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Disaster – Risk Analytics and Solutions (D-RAS)

&

Culture, Heritage, and Sustainable Development

Strengthening of historic buildings: increasing resilience or loosing value?

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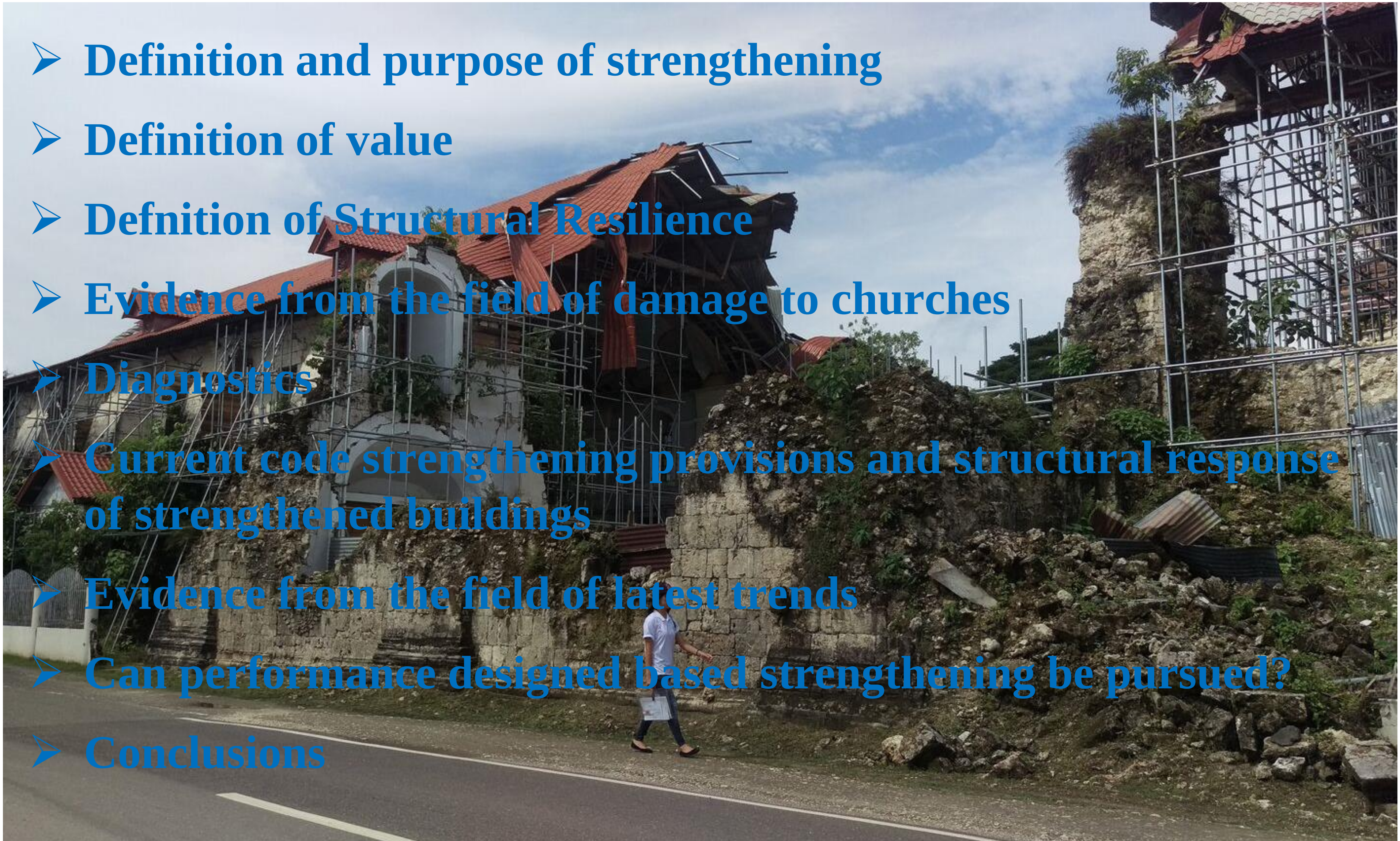

