Analysis and Mitigation of Risks in Infrastructures INFRARISK-

9th Summer School Workshop

Instituto Superior Técnico, *7th July 2023*

Location: Room 4.41, Civil Building

Needs and Challenges in Developing the Italian Seismic Risk Assessment of the School Buildings Stock

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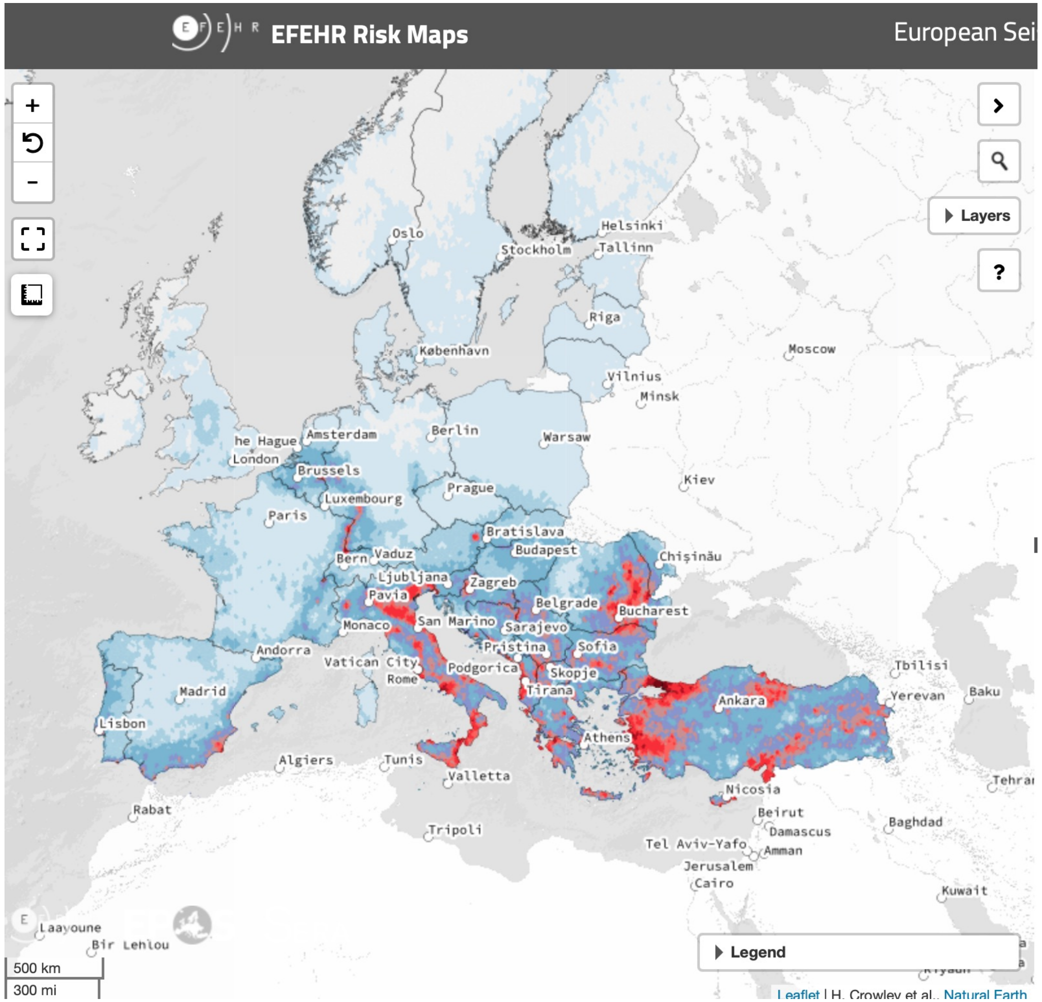
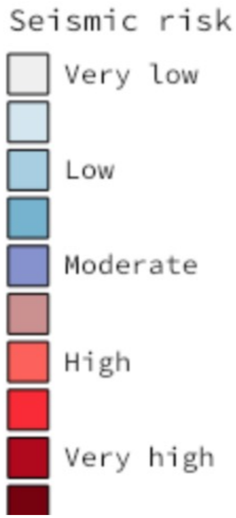
Università di Genova

DICCA - Department of Civil, Chemical and Environmental Engineering

EFFORT WORLDWIDE IN SEISMIC RISK ASSESSMENT



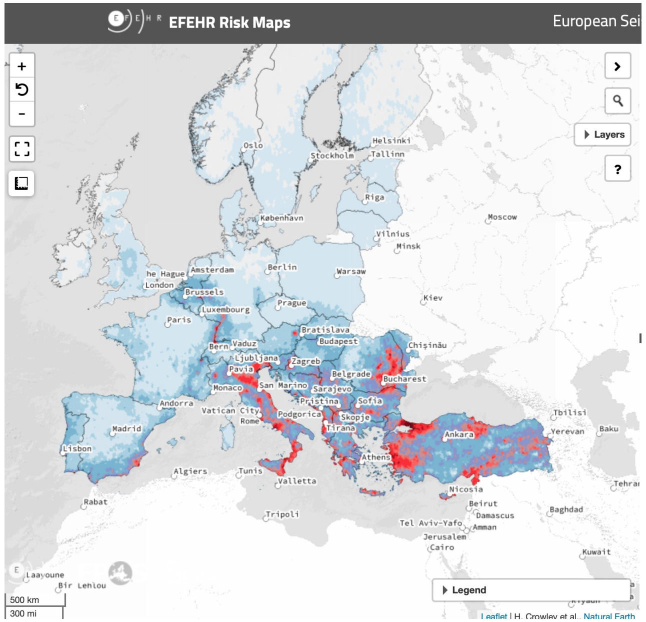
EUROPEAN RISK ACROSS EUROPE

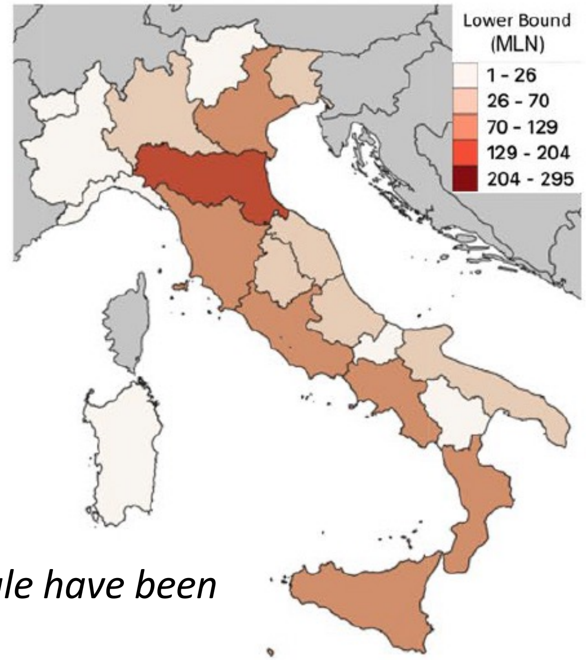


DOI:10.7414/EUC-ESRM20-RISK-INDEX-VIEWER

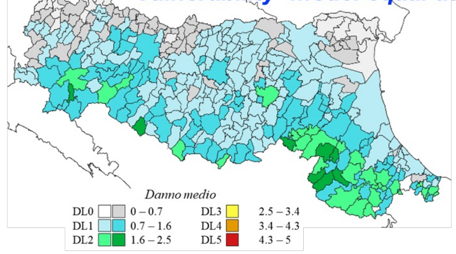
http://risk.efehr.org - developed, maintained and hosted by **EUCENTRE**, in collaboration with the **GEM Foundation** and **EPOS** (European Plate Observing System).

DIFFERENT SCALES OF SEISMIC RISK ASSESSMENT

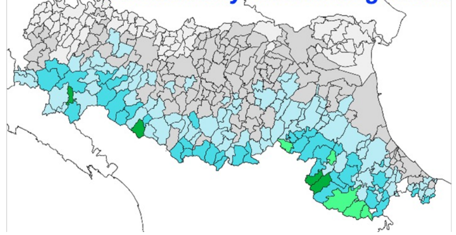




Vulnerability model equal at national scale



Vulnerability model targeted at regional level

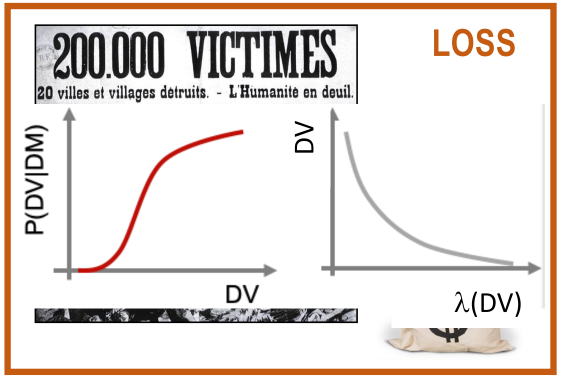


Seismic Risk Assessment at national scale have been recently developed in various countries

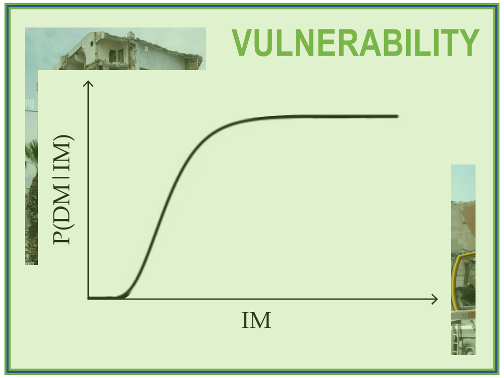
MAIN COMPONENTS OF RISK AND LOSS ANALYSES

Possible refinements may concern all the various components of seismic risk assessment

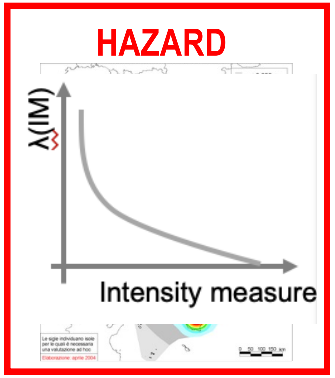
$$\lambda_l = \nu \int P[L > l \mid DM = dm] \cdot \int f_{DM|IM}(dm) \cdot f_{IM}(im)\, d(im) \cdot d(edp) \cdot d(dm)$$



LOSS FUNCTION: *direct cost of damage, indirect economic impact,..*



FRAGILITY FUNCTIONS: *physical damage to buildings, structural performance,..*

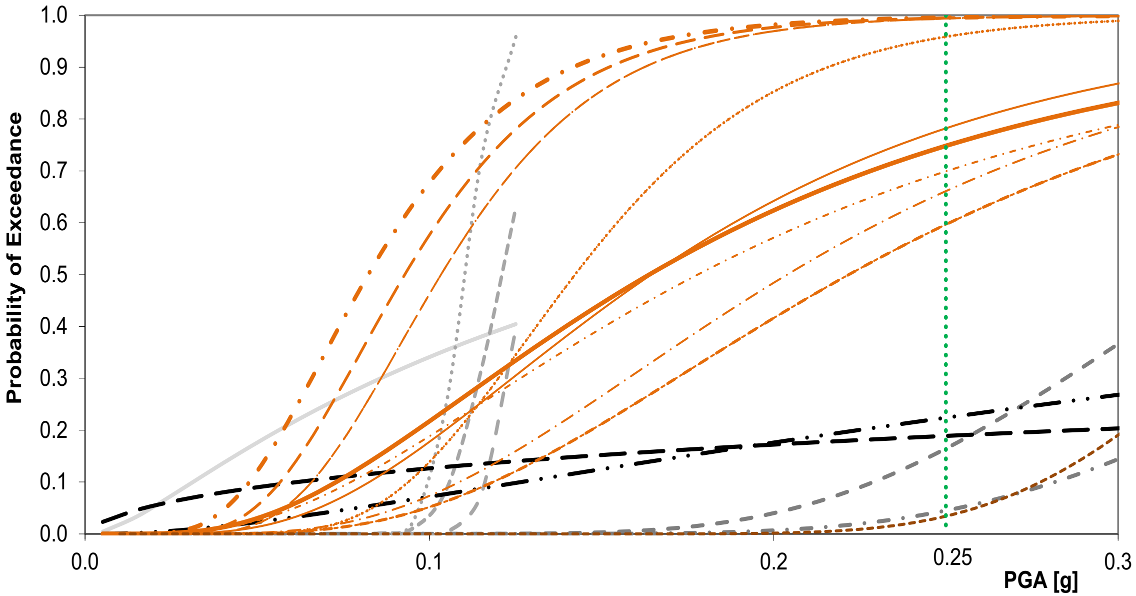


HAZARD CURVE

FRAGILITY CURVES

$$f_{DM|IM}(dm) = f_{DM}(im) = P[dm \geq DM|im] = P[IM_{DM} < im] = \Phi\left[\frac{log\left(\frac{im}{IM_{DM}}\right)}{\beta_{DM}}\right]$$

Italian mid-rise unreinforced masonry buildings with regular layout



European Building Vulnerability Data Repository

X. Romão; N. Pereira; J.M. Castro; H. Crowley; V. Silva; L. Martins; F. De Maio

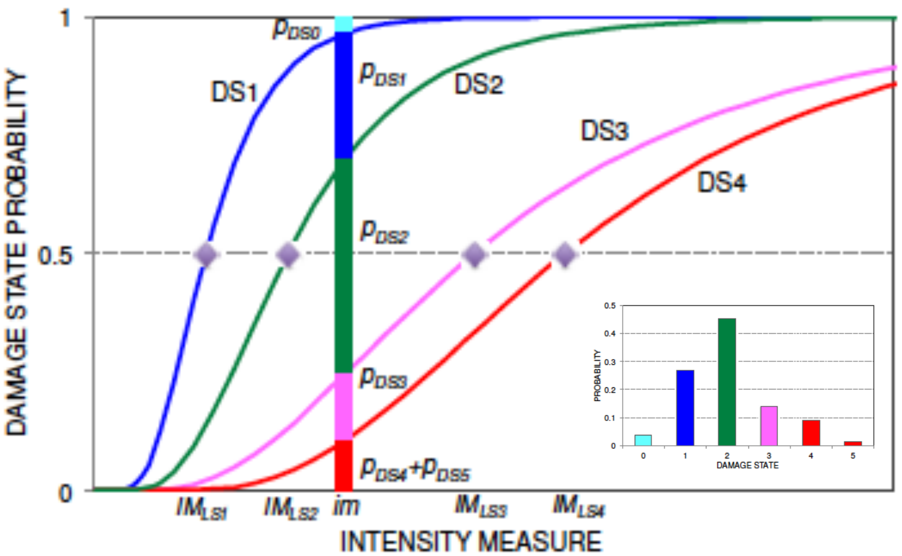
A repository for the European vulnerability database developed as part of the European Seismic Risk Model 2020 (ESRM20).

https://zenodo.org/record/5639318

REF: Rossetto et al (2014) Evaluation of Existing Fragility Curves, DOI:10.1007/978-94-007-7872-6_3

FRAGILITY FUNCTIONS – *possible options and involved uncertainties*

$$P[IM_{DM} < im] = \Phi\left[\frac{\log\left(\frac{im}{IM_{DM}}\right)}{\beta_{DM}}\right]$$

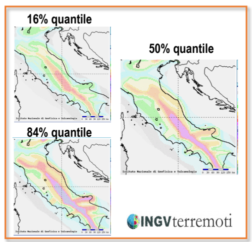


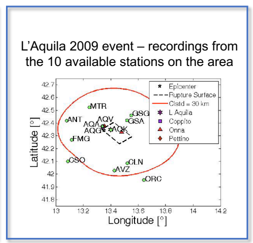
POSSIBLE APPROACHES FOR DEVELOPING FRAGILITY CURVES .....

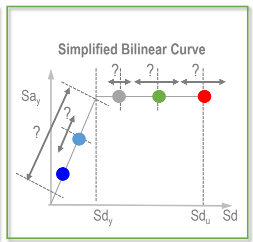
I. Expert elicitation based
II. Empirical
III. Analytical
IV. Hybrid methods

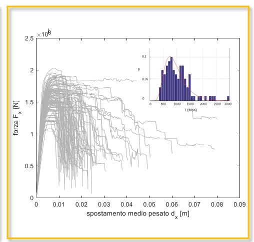
INVOLVED UNCERTAINTIES.....

$$\beta_{DM} = \sqrt{\beta^2_{hazard} + \beta^2_{rec} + \beta^2_{damage\ level} + \beta^2_{capacity}}$$

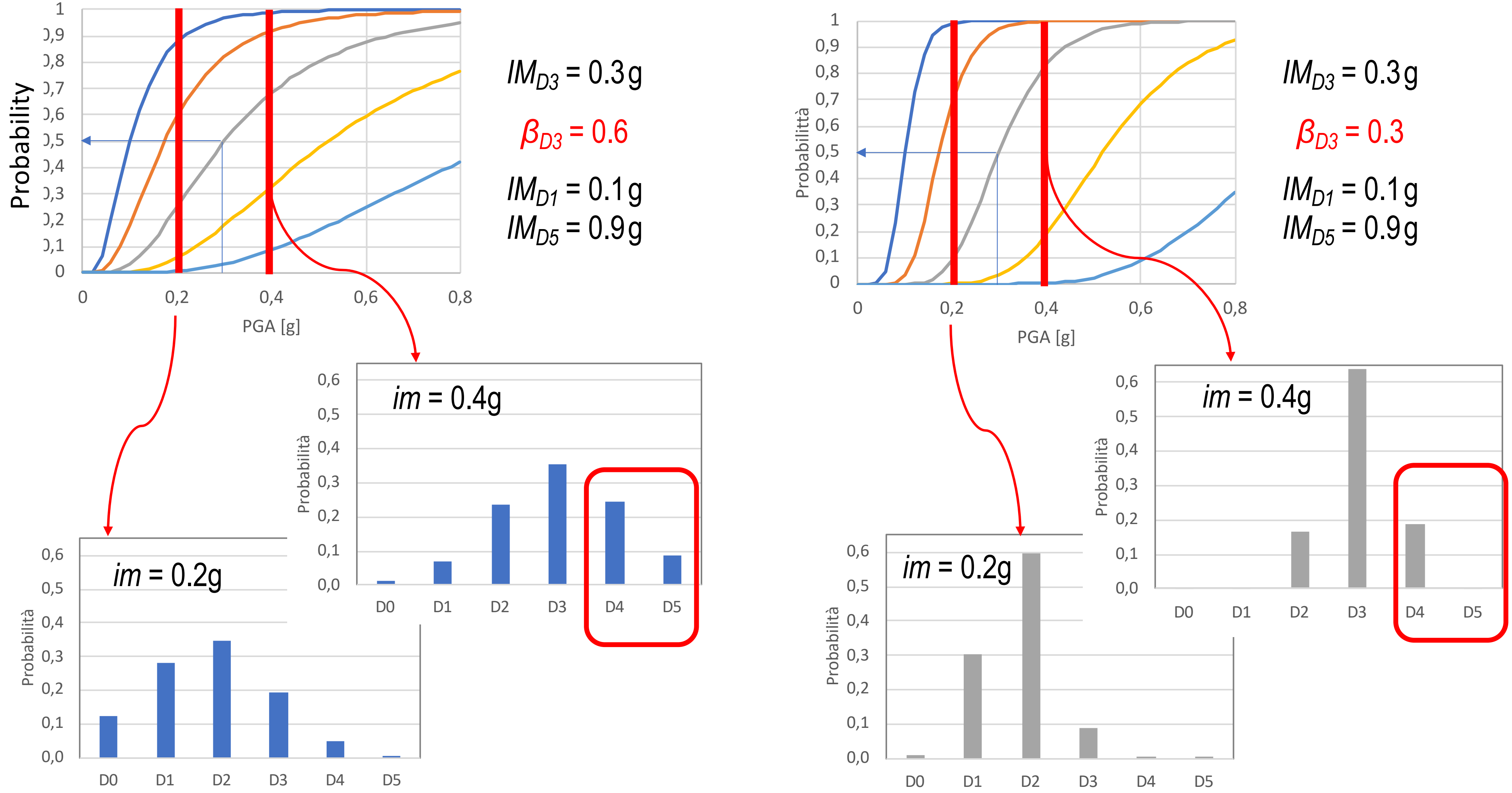








FRAGILITY FUNCTIONS– influence of β



FRAGILITY FUNCTIONS – *possible options and involved uncertainties*

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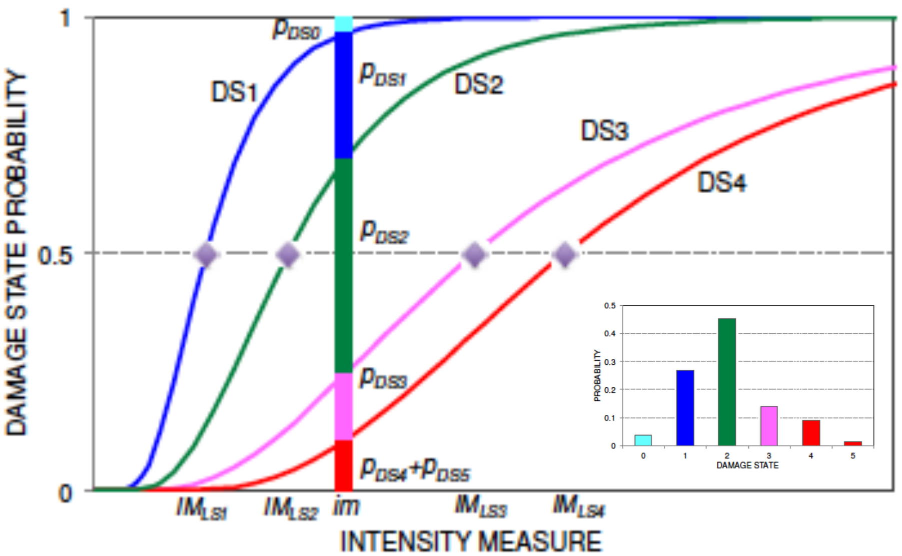
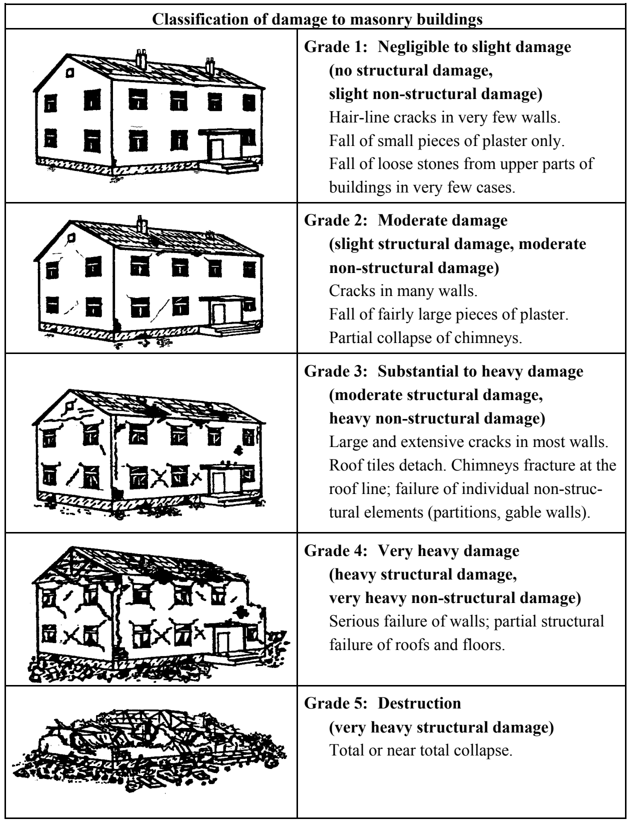


Are we really sure that we are referring to the same thing....?



