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VULNERABILITY CURVES FOR MONUMENTAL BUILDINGS BASED ON SEISMIC DAMAGE OBSERVATION

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VULNERABILITY ANALYSIS FOR MONUMENTAL BUILDINGS

The damage assessment to monumental buildings, after the recent seismic events in Italy, proved the high seismic vulnerability of this kind of structures and the relevance of their vulnerability assessment for the management of the earthquake risk both from the economic and the cultural point of view

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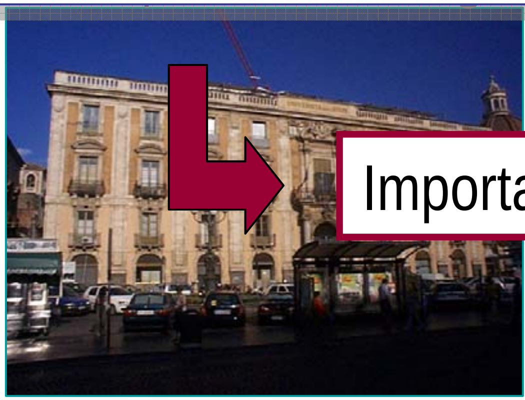
Vulnerability and seismic risk analysis of monuments should be defined and implemented with the aim to:

- make decision makers aware of the potential consequences of an earthquake to the cultural heritage
- list the monuments by seismic vulnerability in order to prioritize preventive interventions for the risk mitigation
- manage the emergency after an earthquake event, estimating in a short time, the potential damage occurred



Importance of an analysis at territorial scale

VULNERABILITY CURVES for MONUMENTAL BUILDINGS

Aiming at developing observational vulnerability models, related to homogeneous monumental typologies, data available from the damage assessment have been processed

The same analytical function proposed for ordinary buildings, has been assumed for correlating the expected mean damage grade μ_d to the macroseimci intensity for monumental buildings

VULNERABILITY CURVE

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

Statistical analyses of observed damage have been performed in order to identify the vulnerability curve defining parameters :

- ✓ vulnerability index V
- ✓ ductility index Q

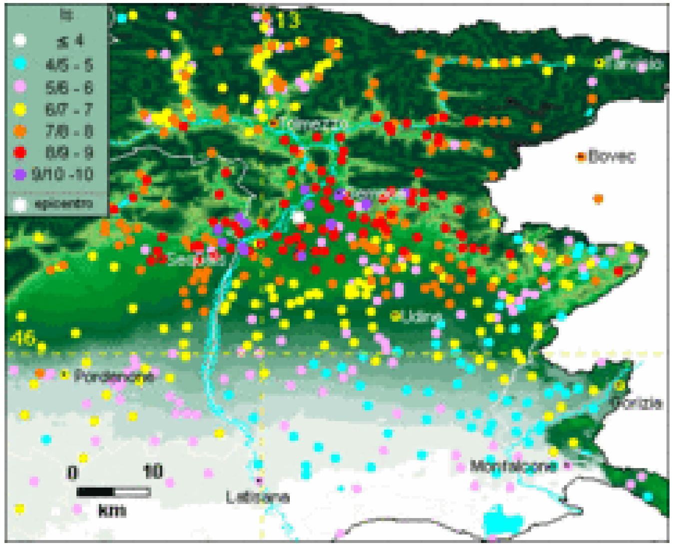
A HOLISTIC APPROACH FOR THE VULNERABILITY ASSESSMENT

	Available information		Vulnerability description	
	Ordinary Buildings	**Monuments**	**Macroseimic approach**	**Mechanic approach**
Level 0	Number of buildings and statistical knowledge of the main features	Typology (church, palace, tower, castle etc.) and expert judgment	Vulnerability index V for each typology	Capacity curve for each typology defined without the use of mechanical methods
Level 1	Existing database with information non specifically surveyed for vulnerability purposes.	A few data related to the seismic behavior and derived from a quick survey specific for the vulnerability assessment	Vulnerability index V, for each single building, refined by taking into consideration behavior modifiers	Capacity curve is evaluated starting from the vulnerability index and accounting for the known structural parameters
Level 2	Detailed information about the typology and the geometrical, structural and technological features from a survey specifically devoted to the vulnerability assessment	More detailed information related both to the building geometry and to the present vulnerability elements	Vulnerability index V for each single building or for each macroelement assessed via an accurate analysis. Specific form are used for the infield vulnerability assessment	Capacity curve derived from mechanical methods usually based on limit equilibrium analysis

THE 1976 FRIULI EARTHQUAKE (ITALY)

The first experience of safety assessment for monumental buildings was developed for the 1976 Friuli earthquake (Italy).

The seismic sequence began on 6 may 1976 - 6.4 ML
965 dead - 60000 homeless

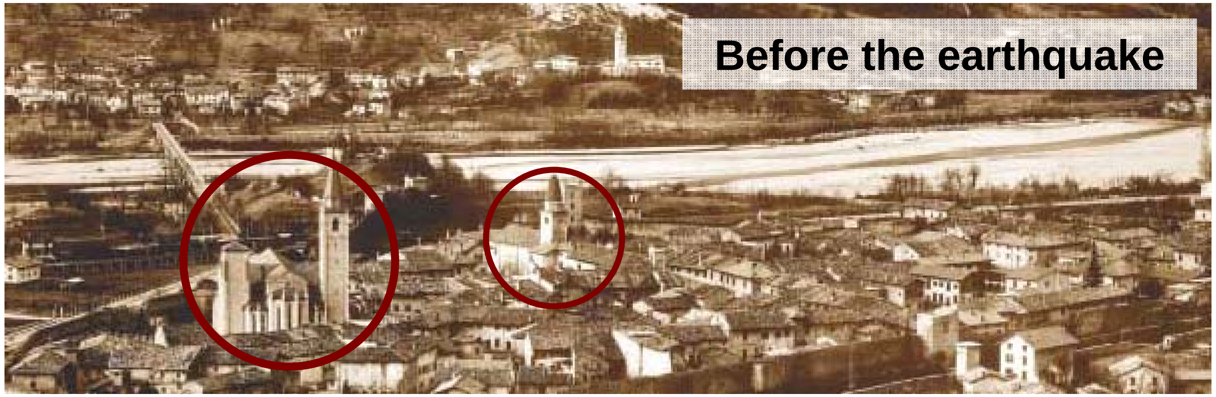


S. Stefano di Ceslans church – Cavazzo (UD)

After the main shock, replica tremors involved this area for four months and on September a shock of magnitude ML equal to 6.1 shocked the already damaged structures

During the damage and safety assessment, phenomena of damage accumulation were analyzed in detail, providing a series of indications useful to understand the seismic behavior of this kind of structures

VENZONE (UD): THE 1976 FRIULI EARTHQUAKE (ITALY)

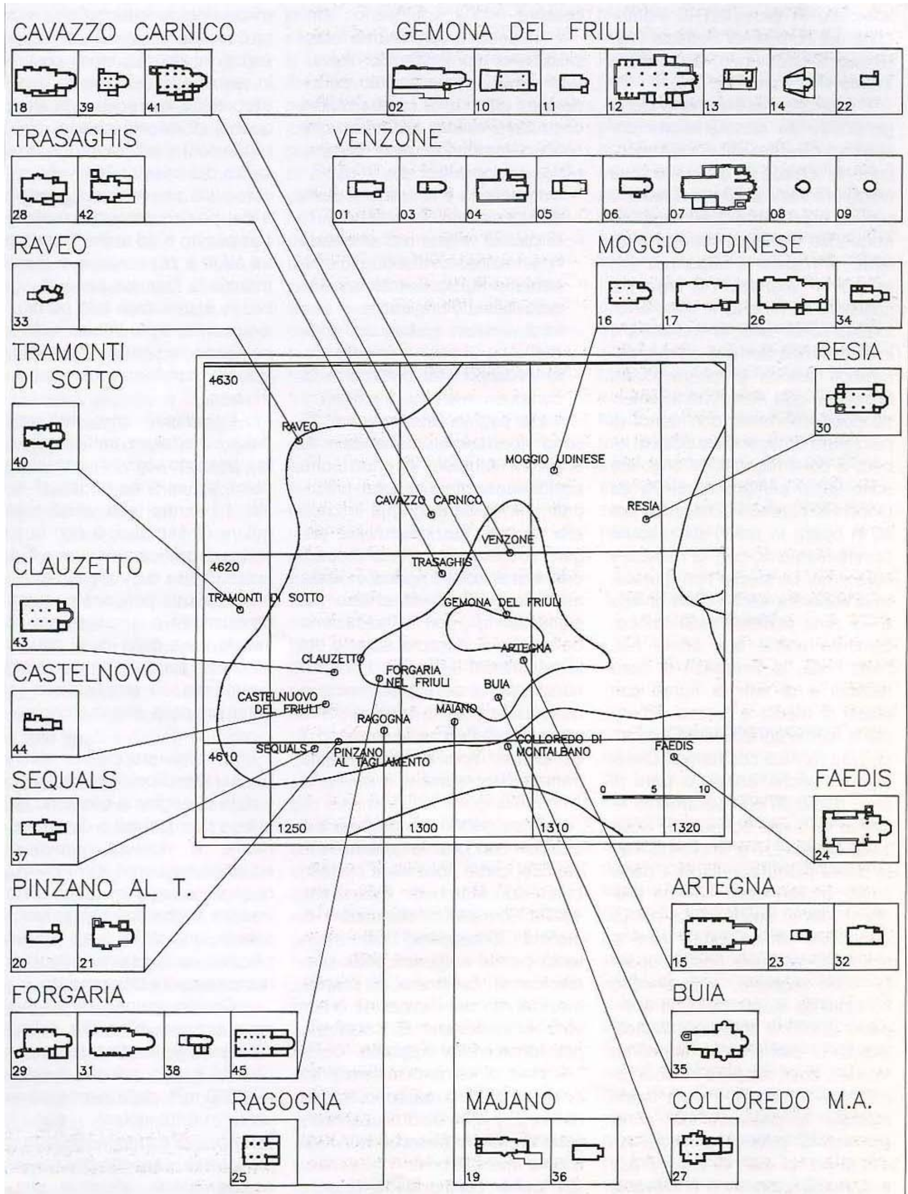


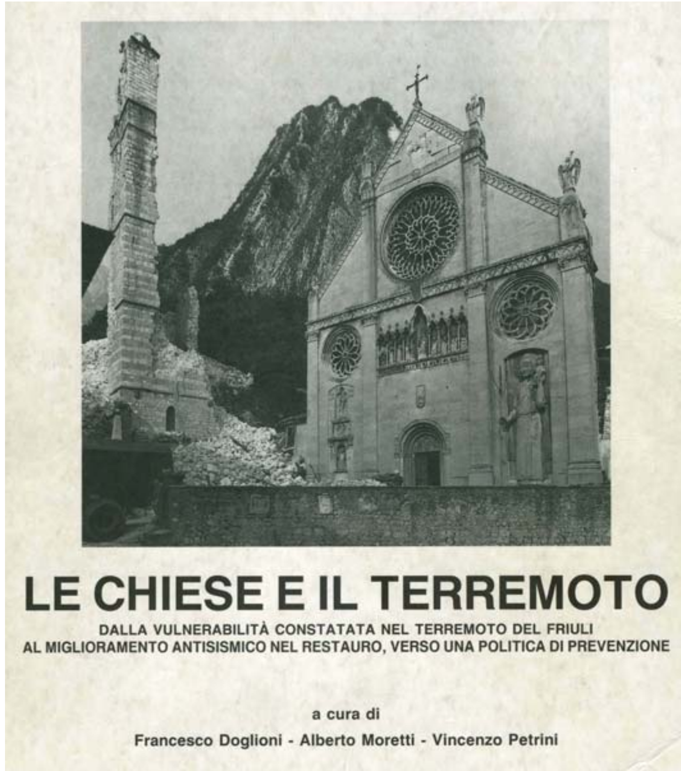
Venzone Cathedral: re-built according to "*anastilosi*" methodology: every ashlars have been catalogued and re-collocated in the original position.

Venzone Cathedral after the first mainshock

<u>S. Anna and S. Giacomo church</u>: collapsed after the earthquake, it was not re-built in memory of the catastrophic event

THE 1976 FRIULI EARTHQUAKE (ITALY)





After the seismic event, for the first time, the collected data were catalogued in systematic way. The results of this research are contained in the book: F. Doglioni, A. Moretti, V. Petrini, The churches and the earthquake" (in Italian), published in 1994 (around 20 years after the earthquake).

For each church, on the basis of photographic documentation and data of the survey carried out during the reconstruction phase, the more recurrent damage mechanisms were identified.

S. Valentino church - Gemona (UD)

S. Maria delle Grazie church - Venzone

3.3

6.54

6.55

6.56

S. Chiara church - Venzone

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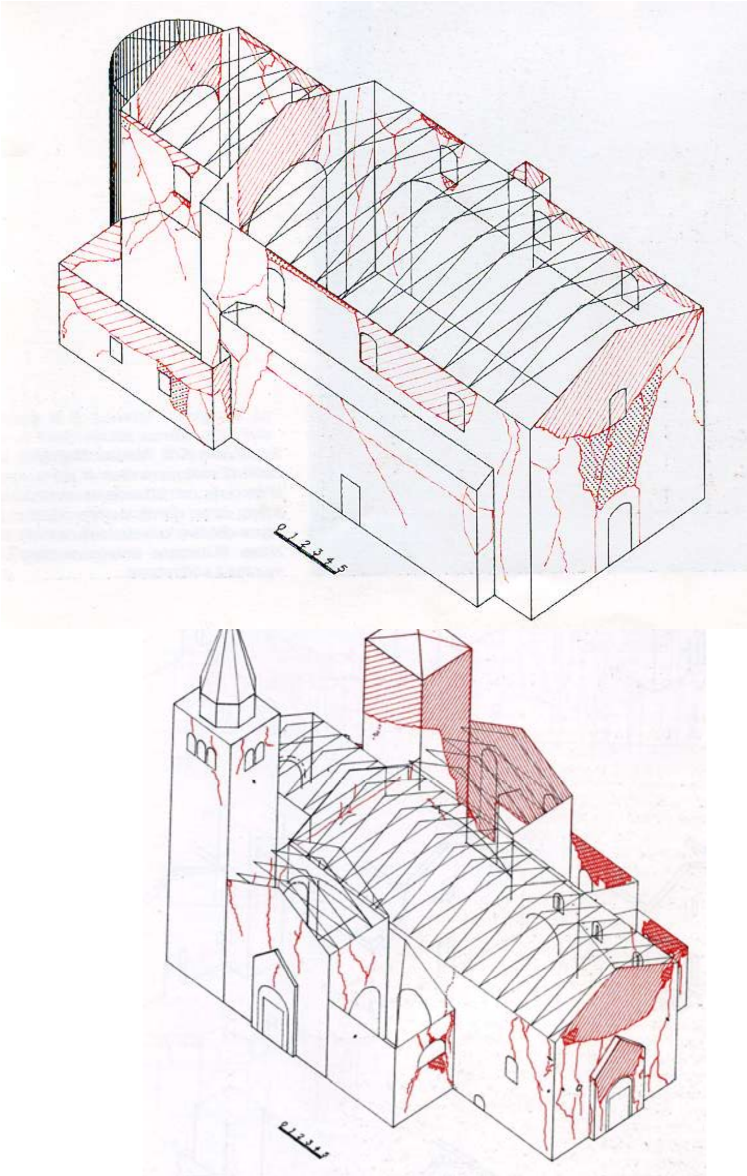
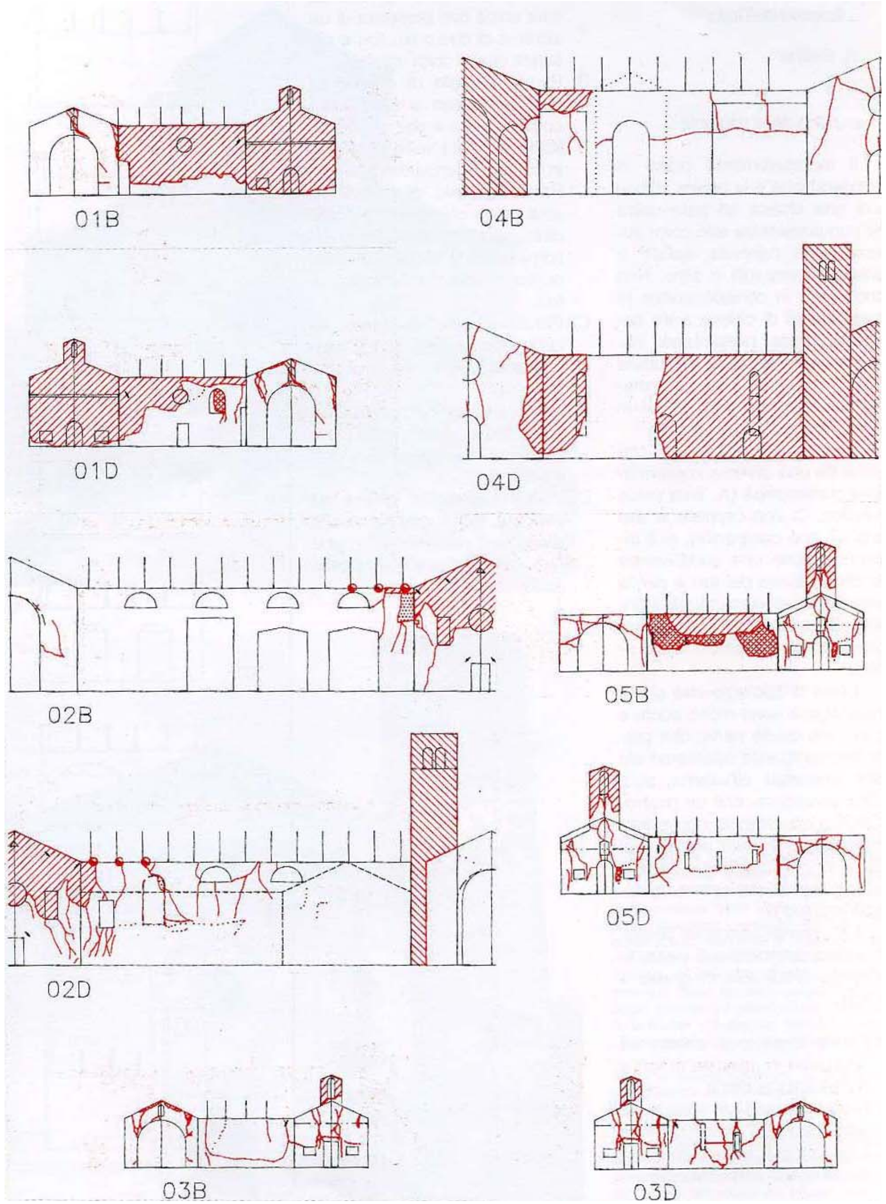