- Definition and purpose of strengthening
- Definition of value
- Defnition of Structural Resilience
- Evidence from the field of damage to churches
- Diagnostics
- Current code strengthening provisions and structural response of strengthened buildings
- Evidence from the field of latest trends
- Can performance designed based strengthening be pursued?
- Conclusions

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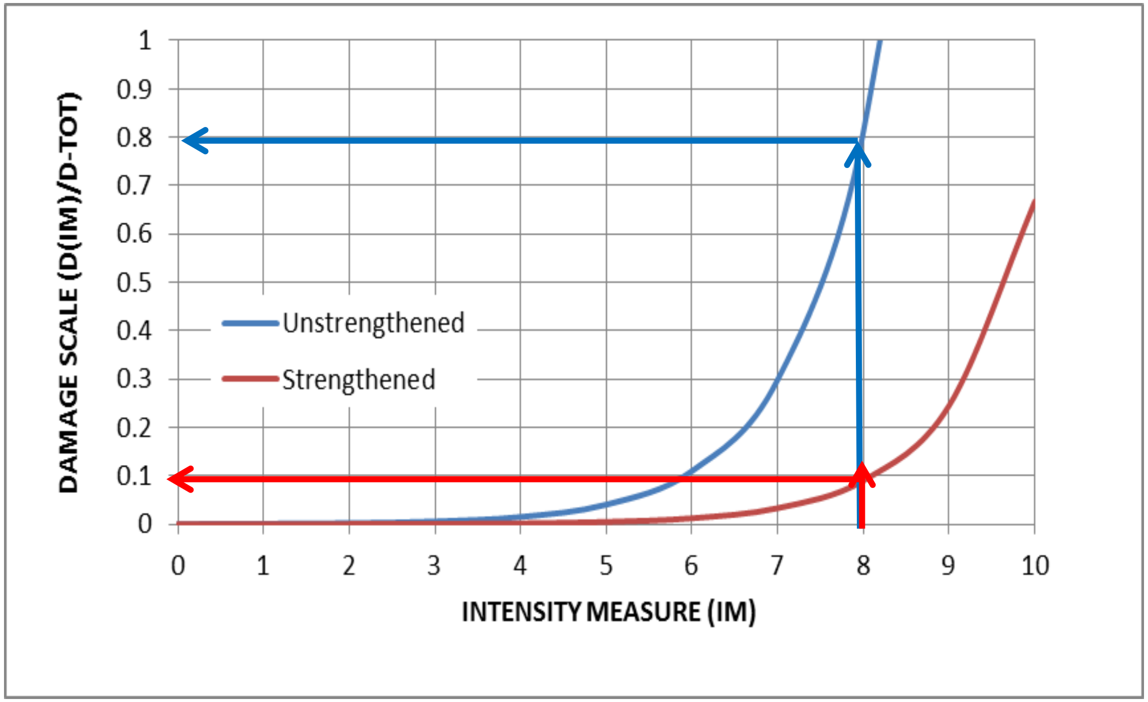
Definition of strengthening

- Strengthening is the action of reducing the vulnerability of a building to the expected seismic action before the occurrence of the probable earthquake[1]
- Survey assessment and analysis are needed to identify weaknesses and determine priorities
- Local or global intervention might be appropriate.



