Derivation of fragility curves to establish a vulnerability metric for the residential building stock

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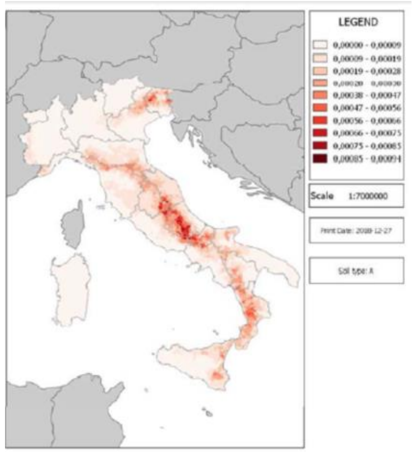
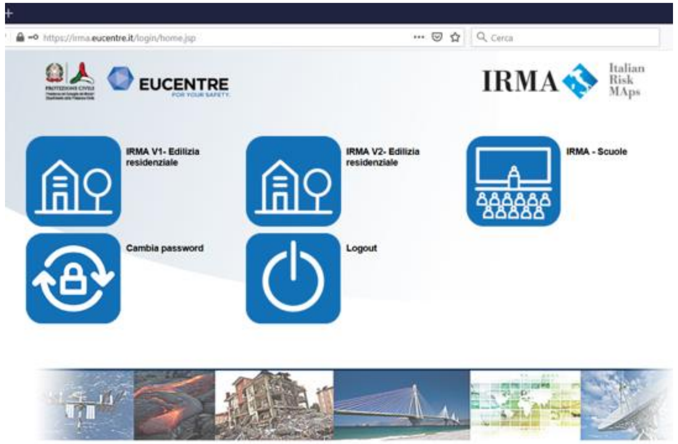
MARS project - Seismic Risk and Damage Maps at National scale

Funded by the Italian Civil Protection Agency and ReLUIS (Network of University Laboratories for Earthq Eng)

Objective: update National Risk Assessment 2018 (Dolce et al., 2021)



Tool: IRMA web platform, developed by EUCENTRE



Risk components:

- Seismic Hazard Model MPS04-S1 (INGV) and CNR-IGAG soil map (V_{s30})
- Exposure: residential buildings at municipality level from ISTAT census
- Vulnerability: fragility curves derived/calibrated with observed damage
- Losses and consequence functions from L'Aquila reconstruction (2009)

Masi A, Lagomarsino S, Dolce M et al. (2021) *Towards the updated Italian seismic risk assessment: exposure and vulnerability modelling*. Bull Earthq Eng 19
Dolce M, Prota A, Borzi B et al. (2021) *Seismic risk assessment of residential buildings in Italy.* Bull Earthq Eng 19

EXPOSURE/VULNERABILITY - Buildings inventory from ISTAT census

Classification - Residential buildings are distinguished according to the following **taxonomy**:

- Masonry / Reinforced Concrete
- Age: <1919, 19-45, 46-60, 61-70, 71-80, 81-90, 91-00, >2000
- Number of floors: 1, 2, 3, 4+
- Earthquake Resistant Design level

The combination of these tags gives: **52 Masonry types** and **64 RC types**

Exposure - At municipality scale, from the ISTAT census we know, for each building type:

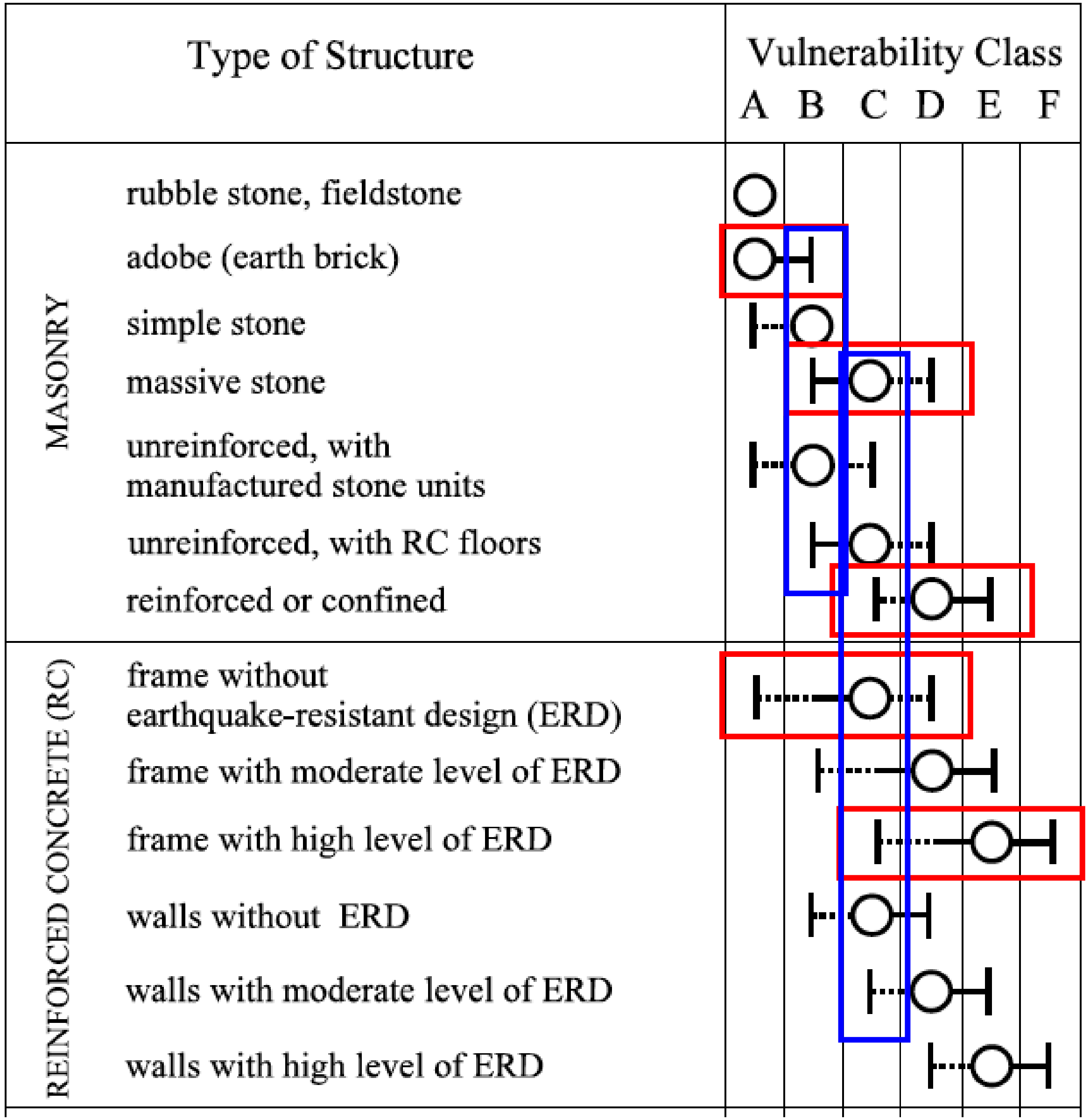
- the number of **inhabitants** (useful for the assessment of expected casualties and displaced)
- the number of **buildings** (collapses) and **flats** (unusable apartments)
- the total **surface area** of the apartments (for the economic loss estimation)

Vulnerability - IRMA platform requires associating to each ISTAT-type the rates of buildings that behave according to **EMS-98 vulnerability classes** (6 classes, from A to F).

For each class, EMS-98 establishes a correlation between the macroseismic intensity and 5 damage states, but in IRMA the PGA is used as intensity measure, therefore one set of fragility curves should be associated to each vulnerability class.

EMS-98 vulnerability classes

Vulnerability Class – group of buildings characterized by a similar seismic performance.



Buildings belonging to a specific building type may behaves differently, according to different vulnerability classes.

This applies both to masonry and RC.

Buildings behaving as a given vulnerability class may belong to different building types.

Masonry and RC buildings have sometimes the same vulnerability.

○ most likely vulnerability class; — probable range;
┈ range of less probable, exceptional cases

IRMA attribution of vulnerability to ISTAT building types

Fragility curves

Class | DS1: PGA_{50}, β | DS2: PGA_{50}, β | DS3: ….. ….. | DS4: ….. ….. | DS5: ….. …..

	A	B	C	D	E	F	G	H	I	J	K	L
1			Livello di danno 1		Livello di danno 2		Livello di danno 3		Livello di danno 4		Livello di danno 5	
2	Classe	N.P.	Mediana [g]	Beta	Mediana [g]	Beta	Mediana [g]	Beta	Mediana [g]	Beta	Mediana [g]	Beta
3	Ad	1										
4	Ad	2										
5	Ad	3										
6	Ad	>= 4										
7	Bd	1										
8	Bd	2										
9	Bd	3										
10	Bd	>= 4										
11	Cd	1										

Excel sheets

Masonry

Material | Age | Floors | Vulnerability class rates

	A	B	C	D	E	F	G	H	I
1	Materiale	Epoca	N.P.	% Classe Ad	% Classe Bd	% Classe Cd	% Classe Dd	% Classe Ed	% Classe Fd
2	mu	< 1919	1	60	30	10			
3	mu	< 1919	2	65	30	5			
4	mu	< 1919	3	75	25				
5	mu	< 1919	>= 4	90	10				
6	mu	1919 - 1945	1		70	30			
7	mu	1919 - 1945	2		80	20			
					80	10			
					80				

Reinforced Concrete

	A	B	C	D	E	F	G	H	I
1	Materiale	Epoca	N.P.	% Classe Ad	% Classe Bd	% Classe Cd	% Classe Dd	% Classe Ed	% Classe Fd
78	c.a.	1971 - 1980	1		40	40	20		
79	c.a.	1971 - 1980	2		50	40	10		
80	c.a.	1971 - 1980	3		60	40			
81	c.a.	1971 - 1980	>= 4		80	20			
82	c.a. cl.sis	1971 - 1980	1			60	40		
83	c.a. cl.sis	1971 - 1980	2		5	60	35		
84	c.a. cl.sis	1971 - 1980	3		20	60	20		
85	c.a. cl.sis	1971 - 1980	>= 4		30	75	5		

IRMA users can implement their own fragility curves, labelling them as vulnerability classes, and associate to building types