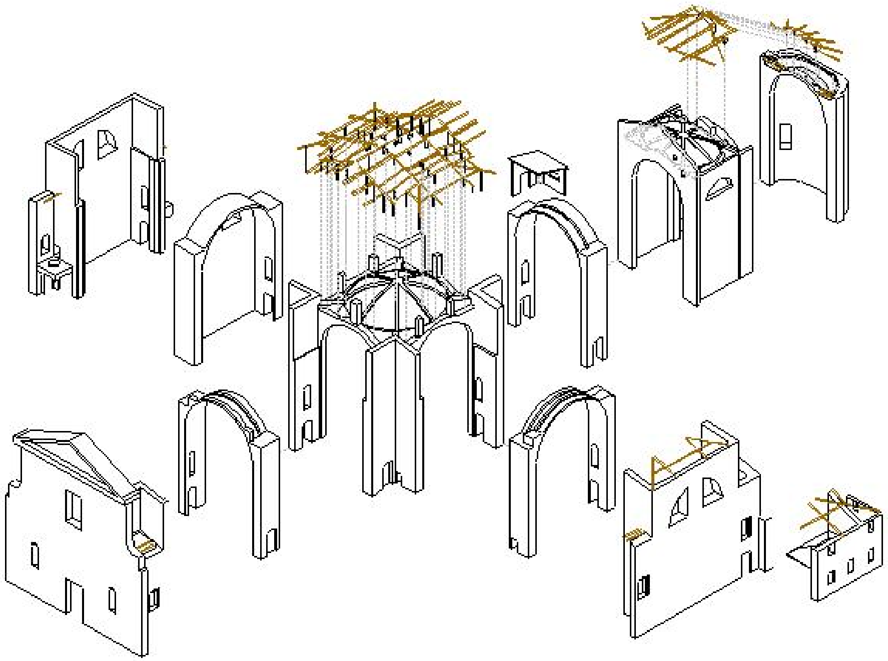
Venzone Cathedral : damage state after the first shock



From the systematic examination of the damaged churches it was possible to observe that the seismic response of this kind of buildings may be described according to recurrent phenomenology, traceable to the damage modes and mechanisms of collapse of different parts called:

MACROELEMENTS

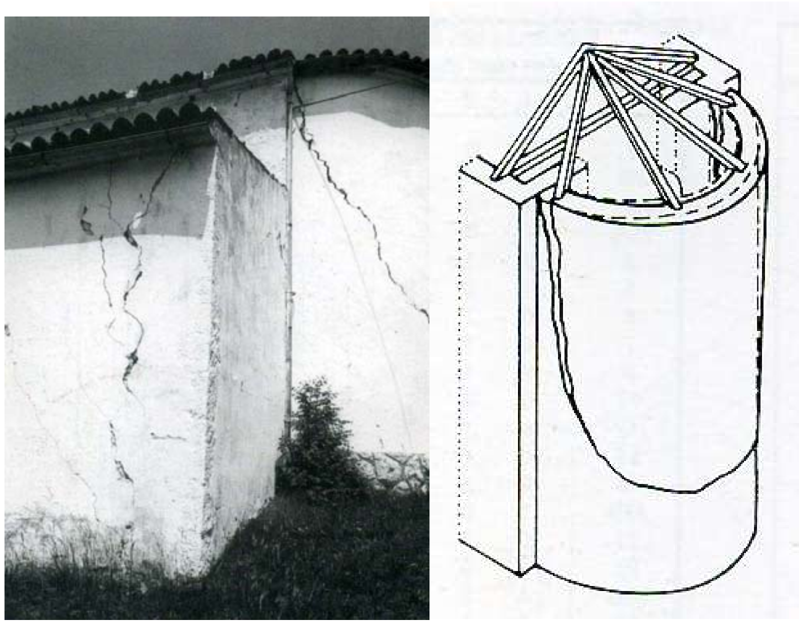
Part of the church characterised by a proper seismic response that can be evaluated almost independently from the rest of the structure. The individuation of the macroelement is strictly connected to the observation of the seismic behaviour and generally does not coincide with the architectonical elements. In particular we have to consider, beyond the architectonical element, an overlap zone in order to describe the constrain degree with the rest of the construction.



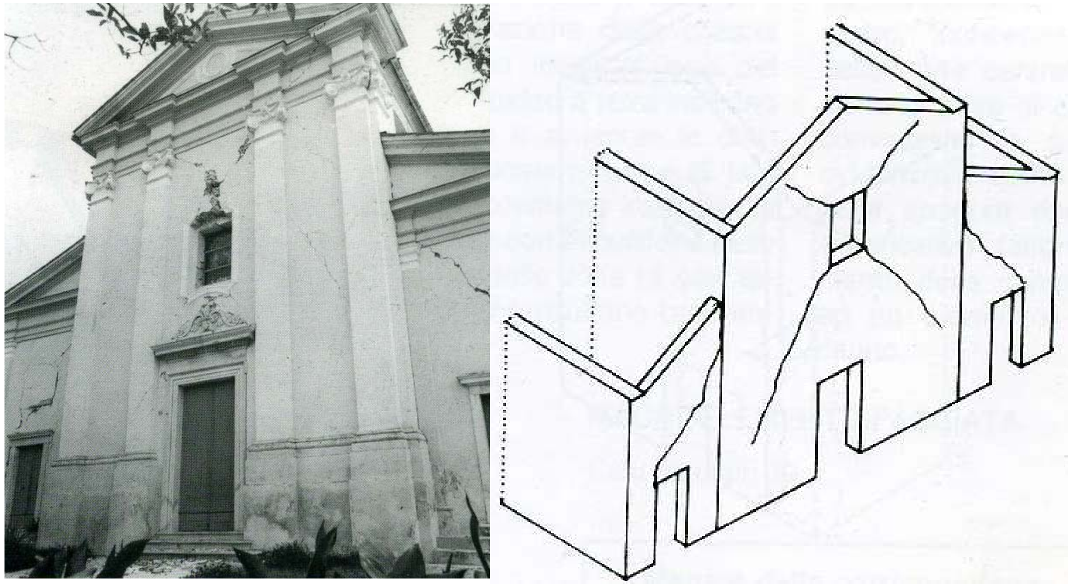
SS. Faustino e Giovita church - Botticino Mattina (BS)

DAMAGE MECHANISMS

Damage mechanism: kinematism through which the different parts of the construction (macroelements) come to collapse. Generally (in case of good masonry quality) the damage mechanism can be associated to rotation or sliding between masonry portions, schematized, for easiness, as rigid bodies.



S. Rocco church - Forgaria (UD)



Pignano Chuch - Ragonga (UD)

Out-of-plane seismic action causes overturning damage mechanisms.

In-plane seismic action induces sliding or shear failures, characterized by oblique (45°) cracks

THE 1997 UMBRIA and THE MARCHES EARTHQUAKE (ITALY)

The Umbria and The Marches seismic sequence is characterized by three main shocks (September 1997 – epicenter Colfiorito; October 1997 – epicenter Sellano; March 1998 – epicenter Gualdo Tadino). More than 1000 churches were damaged by the earthquake (magnitude 5.8). The vaults of S. Francesco d'Assisi Basilica partially collapsed causing the death of 4 people.
The need to survey several monumental buildings, determined, for the first time, the adoption of a specific survey form. The methodology was inspired by the previous experiences, but the damage survey is summarized in a simple and quick form (only 4 pages)

Collapse of S. Francesco d'Assisi vault – Assisi (PG)

S. Rocco - Sellano (PG)

THE FORM FOR THE DAMAGE ASSESSMENT OF CHURCHES

1. OVERTURNING OF THE FACADE	☐
DETACHMENT OF THE FACADE FROM WALLS	☐☐☐
☐ Poor clamping between facade and nave walls ☐ Lack of longitudinal chains or efficient buttresses	

2. DAMAGE AT THE TOP OF THE FACADE	☐
CRACKS IN THE TOP PART OF THE FACADE	☐☐☐
☐ Facade weakened by wide openings ☐ Lack of a connection with the roof covering	

3. SHEAR MECHANISMS IN THE FACADE	☐
SLOPING, VERTICAL AND ARCHED CRACKS	☐☐☐
☐ Presence of many openings (also filled) ☐ Possibility of rotation of the side walls	

4. TRANSVERSAL VIBRATION OF THE NAVE	☐
CRACKS IN ARCHES, DEFORMED WALLS	☐☐☐
☐ Very thin side walls ☐ Lack of transversal chains or efficient buttresses	

5. TRIUMPHAL ARCH	☐
CRACKS IN KEY AND SPINE	☐☐☐
☐ Arch of insufficient thickness or poor masonry ☐ Chains missing or badly placed; weak shear walls	

6. VAULTS OF THE NAVE	☐
CRACKED VAULTS, DETACHMENT FROM ARCHES	☐☐☐
☐ Vaults lowered excessively or thin ☐ Presence of concentrated loads of roof covering	

7. HAMMERING OF THE ROOF COVERING	☐
BEAM SLIDING; DISCONNECTION OF TIE BEAMS	☐☐☐
☐ Roof thrusting; new roof covering rigid and heavy ☐ Lack of connection between tie beams and masonry	

8. DOME	☐
CRACKS IN: DOME, TAMBOUR, LANTERN	☐☐☐
☐ Tambour very high and with large openings ☐ Lack of hoops or external buttresses	

9. OVERTURNING OF THE APSE	☐
VERTICAL OR ARCHED CRACKS IN APSE WALLS	☐☐☐
☐ Lack of hoops or chaining ☐ Weakening from many wall openings	

10. VAULTS IN THE PRESBYTERY OR APSE	☐
CRACKS IN THE VAULT OR APSE BASIN	☐☐☐
☐ Vaults lowered excessively or thin ☐ Presence of concentrated loads by the roof covering	

11. OVERTURNING OF END WALLS	☐
DETACHMENT OF END WALL	☐☐☐
☐ Poor clamping between wall and orthogonal walls ☐ Lack of chains or efficient buttresses	

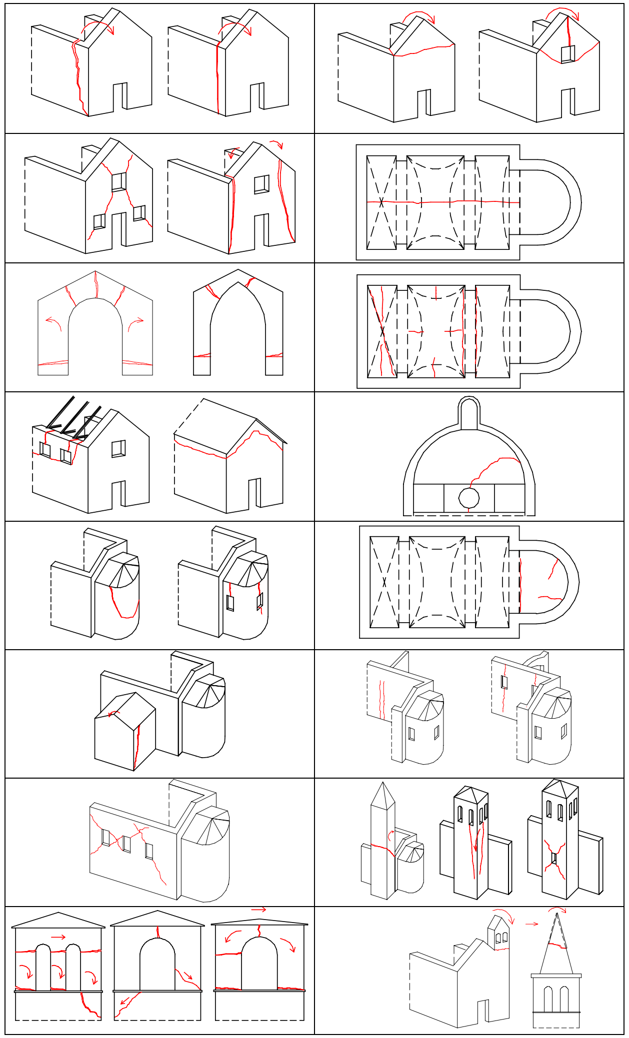
12. LACK OF CONTINUITY IN WALLS	☐
MOVEMENT OF JOINTS OR DISCONNECTEDNESS	☐☐☐
☐ Great difference of stiffness between two parts ☐ Lack of clamping or chains	

13. SHEAR FAILURE OF THE WALLS	☐
SHEAR CRACKS OR LOCAL DISCONTINUITY (OLD OPENINGS etc.)	☐☐☐
☐ Masonry poor or of limited thickness ☐ Great weakening due to the presence of openings	

14. BELL TOWER	☐
CRACKS ON CONTACT WITH THE CHURCH; VERTICAL CRACKS; EXPULSION OF EDGE	☐☐☐
☐ Lack of connections with the church ☐ Masonry decayed, poor, of limited thickness	

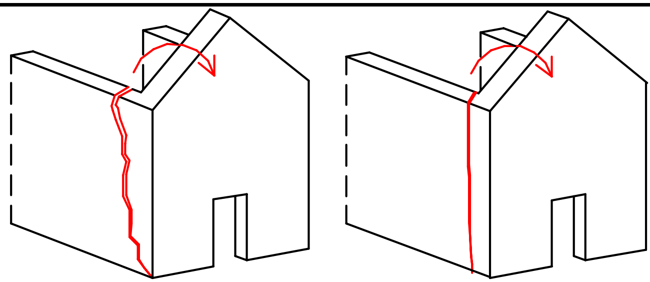
15. BELL CELL	☐
CRACKED ARCHES; PIER ROTATION OR SLIDING	☐☐☐
☐ Lack of chains or hoops; thin piers ☐ Roof covering heavy or thrusting	

16. OVERTURNING OF PROJECTIONS/SPIRES	☐
PERMANENT ROTATION OR SLIDING	☐☐☐
☐ Lack of buttress or other connection ☐ Projection too thin	



The approach for macroelements and damage mechanisms allowed, during inspection operations, the association of the cracks and deformations observed to a particular damage mechanism , more or less developed at the time of the earthquake

the presence of macroelement

1	**OVERTURNING OF THE FACADE**	☐
Damage	DETACHMENT OF THE FACADE FROM WALLS	☐ ☐ ☐
Vulnerability	☐ Poor clamping between facade and nave walls ☐ Lack of longitudinal chains or efficient buttresses	
		

the level damage: 0 - no damage; 1 - light damage; 2 - medium damage; 3 - severe damage/collapse

the intrinsic vulnerability of the building to that mechanism, through two indicators linked to specific construction weaknesses

DAMAGE AND VULNERABILITY SCORES

The vulnerability model is synthesized by two indexes obtained through the simple average of levels of damage in the actual macroelements and the vulnerability scores,

Damage Score: is a continuous variable between 0 and 1 which measures the average level of damage to the church

$$i_d = \frac{1}{3N} \sum_{k=1}^{16} d_k$$

d_k= is the damage in the *k*-th mechanism (from 0 to 3)

N= is the number of mechanisms that can be potentially activated in the church ($N \leq 16$).

Vulnerability Score: is linked to the propensity of the church to be damaged by the earthquake

$$i_v = \frac{1}{2N - m} \sum_{k=1}^{16} v_k$$

v_k= are the indicators of vulnerability present in the *k*-th mechanism (from 0 to 2)

m = is the number of questions about vulnerability to which it was not possible to reply (for example certain zones of the construction may not be inspected in an emergency or elements to supply a judgement are not available).