1. IAEE Manual: ***Guidelines for Earthquake Resistant Non-Engineered Construction, 2004***

DEFINITION OF VALUE IN BUILT HERITAGE

- Cultural significance means aesthetic, historic, scientific, social or spiritual value for past, present or future generations. Cultural significance is embodied in the place itself, its fabric, setting, use, associations, meanings, records, related places and related objects. [2]

- CULTURAL SIGNIFICANCE, HERITAGE SIGNIFICANCE AND CULTURAL HERITAGE VALUE ARE CONSIDERED AS SYNONIMOUS and are directly related to the AUTHENTICITY of the site which can be articulated in the following attributes:

  - ✓ Location
  - ✓ Design
  - ✓ Setting
  - ✓ Materials
  - ✓ Workmanship
  - ✓ Feeling
  - ✓ Association

  } **AUTHENTICITY**

2. Australia ICOMOS Burra Charter 1999.

AUTHENTICITY AND SIGNIFICANCE LOSS

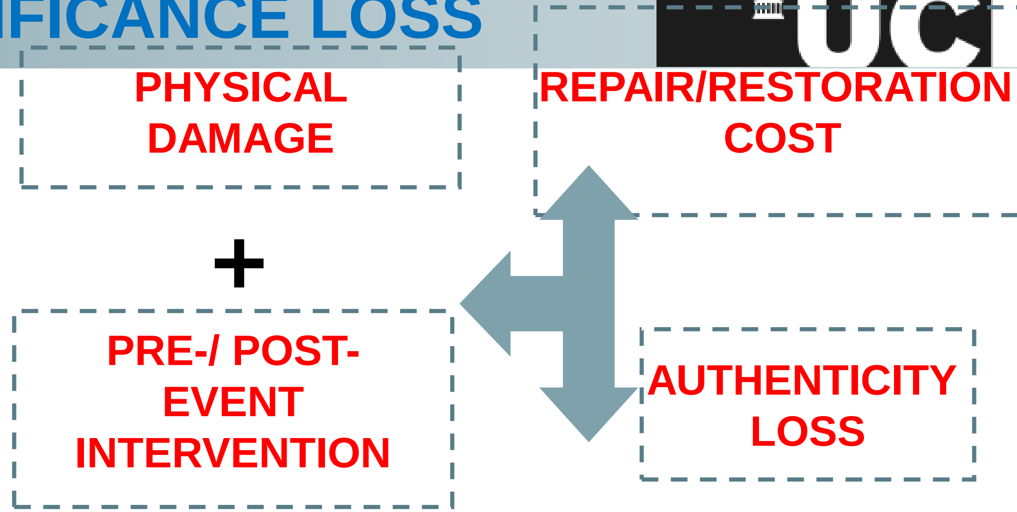
- **Loss function**

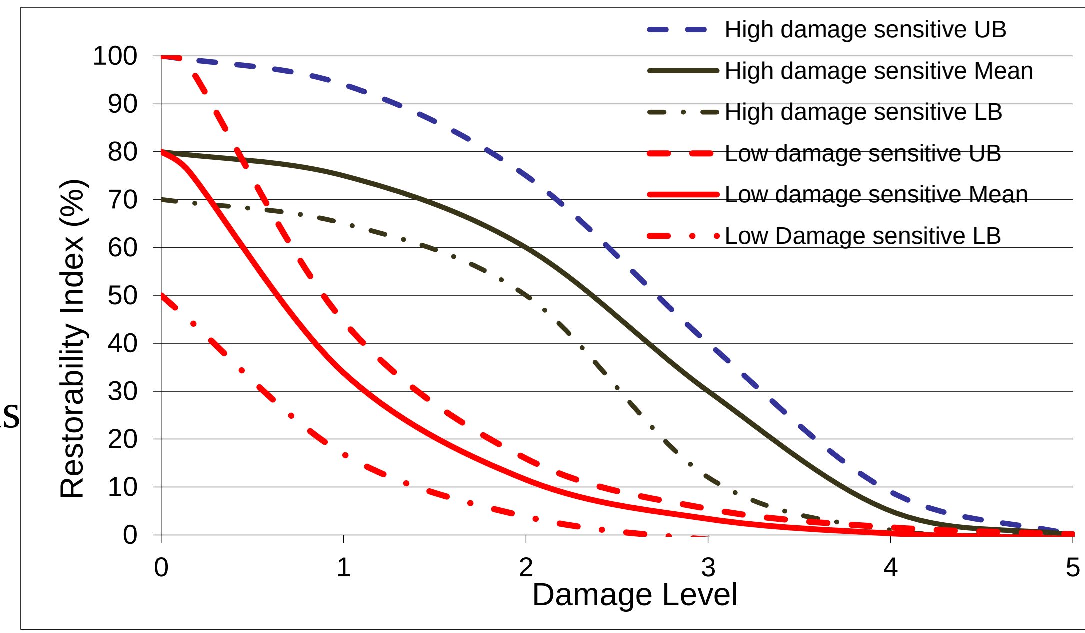
$$L_c = S_i * (1 - R_i)$$

- **where**

$$R_i = f(d_i, c, i, e)$$

- **Restorability depends on availability of:**
  - Original building materials;
  - Original documentation;
  - Traditional craftsmanship or skills
  - Sophisticated technologies;
  - Financial support.





D Ayala, D. F.,et al.(2006). A conceptual model for Multihazard assessment of the vulnerability of historic buildings. SAHC 2006, MacMillan India.

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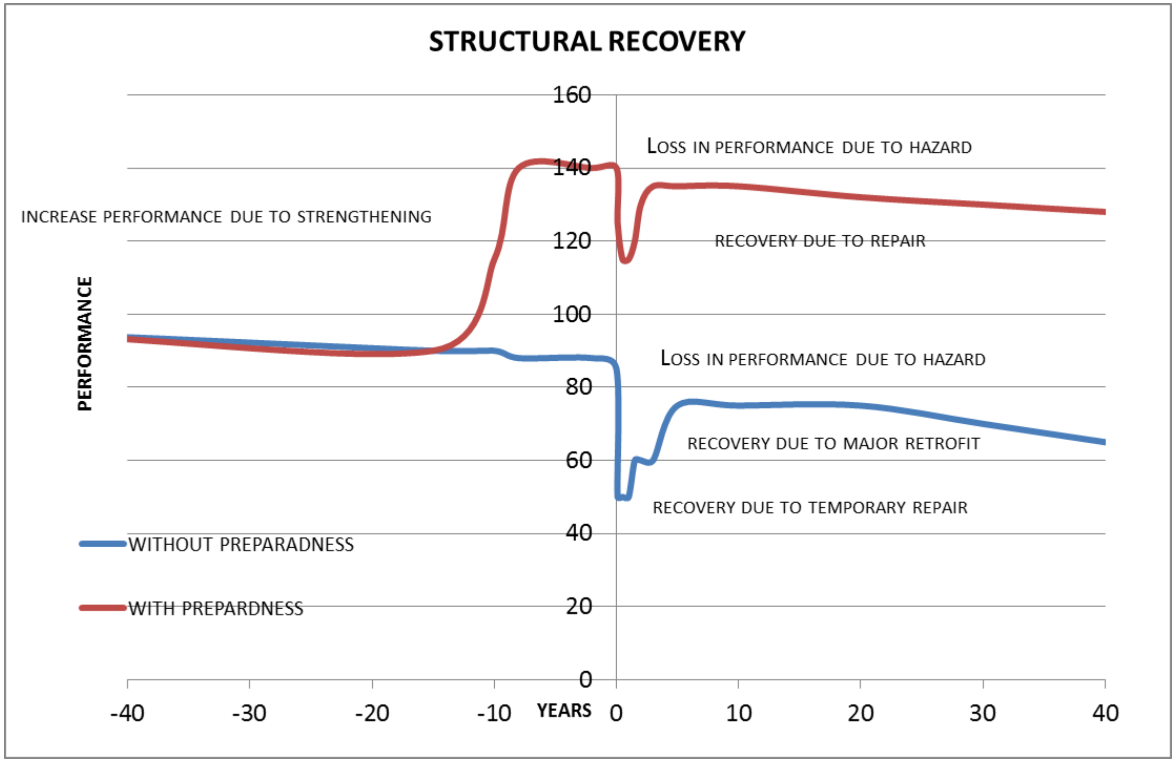
RESILIENCE

