Development of a new post-earthquake damage survey procedure and form sheet for masonry churches

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1976 Friuli | 1997 Umbria-Marche | 2002 Molise | 2009 L'Aquila
2010 Azores (P) | 2011 Christchurch (NZ) | 2012 Emilia

S. Stefano di Ceslans Church – Cavazzo (UD)

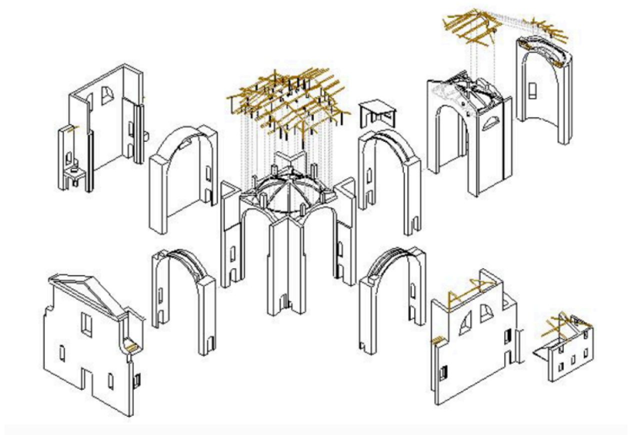
POST- EARTHQUAKE DAMAGE ASSESSMENT OF THE CHURCHES

The seismic response of **MASONRY CHURCHES** can be analyzed through a **MACROELEMENT APPROACH** (Doglioni et al. 1994).

S. Rocco Church - Sellano (PG)

DAMAGE SURVEY FORM (ISF)

The classification into macroelements and collapse mechanisms has allowed the definition of methods to assess damage and to quickly acquire useful information for handling emergencies (G.U. no. 55, 2006).



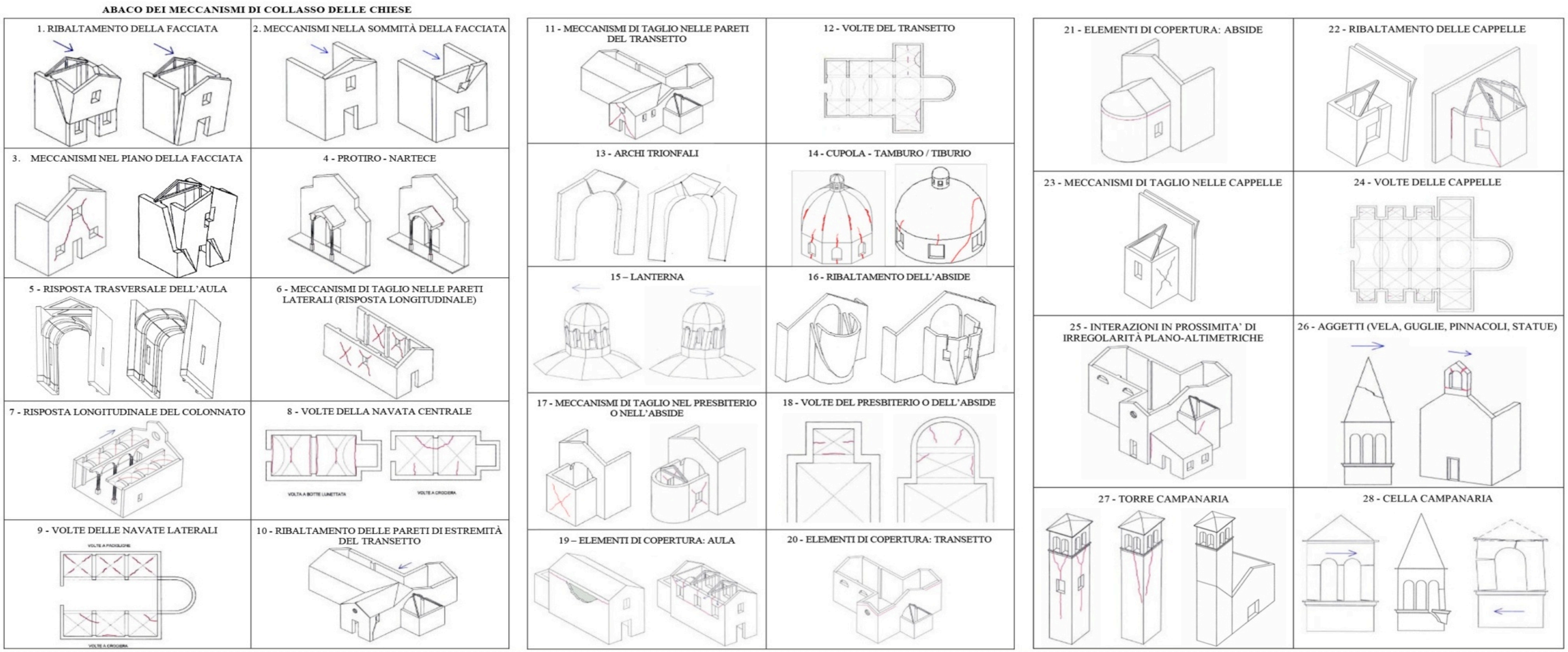
SS. Faustino e Giovita Church - Botticino Mattina (BS)