In order to make the vulnerability analysis of churches consistent with the one of ordinary buildings in territorial risk analysis, it is necessary to transform the damage score into a discrete variable, that is to establish a correlation with the six levels of damage of the EMS-98 Scale

Level	Damage score	Description of structural damage
0	$i_d \leq 0.05$	No damage: light damage only in one or two mechanisms
1	$0.05 < i_d \leq 0.25$	Negligible to slight damage: light damage in some mechanisms
2	$0.25 < i_d \leq 0.4$	Moderate damage: light damage in many mechanisms with one or two mechanisms activated at medium level
3	$0.4 < i_d \leq 0.6$	Substantial to heavy damage: many mechanisms have been activated at medium level, with severe damage in some mechanisms
4	$0.6 < i_d \leq 0.8$	Very heavy damage: severe damage in many mechanisms, with the collapse of some macroelements of the church
5	$i_d > 0.8$	Collapse: at least 2/3 of the mechanisms exhibit severe damage

DPM, obtained from the data collected in Umbria: 1000 churches

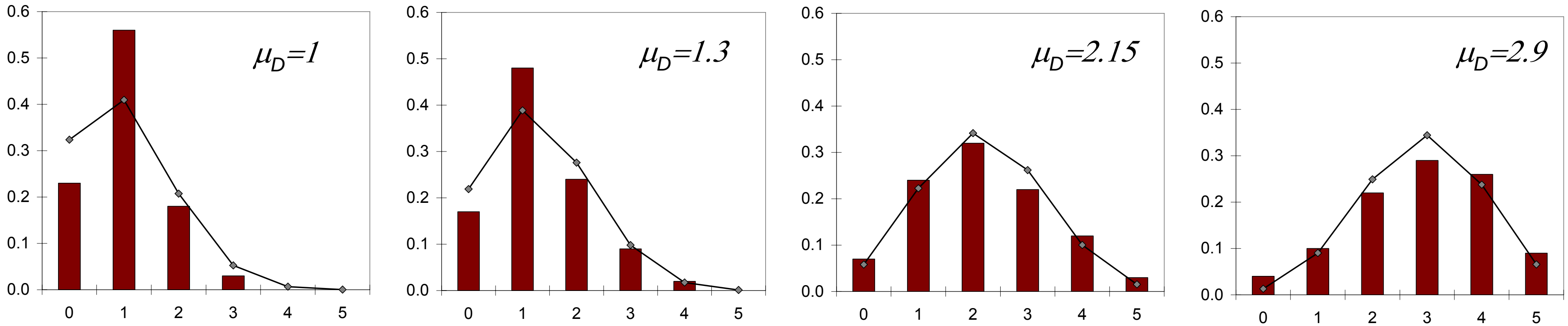
The complete sample has been split into four different groups, with reference to the macroseismic intensities (MCS scale);

The continuous line corresponds to the binomial distribution relative to the mean damage grade of the data set

$$p_k = \frac{5!}{k!(5-k)!}\left(\frac{\mu_D}{5}\right)^k\left(1-\frac{\mu_D}{5}\right)^{5-k} \qquad K = (0, 1, 2, 3, 4, 5)$$

UMBRIA

I_{mcs} = V **I_{mcs} = VI** **I_{mcs} = VII** **I_{mcs} = VIII**

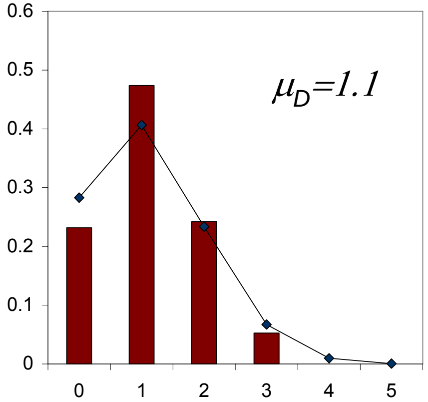


Analogously to the buildings, it emerges the good fit of the binomial function to the observed damage distribution

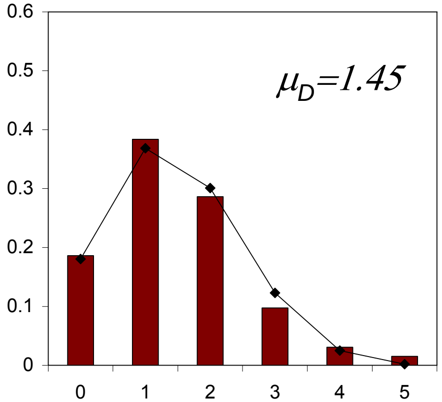
Analogously to the analysis on the Umbria churches, statistical analyses have been made on databases, related to another Italian earthquakes.

THE MARCHES

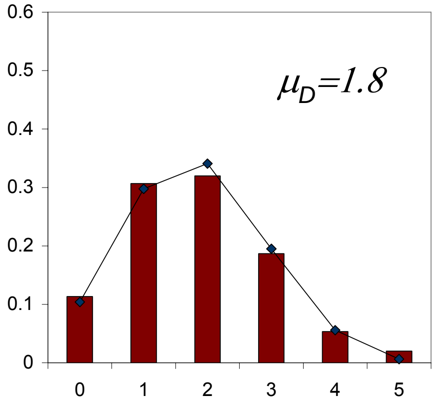
I_{mcs} = V



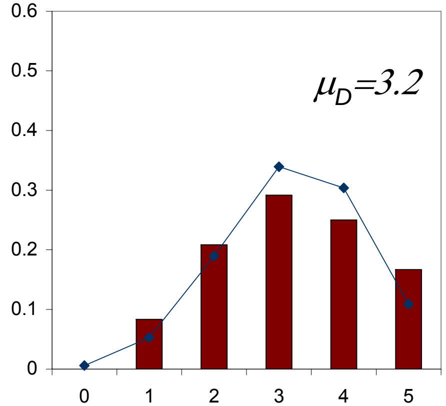
I_{mcs} = VI



I_{mcs} = VII



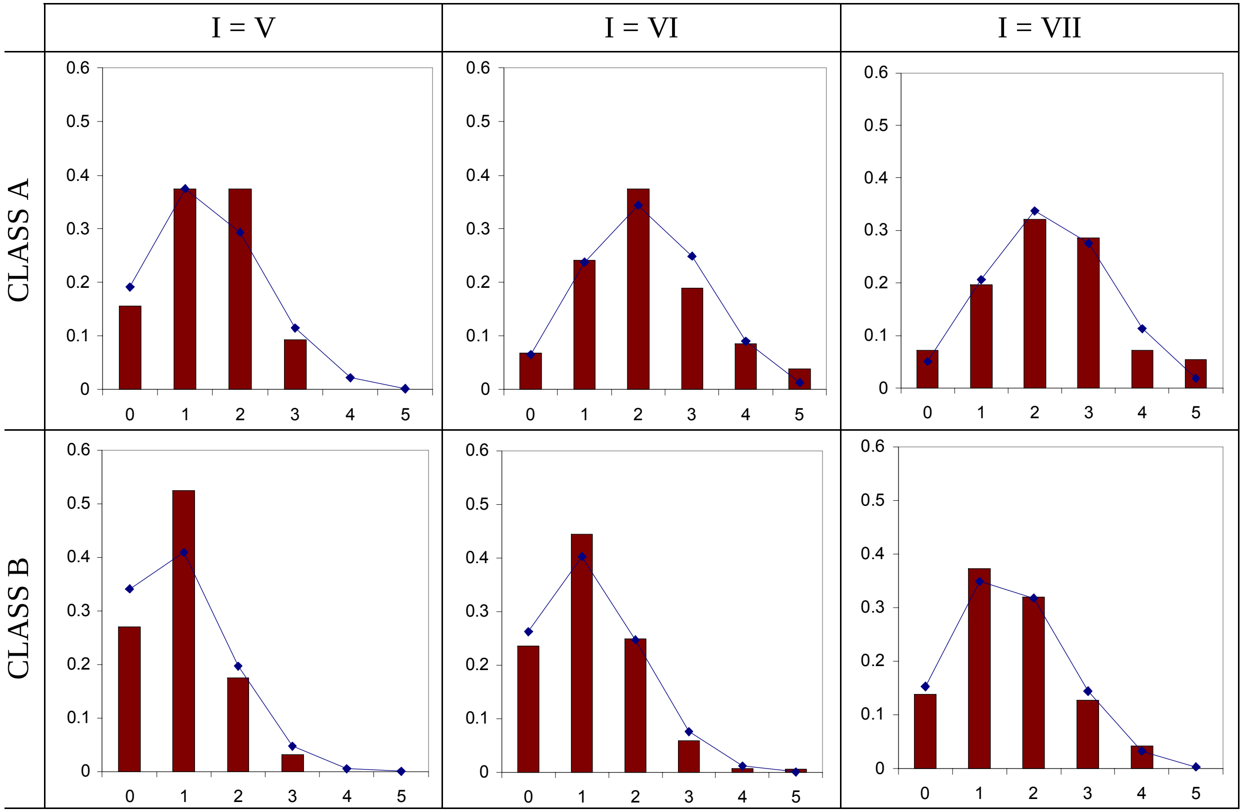
I_{mcs} = VIII



Also in this case the histograms are very well fitted by the binomial distribution and the mean damage grades, associated to each macroseismic intensity, are similar to the one representative of churches in Umbria.

As is obvious, this parameter gradually increases with the intensity of the earthquake

The available data are then spilt by considering the vulnerability score into two classes: A - more vulnerable churches (*iv*≥0.4); B - less vulnerable churches (*iv*<0.4).



THE MARCHES

For the intensity I=VIII the sample is too scant to assure a significant result from the statistical point of view.

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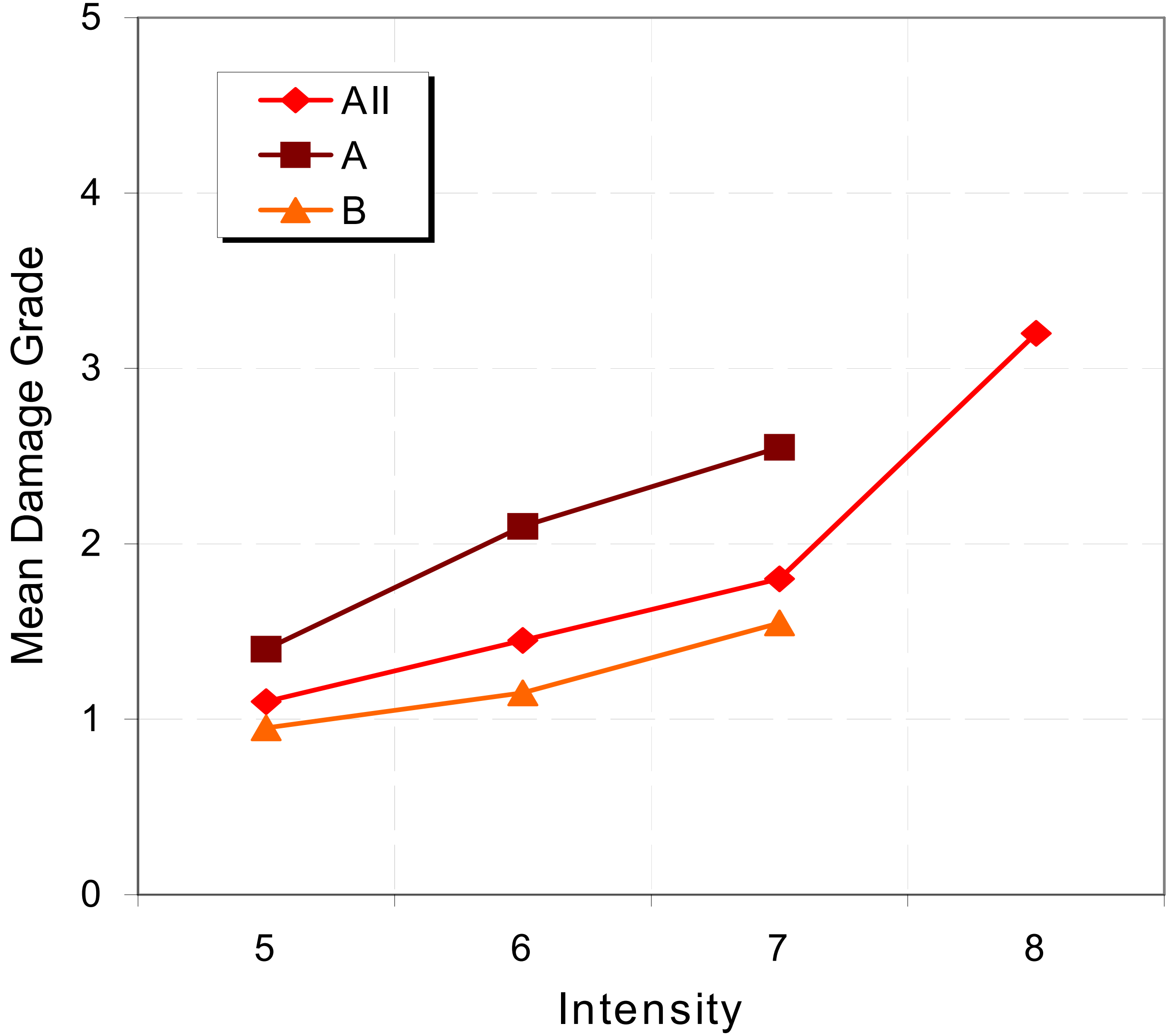

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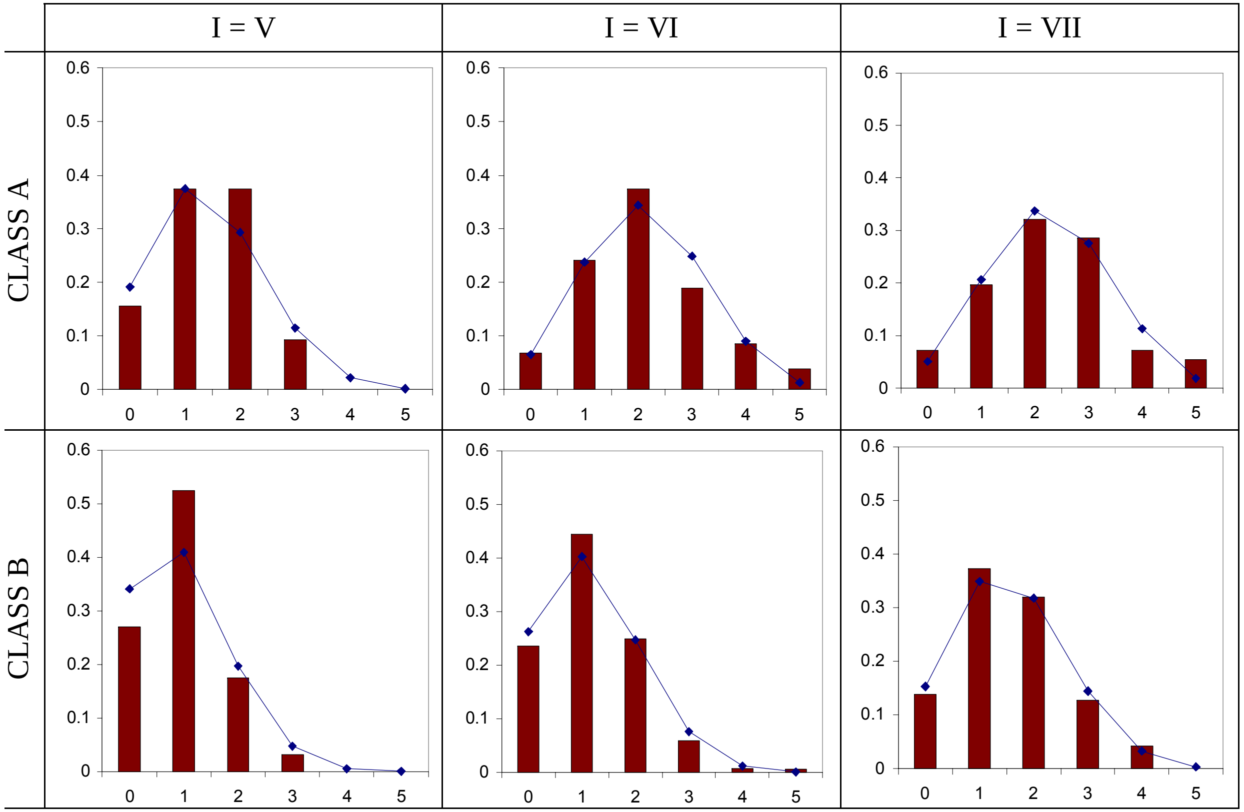

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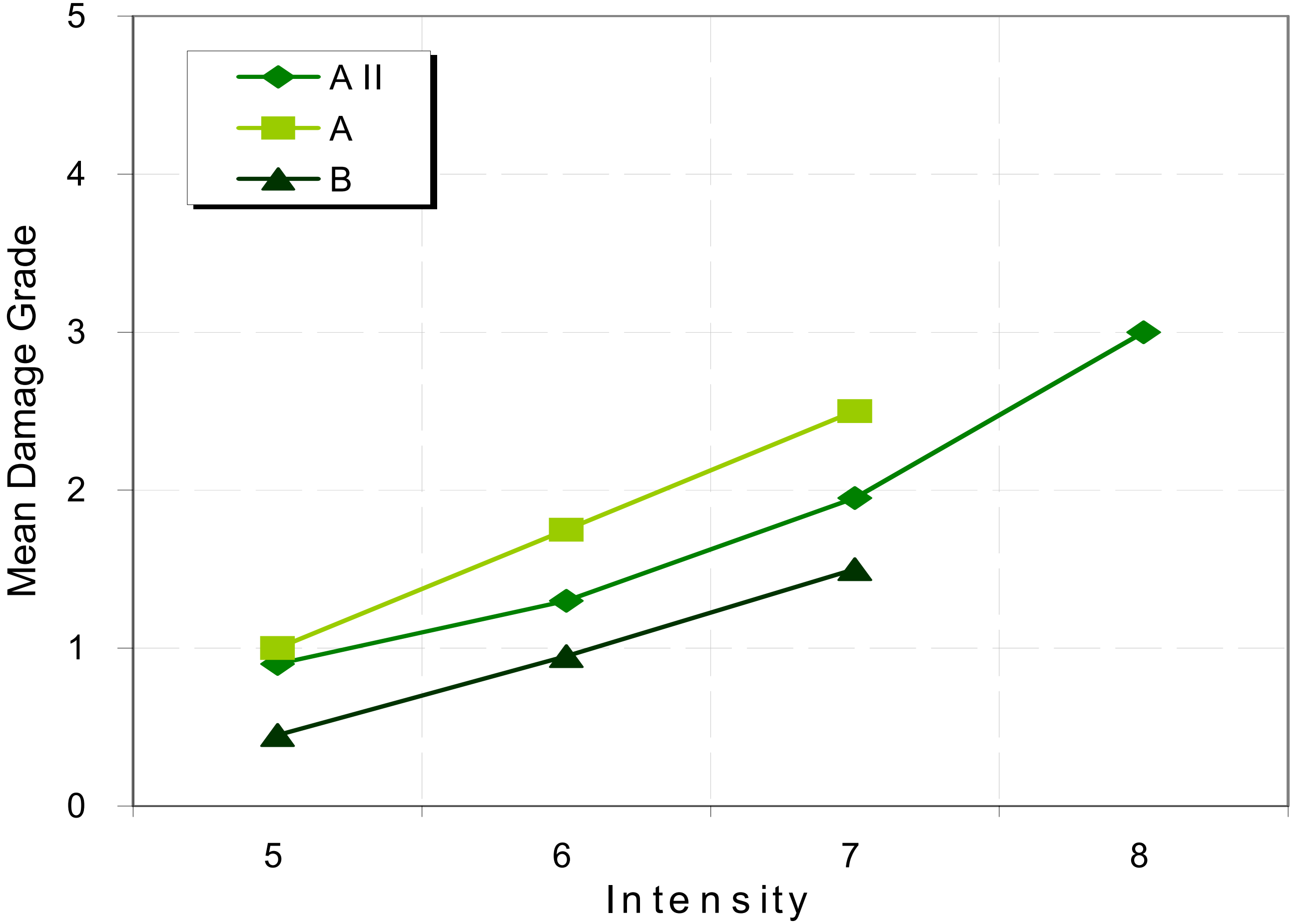


UMBRIA

the churches of Class A are remarkably more vulnerable than the ones of Class B, confirming the meaningfulness of the vulnerability score.