Classification of damage to masonry buildings	
	Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage) Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	Grade 2: Moderate damage (slight structural damage, moderate non-structural damage) Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage) Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
	Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage) Serious failure of walls; partial structural failure of roofs and floors.
	Grade 5: Destruction (very heavy structural damage) Total or near total collapse.

EMS98 scale (Gruntal 1998)

FRAGILITY FUNCTIONS – *possible options and involved uncertainties*

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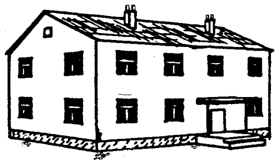
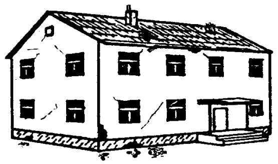
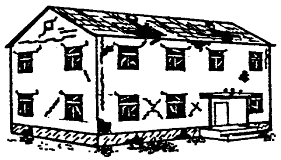
	**Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
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EMS98 scale (Gruntal 1998)

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heavy non-structural damage)
Large and extensive cracks in most walls.
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FRAGILITY FUNCTIONS – *possible options and involved uncertainties*

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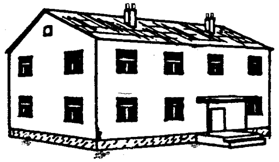
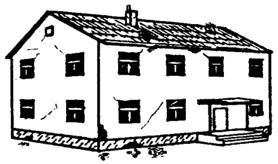
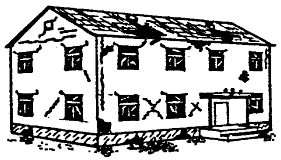
	**Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)** Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases.
	**Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)** Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
	**Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage)** Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls).
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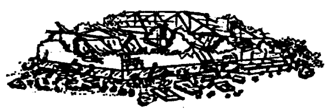	**Grade 5: Destruction (very heavy structural damage)** Total or near total collapse.

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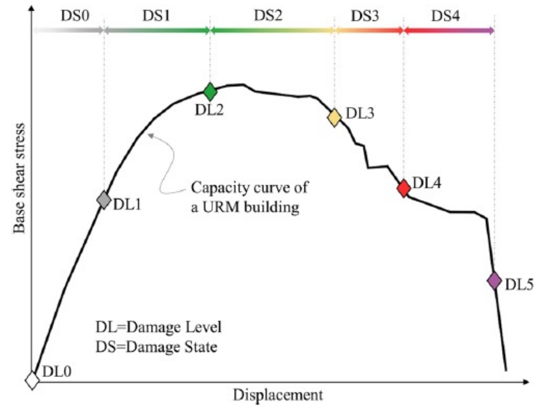
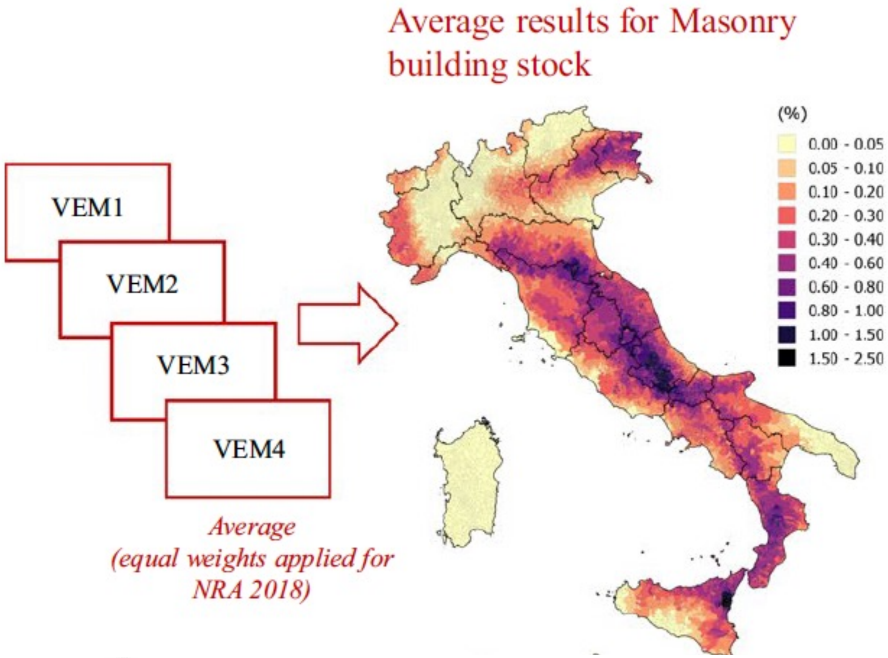
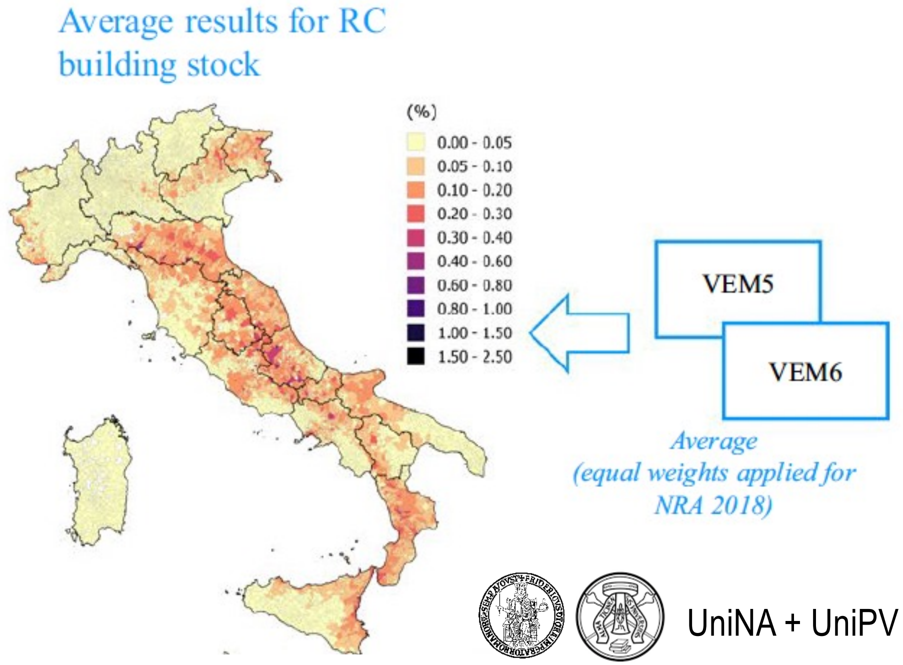


- **EMPIRICAL APPROACH**: IT REQUIRES CONVERSION RULES AND DAMAGE METRICS
- **MECHANICAL- NUMERICAL**: USUALLY BY MONITORING SELECTED EDPs THROUGH THE NUMERICAL MODEL
- **MECHANICAL-ANALYTICAL**: VARYING THE APPROACH, BASED ON EDPs OR CONVENTIONAL THRESHOLDS DIRECTLY DEFINED ON THE PUSHOVER CURVES

THE ITALIAN EXPERIENCE: THE 2018 NRA

The experience of the NATIONAL RISK ASSESSMENT released on 2018 (Dolce et al. 2021)





UniNA + UniPV

Plinivs

UniGE

UniPD

UniPV

EUCENTRE

REF. Dolce M et al. (2021) Seismic risk assessment of residential buildings in Italy , Bulletin of Earthquake Engineering, https://doi.org/10.1007/s10518-020-01009-5

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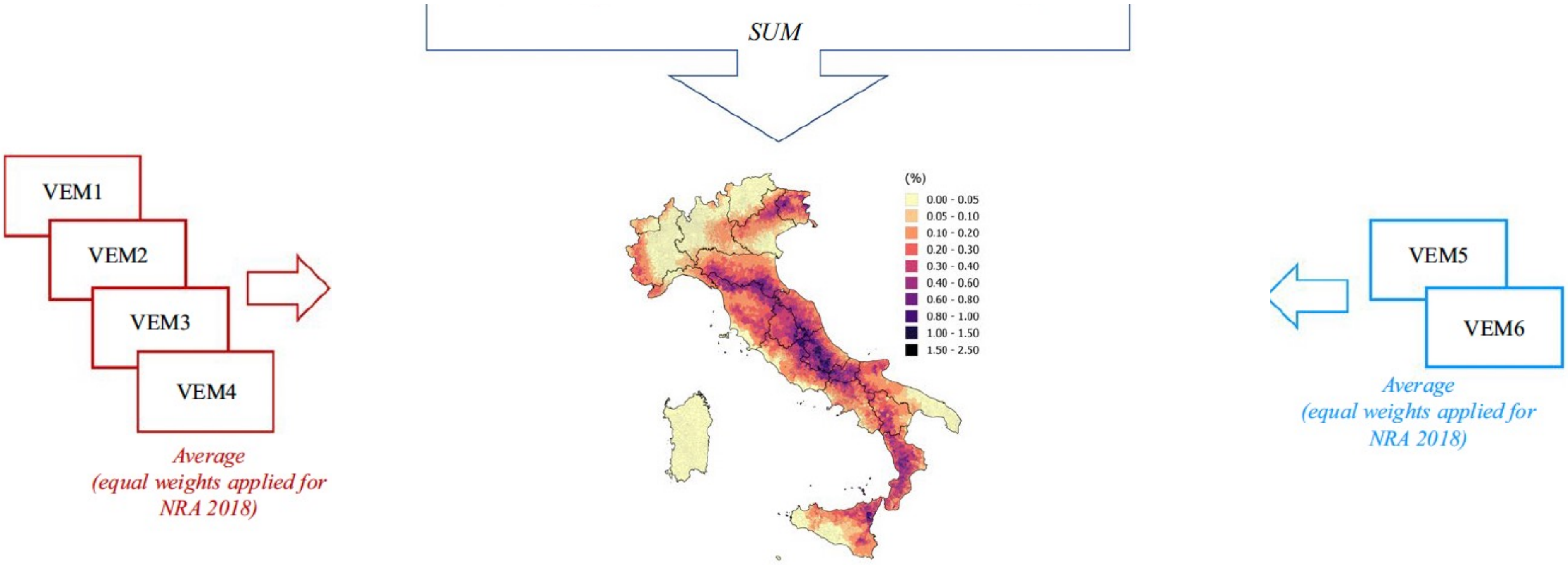


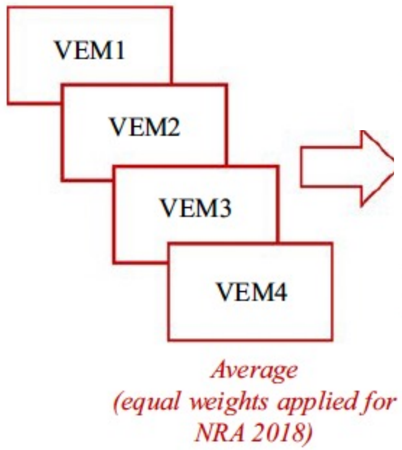
Average results for all buildings (Masonry + RC)

REF. Dolce M et al. (2021) Seismic risk assessment of residential buildings in Italy , Bulletin of Earthquake Engineering, https://doi.org/10.1007/s10518-020-01009-5

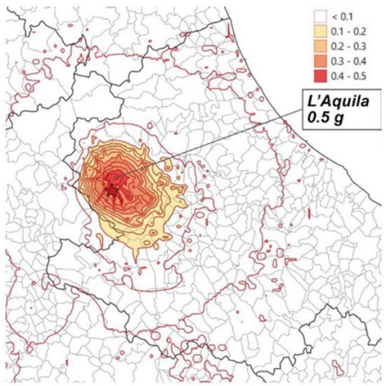
THE ITALIAN EXPERIENCE: THE 2018 NRA

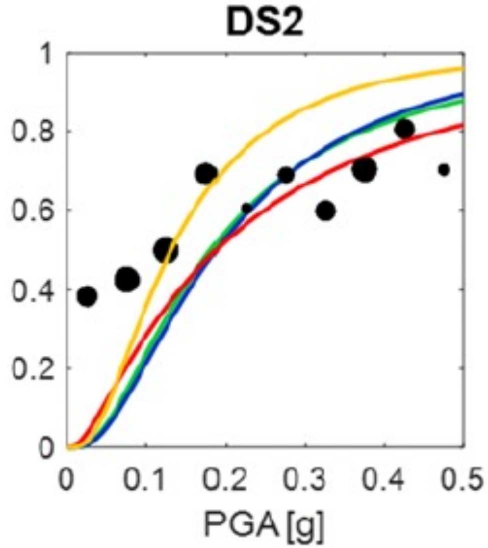
The experience of the NATIONAL RISK ASSESSMENT released on 2018 (Dolce et al. 2021)

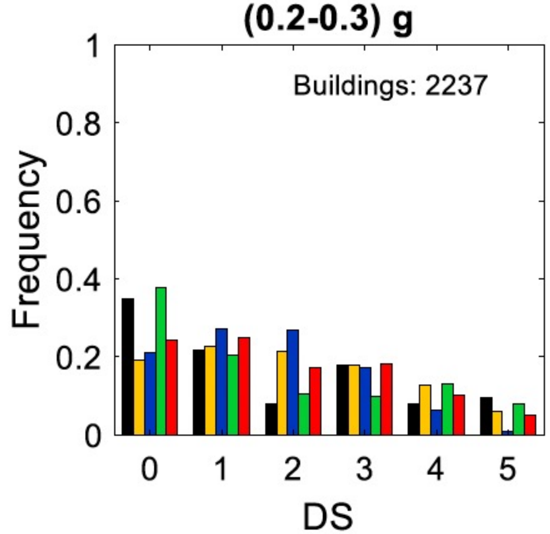
Comparison and validation of vulnerability models against real data…

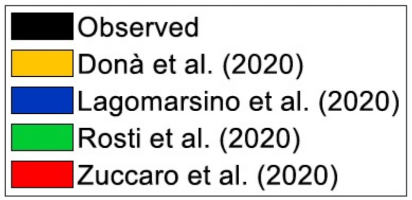


Da.D.O. Platform









Da Porto et al. 2021 Bulletin of Earthquake Engineering
https://doi.org/10.1007/s10518-021-01120-1

THE ITALIAN EXPERIENCE: THE MARS PROJECT – MAps for the Seismic Risk

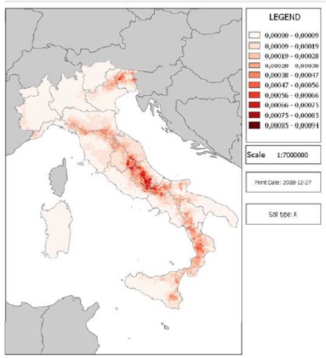
Funded by the Italian Civil Protection Agency and ReLUIS (Network of University Laboratories for Earthq Eng) and Coordinated by Proff. Angelo Masi and Sergio Lagomarsino

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


Presidency of the Council of Ministers
Italian Civil Protection Department

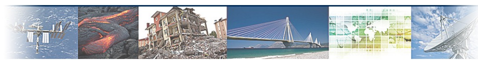
National risk assessment

Overview of the potential major disasters in Italy:
seismic, volcanic, tsunami, hydro-geological/hydraulic and extreme weather, droughts and forest fire risks



Only residential buildings..

Tool: IRMA web platform, developed by EUCENTRE



…. Assessment extended to schools and churches .. and now also to industrial buildings, hospitals, ..

Risk components:

- Seismic Hazard Model MPS04-S1 (INGV) and CNR-IGAG soil map (V_{s30})
- Exposure: ISTAT census (residential buildings), other database for other specific assets
- Vulnerability: fragility curves derived/calibrated with observed damage
- Losses and consequence functions calibrated from data of 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
Lagomarsino et al. (2022) The MARS vulnerability model: a new metrics based on EMS-98 vulnerability classes, 3ECEES Conference, Bucarest 2022

The MARS-Schools project

Research units enrolled in the MARS project - Task 4.7
coordinated by Serena Cattari, Angelo Masi and Vincenzo Manfredi

UniGE – Cattari S.

UniBAS – Masi A. - Manfredi V.

UniCAM – Dall'Asta A.

UniNA – Di Ludovico M. – Verderame G.

UniPD –da Porto F.

UniTS – Gattesco N.

Fondazione Eucentre – Borzi B.

WHICH IS THE MAIN GOAL?

To define a **consensus-based model** of fragility/vulnerability representative of **Italian school buildings** and effective tools for supporting risk mitigation strategies at national scale.

CUSTOMIZATION OF THE STANDARD STEPS OF RISK ASSESSMENT:

- ❑ INVENTORY AND TAXONOMY
- ❑ REFERENCE ARCHETYPES
- ❑ DEVELOPMENT OF FRAGILITY CURVES
- ❑ RISK ASSESMENT AT NATIONAL SCALE

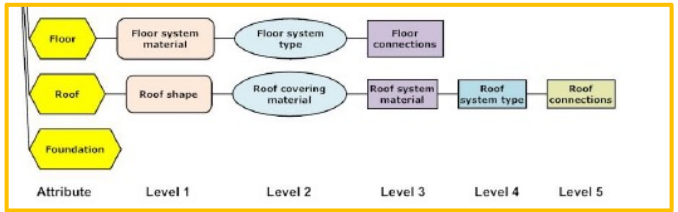
The MARS-Schools project - *Taxonomy*

Both **TAXONOMY** (i.e. *list of attributes that influence the vulnerability*) and **CLASSIFICATION** (i.e. *groups of buildings with the same attributes*) can be defined **IN GENERAL** but then the attributes to be actually considered in a specific risk analysis depend on the **availability of data**.

MINISTRY OF EDUCATION

GLOBAL EARTHQUAKE MODEL
working together to assess risk

Reference:
GEM Building Taxonomy Version 2.0
GEM Technical Report 2013-02
Version: 1.0.0
Date: November 2013



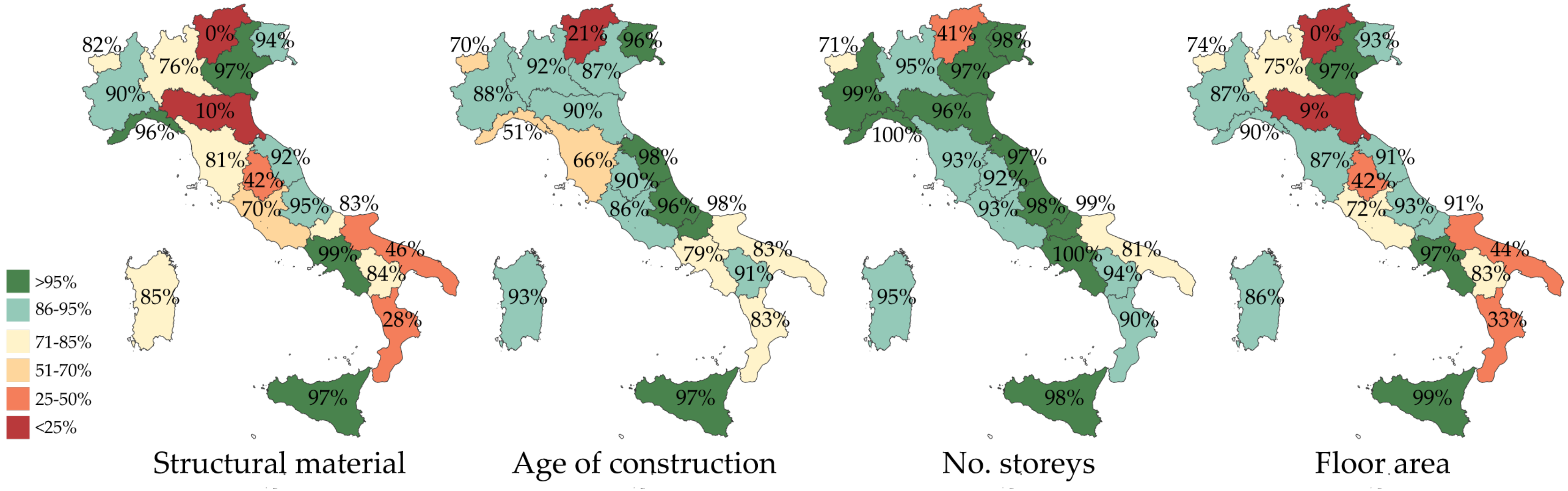
LIST OF 13 ATTRIBUTES

1. Direction
2. Mater
3. Later
4. Heigh
5. Date
6. Occu
7. Buildi
8. Shap
9. Struc
10. Exter
11. Roof
12. Floor
13. Foundation system

BUT …..what is the actual completeness and reliability of the available data?

