EERI World Housing Encyclopedia International Workshop
on Vulnerability Parameters for Common Building Types
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Seismic vulnerability assessment of R/C buildings with brick masonry infills

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Previous contributions of the AUTh Team to PAGER

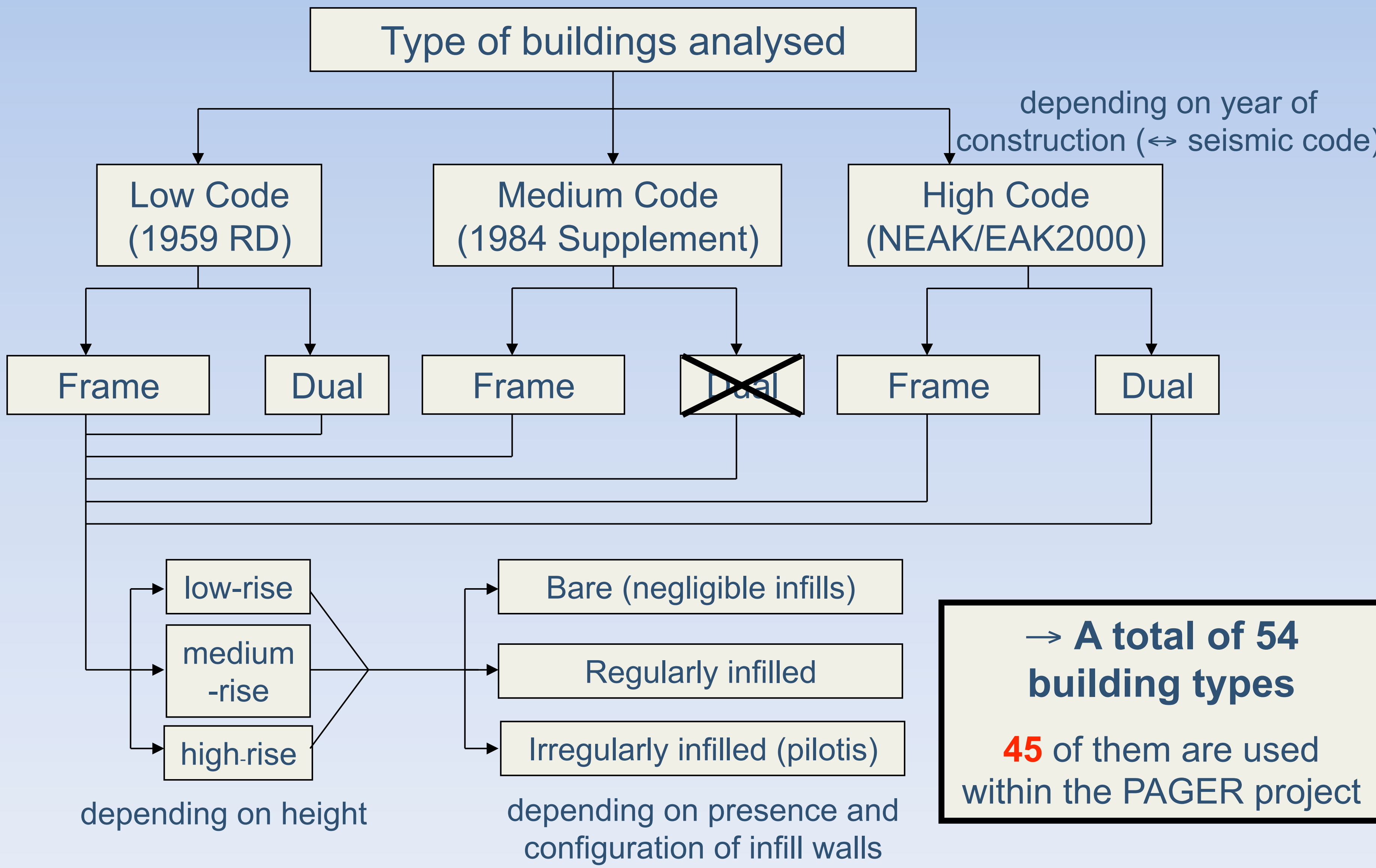
- The AUTh team contributed to Phase I of the WHE-PAGER project jointly with the RMS-Greece Team (A. Pomonis)
- Collapse probability values for several intensity levels, as well as population distribution data, were provided for all common R/C and URM building types (see also *Pomonis, Kappos et al., 2008, 2009*)
- A hybrid methodology was utilized (see SF meeting), combining analytical results and statistical data from past earthquakes. Two different approaches were adopted re. the definition of *collapse*.

WHE Construction Type or Material *refer to Table 2 for suggested category(ies)* (1)	Description of construction type (type of load-bearing structure) *(refer to Tables 2 and 3 for suggested categories and sources of data to help answer this question)* (2)	Estimate of probability of collapse (%) of the building type when subjected to the specified shaking intensity (expressed as a range) *(refer to instructions page 5)* (3) **MMI / EMS / MSK**				Fraction of population who LIVES in this building type *(refer to instructions for help in estimating)*	
		IX (~0.65-1.24g)	VIII (~0.34-0.65g)	VII (~0.18-0.34g)	VI (~0.092-.18g)	urban areas (4)	rural areas (5)
16	R/C Moment Resisting Frames Old Codes - Pre 1985	15	5	2	0.5	50	25
16	R/C Moment Resisting Frames Modern Codes - Post 1985	4	0.5	.02	0	7.5	9
19	R/C Dual Structures (Frames + Shear Walls), Old Codes - Pre 1985	11.5	3	.15	0	12.5	3
19	R/C Dual Structures (Frames + Shear Walls), Modern Codes - Post 1985	3	.3	.01	0	22	9
1	Stone masonry	80	14	8	5	1.5	23
9	Unreinforced brick masonry	37	4	.6	.2	5.5	30

WHE-PAGER Phase III

- Objective of phase III of the WHE-PAGER project: to propose "HAZUS-type" vulnerability parameters for R/C buildings, presented in tailor-made and homogenized MS Excel forms.
- The AUTh team was asked to fill in the forms for ductile and non-ductile reinforced concrete frame buildings with/without masonry infill walls as well as R/C moment resisting frame with shear wall - dual systems (classes C1, C3, C4 and C6 using the PAGER nomenclature).
- These building classes practically cover all common R/C building types in Greece and several other S. European countries.
- Data for R/C frame buildings were provided almost a year ago.
- This presentation focuses mainly on R/C dual structures (same methodology adopted as for infilled frames)

Inelastic analysis phase – Building typologies

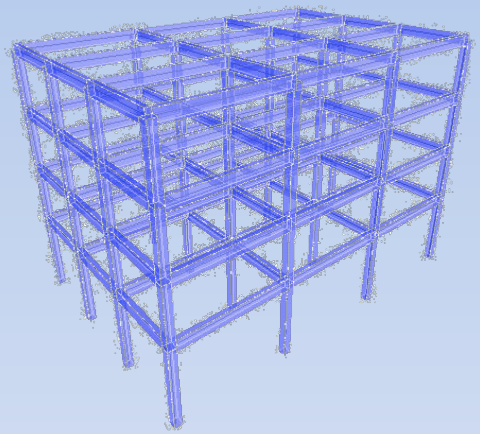


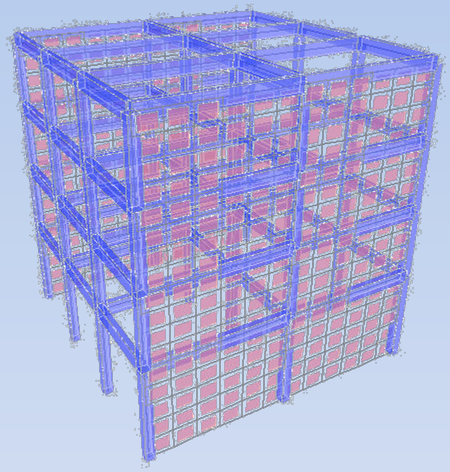
AUTh (Risk-UE) vs. PAGER building typologies

