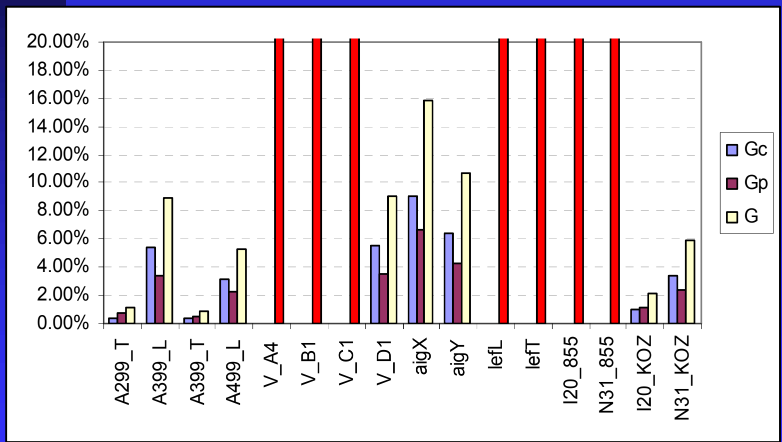

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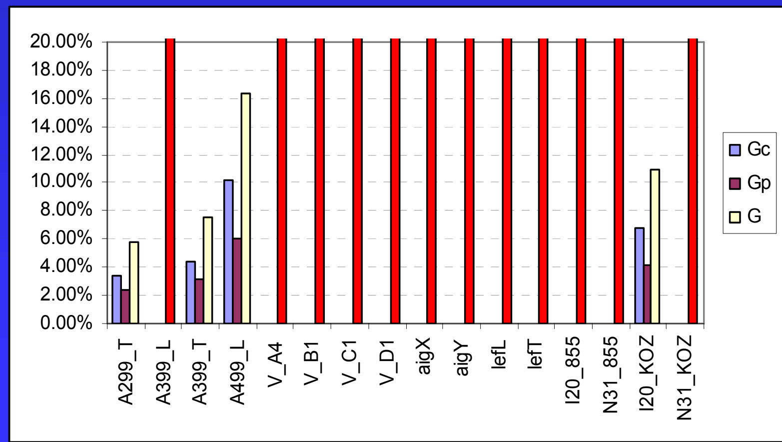
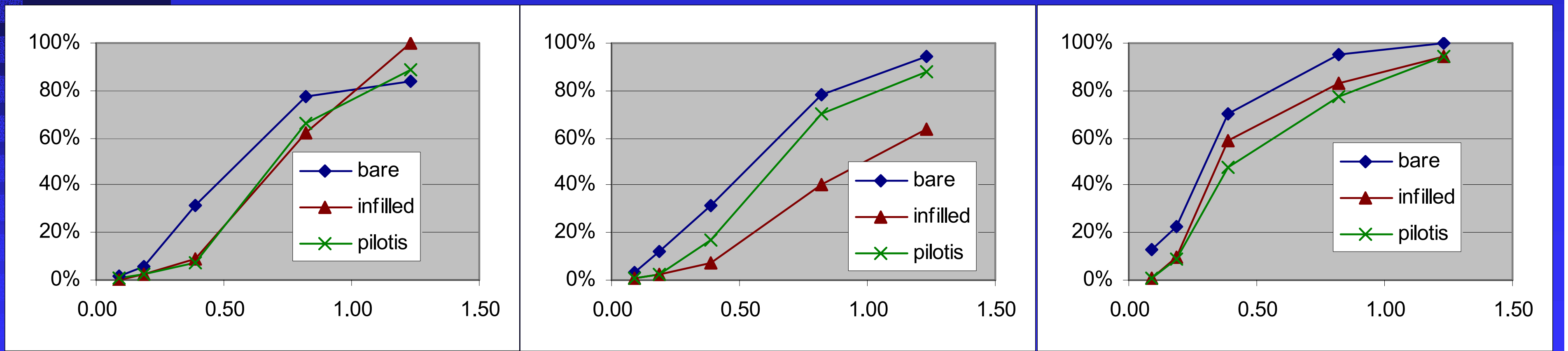


I=9

Loss index accumulation (L vs. PGA)

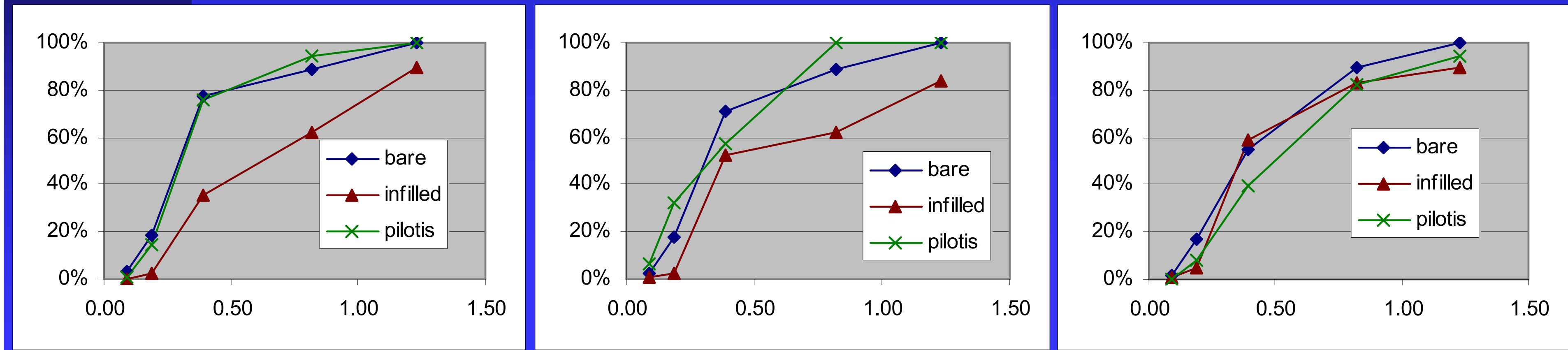
RC4 (dual) Low Code structures									
	Low-rise			Medium-rise			High-rise		
PGA	**bare**	**infilled**	**pilotis**	**bare**	**infilled**	**pilotis**	**bare**	**infilled**	**pilotis**
0.09	1.43%	0.28%	0.54%	3.19%	0.47%	0.55%	13.28%	0.64%	0.49%
0.19	5.39%	2.52%	2.05%	11.70%	2.64%	2.19%	22.39%	9.49%	8.93%
0.39	31.59%	8.69%	6.86%	31.61%	7.37%	16.72%	70.37%	58.59%	47.48%
0.82	77.72%	62.32%	66.34%	77.96%	40.64%	70.49%	94.83%	83.00%	77.54%
1.23	83.66%	100.00%	88.92%	94.62%	63.71%	88.14%	100.00%	94.62%	94.44%



→ the L vs. PGA relationship is used to estimate median values of fragility curves

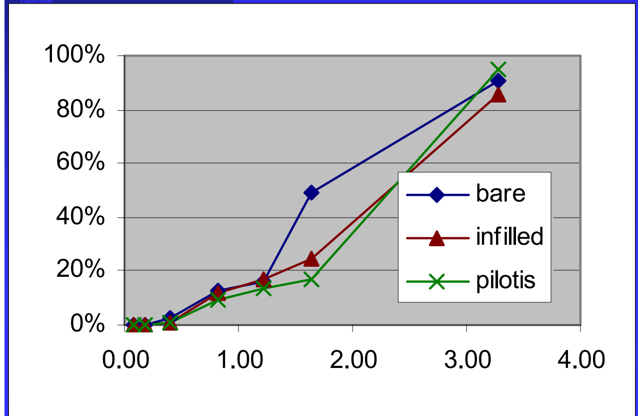
Loss index accumulation (L vs. PGA) – contnd.

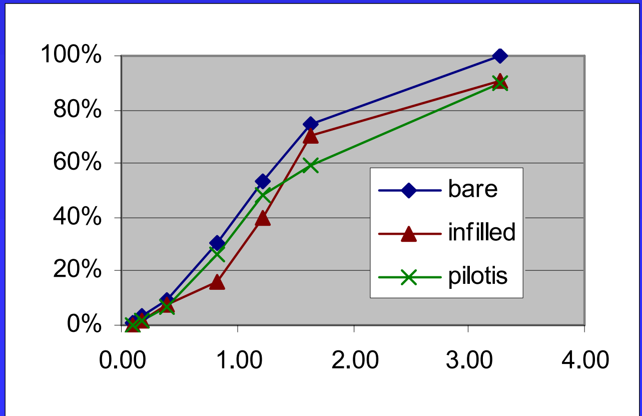
RC1 (frame) and RC3 (infilled frame) Low Code structures									
	Low			Medium			High		
PGA	bare	infilled	pilotis	bare	infilled	pilotis	bare	infilled	pilotis
0.09	3.51%	0.19%	0.84%	2.14%	0.51%	6.69%	1.65%	0.78%	0.23%
0.19	18.32%	2.35%	14.58%	17.35%	2.30%	31.99%	17.30%	5.01%	7.78%
0.39	77.22%	35.40%	75.67%	70.92%	52.24%	57.32%	55.14%	58.66%	39.64%
0.82	89.05%	62.28%	93.98%	88.99%	62.28%	100.00%	89.58%	82.85%	81.99%
1.23	100.00%	89.44%	100.00%	100.00%	83.94%	100.00%	100.00%	89.90%	94.08%

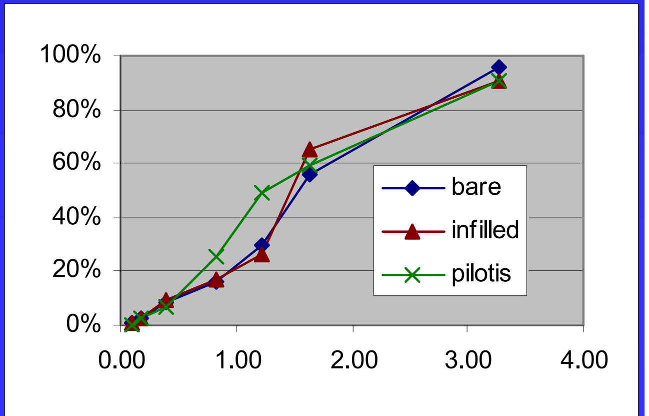


Loss index accumulation (L vs. PGA) – contnd.

RC4 (Dual) High-Code structures									
	Low			Medium			High		
PGA	bare	infilled	pilotis	bare	infilled	pilotis	bare	infilled	pilotis
0.09	0.01%	0.01%	0.01%	0.44%	0.07%	0.14%	0.62%	0.52%	0.42%
0.19	0.22%	0.11%	0.18%	3.12%	1.34%	1.31%	2.95%	2.89%	2.37%
0.39	2.71%	0.91%	1.16%	9.67%	7.42%	6.64%	8.50%	8.97%	7.13%
0.82	12.80%	11.76%	9.69%	30.55%	15.82%	26.39%	15.91%	16.87%	25.23%
1.23	16.45%	17.25%	13.36%	53.26%	39.49%	48.57%	29.72%	26.05%	49.08%
1.64	48.82%	24.24%	17.27%	74.40%	70.19%	59.67%	55.65%	65.43%	59.64%
3.28	90.40%	85.40%	94.98%	100.00%	90.48%	90.12%	95.37%	91.01%	90.50%

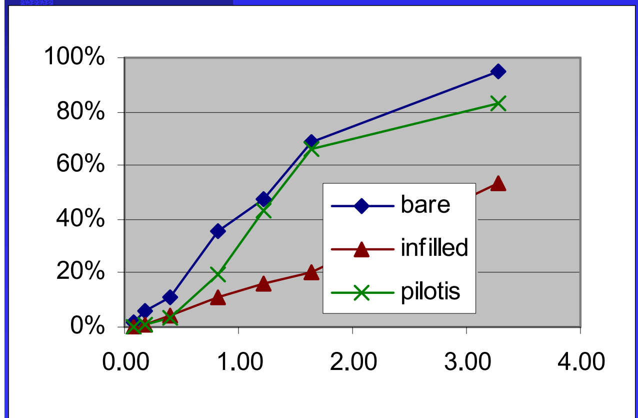


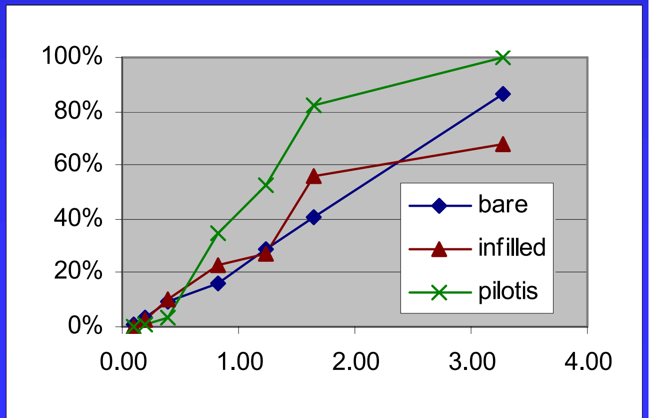




Loss index accumulation (L vs. PGA) – contnd.

RC1 (frame) and RC3 (infilled frame) High Code structures									
	Low			Medium			High		
PGA	bare	infilled	pilotis	bare	infilled	pilotis	bare	infilled	pilotis
0.09	1.98%	0.00%	0.00%	1.48%	0.05%	0.12%	0.96%	0.42%	0.13%
0.19	5.71%	0.94%	0.58%	4.26%	1.15%	1.26%	3.77%	2.92%	1.08%
0.39	10.82%	3.98%	3.20%	8.40%	6.17%	3.67%	9.53%	9.93%	3.05%
0.82	35.99%	10.87%	19.54%	12.91%	13.68%	29.00%	16.39%	22.68%	34.48%
1.23	47.79%	16.36%	43.31%	20.36%	18.66%	41.27%	29.13%	26.73%	52.77%
1.64	68.94%	20.16%	66.09%	26.70%	22.06%	64.73%	40.89%	55.78%	82.24%
3.28	95.08%	53.67%	83.43%	27.21%	80.42%	88.39%	86.03%	68.12%	100.00%





Fragility curves

- derived based on hybrid approach
- for six (5+1) damage states (DS0 to DS5)

Damage State	Damage state label	Range of damage factor	Central damage factor (%)
DS0	None	0	0
DS1	Slight	0-1	0.5
DS2	Moderate	1-10	5
DS3	Substantial to heavy	10-30	20
DS4	Very heavy	30-60	45
DS5	Collapse	60-100	80

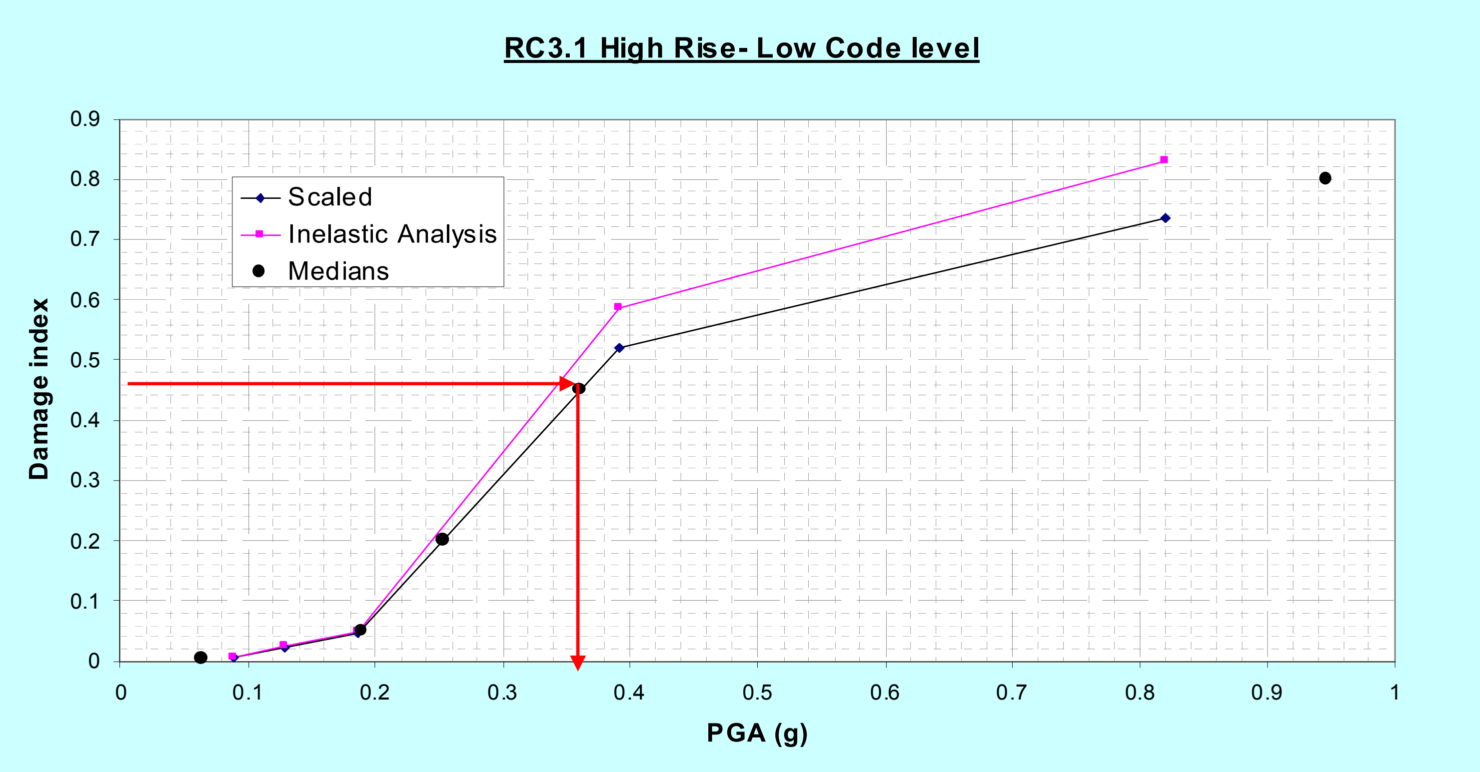
- lognormal distribution assumed

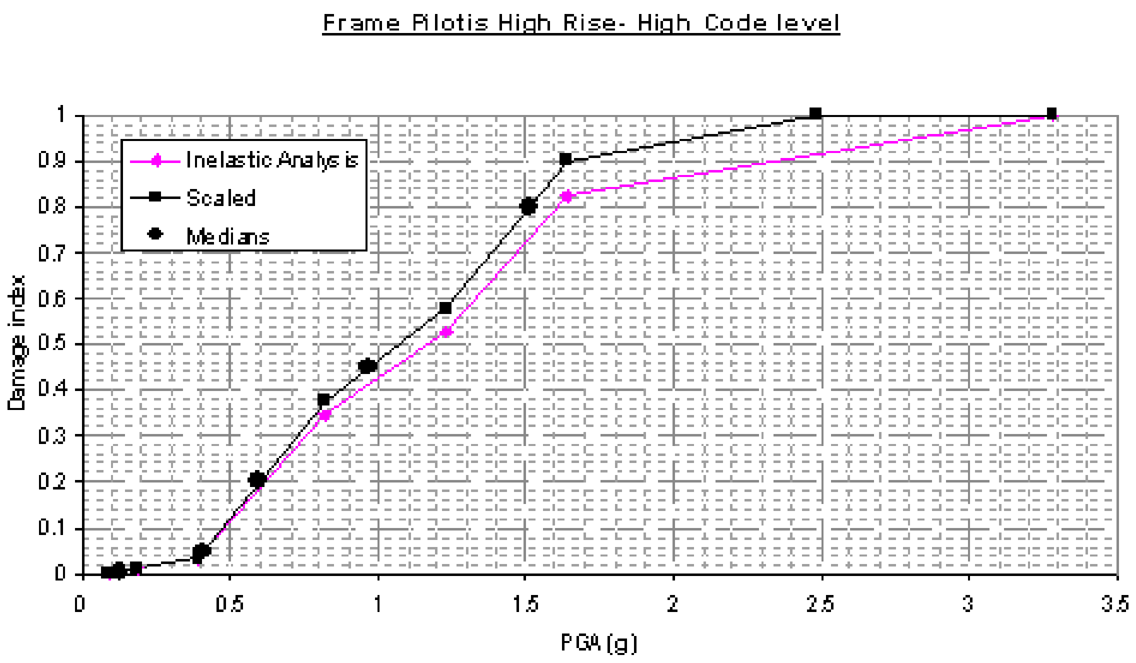
$$P[ds \geq ds_i / PGA] = \Phi[\frac{1}{\beta_{ds_i}} \ln(\frac{PGA}{\overline{PGA}, ds_i})]$$