The MARS-Schools project - *Taxonomy*

COMPLETENESS RATE OF DATA AT REGIONAL SCALE – AES 2005



	Structural typology	Age	No. storeys	Floor Area
AES 2005	69%	86%	93%	69%
AES 2022	**92%**	**78%**	**95%**	**94%**

The MARS-Schools project - *Taxonomy*

- **STRUCTURAL TYPOLOGY**
- NUMBER OF FLOORS
- AGE OF CONSTRUCTION
- PLAN AREA

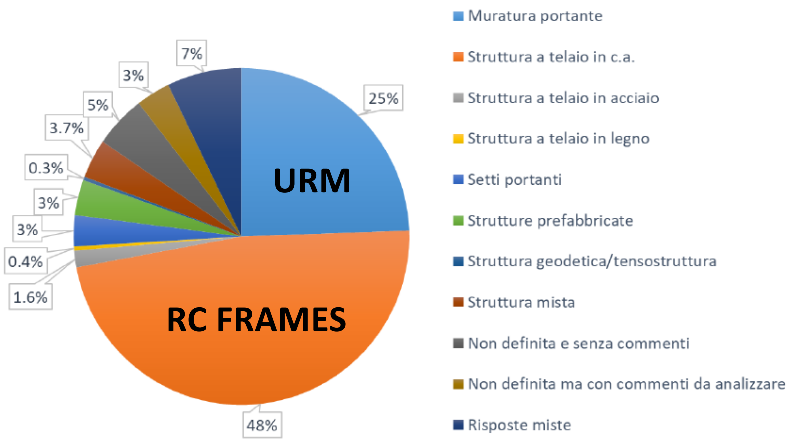


Figura 14 – Distribuzione delle US in funzione della tipologia strutturale

UNREINFORCED MASONRY

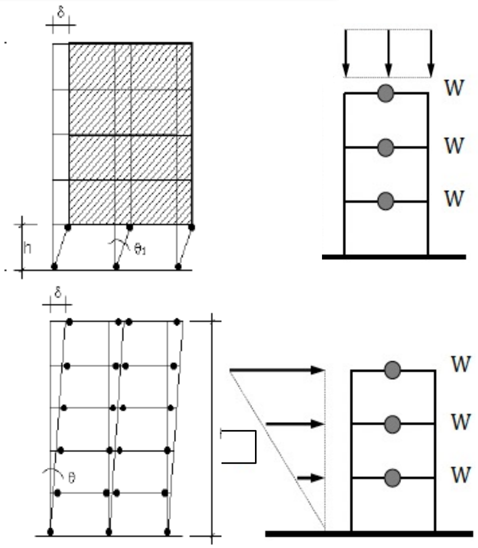
REINFORCED CONCRETE

The MARS-Schools project - *Taxonomy*

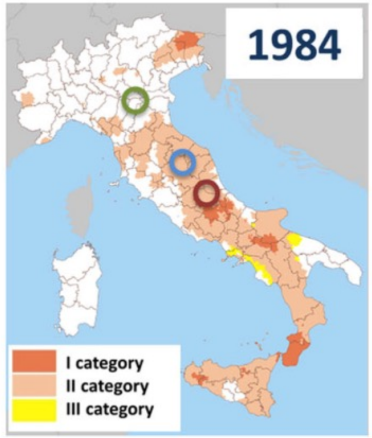
- STRUCTURAL TYPOLOGY
- NUMBER OF FLOORS
- **AGE OF CONSTRUCTION**
- PLAN AREA

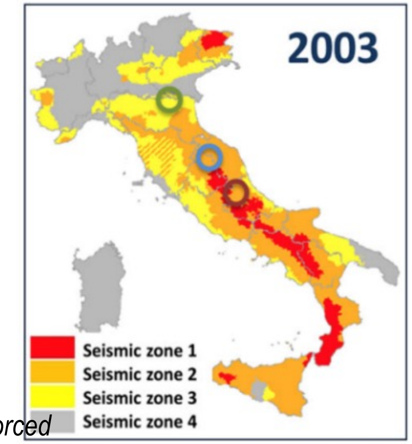
REINFORCED CONCRETE BUILDINGS

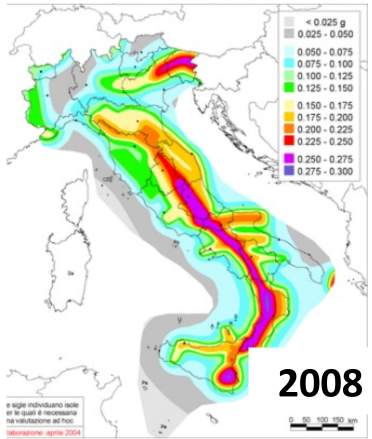
Technical Codes	RC columns: longitudinal reinforcement	RC columns: transverse reinforcement
RD 16/11/1939	$A_{s,tot} \geq (0.5\text{–}0.8)\%\ A_{c,min}$	$s \leq B/2$ $s \leq 10\ d_{b,min}$
DM 30/05/1972	$A_{s,tot} = (0.6\text{–}5.0)\%\ A_{c,min}$	$s \leq 15\ d_{b,min}$
DM 30/05/1974	$A_{s,tot} \geq 0.3\%\ A_g$	$s \leq 250$ mm
DM 16/06/1976	$d_{b,min} = 12$ mm	min stirrup diameter = 6 mm
DM 26/03/1980	$A_{s,tot} = (0.3\text{–}6.0)\%\ A_g$	
DM 27/07/1985	$A_{s,tot} \geq 0.8\%\ A_{c,min}$	
DM 14/02/1992	$d_{b,min} = 12$ mm	



SEISMIC HAZARD CLASSIFICATION





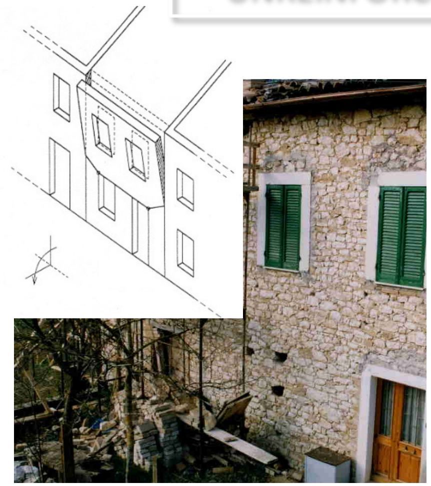


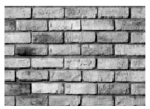
REF: De Risi et al (2022): Modelling and Seismic Response Analysis of Italian pre-code and low-code Reinforced Concrete Buildings. Part I: Bare Frames, Journal of Earthquake Engineering, DOI: 10.1080/13632469.2022.2074919

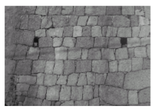
The MARS-Schools project - *Taxonomy*

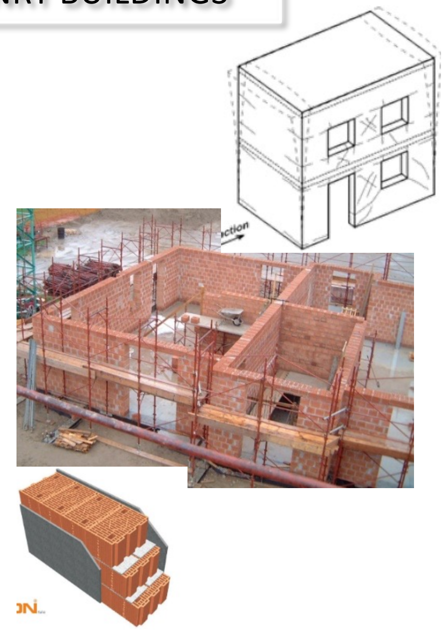
- STRUCTURAL TYPOLOGY
- NUMBER OF FLOORS
- **AGE OF CONSTRUCTION**
- PLAN AREA

UNREINFORCED MASONRY BUILDINGS

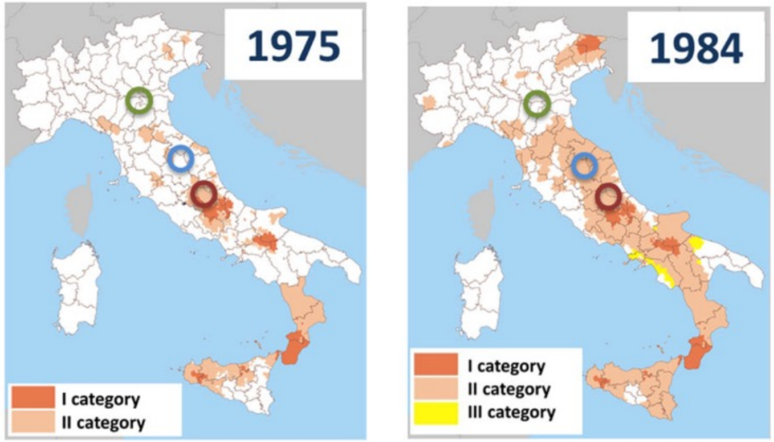


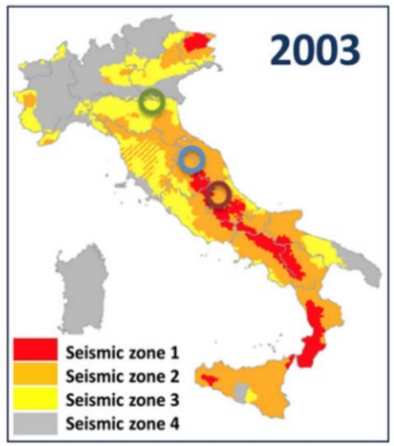


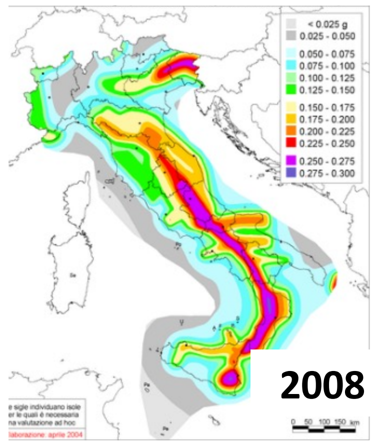




SEISMIC HAZARD CLASSIFICATION







The MARS-Schools project – *Approaches for developing fragility curves*

DEVELOPMENT OF FRAGILITY CURVES - Overview of the adopted approaches

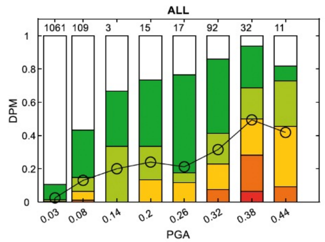
MASONRY SCHOOLS

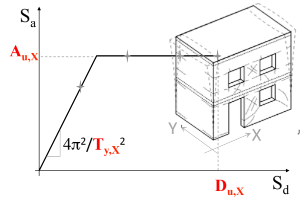
Approach	Research unit & Approach name
Empirical and empirical-binomial	UniNA
Heuristic	UniGE
Empirical	UniCAM
Analytical-mechanical	UniGE (DBV-Masonry)
	UniTS (Firstep-M)
Hybrid analytical-mechanical	UniPD (VULNUS)

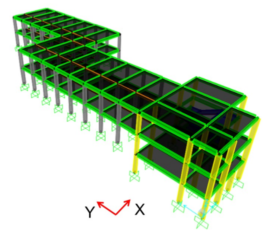
REINFORCED CONCRETE SCHOOLS

Approach	Approach's name or Software adopted & RU
Empirical and empirical-binomial	UniNA
Heuristic	UniGE
Empirical	UniCAM
Hybrid analytical-mechanical	UniNA (POST)
	Eucentre (SP-BELA)
Analytical-numerical	UniNA (SAP 2000)
	UniBAS (OpenSees)
	UniPD (MIDAS)
	UniCAM (SAP 2000)

- ❑ EMPIRICAL APPROACH
- ❑ ANALYTICAL-MECHANICAL
- ❑ ANALYTICAL-NUMERICAL
- ❑ HYBRID – I.E. ANALYTICAL-MECHANICAL COMBINED WITH FACTORS CALIBRATED ON BASIS OF OBSERVED DATA OR HEURISTIC APPROACHES







Cattari et al. (2022) Risk assessment of italian school buildings at national scale: the MARS project experience , 3ECEES Conference, Bucarest 2022

The MARS-Schools project – *Approaches for developing fragility curves*

DEVELOPMENT OF FRAGILITY CURVES - Overview of the adopted approaches

MASONRY SCHOOLS

Approach	Research unit & Approach name	Reference school buildings stock	References
Empirical and empirical-binomial	UniNA	School buildings of the Abruzzo region hit by the L'Aquila 2009 earthquake	Di Ludovico et al (2022)
Heuristic	UniGE		
Empirical	UniCAM	School buildings hit by the 2016-2017 Central Italy earthquake	
Analytical-mechanical	UniGE (DBV-Masonry)	Archetypes defined in MARS project (Task 4.7)	
	UniTS (Firstep-M)	School buildings of Friuli-Venezia Giulia region	
Hybrid analytical-mechanical	UniPD (VULNUS)	Archetypes defined in MARS project (Task 4.7)	

REINFORCED CONCRETE SCHOOLS

Approach	Approach's name or Software adopted & RU	Reference school buildings stock
Empirical and empirical-binomial	UniNA	School buildings of the Abruzzo region hit by the L'Aquila 2009 earthquake
Heuristic	UniGE	
Empirical	UniCAM	School buildings hit by the 2016-2017 Central Italy earthquake
Hybrid analytical-mechanical	UniNA (POST)	Archetypes defined in MARS project (Task 4.7)
	Eucentre (SP-BELA)	
Analytical-numerical	UniNA (SAP 2000)	Archetypes defined in MARS project (Task 4.7) (for a total of 7 schools)
	UniBAS (OpenSees)	
	UniPD (MIDAS)	
	UniCAM (SAP 2000)	

- Building stock hit by earthquake
- School buildings of specific geographical area
- Reference archetypes

14 school buildings selected from three regional databases

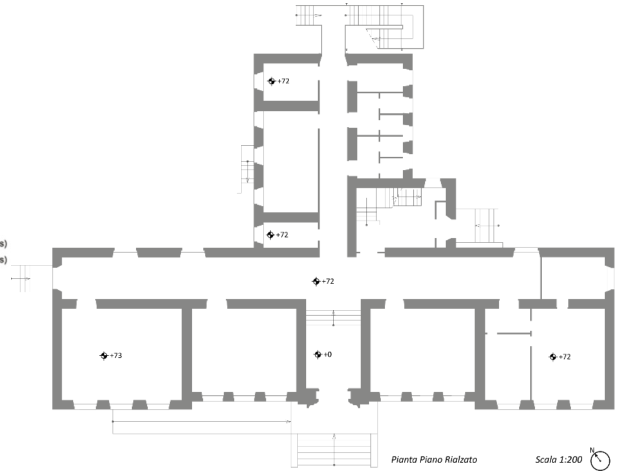
provided by the University of Naples and Genoa (database A), the University of Padua (database B) [22] and the University of Trieste (C)

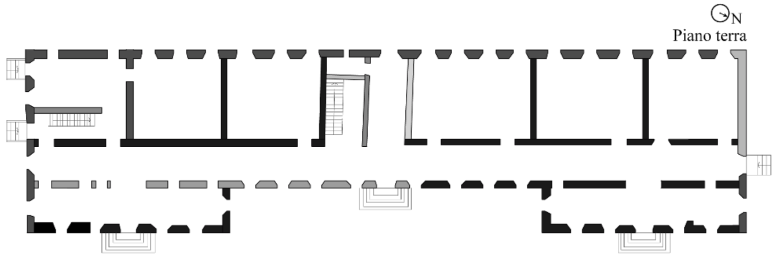
Database A includes school buildings (54) from various areas of Central Italy. Instead, database B and C refer to the data collected in the municipal area of Padua (B, 25) and in the regional area of Friuli-Venezia Giulia (C, 92).

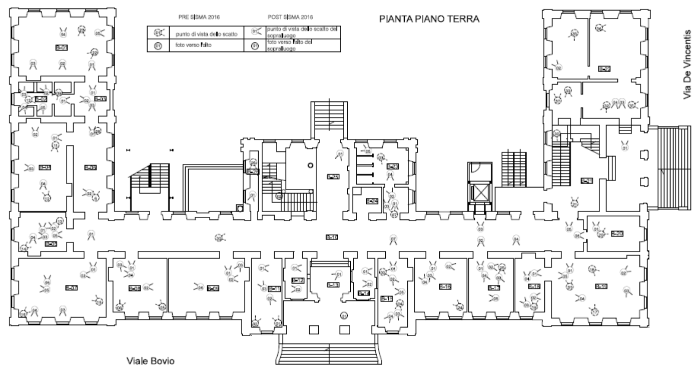
Cattari et al. (2022) Risk assessment of italian school buildings at national scale: the MARS project experience , 3ECEES Conference, Bucarest 2022

The MARS-Schools project – *Approaches for developing fragility curves*

DEVELOPMENT OF FRAGILITY CURVES - Overview of the adopted approaches







ARCHETYPE INSPIRED BY EXISTING BUILDINGS
14 – URM SCHOOLS
18 – RC SCHOOLS

THE SET OF ARCHETYPE IS ONGOING TO BE ENRICHED

Cattari et al. (2022) Risk assessment of italian school buildings at national scale: the MARS project experience , 3ECEES Conference, Bucarest 2022

The MARS-Schools project - *Fragility curves from EMPIRICAL APPROACH*

BASIC STEPS OF THE EMPIRICAL APPROACH

1) COLLECTION OF DATA: CHECK ON THE COMPLETENESS RATIO

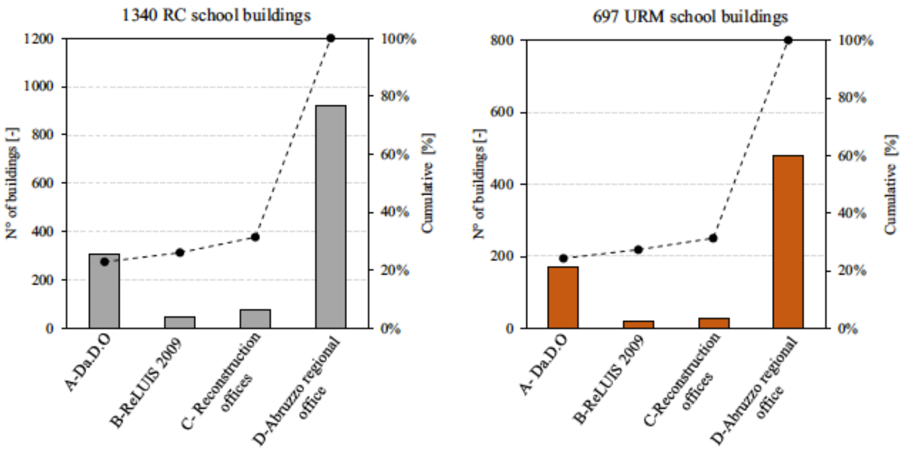
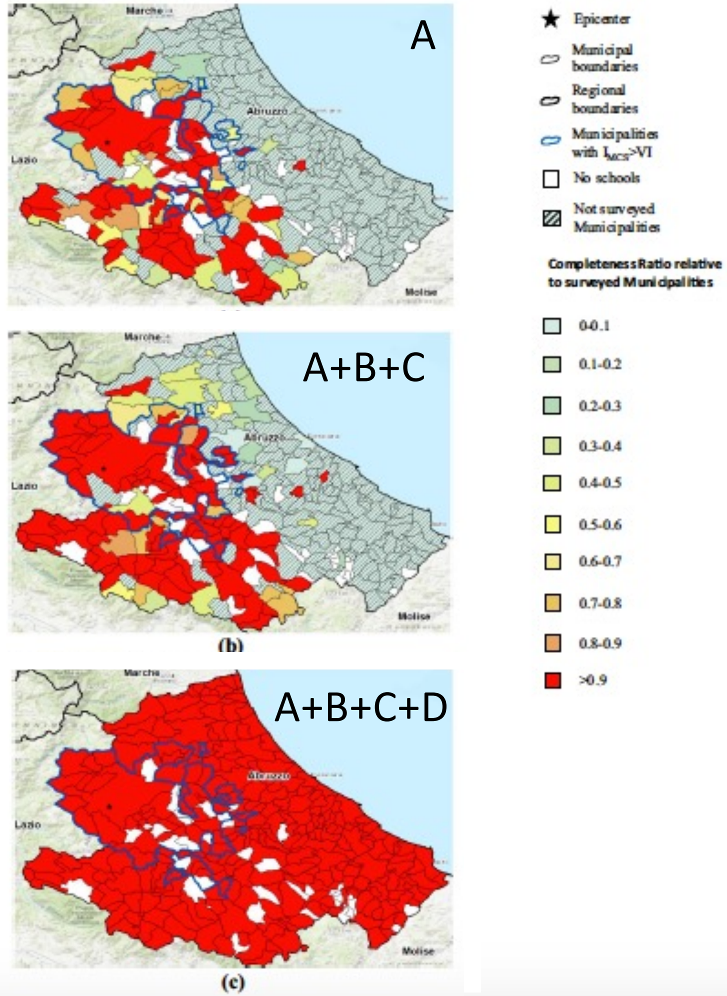


Table 1 Available database of school buildings in the Abruzzo region

Database	No. schools	No. buildings	Name	Address	Coordinates	Build-ing features	Observed damage
A—Da.D.O (L'Aquila 2009)	–	695	✗	✗	✓	✓	✓
B—ReLUIS 2009	–	481	✓	✓	✗	✓	✓
C—Reconstruction offices	–	156	✓	✓	✓	✓	✓
D—Registry of Abruzzi regional authority	1452	2229	✓	✓	✓	✓	✗



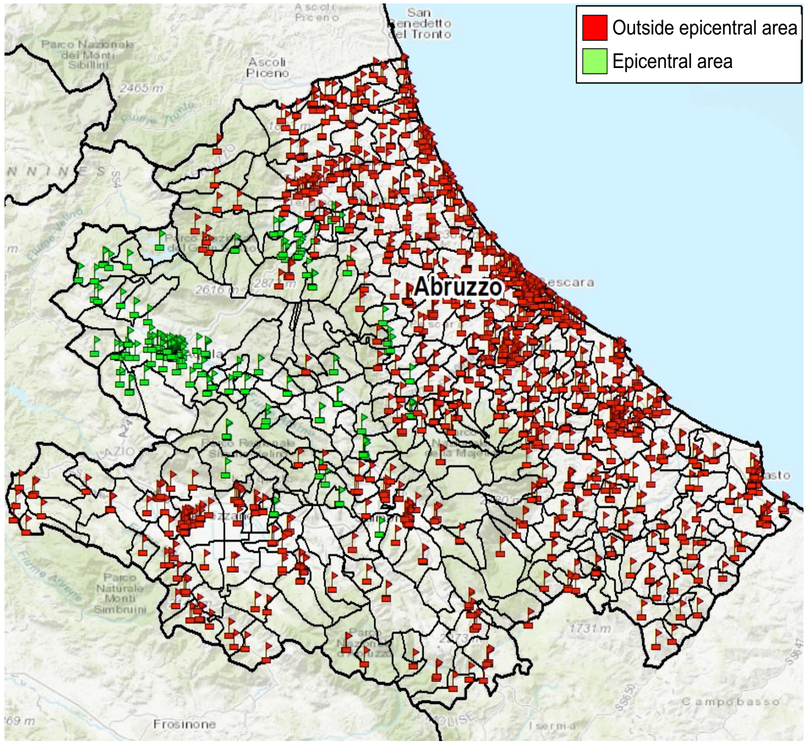
Di Ludovico M. et al (2022) Bulletin of Earthquake Engineering, https://doi.org/10.1007/s10518-022-01535-4

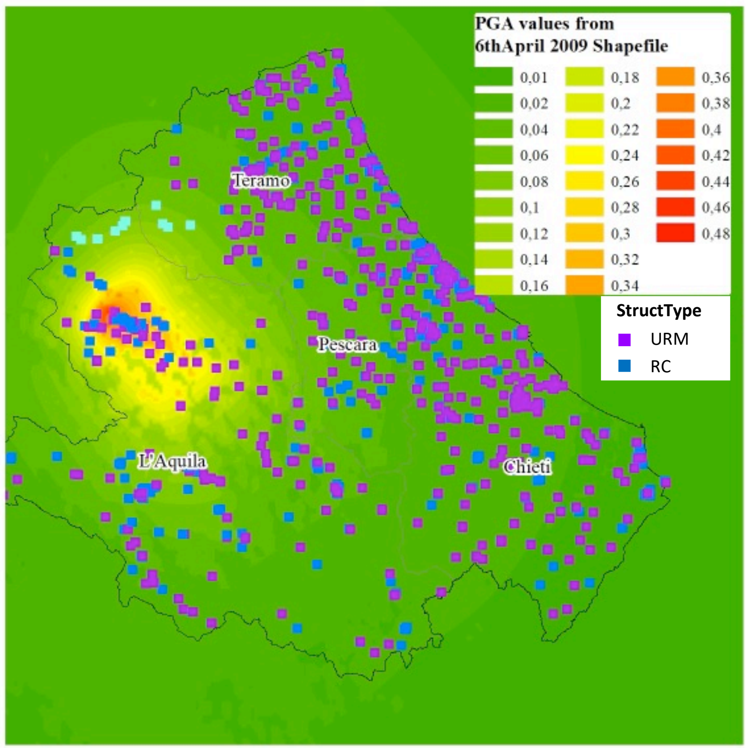
The MARS-Schools project - *Fragility curves from EMPIRICAL APPROACH*

BASIC STEPS OF THE EMPIRICAL APPROACH

1) COLLECTION OF DATA : CHECK ON THE COMPLETENESS RATIO
2) ASSIGNMENT OF THE IM VALUE TO EACH BUILDING

Shakemaps of 6th April 2009 Earthquake from shapefiles (Michelini et al. 2020).