The choice of considering two vulnerability classes derives from the analogous approach used in MSK scale for the ordinary buildings; the damage of class B, is nearly the same as that in the churches of class A, for an intensity one degree less

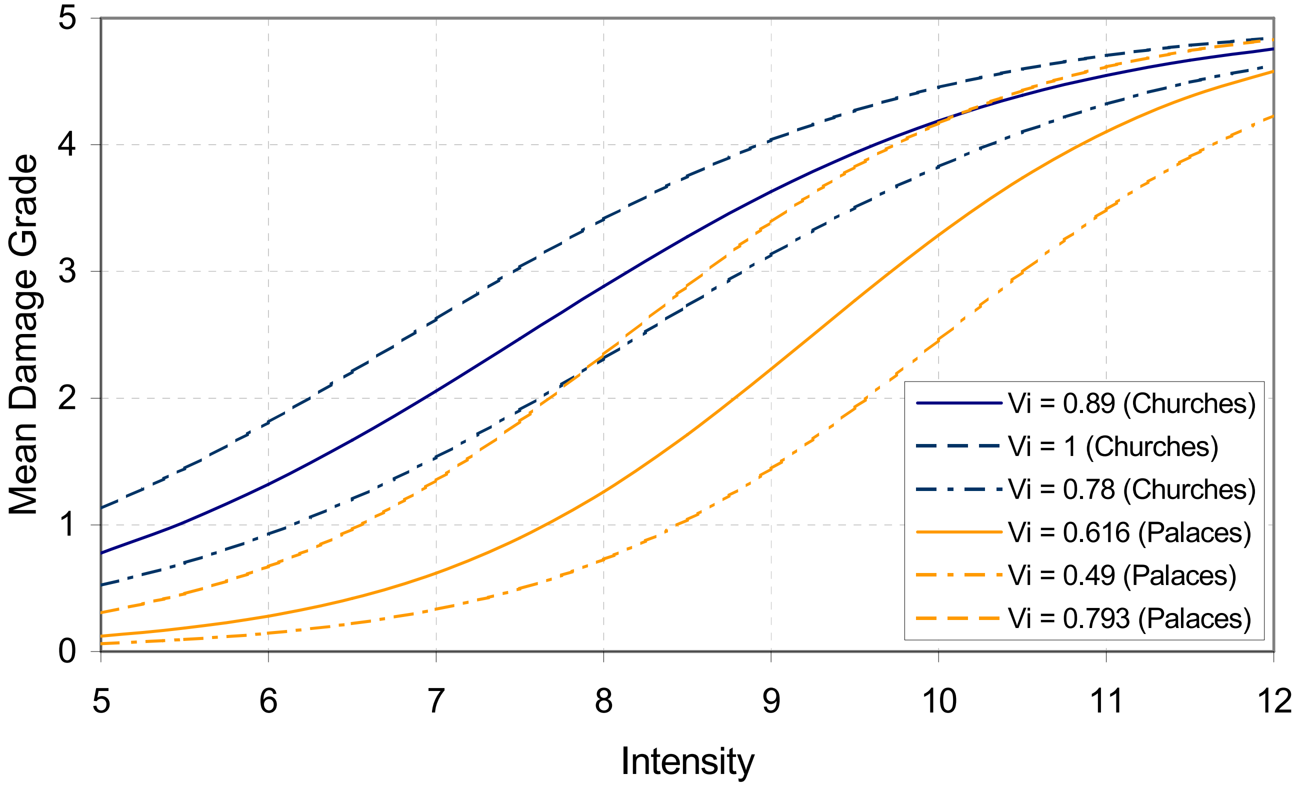
I_{MCS}	μ_D	UMBRIA				THE MARCHES			
		N°	All	Class A	Class B	N°	All	Class A	Class B
V	1.025	295	1	1.15	0.45	95	1.1	1.4	0.95
VI	1.385	616	1.3	1.8	0.95	779	1.45	2.1	1.15
VII	2.015	245	2.15	2.25	1.5	150	1.8	2.25	1.55
VIII	3	47	2.9	-	-	24	3.2	-	-

PALACES

Q = 2.3	V_{max} = 0.79
	V = 0.49
	V_{min} = 0.62

CHURCHES

Q = 3	V_{max} = 1
	V = 0.89
	V_{min} = 0.78



The two models confirm what is normally observed after a seismic event: churches are more vulnerable than buildings, especially in the case of low intensity earthquakes.
It is worth noting that the values of the denominator in the two function are different; this parameter determines the slope of the curve.

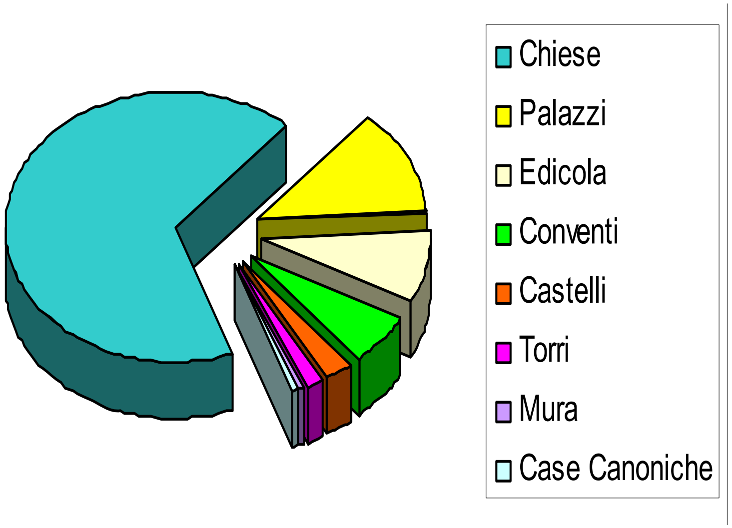
ARCHIVE RESEARCH

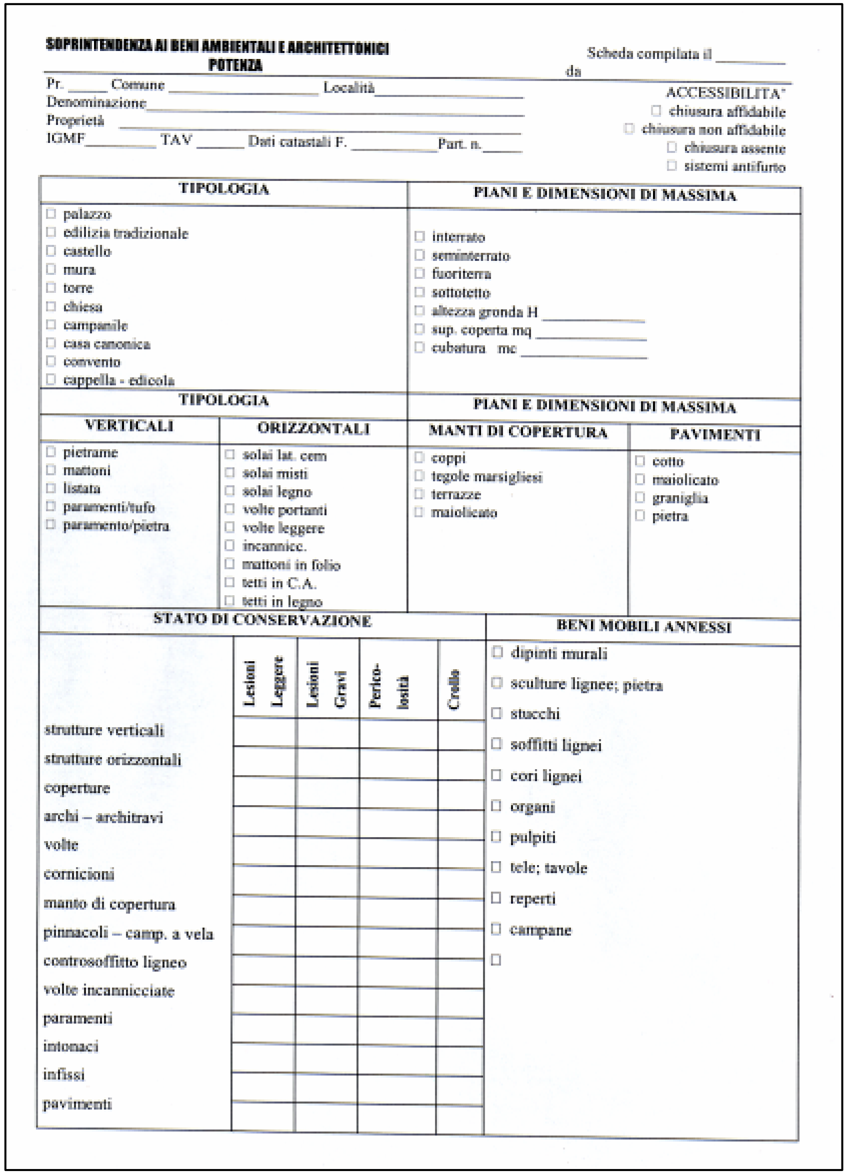
Seismic events	*Typologies*	*Material sources*
Irpinia (Italy) November 23, 1980	Churches, Convents, Towers, Castles	SBBA di Potenza - MBC
Lunigiana e Garfagnana October 10, 1995	Churches	Region Tuscany
Umbria and The Marches September 26, 1997	Churches, Convents, Towers, Castles	Region Umbria - MBC
Molise November 1, 2002	Churches, Convents, Towers, Castles	Region Molise - MBC
Piedmont April 11, 2003	Churches	Regione Piedmont – MBC
Lombardy November 24, 2004	Churches	Regione Lombardy – MBC

This archive research has been finalized to individuate, as for the churches, a wide observation information about the damage levels and the collapse modes for other monumental typologies.

IRPINIA - BASILICATA

Specific survey form: the data collected are very poor but allows the identification of the typology of the monumental building





SOPRINTENDENZA AI BENI AMBIENTALI E ARCHITETTONICI
POTENZA

Scheda compilata il ________ da

Pr. _____ Comune ________________ Località ________________
Denominazione ____________________________________
Proprietà ____________________________________
IGMF ________ TAV ______ Dati catastali F. __________ Part. n. _____

ACCESSIBILITA'
☐ chiusura affidabile
☐ chiusura non affidabile
☐ chiusura assente
☐ sistemi antifurto

TIPOLOGIA	PIANI E DIMENSIONI DI MASSIMA
☐ palazzo ☐ edilizia tradizionale ☐ castello ☐ mura ☐ torre ☐ chiesa ☐ campanile ☐ casa canonica ☐ convento ☐ cappella - edicola	☐ interrato ☐ seminterrato ☐ fuoriterra ☐ sottotetto ☐ altezza gronda H ________ ☐ sup. coperta mq ________ ☐ cubatura mc ________

TIPOLOGIA		PIANI E DIMENSIONI DI MASSIMA	
VERTICALI	ORIZZONTALI	MANTI DI COPERTURA	PAVIMENTI
☐ pietrame ☐ mattoni ☐ listata ☐ paramenti/tufo ☐ paramento/pietra	☐ solai lat. cem ☐ solai misti ☐ solai legno ☐ volte portanti ☐ volte leggere ☐ incannicc. ☐ mattoni in folio ☐ tetti in C.A. ☐ tetti in legno	☐ coppi ☐ tegole marsigliesi ☐ terrazze ☐ maiolicato	☐ cotto ☐ maiolicato ☐ graniglia ☐ pietra

STATO DI CONSERVAZIONE

	Lesioni Leggere	Lesioni Gravi	Pericolosità	Crollo
strutture verticali				
strutture orizzontali				
coperture				
archi – architravi				
volte				
cornicioni				
manto di copertura				
pinnacoli – camp. a vela				
controsoffitto ligneo				
volte incannicciate				
paramenti				
intonaci				
infissi				
pavimenti				

BENI MOBILI ANNESSI

☐ dipinti murali
☐ sculture lignee; pietra
☐ stucchi
☐ soffitti lignei
☐ cori lignei
☐ organi
☐ pulpiti
☐ tele; tavole
☐ reperti
☐ campane
☐

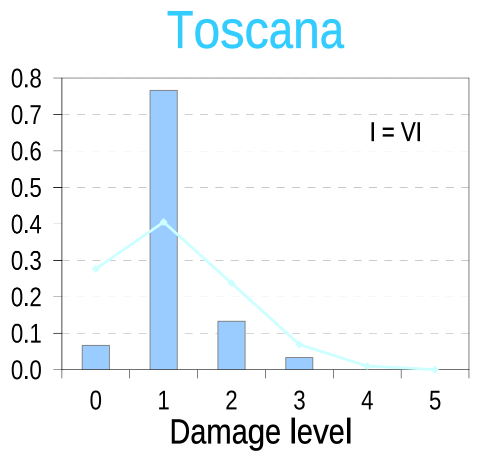
Damage level:

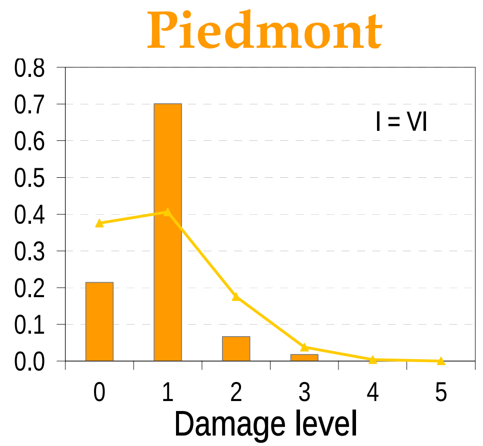
No Damage	→	-	→	0
Slight Damage	→	A	→	1
Moderate Damage	→	B	→	2
Heavy Damage	→	C	→	3
Collapse	→	D	→	4

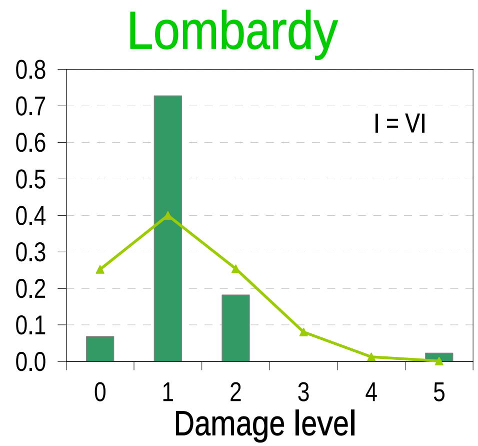
$$\rightarrow \quad i_d = \frac{\sum_i p_i \cdot D_i}{4} \quad \rightarrow$$

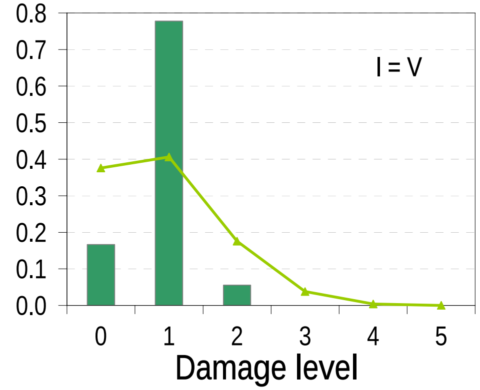
EMS-98 Damage Level

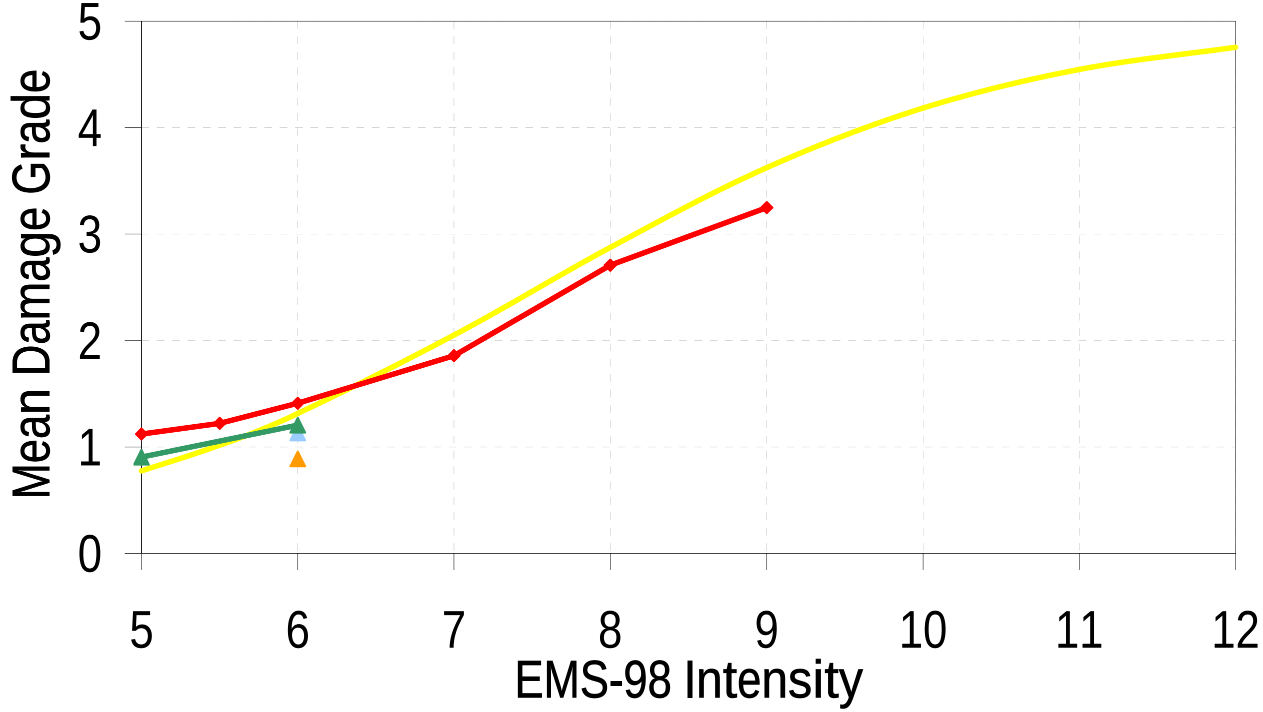
CHURCHES


Toscana
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
I = VI
0
1
2
3
4
5
Damage level