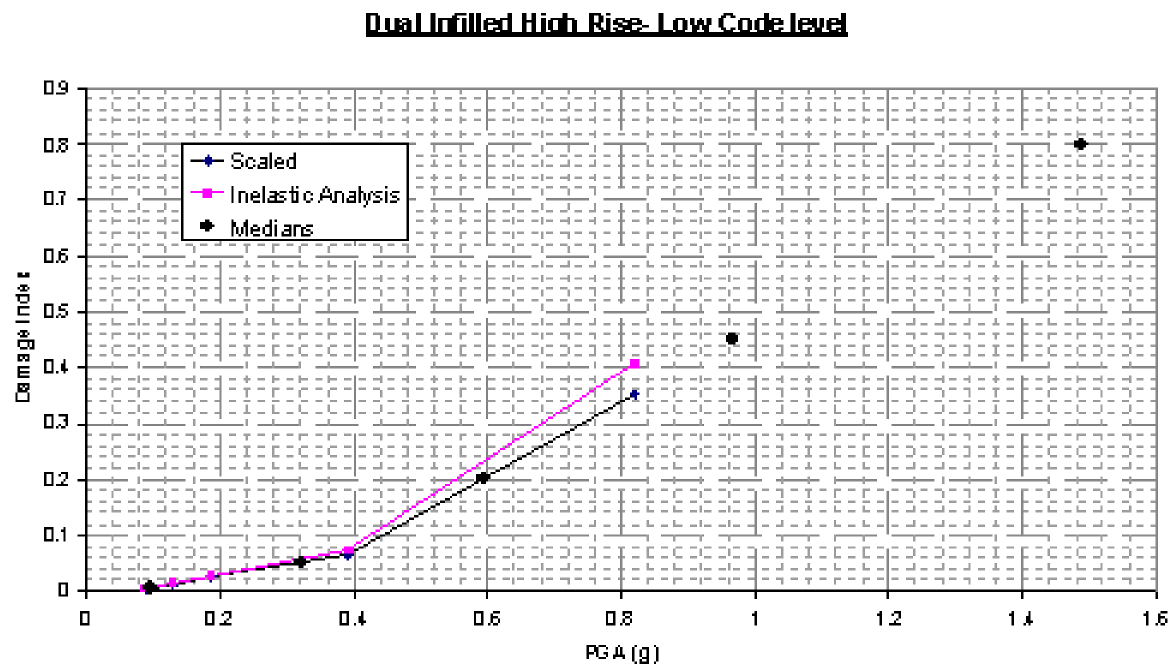
Damage-state medians

- from analytical L – PGA relationship, scaled based on statistical data available

e.g. DS4 (L=45%)




Frame Pilotis High Rise- High Code level
Inelastic Analysis
Scaled
Medians
Damage index
PGA (g)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5
2
2.5
3
3.5


Dual Infilled High Rise- Low Code level
Scaled
Inelastic Analysis
Medians
Damage Index
PGA (g)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6

Damage-state variability

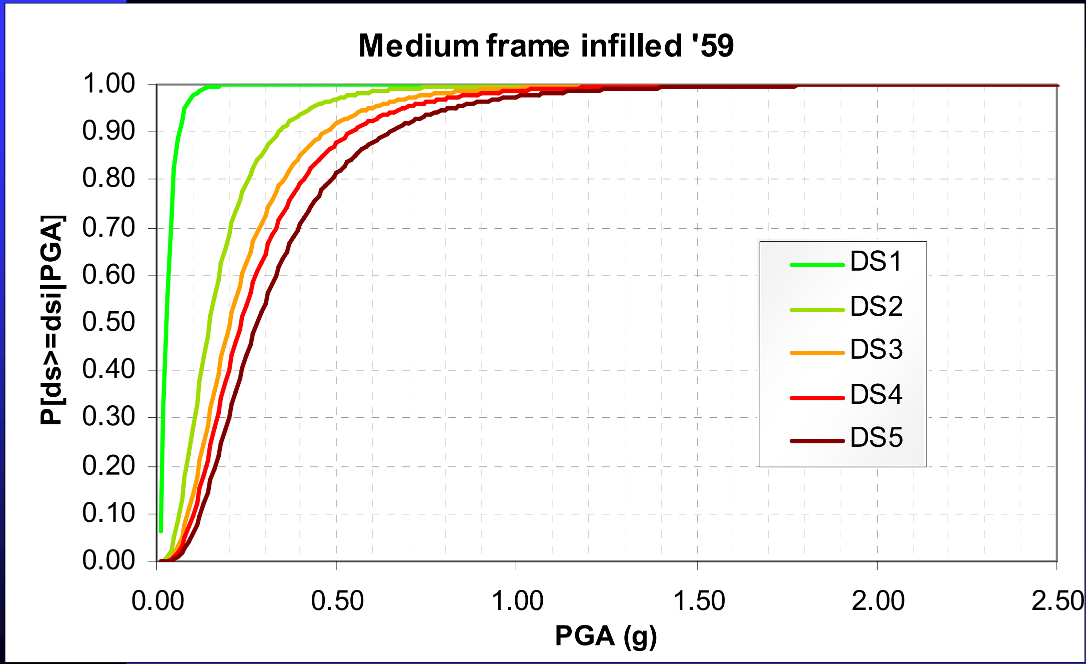
- Uncertainty associated with *seismic demand*: estimated from the variability in the results of inelastic dynamic analyses carried out for a total of 16 motions at each level of PGA considered
- Variability in *capacity*
  - for low code buildings β=0.3 assumed (Hazus)
  - for high code β=0.25 assumed (Hazus)
- Uncertainty in the *definition of damage state*: for all building types and all damage states, β=0.4 (Hazus)
- Total variability $\beta \approx (\beta_D + \beta_C + \beta_{ds})^{1/2}$

Estimated fragility curve parameters, Low-Code Design

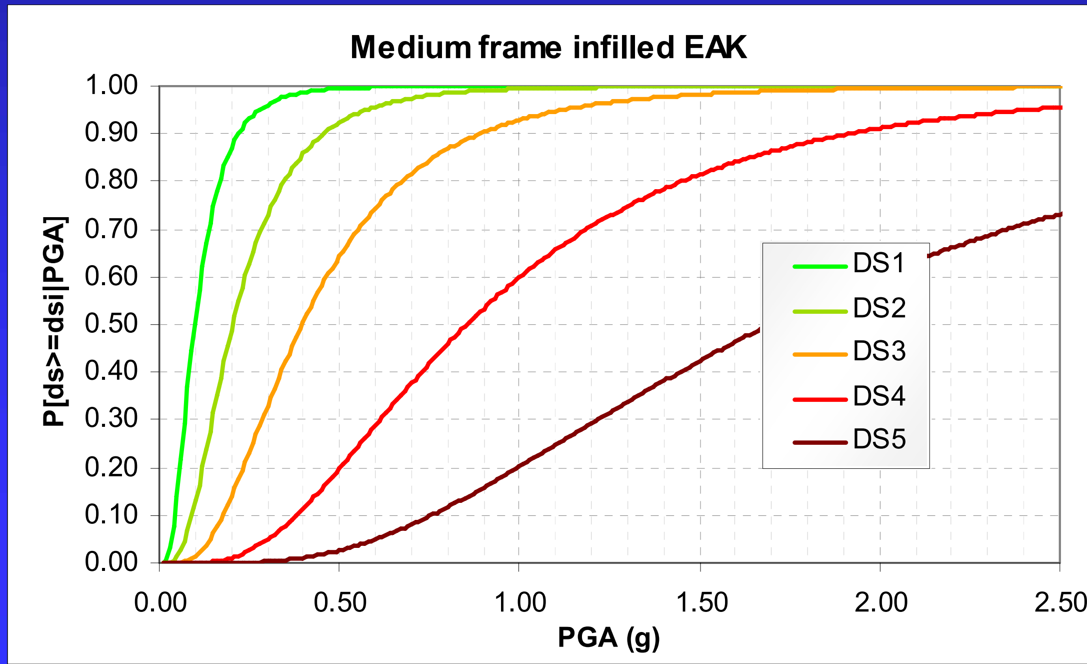
BTM	Slight		Moderate		Substantial to heavy		Very Heavy		Complete	
	Median	*Beta*	*Median*	*Beta*	*Median*	*Beta*	*Median*	*Beta*	*Median*	*Beta*
RC1L	0.0058	0.7328	0.0583	0.7328	0.1265	0.7328	0.1948	0.7328	0.2507	0.7328
RC1M	0.0065	0.6512	0.0653	0.6512	0.1155	0.6512	0.1658	0.6512	0.2161	0.6512
RC1H	0.0304	0.6292	0.1139	0.6292	0.2147	0.6292	0.3667	0.6292	0.8356	0.6292
RC3.1L	0.0908	0.7328	0.1844	0.7328	0.2290	0.7328	0.3001	0.7328	0.4129	0.7328
RC3.1M	0.0274	0.6512	0.1465	0.6512	0.2029	0.6512	0.2349	0.6512	0.2798	0.6512
RC3.1H	0.0643	0.6292	0.1890	0.6292	0.2533	0.6292	0.3605	0.6292	1.2344	0.6292
RC3.2L	0.0243	0.7328	0.0994	0.7328	0.1483	0.7328	0.2071	0.7328	0.2609	0.7328
RC3.2M	0.0021	0.6512	0.0208	0.6512	0.0834	0.6512	0.1176	0.6512	0.1599	0.6512
RC3.2H	0.0934	0.6292	0.1588	0.6292	0.2811	0.6292	0.5023	0.6292	1.0908	0.6292
RC4L	0.0265	0.7647	0.1585	0.7647	0.2773	0.7647	0.4531	0.7647	0.7296	0.7647
RC4M	0.0161	0.7005	0.1187	0.7005	0.3040	0.7005	0.5799	0.7005	1.1769	0.7005
RC4H	0.0094	0.7004	0.0974	0.7004	0.3309	0.7004	1.9462	0.7004	4.6052	0.7004
RC4.1L	0.0954	0.7647	0.2441	0.7647	0.4576	0.7647	0.6275	0.7647	0.8816	0.7647
RC4.1M	0.0940	0.7005	0.3223	0.7005	0.5941	0.7005	1.0221	0.7005	1.7409	0.7005
RC4.1H	0.0975	0.7004	0.2056	0.7004	0.3813	0.7004	2.3550	0.7004	5.8269	0.7004
RC4.2L	0.0701	0.7647	0.2803	0.7647	0.4643	0.7647	0.6174	0.7647	0.8500	0.7647
RC4.2M	0.0905	0.7005	0.2372	0.7005	0.4422	0.7005	0.6726	0.7005	1.3305	0.7005
RC4.2H	0.0996	0.7004	0.2138	0.7004	0.5159	0.7004	2.0080	0.7004	4.3955	0.7004

Estimated fragility curve parameters, High-Code Design

BTM	Slight		Moderate		Substantial to heavy		Very Heavy		Complete	
	Median	Beta	Median	Beta	Median	Beta	Median	Beta	Median	Beta
RC1L	0.0103	0.7138	0.0973	0.7138	0.3258	0.7138	0.5591	0.7138	0.8468	0.7138
RC1M	0.0094	0.6297	0.0921	0.6297	0.2856	0.6297	0.8847	0.6297	1.5334	0.6297
RC1H	0.0520	0.6070	0.2525	0.6070	1.0164	0.6070	1.8682	0.6070	2.7928	0.6070
RC3.1L	0.1129	0.7138	0.2781	0.7138	0.7154	0.7138	1.6561	0.7138	2.1649	0.7138
RC3.1M	0.0984	0.6297	0.2037	0.6297	0.3966	0.6297	0.8536	0.6297	1.6941	0.6297
RC3.1H	0.0945	0.6070	0.2655	0.6070	0.8136	0.6070	1.5668	0.6070	4.5780	0.6070
RC3.2L	0.1275	0.7138	0.3205	0.7138	0.5483	0.7138	0.8395	0.7138	1.1169	0.7138
RC3.2M	0.0918	0.6297	0.2125	0.6297	0.4350	0.6297	0.5675	0.6297	0.7531	0.6297
RC3.2H	0.1332	0.6070	0.4263	0.6070	0.6564	0.6070	1.1815	0.6070	2.1018	0.6070
RC4L	0.2034	0.7465	0.4565	0.7465	1.2368	0.7465	1.5059	0.7465	2.1288	0.7465
RC4M	0.0941	0.6806	0.2697	0.6806	0.6672	0.6806	1.2074	0.6806	2.3881	0.6806
RC4H	0.1221	0.6805	0.7127	0.6805	1.8654	0.6805	3.3640	0.6805	5.4622	0.6805
RC4.1L	0.2673	0.7465	0.5232	0.7465	1.2112	0.7465	1.8826	0.7465	2.3983	0.7465
RC4.1M	0.1279	0.6806	0.3359	0.6806	0.9463	0.6806	1.3971	0.6806	2.8041	0.6806
RC4.1H	0.1256	0.6805	0.6674	0.6805	1.6634	0.6805	3.7579	0.6805	6.6903	0.6805
RC4.2L	0.2377	0.7465	0.5464	0.7465	1.6118	0.7465	1.9261	0.7465	2.3319	0.7465
RC4.2M	0.1257	0.6806	0.3582	0.6806	0.7489	0.6806	1.3571	0.6806	2.7817	0.6806
RC4.2H	0.1385	0.6805	0.5553	0.6805	1.8107	0.6805	3.6344	0.6805	6.1875	0.6805

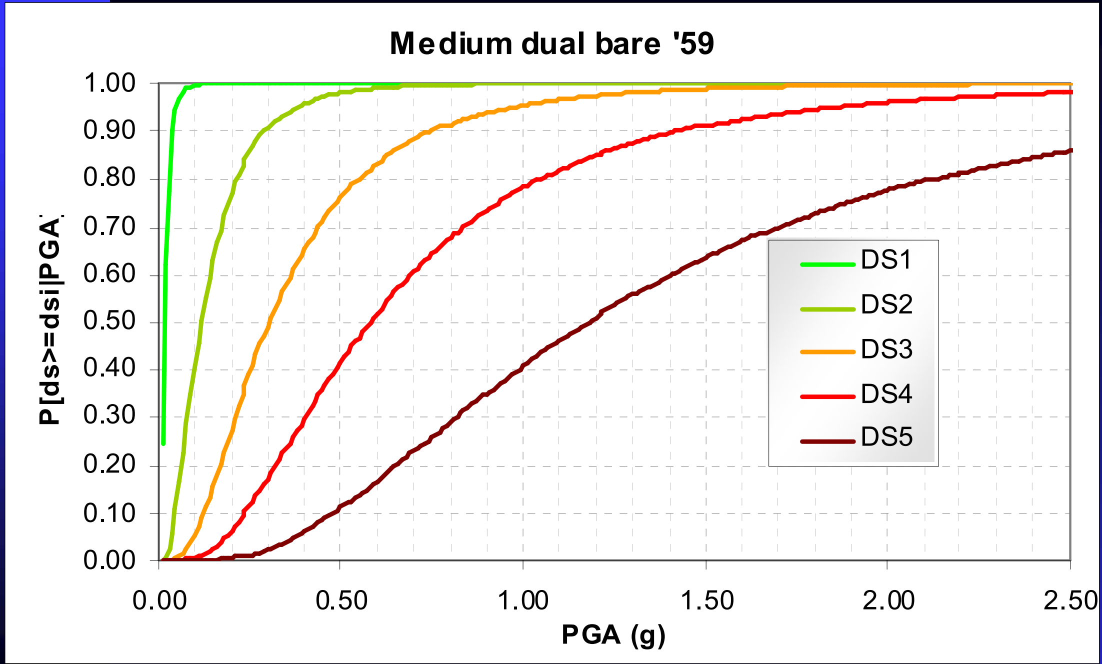


low code



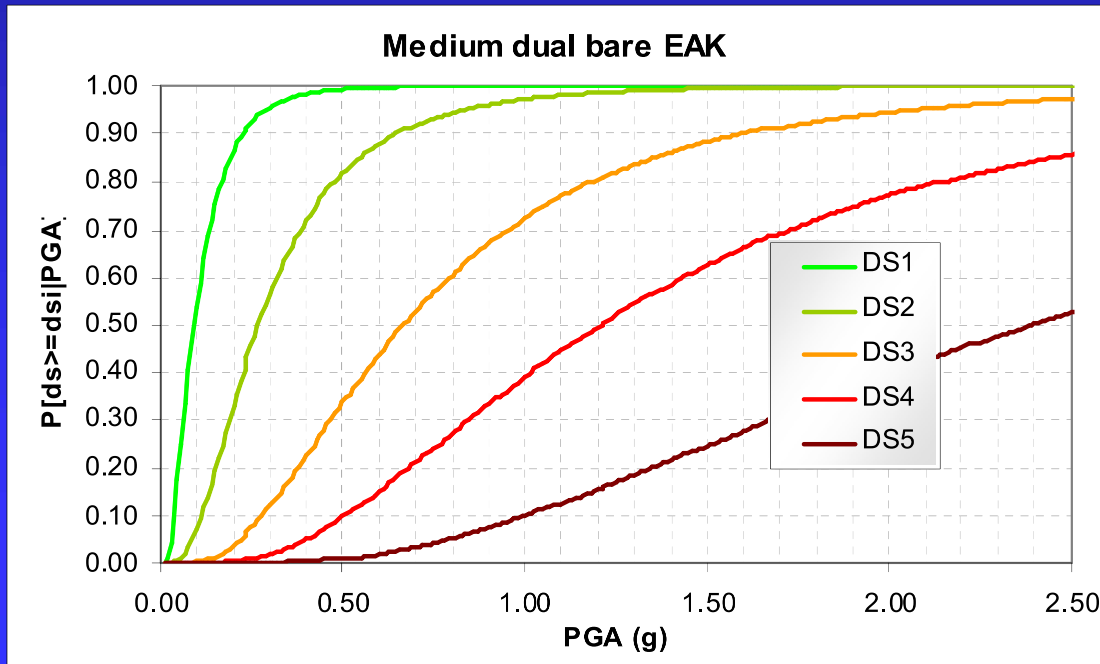
fragility curves for RC3.1M (medium-rise infilled frame)

high code



low code

fragility curves
for RC4M
(medium-rise
dual system)

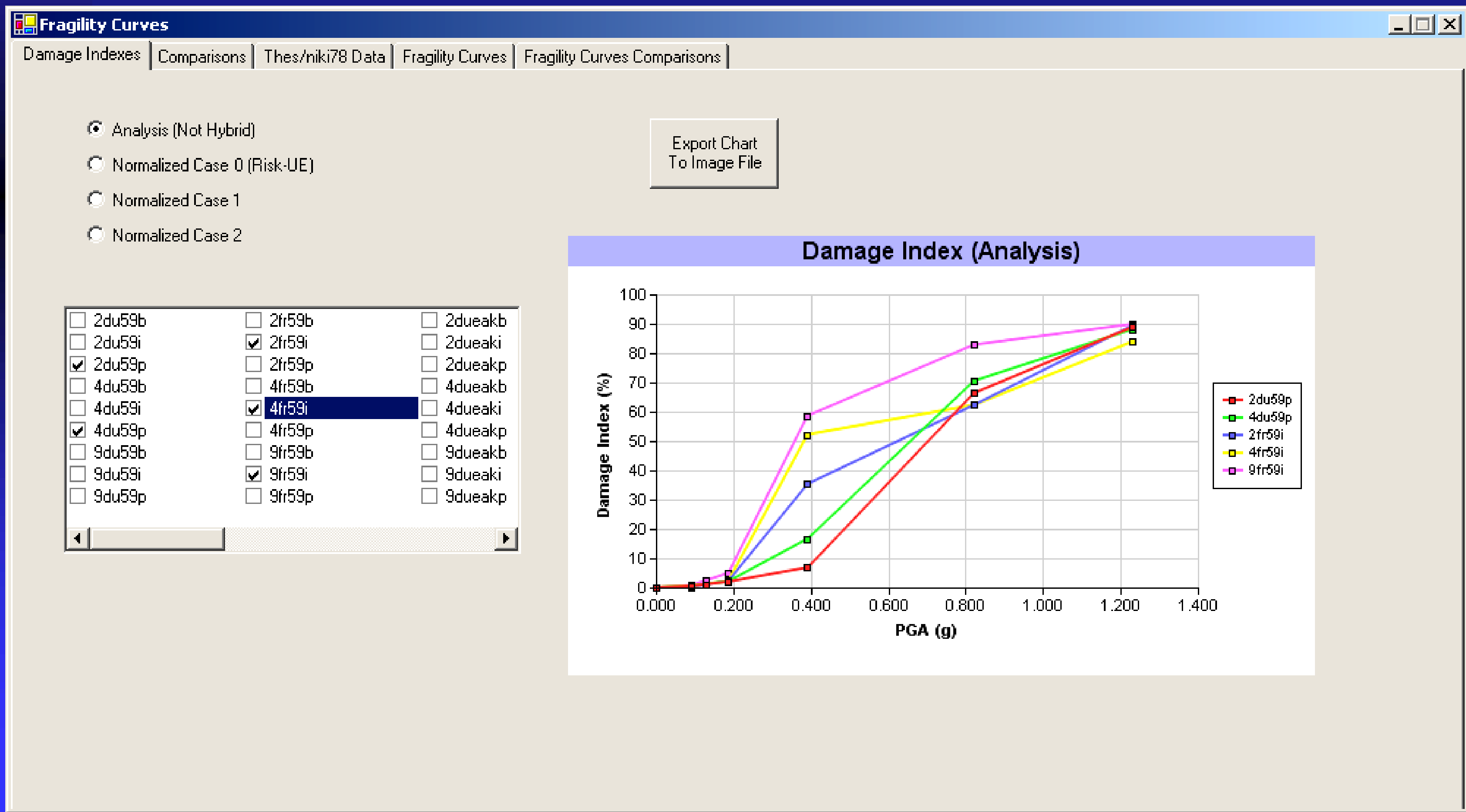


high code

Development of special-purpose software (HyFragC) for processing of results & derivation of fragilty curves