CHURCHES FORM with 28 COLLAPSE MECHANISMS

(Lagomarsino and Podestà, *Earthquake Spectra*, 2004)

1. Identification of the macroelements/mechanisms that can be activated during the earthquake – *N* – from the 28 collapse mechanisms a priori selected in the form
2. Assignment of a damage level – d_k – at the specific mechanism
3. Computation of the global damage index – i_d – of the church, as normalized mean function of the weights assigned – r_k – and of d_k

$$i_d = \frac{1}{5}\frac{\sum_{k=1}^{N}\rho_k d_k}{\sum_{k=1}^{N}\rho_k}$$



CHURCHES FORM with 28 COLLAPSE MECHANISMS (Lagomarsino and Podestà, 2004)

Extensive use at the national and international scale

VALIDATION:

- The macroelements approach is effective having observed the recurrence of collapse mechanisms identified in the form.

Database of the Canterbury churches hit by the 2010-2011 earthquake.

DRAWBACKS:

- The resulting damage index usually is not high enough in presence of local peaks of damage;
- Not flexibility and versatility → in considering the presence of macroelements that have been observed in other countries than Italy.

Chapel and narthex for New Zealand churches.

Choir for Portuguese churches (Magalhães et al. 2012).

NEW POST - EARTHQUAKE DAMAGE SURVEY FORM FOR MASONRY CHURCHES
(Cattari et al, 2015)

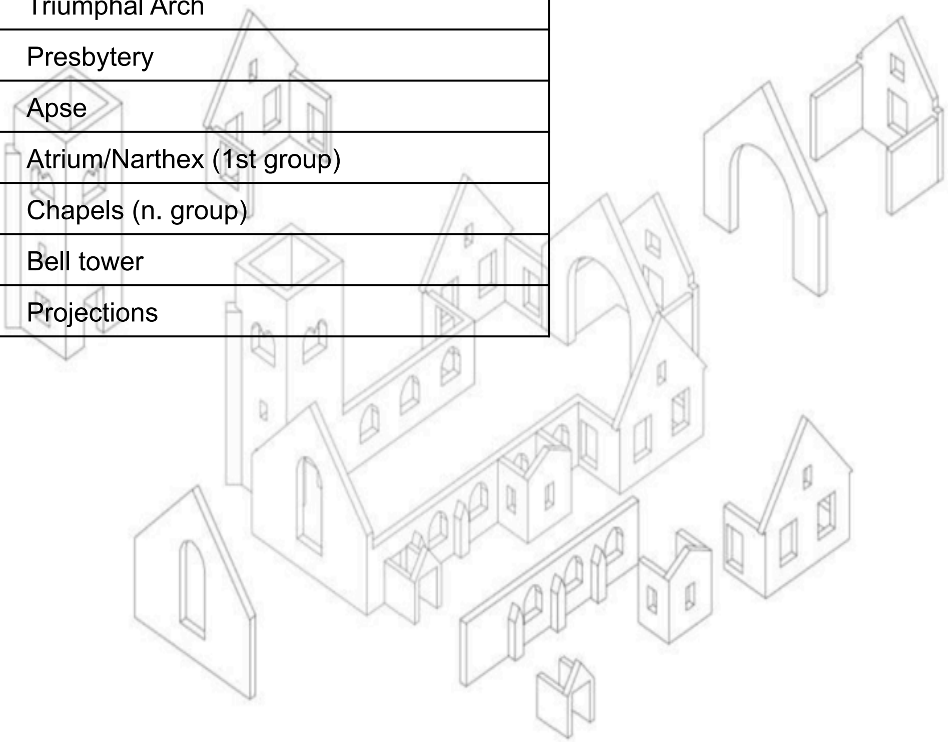
Separated definition of:

MACROELEMENTS of the church.