- **Resilience is the ability of a system to resist, adapt to, and recover from exposure to damaging events:**
- Recovery is defined by time and cost needed or prescribed to go back to pre-event functionality level
- **Robustness**
- **Redundancy**
- **Rapidity**
- **Resourcefulness**



Bruneau, M., et al., 2003. A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities, EERI Spectra Journal, Vol.19, No.4, pp.733-752

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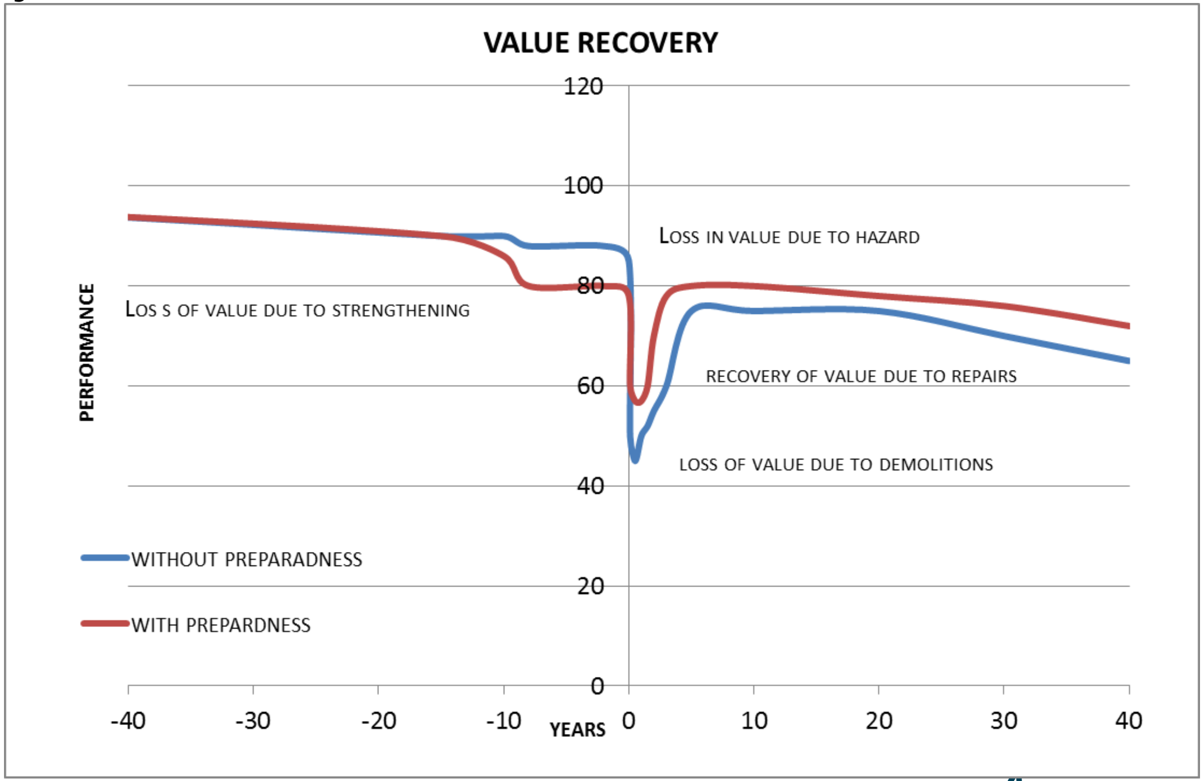

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Process of recovery

- Tagging
- Debris clearance, documentation and storage
- Shoring / Demolition

IMMEDIATE

- Documentation + Monitoring +Analysis = Understanding
- Review and definition of new/continued function
- Preliminary Design of restoration and strengthening

SHORT TERM

- Approval process + Funding
- Detailed design
- Site construction and modifications on site