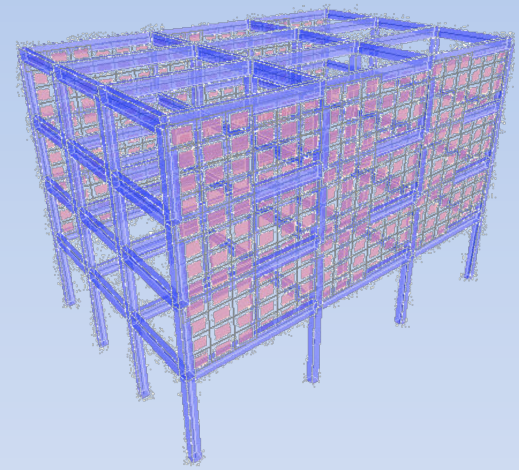
Type	Structural system	Height (number of storeys)	Seismic design level
RC1	Concrete moment frames		
RC3	Concrete moment frames with unreinforced masonry infill walls		
3.1	Regularly infilled frames	(L)ow-rise (1–3)	(L)ow code
3.2	Irregularly infilled frames (pilotis)	(M)id-rise (4–7)	(M)edium code
RC4	RC dual systems (RC frames and walls)	(H)igh-rise (8+)	(H)igh code
4.1	Bare frames (no infill walls)		
4.2	Regularly infilled dual systems		
4.3	Irregularly infilled dual systems (pilotis)		

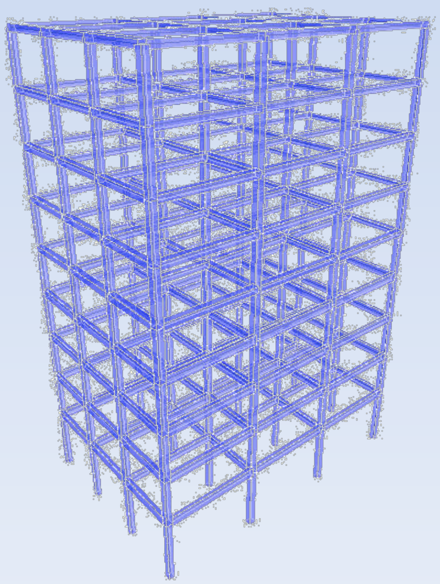
Sr. No.	PAGER-STR	Description of Structure
18	C1	Ductile reinforced concrete moment frame with or without infill
19	C3	Nonductile reinforced concrete frame with masonry infill walls
20	C4	Nonductile reinforced concrete frame without masonry infill walls
21	C6	Concrete moment resisting frame with shear wall - dual system