Id.	Description of the Macroelements
Nc	Central Nave
NI_{LEFT}	Left Lateral Nave
NI_{RIGHT}	Right Lateral Nave
F	Facade
T_{LEFT}	Left Transpet
T_{RIGHT}	Right Transpet
D	Dome
TA	Triumphal Arch
P	Presbytery
A	Apse
A-N	Atrium/Narthex (1st group)
C	Chapels (n. group)
BT	Bell tower
PR	Projections

10 DIFFERENT SEISMIC MECHANISMS, that can be potentially activated into the macroelements

Id.	Dir.	Description of the Collapse Mechanism
1	L, T	Out-of-plane of masonry walls
2	L, T	Out-of-plane at the top of walls
3	L, T	In-plane response
4	L, T	Rocking of multi macro blocks kinematics
5	L, T	Flexural or shear damage in monodimencional hollow section structures
6		Vaults
7		Domes
8		Interactione between roof and walls
9		Damage due to interaction with other buildings
10		Rocking of single blocks



NEW POST - EARTHQUAKE DAMAGE SURVEY FORM FOR MASONRY CHURCHES

(Cattari et al, 2015)

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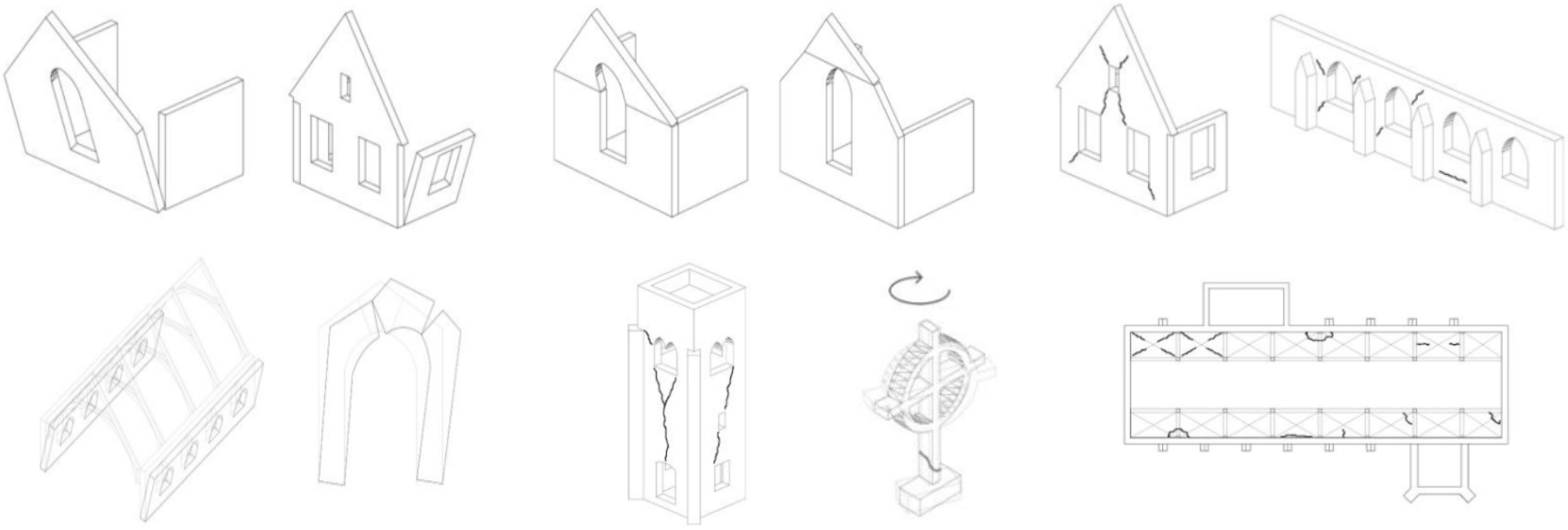
10 DIFFERENT SEISMIC MECHANISMS, that can be potentially activated into the macroelements

COLLAPSE MECHANISMS



NEW POST - EARTHQUAKE DAMAGE SURVEY FORM FOR MASONRY CHURCHES
(Cattari et al, 2015)

Example: **Macroelement - Narthex**

Id.	Description of the Macroelements
Nc	Central Nave
Nl_{LEFT}	Left Lateral Nave
Nl_{RIGHT}	Right Lateral Nave
F	Facade
T_{LEFT}	Left Transpet
T_{RIGHT}	Right Transpet
D	Dome
TA	Triumphal Arch
P	Presbytery
A	Apse
A-N	Atrium/Narthex (n. groups)
C	Chapels (n. groups)
BT	Bell tower
PR	Projections