Di Ludovico M. et al (2022) Bulletin of Earthquake Engineering, https://doi.org/10.1007/s10518-022-01535-4

The MARS-Schools project - *Fragility curves from EMPIRICAL APPROACH*

BASIC STEPS OF THE EMPIRICAL APPROACH

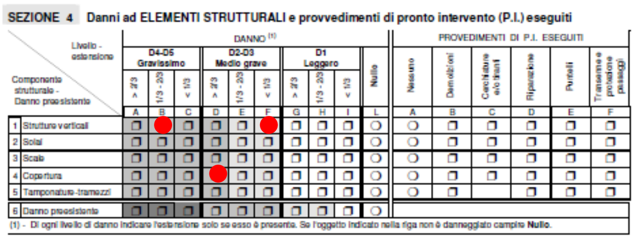
1) COLLECTION OF DATA : CHECK ON THE COMPLETENESS RATIO
2) ASSIGNMENT OF THE IM VALUE TO EACH BUILDING
3) ASSIGNMENT OF THE DAMAGE LEVEL TO EACH BUILDING

Level / Extension		DAMAGE									
		D4-D5 Very heavy or collapse			D2-D3 Medium or heavy			D1 Slight			D0 Null
		> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	
Component		A	B	C	D	E	F	G	H	I	L
1	Vertical structures	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
2	Horizontal structures	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
3	Stairs	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
4	Roof	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
5	URM Infill walls	☐	☐	☐	☐	☐	☐	☐	☐	☐	○
6	Pre-existing damage	☐	☐	☐	☐	☐	☐	☐	☐	☐	○

SCHEDA DI 1° LIVELLO DI RILEVAMENTO DANNO, PRONTO INTERVENTO E AGIBILITÀ
PER EDIFICI ORDINARI NELL'EMERGENZA POST-SISMICA
(AeDES 07/2013)

PROTEZIONE CIVILE
Presidenza del Consiglio dei Ministri
Dipartimento della Protezione Civile

CONFERENZA DELLE REGIONI E DELLE PROVINCE AUTONOME



SEZIONE 4 Danni ad ELEMENTI STRUTTURALI e provvedimenti di pronto intervento (P.I.) eseguiti

Livello - estensione / Componente strutturale - Danno preesistente		DANNO (1)										PROVEDIMENTI DI P.I. ESEGUITI					
		D4-D5 Gravissimo			D2-D3 Medio grave			D1 Leggero			Nullo	Nessuno	Demolizioni	Cerchiature e/o tiranti	Riparazione	Puntelli	Transenne e protezione passaggi
		> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3							
		A	B	C	D	E	F	G	H	I	L	A	B	C	D	E	F
1	Strutture verticali	☐	●	☐	☐	☐	●	☐	☐	☐	○	○	☐	☐	☐	☐	☐
2	Solai	☐	☐	☐	☐	☐	☐	☐	☐	☐	○	○	☐	☐	☐	☐	☐
3	Scale	☐	☐	☐	☐	☐	☐	☐	☐	☐	○	○	☐	☐	☐	☐	☐
4	Copertura	☐	☐	☐	●	☐	☐	☐	☐	☐	○	○	☐	☐	☐	☐	☐
5	Tamponature-tramezzi	☐	☐	☐	☐	☐	☐	☐	☐	☐	○	○	☐		☐	☐	☐
6	Danno preesistente	☐	☐	☐	☐	☐	☐	☐	☐	☐	○						

(1) - Di ogni livello di danno indicare l'estensione solo se esso è presente. Se l'oggetto indicato nella riga non è danneggiato campire **Nullo**.

DAMAGE TO EACH ELEMENT

- Multiple choice possibility
- Combination rule function of the extension of damage: $\sum e_i \leq 1$
- With *i* each structural or non-structural element

?
CONVERSION RULE

ESTIMATE OF THE GLOBAL DAMAGE LEVEL

TRICKY ISSUES IN THE EMPIRICAL APPROACH

3) ASSIGNMENT OF THE DL TO EACH BUILDING

Integral damage metric (UniGE) Lagomarsino et al. 2021

$$D_{AeDES} = \sum_{i=1}^{5} w_i \sum_{j=1}^{3} (2j-1) v_{i,j}$$

Weigth assigned to components

Survey	Vertical	Horizontal	Stairs	Roof	Infills
Complete survey	0.6	0.2	0	0.2	0
Survey from outside	0.8	0	0	0.2	0

It accounts for the spread and severity of damge

vi,j : 1 (A); 2/3 (B), 1/3 (C), 0 (when no option is indicated). Where: A—spread on more than 2/3; B— between 1/3 and 2/3; C—< 1/3).

Peak damage metric (DADO) Dolce et al. 2019

D4-D5 Gravissimo	D3-D2 Medio-Grave	D1 Leggero	Danno nullo	Livello danno
			✓	0
			✓	0
		<1/3		1
		1/3-2/3		1
		>2/3		1
	<1/3			2
	<1/3	<1/3		2
	<1/3	1/3-2/3		2
	<1/3	>2/3		2
	1/3-2/3	<1/3		3
	1/3-2/3			3
	>2/3			3
<1/3				3
<1/3		<1/3		3
<1/3		1/3-2/3		3
<1/3	<1/3			3
<1/3	<1/3	<1/3		3
<1/3	1/3-2/3			4
<1/3	>2/3			4
1/3-2/3				4
1/3-2/3		1/3-2/3		4
1/3-2/3	<1/3			4
1/3-2/3	1/3-2/3			5
>2/3				5
>2/3		<1/3		5
>2/3	<1/3			5

Peak damage metric (UniGE) Di Ludovico et al. 2022

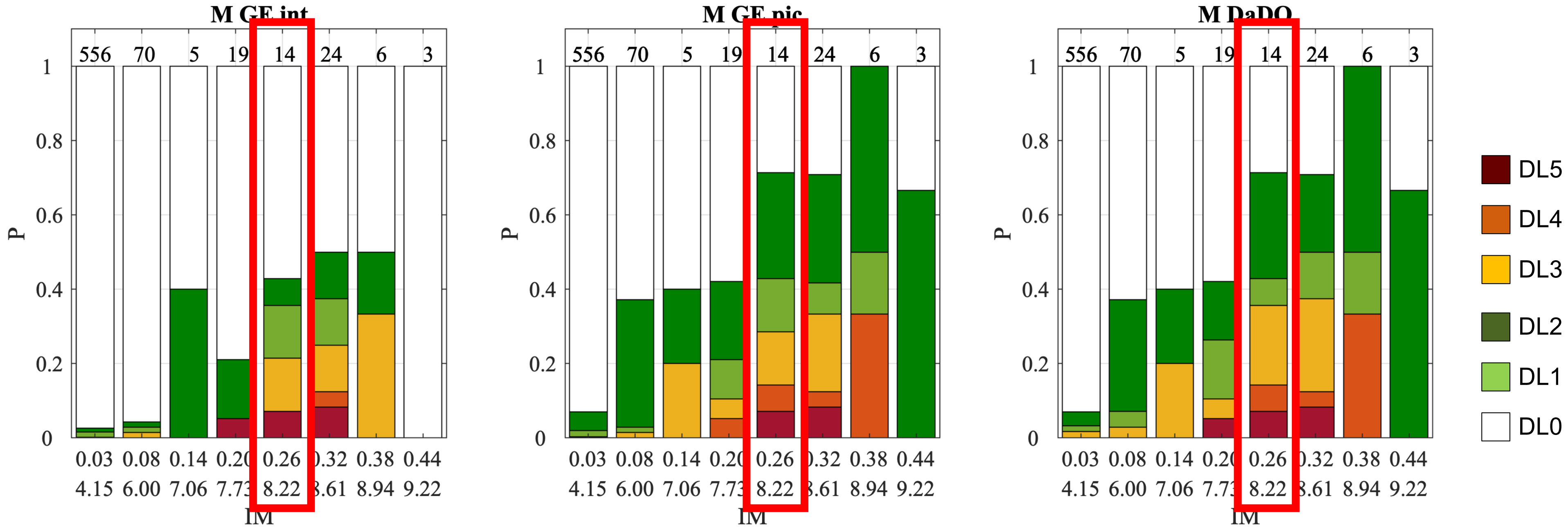
EMS-98	URM buildings	
	Peak damage	Secondary damage
DS0	D0	
DS1	D1- <1/3 D1 - 1/3-2/3 D1- >2/3 D2-D3 - <1/3	D1 =0
DS2	D2-D3 - <1/3 D2-D3 - 1/3-2/3	D1 >0
DS3	D2-D3 - >2/3 D4-D5 - <1/3	D2-D3 <1/3
DS4	D4-D5 - <1/3 D4-D5 - 1/3-2/3	D2-D3 ≥1/3
DS5	D4-D5 - >2/3	

Lagomarsino, Cattari, Ottonelli (2021) Bulletin of Earthquake Engineering, 10.1007/s10518-021-01063-7
Di Ludovico M. et al (2022) Bulletin of Earthquake Engineering, https://doi.org/10.1007/s10518-022-01535-4
Dolce et al. (2019) Bollettino Di Geofisica Teorica Ed Applicata, 60(2), 141-164. doi:10.4430/bgta0254

TRICKY ISSUES IN THE EMPIRICAL APPROACH

IMPACT OF CONVERSION RULES IN DPMs

URM schools , L'Aquila 2009 earthquake



Integral damage metric (UniGE)
Lagomarsino et al. 2021

Peak damage metric (UNIGE)
Di Ludovico et al. 2022

Peak damage metric (DADO)
Dolce et al. 2019

TRICKY ISSUES IN THE EMPIRICAL APPROACH

3) ASSIGNMENT OF THE DL TO EACH BUILDING

Example for RC buildings ….

Damage metric accounting for both NON STRUCTURAL & STRUCTURAL COMPONENTS

Table 1 Assumed equivalence between EMS-98 DSs and damage levels described in AeDES survey form (Baggio et al. 2007)

EMS-98	AeDES Inspection form	
	Infills	Vertical structures
DS1	D1 <⅓ D1 ⅓-⅔ D1 >⅔	D1 <⅓ D1 ⅓-⅔ D1 >⅔
DS2	D2-D3 <⅓ D2-D3 ⅓-⅔ D2-D3 >⅔	D2-D3 <⅓
DS3	D4-D5<⅓ D4-D5⅓-⅔ D4-D5>⅔	D2-D3 ⅓-⅔ D2-D3 >⅔
DS4		D4-D5<⅓ D4-D5⅓-⅔
DS5		D4-D5>⅔

REF: Del Gaudio et al. (2016) Bull Earthquake Eng 14: 2643-2678, DOI 10.1007/s10518-016-9919-2

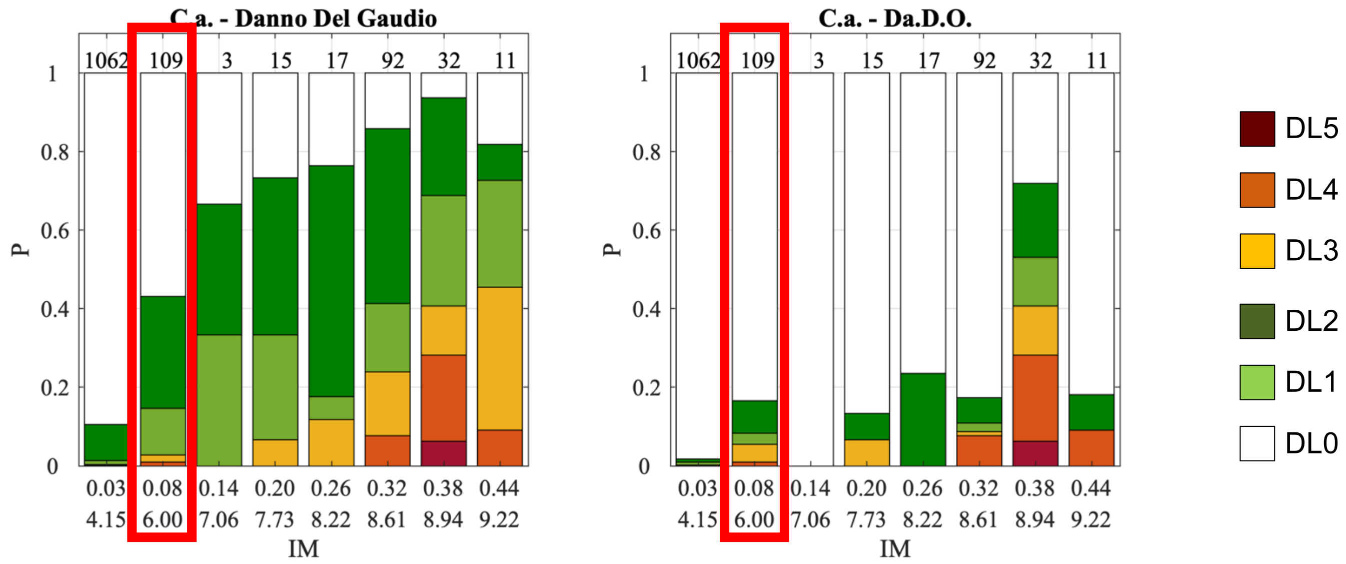
Damage metric accounting ONLY for STRUCTURAL COMPONENTS

D4-D5 Gravissimo	D3-D2 Medio-Grave	D1 Leggero	Danno nullo	Livello danno
			✓	0
			✓	0
		<1/3		1
		1/3-2/3		1
		>2/3		1
	<1/3			2
	<1/3	<1/3		2
	<1/3	1/3-2/3		2
	<1/3	>2/3		2
	1/3-2/3	<1/3		3
	1/3-2/3			3
	>2/3			3
<1/3				3
<1/3		<1/3		3
<1/3		1/3-2/3		3
<1/3	<1/3			3
<1/3	<1/3	<1/3		3
<1/3	1/3-2/3			4
<1/3	>2/3			4
1/3-2/3				4
1/3-2/3		1/3-2/3		4
1/3-2/3	<1/3			4
1/3-2/3	1/3-2/3			5
>2/3				5
>2/3		<1/3		5
>2/3	<1/3			5

REF: Dolce et al. (2017)

IMPACT OF CONVERSION RULES IN DPMs

RC schools , L'Aquila 2009 earthquake



DAMAGE METRIC THAT CONSIDER BOTH NON-STRUCTURAL COMPONENTS AND STRUCTURAL COMPONENTS

DAMAGE METRIC THAT CONSIDER **ONLY** STRUCTURAL COMPONENTS

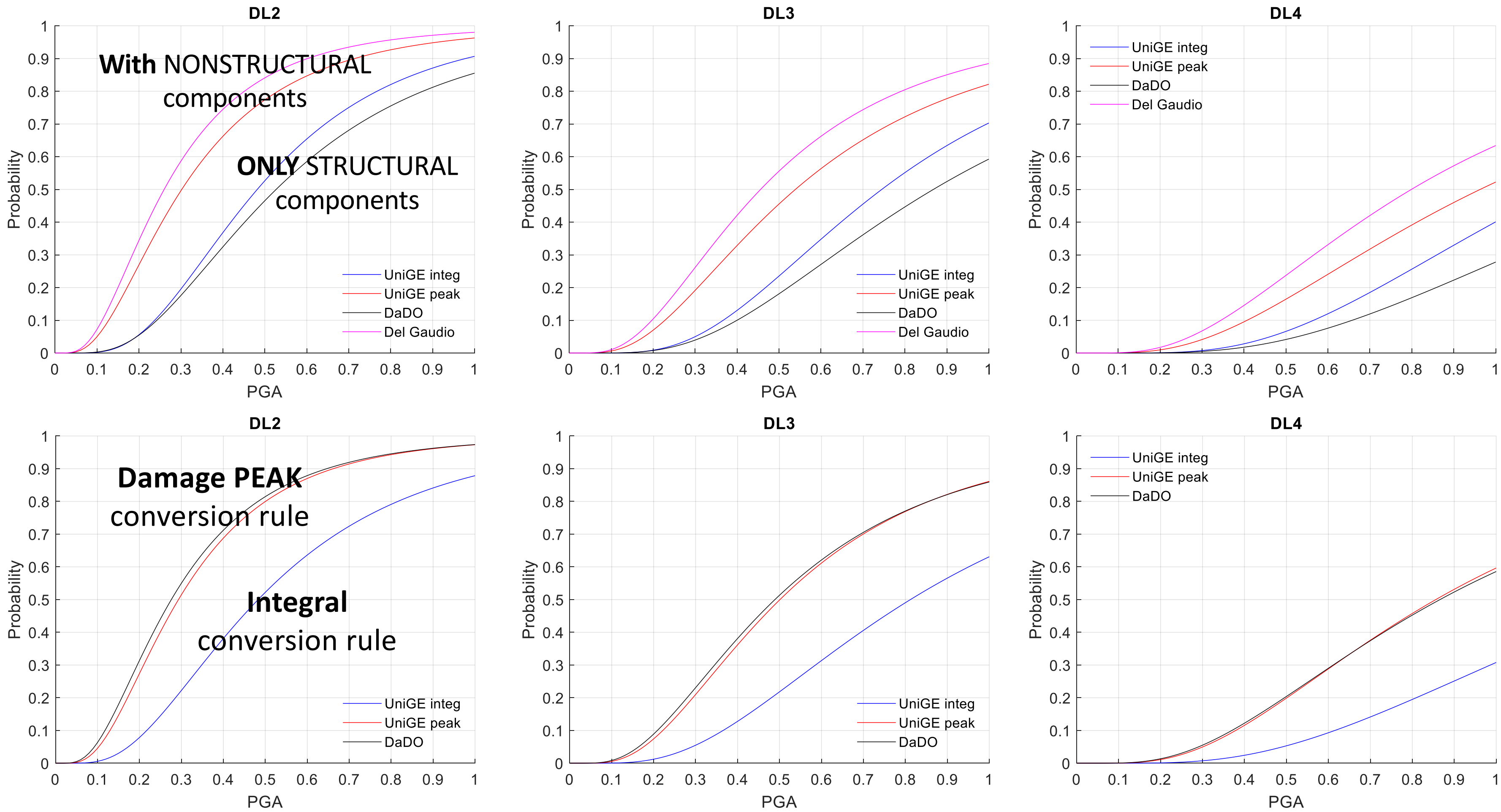
Del Gaudio et al. (2016) Bull Earthquake Eng 14: 2643-2678, DOI 10.1007/s10518-016-9919-2
Di Ludovico M. et al (2022) Bulletin of Earthquake Engineering, https://doi.org/10.1007/s10518-022-01535-4

TRICKY ISSUES IN THE EMPIRICAL APPROACH

2) ASSIGNMENT OF THE DL TO EACH BUILDING – impact on fragility curves

RC school buildings

URM school buildings



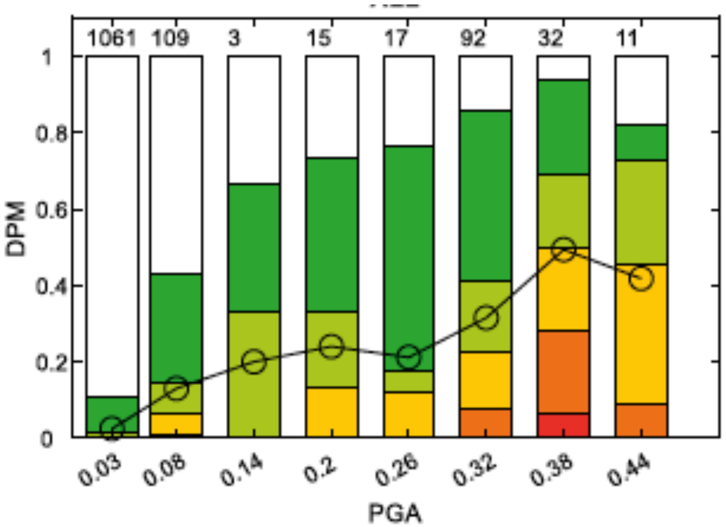
The MARS-Schools project - *Fragility curves from EMPIRICAL APPROACH*