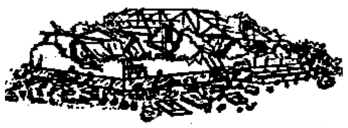
5 Damage Grades

GRADE 1:
Negligible to slight damage

GRADE 2:
Moderate damage

GRADE 3:
Substantial to heavy damage

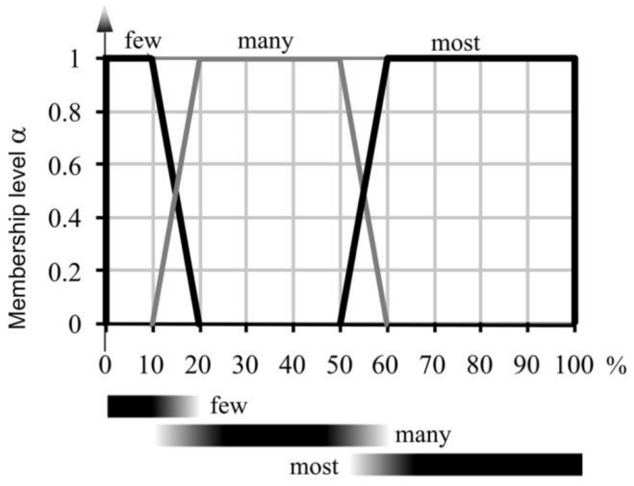
GRADE 4:
Very heavy damage



GRADE 5:
Destruction

Macroseismic table, for the attribution of the intensity after the macroseismic survey (Grünthal et al., 1998)

I	D1 negligible to slight	D2 moderate	D3 substantial to heavy	D4 very heavy	D5 destruction
5	Few A/B				
6	Many A/B, Few C	Few A/B			
7		Many B, Few C	Many A, Few B	Few A	
8		Many C, Few D	Many B, Few C	Many A, Few B	Few A
9		Many D, Few E	Many C, Few D	Many B, Few C	Many A, Few B
10		Many E, Few F	Many D, Few E	Many C, Few D	Most A, Many B, Few C
11		Many F	Many E, Few F	Most C, Many D, Few E	Most B, Many C, Few D
12					All A/B, Most D/E/F, Nearly All C

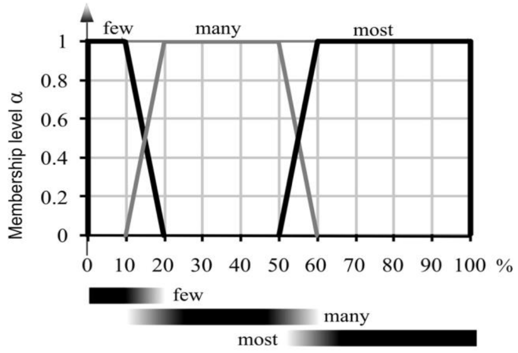


Class A - DPM					
	D1	D2	D3	D4	D5
V	Few				
VI	Many	Few			
VII			Many	Few	
VIII				Many	Few
IX					Many
X					Most
XI					All

Macroseismic Vulnerability Model, implicitly contained in EMS-98, is defined through fuzzy set theory

(Lagomarsino and Giovinazzi, BEE 2006)

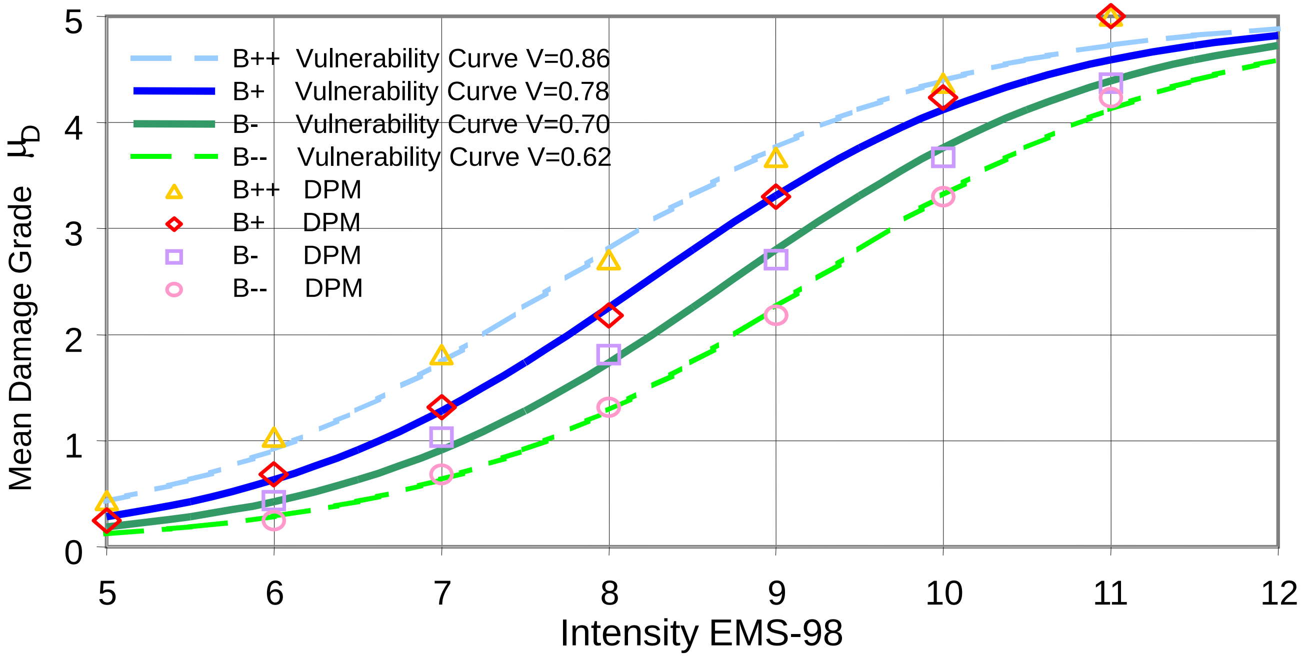
Class A					
	1	2	3	4	5
V	Few				
VI	Many	Few			
VII			Many	Few	
VIII				Many	Few
IX					Many
X					Most
XI					All



Binomial distribution

$$p_k = \frac{5!}{k!(5-k)!}\left(\frac{\mu_D}{5}\right)^k\left(1-\frac{\mu_D}{5}\right)^{5-k}$$

Class A+ (upper bound)						μ_D
	1	2	3	4	5	
V	10	1.6	0.2	0.0	0.0	**0.25**
VI	32.0	10	1.9	0.2	0.0	**0.68**
VII	22.4	35.6	27.6	10	0.8	**2.18**
VIII	4.1	17.7	34.2	33.9	10	**3.30**
IX	0.2	2.5	12.2	35.0	50	**4.23**
X	0	0	0	0	100	**5**
XI	0	0	0	0	100	**5**



$$\mu_D = 2.5\cdot\left[1+\tanh\left(\frac{I+6.25\cdot V_I-13.1}{2.3}\right)\right]$$

The Heuristic-Macroseismic Vulnerability Model

Heuristic-Macroseismic Model, calibrated with observed damage (DaDO database)

- Within the MARS project, the model has been improved by the addition of a second free parameter Q, named ductility index, which changes the slope of the macroseismic curve $\mu_D(I)$.

$$\mu_D = 2.5\left[1 + tanh\left(\frac{I + 5V - 0.38Q - 11.6}{Q}\right)\right]$$

  - By increasing Q the mean damage grade is less sensitive to the increase of I. This may be due to an increase of the buildings ductility, but also to a higher dispersion of performance within the building type.
  - The free parameter V and Q may be fitted for a specific building type by using the observed damage, if the survey in the municipality subjected to different macroseismic intensities is complete. The method is robust even in presence of a limited number of data, because fitting is referred only to one synthetic parameter, the mean damage grade μ_D, instead of considering each single damage state.
  - Reference values of V and Q have been obtained for each ISTAT type, both for masonry and r.c. buildings, with observed damage in DaDO, for the Irpinia (1980) and L'Aquila (2009) earthquakes.
  - Fragility curves in terms of intensity are obtained analytically by assuming the binomial distribution:

$$\mu_{D,k} = 0.9k - 0.2 \qquad I_{Dk} = 11.6 - 5V + Q[0.38 + atanh(0.36k - 1.08)]$$

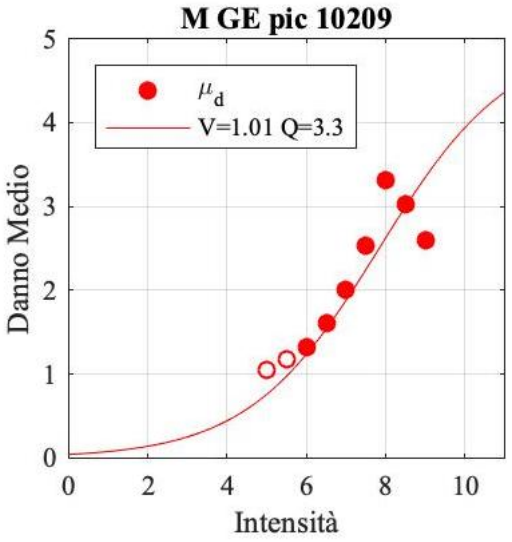
  - By using a correlation I-PGA, the parameter V and Q may be fitted using shakemaps, and lognormal fragility curves in PGA are obtained analytically:

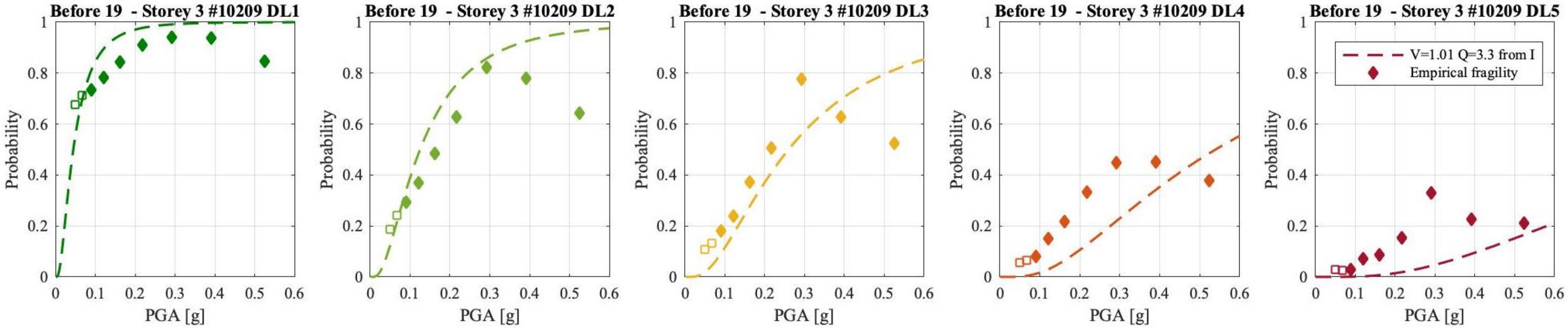
$$Log(PGA) = a\,I + b \qquad PGA = c_1\,c_2^{I-5}$$

$$PGA_{Dk}(V,k) = c_1 c_2^{[6.6-5V+Q[0.38+atanh(0.36k-1.08)]]}$$

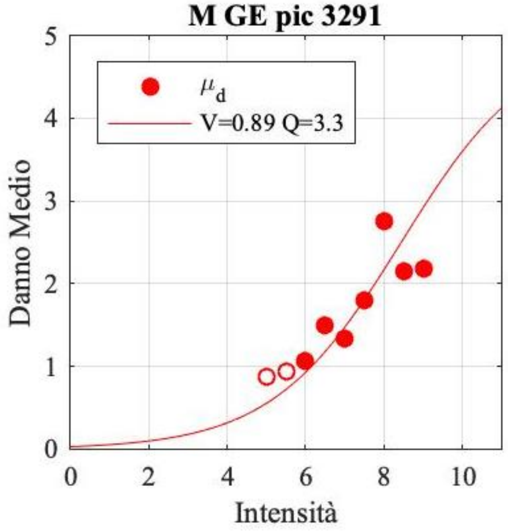
The Heuristic-Macroseismic Vulnerability Model