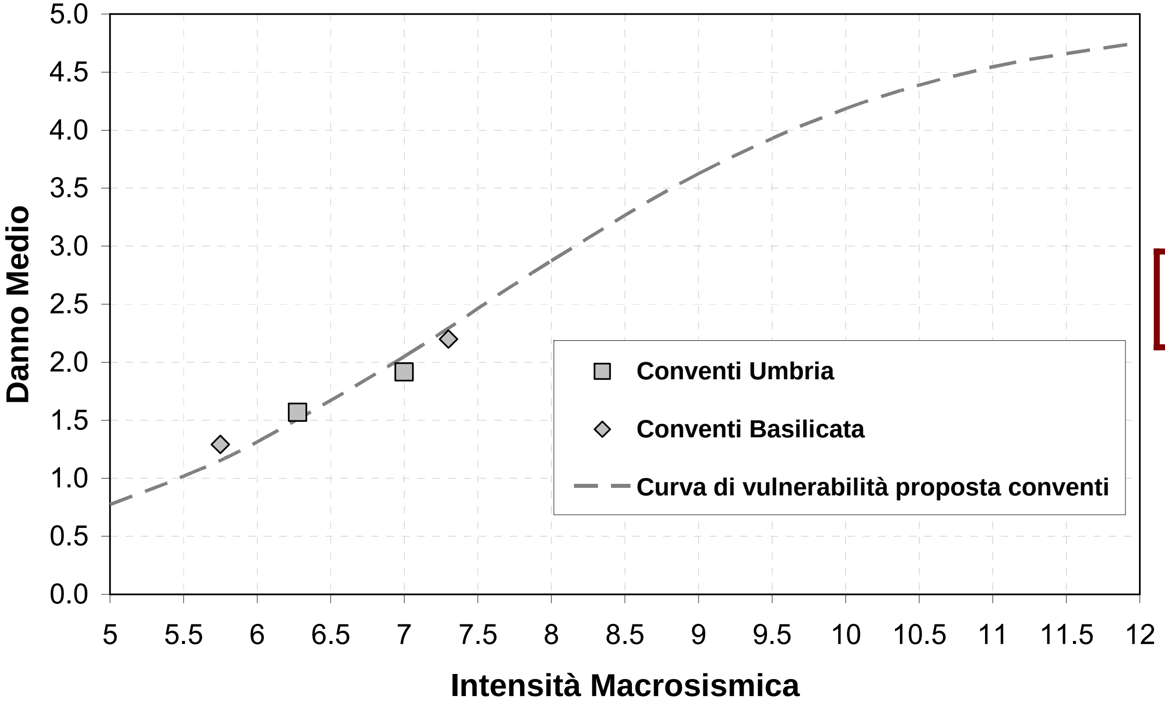

Piedmont
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
I = VI
0
1
2
3
4
5
Damage level


Lombardy
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
I = VI
0
1
2
3
4
5
Damage level


0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
I = V
0
1
2
3
4
5
Damage level


Mean Damage Grade
5
4
3
2
1
0
5
6
7
8
9
10
11
12
EMS-98 Intensity

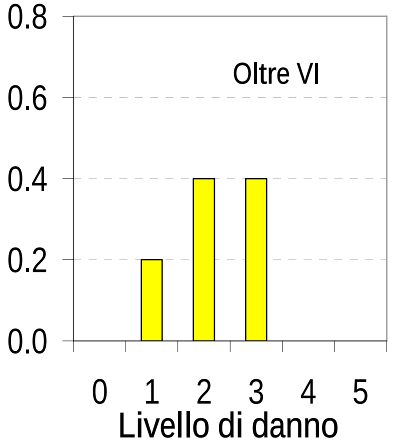
CONVENTS

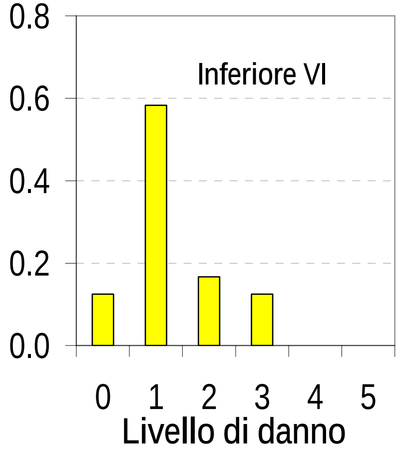


Q = 3	V = 0.89

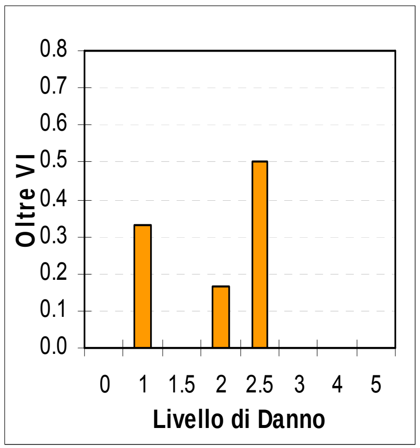
The same vulnerability curve used for the churches is adopted for the convents

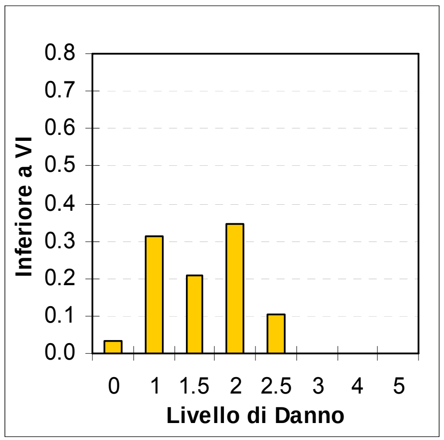
Basilicata





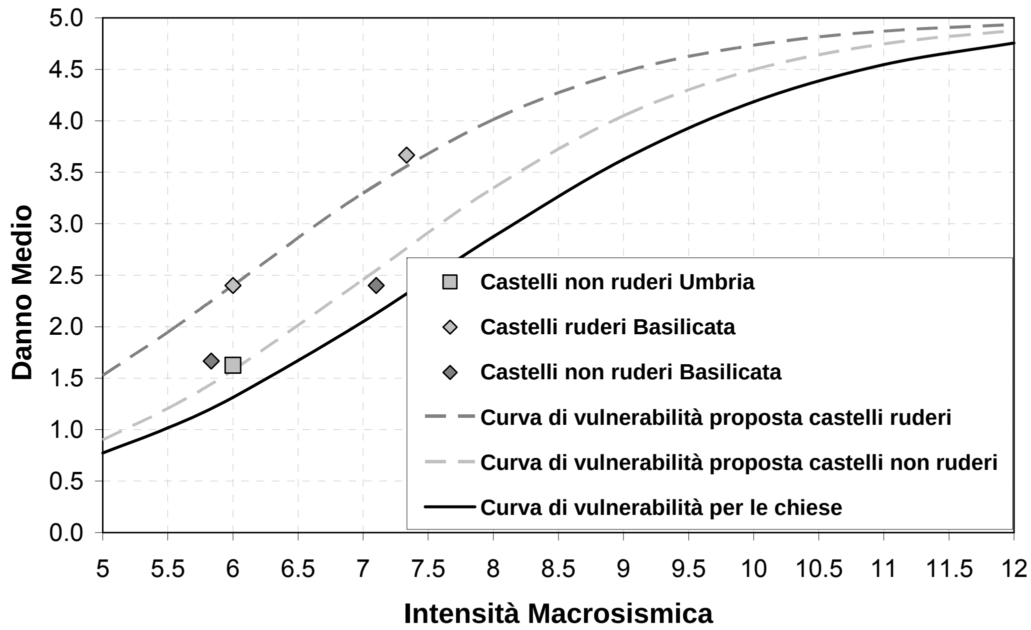
Umbria





CASTLES

Q = 2.7	V = 0.97
Behaviour Modifier $\Delta V_I = 0.2$	



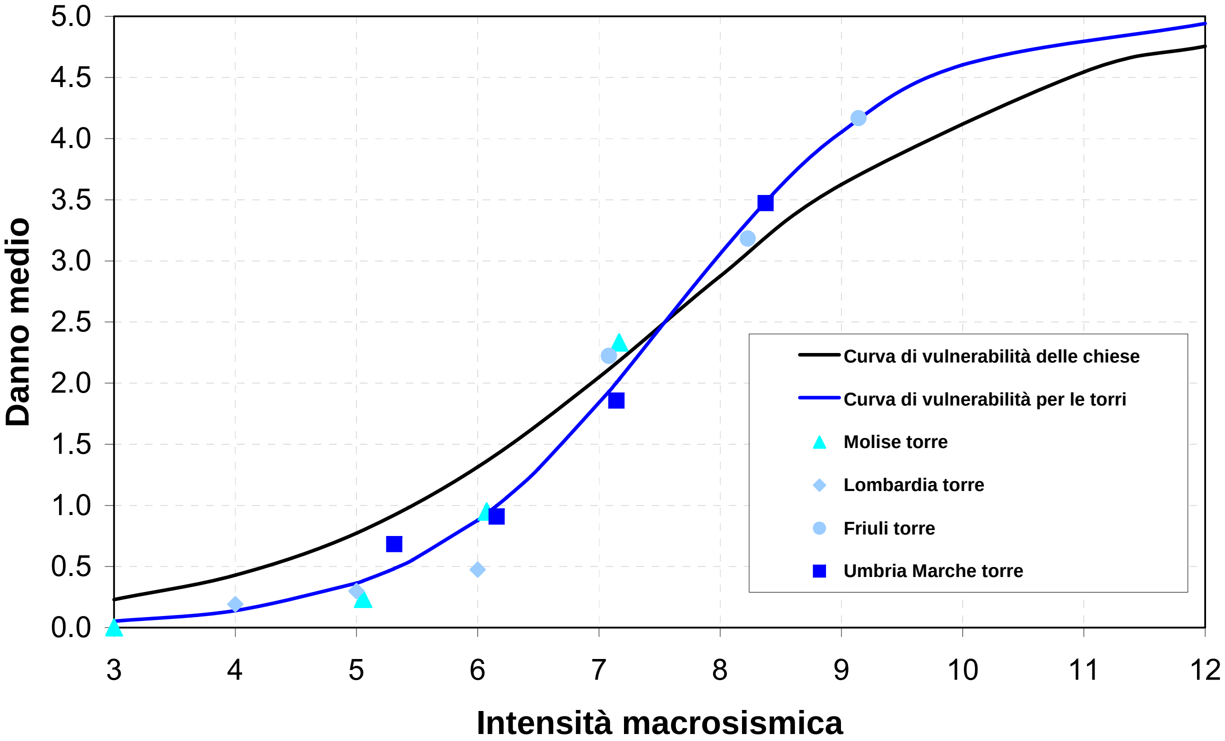
State of maintenance before the seismic event: **ruin**



State of maintenance before the seismic event: **not-ruin**



BELL TOWER

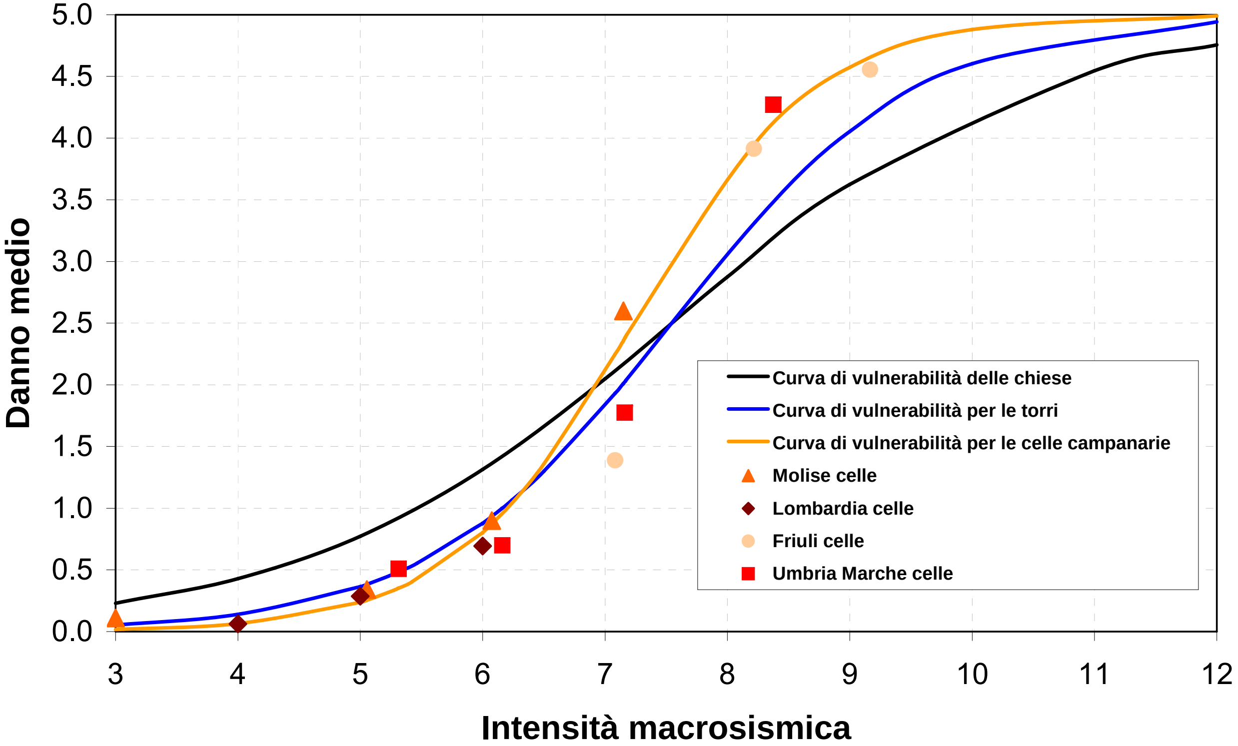


Q = 2	V = 0.89

Limited vulnerability for low macroseimic intensity. Rapid increment of the damage when the seismic severity increases

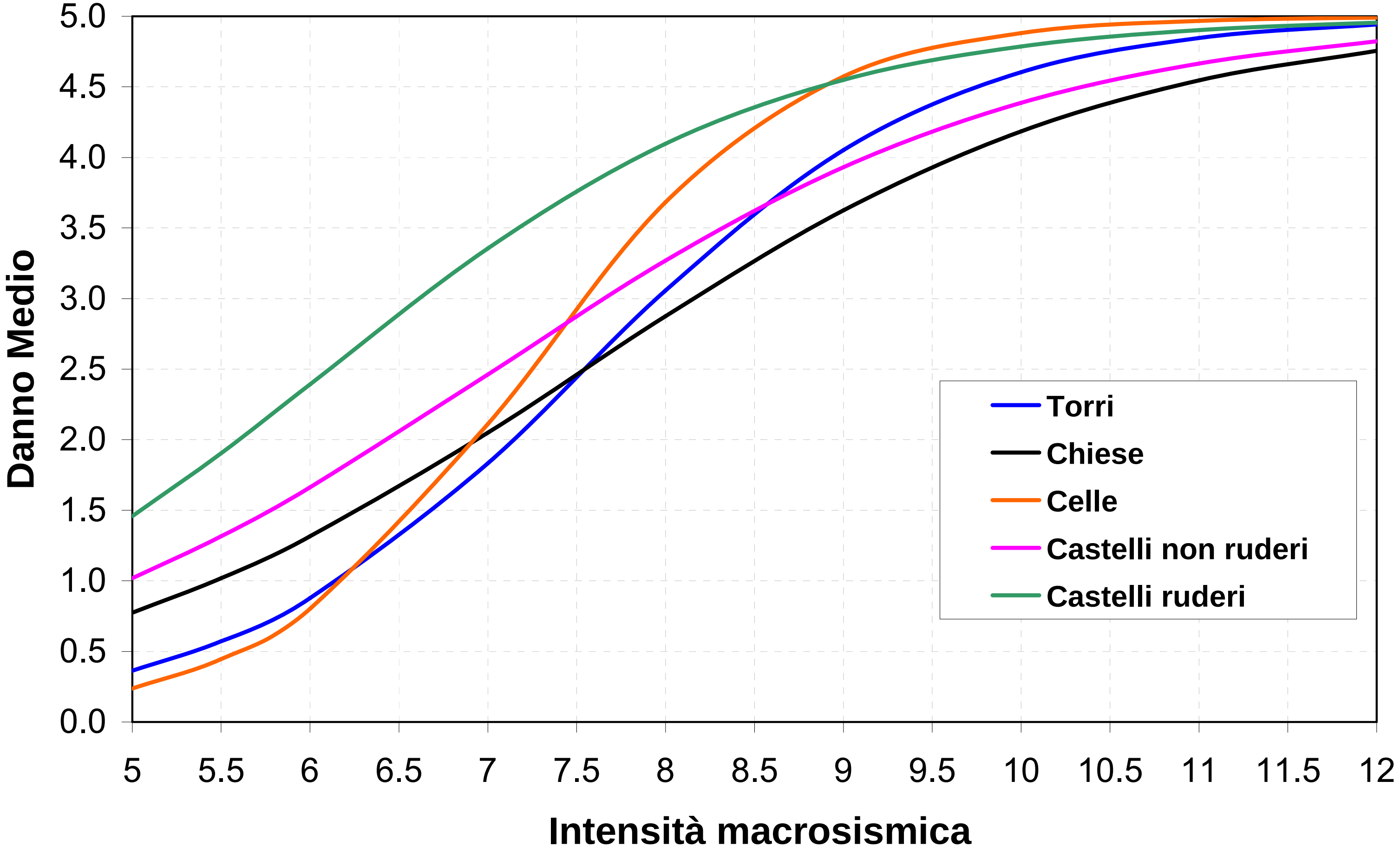



CELL OF THE BELL TOWER



Q = 1.49	V = 0.94

- Lower displacement capacity for the pier of the cell
- The seismic demand, in term of displacement, is higher for the cell