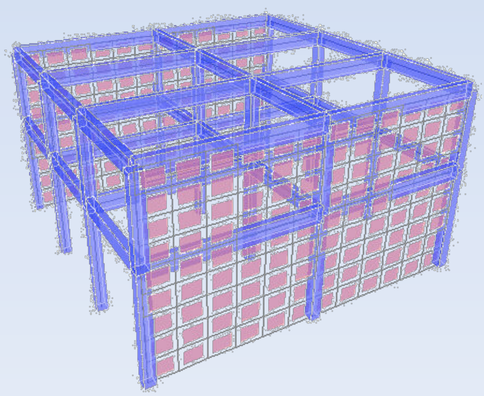
Examples of R/C frame structures

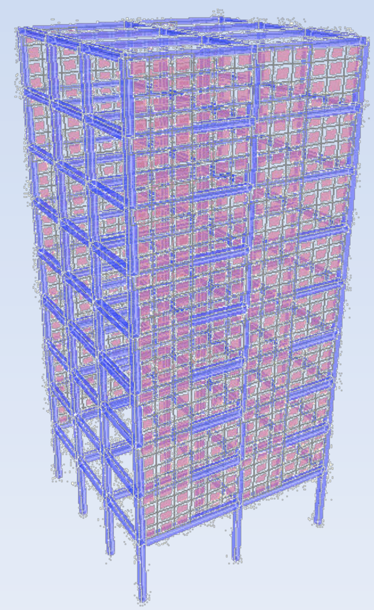




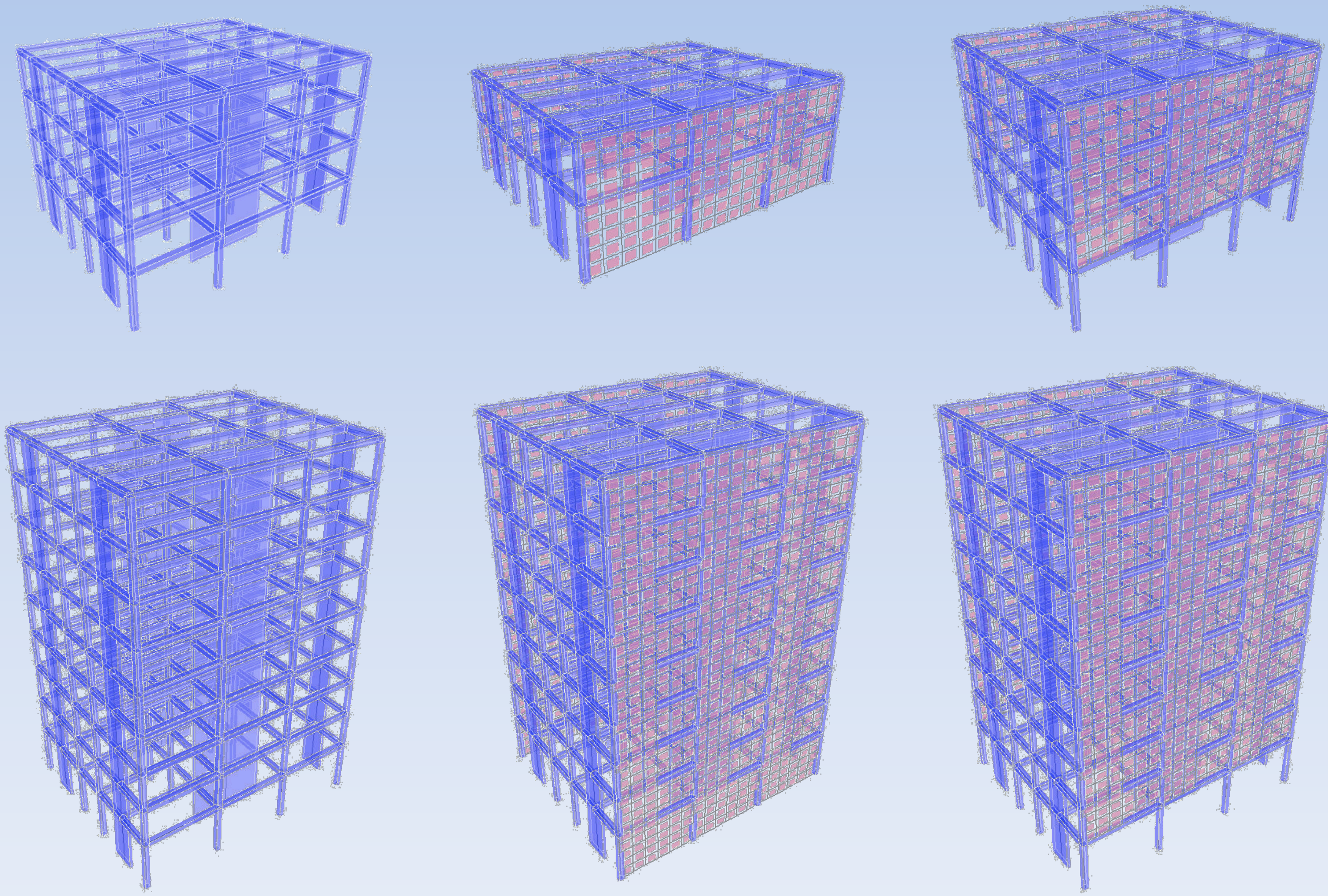




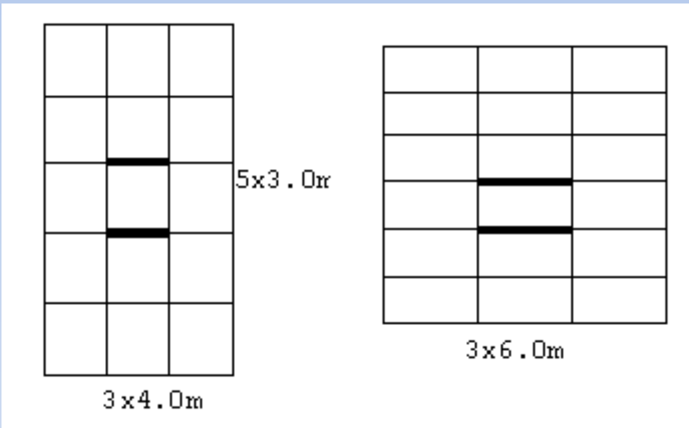




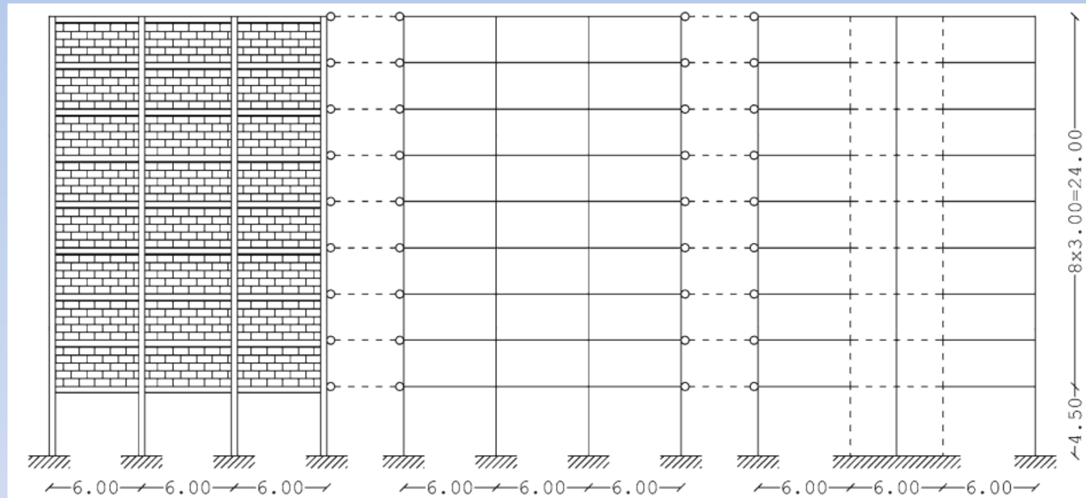
Examples of R/C dual structures



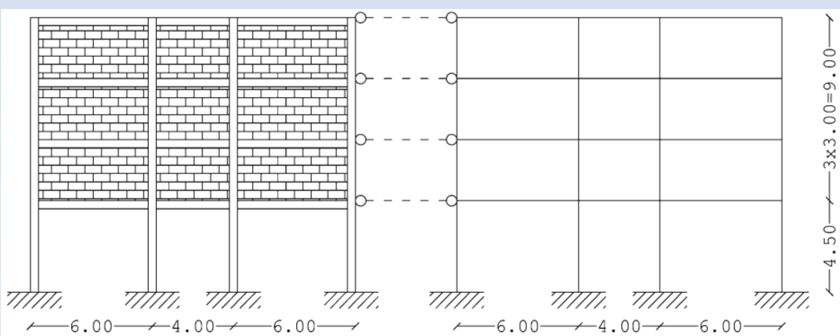
2D building models for pushover analysis



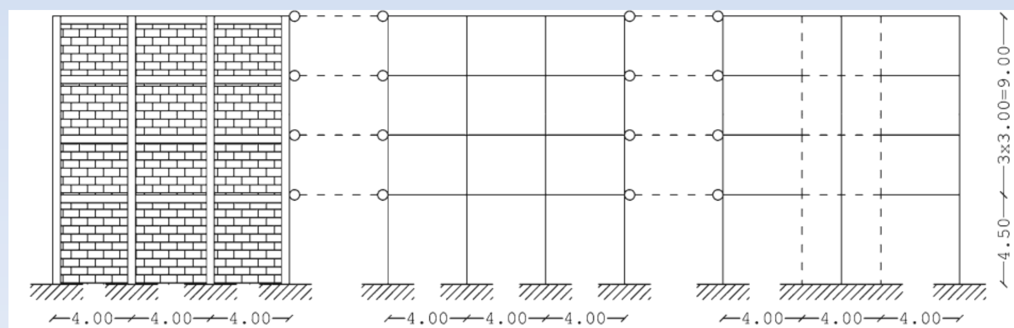
direction of interest



Nine-storey, irregularly infilled, R/C dual system (RC4.3H)



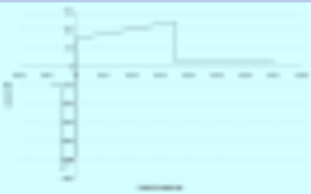
Four-storey, irregularly infilled, R/C frame building (RC3.2M)



Four-storey, regularly infilled, R/C dual system (RC4.2M)

Modelling of R/C members:

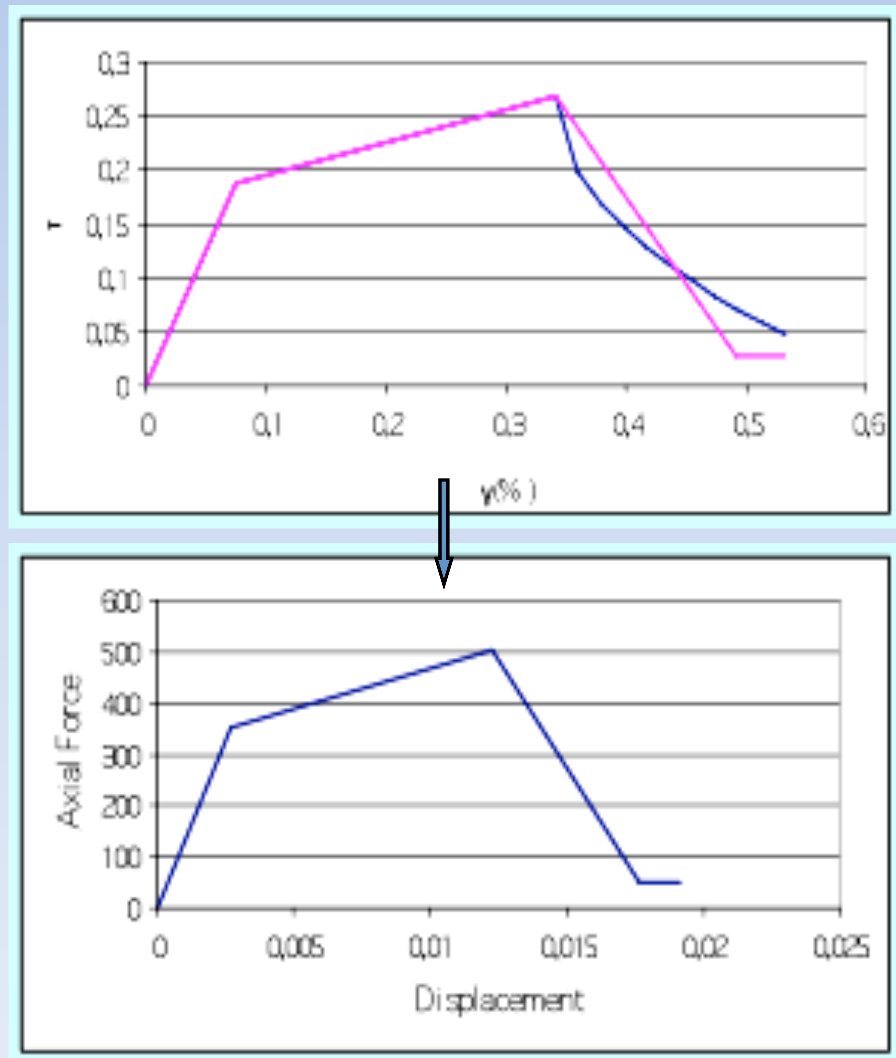
Point hinge approach



moment – rotation (θ_p) curve for a beam (SAP 2000)