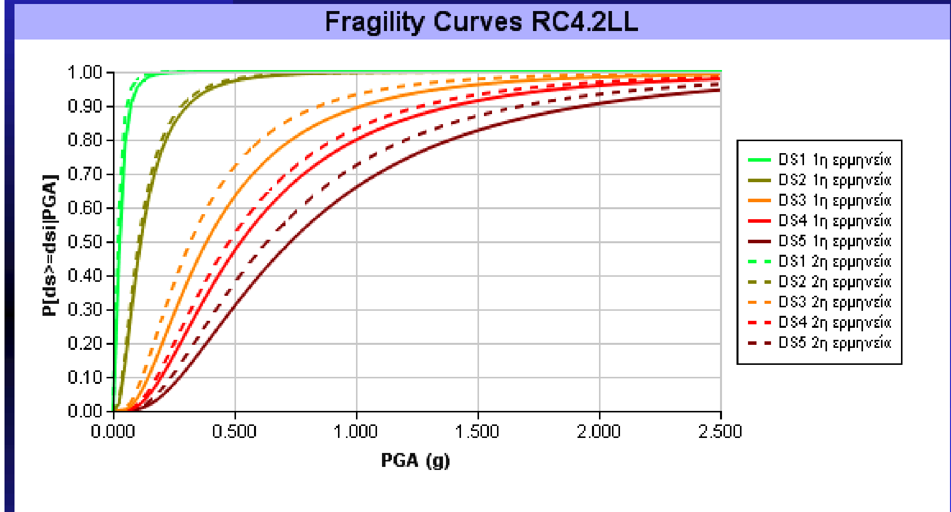
- large no. of analyses
- large no. of structural systems
- sensitivity analyes at various stages

need to develop special-purpose software

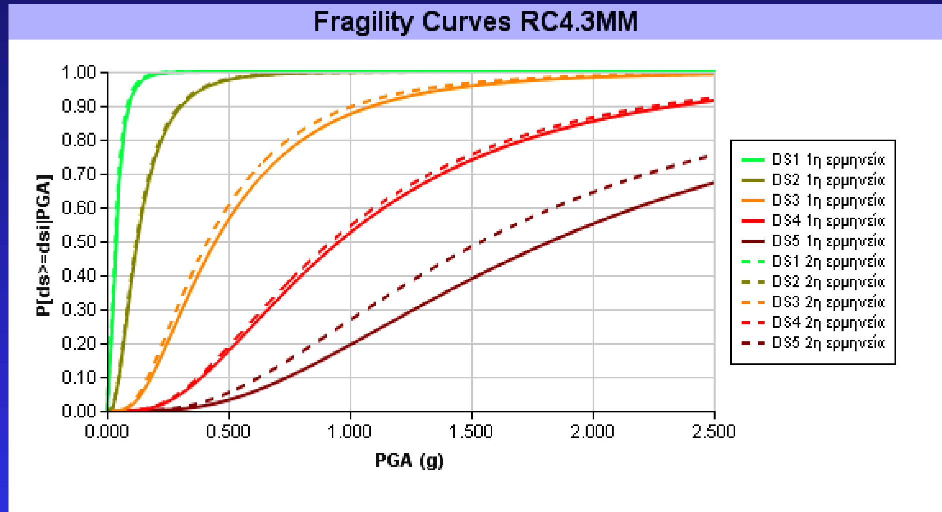


Implementation of hybrid procedure: Sensitivity analysis (different interpretation of statistical data)

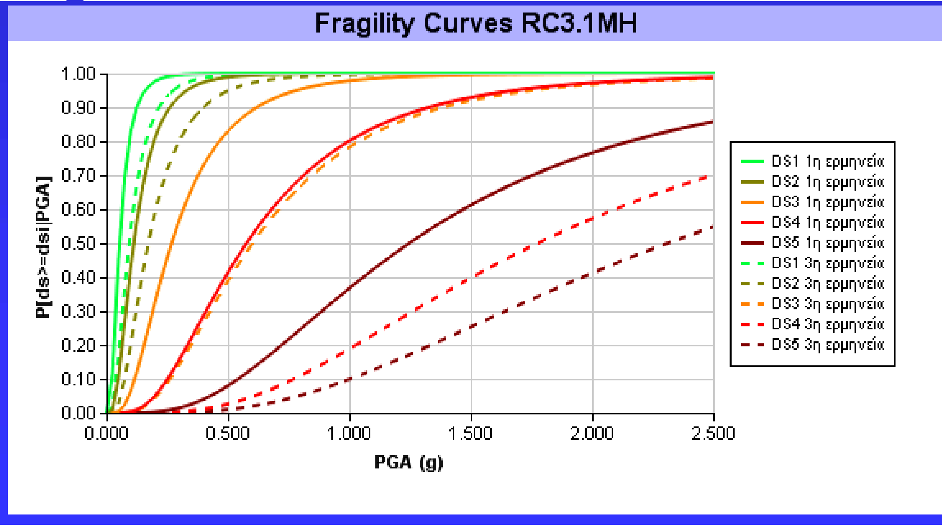
low-rise dual structures, regularly-infilled, designed to Low code (RD'59)



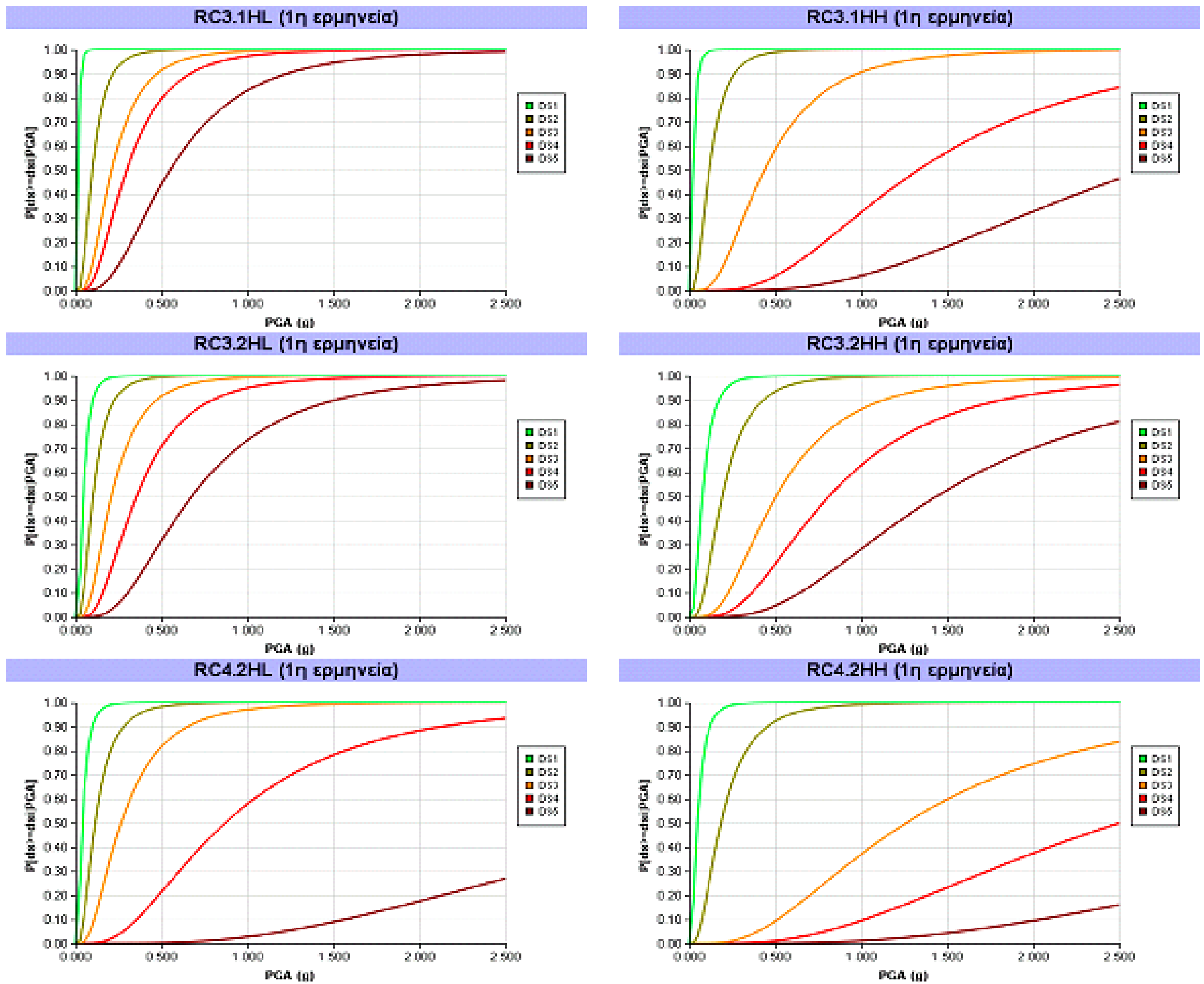
medium-rise dual structures with pilotis, designed to Medium code (1984 Suppl.)



high-rise frame structures, regularly-infilled, designed to High code (NEAK/EAK2000)



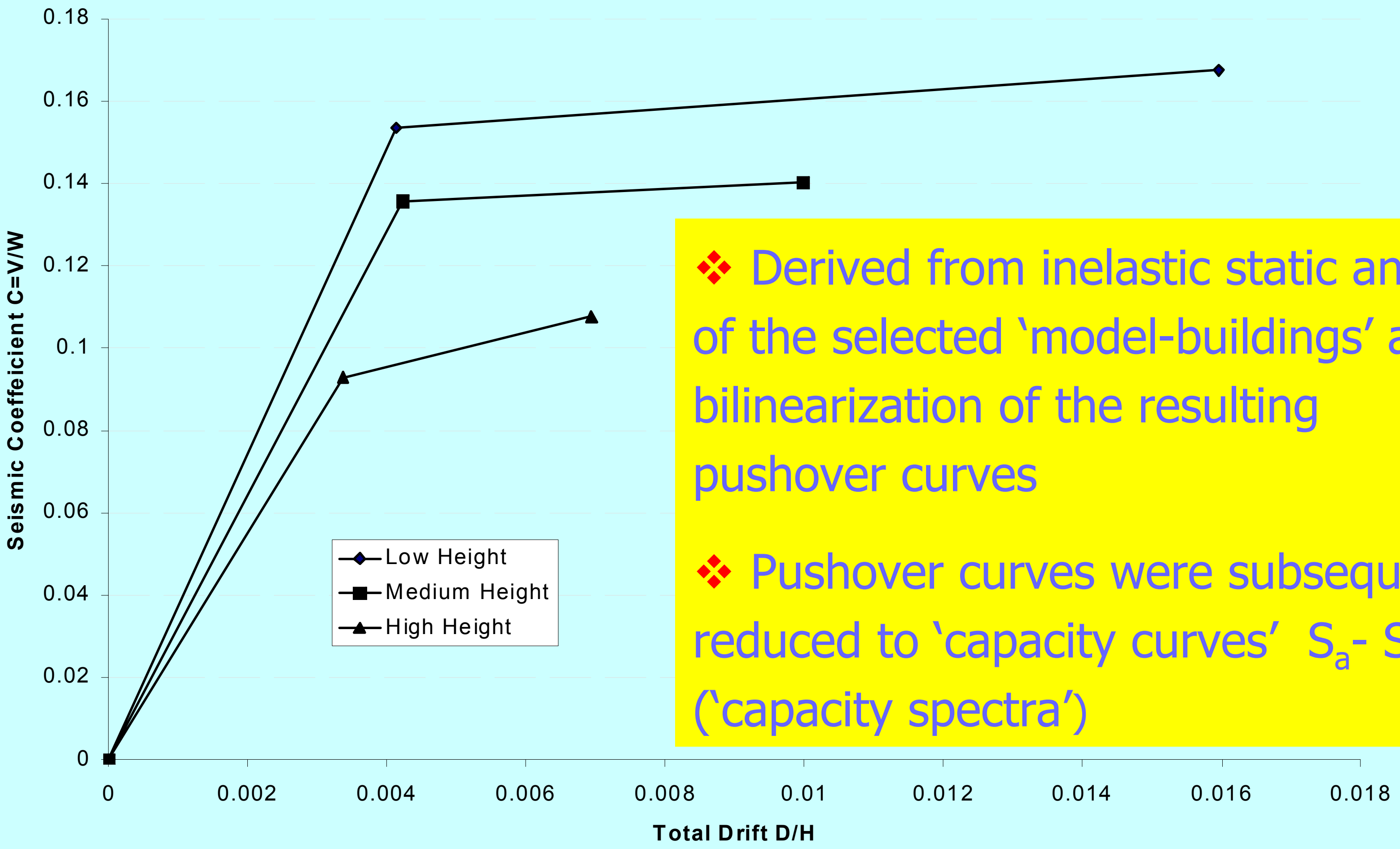
Implementation of hybrid procedure – a complete set of fragilty curves for R/C structures was derived



παλιά (ΒΔ'59)

σύγχρονα (ΕΑΚ)

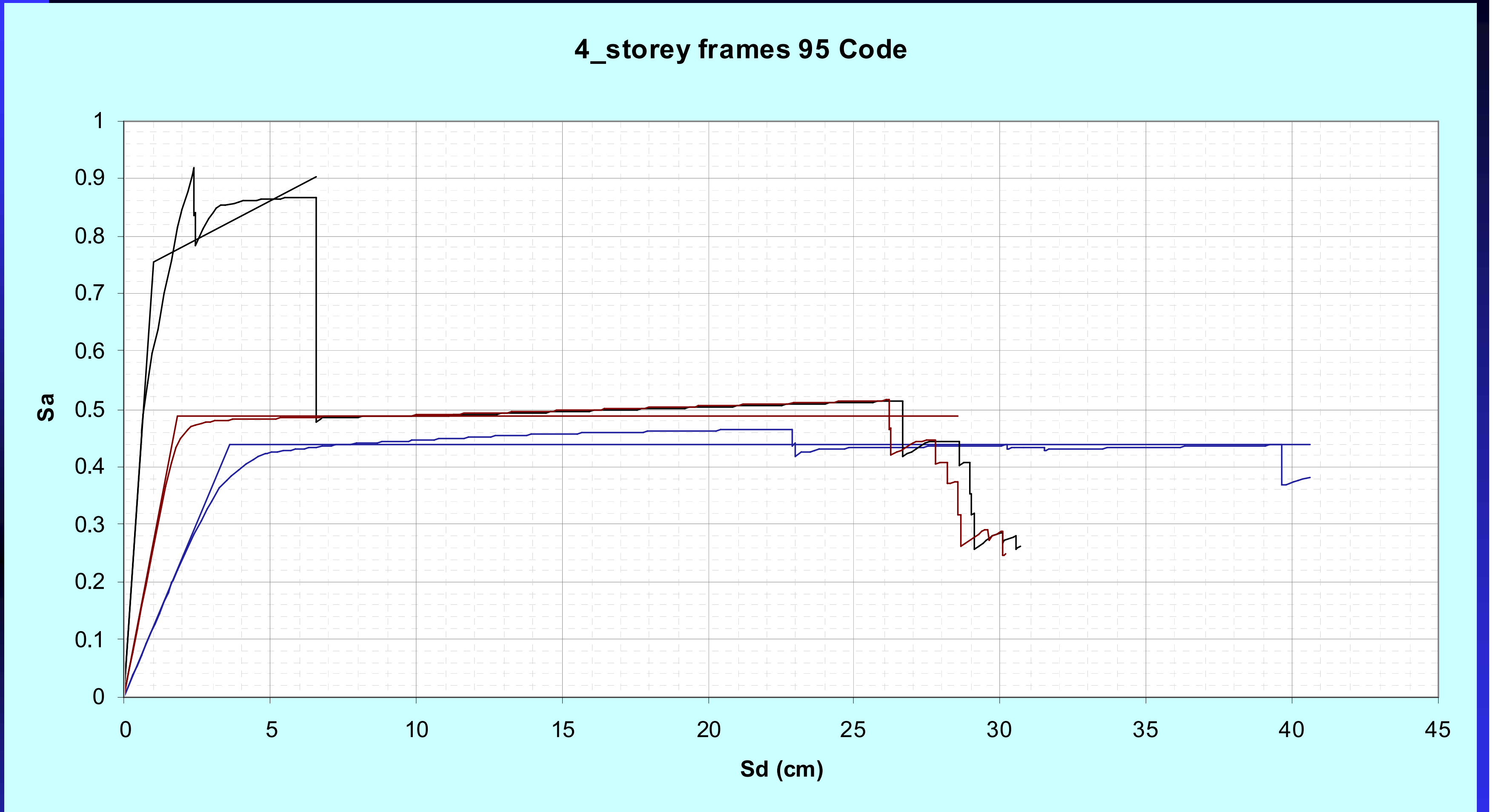
S_d-based fragilty curves – Methodology used



- ❖ Derived from inelastic static analysis of the selected 'model-buildings' and bilinearization of the resulting pushover curves

- ❖ Pushover curves were subsequently reduced to 'capacity curves' S_a- S_d ('capacity spectra')

Pushover curve (bilinear form); RC1 - 1959 code



- 4 storey (High code) frame building's capacity curves for (from top to bottom) infilled, pilotis and bare building

for infilled buildings ⇒ 2 bilinear models needed!

Capacity curves - old buildings ('Low Code')

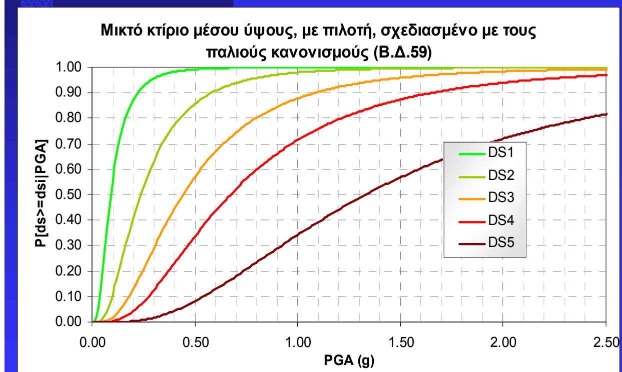
Building Type	Yield Capacity Point				Ultimate Capacity Point			
	S_{dy} (cm)	S_{dy} (Hazus)	S_{ay} (g)	S_{ay} (Hazus)	S_{du} (cm)	S_{du} (Hazus)	S_{au} (g)	S_{au} (Hazus)
RC1L (C1L)	2.320	0.250	0.192	0.062	9.580	3.730	0.209	0.187
RC1M (C1M)	4.270	0.740	0.170	0.052	10.770	7.320	0.175	0.156
RC1H (C1H)	5.760	1.270	0.124	0.024	14.830	9.580	0.144	0.073
RC3.1L (C3L)	0.460 0.416	0.300	0.840 0.430	0.100	1.725 4.373	3.430	1.191 0.525	0.225
RC3.1M (C3M)	0.850 0.841	0.660	0.423 0.203	0.083	2.625 6.443	4.950	0.635 0.357	0.188
RC3.1H (C3H)	2.330 2.273	1.880	0.280 0.125	0.063	6.305 10.032	10.490	0.397 0.256	0.143
RC3.2L	1.790 1.761	-	0.200 0.200	-	8.475 8.545	-	0.223 0.221	-
RC3.2M	1.990 2.288	-	0.204 0.204	-	7.575 8.077	-	0.230 0.222	-
RC3.2H	2.930 2.796	-	0.243 0.187	-	7.280 9.330	-	0.293 0.227	-
RC4.1L (C2L)	1.080	0.300	0.385	0.100	5.050	3.810	0.466	0.250
RC4.1M (C2M)	1.460	0.660	0.182	0.083	8.250	5.490	0.253	0.208
RC4.1H (C2H)	3.860	1.880	0.204	0.063	15.600	11.660	0.260	0.159
RC4.2L	0.320 0.301	-	0.584 0.446	-	2.475 3.054	-	0.877 0.598	-
RC4.2M	0.820 0.983	-	0.331 0.271	-	4.875 5.869	-	0.451 0.309	-
RC4.2H	2.810 2.774	-	0.361 0.305	-	9.880 9.460	-	0.411 0.339	-
RC4.3L	0.390 0.258	-	0.472 0.343	-	3.225 3.047	-	0.623 0.517	-
RC4.3M	0.890 0.863	-	0.296 0.225	-	4.800 5.432	-	0.374 0.302	-
RC4.3H	2.500 2.565	-	0.309 0.257	-	8.125 9.958	-	0.370 0.294	-

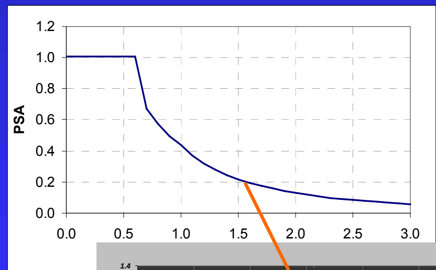
Capacity curves - 'Moderate Code'