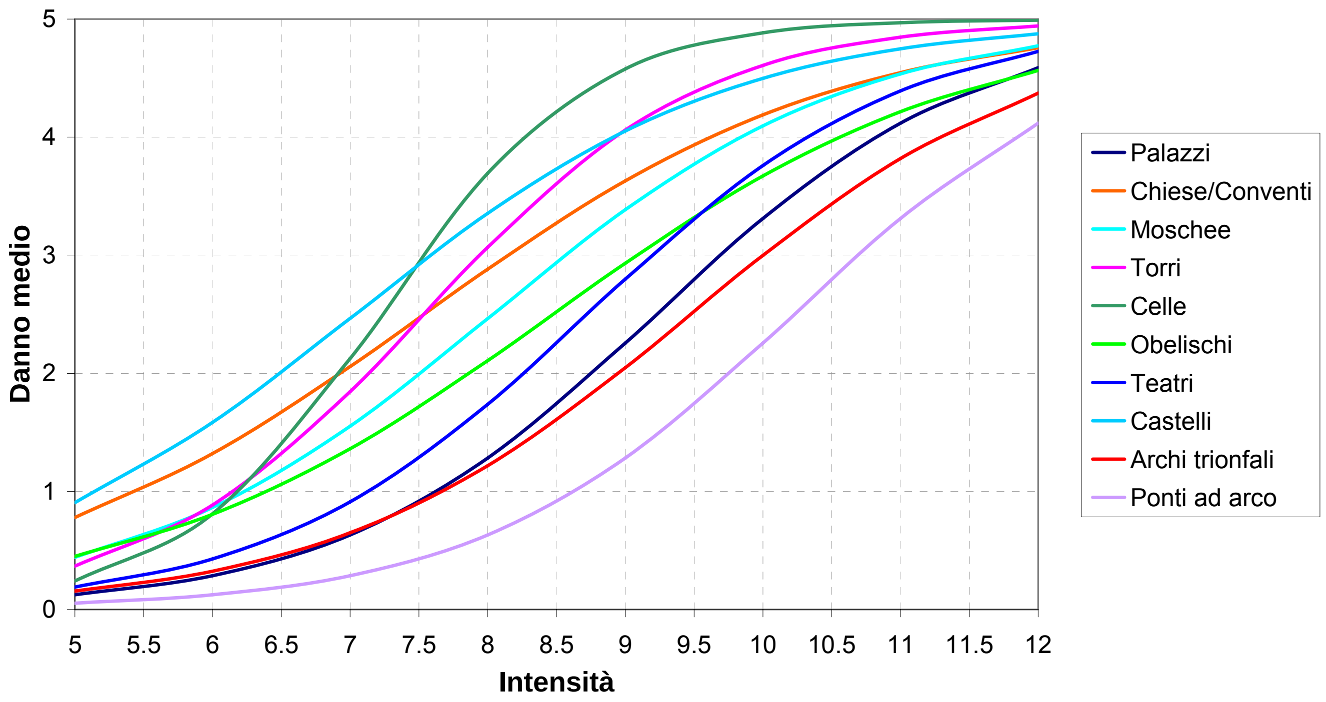


TIPOLOGY	Q	V
Churches	3.0	0.89
Convents	3.0	0.89
Castles	2.7	0.97
Towers	2.0	0.89
Cells	1.49	0.94

LEVEL 0: Macroseimic Approach

Typology	V	Q
Palaces	0.62	2.3
Churches	0.89	3.0
Convents	0.89	3.0
Mosques	0.81	2.6
Towers	0.89	2.0
Cells	0.94	1.49

Typology	V	Q
Obelisks	0.74	3
Theaters	0.70	2.3
Castles	0.97	2.7
Triumphal arches	0.58	2.6
Arch Bridges	0.46	2.3



LEVEL 1: Macroseimic Approach

The vulnerability index is modified taking into account the further information available

State of preservation	worst	+ 0.04
	medium	0
	good	- 0.04
Damage level	severe	+ 0.04
	light	+ 0.02
	none	0
Architectural transformations	yes	+ 0.02
	no	0
Recent interventions	yes	+ 0.02
	no	- 0.02

Masonry quality	yes	+ 0.05
	no	0
Site morphology	ridge	+ 0.04
	sloping	+ 0.02
	flat ground	0
Plan regularity	*It depends from the typology*	
Section regularity	*It depends from the typology*	
Position	*It depends from the typology*	

- parametri *specifici* per ogni tipologia (ad es. chiese)

Plan regularity: nave typology	central	- 0.02
	one	0
	three	+ 0.02
Section regularity: raising elements or façade	yes	+ 0.04
	no	0
Position	included	- 0.02
	additions	+ 0.02
	isolated	0

Domes/Vaults	yes	+ 0.04
	no	0
Lateral walls height	low (< 6 m)	- 0.02
	medium (> 6 m and < 12 m)	0
	high (> 12 m)	+ 0.04

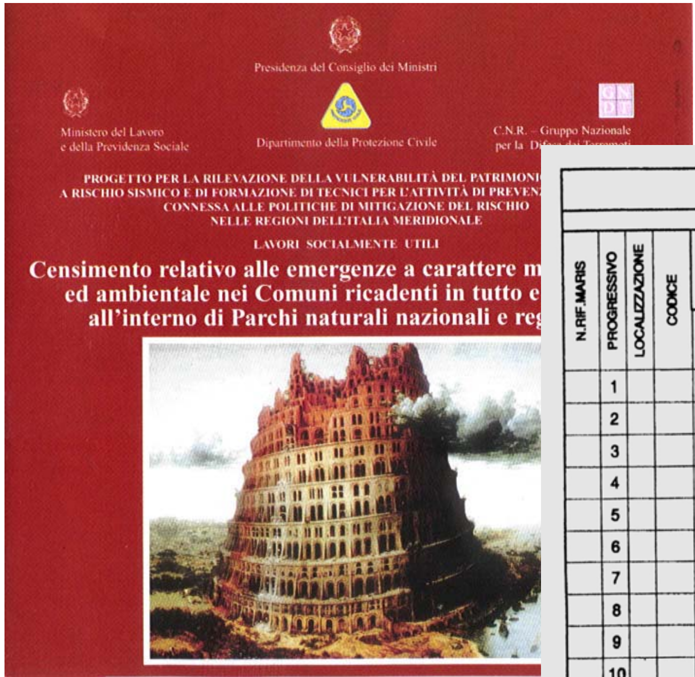
SAVE: Strumenti Aggiornati per la Vulnerabilità sismica del patrimonio Edilizio e dei sistemi urbani

INGV

PROTEZIONE CIVILE NAZIONALE

GNDT

Censimento LSU – Parchi: edito dal Dipartimento di Protezione Civile



CHECK - LIST

ISTAT COMUNE | COMUNE | Data | Squadra | LISTA n.

DATI GENERALI | PARTE "A VISTA" | PARTE "NON A VISTA"

N.RIF.MARIS	PROGRESSIVO	LOCALIZZAZIONE	CODICE	CARTOGRAFIA DI RIFERIMENTO QUA	FOG	TAV	ALL	N. RIFER.IN CARTA	DENOMINAZIONE	LOCALITA' O INDIRIZZO	QUOTA	FOTO n° Roll	n° foto	distan.	POSIZIONE	ACCESSIB. sito	edificio	MORFOLOGIA	STATO CONSERV.	DESTINAZIONE	CONSISTENZA LU (m.)	LA (m.)	H (m.)	UTILIZZAZIONE	VINCOLO	PROPRIETA'	DOCUMENTAZIONE	CODICE T.C.I.	PARCO	DATAZIONE
	1																												
	2																												
	3																												
	4																												
	5																												
	6																												
	7																												
	8																												
	9																												
	10																												
	11																												
	12																												
	13																												
	14																												
	15																												

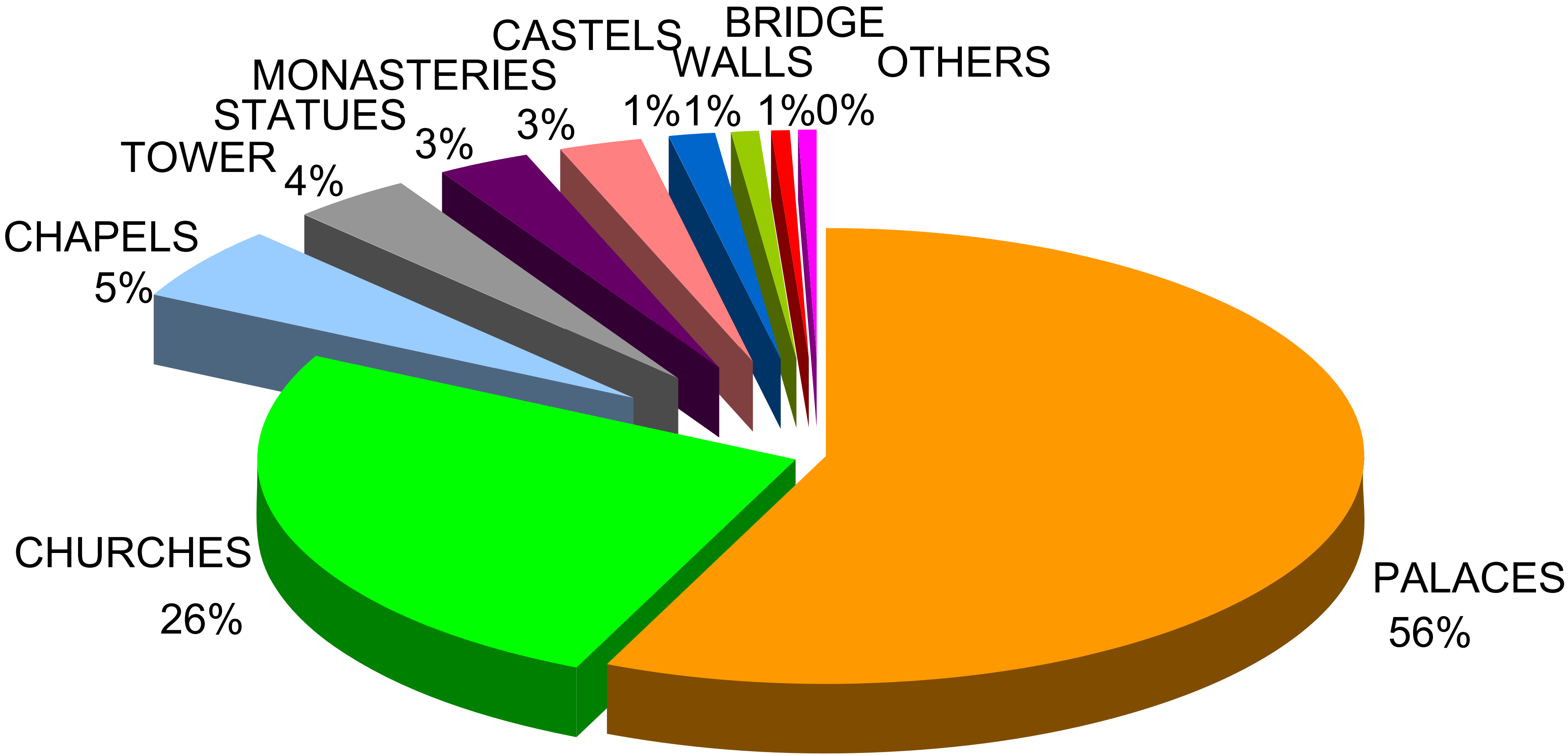
NOTE: indicare, richiamando il n° progressivo, le eventuali DENOMINAZIONI storiche, le eventuali modalità per l'ACCESSIBILITA' all'edificio, la fonte della DATAZIONE e il numero Scheda MARIS se esistente

Scheda LSU – Parchi : *check-list* usata per catalogare gli edifici monumentali nelle località situati all'interno dei Parchi Nazionali dell'Italia Medionale.

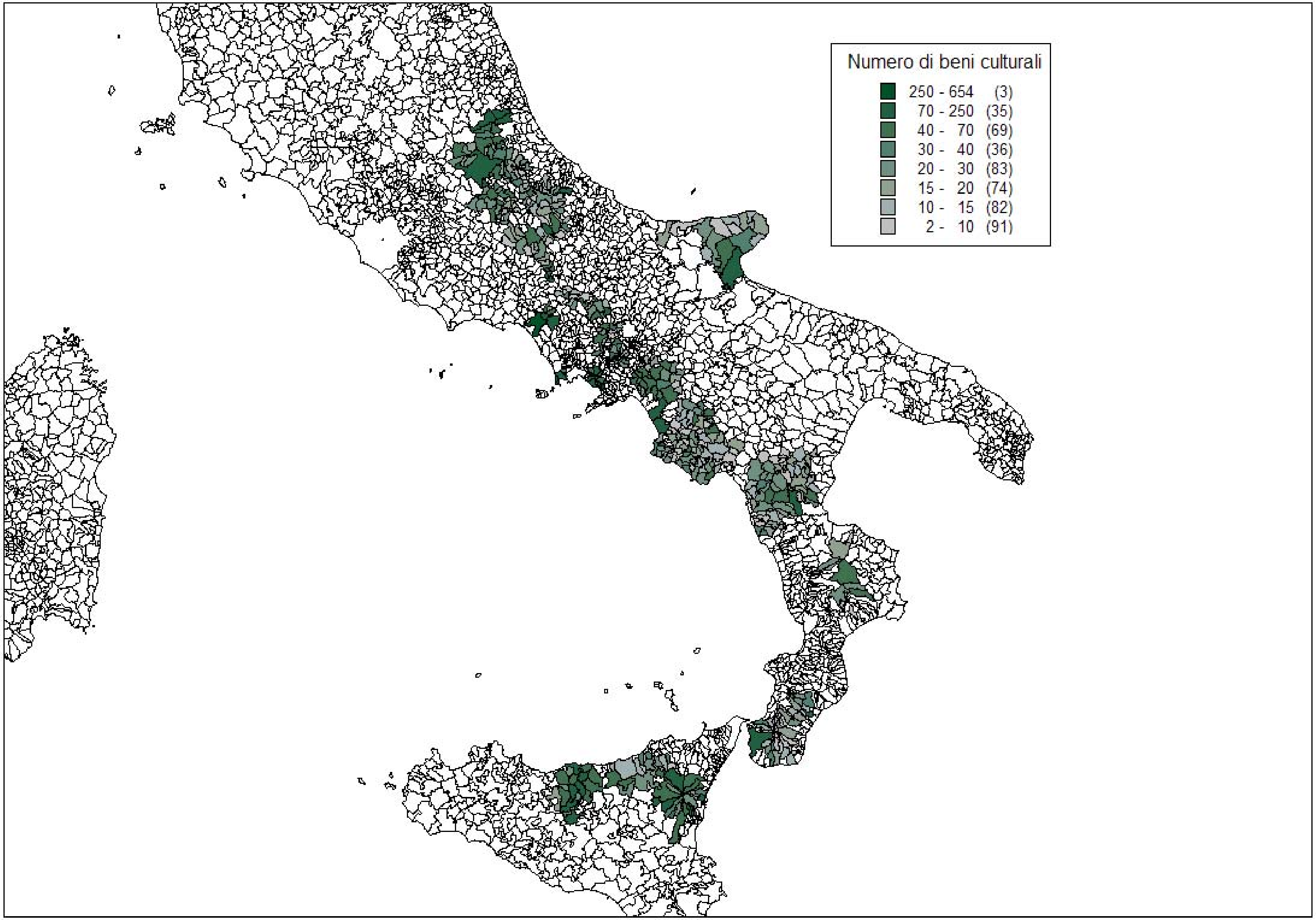
Macroseismic Method for monuments– Level 1

Level 1 vulnerability analysis of the cultural heritage for the parks of South of Italy (LSU Park Project)