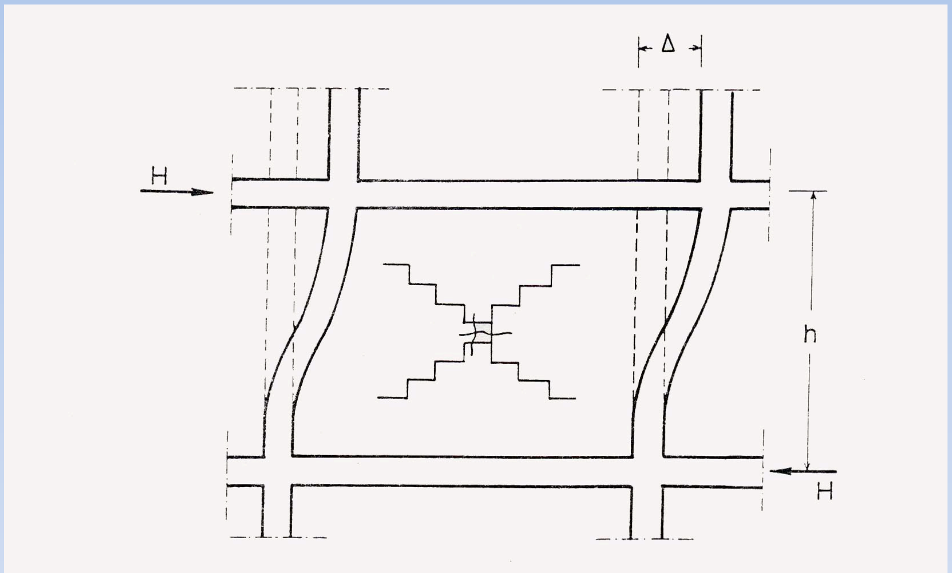
Modelling of infills *[Kappos et al. 1997]*

Strut model



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

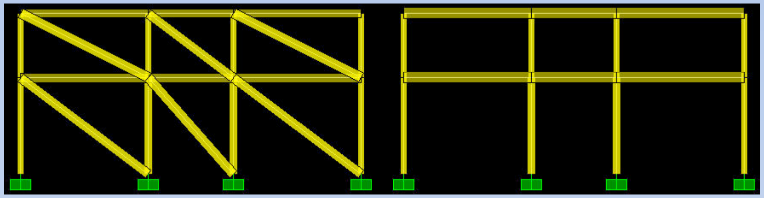
Typical damage of a brick-masonry infill wall

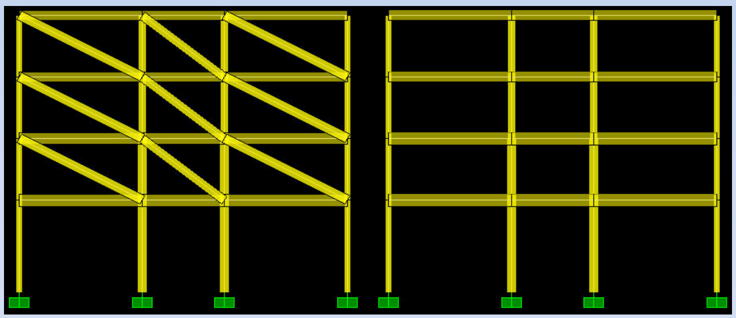


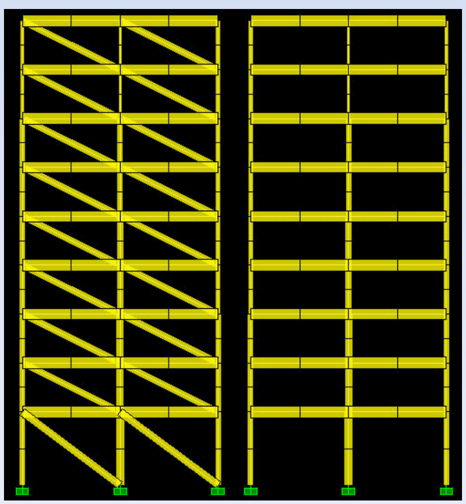
Diagonal cracking of the brick-masonry infill in an R/C infilled frame