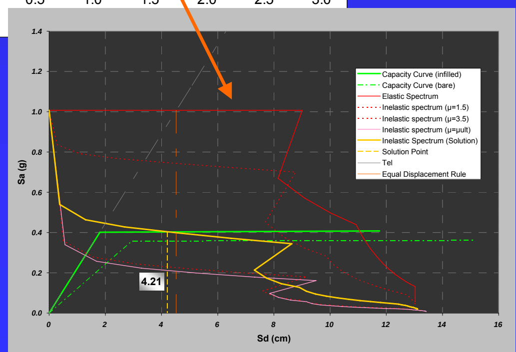
Building Type	Yield Capacity Point				Ultimate Capacity Point			
	S_{dy} (cm)	S_{dy} (Hazus)	S_{ay} (g)	S_{ay} (Hazus)	S_{du} (cm)	S_{du} (Hazus)	S_{au} (g)	S_{au} (Hazus)
RC1L (C1L)	2.166	0.508	0.571	0.125	14.363	8.941	0.577	0.375
RC1M (C1M)	2.947	1.473	0.358	0.104	15.139	17.551	0.361	0.312
RC1H (C1H)	5.041	2.565	0.209	0.049	16.992	22.987	0.224	0.147
RC3.1L (C3L)	0.486 0.504	-	1.336 0.790	-	2.713 4.897	-	1.550 0.922	-
RC3.1M (C3M)	0.857 0.863	-	0.656 0.406	-	3.564 6.195	-	0.823 0.548	-
RC3.1H (C3H)	1.961 2.070	-	0.395 0.284	-	6.906 12.871	-	0.479 0.341	-
RC3.2L	1.467 1.536	-	0.616 0.609	-	12.299 13.085	-	0.623 0.615	-
RC3.2M	1.531 1.807	-	0.404 0.402	-	11.142 11.764	-	0.411 0.408	-
RC3.2H	2.296 2.766	-	0.309 0.290	-	9.246 12.461	-	0.330 0.305	-
RC4.1L (C2L)	0.413	0.610	0.739	0.200	5.450	9.144	0.861	0.500
RC4.1M (C2M)	1.116	1.321	0.329	0.167	12.286	13.183	0.374	0.417
RC4.1H (C2H)	4.266	3.734	0.396	0.127	21.997	27.991	0.523	0.317
RC4.2L	0.401 0.353	-	1.103 0.804	-	4.557 6.649	-	1.227 0.928	-
RC4.2M	0.978 0.979	-	0.529 0.420	-	8.234 8.270	-	0.595 0.432	-
RC4.2H	2.333 2.624	-	0.500 0.416	-	12.258 12.758	-	0.646 0.560	-
RC4.3L	0.364 0.366	-	0.836 0.759	-	6.270 7.026	-	0.976 0.889	-
RC4.3M	0.952 0.859	-	0.473 0.352	-	8.481 11.910	-	0.496 0.415	-
RC4.3H	2.172 2.511	-	0.453 0.392	-	13.322 16.772	-	0.622 0.540	-

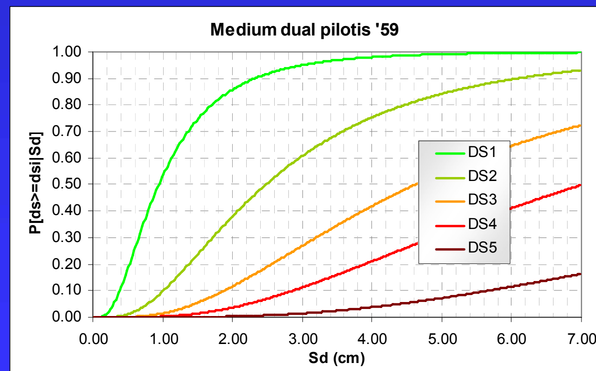
S_d-based fragilty curves – Methodology used

- At the present stage of development the PGA-based fragility curves were used as a basis
- Two typical 'demand spectra' were considered
  - average spectrum from Thessaloniki microzonation study (Pitilakiws et al.)
  - Seismic Code (EAK2000-Annex A) spectrum
- The capacity spectrum method (C.S.M.) was adopted
- Median values for each damage level from the fragility curves of the 1st apporaoch (PGA-based) were transformed into S_d terms (from T_o and the selected spectra)





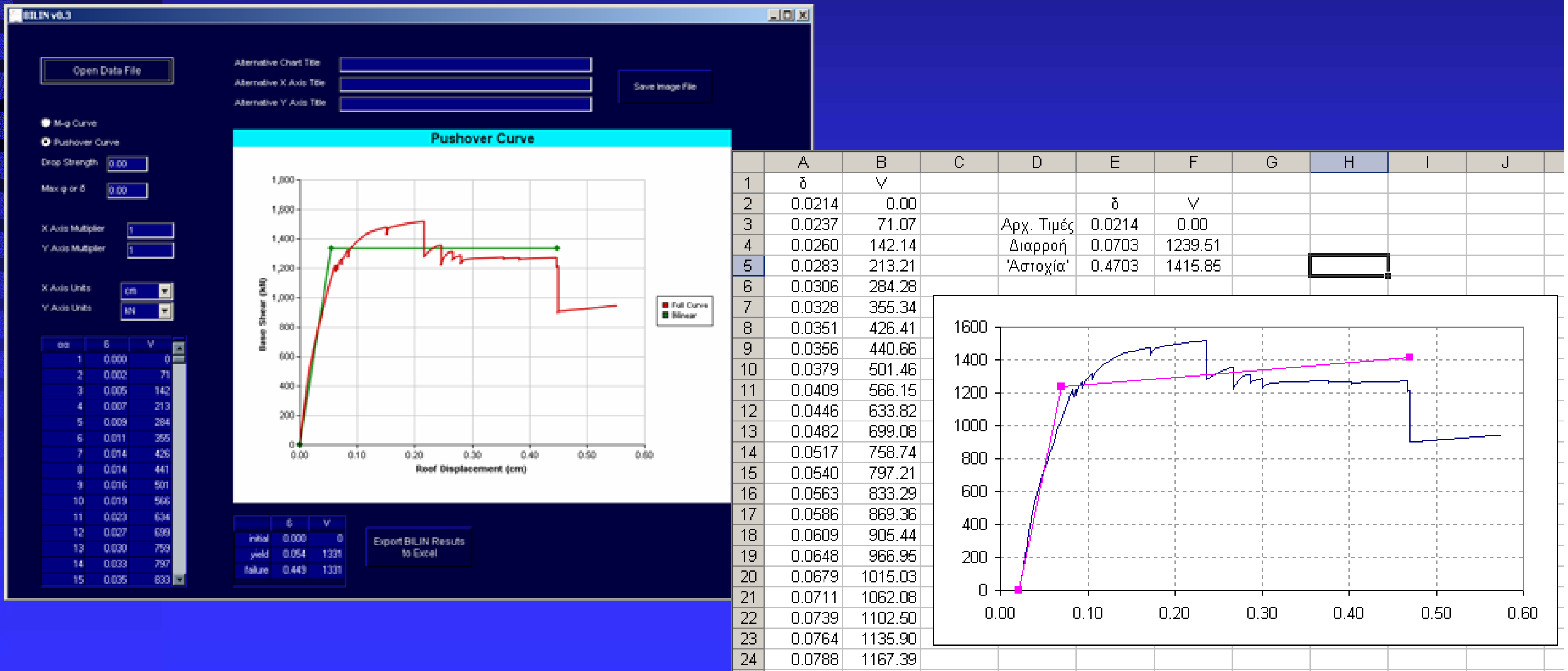




To carry out ‘automatically’ the bilinearization of

- pushover and capacity curves
- of moment – curvature curves

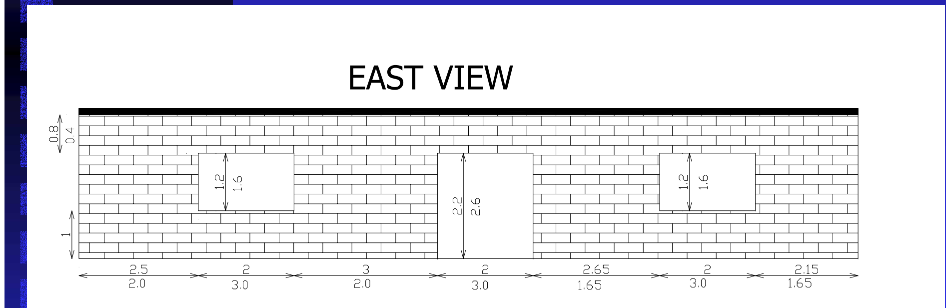
➢an appropriate software (BILIN) was developed at AUTh-LRCMS, both in a stand-alone (.exe) form and as an MS Excel function

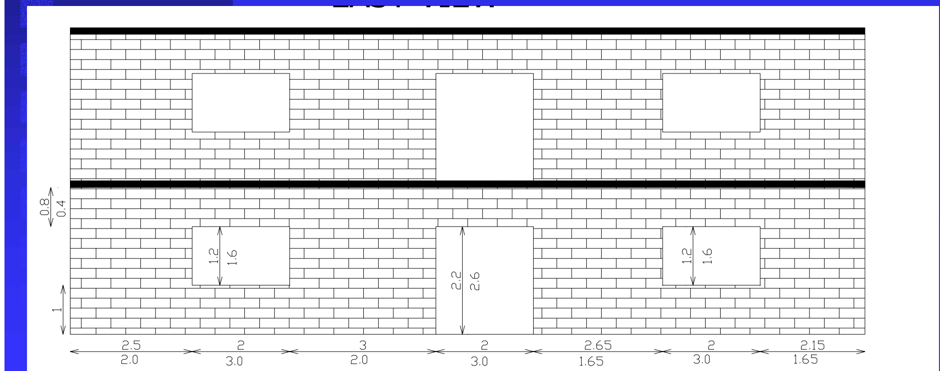


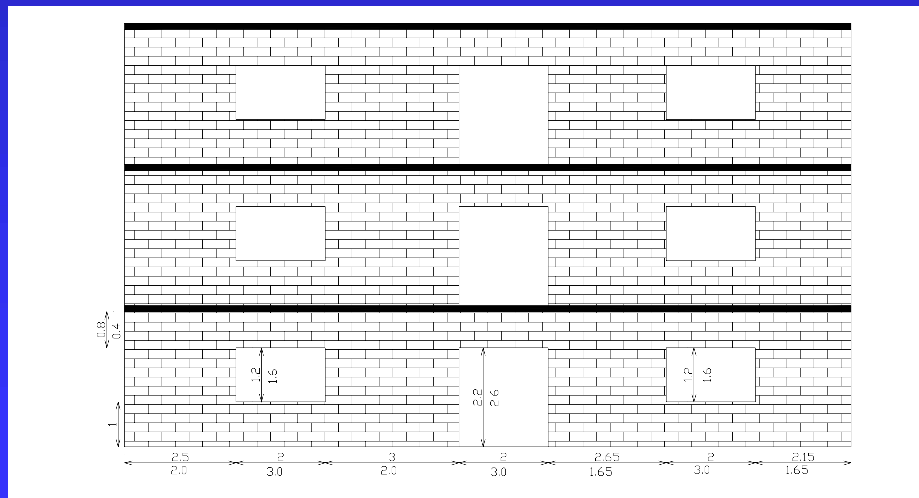
	A	B	C	D	E	F
1	δ	V				
2	0.0214	0.00			δ	V
3	0.0237	71.07		Αρχ. Τιμές	0.0214	0.00
4	0.0260	142.14		Διαρροή	0.0703	1239.51
5	0.0283	213.21		'Αστοχία'	0.4703	1415.85
6	0.0306	284.28				
7	0.0328	355.34				
8	0.0351	426.41				
9	0.0356	440.66				
10	0.0379	501.46				
11	0.0409	566.15				
12	0.0446	633.82				
13	0.0482	699.08				
14	0.0517	758.74				
15	0.0540	797.21				
16	0.0563	833.29				
17	0.0586	869.36				
18	0.0609	905.44				
19	0.0648	966.95				
20	0.0679	1015.03				
21	0.0711	1062.08				
22	0.0739	1102.50				
23	0.0764	1135.90				
24	0.0788	1167.39				

Methodology for deriving fragility curves for URM buildings

- Objective: to derive fragility curves for unreinforced masonry (URM) buildings (stone masonry, brick masonry)
- The methodology starts with inelastic static (pushover) analysis of typical URM building types
- Buildings with different height (1-3 storeys) and different quality of masonry (f_{wm}=1.5÷3.0MPa) are considered

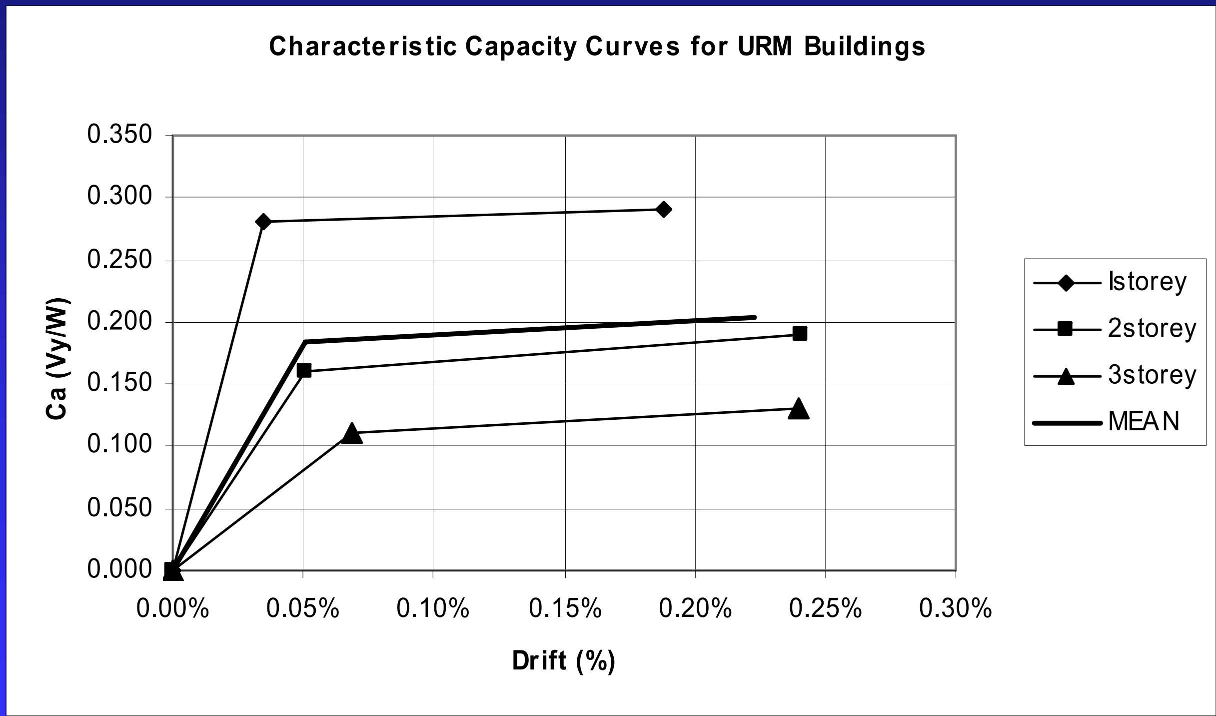






Methodology for deriving fragility curves for URM buildings

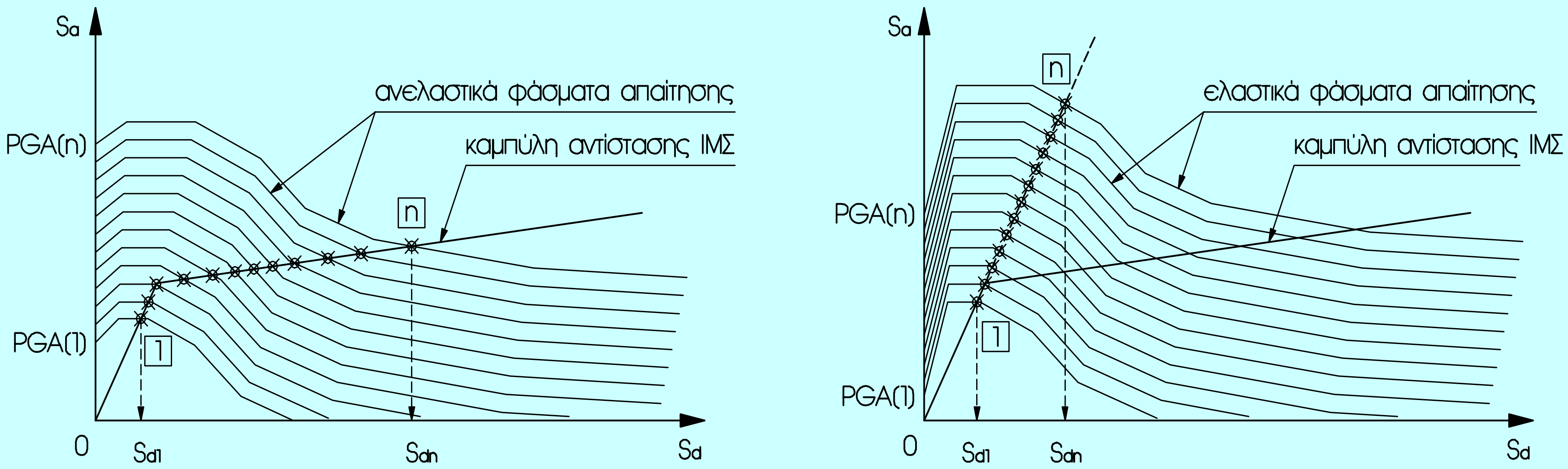
- Pushover curves for typical structures are first derived and then converted to capacity 'spectra' S_a-S_d
- The capacity and demand spectra approach is then utilised



- On the 'hybrid' side, statistical data from the Thessaloniki, Aegion, and Pyrgos earthquakes are taken into account

Estimation of damage in terms of displacements

• The estimation of parameter S_{mi} is made using the capacity and demand spectra approach (for increasing levels of earthquake intensity)



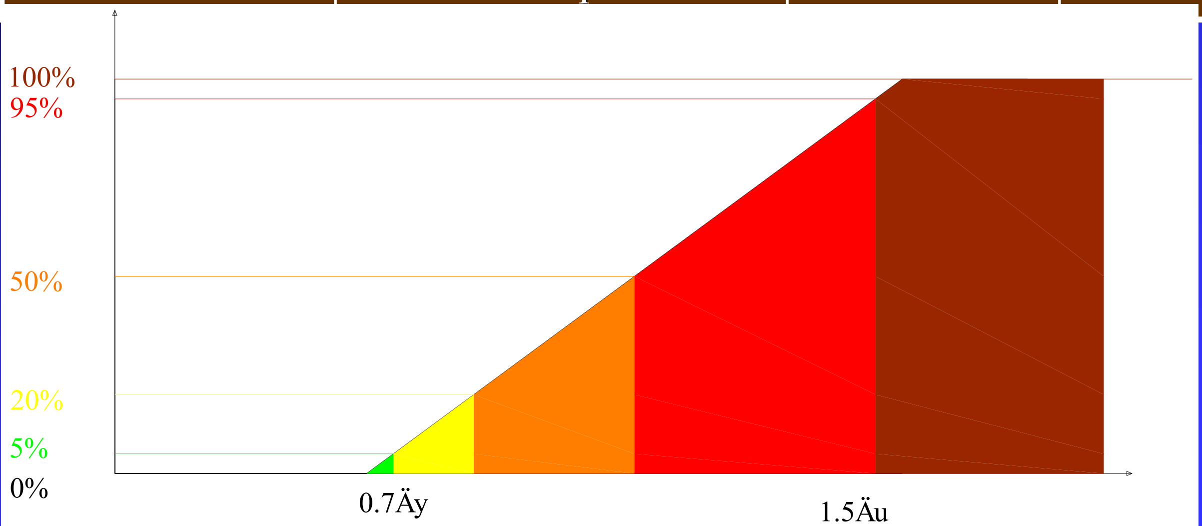
α. $T < 0.5\text{-}0.6$ sec

β. $T > 0.5\text{-}0.6$ sec

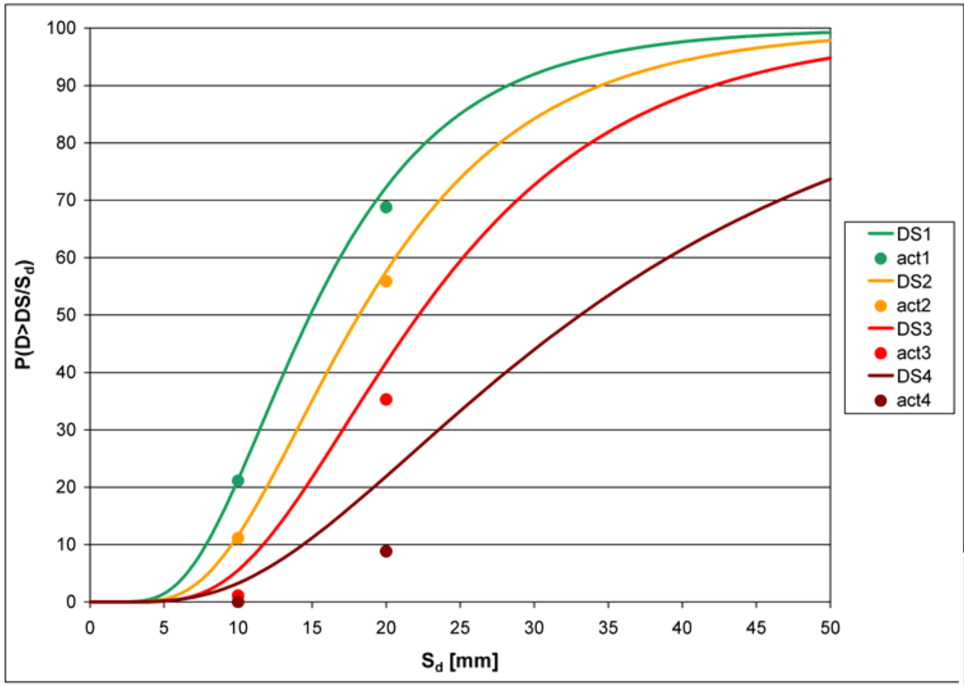
Methodology for deriving fragility curves for URM buildings