Id.	Dir.	Description of the Collapse Mechanism
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NEW POST - EARTHQUAKE DAMAGE SURVEY FORM FOR MASONRY CHURCHES
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Example: **Macroelement - Narthex**

New procedure

AN_1 – ATRIUM/NARTHEX	❑	w_{AN1} = ... (0.2-0.8)
$AN_1 1(L)$ – Out-of-plane of the end wall	4	❑ ❑ ❑ ❑ ❑
$AN_1 3(L)$ – cracks due to the in-plane response of walls	4	❑ ❑ ❑ ❑ ❑
$AN_1 4(L)$ – rocking of multiple block kinematisms of columns	4	❑ ❑ ❑ ❑ ❑
$AN_1 1(T)$ – out-of-plane of the end wall	4	❑ ❑ ❑ ❑ ❑
$AN_1 3(T)$ – cracks due to the in-plane response of walls	4	❑ ❑ ❑ ❑ ❑
$AN_1 4(T)$ – rocking of multiple block kinematisms of columns	4	❑ ❑ ❑ ❑ ❑
$AN_1 6$ – damage in the vaults of the atrium or narthex	4	❑ ❑ ❑ ❑ ❑
$AN_1 8$ – damage at connection between roof and atrium/narthex	-	❑ ❑ ❑ ❑ ❑

Damage Survey Form (ISF) – 28 mechanisms

4 – PROTIRO-NARTECE			
Danno	attuale	Lesioni nella trabeazione per rotazione delle colonne – Distacco complessivo dalla facciata – Martellamento del protiro – Archi lesionati	❑ ❑ ❑ ❑ ❑
	vecchio	Lesioni nella trabeazione per rotazione delle colonne – Distacco complessivo dalla facciata – Martellamento del protiro – Archi lesionati	❑ ❑ ❑ ❑ ❑

NEW POST - EARTHQUAKE DAMAGE SURVEY FORM FOR MASONRY CHURCHES

(Cattari et al, 2015)

1. Subdivision of the church into macroelements (i =1... N);

2. **Identification of the most important macroelement in the church**, to which a weight (w_i) equal to 1 is associated. Following the other weights less than one are associated to others macroelements;

3. Identification of the possible seismic responses for each macroelement, considering the directionality of the structure response according to the seismic action (if longitudinal or transversal), **defining thus the collapse mechanism of each macroelements**;

4. For each macroelement, a damage level d_k, according to the EMS98 damage scale, has to be ascribed to any activated mechanism;

5. Then, the damage grade of the macroelement is computed, according to different rules that consider peak and mean values of the different mechanisms, as well as their relative importance. **It also takes into account both the directionality and the distinction between damage to the horizontal and vertical structural elements,** thus allowing to evaluate, for each macroelement, three damage indeces: longitudinal ($D_{i,L}$), transversal ($D_{i,T}$) and global (D_i);

$$\overline{D}_i = w_i D_i$$

6. Afterwards, through the weighted arithmetic average of damage grades in the macroelements, the global damage index of the church can be estimated, together with the longitudinal, transversal and the peak.

$$D_{CHURCH} = \frac{\sum_{i=1}^{N} \overline{D}_i}{\sum_{i=1}^{N} w_i}$$

$$D_{CHURCH,L/T} = \sum_{i=1}^{N} \delta_{i,L/T} w_i D_{i,L/T}$$

$$\delta_{i,L/T} = \begin{cases} 0 & \text{if the macroelement does not allow mechanisms in direction L/T} \\ 1 & \text{if the macroelement allow mechanisms in direction L/T} \end{cases}$$

$$D_{CHURCH,PEAK} = \max\left(\overline{D}_i\right)$$

NEW POST - EARTHQUAKE DAMAGE SURVEY FORM FOR MASONRY CHURCHES

(Cattari et al, 2015)

Innovative features of the new form:

- Form more flexible and complete of the failure mechanisms that can be activated
- Introduction of the weight of the macroelements in the combination rules
- Directionality of the seismic action
- Possibility of two different ways to fill the form: accurate and quick use