SAP2000 model examples for pushover analysis

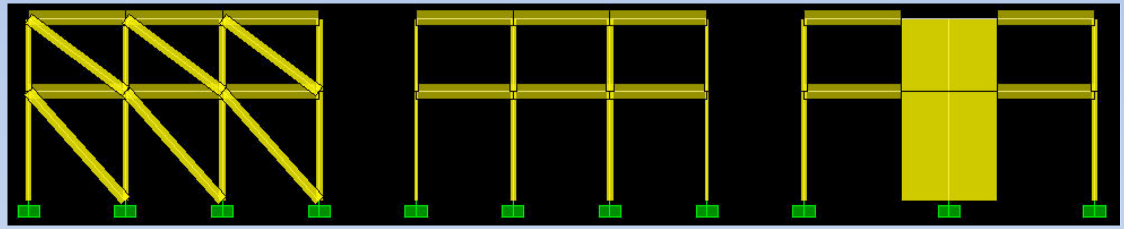
Frame systems

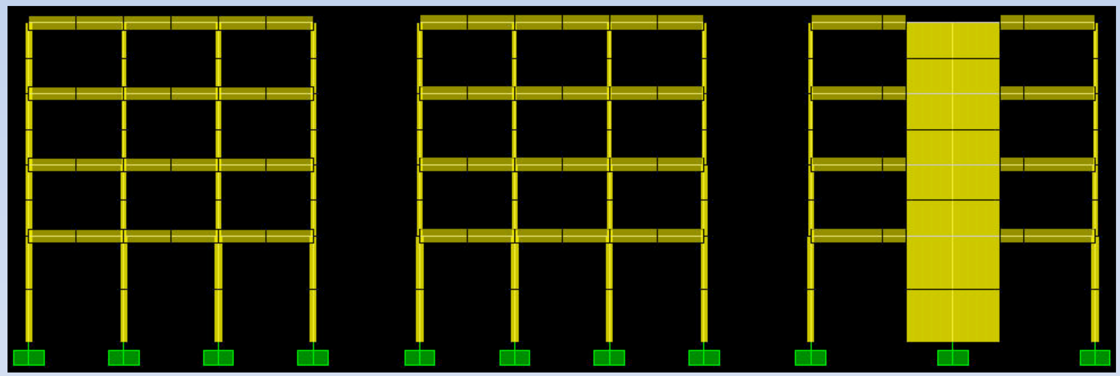


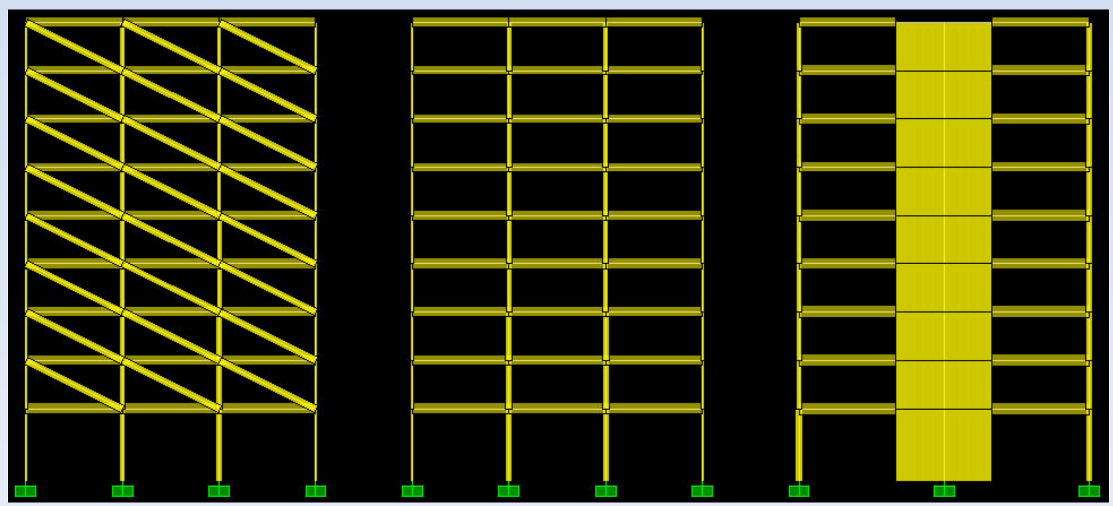




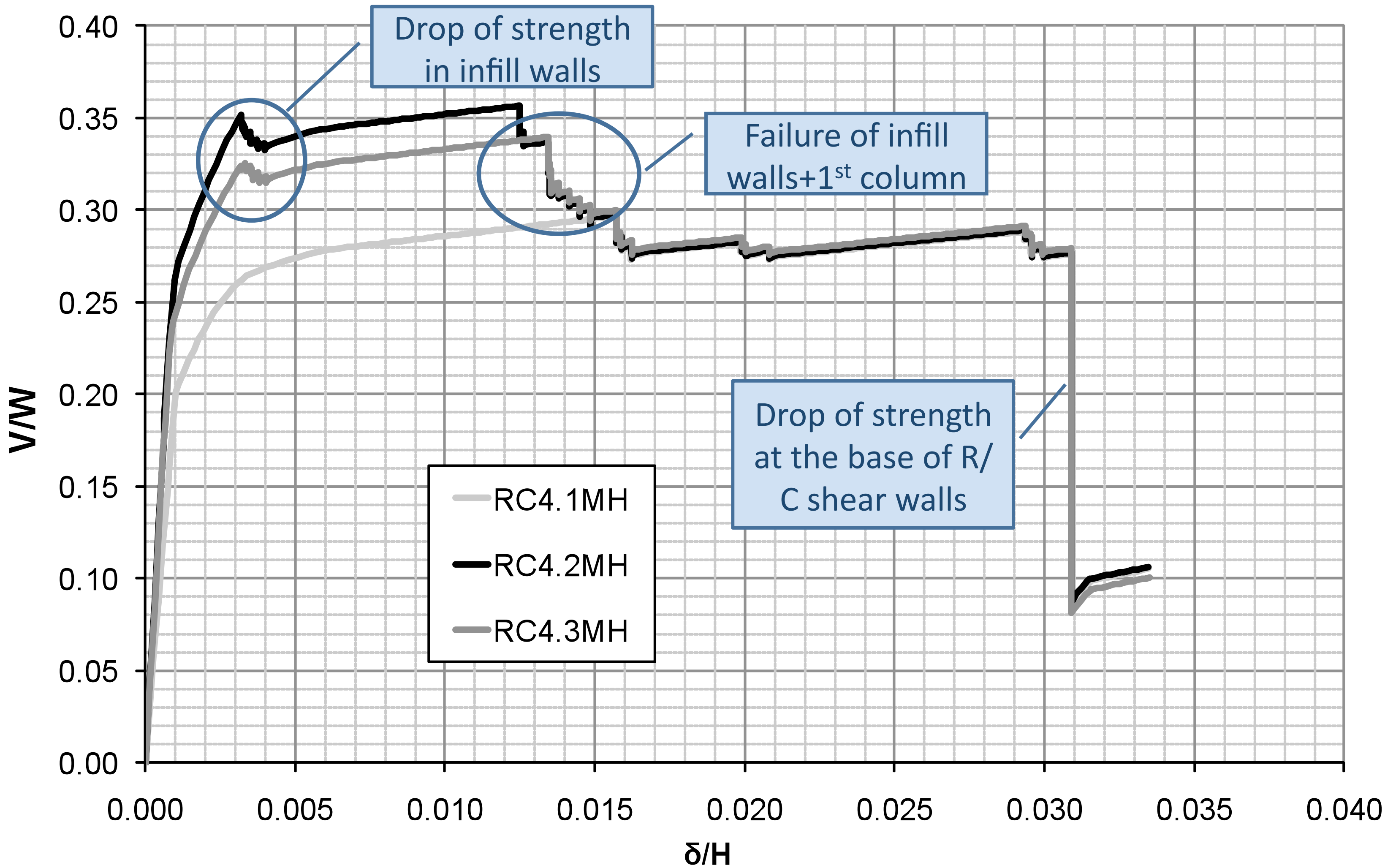
Dual systems





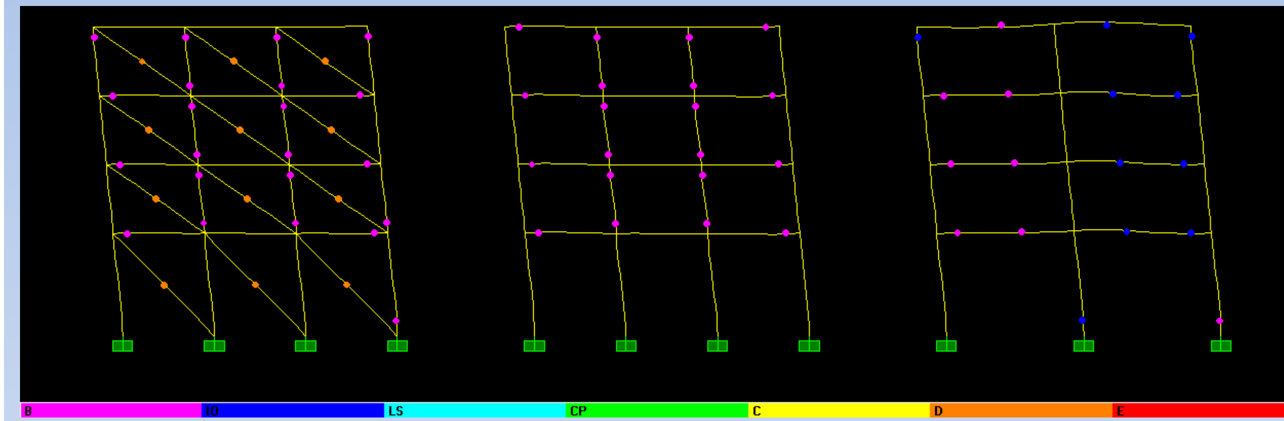


Typical pushover curves for dual systems

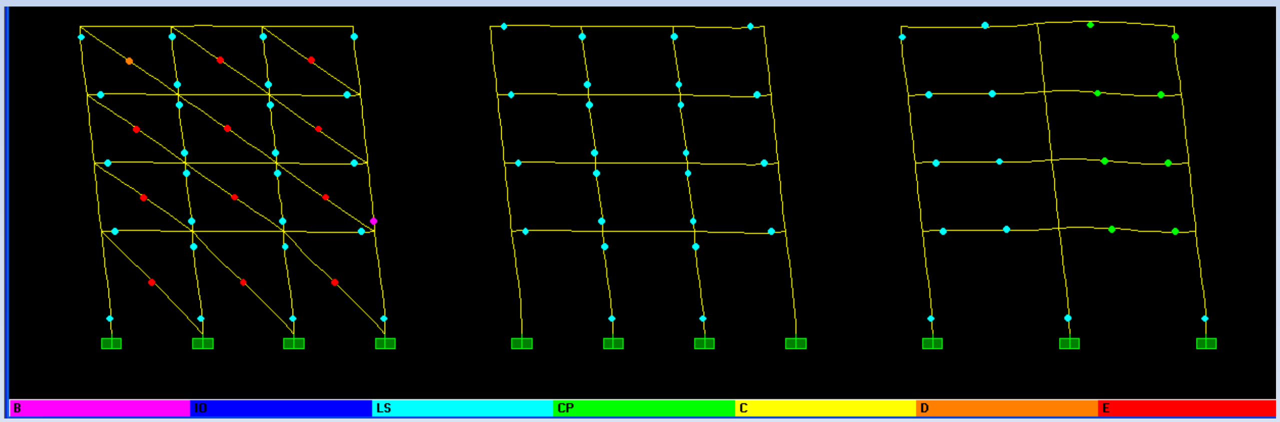


Medium-rise (4 storey) R/C dual systems designed to modern seismic codes

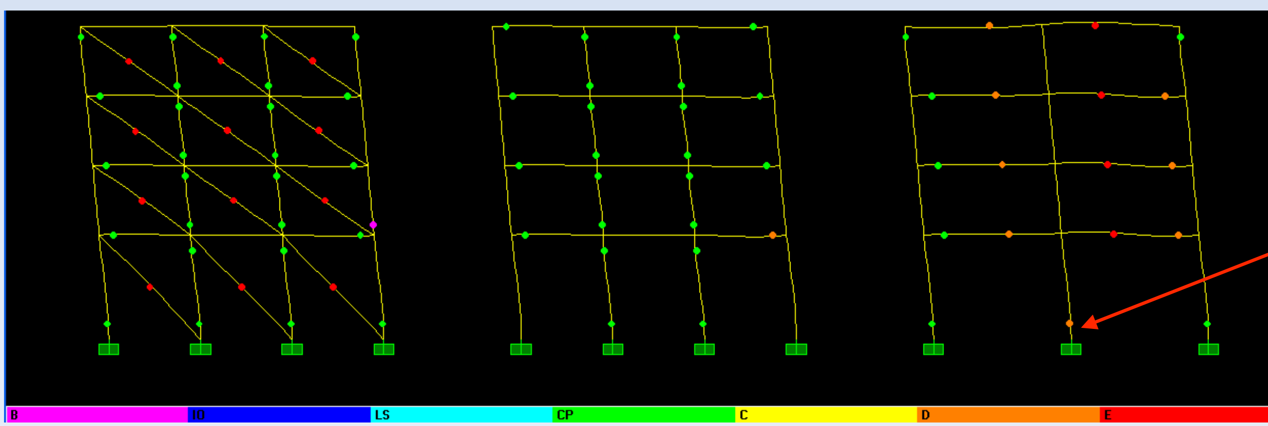
Typical pushover curves for dual systems



Drop of strength in infill walls



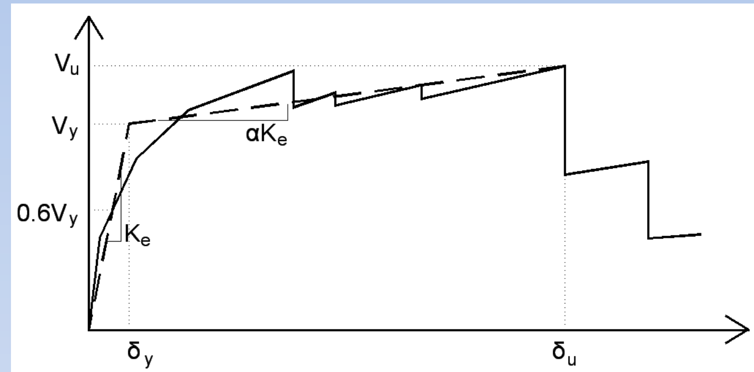