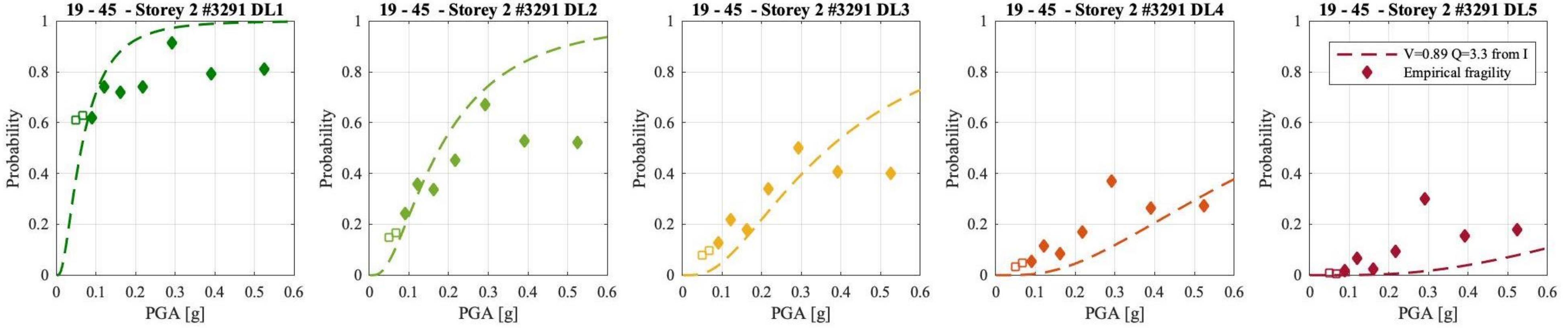
Masonry buildings – 3 storeys – built before 1919

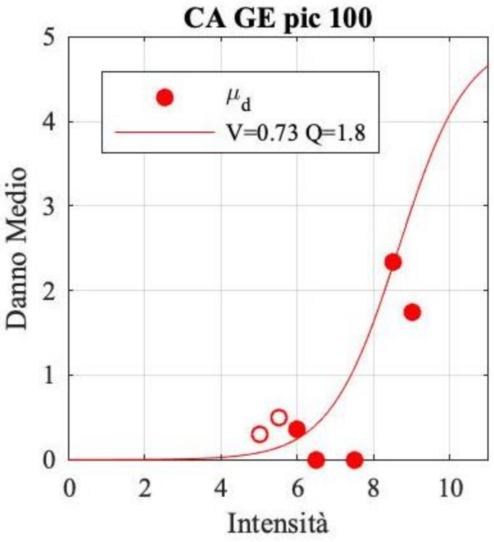




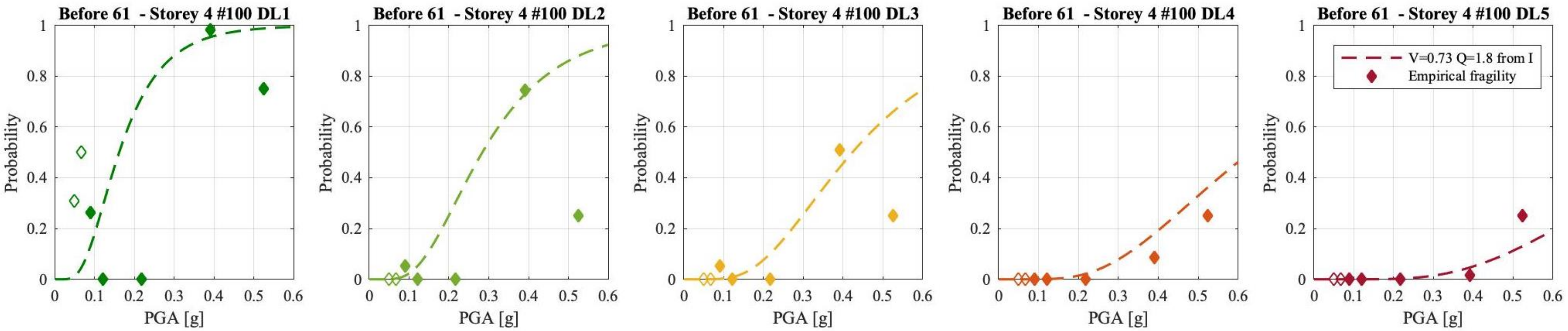
Masonry buildings – 2 storeys – built 1919-1945

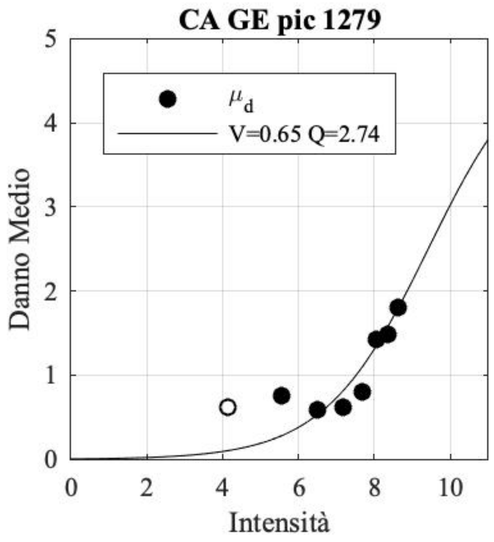




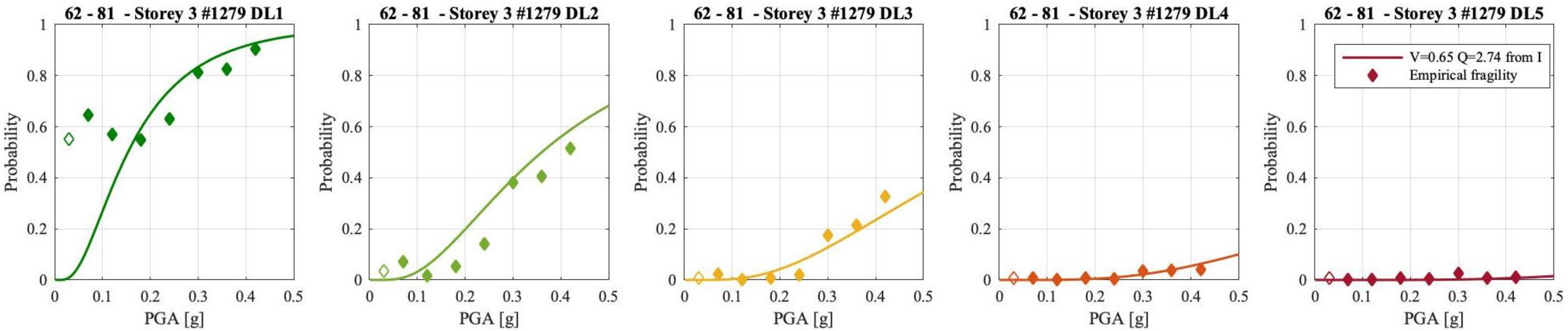


Reinforced Concrete buildings – ≧4 storeys – built before 1961



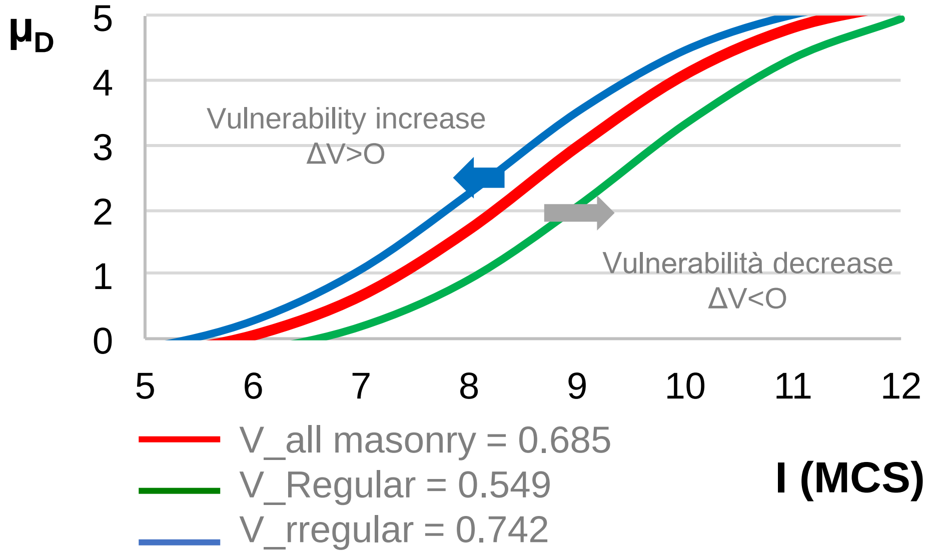


Reinforced Concrete buildings – 3 storeys – built 1961-1980



Refinement of vulnerability (when additional information are available)

Estimation from observed damage of vulnerability modifiers, in order to consider the masonry typology, the horizontal diaphragms and the structural details, as well as strengthening intervention (risk mitigation)



$$V = V_i + \Delta V_m$$

MODIFIERS

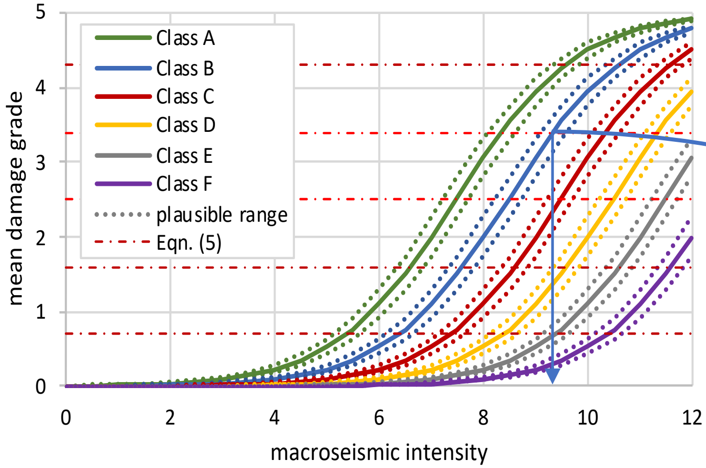
ΔV_Regular = -0.136
ΔV_Irregular = +0.057