- Damage levels are defined with respect to critical points along the pushover (or capacity) curve of the building

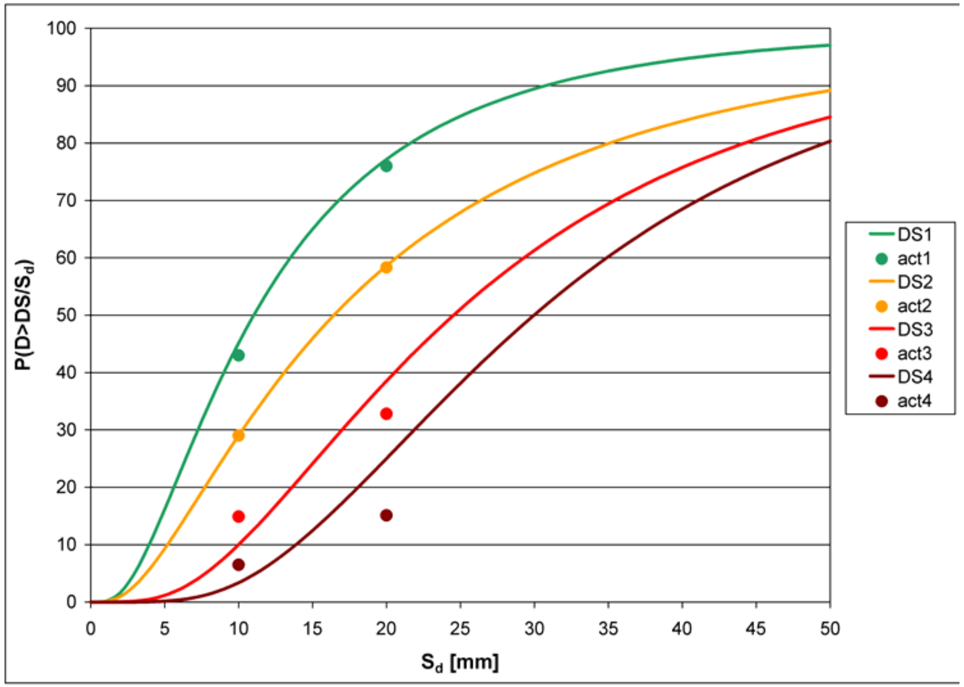
Damage State	Damage State label	Range of loss index (%)	Spectral displacement (related to δ_{target})
D0	None	0	$\delta t<0.7\delta y$
D1	Slight	0 ÷ 5	$0.7\delta y<\delta t<0.7\delta y+5(0.9\delta u-0.7\delta y)/100$
D2	Moderate	5 ÷ 20	$0.7\delta y+5(0.9\delta u-0.7\delta y)/100<\delta t< 0.7\delta y+20(0.9\delta u-0.7\delta y)/100$
D3	Substantial to heavy	20 ÷ 50	$0.7\delta y+20(0.9\delta u-0.7\delta y)/100<\delta t<0.9\delta u$
D4	Very heavy	50 ÷ 95	$0.9\delta u<\delta t<1.5\delta u$
D5	Collapse	>95	$1.5\delta u<\delta t$



Economic loss index in URM buildings, as a function of roof displacement



low-rise brick masonry buildings



low-rise stone masonry buildings

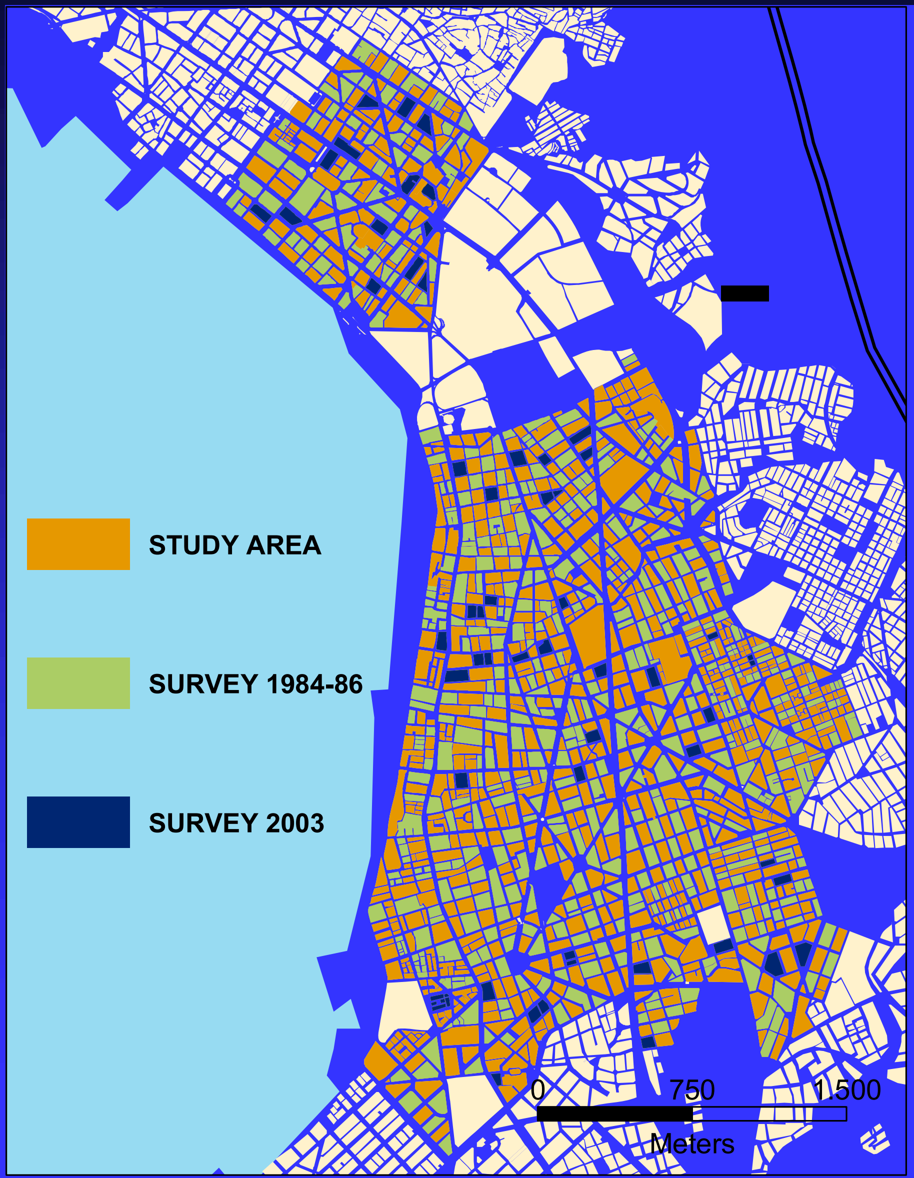
Vulnerability (fragility) curves for URM buildings

Vulnerability assessment and loss scenario for Thessaloniki buildings

A.J. Kappos (coordinator),
Ch. Panagiotopoulos, G. Panagopoulos

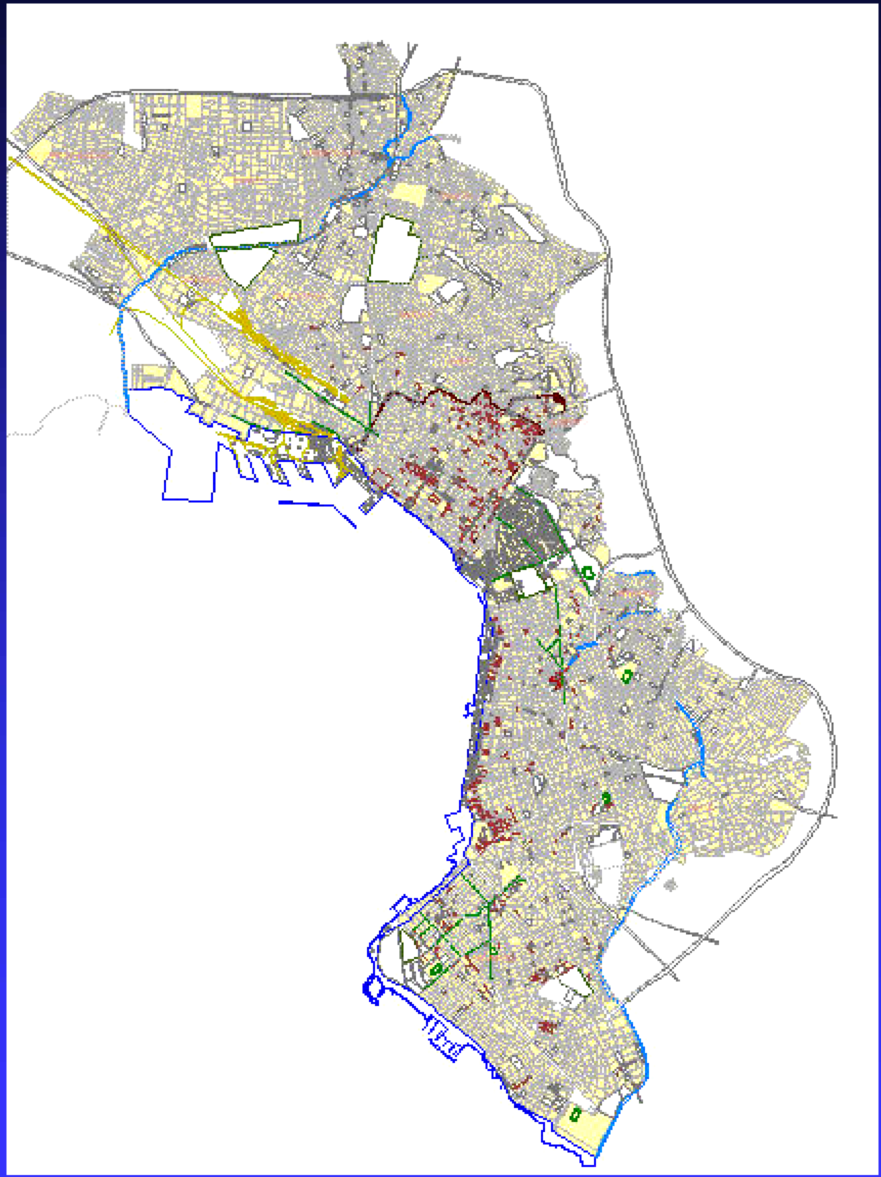
Inventory of buildings

- **Global analysis** of the building stock in the municipality of Thessaloniki
  - 1991 ESYE data
  - Detailed data for a total of 5740 buildings struck by the 1978 earthquake from Penelis et al. project (1986)
- **"block-by-block"** analysis of a selected part of the city
  - *update* of the detailed data using a new in-situ collection of data for a number of blocks (50)
  - in-situ work carried out by the members of the AUTh Structural Group covering a selected sample (>10%) of the 1984-86 survey that belong to the municipality of Thessaloniki



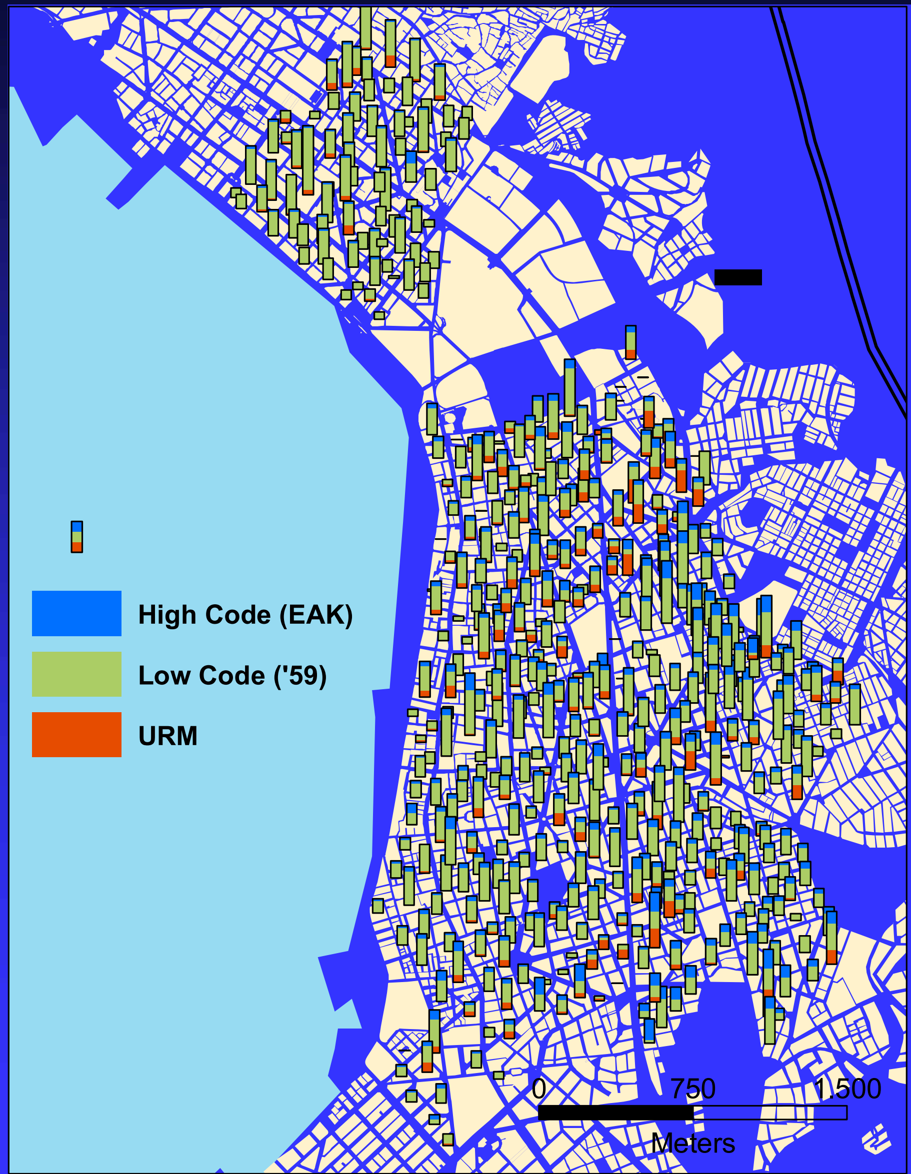
Inventory of buildings

- **Data collected within another (nationally funded) programme for**
  - all hospital (red dots) buildings (a total of 330) in the major area
  - a percentage of secondary school (green dots) buildings in the centre of Thessaloniki (a total of 170)



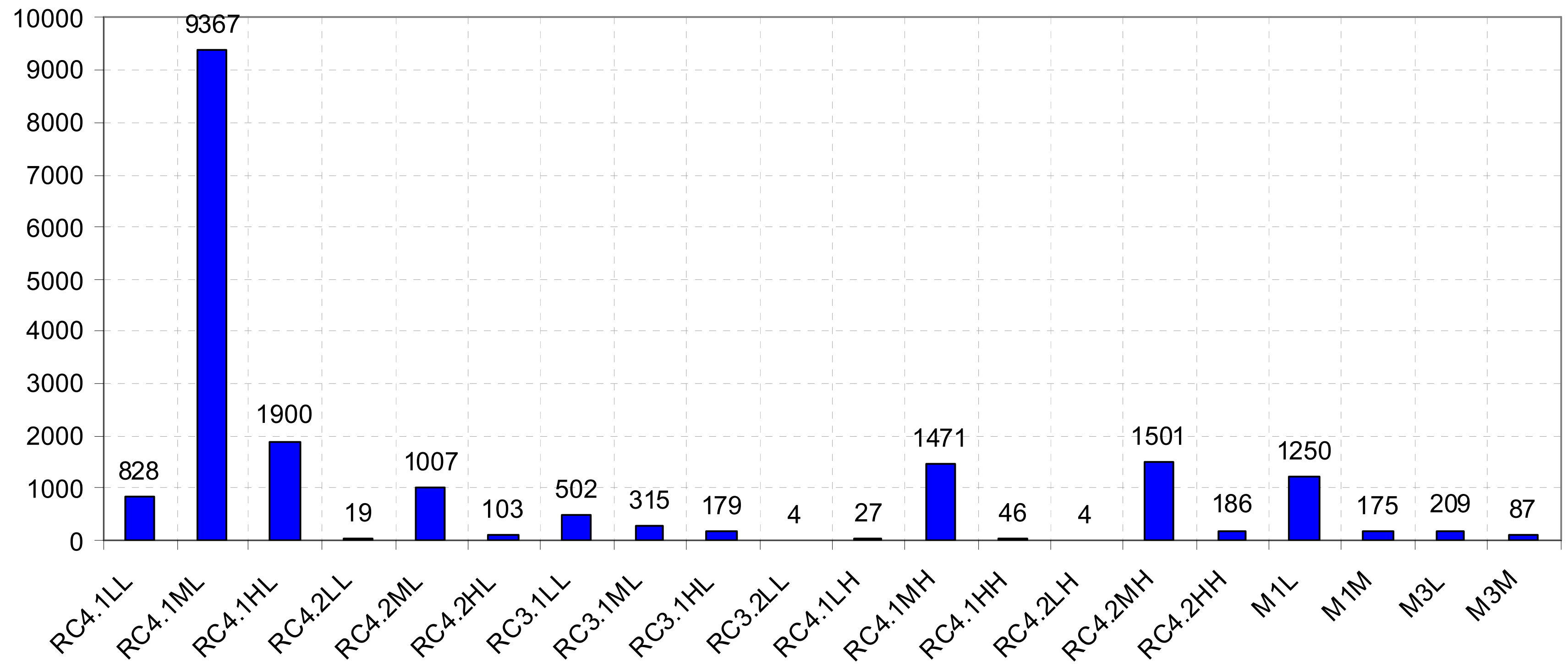
Building type distribution

- **General composition of building blocks in the study area**
  - R/C buildings designed to 'old' (pre-1984) seismic codes
  - R/C buildings designed to 'new' (post-1985) seismic codes
  - URM buildings



Building type distribution

Building type distribution for the Municipality of Thessaloniki (RISK-UE typology)



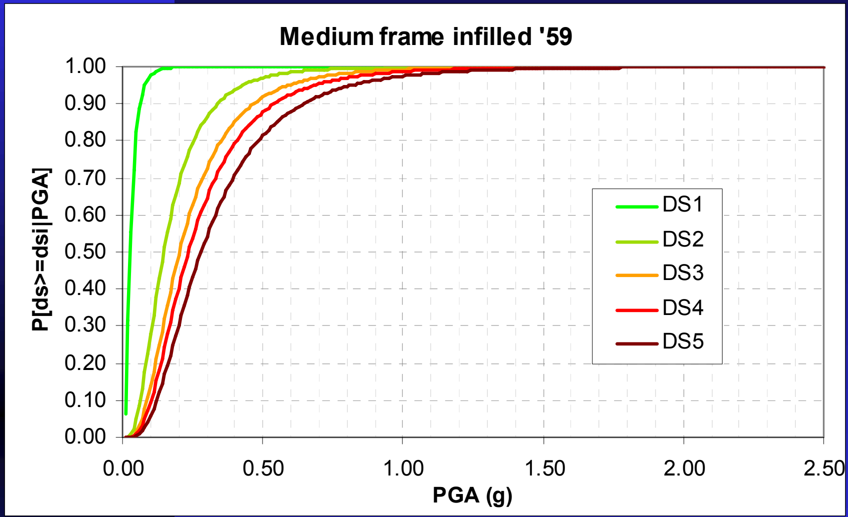
Methodology for building damage assessment