Failure of infill walls

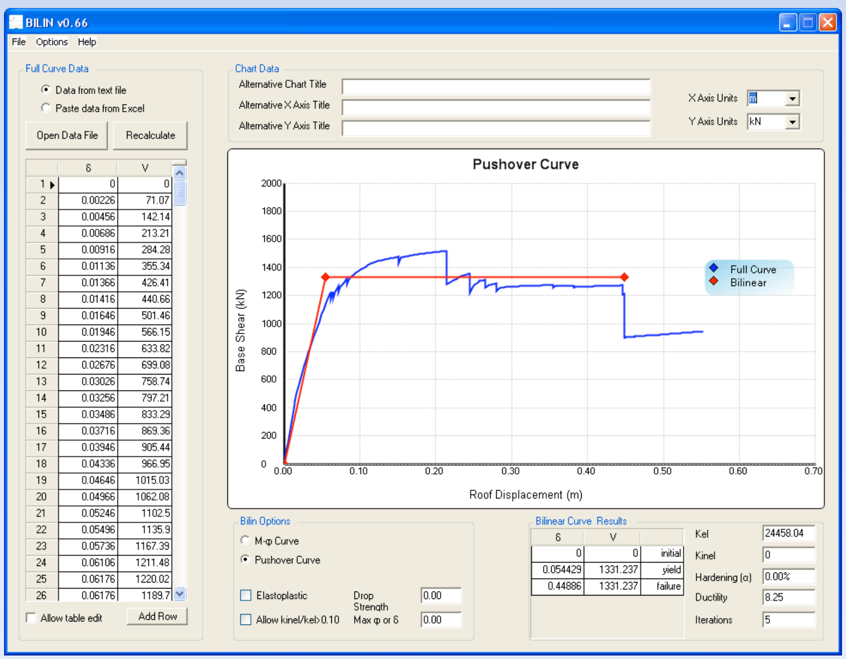


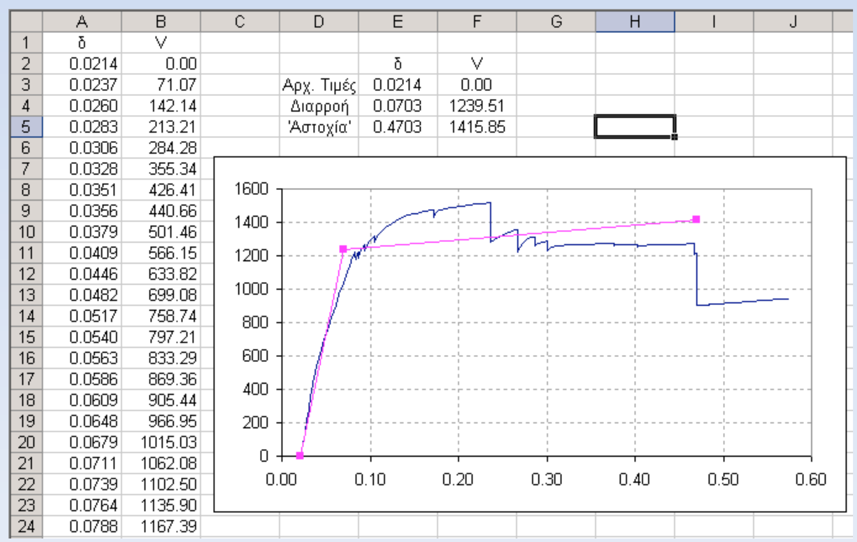
Drop of strength at the base of R/C shear walls

Bilinear approximations of pushover curves

- Bilinear approximation of pushover curves using a procedure close to the FEMA/ATC guidelines (adopting the equal areas rule)
- The end of the bilinear curve is assumed at the point of significant drop in strength (15%÷25%)
- In-house developed software (BILIN) available as a stand-alone application or as a function for MS Excel
- Whenever feasible a quatri-linear approach is utilized