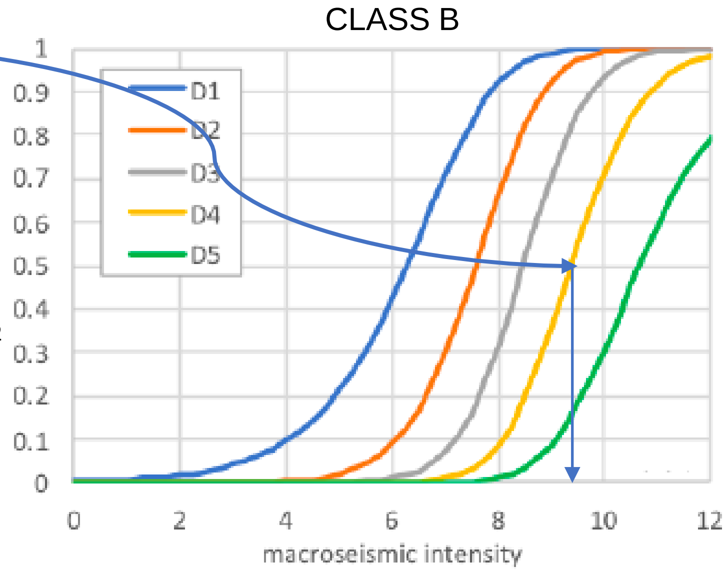
			DETTAGLI			SOLAI					NUMERO DI PIANI	
			LQD	HQD		F-V	F	R	R-RC		L	M
IRR	+0,059	IRR	+0,013	-0,037	IRR-LQD	+0,013	+0,034	-0,034	-0,071	IRR-LQD-F-V	-0,004	+0,000
										IRR-LQD-F	+0,000	+0,003
										IRR-LQD-R	-0,010	+0,010
										IRR-LQD-R-RC	-0,005	+0,010
					IRR-HQD	+0,046	+0,055	-0,025	-0,075	IRR-HQD-F-V	-0,020	+0,022
										IRR-HQD-F	-0,010	+0,011
										IRR-HQD-R	-0,019	+0,015
										IRR-HQD-R-RC	-0,014	-0,042
REG	-0,121	REG	+0,039	-0,026	REG-LQD	+0,059	+0,028	-0,006	-0,037	REG-LQD-F-V	-0,008	+0,019
										REG-LQD-F	-0,025	+0,044
										REG-LQD-R	-0,012	+0,027
										REG-LQD-R-RC	-0,015	+0,033
					REG-HQD	+0,092	+0,044	+0,011	-0,014	REG-HQD-F-V	-0,007	+0,009
										REG-HQD-F	-0,010	+0,016
										REG-HQD-R	-0,025	+0,039
										REG-HQD-R-RC	-0,009	+0,015

Derivation of reference sets of fragility curves for vulnerability classes

Derivation of fragility curves in Intensity

A binomial damage distribution is assumed

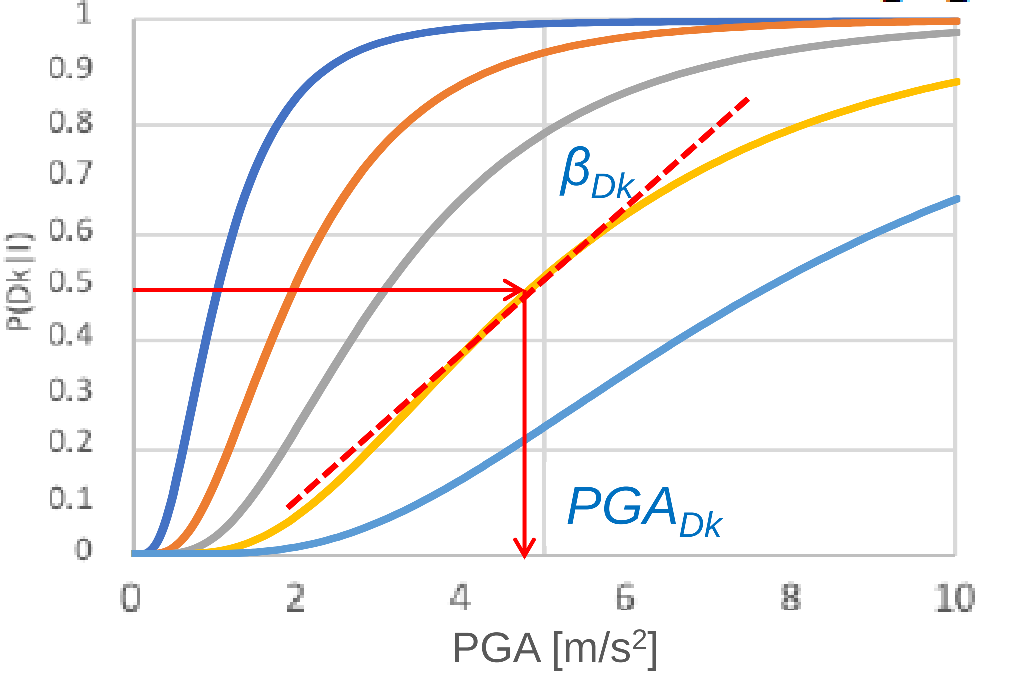




Given from the binomial the value of μ_D that provides the median value of the different DS, the correspondent intensity is obtained

Fragility curves in PGA

It is assumed the correlation $PGA = c_1 \, c_2^{I-5}$



- lognormal fragility curve of damage *Dk* depends on 2 parameters: $PGA_{Dk}(V)$ and $\beta_{Dk}(Q)$
- 5 damage states are considered (EMS98) → for each class: 10 parameters!!!

- spacing between DS is regular (depends on the ductility Q)
- dispersion is assumed constant (in order to avoid intersections)

$$PGA_{Dk} = PGA_{D2} \, e^{\alpha(k-2)} \quad k = 1,..,5$$

$$0.36 \leq \alpha \leq 0.66$$

brittle ductile

3 parameters

$PGA_{D2}(V) - \alpha / \beta(Q)$

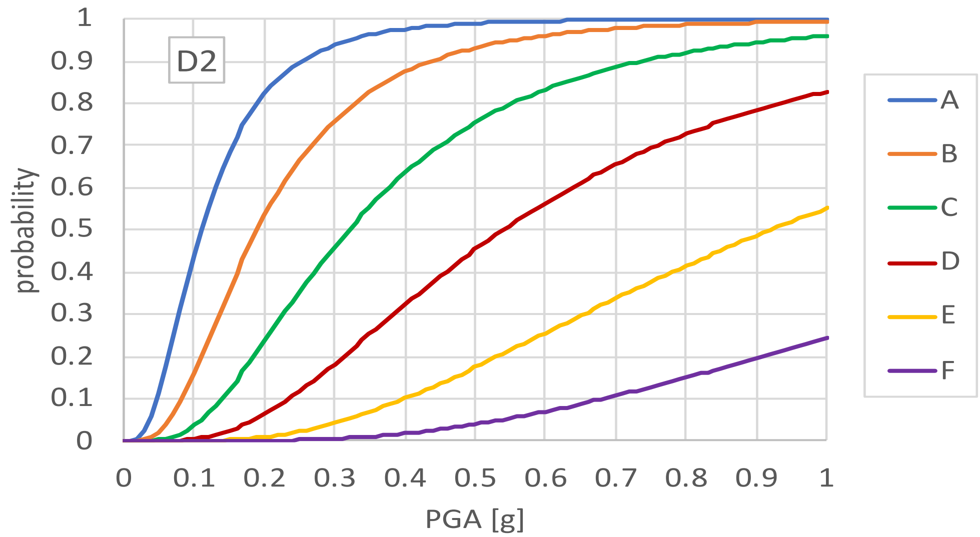
The MARS fragility curves metric

- each EMS-98 vulnerability class is represented by a value of PGA_{D2}

Vulnerability class	A	B	C	D	E	F
PGA_{D2} [g]	0.11	0.19	0.32	0.54	0.92	1.57

Note: In EMS-98, passing from one vulnerability class to the following (best) one means that you need an increase of 1 of the intensity to get the same damage

$$PGA = c_1\, c_2^{I-5} \qquad c_2 = 1.8$$

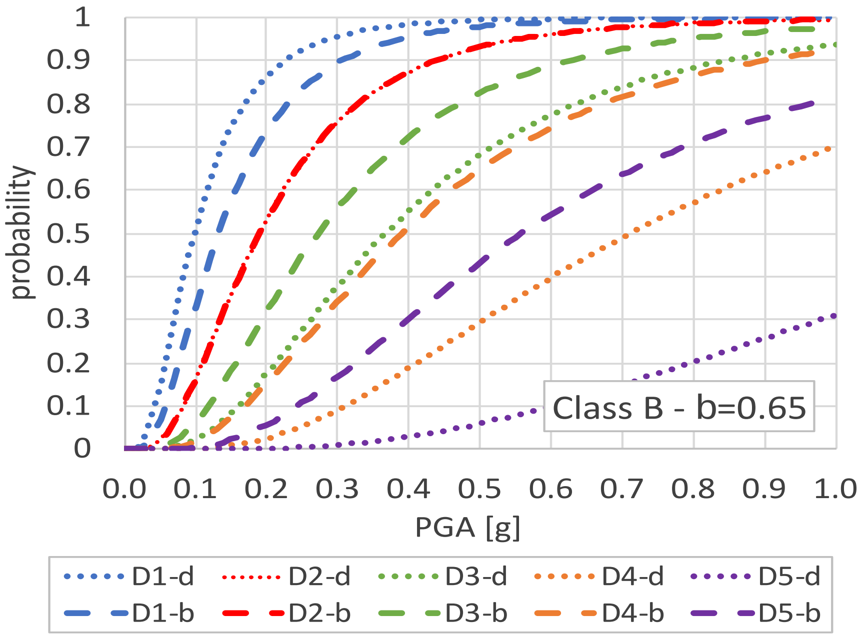


- two sets of fragility curves (brittle and ductile) are defined

		PGA_{Dk}/PGA_{D2}				
Vulnerability Class	α	D1	D2	D3	D4	D5
brittle	0.36	0.70	1	1.43	2.05	2.95
ductile	0.66	0.52	1	1.94	3.74	7.24

$$PGA_{Dk} = PGA_{D2}\, e^{\alpha(k-2)} \qquad 0.36 \le \alpha \le 0.66$$

- the dispersion β depends on the building classification; for the ISTAT types 0.65 is a good value