BASIC STEPS OF THE EMPIRICAL APPROACH

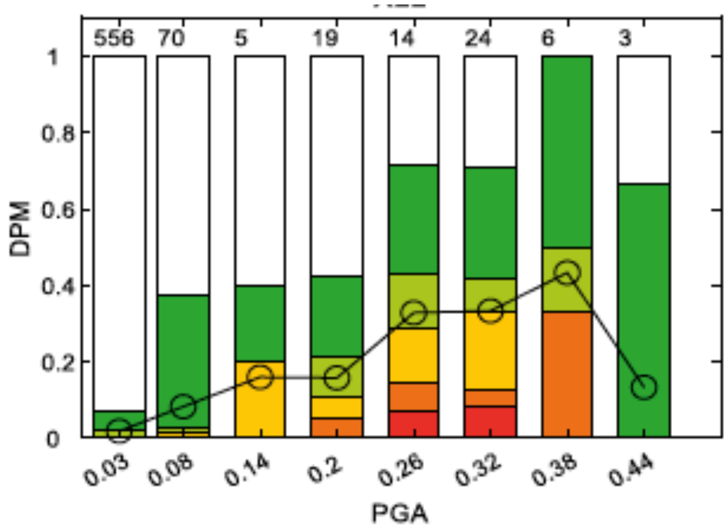
3) ASSIGNMENT OF THE DAMAGE LEVEL TO EACH BUILDING

EMS-98	RC buildings		URM buildings	
	Vertical structures	Infills/partitions	Peak damage	Secondary damage
DS0	D0	D0	D0	
DS1				
DS2				
DS3				
DS4				
DS5				

REINFORCED CONCRETE SCHOOLS



MASONRY SCHOOLS



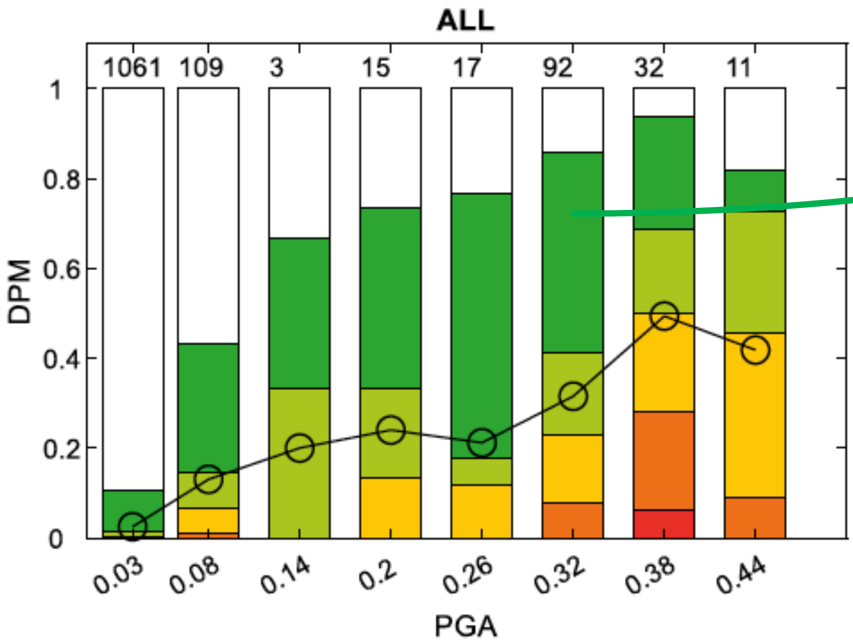
Di Ludovico M. et al (2022) Bulletin of Earthquake Engineering, https://doi.org/10.1007/s10518-022-01535-4

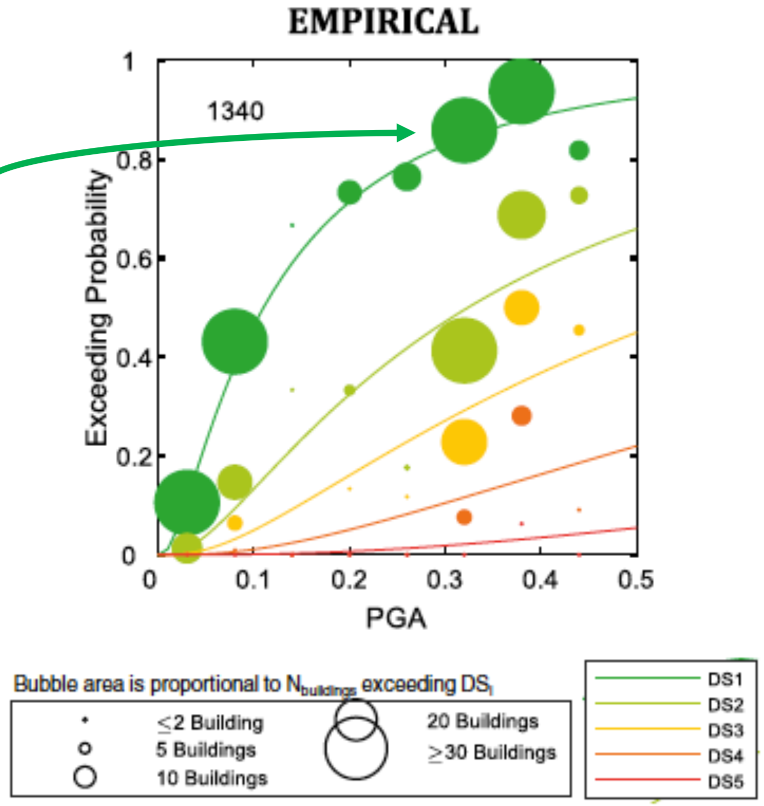
The MARS-Schools project - *Fragility curves from EMPIRICAL APPROACH*

BASIC STEPS OF THE EMPIRICAL APPROACH

4) FITTING THE EMPIRICAL POINTS FOR DERIVING THE FRAGILITY CURVES

OPTION 1 adopted in Di Ludovico et al. (2023) : THE PURE EMPIRICAL APPROACH





EXAMPLES: REINFORCED CONCRETE SCHOOLS

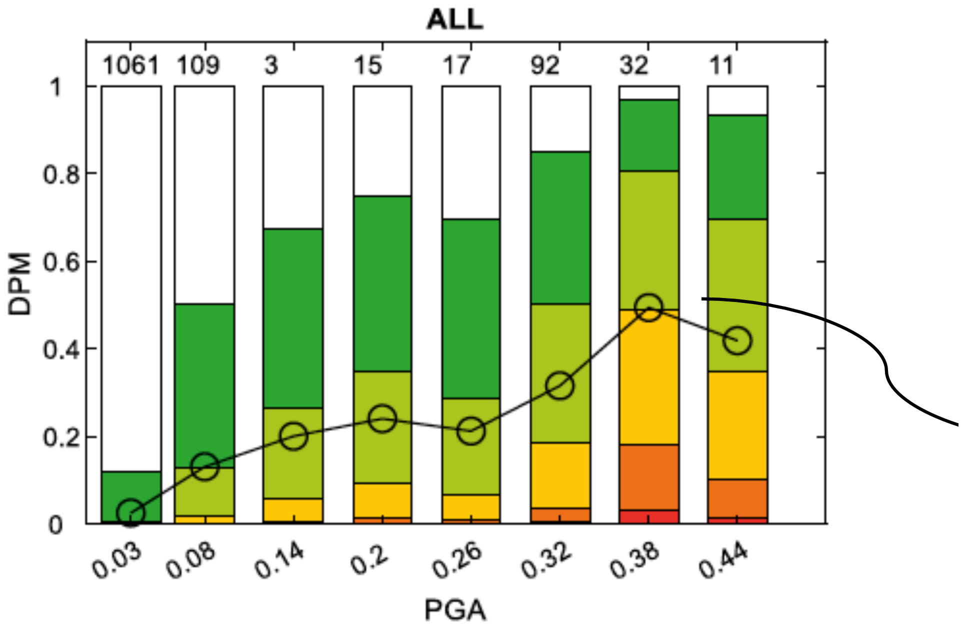
Di Ludovico M. et al (2022) https://doi.org/10.1007/s10518-022-01535-4

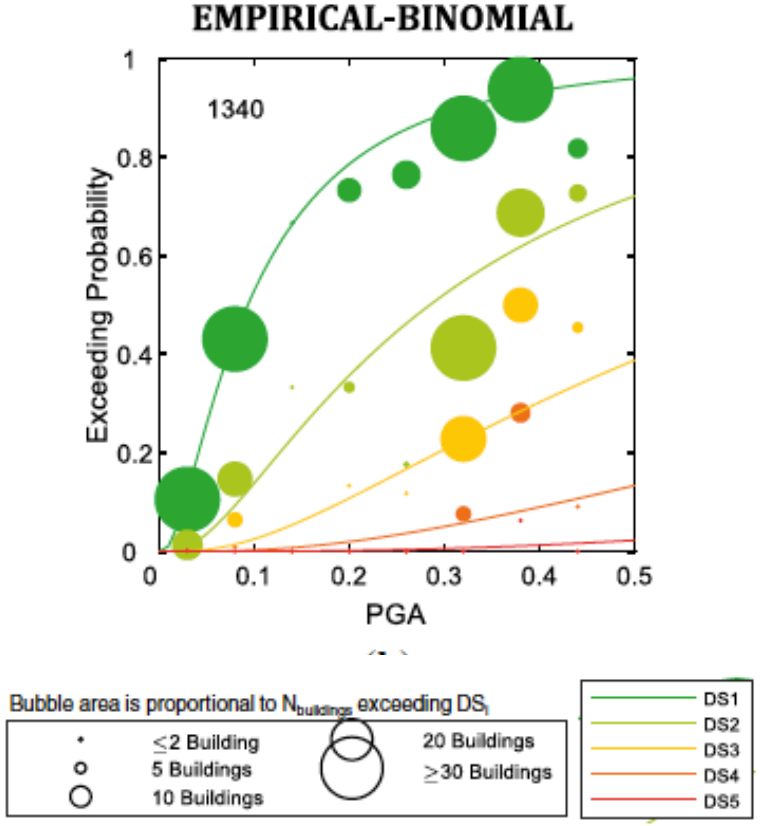
The MARS-Schools project - *Fragility curves from EMPIRICAL APPROACH*

BASIC STEPS OF THE EMPIRICAL APPROACH

4) FITTING THE EMPIRICAL POINTS FOR DERIVING THE FRAGILITY CURVES

OPTION 2 adopted in Di Ludovico et al. (2023) : THE EMPIRICAL-BINOMIAL APPROACH





EXAMPLES: REINFORCED CONCRETE SCHOOLS

Di Ludovico M. et al (2022) https://doi.org/10.1007/s10518-022-01535-4

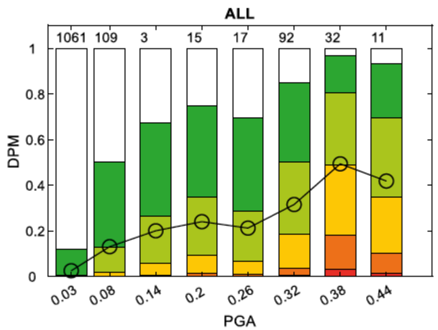
The MARS-Schools project - *Fragility curves from EMPIRICAL APPROACH*

BASIC STEPS OF THE EMPIRICAL APPROACH

4) FITTING THE EMPIRICAL POINTS FOR DERIVING THE FRAGILITY CURVES

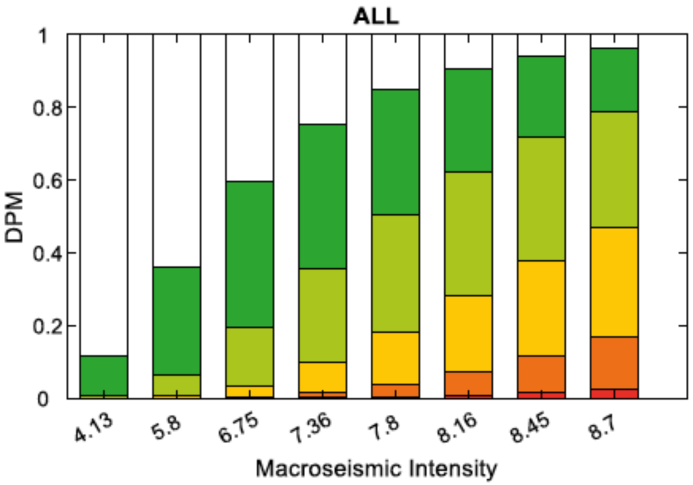
OPTION 3 adopted in Di Ludovico et al. (2023) : THE EURISTIC APPROACH

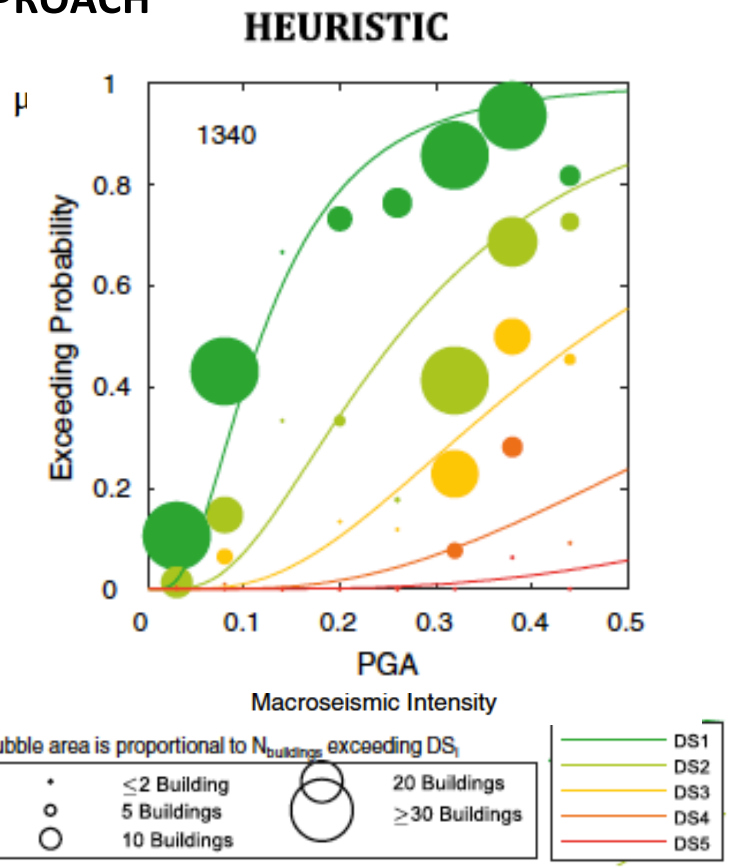
Same of empirical-binomial approach



$$\mu_{D,i} = \frac{\sum_{DS}\left(I_{i,DS} \cdot DS\right)}{5\sum_{DS} I_{i,DS}}$$

PGA-I correlation law to convert the PGA-bins into I-bins





EXAMPLES: REINFORCED CONCRETE SCHOOLS

Di Ludovico M. et al (2022) https://doi.org/10.1007/s10518-022-01535-4

The MARS-Schools project - *Fragility curves from EMPIRICAL APPROACH*

BASIC STEPS OF THE EMPIRICAL APPROACH

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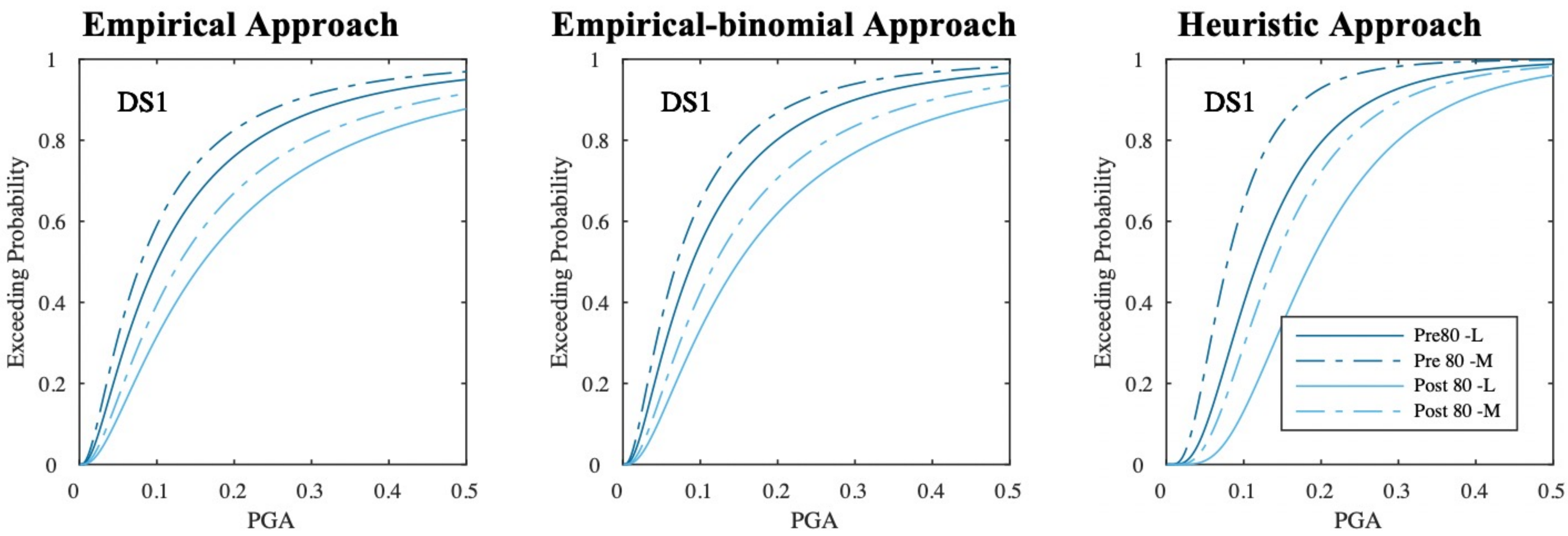
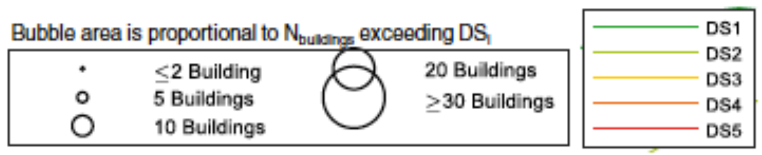


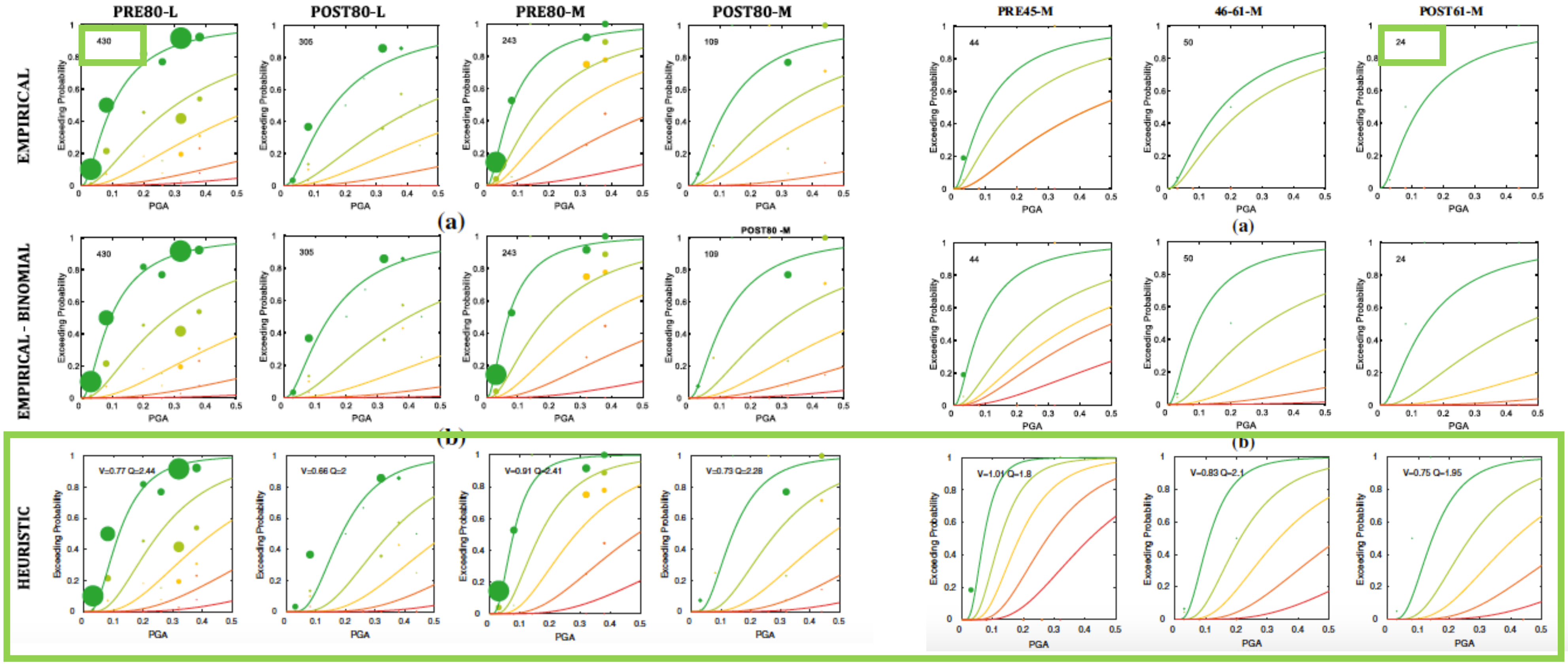
EXAMPLES: REINFORCED CONCRETE SCHOOLS



Di Ludovico M. et al (2022) https://doi.org/10.1007/s10518-022-01535-4

The MARS-Schools project - *Fragility curves from EMPIRICAL APPROACH*

REINFORCED CONCRETE SCHOOLS | **UNREINFOCED MASONRY SCHOOLS**



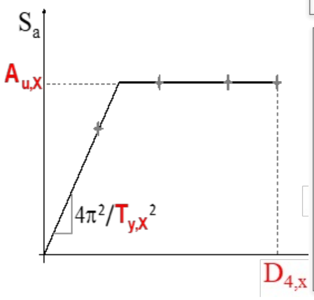
Di Ludovico M. et al (2022) https://doi.org/10.1007/s10518-022-01535-4

The MARS-Schools project - *Fragility curves from MECHANICAL-ANALYTICAL APPROACH*

BASICS OF THE ANALYTICAL-MECHANICAL APPROACH

based on simplified models that make use of a limited number of geometric and mechanical parameters and corrective factors to account for structural details;

EXAMPLE: DBV-Masonry model (Lagomarsino and Cattari 2014) , CATTARI ET al. (2021)



PERIOD

$$T_{y,X} = 2\pi\sqrt{\frac{m^*}{g k_X^*}} = 2\pi H \sqrt{\frac{\sum m_i \phi_{X,i}}{g\prod_{5}^{6} K_{i,X}\sum G_{X,i} h_i \alpha_{X,i}}}$$

$K_{STIFFNESS}$ - Corrective factors to account for the flexural contribution in piers and the role of spandrels