Distribution of the typology for the 1400 analyzed buildings

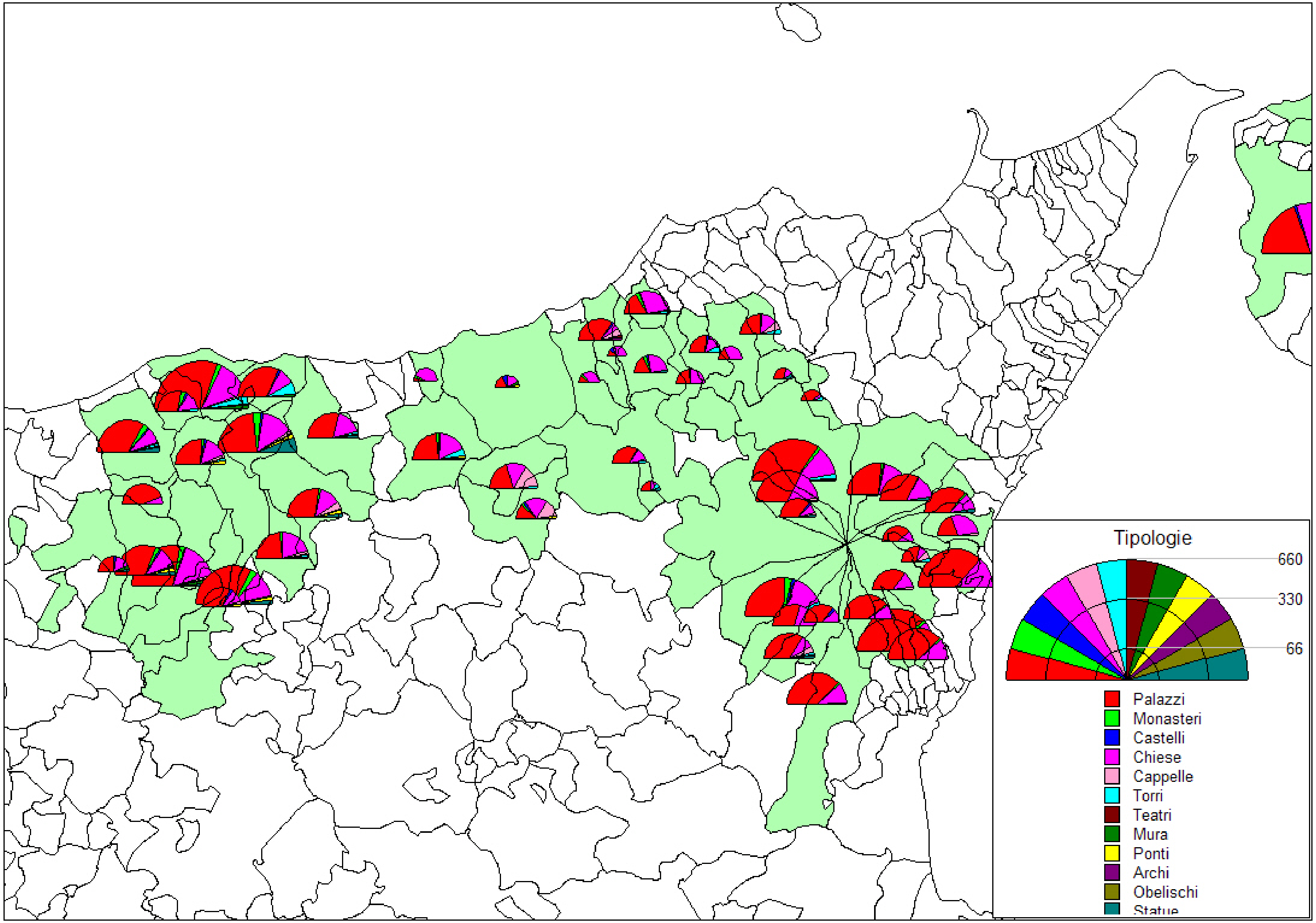


LSU Park Project - Exposure analysis and geocoding



Number of monumental building for each municipality

LSU Park Project - **Exposure analysis and geocoding**



Distribution of the typologies of monumental buildings within the municipality of Sicily region

	S. AGOSTINO CHURCH	S. AGOSTINO CONVENT	MONTE DEI PEGNI PALACE
V	0.89	0.89	0.62
Q	3	3	2.3

TYPOLOGICAL IDENTIFICATION

Level 0

Chiave	61004451/4 3	61004451/4 4	61004451/4 5
Istat Comune	61004	61004	61004
Squadra	45	45	45
Lis			
Pr			
Sc			
Lo			
Co			
Codice Maris2	1	1	3
Codice Maris3	7	13	10
Quadrante	4	4	4
Foglio	3	4	5
Tavola			
Allegato			
Riferimento Carta			
Denominazione	CHIESA DI S. AGOSTINO	CONVENTO DI S. AGOSTINO	PALAZZO MONTE DEI PEGNI
Località			
Indirizzo	VIA ROMA P.ZZA S. AGOSTINO	P.ZZA S. AGOSTINO	V. DELL'ANNUNZIATA
Quota	100	100	100
Numero Roll	1	1	1
Numero Foto			6
Distanza			20
Posizione			2
Sito			0
Edificio			1
Morfologia			1
Stato Conservativo	0	0	0
Destinazione	S62	S32	
Lunghezza	30	33	14
Larghezza	12	50	6
Altezza	18	13	11
Utilizzazione	2	1	1
Vincolo1	2	2	2
Vincolo2			
Vincolo3			
Proprieta'	0	0	0
Documentazione	3	3	1
Codice TCI	1	1	1
Parco			
Datazione	XIV	XIV	1687
Denom storic			
Accessib			
Fonte datazione			
Note			
Memorizzazione	21/10/1998	23/10/1998	23/10/1998
Codice Istat Regione	15	15	15
Denom_Parco	Regionale Partenio	Regionale Partenio	Regionale Partenio

	S. AGOSTINO CHURCH	S. AGOSTINO CONVENT	MONTE DEI PEGNI PALACE
V_O	0.89	0.89	0.62
Q	3	3	2.3
V	0.87	0.93	0.64

Chiave	61004451/4 3	61004451/4 4	61004451/4 5
Istat Comune	61004	61004	61004
Squadra	45	45	45
Lis			
Pr			
Sc			
Lo			
Co			
Co			
Co			
Quadrante	4	4	4
Foglio	3	4	5
Tavola			
Allegato			
Riferimento Carta			
Denominazione	CHIESA DI S. AGOSTINO	CONVENTO DI S. AGOSTINO	PALAZZO MONTE DEI PEGNI
Localita			
Indirizzo	VIA ROMA P.ZZA S. AGOSTINO	P.ZZA S. AGOSTINO	V. DELL'ANNUNZIATA
Quota	100	100	100
Numero Roll	1	1	1
Numero Foto			6
Distanza			20
Posizione			2
Sito			0
Edificio			1
Morfologia	1	1	1
Stato Conservativo	0	0	0
Destinazione	S62	S32	
Lunghezza			14
Larghezza			6
Altezza			11
Utilizzazione			1
Vincolo1			2
Vincolo2			
Vincolo3			
Proprieta'	0	0	0
Documentazione	3	3	1
Codice TCI			1
Parco			
Datazione			1687
Denom storic			
Accessib			
Fonte datazione			
Note			
Memorizzazione	21/10/1998	23/10/1998	23/10/1998
Codice Istat Regione	15	15	15
Denom_Parco	Regionale Partenio	Regionale Partenio	Regionale Partenio

TYPOLOGICAL IDENTIFICATION

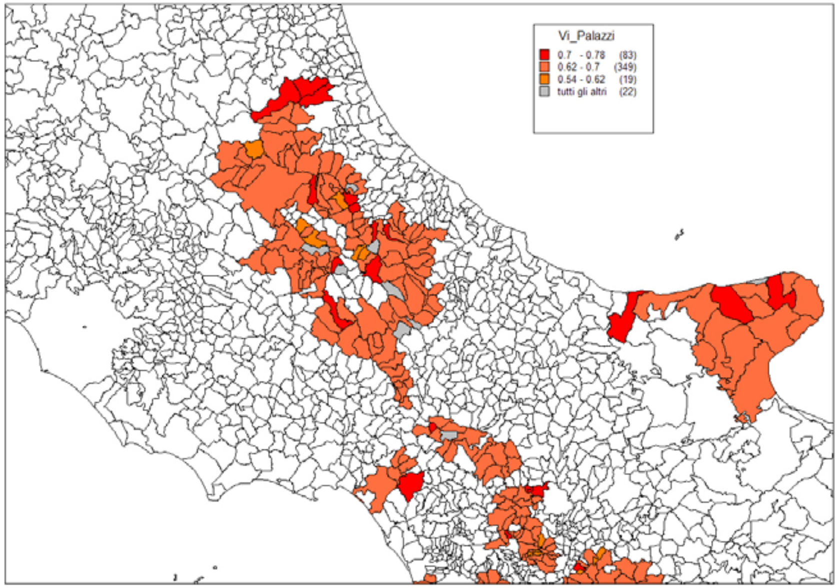
Level 0

Position

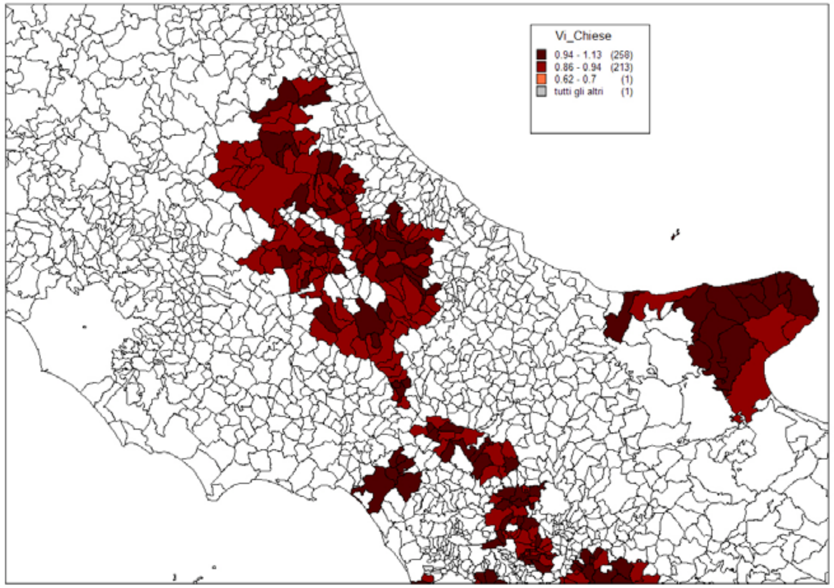
Maintenance

Height

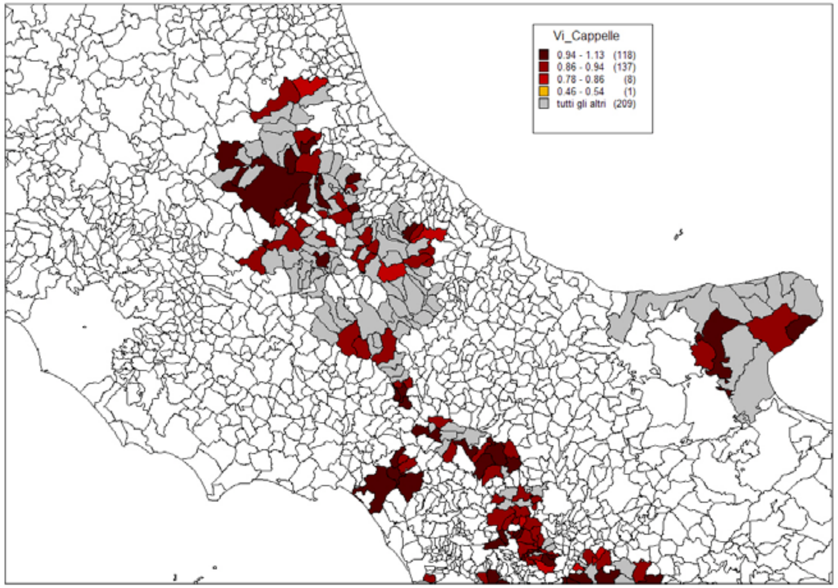
LSU Park Project - **VULNERABILITY ANALYSIS**