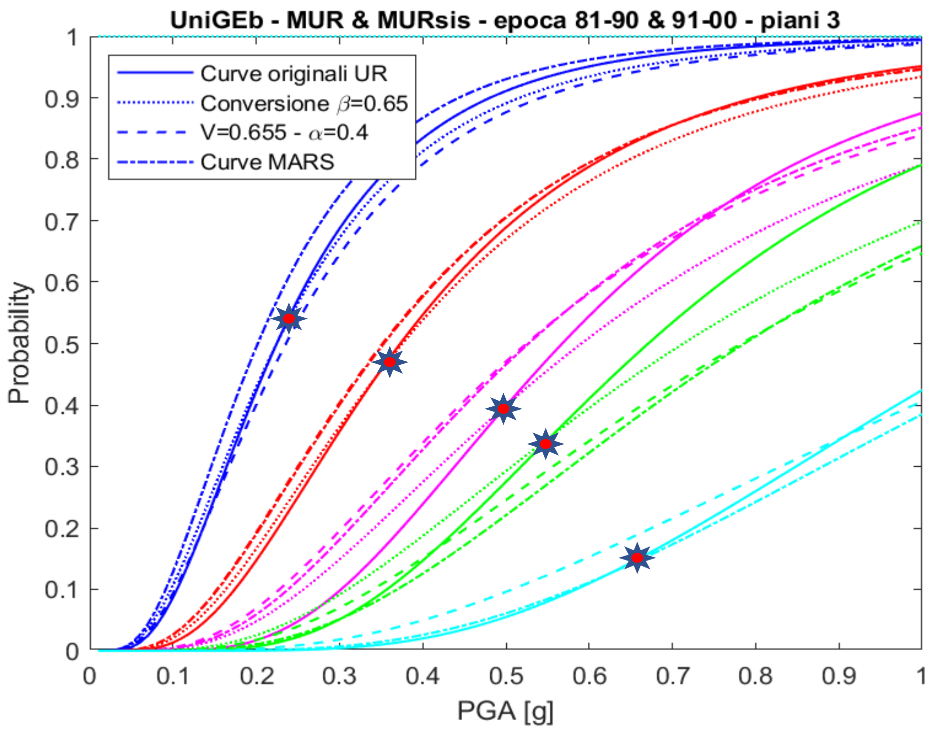
Conversion of fragility models with the MARS vulnerability metric

- Vulnerability models developed by the Research Units in MARS have been converted with the proposed metric, based on EMS-98 vulnerability classes, and integrated altogether in a logic tree.
- For each ISTAT building type, the set of fragility curves (five Damage States) may be represented as a weighted combination of four predefined sets, associated to two EMS-98 vulnerability class, in the case of brittle and ductile behavior.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1				DS1		DS2		DS3		DS4		DS5	
2	**Material**	**Age**	**Floors**	**PGA$_{D1}$ [g]**	**β**	**PGA$_{D2}$ [g]**	**β**	**PGA$_{D3}$ [g]**	**β**	**PGA$_{D4}$ [g]**	**β**	**PGA$_{D5}$ [g]**	**β**
3	Masonry	1981-1990	3	0,22	0,59	0,37	0,59	0,57	0,49	0,67	0,49	1,10	0,52

Three steps procedure:

1. Modification of PGA_{Dk} (for each DS) in order to be coincident with the proposed curve in a relevant point with the selected value of the dispersion β
2. Least squares fitting of the other two parameters that define the set of fragility curves, in order to minimize the difference with the proposed curves: PGA_{Dk} and α
3. Selection of the 2 reference EMS-98 vulnerability classes and evaluation of the 4 weights (ductile and brittle sets)



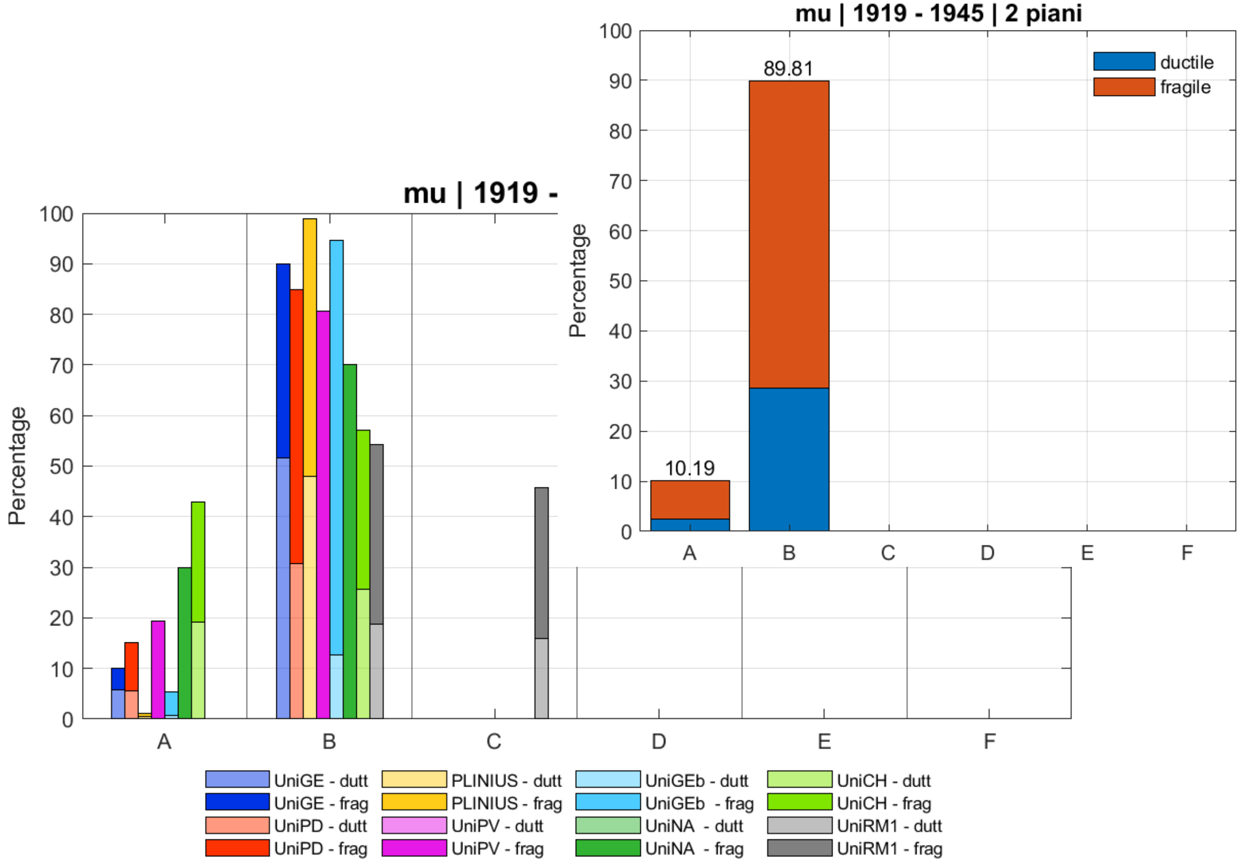
Conversion of fragility models with the MARS vulnerability metric

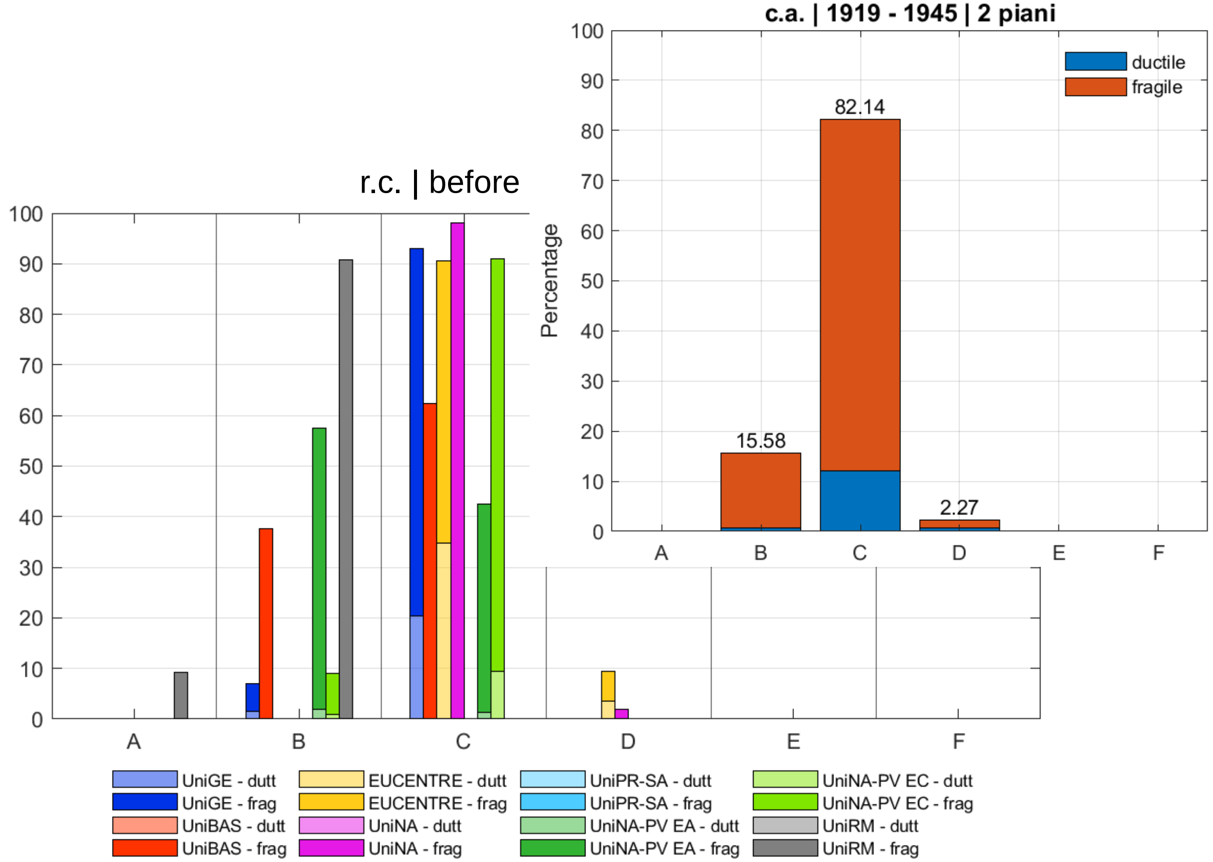
MASONRY

#	R.U.	Coordinator	Method
1	UniGE	Lagomarsino	Heuristic-macroseismic
2	UniPD	da Porto	Hybrid
3	PLINIUS	Zuccaro	Hybrid
4	UniPV	Penna	Empiric-observational
5	UniGEb	Cattari	Mechanic (analytic)