MACROELEMENTS		w	w'	w_A (≥1)	w'_A	D_L	D_T	D
Nc – CENTRAL NAVE	❑	1		.....		....	....	....
NI_{LEFT} – LEFT LATERAL NAVES	❑	..... (0.5-1)		.....		....	....	....
NI_{RIGHT} – RIGHT LATERAL NAVES	❑	..... (0.5-1)		.....		....	....	....
F – FAÇADE	❑	..... (0.6-1.2)		.....		....	....	....
T_{LEFT} – LEFT TRANSEPT	❑	..... (0.5-0.8)		.....		....	....	....
T_{RIGHT} – RIGHT TRANSEPT	❑	..... (0.5-0.8)		.....		....	....	....
D – DOME	❑	..... (0.5-1)		.....		....	....	....
TA – TRIUMPHAL ARCH	❑	..... (0.2-0.7)		.....			....	....
P – PRESBYTERY	❑	..... (0.2-0.6)		.....		....	....	....
A – APSE	❑	..... (0.4-0.8)		.....		....	....	....
AN_1 – ATRIUM/NARTHEX	❑	..... (0.2-0.8)		.....		....	....	....
AN_2 – ATRIUM/NARTHEX	❑	..... (0.2-0.8)		.....		....	....	....
C_1 – CHAPELS (1st group)	❑	..... (0.2-0.8)		.....		....	....	....
C_2 – CHAPELS (2nd group)	❑	..... (0.2-0.8)		.....		....	....	....
C_n – CHAPELS (nth group)	❑	..... (0.2-0.8)		.....		....	....	....
BT – BELL TOWER	❑	..... (0.5-1.2)		.....		....	....	....
PR_1 – PROJECTIONS (1st group)	❑	..... (0.2-0.7)		.....		....	....	....
PR_2 – PROJECTIONS (2nd group)	❑	..... (0.2-0.7)		.....		....	....	....
PR_n – PROJECTIONS (nth group)	❑	..... (0.2-0.7)		.....		....	....	....
						$D_{CHURCH,L}$	$D_{CHURCH,T}$	D_{CHURCH} ....
								$D_{CHURCH,A}$ ....

QUICKLY

1. Definition of the macroelements and relative weights;
2. Assignment of the damage level to the macroelement;
3. Computation of the global damage index.

APPLICATION: *Damage and vulnerability analysis of urm churches after the Canterbury earthquake sequence 2010-2011*

Vulnerability of architectural heritage to seismic action, in particular of churches, as testified once again by the 2010-2011 Canterbury earthquake

Anagnostopoulou et al (2010), Ingham et al (2012), Leite et al (2013) e Lourenco et al (2013)

84% and 81% of the heritage unreinforced stone and clay brick masonry churches, respectively, were **inaccessible** (Leite et al 2013).

Typological analysis and classification of New Zealand churches: these churches show typological and dimensional data different from Italian churches, having generally a more regular plan configuration.

St. Barnaba's Church, Fendalton

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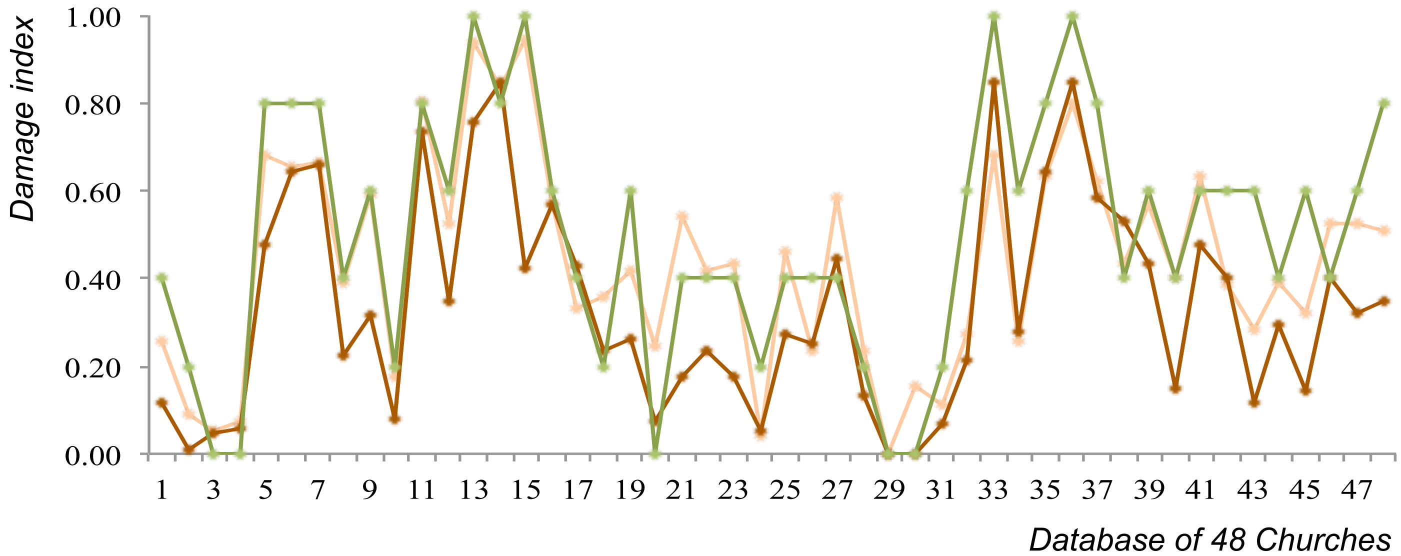
DAMAGE SURVEY of the Christchurch Churches through different approaches:

1. The computation of the damage index (id) starting from the ISF, based on 28 mechanisms, Leite et al. (2013);
2. The definition of a damage grade Dk (k = 1...5), based on expert judgment, folowing EMS98 (Grunthal 1998);
3. The proposed procedure.



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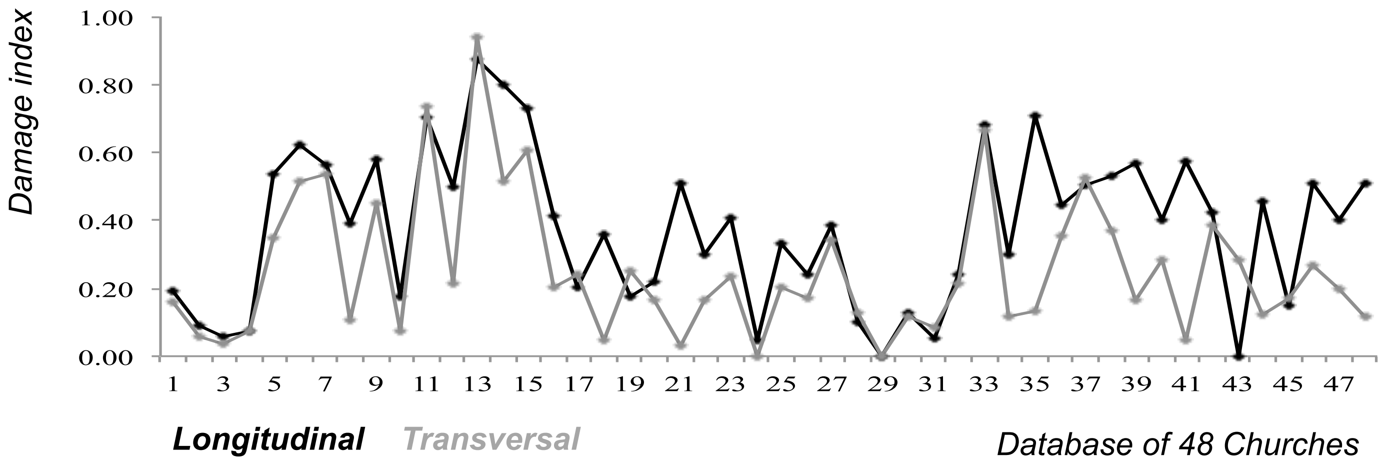
DAMAGE SURVEY of the Christchurch Churches through different approaches:

3. **The proposed procedure –** New results in terms of transversal index, longitudinal index and peak of damage.