ACCELERATION

$$A_{u,X} = \frac{f_X}{m_X^* \Gamma_X} g$$

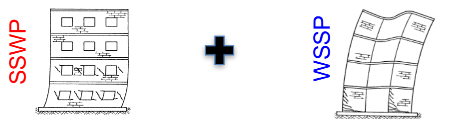
$$\tau_X = \tau_{k,X}\sqrt{1+\frac{\sigma_X}{1.5\tau_{k,X}}}$$

$$f_X = \alpha_{X,1}\tau_X \prod_{1}^{4} K_{i,X}$$

$K_{STRENGTH}$ - Corrective factors to account for the irregularity and the role of spandrels

ULTIMATE DISPLACEMENT

$$D_{u,X} = \varepsilon_X D_{u,SSWP} + (1-\varepsilon_X) D_{u,WSSP}$$



$$D_{u,SSWP} = \Delta_{LS4}\frac{H}{\Gamma_X}$$

$$D_{u,SSWP} = \Delta_{LS4} h_1 + D_{y,X}\left(1-\frac{\Gamma_X}{N}\right)$$

The evaluation of these variables requires:

- the definition of a limited number of mechanical and geometrical parameters
- the assumption of a fundamental modal shape
- the attribution of specific correction factors, aimed to take into account the effects related to the comprehensive set of constructive and morphological details

The seismic input is described in terms of ADRS format (ACCELERATION-DISPLACEMENT RESPONSE SPECTRUM) for nonlinear static analyses

Cattari S, Alfano S, Ottonelli D, et al. (2021) Comparative study on two analytical mechanical-based methods for deriving fragility curves targeted to masonry school buildings. 8th ECCOMAS COMPDYN Conference, Athens, Greece, 27-30 June 2021

The MARS-Schools project - *Fragility curves from MECHANICAL-ANALYTICAL APPROACH*

DEFINITION of the CLASSES of REFERENCE

MASONRY TYPOLOGY GROUPED → DIAPHRAGMS GROUPED → DETAILS GROUPED

LQD-V-IRR-Pietrame
LQD-V-IRR-Conci
LQD-V-IRR-Pietra Tenera
LQD-F-IRR-Pietrame
LQD-F-IRR-Conci
LQD-F-IRR-Pietra Tenera
LQD-SR-IRR-Pietrame
LQD-SR-IRR-Conci
LQD-SR-IRR-Pietra Tenera
LQD-R-IRR-Pietrame
LQD-R-IRR-Conci
LQD-R-IRR-Pietra Tenera
HQD-TR-V-IRR-Pietrame
HQD-TR-V-IRR-Conci
HQD-TR-V-IRR-Pietra Tenera
HQD-TR-F-IRR-Pietrame
HQD-TR-F-IRR-Conci
HQD-TR-F-IRR-Pietra Tenera
HQD-TR-SR-IRR-Pietrame
HQD-TR-SR-IRR-Conci
HQD-TR-SR-IRR-Pietra Tenera
HQD-TR-R-IRR-Pietrame
HQD-TR-R-IRR-Conci
HQD-TR-R-IRR-Pietra Tenera
HQD-RB-V-IRR-Pietrame
HQD-RB-V-IRR-Conci
HQD-RB-V-IRR-Pietra Tenera
HQD-RB-F-IRR-Pietrame
HQD-RB-F-IRR-Conci
HQD-RB-F-IRR-Pietra Tenera
HQD-RB-SR-IRR-Pietrame
HQD-RB-SR-IRR-Conci
HQD-RB-SR-IRR-Pietra Tenera
HQD-RB-R-IRR-Pietrame
HQD-RB-R-IRR-Conci
HQD-RB-R-IRR-Pietra Tenera

- Vault
- Flexible
- Rigid
- Reinforced concrete

→ Low Quality Details

- Vault
- Flexible
- Rigid
- Reinforced concrete

→ High Quality Details (Tie rods)

- Vault
- Flexible
- Rigid
- Reinforced concrete

→ Low Quality Details (Ring beams)

→ Uncut masonry

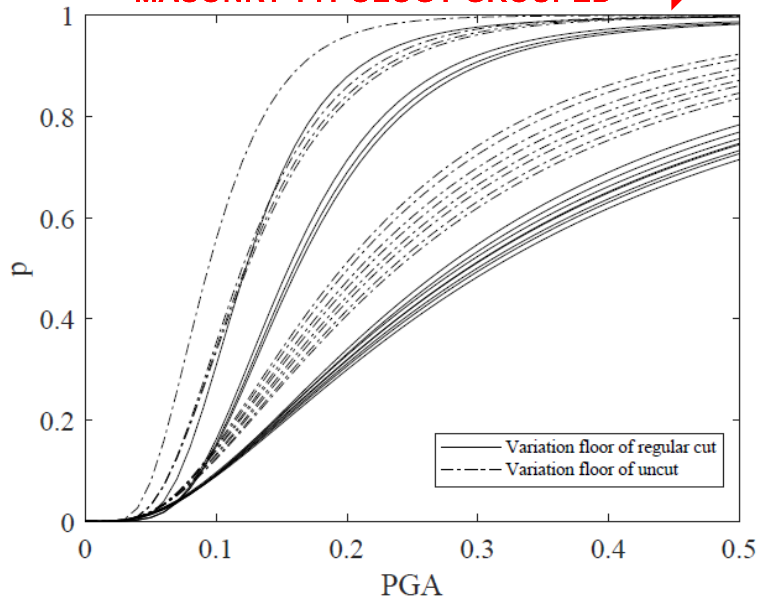
The same for the cut masonry……

Masonry – < 1919 –
Number of storeys 3

The MARS-Schools project - *Fragility curves from MECHANICAL-ANALYTICAL APPROACH*

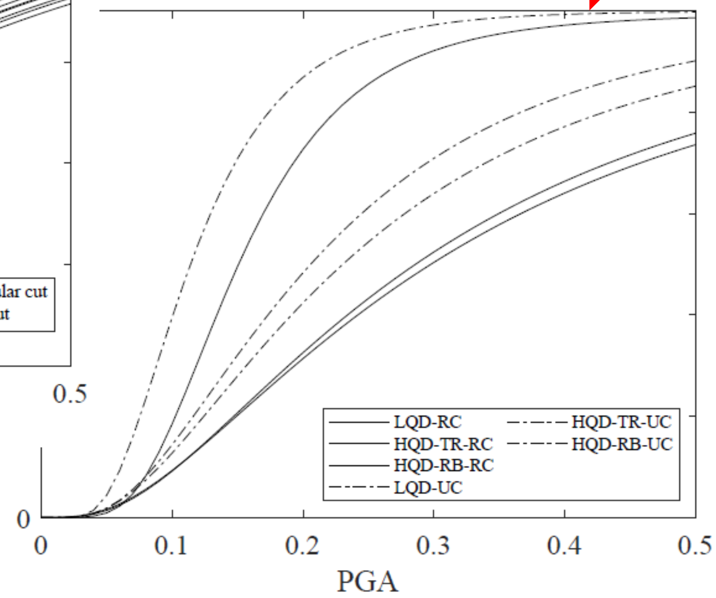
EXAMPLE: DBV-Masonry model (Lagomarsino and Cattari 2014) , CATTARI ET al. (2021)

MASONRY TYPOLOGY GROUPED

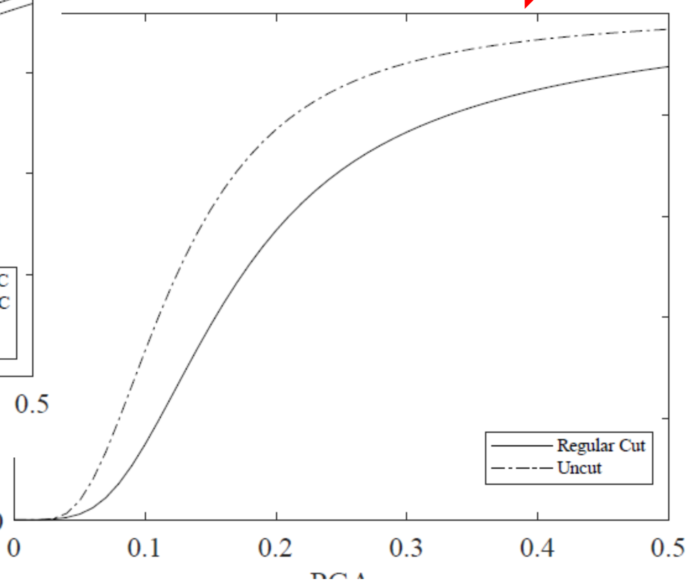


DBV-Masonry (Lagomarsino and Cattari 2014)

DIAPHRAGMS GROUPED



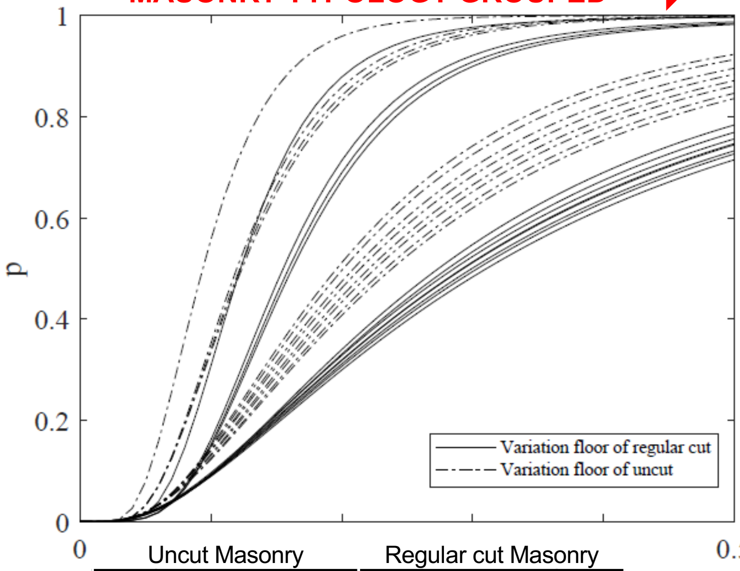
DETAILS GROUPED



The MARS-Schools project - *Fragility curves from MECHANICAL-ANALYTICAL APPROACH*

EXAMPLE: DBV-Masonry model (Lagomarsino and Cattari 2014) , CATTARI ET al. (2021)

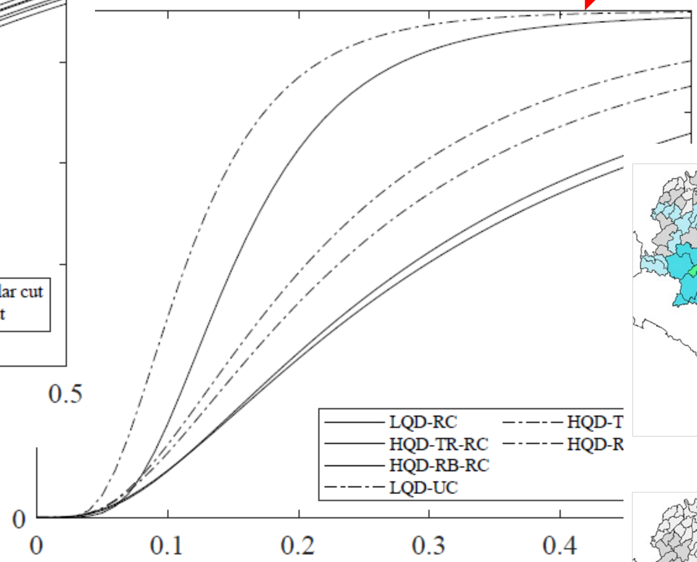
MASONRY TYPOLOGY GROUPED



	Uncut Masonry			Regular cut Masonry	
LQD	Vault	26%	LQD	Vault	20%
	Flexible	34%		Flexible	22%
	Rigid	36%		Rigid	47%
	Reinforced concrete	4%		Reinforced concrete	11%
HQD	Vault	24%	HQD	Vault	13%
	Flexible	24%		Flexible	13%
	Rigid	39%		Rigid	34%
	Reinforced concrete	13%		Reinforced concrete	40%

DBV-Masonry (Lagomarsino and Cattari 2014)

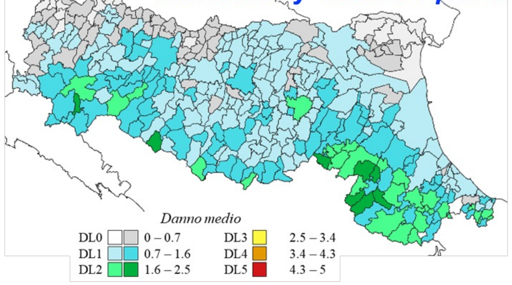
DIAPHRAGMS GROUPED



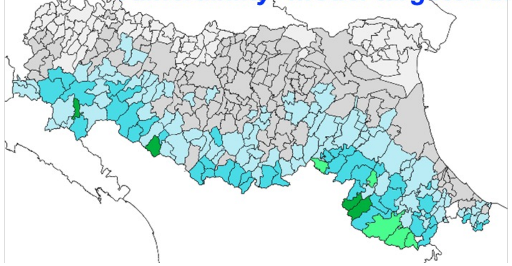
Uncut Masonry	Low Quality Details	77%
	High Quality Details	23%
Regular cut Masonry	Low Quality Details	62%
	High Quality Details	38%

DETAILS GROUPED

Vulnerability model equal at national scale



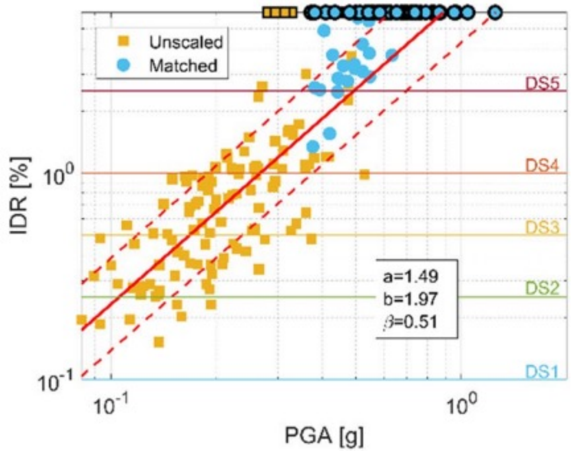
Vulnerability model targeted at regional level



The MARS-Schools project- *Fragility curves from MECHANICAL-NUMERICAL APPROACH*

Based on the execution of Nonlinear Dynamic Analyses (NLDA) on detailed models inspired by the reference archetypes

Selection of 125 real accelerograms for NLDAs



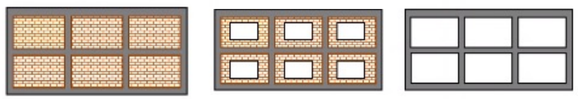
CLOUD APPROACH

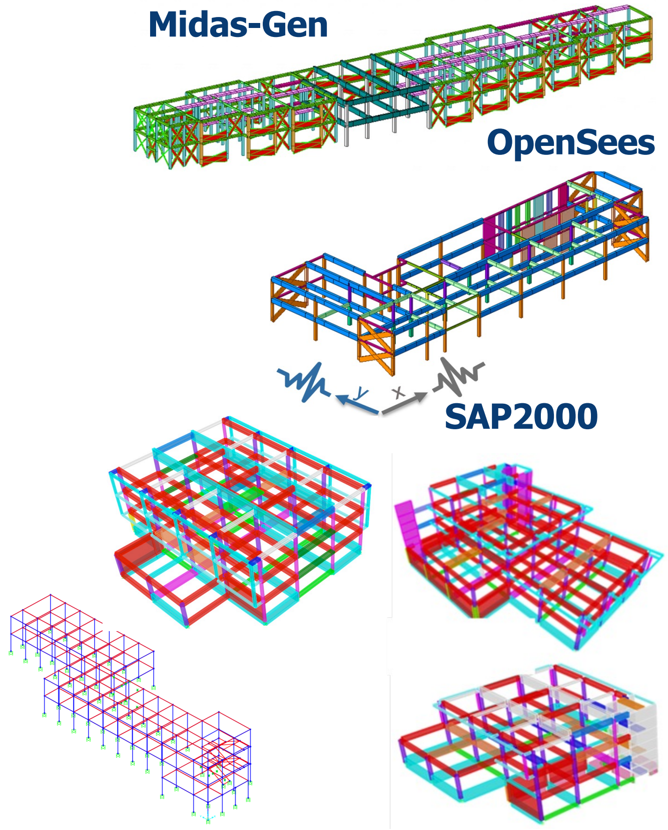
Manfredi V, et al (2022)
https://doi.org/10.1007/s10518-022-01393-0

Shared hyphotheses on modelling assumption and EDP

UR	Infill modelling	Typology of infills
UniBAS	Explitic modelling	Combination of different % openings
UniCAM	Through appropriate interstory drift thresolds	100% Bare frame
UniNA _ ADNL		
UniPD		100% Bare frame

Interstory drift Thrsholds - IDR [%]				
DL1	DL2	DL3	DL4	DL5
0.1-0.25	0.25-0.5	0.5-1.0	1.0-2.5	>2.5

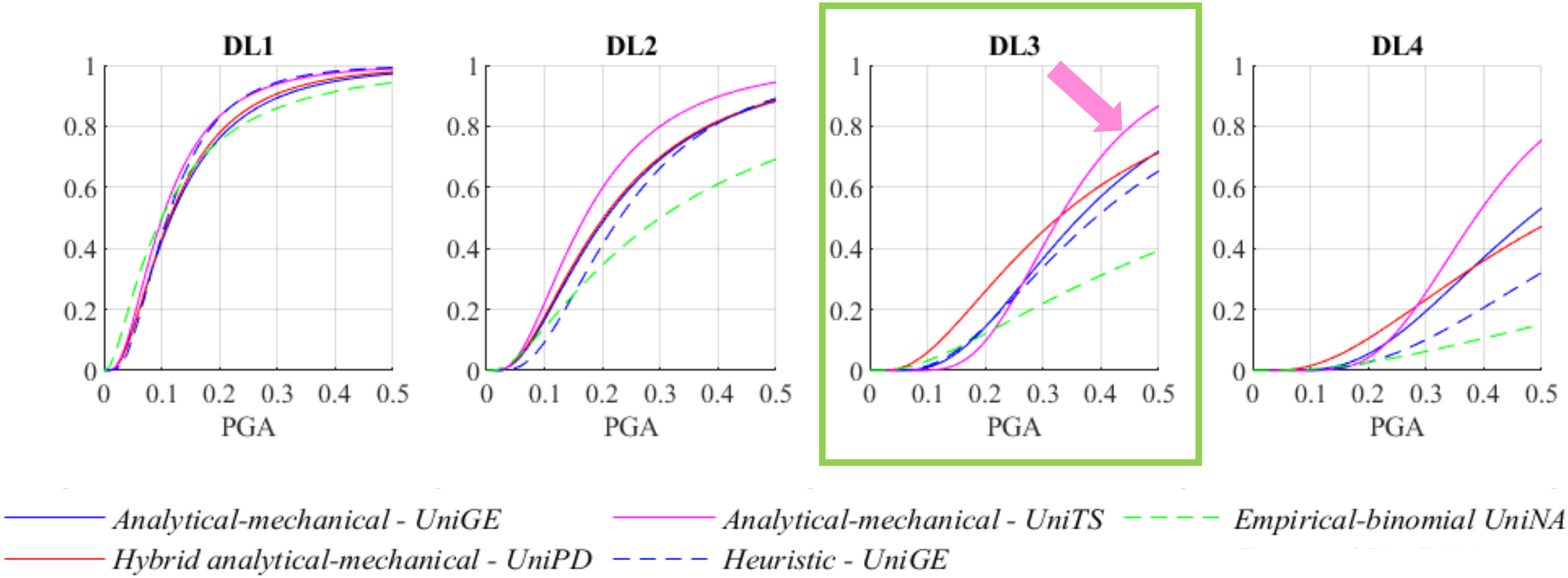




The MARS-Schools project -*Comparison of fragility curves from different approaches*

COMPARISON FOF THE FRAGILITY CURVES AS DIRECTLY OBTAINED BY THE RUs

URM school buildings – AGE: 1946-60 – No. floors 2 – Area < 500 m2

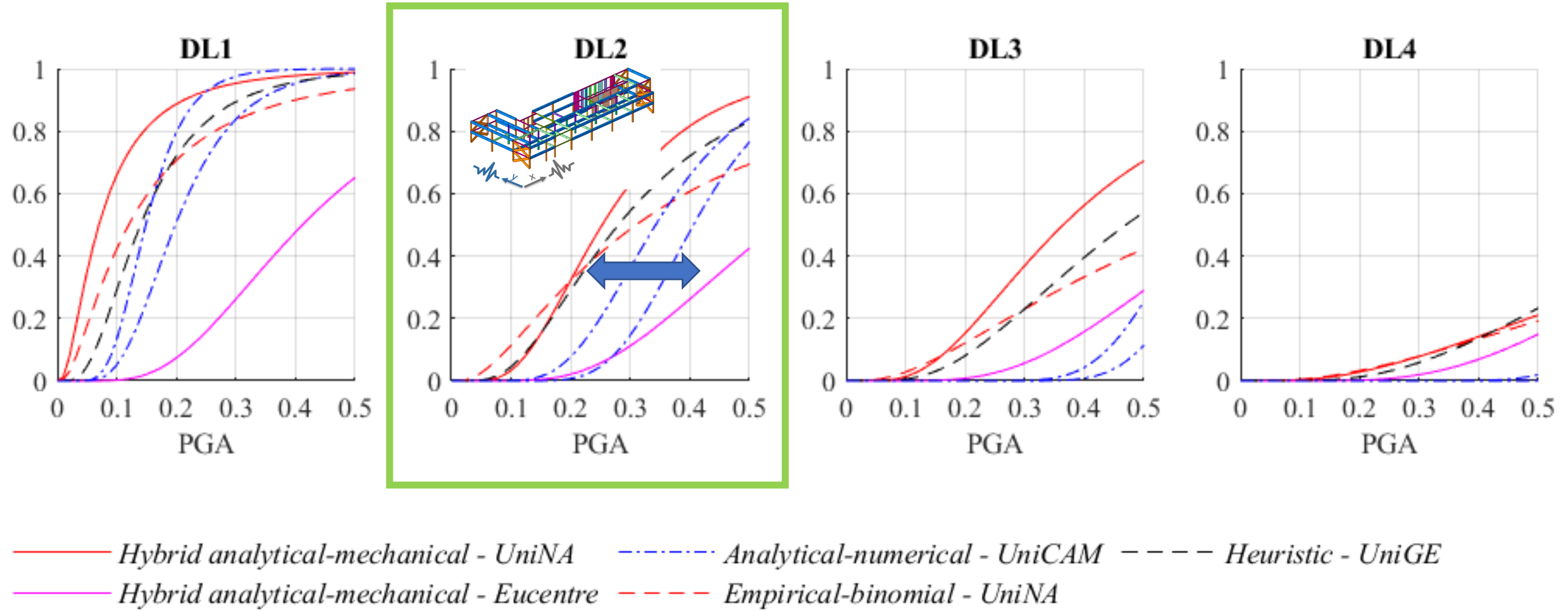


Cattari et al. (2022) Risk assessment of italian school buildings at national scale: the MARS project experience, 3ECEES Conference, Bucarest 2022

The MARS-Schools project -*Comparison of fragility curves from different approaches*

COMPARISON FOF THE FRAGILITY CURVES AS DIRECTLY OBTAINED BY THE RUs

RC school buildings – AGE: after 1976 – No. floors 3 – Area < 500 m2 – seismic design

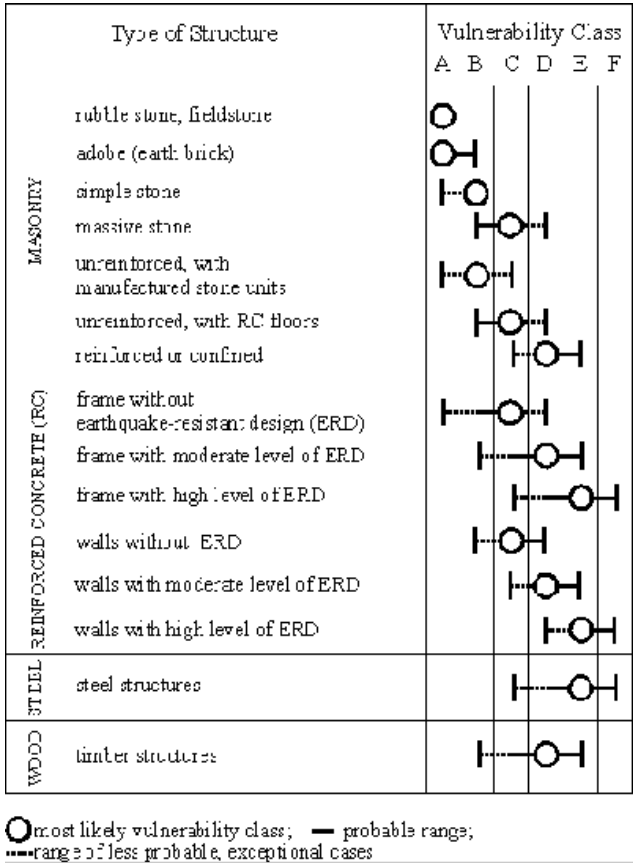


Cattari et al. (2022) Risk assessment of italian school buildings at national scale: the MARS project experience, 3ECEES Conference, Bucarest 2022

How we may pass from the fragility curves developed by single research units to the consensus-based model…..?