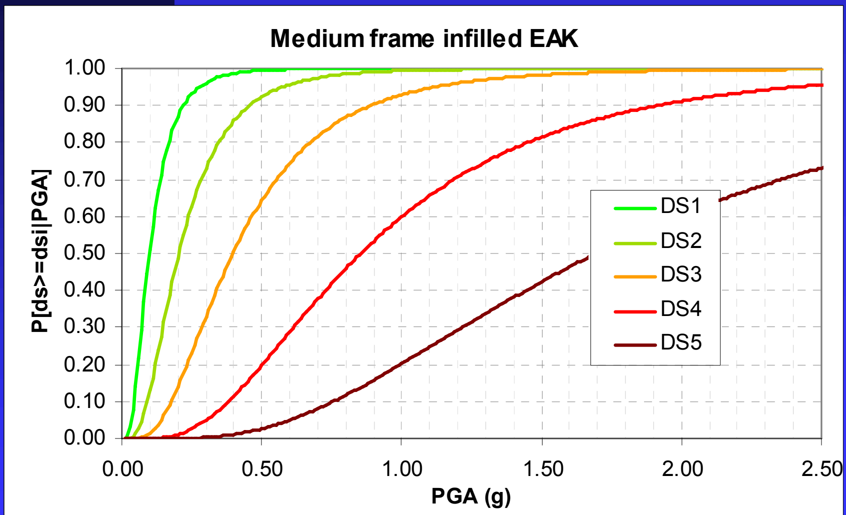
- Fragility curves for all building types were developed using a combination of analysis and statistical data, the so-called 'hybrid' approach (Kappos et al. 1998, 2001)
- 6 damage states (DS0 to DS5) were used in order to better suit the needs of WP7 and obtain a more complete scenario

Damage State	Damage state label	Range of loss index-R/C	Central index (%)	Range of loss index - URM	Central index (%)
DS0	None	0	0	0	0
DS1	Slight	0-1	0.5	0-4	2
DS2	Moderate	1-10	5	4-20	12
DS3	Substantial to heavy	10-30	20	20-40	30
DS4	Very heavy	30-60	45	40-70	55
DS5	Collapse	60-100	80	70-100	85

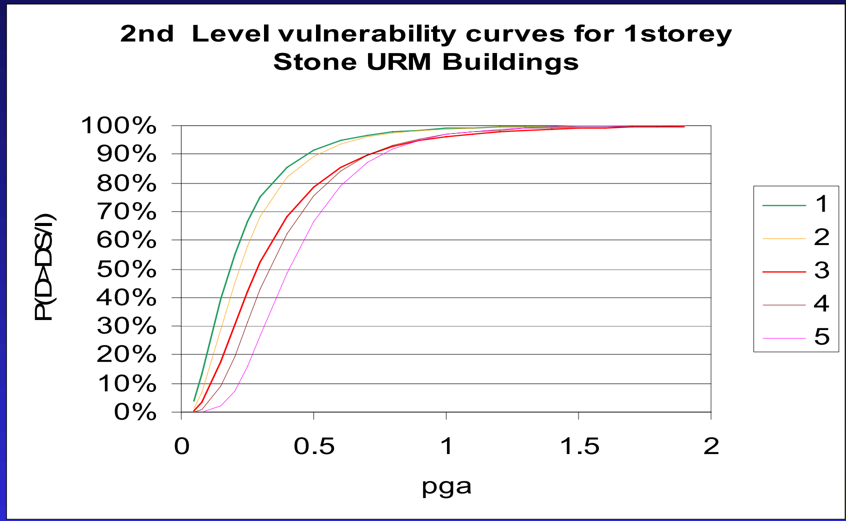
Methodology for building damage assessment

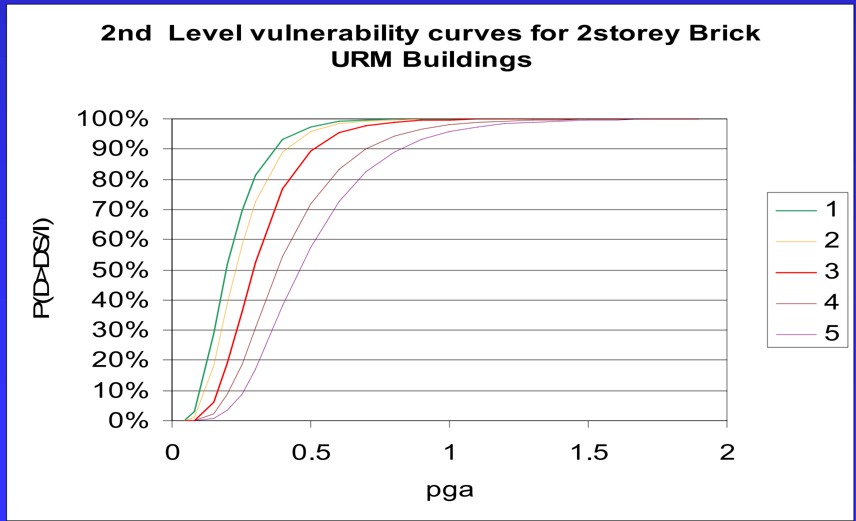
Typical fragility curves for R/C buildings





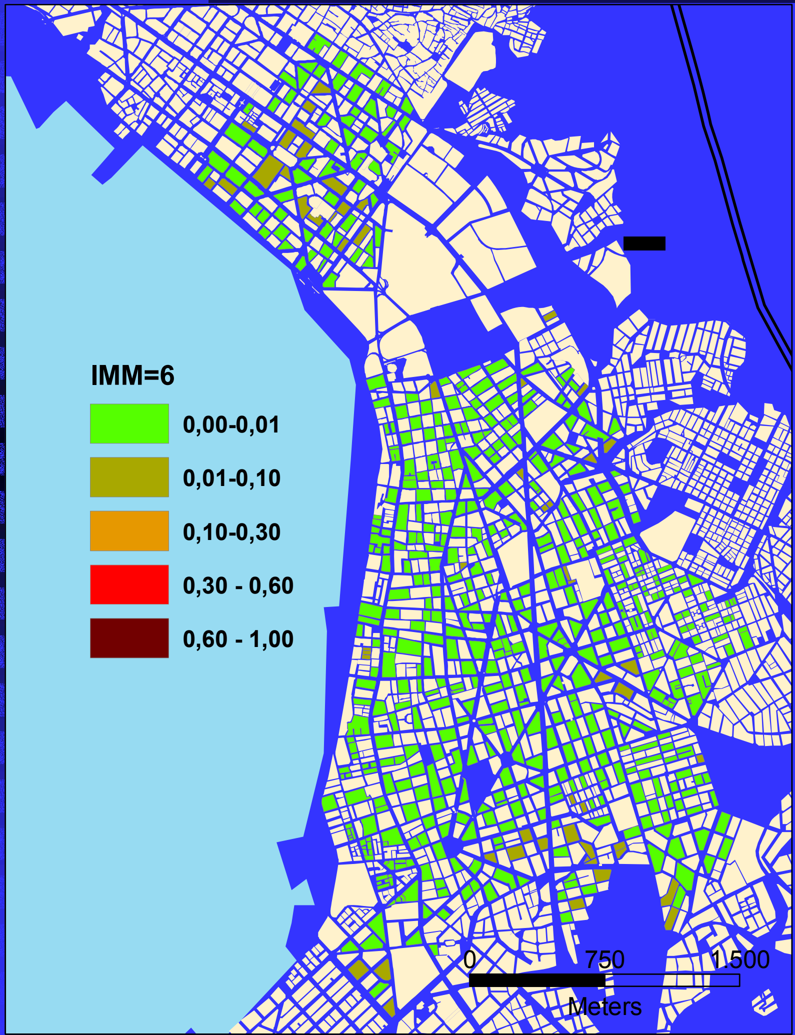
Typical fragility curves for URM buildings

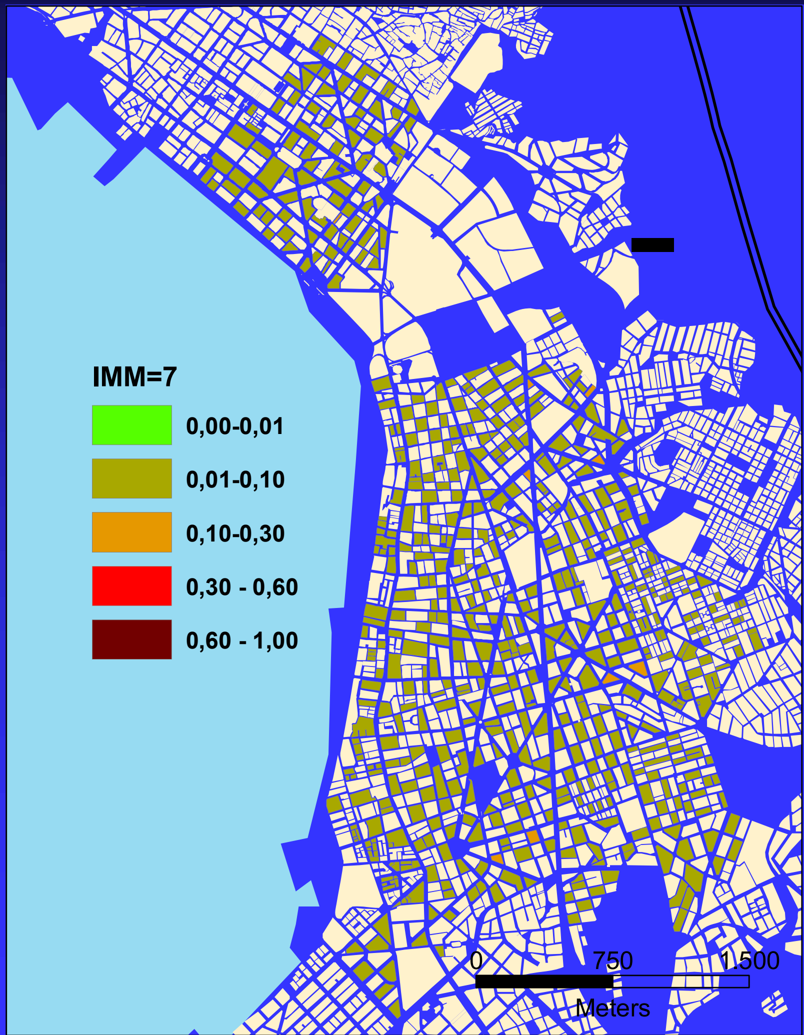




Scenario for current buildings

"Idealized" damage distribution for uniform intensities

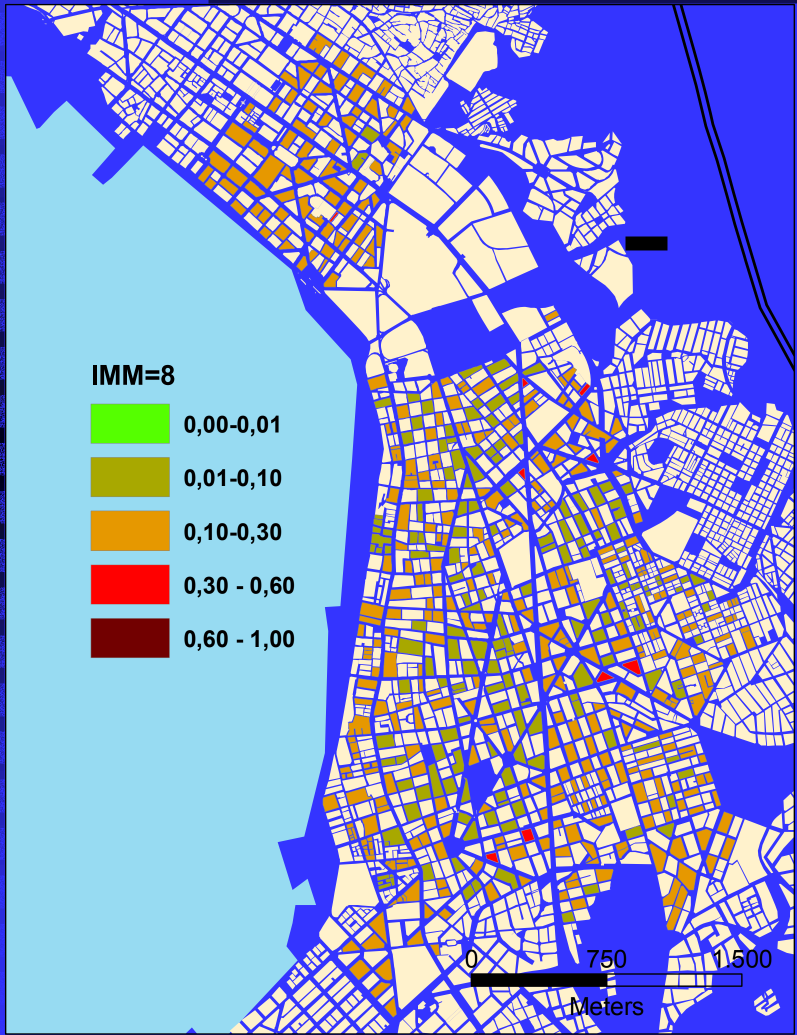


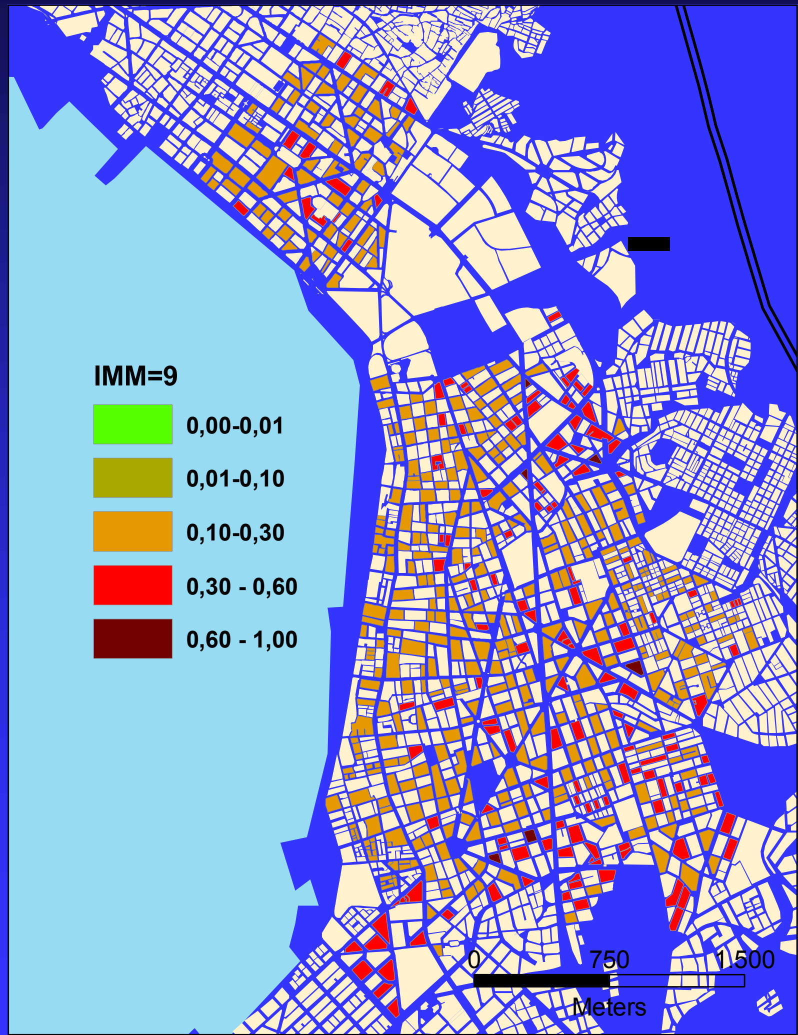


$$\frac{\Sigma(MDF_i \cdot V_i)}{V_{tot}}$$

Scenario for current buildings

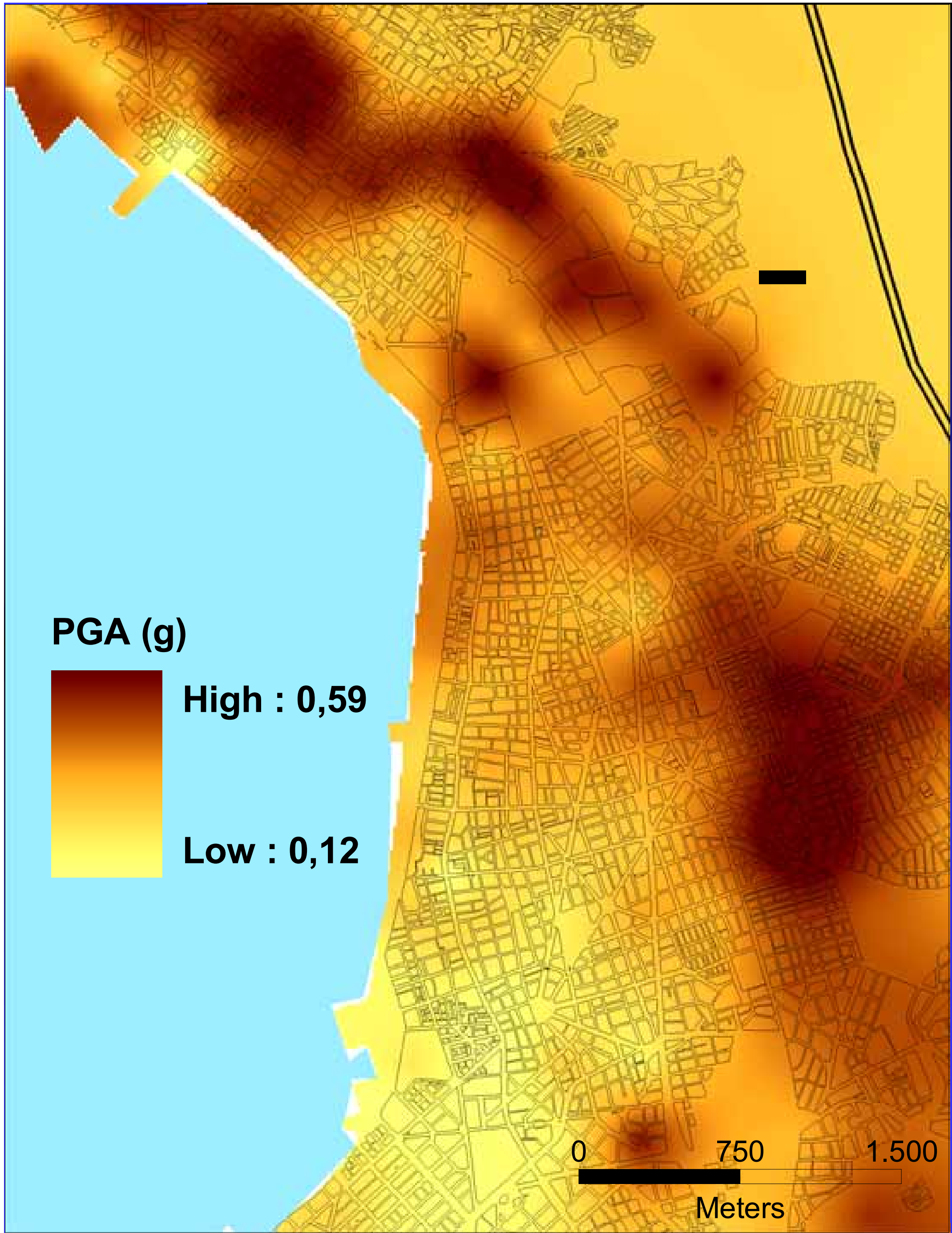
"Idealized" damage distribution for uniform intensities





$$\frac{\Sigma(MDF_i \cdot V_i)}{V_{tot}}$$

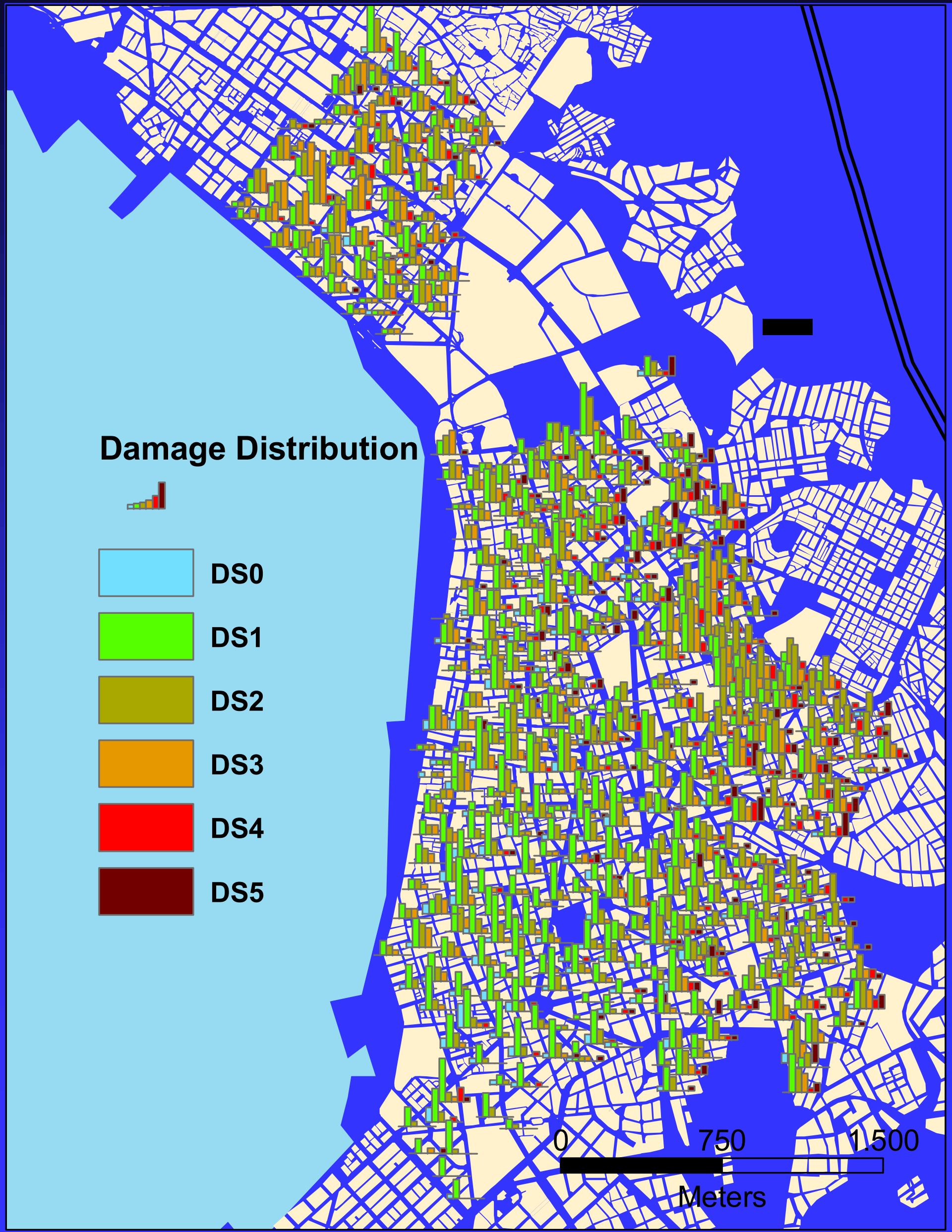
WP2 scenario for Thessaloniki



Map of area for which vulnerability assessment was carried out

Scenario for current buildings

Number of buildings suffering damage states DS0 to DS5 in each building block for the earthquake scenario developed in WP2