MEDIUM TERM

- Monitoring

LONG TERM

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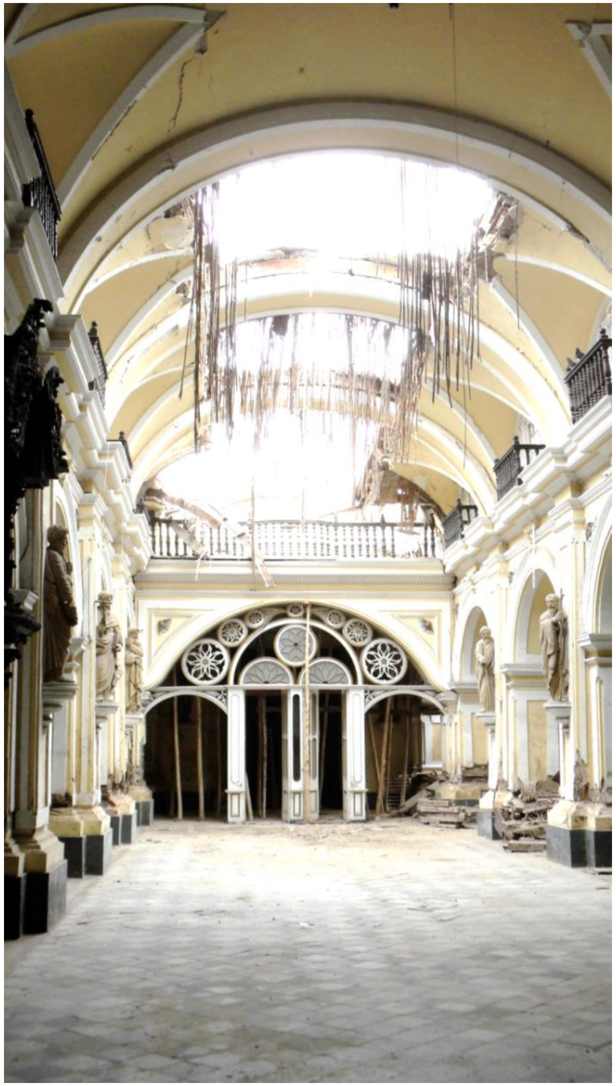
CONSERVATION PRINCIPLES

- Preservation of Structural Authenticity and Integrity
  - searches for significant data and information
  - identification of the causes of damage and decay
  - choice of remedial measures
  - implementation and **monitoring of effectiveness**

- Enforcement of Structural Reliability
  - Optimal Intervention: one that balances the safety requirements with the protection of character-defining elements, ensuring the least harm to heritage values", *(ISO/TC96/SC2, 2010)*
  - Design should be a direct consequence of the safety judgement
  - Remedial measures should address root causes

- Compatibility, durability, reversibility, monitorability of interventions
  - Act as sacrificial elements
  - Extend the life of the building
  - Be retractable
  - Be possible to observe the +/- effect on original and amend



- *ICOMOS/ISCARSAH Recommendations for the Analysis and Restoration of Structures of Architectural Heritage, (ICOMOS/ISCARSAH, 2003)*
- *Annex on Heritage Structures of ISO/FDIS 13822, (ISO/TC96/SC2, 2010)*

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KNOWLEDGE FRAMEWORK FROM SEISMIC CODES