Distinction between transversal and longitudinal index of damage



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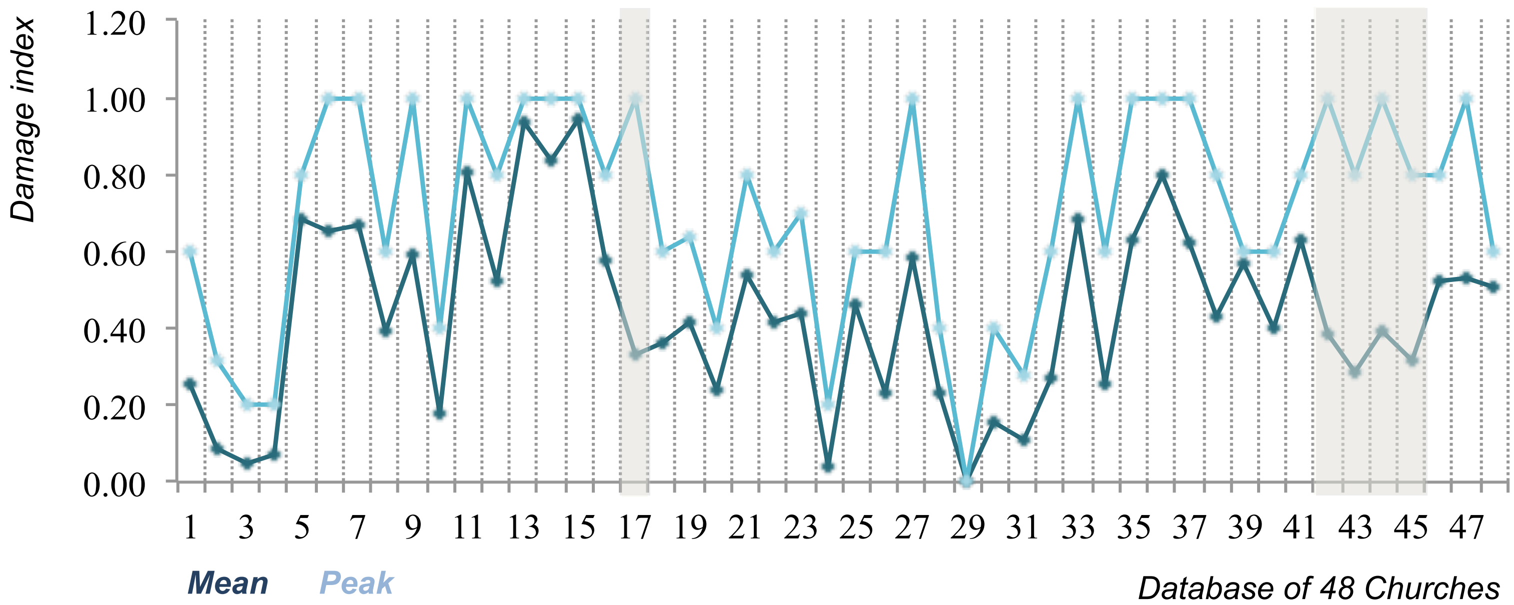
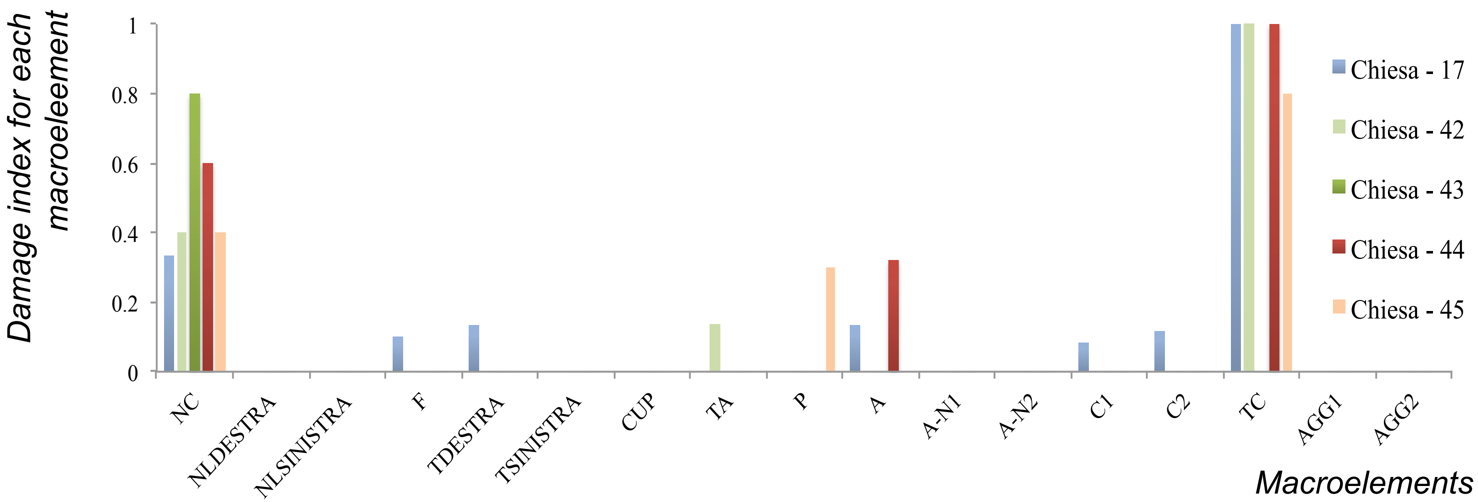
DAMAGE SURVEY of the Christchurch Churches through different approaches:

3. **The proposed procedure –** New results in terms of transversal index, longitudinal index and peak of damage.

Distinction between peak of damage and mean damage index.