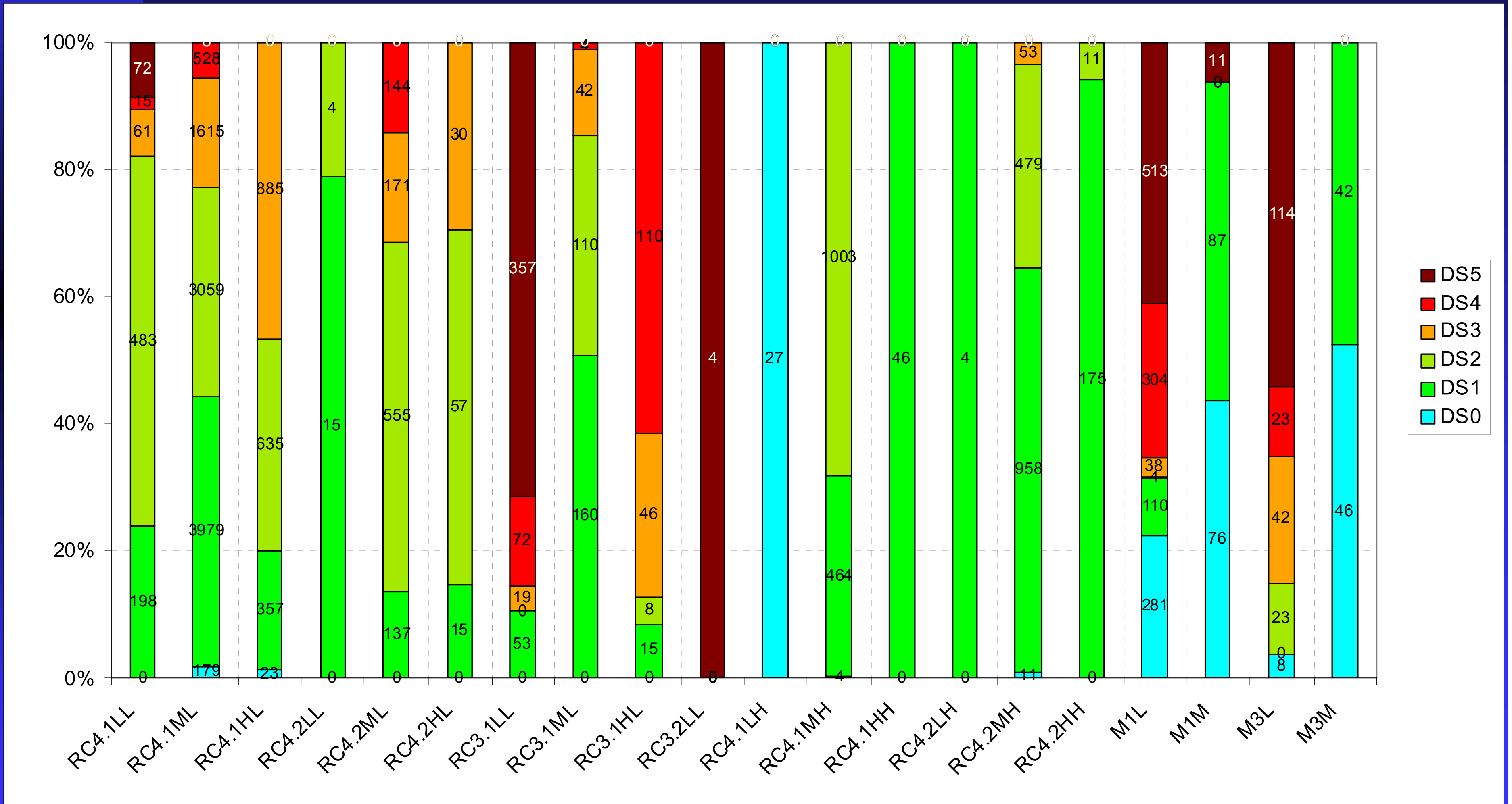


Total number of buildings in each damage state

Damage State	Number of buildings	Percentage (%)
DS0	654	3.41%
DS1	6813	35.53%
DS2	6430	33.52%
DS3	3002	15.65%
DS4	1201	6.26%
DS5	1079	5.63%

Scenario for current buildings

Damage distribution (% of buildings) for all building types (Municipality of Thessaloniki)

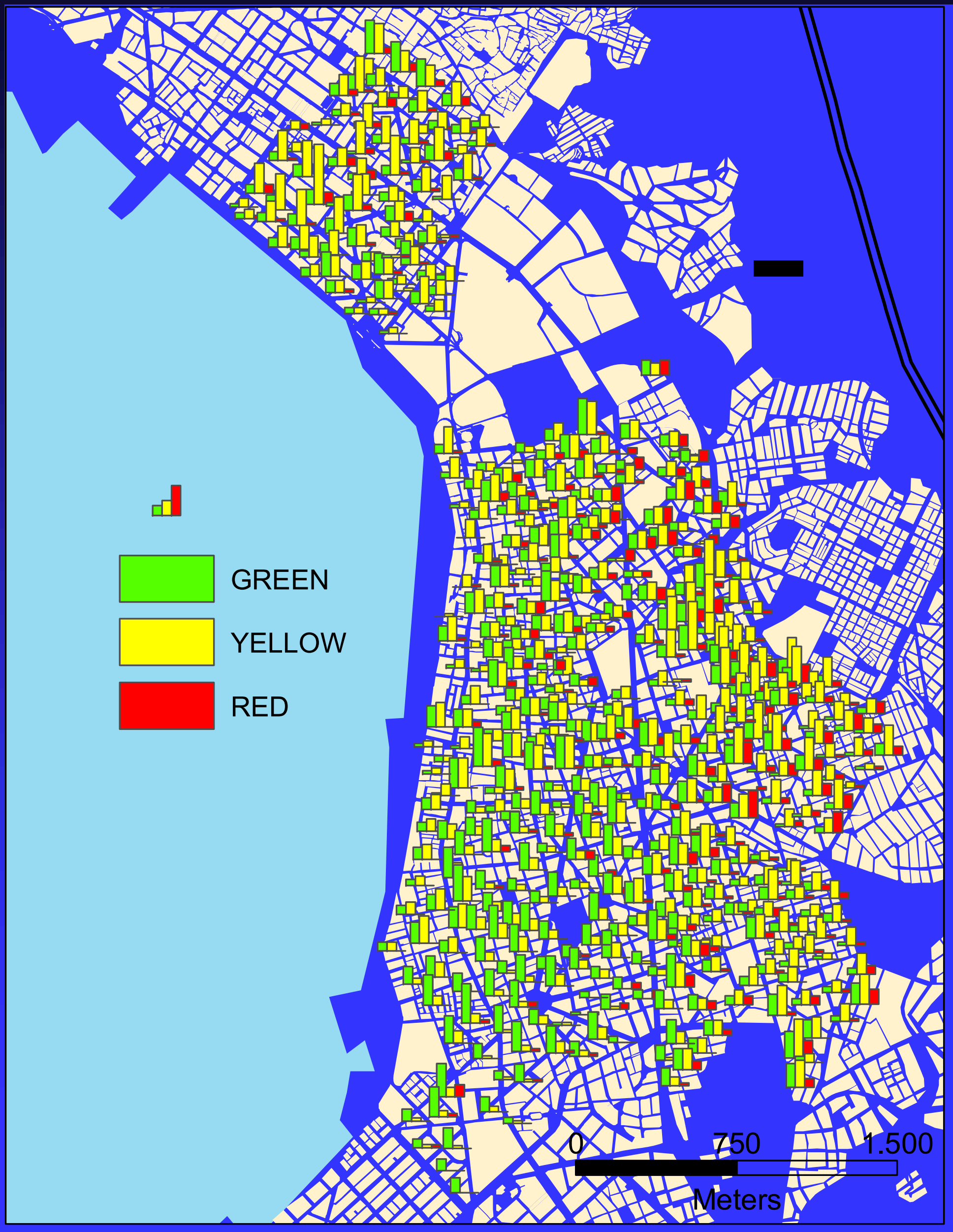


Scenario for current buildings

Predicted tagging of buildings
- Green: DS0 & DS1
- Yellow: DS2 & DS3
- Red: DS4 & DS5

Total number of buildings in each damage label

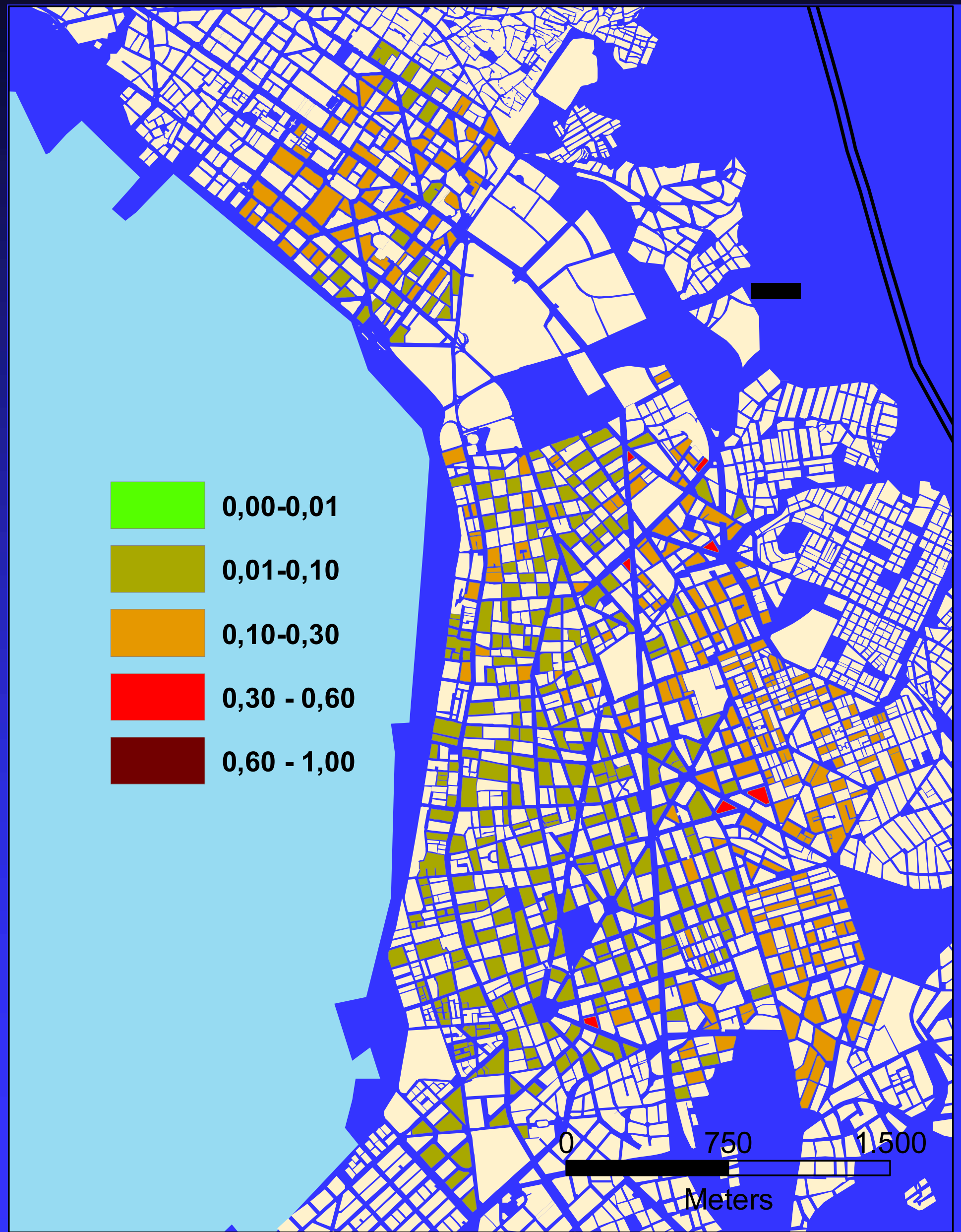
Damage Label	Number of buildings	Percentage (%)
Green	7467	38.93%
Yellow	9432	49.18%
Red	2280	11.89%



Scenario for current buildings

Expected distribution of damage due to the scenario earthquake

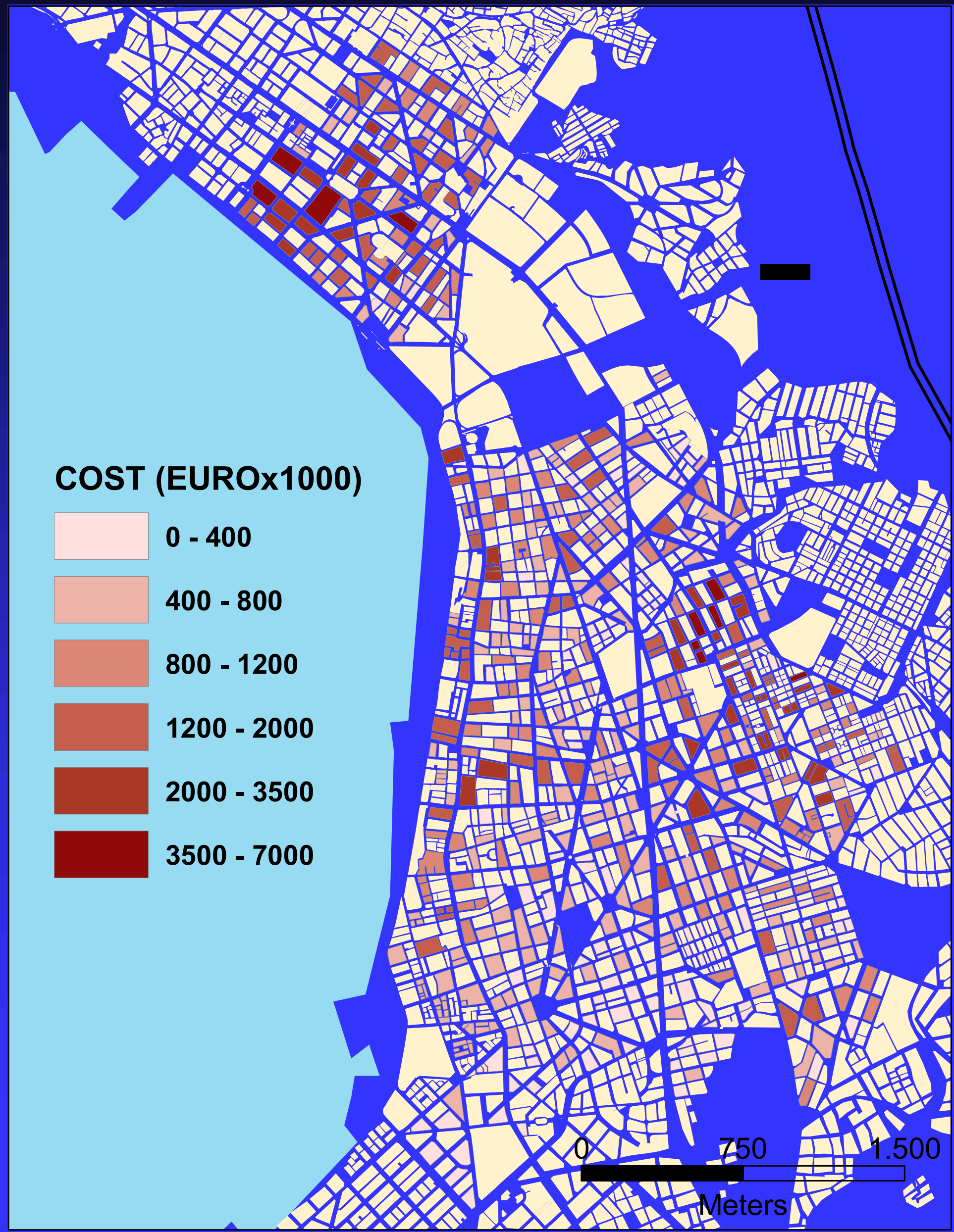
$$\frac{\Sigma(MDF_i \cdot V_i)}{V_{tot}}$$



Scenario for current buildings

Repair cost distribution

- An average replacement cost of €700 /m² was assumed
- Cost=Σ[(Vi•MDFi]• 700 in each block
- A very heavy cost of over 460 million € is predicted for the area studied (the figure should be multiplied by about 4 for the entire municipality)



a couple of notes of caution appear in order:

- All evidence from the present study clearly indicates that the scenario earthquake estimated within WP02 is an event significantly stronger than the 'historical' (1978) earthquake
- On the vulnerability assessment side, it has to be pointed out that the methodology applied was cast into PGA terms (pros & cons…)
- Perhaps, a 'purely Level II' approach, based on spectral displacements would have resulted in lower predictions of damage degree, at least for some types of structures …

Vulnerability assessment of monumental buildings

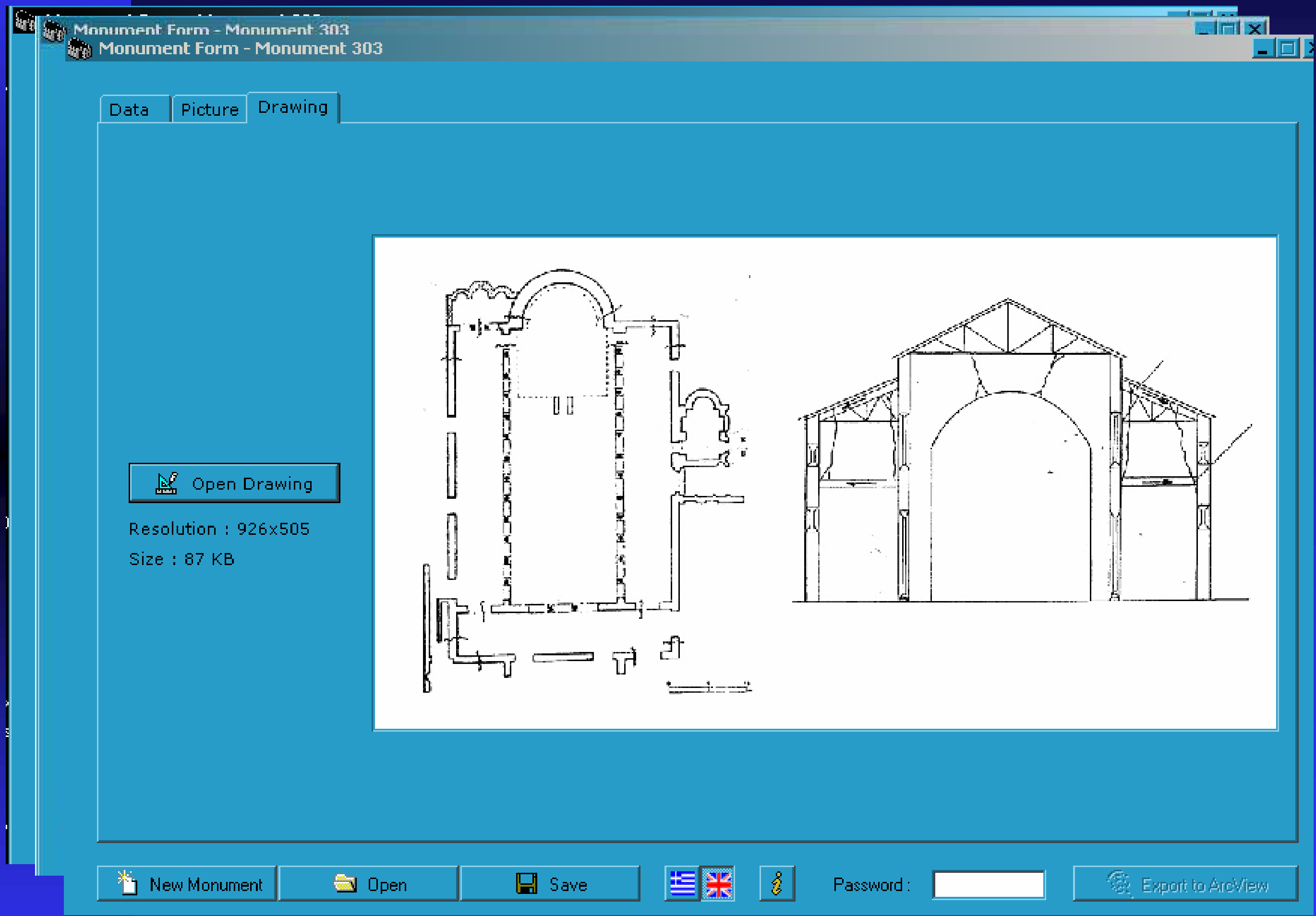
Gr. G. Penelis, A. J. Kappos (coord.),
K.C. Stylianidis, V.K. Papanikolaou