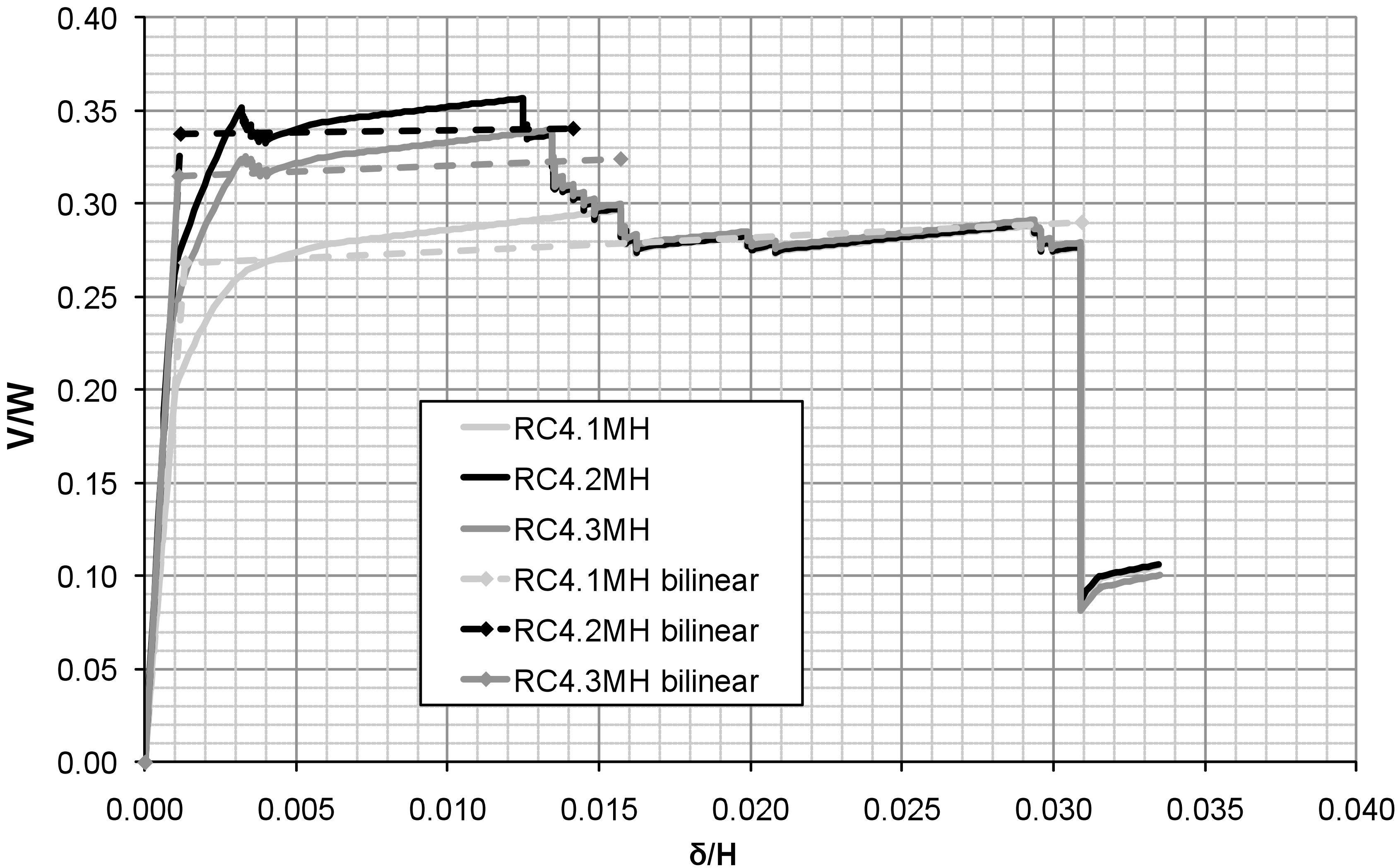




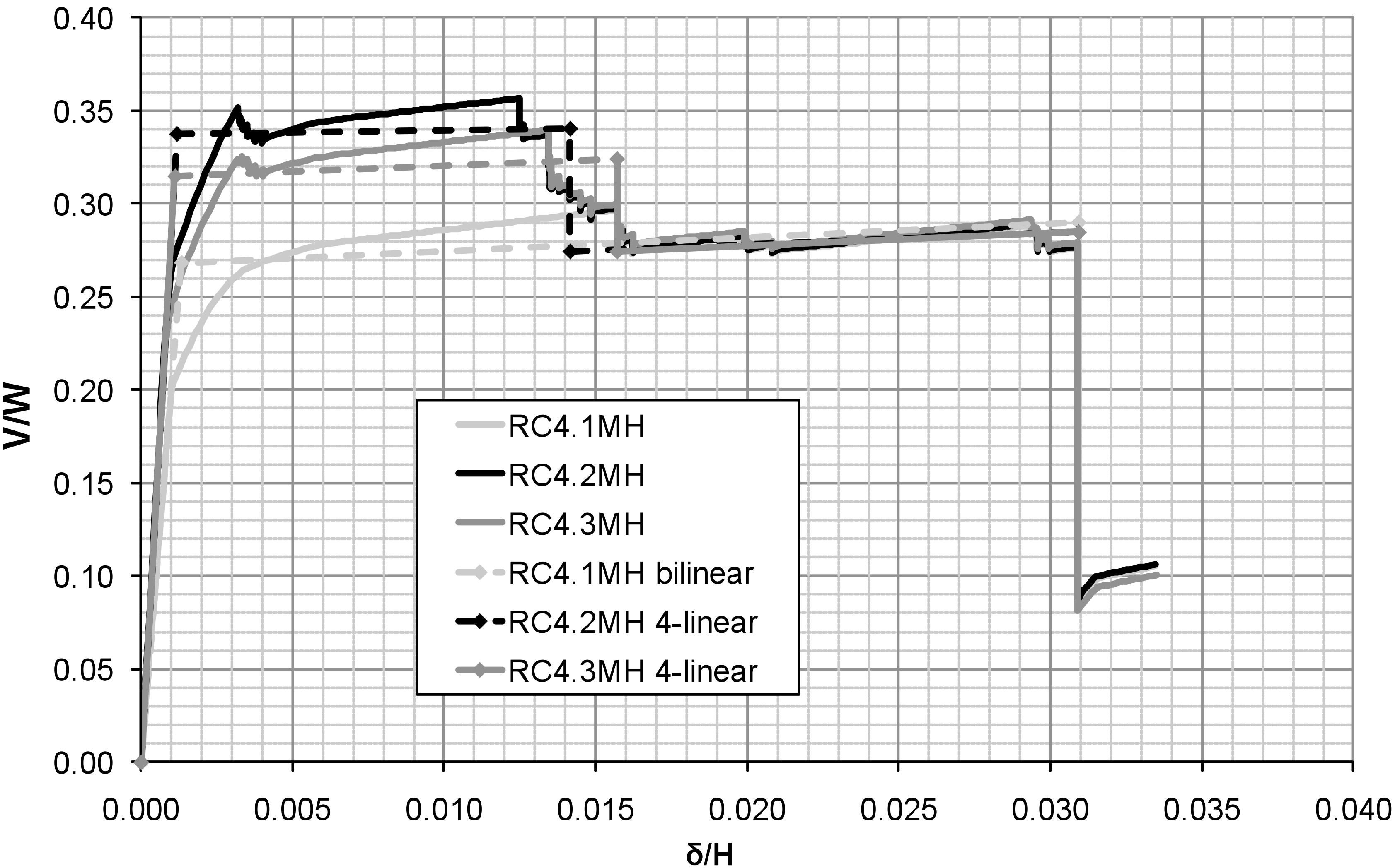


	A	B	C	D	E	F
1	δ	V				
2	0.0214	0.00			δ	V
3	0.0237	71.07		Αρχ. Τιμές	0.0214	0.00
4	0.0260	142.14		Διαρροή	0.0703	1239.51
5	0.0283	213.21		'Αστοχία'	0.4703	1415.85
6	0.0306	284.28				
7	0.0328	355.34				
8	0.0351	426.41				
9	0.0356	440.66				
10	0.0379	501.46				
11	0.0409	566.15				
12	0.0446	633.82				
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				

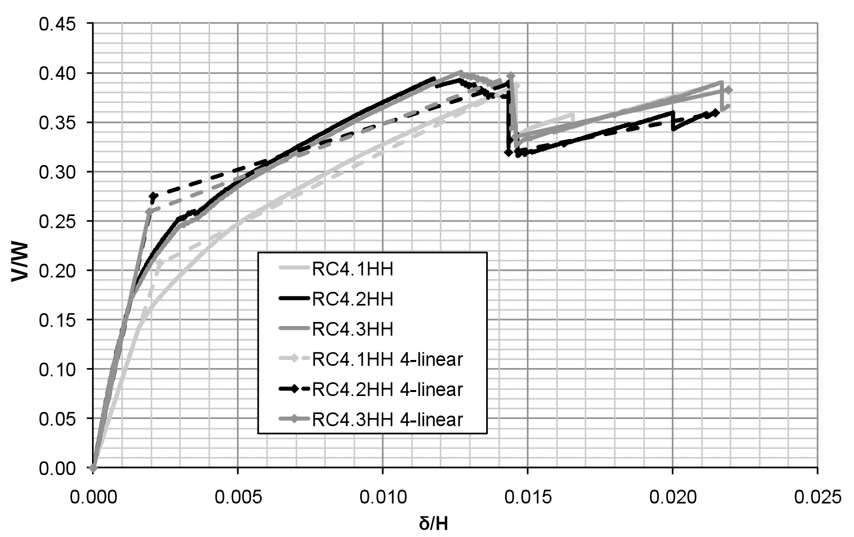
Bilinear approximations of pushover curves