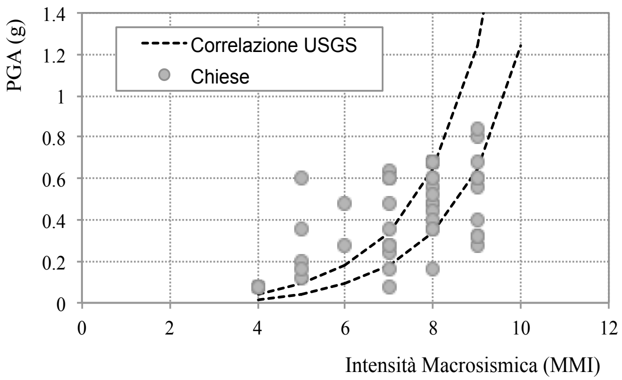


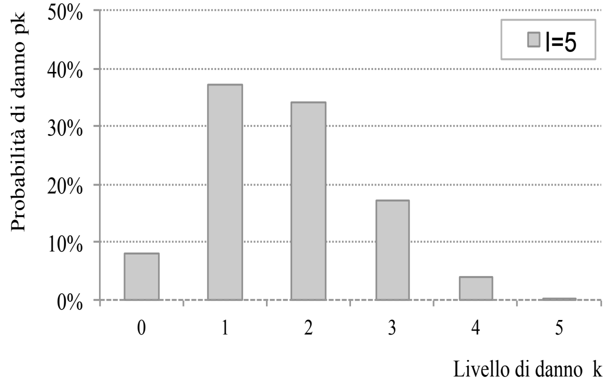


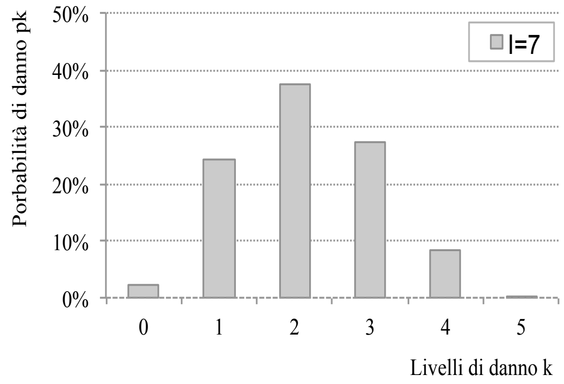
APPLICATION: *Damage and vulnerability analysis of urm churches after the Canterbury earthquake sequence 2010-2011*

From the damage index to the definition of the vulnerability curves

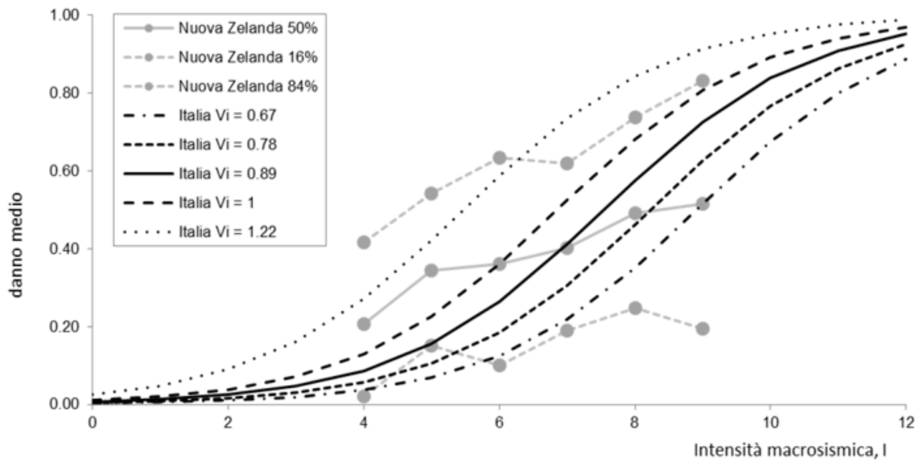
- Damage Probability Matrix (DPM) for different values of macroseismic intensities from 4-9 (MMI), obtained from PGA data taken from shake maps, by using an Intensity-PGA correlation, calibrated in the study area through the data of the US Geological Survey (USGS 2011);







- From the mean damage index and the values corresponding to the 16 and 84 percentiles, the empirical vulnerability curves of New Zealand churches were drawn, which correlate the intensity to damage;



Coherence between New Zealand and Italian curves, both as regards the average values that extremes.

CONCLUSIONS

The damage assessment of churches after an earthquake by a schematic survey form, which considers the possible collapse mechanisms in the macroelements that are identified in the church, can be useful for:

- a preliminar interpretation of the seismic behavior and of specific vulnerability;
- identify the need of provisional interventions (shoring) to prevent from further damage due to aftershocks;
- getting an overall picture of the damage in churches at territorial scale, in order to plan restoration and retrofitting strategies;
- increasing the knowledge on seismic vulnerability of churches and calibrating fragility curves for preventive risk analyses.