Inventory of buildings

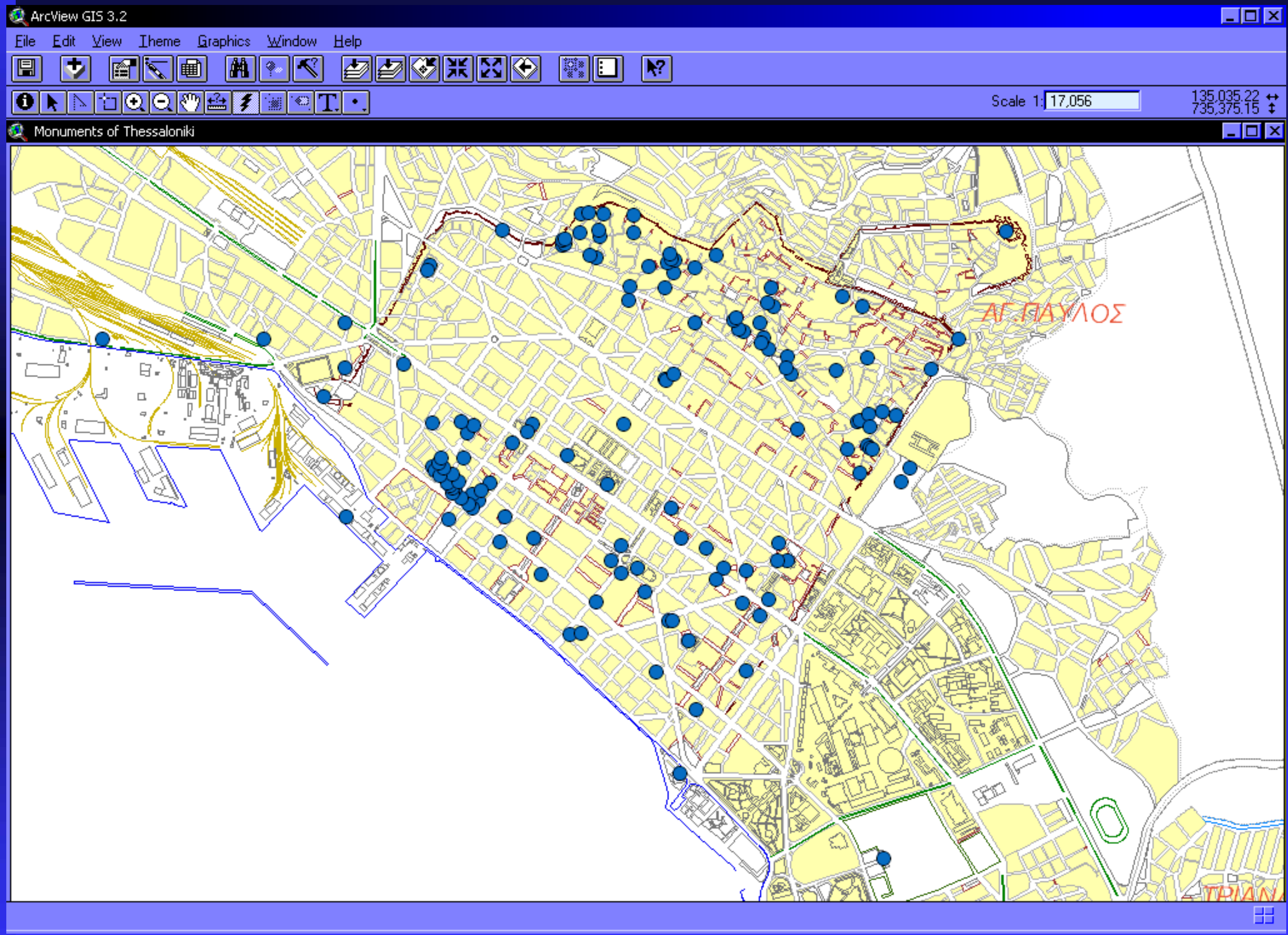
All registered (preserved) buildings have been included in a GIS based database

All monumental buildings have been assigned a vulnerability index following the vulnerability assessment methodology for monumental buildings developed within the RISK UE project (WP5)

GIS Database



GIS Database



Vulnerability index

The index is calculated based on data from a survey form

TYPOLOGY	Vi-	Vi*	Vi+	β
Palace/Buildings	0.496	0.616	0.956	2.3
Monasteries	0.616	0.736	1.076	2.3
Castles	0.356	0.456	0.766	2.3
Churches	0.77	0.89	1.26	3
Chapels/Oratories	0.65	0.77	1.14	3
Mosques	0.67	0.73	0.94	2.65
Theatres	0.616	0.736	1.086	2.65
Towers	0.636	0.776	1.136	2.3
Bridges	0.216	0.296	0.566	2.3
Walls	0.396	0.496	0.746	2.3
Triumphal Arches	0.376	0.456	0.706	2.3
Obelisks	0.396	0.456	0.746	1.95
Statues/Fountains	0.236	0.296	0.606	1.95

General parameters		Vi
STATE OF MAINTENANCE	worst	0.04
	medium	0
	good	-0.04
DAMAGE LEVEL	severe	0.04
	light	0.02
	nihil	0
ARCHITECTURAL TRANSFORMATIONS	yes	0.02
	no	0
RECENT INTERVENTIONS	yes	-0.02
	no	0.02
MASONRY QUALITY	yes	0.05
	no	0
SITE MORPHOLOGY	ridge	0.04
	sloping	0.02
	flat ground	0
PLAN REGULARITY	it depends	
SECTION REGULARITY	it depends	
POSITION	it depends	

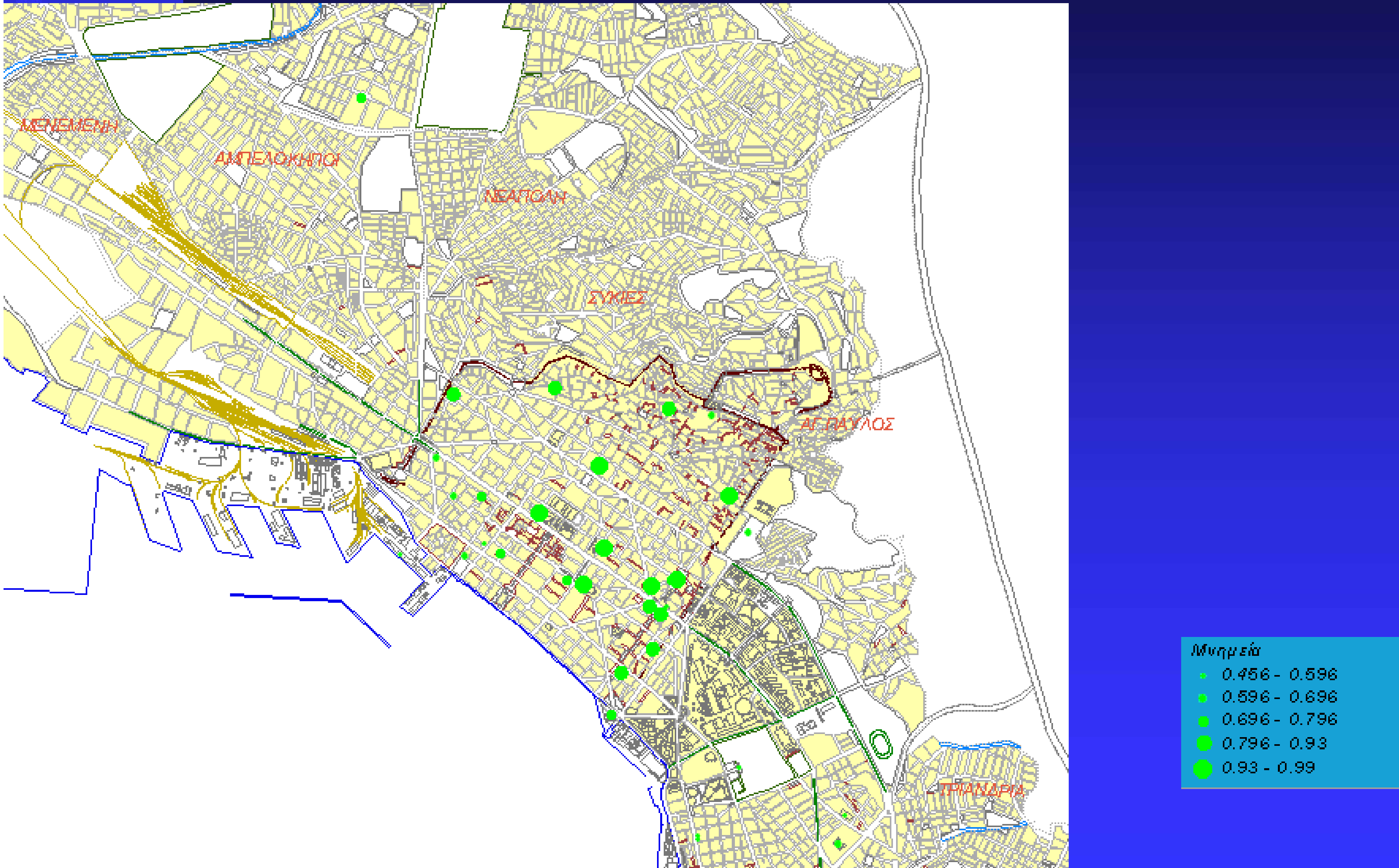
CHURCHES

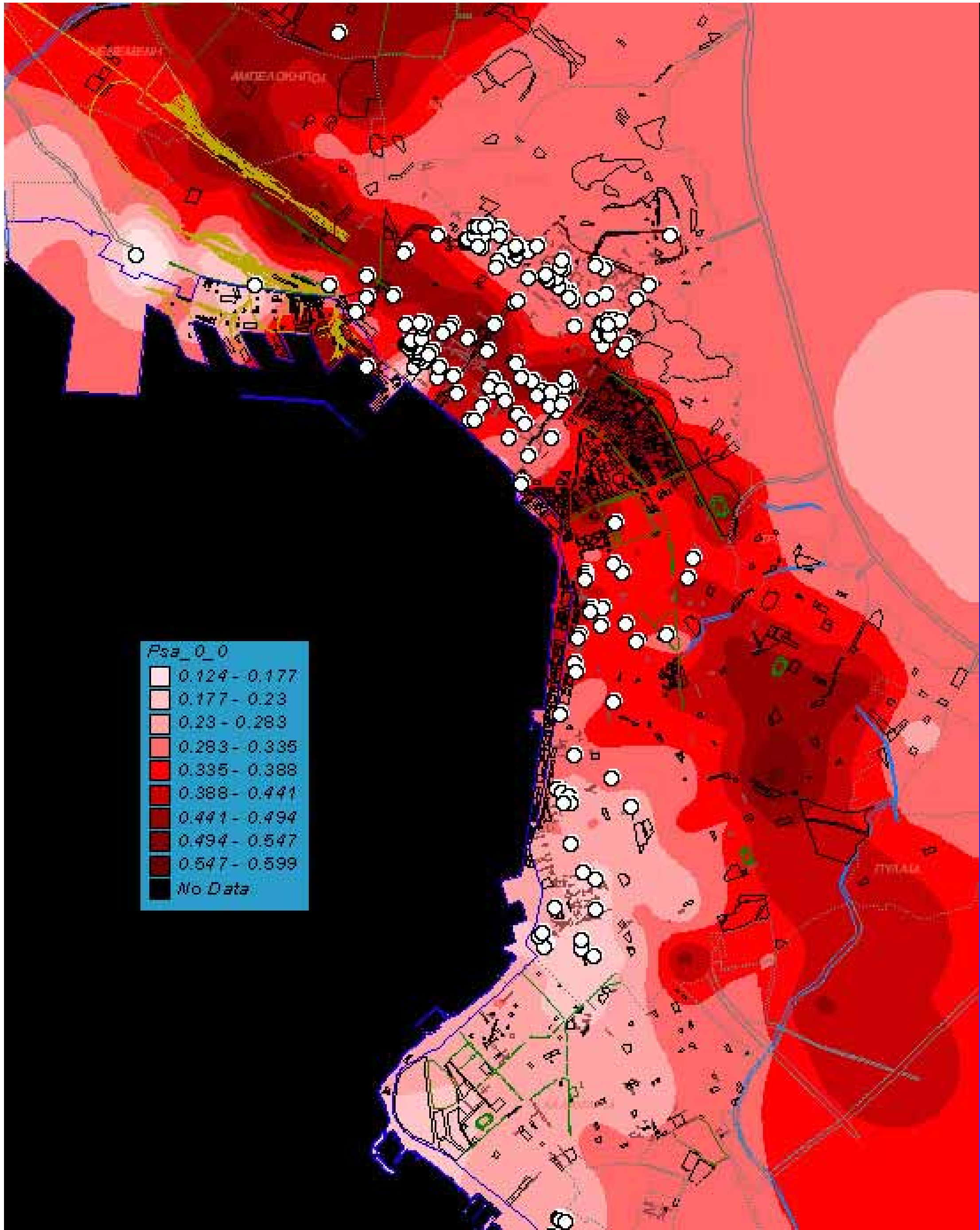
General parameters		Vi
NAVE TYPOLOGY	central nave	-0.02
	one nave	0
	three naves	0.02
SAILING FACADE/RAISED ELEMENTS	yes	0.04
	no	0
POSITION	included	-0.02
	additions	0.02
	isolated	0
Specific parameters		**Vi**
DOMES/VAULTS	yes	0.04
	no	0
LATERAL WALL HEIGHT	<6 m	-0.02
	6<x<12 m	0
	>12	0.04

examples of vulnerability index estimation

NAME	TYPOLOGY	AGE	KIND OF USE	FREQUENCY	CROWD	MAINTENANCE	DAMAGE LEVEL	Arch TRAN	REC. INTER	MAS QUAL	SITE	PLAN REG.	POSITION	I_v
The Customs	Palaces - Vilas	1910	Offices in the main building and warehouses in the rest buildings	Daily	yes	good	severe	no	yes	yes	flat ground	yes	isolated	0.576
Ioniki and Laiki Bank	Palaces - Vilas	1929	Bank	Daily	yes	medium	nihil	no	no	yes	flat ground	yes	corner	0.656
Vlatadon Monastery	Monasteries	1351	0	occasional	yes	good	medium	no	yes	yes	ridge	yes	isolated	0.676
The Rotunda	Churches	300	0	Occasional	yes	good	severe	yes	yes	good	flat ground	central	isolated	0.97
The Church of Achiropiitos	Churches	500	church	daily	yes	good	severe	no	yes	good	sloping	three	isolated	0.99
The Church of St.Panteleimon	Churches	1300	church	Daily	yes	good	severe	no	yes	good	flat ground	one	isolated	0.95
The Church of Ayia Sophia	Churches	800	church	daily	yes	good	light	no	yes	good	flat ground	three	isolated	0.99
The Church of Ayios Nikolaos Orphanos	Churches	1400	church	daily	yes	medium				good	flat ground	three	isolated	0.95
The Church of Hosios David	Churches	600	church	daily	yes	good	severe	no	yes	good	flat ground	one	isolated	0.89
The Rotunda Minaret	Minaret	300	0	Occasional	yes	good	severe	no	yes	good	flat ground	circular	isolated	0.736
The White Tower	tower	0	Museum	daily	yes	good	light	no	yes	good	slopping	circular	isolated	0.796
Galerios Arch (Kamara)	arch	0	0	Daily	yes	good	light	yes	yes	good	flat ground	not meaningful	isolated	0.456

The vulnerability index is then inserted in the GIS database





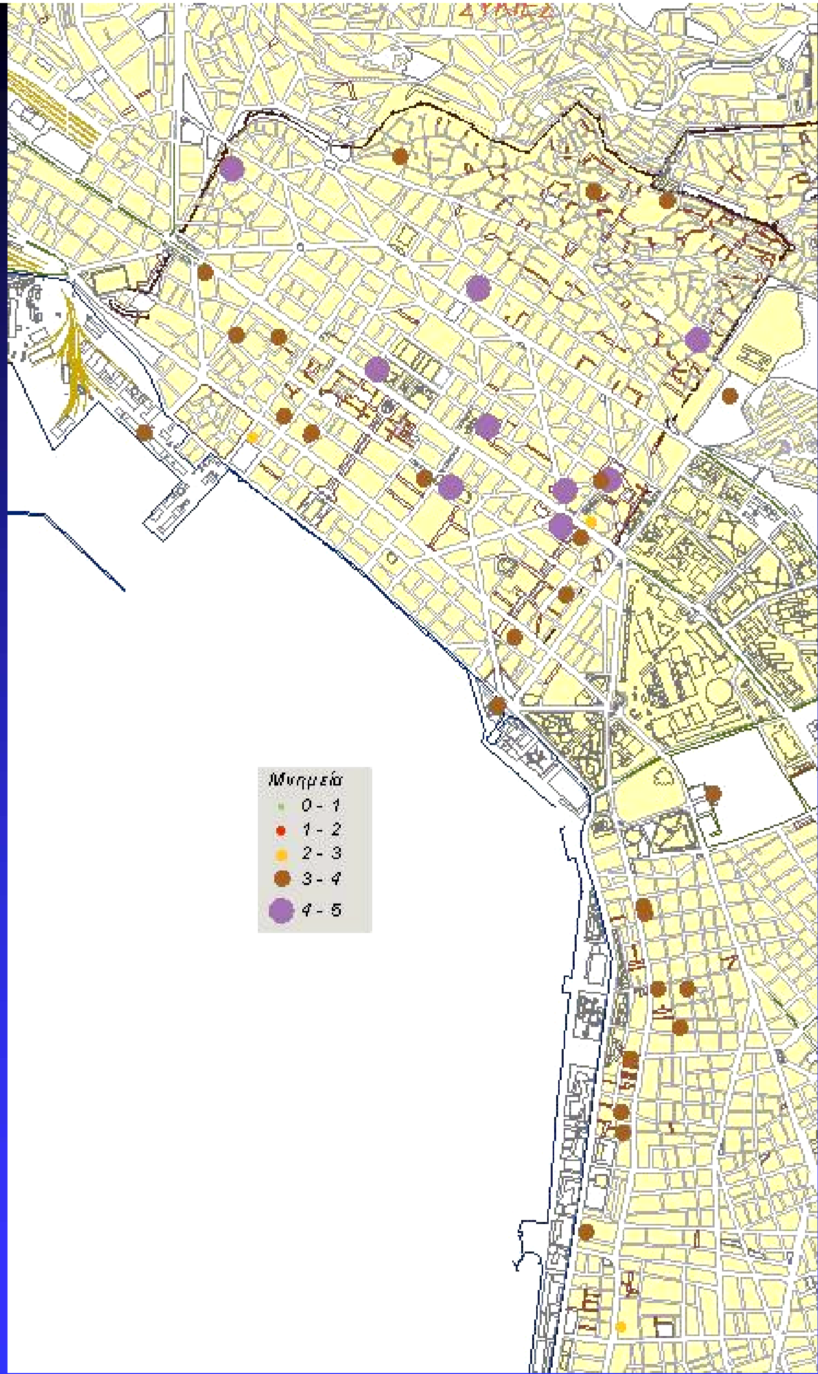
Earthquake scenario

maximum predicted PGA’s are overlaid on the GIS map showing the locations of monuments

Predicted damage

$$\mu_D = 2.5 \cdot \left[1 + \tanh\left(\frac{I + 3.4375 \cdot i_v - 8.9125}{3} \right) \right]$$

predicted damage grade is plotted on the GIS map



Results of the earthquake scenario for monumental buildings

RANGE	NUM	PER
0 -1	0	0%
1-2	0	0%
2-3	5	11%
3-4	32	70%
4-5	9	20%

- the majority of monuments will suffer a damage grade of 3-4 while a significant number will sustain damage of 4-5 (near collapse)
- this prediction is, of course, related to the severity of the scenario earthquake, and all comments made in this respect in the WP04 section are also pertinent herein

Thank you!