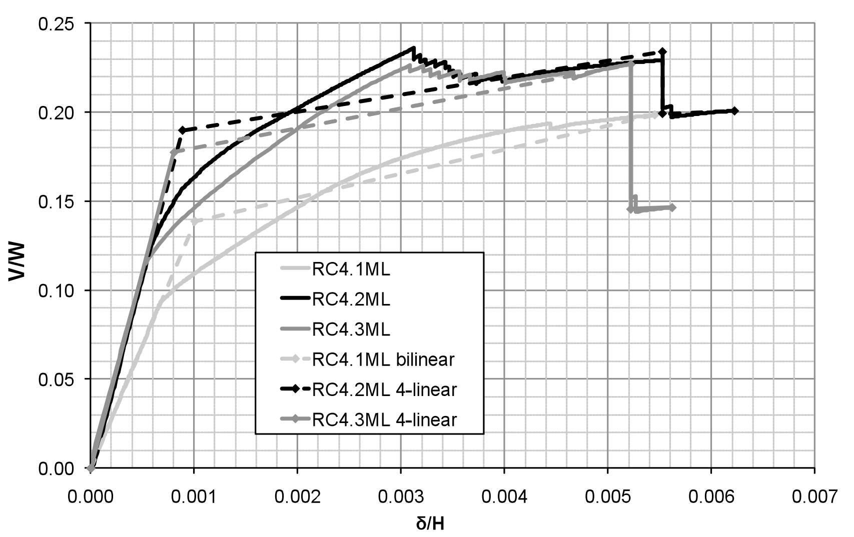


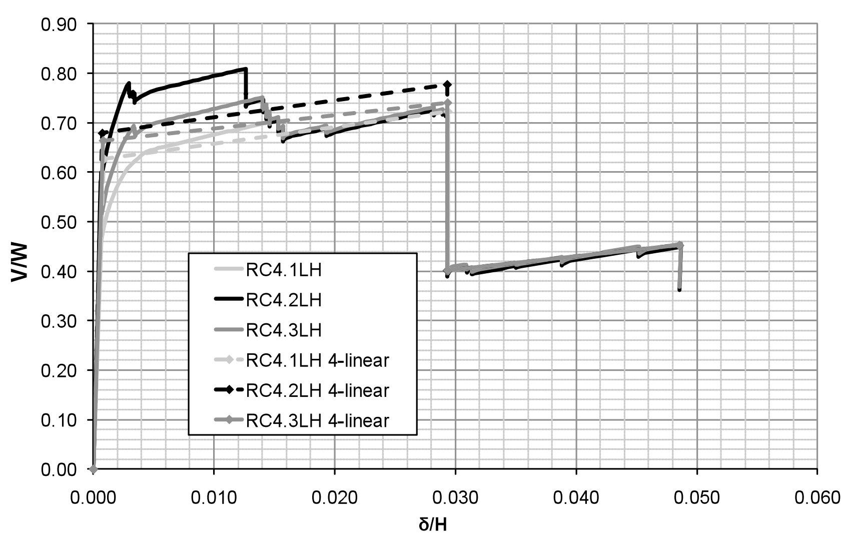
quatrilinear approximations of pushover curves (when appropriate)

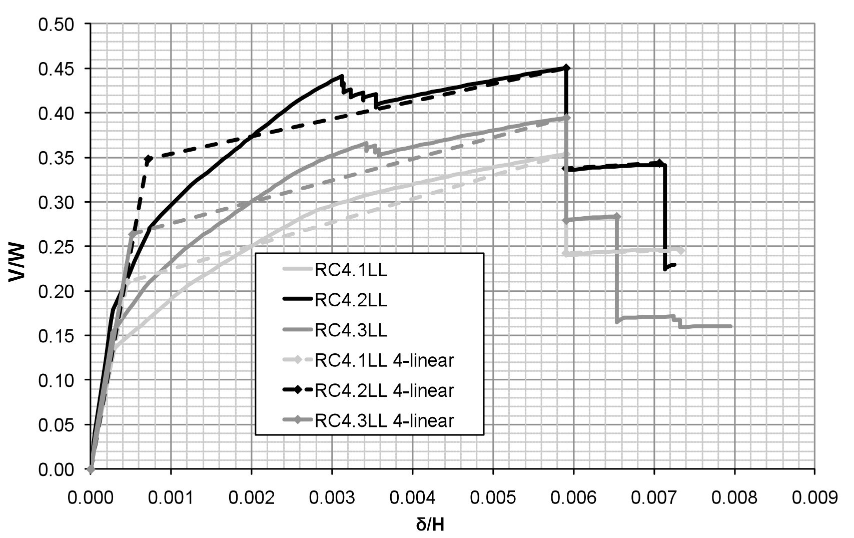


Pushover curves for several building classes









WHE-PAGER forms

- The derived pushover curves were transformed to the corresponding spectral quantities (S_a - S_d) in order to fill in the WHE-PAGER forms
- Quantities for which no reliable data are available were left blank

WHE-PAGER PHASE 2: DEVELOPMENT OF ANALYTICAL SEISMIC VULNERABILITY FUNCTIONS					
Author:	Kappos Andreas, Panagopoulos Georgios				
Date:	15/9/2009				
Structure type (describe as broadly as possible):	RC4.1HL RC dual system, Low seismic code design (1959), High-rise (9 storeys), No infill walls				
Geographic or other limitations:	Greece, Southern Europe				
					Add rows as desired
Basic pushover curve for this structure type					
Pushover X-axis:	Sd (cm)	Choose spectral displacement (Sd), inches; or Roof displacement (Deltar), inches. Change and state units if desired.			
Pushover Y-axis:	Sa (g)	Choose spectra acceleration (Sa), g; or base shear (V), kip. Change and state units if desired.			
Elastic damping ratio:		Small-amplitude damping ratio, fraction of critical			
1st mode participation factor:	1.45	PFfR; generally 1.3 to 1.5; same as (effective height)/(total roof height)			
Effective mass coefficient:	0.71	alpha1; generally 0.7 to 0.8			
Building weight:	12457.38	W, kN. Change and state units if desired			
How were these values & pushover points derived?					
					Add rows as desired
Pushover curve control point	X	Y	Damping	Comment	
0	0	0	5		Control point for plotting purposes
1	3.52	0.19			apparent yield point
2	16.97	0.20			ultimate point (15% drop in strength)
3					beginning of lower plateau
4					end of lower plateau
Other requested parameters					
D14	16.97	median drift (in same units as pushover X-axis) associated with complete structural damage, i.e., drift with 50% chance that the structur			
B14	0.60-0.80	logarithmic standard deviation of drift associated with complete structural damage. May need to be guessed			
Sdc	18.66	the median value of drift (in same units as pushover X-axis) associated with collapse, e.g., Sdc = (roof drift at collapse)/PFfR.			
L15		indoor fatality rate given collapse. Many contributors may be unable to provide this value. Porter, Comartin, and Holmes will fill such gaps			
PC		mean fraction of building area collapsed, given complete structural damage. Again Porter, Comartin, and Holmes will fill gaps			
kshort		If HAZUS-style damping preferred, and author can judge, this is the degradation factor for short-duration (M <= 5.5) events			
kmed		If HAZUS-style damping preferred, and author can judge, this is the degradation factor for medium-duration (5.5 < M < 7.5) events			
klong		If HAZUS-style damping preferred, and author can judge, this is the degradation factor for long-duration (M >= 7.5) events			
Explain how these values were arrived at, providing citations if appropriate	D14=Sd(4) for 4-linear curves or Sd(2) for bilinear curves				
For frame systems Sdc/D14=1.3 for low, 1.4 for medium and 1.5 for high code design					
For dual systems Sdc/D14=1.1 for low and 1.2 for high code design					Add rows as desired

Concluding remarks

- Vulnerability parameters have been presented for almost all typical R/C building typologies that appear in Greece (and Southern Europe)

- All values have been derived based solely on analytical results (pushover analyses), no experimental verification so far

- The estimation of quantities such as θ_{14} or S_{dc} is based on rather arbitrary criteria (e.g. $S_{dc} = (1.1 \div 1.3)\ \theta_{14}$)

- Current research activities at AUTh include:
  - efforts to integrate the hybrid and the purely analytical approaches, utilizing available statistical damage data along with the pushover/capacity curves,
  - analysis of additional buildings, designed using different parameters (soil type, design PGA etc.)