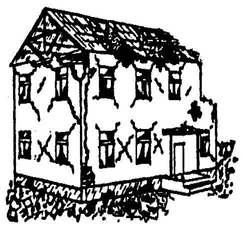
The MARS-Schools project- *Integration of fragility curves from different approaches*

Vulnerability classes proposed by the EMS98

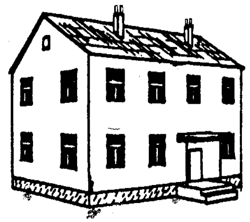


For a given intensity of earthquake

CLASS A



CLASS F



D_k/I	$k = 0$	$k = 1$ (negligible to slight)	$k = 2$ (moderate)	$k = 3$ (substantial to heavy)	$k = 4$ (very heavy)	$k = 5$ (destruction)
5		Few A or B				
6		Many A or B, Few C	Few A or 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 or B, Nearly All C, Most D or E or F

Lagomarsino et al. (2022) The MARS vulnerability model: a new metrics based on EMS-98 vulnerability classes, 3ECEES Conference, Bucarest 2022
Masi et al. (2021) Towards the updated Italian seismic risk assessment: exposure and vulnerability modelling. Bulletin of Earthquake Engineering, Springer. https://doi.org/10.1007/s10518-021-01065-5

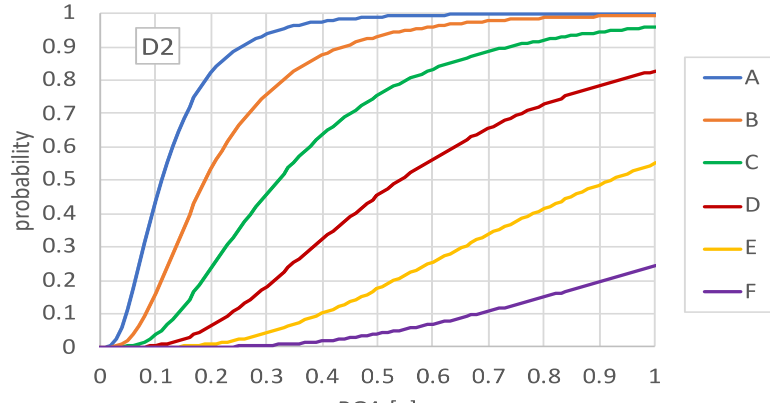
The MARS fragility curves metric

- 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

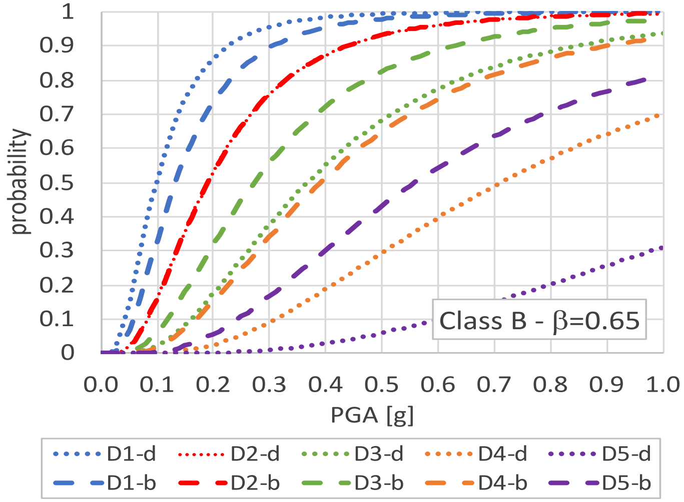
$$PGA = c_1 \, c_2^{I-5} \qquad c_2 = 1.8$$



- 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

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

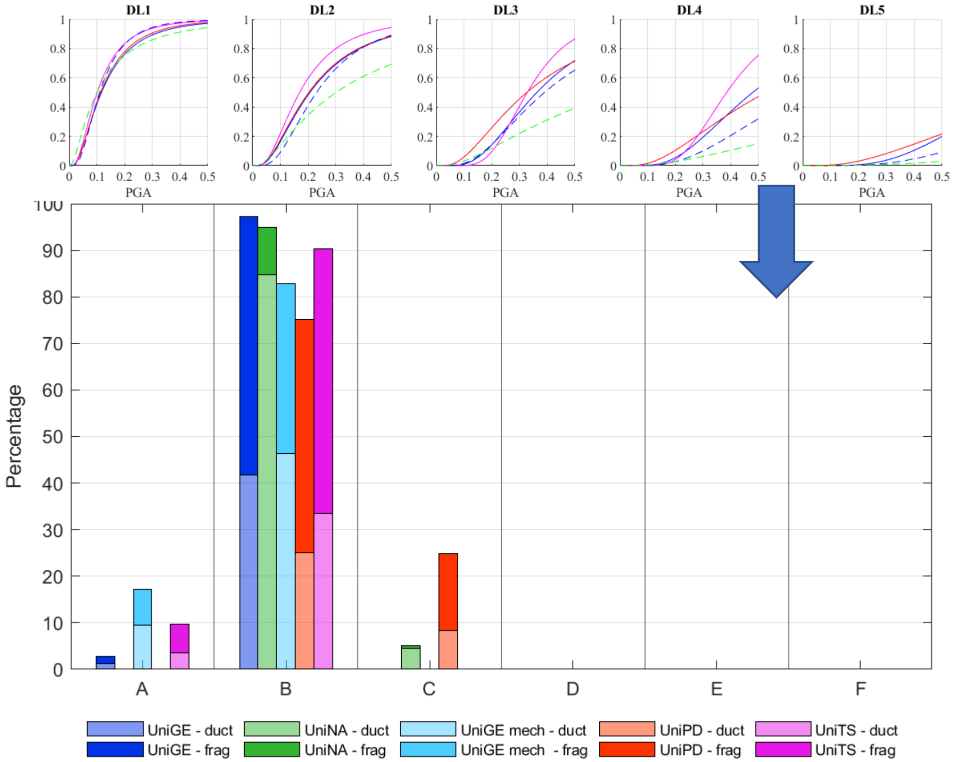


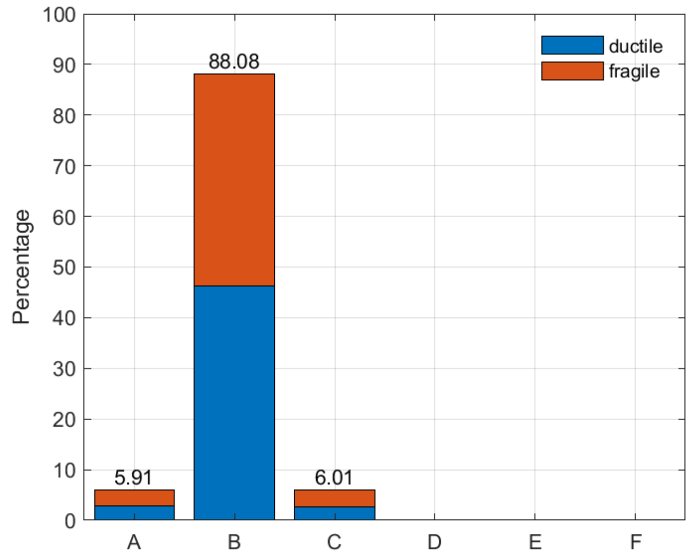
- the dispersion β depends on the building classification; for the ISTAT types 0.65 is a good value

Lagomarsino 2023

The MARS-Schools project- *Integration of fragility curves from different approaches*

MARS-Schools model – 1921-1945 | 2 Storeys | Area < 500 sqm
URM SCHOOL BUILDINGS

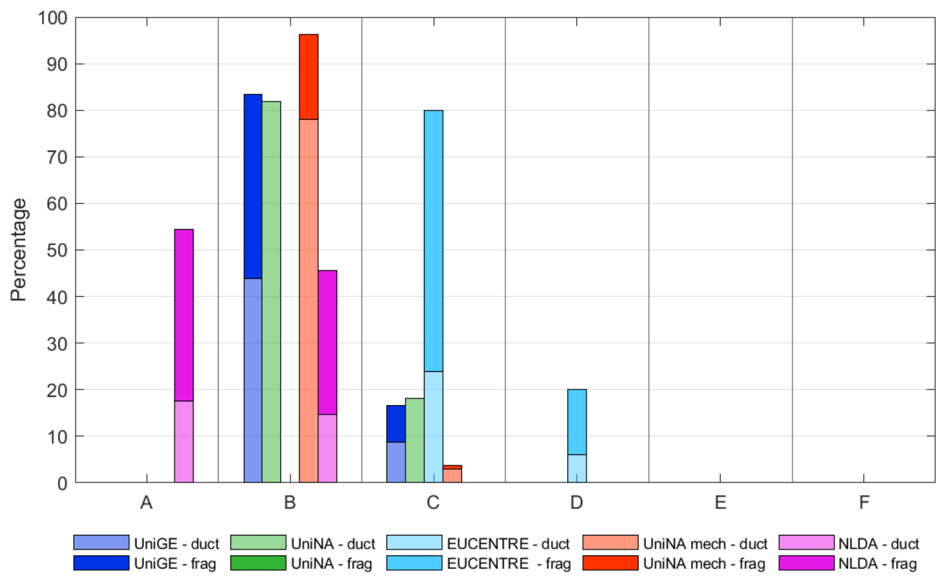


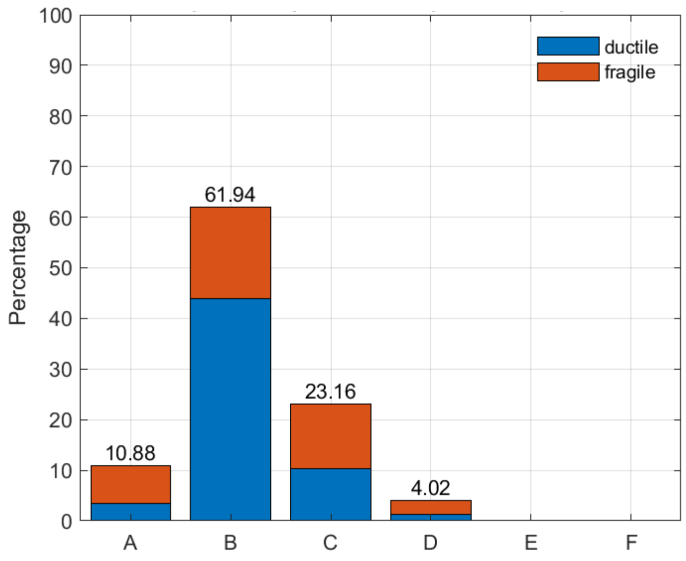


Cattari et al. (2022) Risk assessment of italian school buildings at national scale: the MARS project experience , 3ECEES Conference, Bucarest 2022

The MARS-Schools project- *Integration of fragility curves from different approaches*

MARS-Schools model – Before 1946 | 2 Storeys | Area < 500 sqm
RC Gravitational Design SCHOOL BUILDINGS



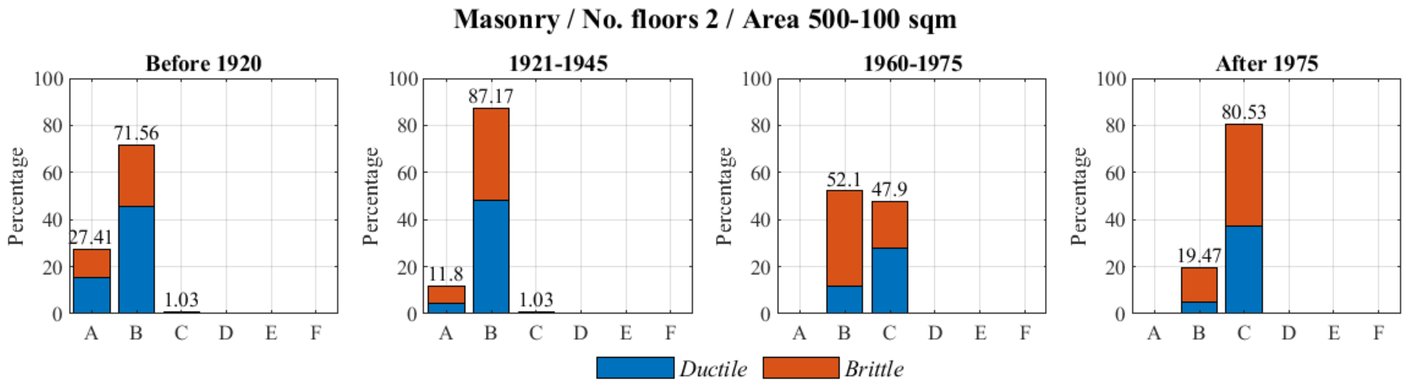


Cattari et al. (2022) Risk assessment of italian school buildings at national scale: the MARS project experience , 3ECEES Conference, Bucarest 2022

The MARS-Schools project- *Integration of fragility curves from different approaches*

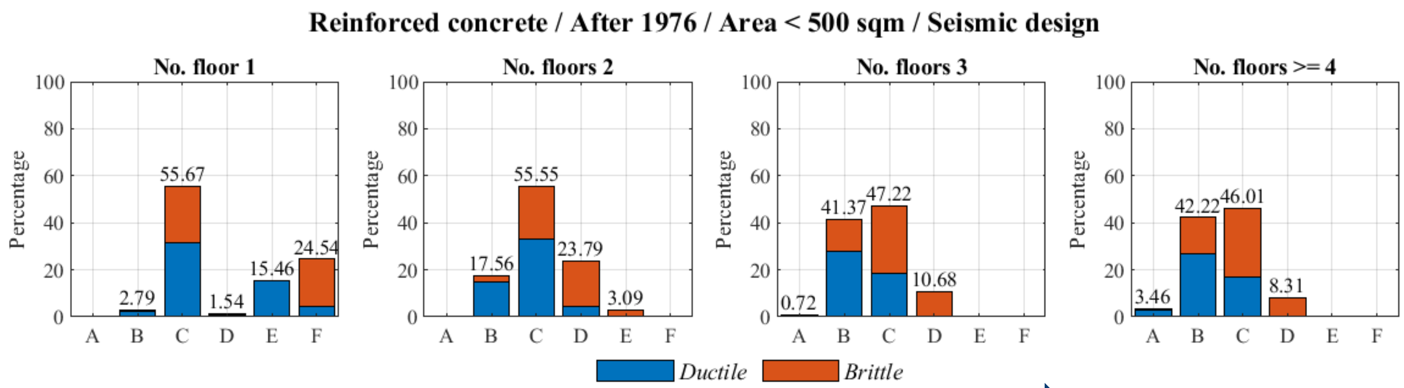
The MARS vulnerability model

URM



Reduction in vulnerability as the age of construction increases

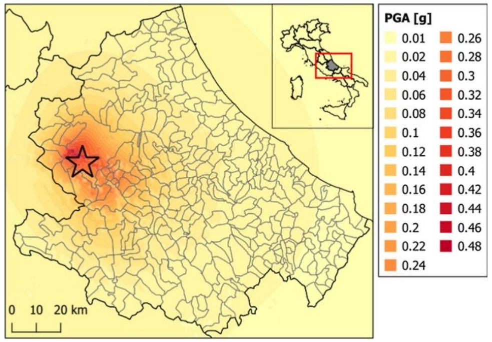
RC

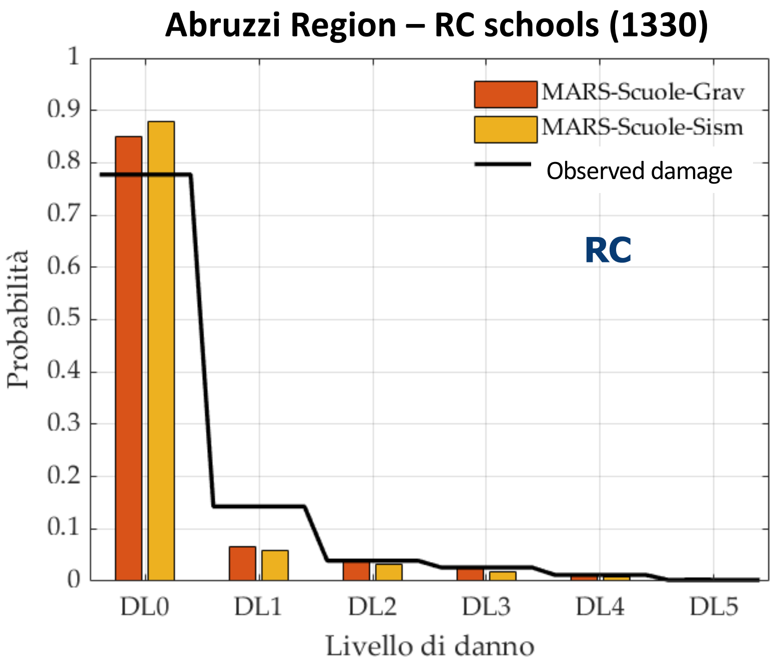


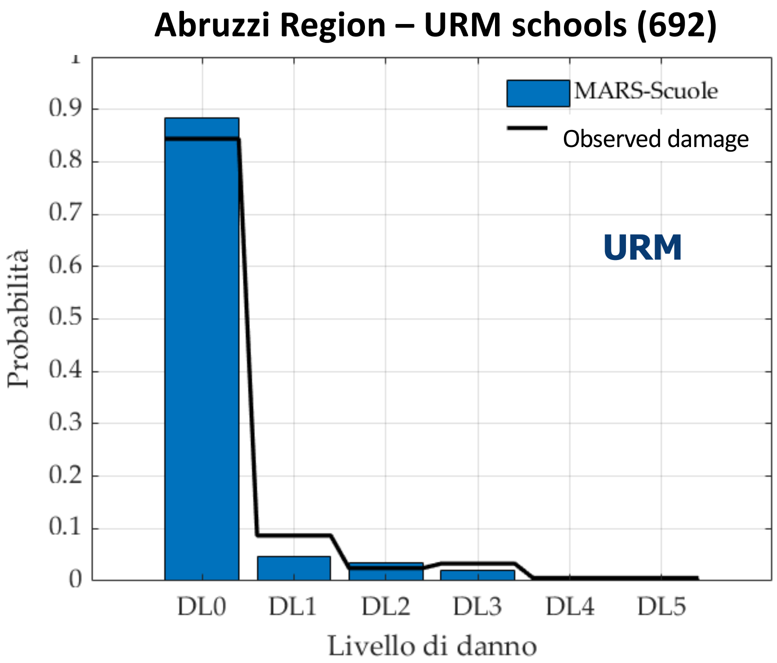
Increased vulnerability as the number of floors increases

The MARS-Schools project - *Validation of results*

Validation of results obtained with data observed following the earthquake that hit Abruzzo in 2009