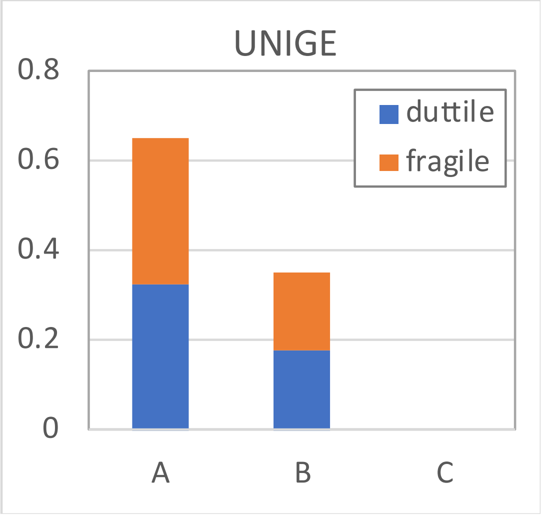
REINFORCED CONCRETE

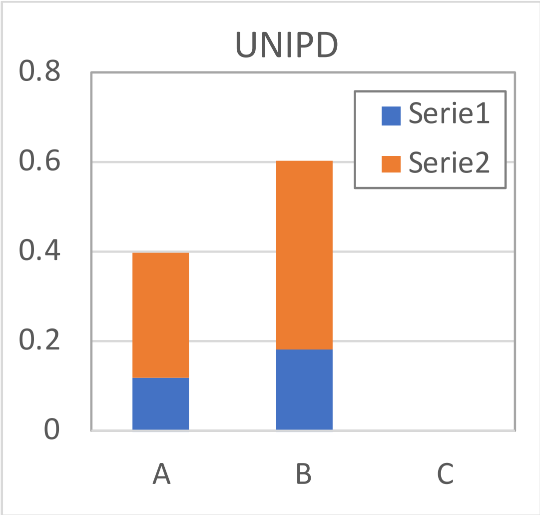
#	R.U.	Coordinator	Method
1	UniGE	Lagomarsino	Heuristic-macroseismic
2	UniBAS	Masi	Mechanic (NLDA)
3	EUCENTRE	Borzi	Mechanic (analytic)
4	UniNA-PV	Penna-Verderame	Empiric-observational
5	UniNA	Verderame	Mechanic (analytic)

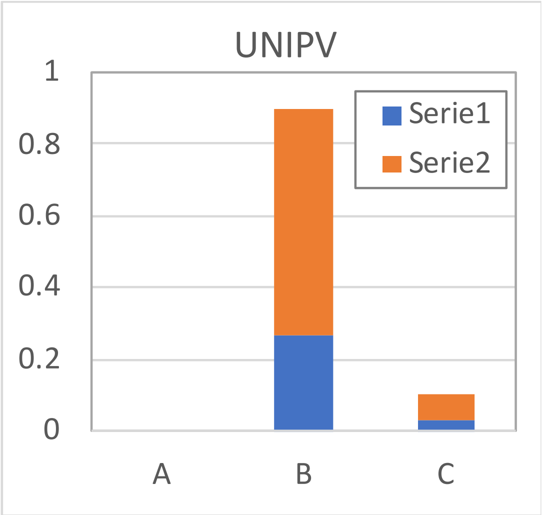


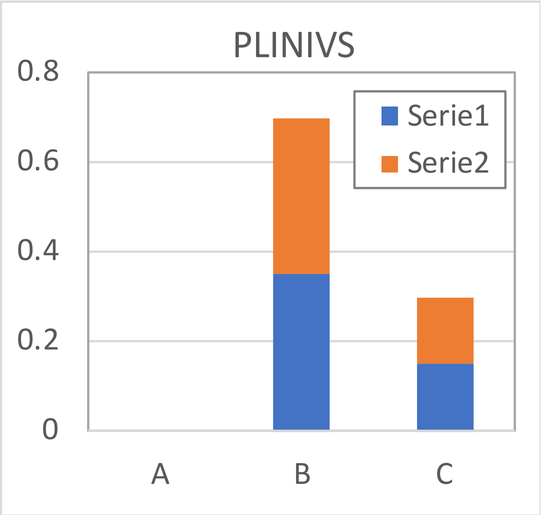


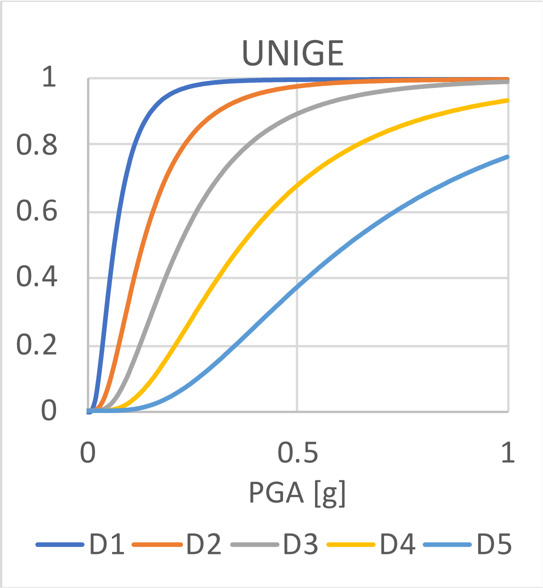
MASONRY / 1946-1960 / 1 storey

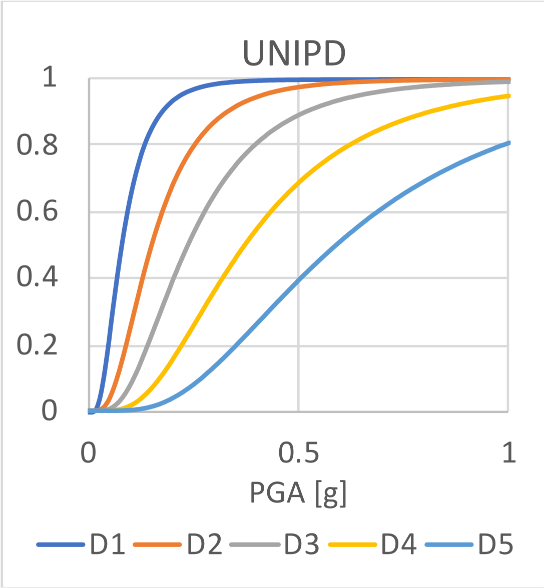


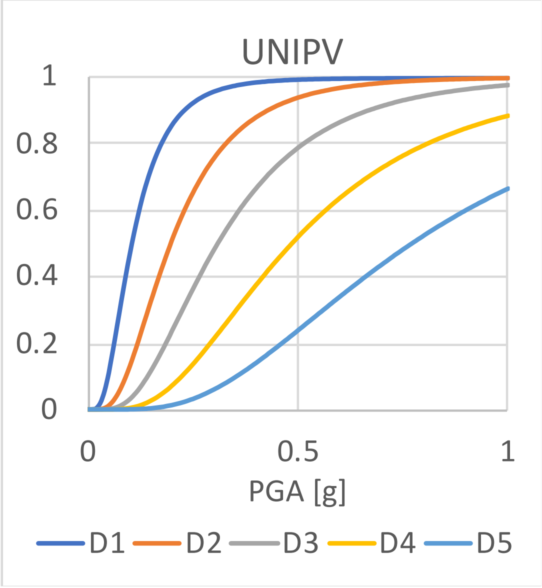


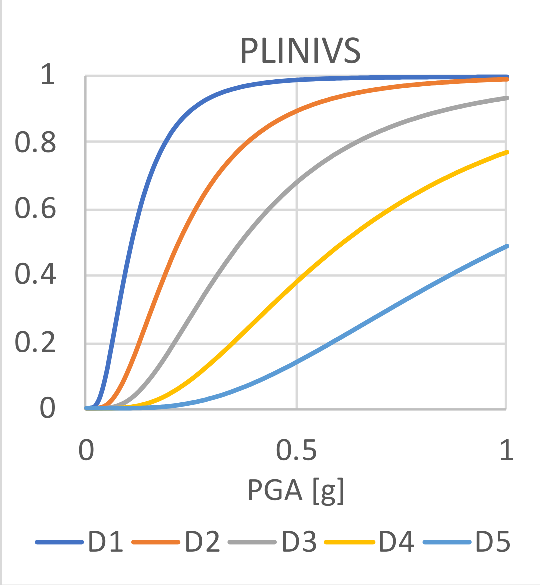






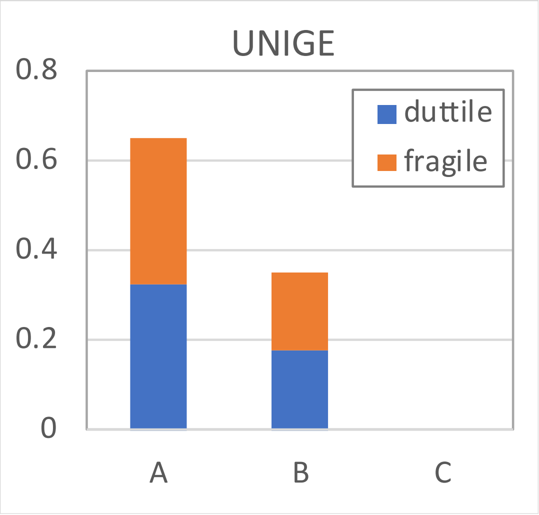


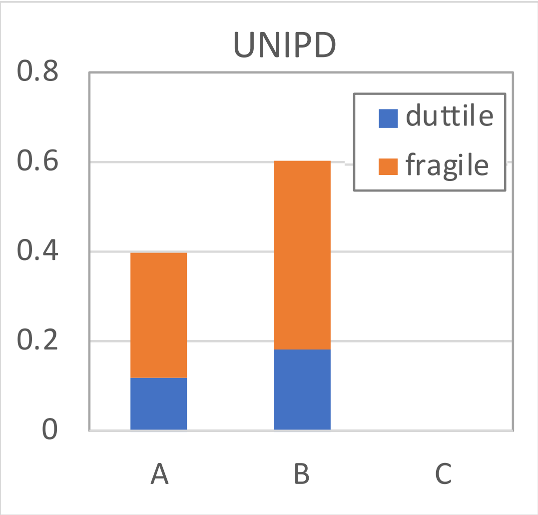


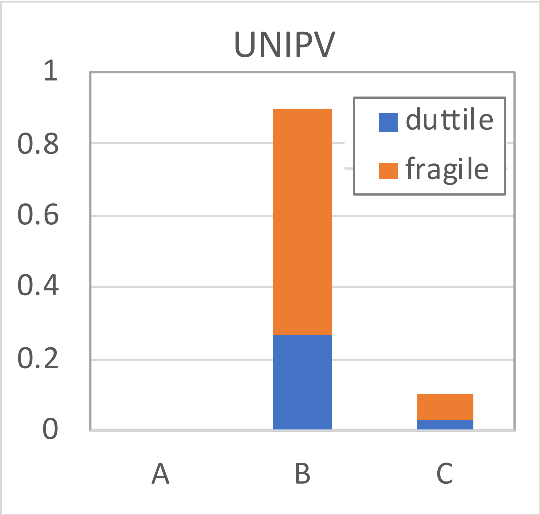


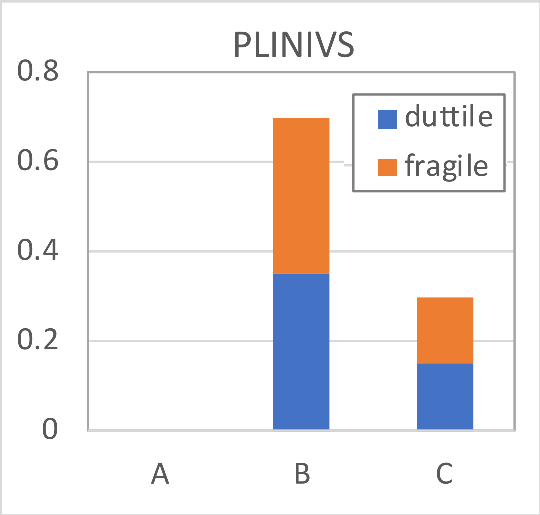
Integration of different models with the MARS vulnerability metric