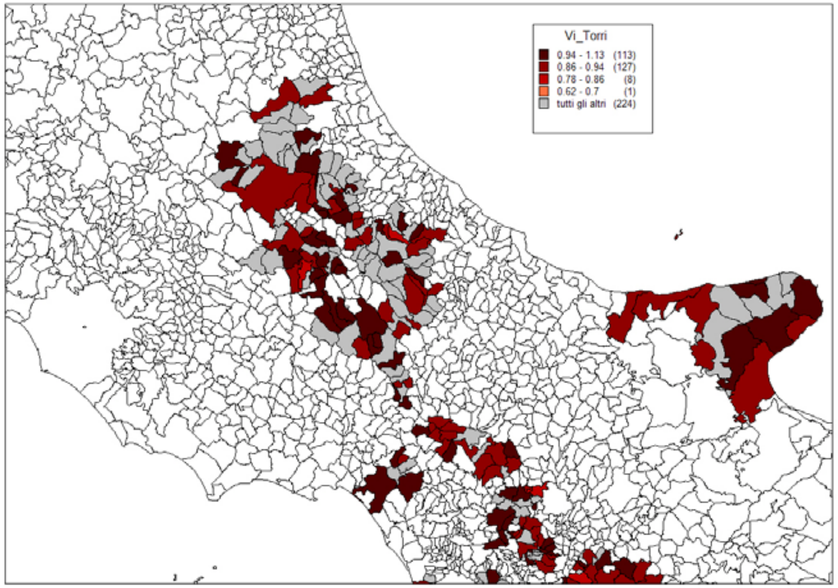
Vulnerability index for the palaces



Vulnerability index for the churches



Vulnerability index for the chapels

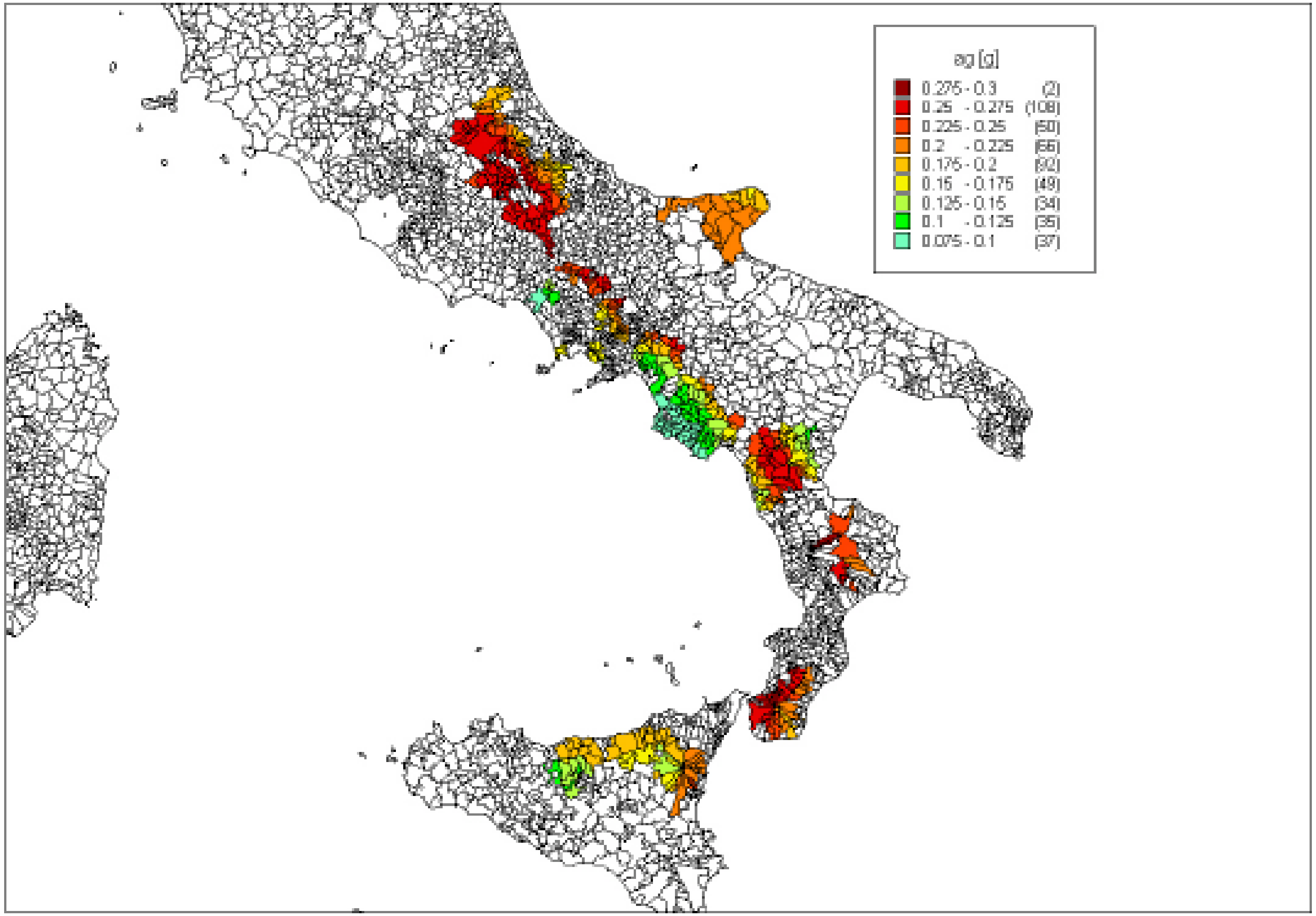


Vulnerability index for the towers

LSU Park Project – **HAZARD**

Italian Seismic Code (OPCM 3431) PGA map
Return Period 475 years

→ PGA



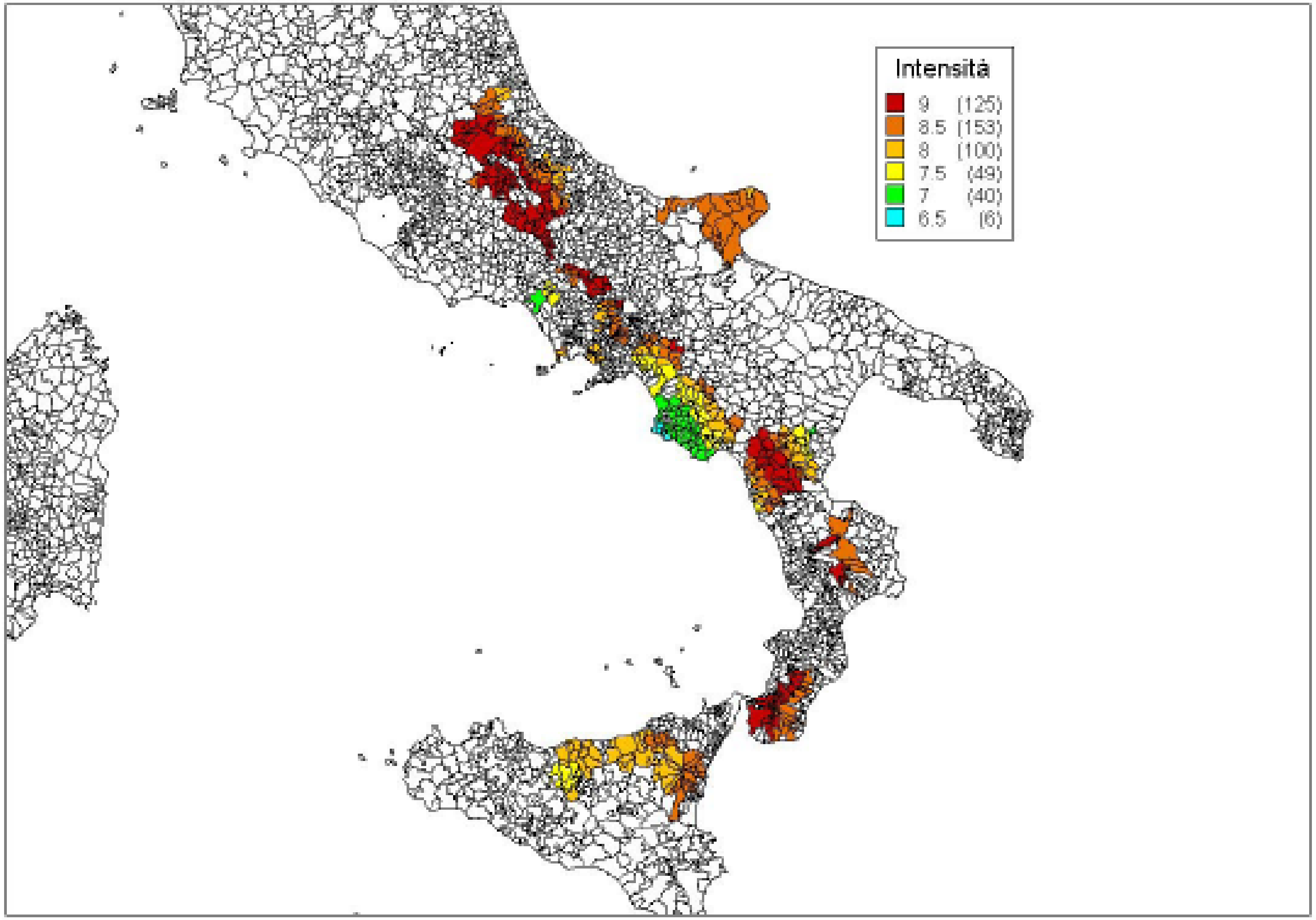
LSU Park Project – **HAZARD**

Italian Seismic Code (OPCM 3431) PGA map
Return Period 475 years

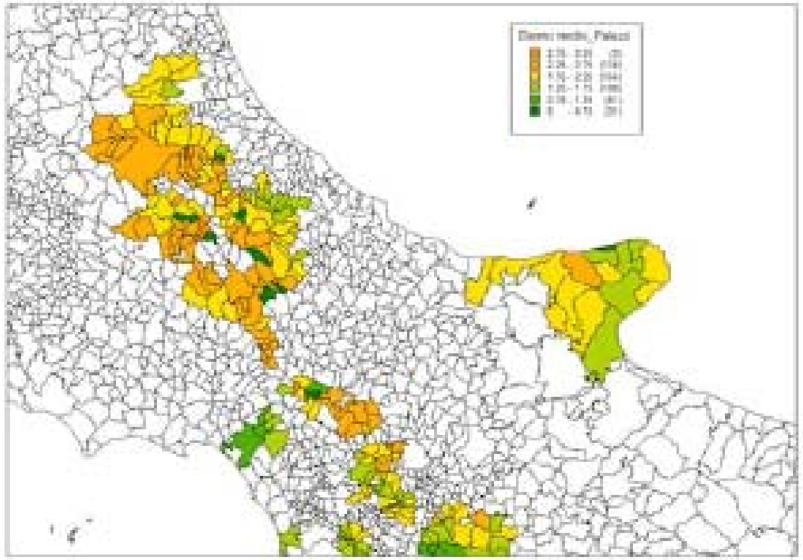
→ PGA

$$I = 5 + \frac{1}{\ln c_2}\left(\ln a_g - \ln c_1\right)$$

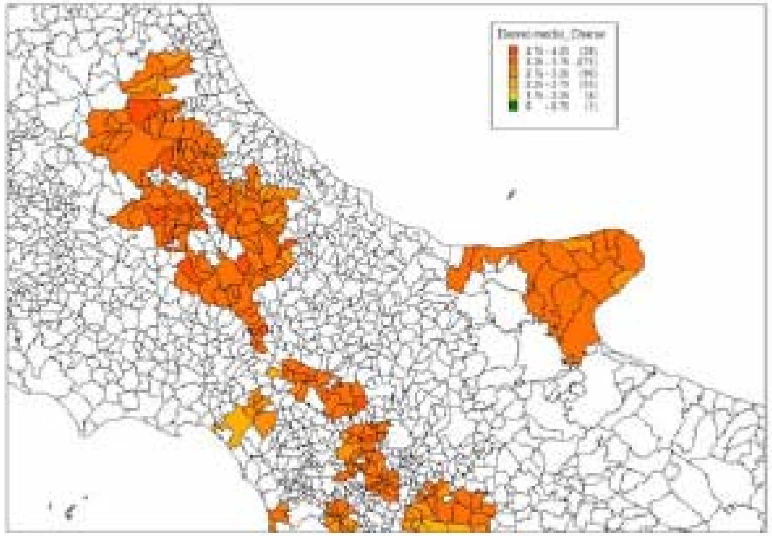
→ Intensity



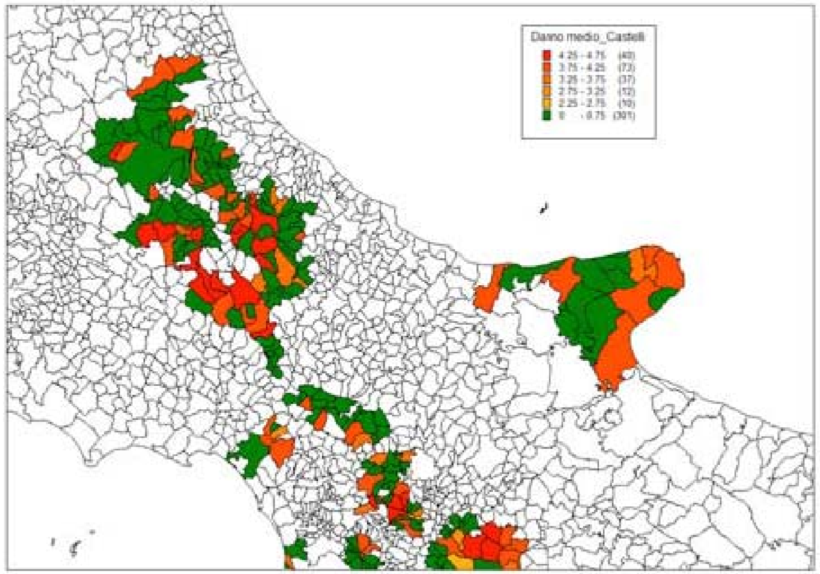
LSU Park Project – **DAMAGE SCENARIO**



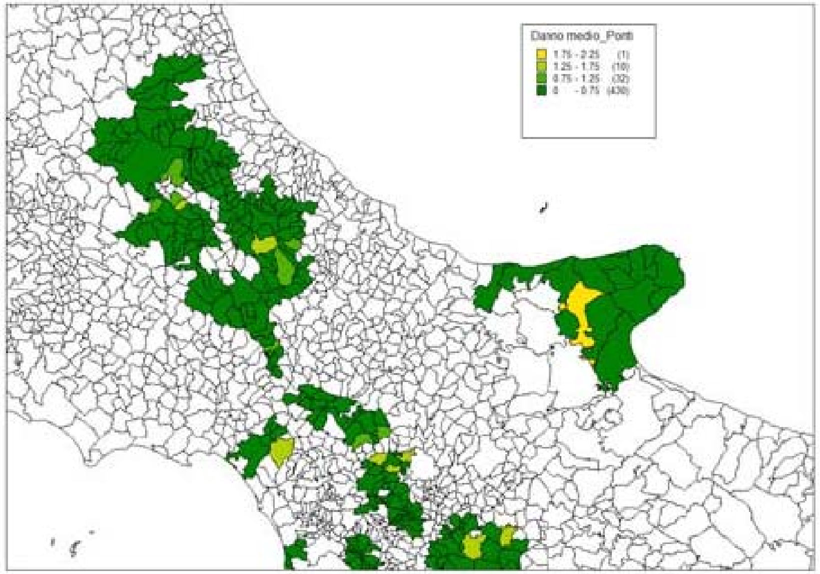
Mean damage for the palaces



Mean damage for the churches



Mean damage for the castles



Mean damage for the bridges

LSU Park Project – **DAMAGE SCENARIO**

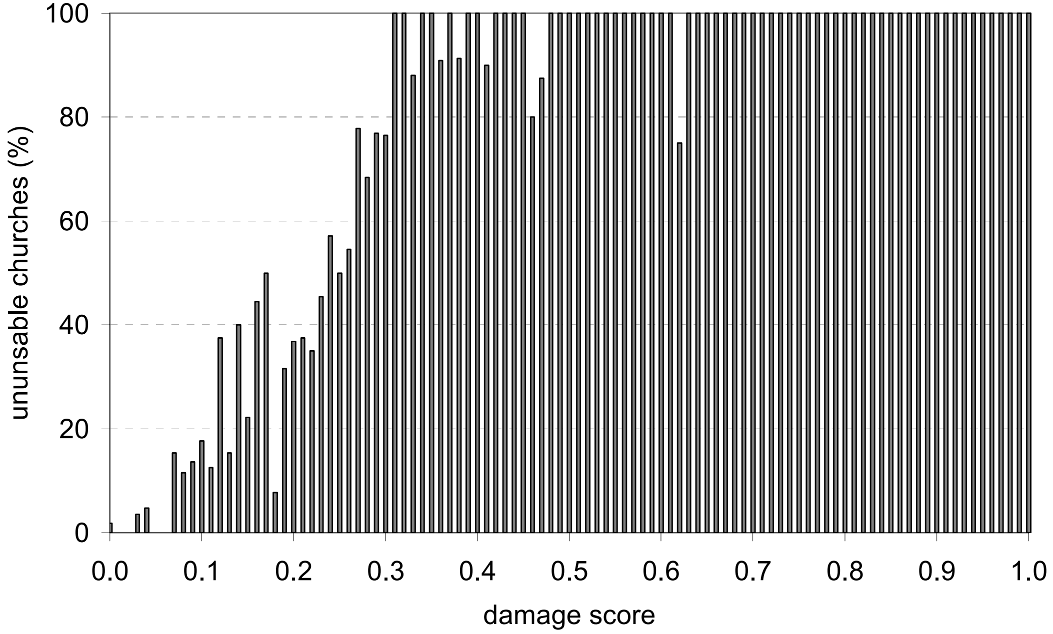
DENOMINAZIONE	INDIRIZZO	ETA' (ORIGINALE)	LSU-codice	STATO CONSERVATIVO	MORFOLOGIA SITO	POSIZIONE DEL CONTESTO	ALTEZZA PARETI LATERALI	V	Q	I	µd
CHIESA DI SAN FRANCESCO		XVI	80063295/715	worst	ridge	additions	high	1.05	3	9.5	4.391
SANTUARIO DEL BEATO NUNZIO SULPRIZIO	PIAZZA S. GIORGIO	XVII	68029 61/2 7	worst	ridge	additions	high	1.05	3	9.5	4.391
CHIESA DI SANTA MARIA DI LORETO	VIA GALDIERI	1634	66053281/2 5	worst	sloping	additions	high	1.03	3	9.5	4.345
CHIESA DI S.PIETRO		XVII	66054282/4 3	worst	ridge	additions	high	1.03	3	9.5	4.345
CHIESA DEGLI ALAMI		XVIII	66002323/415	worst	sloping	isolated	high	1.01	3	9.5	4.296
CHIESA DEL SS.CORPO DI CRISTO		1800	62030572/2 4	worst	ridge	isolated	high	1.01	3	9.5	4.296
CHIESA DELLA SPIRITO SANTO	MONTE DRAGO STRAPIOMBO DEL FUNNO	940	80011241/2 1	worst	sloping	isolated	high	1.01	3	9.5	4.296
CHIESA DI S. FELICE	LARGO S. DOMENICO	1485	61041611/3 5	worst	sloping	additions	high	1.01	3	9.5	4.296
CHIESA DI SANTA LUCIA	VIA DEL SEMINARIO	VI	69043174/7 4	worst	ridge	additions	medium	1.01	3	9.5	4.296
CHIESA DI SAN SALVATORE	P.ZZA DELLA VITTORIA	XVIII	80063296/7 8	worst	sloping	additions	high	1.01	3	9.5	4.296
CHIESA MADRE S. LUCIA	P.ZA DELLA MISERICORDIA	1348	83052131/410	worst	ridge	additions	medium	1.01	3	9.5	4.296
CHIESA S. MARIA DEL CARMINE	VIA S. GIUSTA	1681	61041612/313	worst	flat ground	additions	high	1.01	3	9.5	4.296
CHIESA S. NICOLA	PIAZZA MARGHERITA	XVI	80060172/2 5	worst	sloping	additions	high	1.01	3	9.5	4.296
CHIESA S.BIAGIO		1546	65018131/2 7	worst	ridge	additions	medium	1.01	3	9.5	4.296
CHIESA S.ROCCO			62029621/412	worst	ridge	isolated	high	1.01	3	9.5	4.296
MADONNA DELLE GRAZIE	CONTRADA BADIA GRANDE	XII	66013 23/4 5	worst	sloping	additions	high	1.01	3	9.5	4.296
S.ANTONIO		XVIII	69062191/212	worst	ridge	additions	medium	1.01	3	9.5	4.296

Database in Access®

Macroseismic Method for monuments – Consequences assessment

•a synthetic parameter, which allows the definition of a **hierarchy in the seriousness** of the structural damage for the large number of damaged churches;

•the **usability of the church**, defined by the surveyors by an expert judgment.



Although it is impossible to fix a threshold of the damage score, directly connected with the usability, it is possible to notice that for *id*>0.3, almost all the churches surveyed after the Umbria and The Marches earthquake were judged unsafe.

- define the **provisional interventions** (normally we could begin with the most damaged churches), as well as the **first interventions of retrofitting** and also for **programming the final intervention of consolidation**

Macroseismic Method for monuments – Consequences assessment

ECONOMIC LOSSES MODEL

The economic losses model was developed taking into account three virtual churches:

	Small church	Medium Church	Large church
Nave dimension (m)	7 × 12	14 × 25	25 × 50
Maximum height (m)	9	12	35
Plan area (m^2)	84	350	1250

The partial cost related to each collapse mechanism has been evaluated, for three damage levels (light, medium, severe).

LIGHT DAMAGE		*MEDIUM DAMAGE*		*SEVERE DAMAGE*	
<u>*Damage description*</u> Intradossal cracks are localized in the apex stone, for flat or barrel arches, or in proximity of the apex stone for all the other kinds of arches.		<u>*Damage description*</u> In flat or barrel arches, wide cracks are present in the apex stone and in the skewbacks. Alternatively, two cracks are located near to the intrados of the arch and the opposite skewback. Possibility of small cracks in the lateral piers.		<u>*Damage description*</u> The crack pattern is analogous to the one described for the *medium damage* but with an increase of the cracks (with crushing at the base of the piers). Possibility of an arch profile deformation and sliding between the stones.	
<u>*Repair and retrofitting*</u> Spackling of the cracks. Insertion of a tie-rod or control of the efficiency, if it is already present.		<u>*Repair and retrofitting*</u> Insertion of a tie-rod in order to eliminate the horizontal thrust (don't inject the holes, to allow the retensioning of the tie-rod). Mortar injections in the cracked areas, in order to repair the masonry.		<u>*Repair and retrofitting*</u> Propping of the triumphal arches. Insertion of a tie-rod. Repairing of the damaged masonry by mortar injections and insertion of steel bars. In the case of partial collapse, the parts are rebuilt.	
<u>*Estimate of quantities*</u> • Insertion of a tie-rod: • Spackling and key of the cracks near the apex stone: • Plaster of the walls:	k€ 1.5 0.5 0.3	<u>*Estimate of quantities*</u> • Insertion of a tie-rod: • Mortar injection (20 m^2) to consolidate the arch and the lateral piers: • Spackling and key of the cracks in the apex stone and in the skewbacks: • Plaster of the walls:	k€ 1.5 1.7 0.8 0.5	<u>*Estimate of quantities*</u> • Insertion of a tie-rod: • Mortar injection (30m^2) in the arch and the piers • Insertion of steel bars in the piers: • Rebuilt of collapsed parts: • Plaster of the walls: • Propping of the arch:	k€ 1.5 2.4 2.0 2.0 1.3 1.8
<u>*Cost*</u> 2.3 kEuro		<u>*Cost*</u> 4.5 kEuro		<u>*Cost*</u> 11 kEuro	

Triumphal arch: damage description, proposed interventions and estimation of costs for the virtual church of medium size.