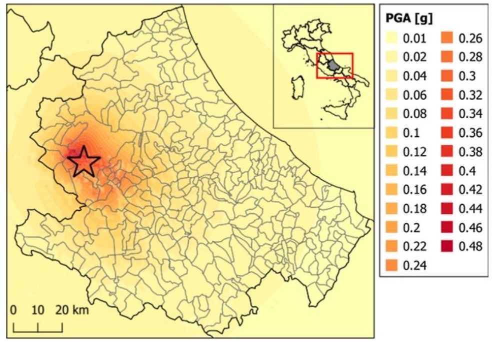




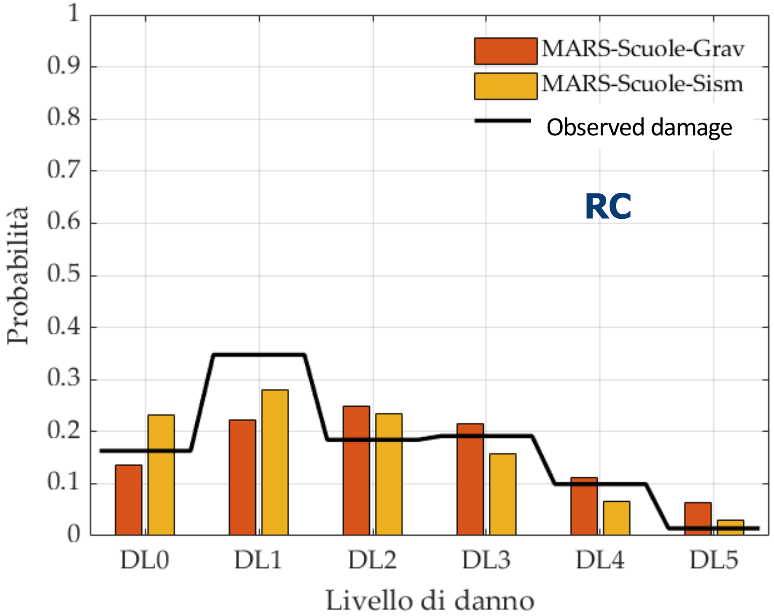


The MARS-Schools project - *Validation of results*

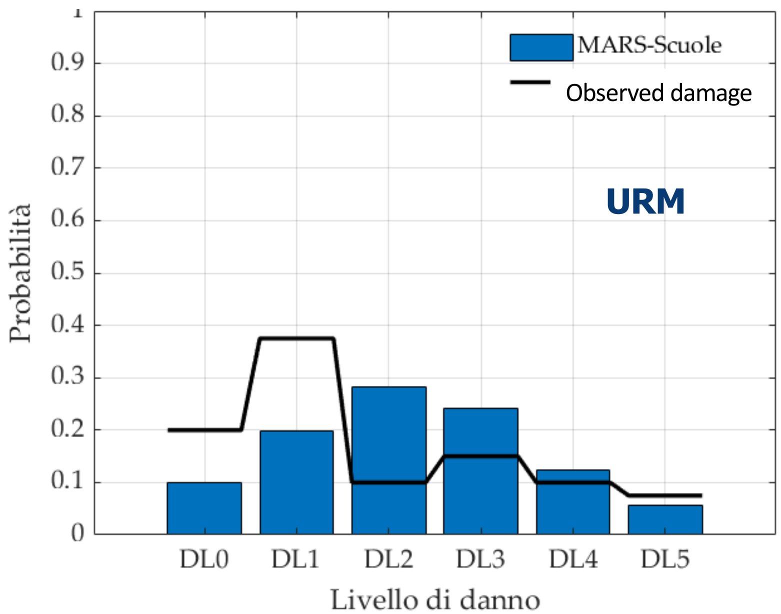
Validation of results obtained with data observed following the earthquake that hit Abruzzo in 2009



L'Aquila– RC schools (141)

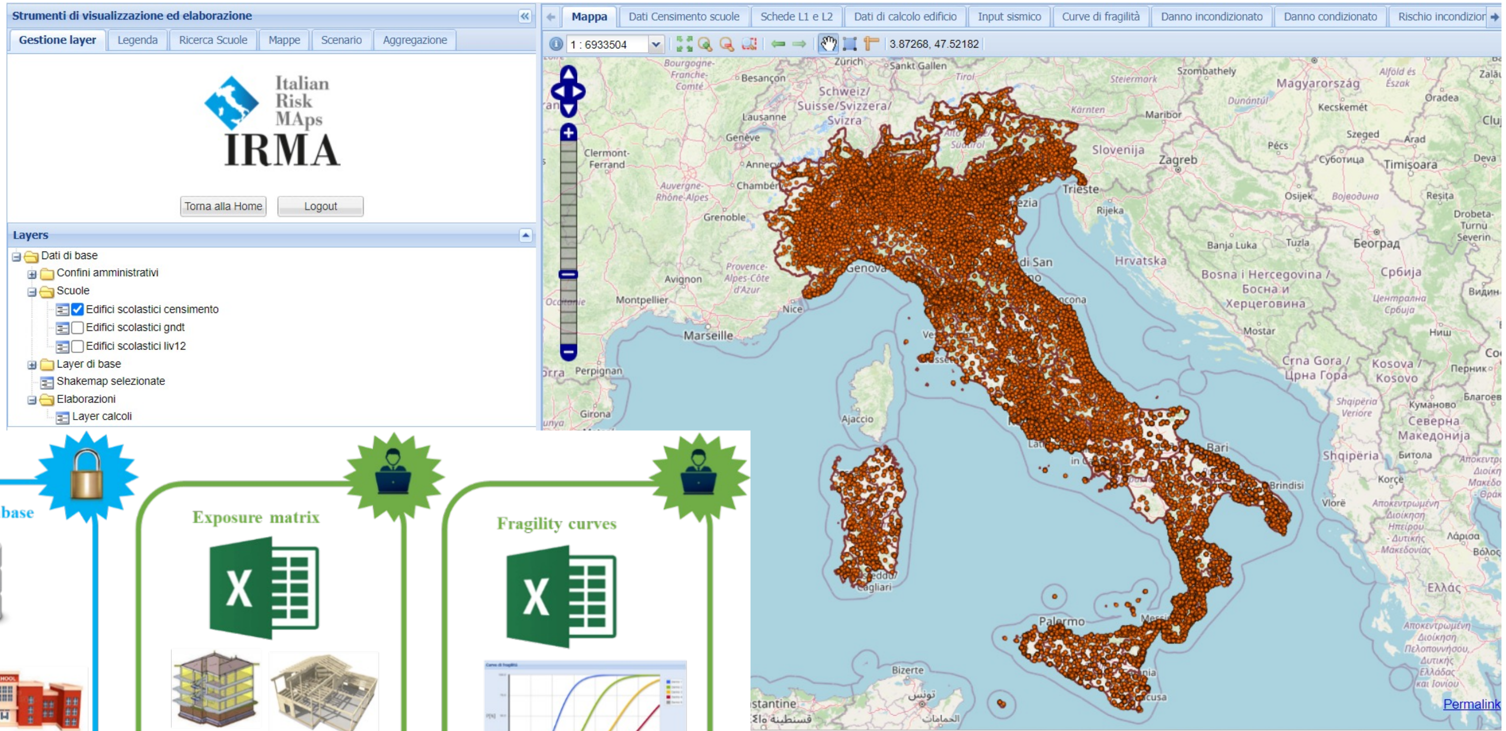


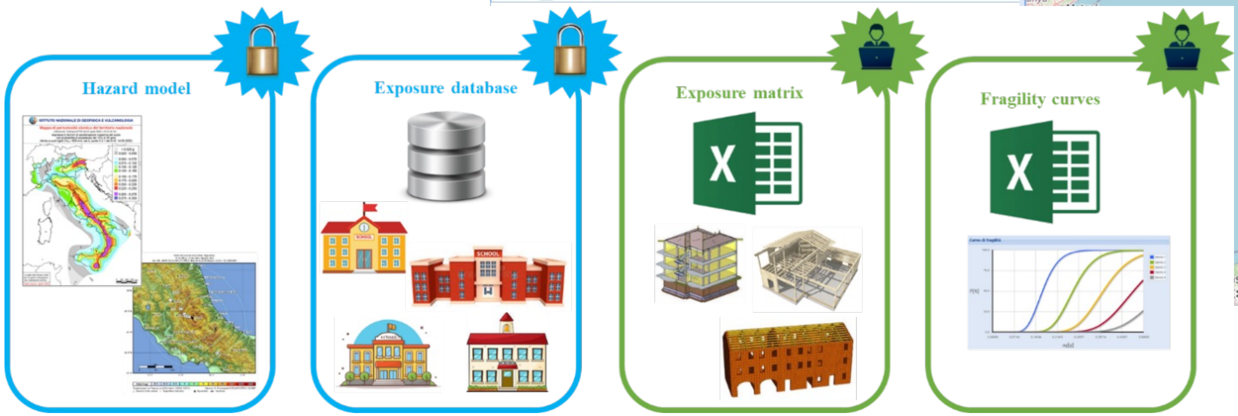
L'Aquila– URM schools (40)



The MARS-Schools project – *IRMA Platform*

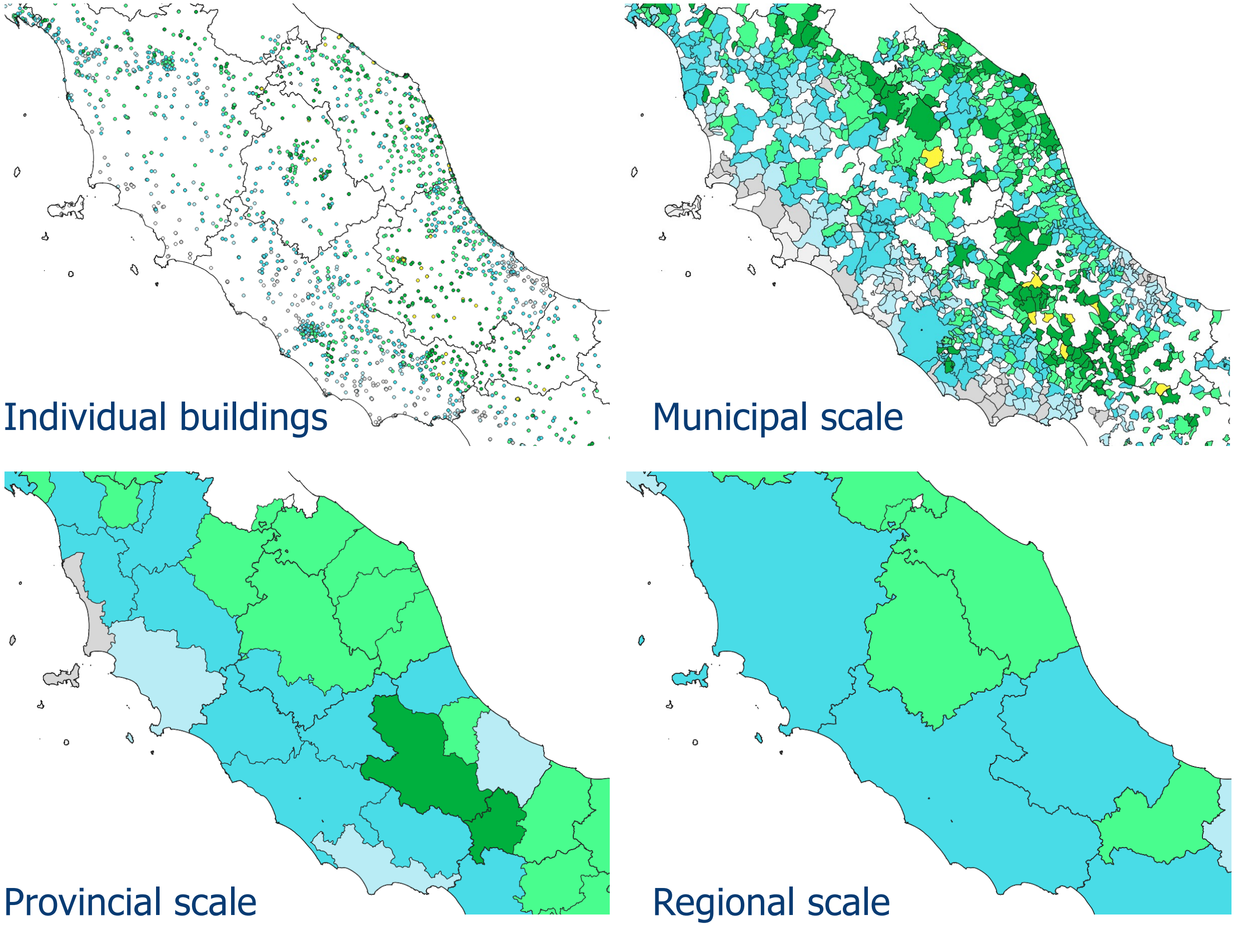
IRMA Platform – Tool for schools





Faravelli M. et al. (2021) An Italian platform for the seismic risk assessment of school buildings. XIX ANIDIS Conference, Seismic Engineering in Italy, Turin, 11-15 September 2022

The MARS-Schools project – *IRMA Platform*



Parameters adopted for aggregation:

- *Number of buildings*
- *Surface area*

Scales adopted for aggregation:

- *Municipal*
- *Provincial*
- *Regional*

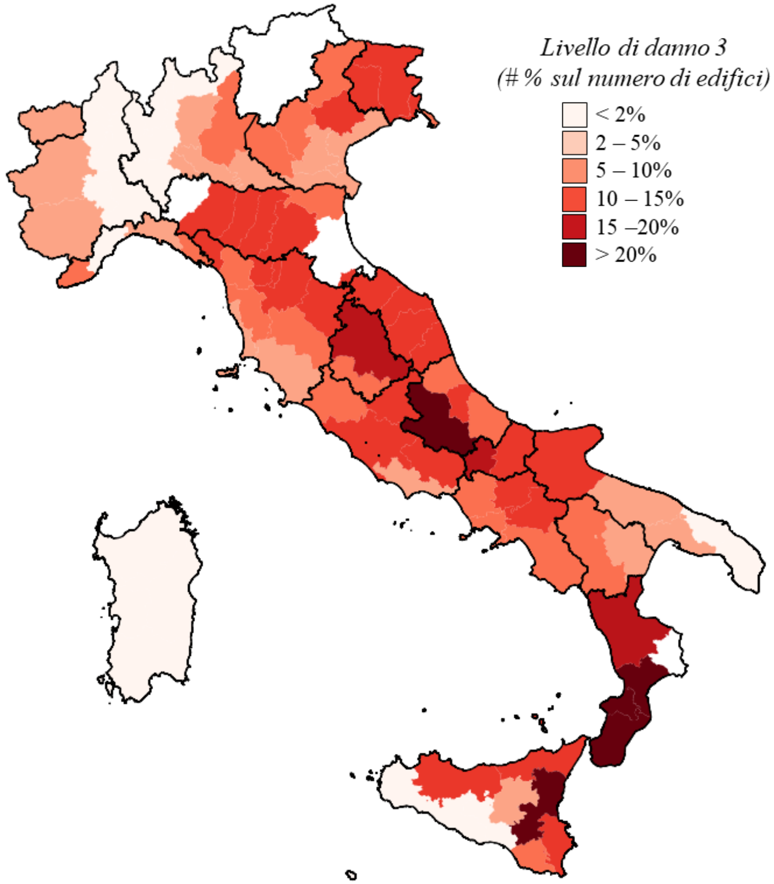
Average damage

DL0		0 – 0.7	DL3		2.5 – 3.4
DL1		0.7 – 1.6	DL4		3.4 – 4.3
DL2		1.6 – 2.5	DL5		4.3 – 5

Faravelli M. et al. (2021) An Italian platform for the seismic risk assessment of school buildings. XIX ANIDIS Conference, Seismic Engineering in Italy, Turin, 11-15 September 2022

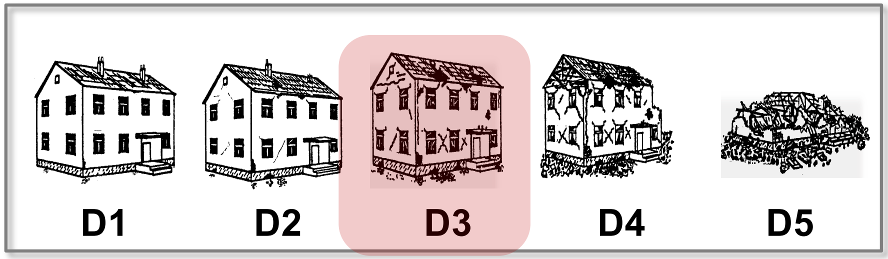
The MARS-Schools project – *Preliminary results*

Results obtained with the MARS-Schools model - Unconditional damage



Results in terms of unconditional damage over 50-year time window for damage level 3, aggregated to provincial scale over the number of buildings

(e.g., extracted map for masonry buildings)



The MARS-Schools project -*Adopted consequence functions*

From real data…..

Di Ludovico M. et al (2022) https://doi.org/10.1007/s10518-022-01535-4

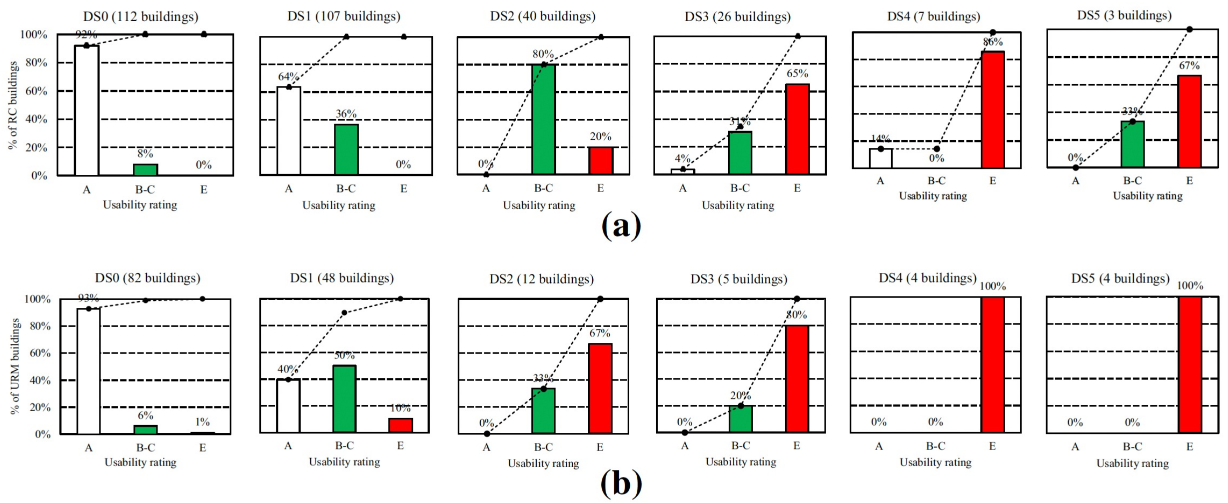


Fig. 11 Distribution of the usability rating as function of the damage state for RC (**a**) and URM school buildings (**b**)

RC school buildings

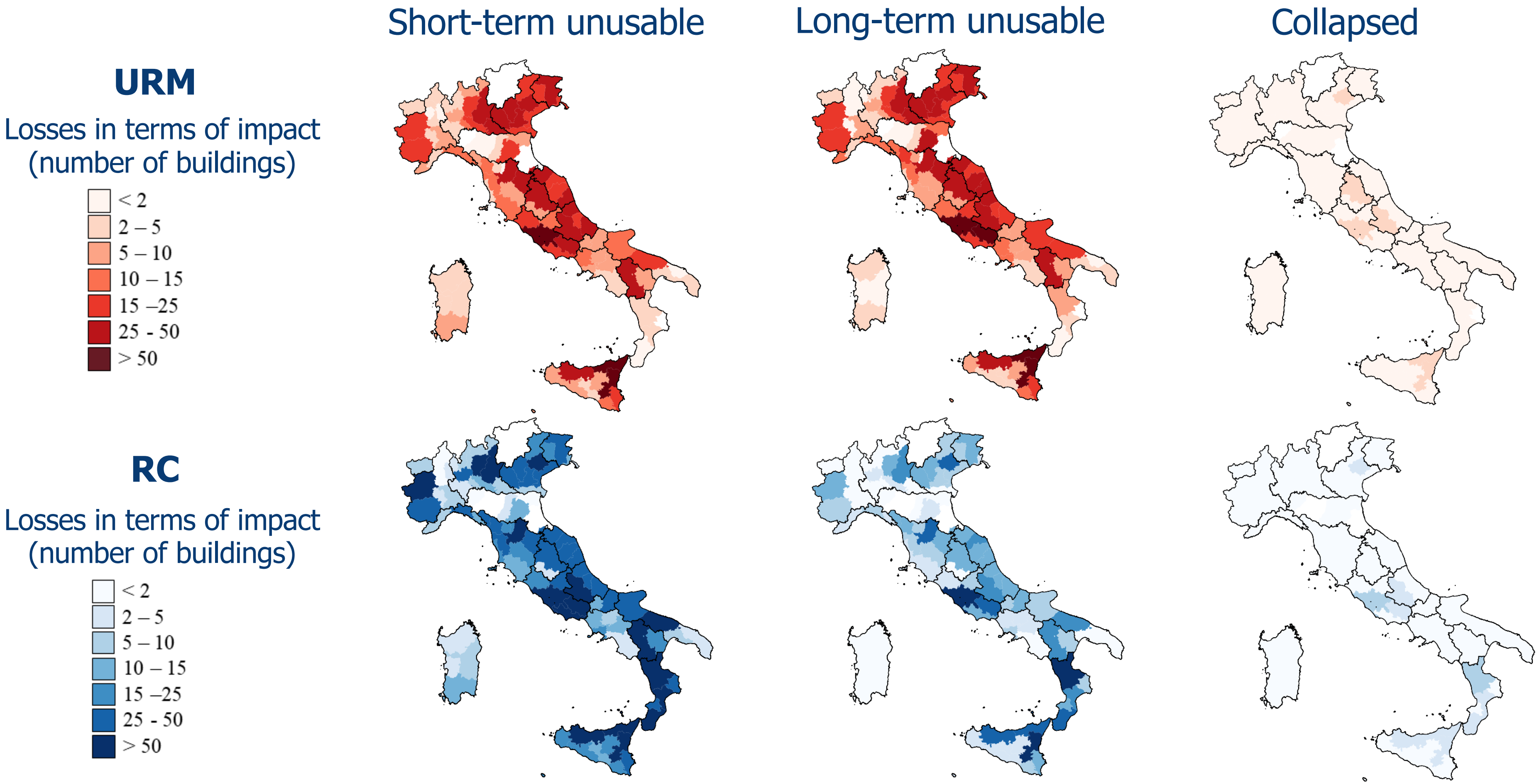
	Usable	Short-term unusable	Long-term Unusable	Collapsed
D1	65	35	0	0
D2	0	80	20	0
D3	0	35	65	0
D4	0	15	85	0
D5	0	0	0	100

URM school buildings

	Usable	Short-term unusable	Long-term Unusable	Collapsed
D1	40	50	10	0
D2	0	33	67	0
D3	0	20	80	0
D4	0	0	100	0
D5	0	0	0	100

The MARS-Schools project – *Preliminary results*

Risk maps – *the updating with AES 2022 is still ongoing….*



FINAL REMARKS

Is there a perfect method to develop fragility curves?

I. Empirical
II. Expert elicitation based
III. Analytical
IV. Hybrid methods

All of them pose various critical issues on:

- the incompleteness/reliability of empirical data (Empirical/Observational/Euristic)
- the definition of a robust METRIC of DAMAGE (All)
- the representativeness of archetype buildings (Analytical)
- the need of calibration & validation (Analytical and Hybrid)
- the difficulties on defining proper relationships to relate damage to consequence functions (All)
- ……

?

The integration of outcomes resulting from different approaches is really beneficial but it requires appropriate strategies!

!

THANK YOU FOR YOUR KIND ATTENTION!

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