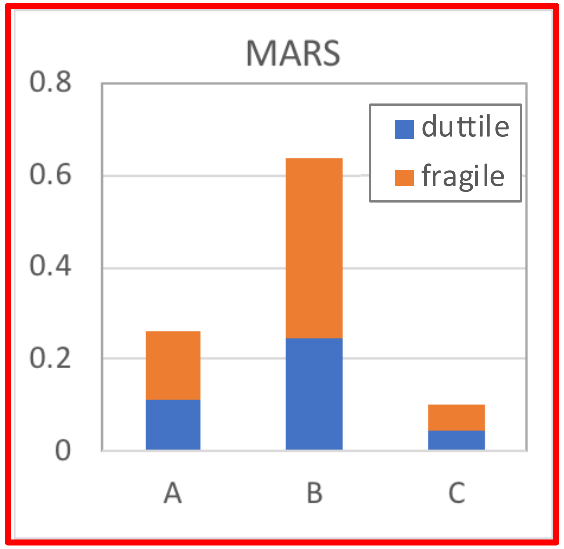
MASONRY / 1946-1960 / 1 storey

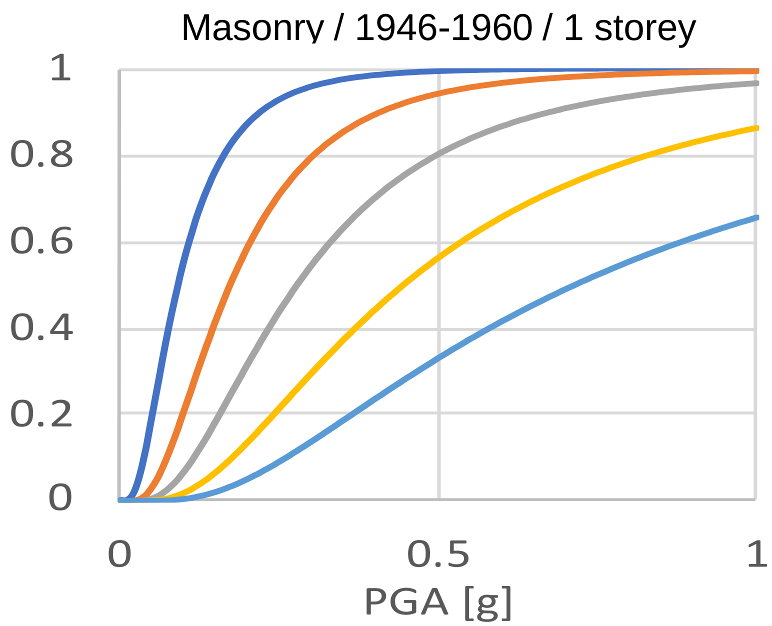


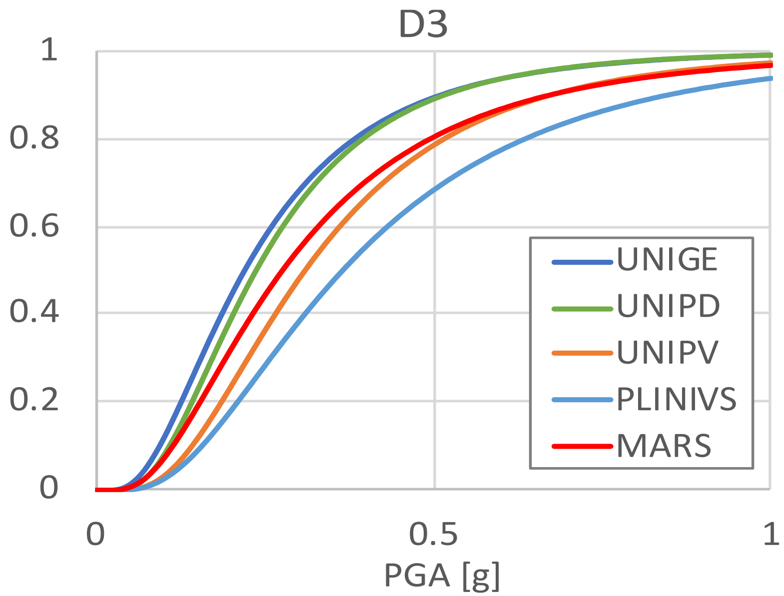








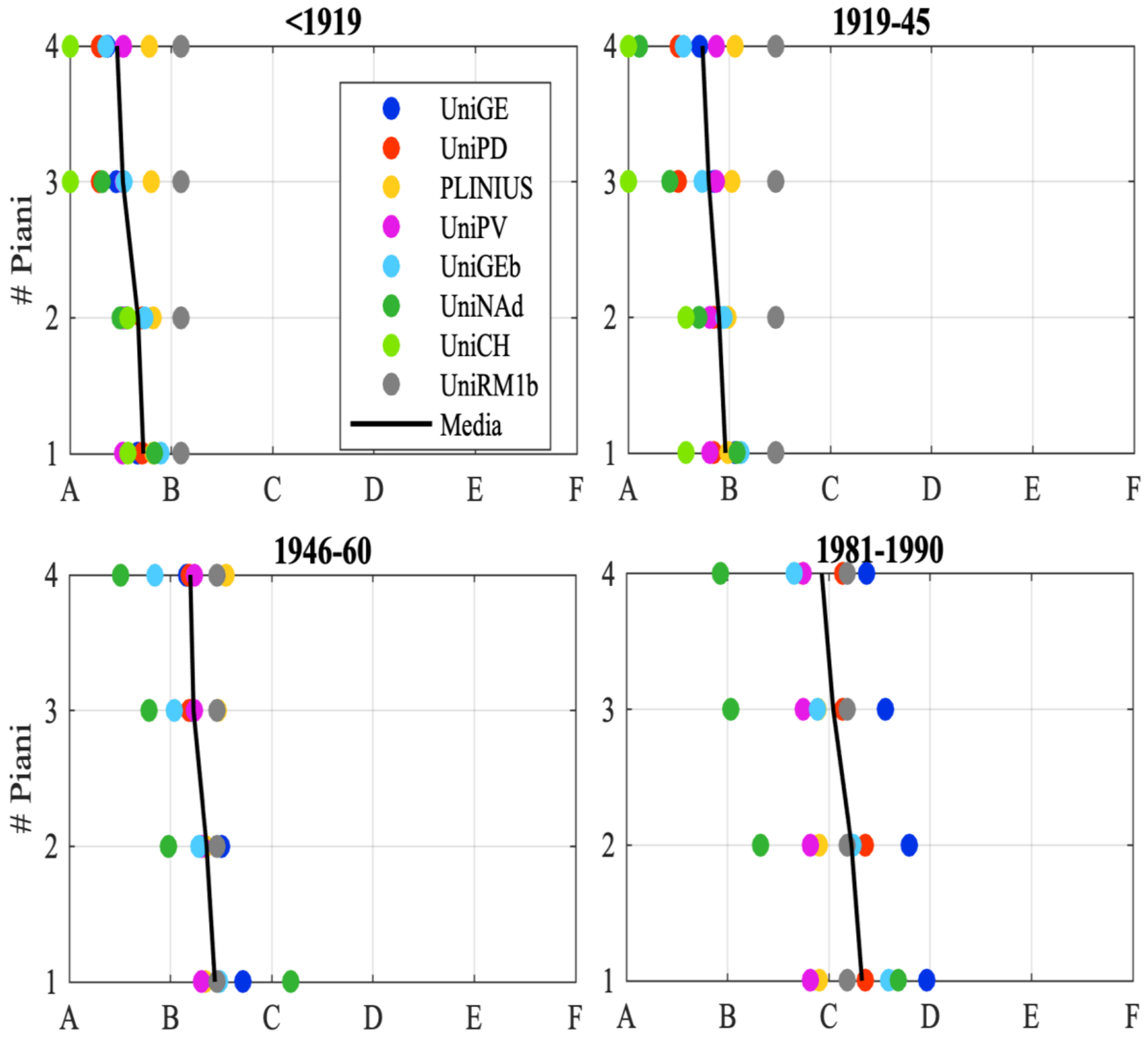




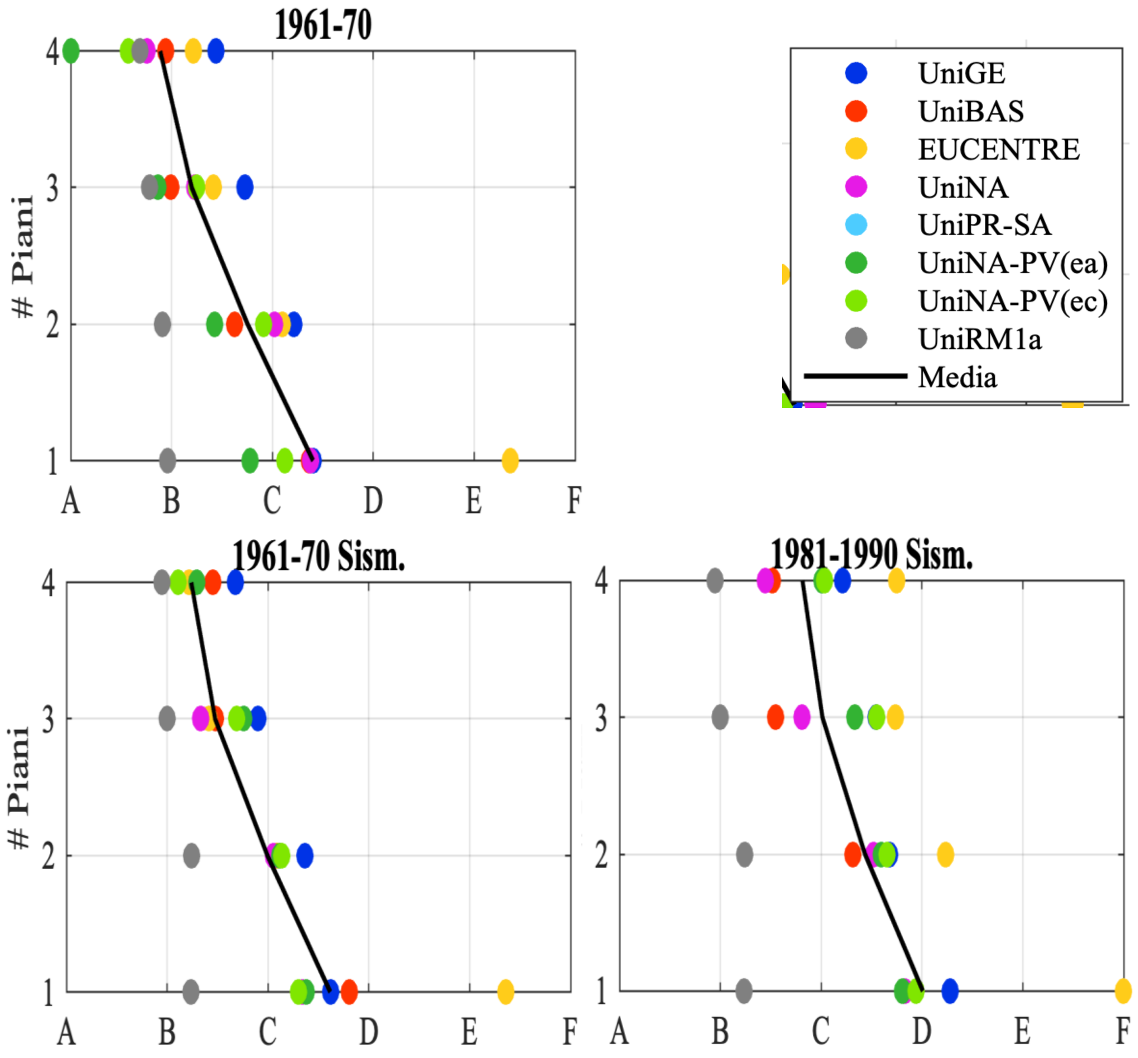
Fragility comparison of ISTAT types by the MARS vulnerability metric

- Influence of building age and height on the EMS-98 vulnerability classes (epistemic uncertainty)

MASONRY



REINFORCED CONCRETE



Fragility comparison of ISTAT types by the MARS vulnerability metric

REINFORCED CONCRETE

REINFORCED CONCRETE	Exposure	Population		Built area [m^2]	Number of flats		N. buildings
		32 Milions		1269 10^6	12,9 Milions		4,3 Milions
		Human loss		Economic loss	Unusable flats		Buildings
Research groups	Fragility model	casualties	injured	(M€)	short term	long term	collapsed
UniGE (Lagomarsino)	Originali	41	155	591 €	6971	2757	23
	Conversione (M2)	48	177	566 €	6776	2618	29
UniBAS (Masi)	Original FCs	332	1147	1006 €	11581	5957	269
	Conversion MARS metric	252	890	1101 €	11848	7654	193
EUCENTRE (Borzi)	Original FCs	50	177	403 €	3815	896	30
	Conversion MARS metric	106	382	756 €	8882	4328	68
UniNA (Verderame)	Original FCs	1063	3219	1161 €	4257	3244	1059
	Conversion MARS metric	246	863	1124 €	12458	7428	147
UniNA-PV (Verderame-Penna)	Original FCs (model 1)	313	1119	1535 €	15329	9486	231
	Conversion MARS metric	284	1007	1629 €	19812	10426	188
	Original FCs (model 2)	566	1782	1483 €	14961	8725	486
	Conversion MARS metric	300	1044	1352 €	15257	8805	151

	Fragility model	casualties	injured	economic loss	unsuable s.t.	unsuable l.t.	collapsed
	MARS - Soil B	**189**	**668**	**1008 €**	**11500**	**6329**	**121**
	dispersion	**0.77**	**0.75**	**0.38**	**0.36**	**0.53**	**0.80**
	Soil map (CNR-IGAG)	**247**	**870**	**1253 €**	**14230**	**8075**	**152**

Fragility comparison of ISTAT types by the MARS vulnerability metric

MASONRY

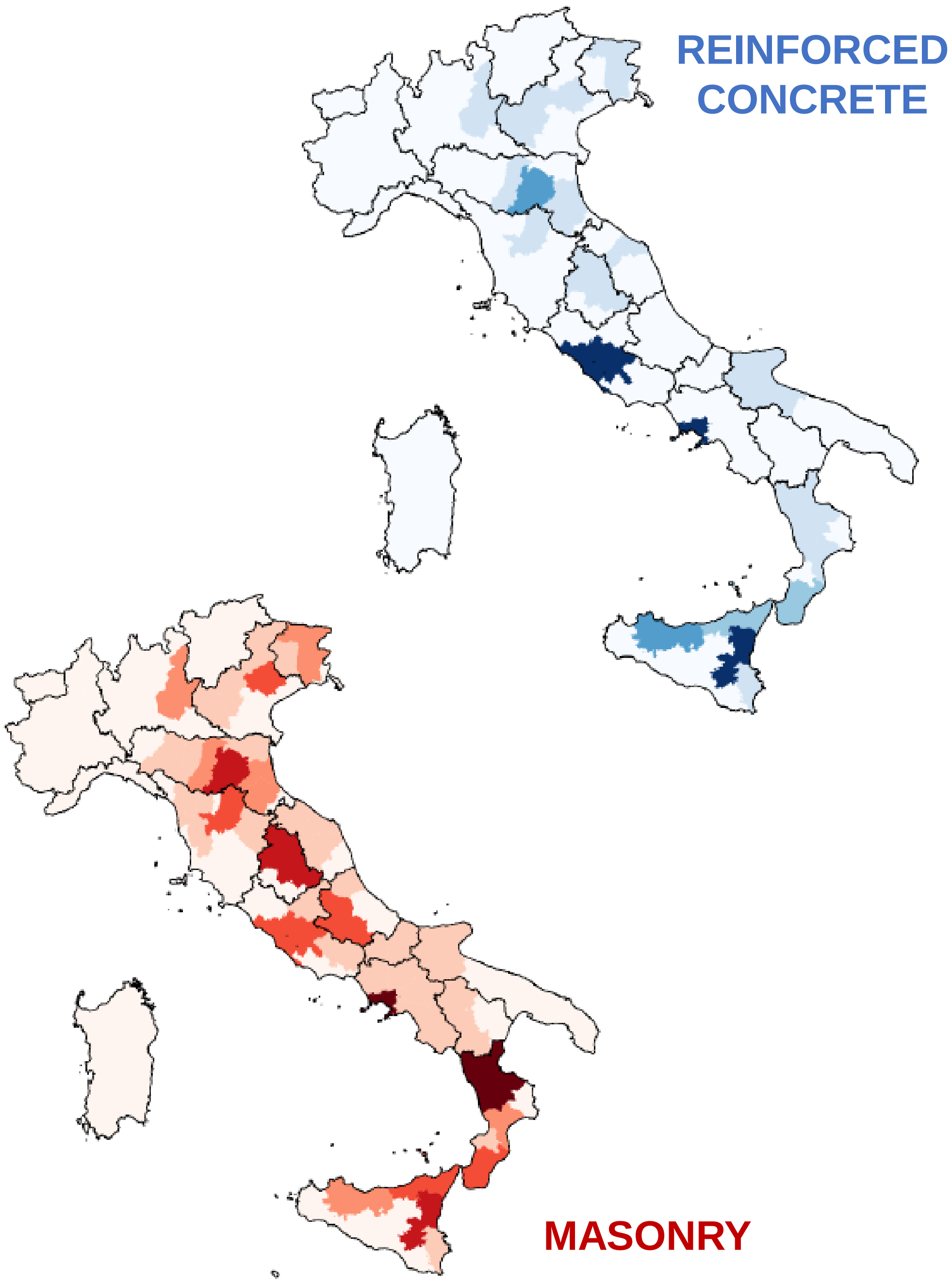
MASONRY	Exposure	Population		Built area [m²]	Number of flats		N. buildings
		26,7 Milions		1127 10^6	11,1 Milions		7,9 Milions
		Human loss		Economic loss	Unusable flats		Buildings
Research groups	Fragility model	casualties	injured	(M€)	short term	long term	collapsed
UniGE (Lagomarsino)	Original FCs	175	624	956 €	11636	6653	440
	Conversion MARS metric	240	831	1068 €	12817	7298	638
UniPD (da Porto)	Original FCs	479	1667	1586 €	15378	11880	1182
	Conversion MARS metric	333	1149	1334 €	15373	9297	865
PLINIUS (Zuccaro)	Original FCs	387	1349	1537 €	14944	11526	1039
	Conversion MARS metric	171	608	972 €	12134	6344	452
UniPV (Penna)	Original FCs	1141	3834	2130 €	12344	16358	3245
	Conversion MARS metric	458	1569	1412 €	14191	10679	1336
UniGEb (Cattari)	Original FCs (no DS5)						
	Conversion MARS metric	313	1092	1287 €	14842	9236	794

Fragility model	casualties	injured	economic loss	unusable s.t.	unusable l.t.	collapsed
MARS - Soil B	**303**	**1050**	**1215 €**	**13871**	**8571**	**817**
dispersion	**0.37**	**0.36**	**0.16**	**0.10**	**0.21**	**0.40**
Soil map (CNR-IGAG)	**375**	**1297**	**1473 €**	**16584**	**10433**	**950**

REINFORCED CONCRETE

Fragility model	casualties	injured	economic loss	unusable s.t.	unusable l.t.	collapsed
MARS - Soil B	**189**	**668**	**1008 €**	**11500**	**6329**	**121**
dispersion	**0.77**	**0.75**	**0.38**	**0.36**	**0.53**	**0.80**
Soil map (CNR-IGAG)	**247**	**870**	**1253 €**	**14230**	**8075**	**152**

- The MARS vulnerability metric allows to characterize a set of fragility curves by only three parameters:
  - the position between two EMS-98 vulnerability classes
  - the “ductility” (spacing between DSs)
  - the dispersion
- The MARS vulnerability metric is a useful tool to compare and integrate fragility models developed by different approaches: empirical, hybrid, macroseismic, mechanical (analytical or NLDA)
- The heuristic rationale inside the model allows to correct small inconsistency that may implicitly derive from the possible limitations and drawbacks of the original models.



expected annual number of collapsed buildings