LEVEL OF KNOWLEDGE → **CONFIDENCE FACTOR**

SEISMIC INTENSITY MEASURE

Peak Ground Acceleration

Linear spectra

Nonlinear spectra

Accelerogrammes

STRUCTURAL ANALYSIS / RESPONSE

Simplified models/limit analysis

ElasticFE. models /static analysis

Non linearFE. models /pushover

Non linearFE. models/ time history

RISK

Ratio of demand/capacity

Performance based criteria, drift

Life cycle analysis

INTERVENTIONS

Strength

Ductility

Energy dissipation/ Damage control

- **Double flat jack test**

DAMAGE STATISTICS

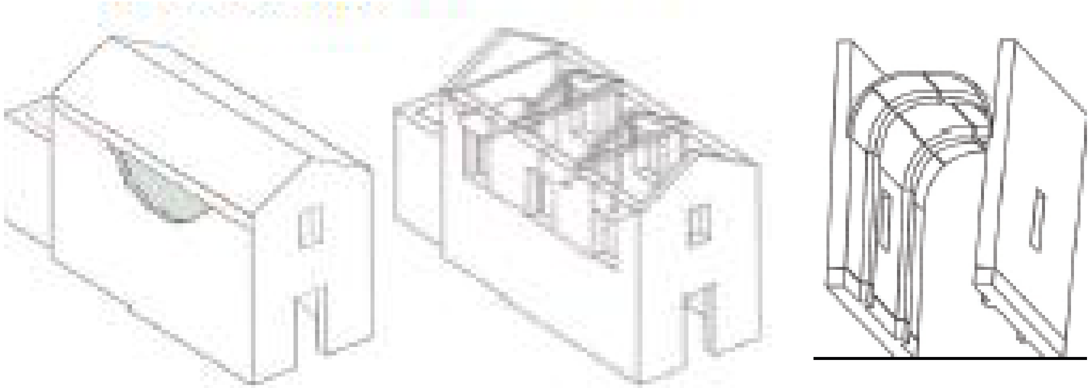
Earthquake	Magnitude MW	% of historic buildings severe damaged	Losses
Pisco, Peru', 2007	8.0	80%	*240 ML$?*
L'Aquila, Italy, 2009	6.3	54%	*16 BL€ ?*
Maule,Chile, 2010	8.8	75%	290 ML $?
Christchurch, NewZealand, 2010 -2011	7.1	40%	*15BL$?*
Great East Japan Earthquake, 2011	9.0	744	US$235 billion,
Emilia, 2012	5.9 +5.8	27%	*1965M€*
Bohol, Philippines 2013	7.2	60%	*89.4 ML$*
Nepal 2015	7.7	700	*200ML$ (heritage only) WB*

- **Concept of improvement**
- **Concept of upgrading**
- **NZ Guidelines indicate that for building that have capacity <1/3 of normal building they should be designed for 0.75 of design action**
- **Revision of Italian standards voted by Consiglio superiore Lavori Pubblici (14/11/2014)**
- **Improvement: for buildings in class 2 & 3 the capacity to demand ratio should be >0.10**
- **In the reconstruction in L'Aquila the capacity to demand ratio upper threshold was set = 0.6**

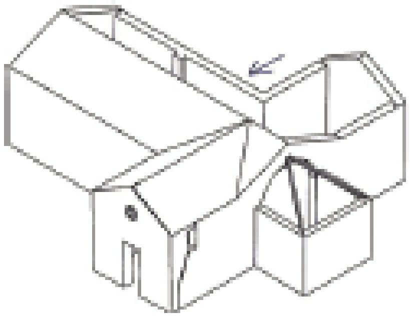
Ministero LL.PP..Bozza di Revisione per le Norme Techniche delle Costruzioni . November 2015
NZSEE Guidelines for the Assessment and Improvement of the Seismic Performance of Buildings in Earthquakes –Section 3 – November 2013

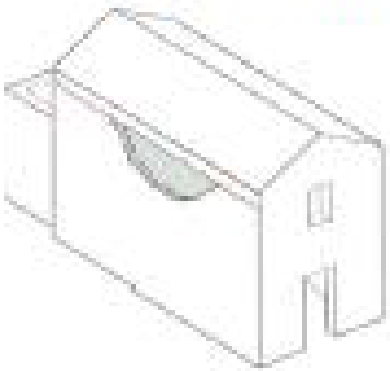
EVIDENCE FROM THE FIELD: WHAT DOES NOT WORK

- **Poor performance of shotcreting : Chile**



POOR PERFORMANCE OF RING BEAMS AND STIFF DIAPHRAGMS : L'AQUILA





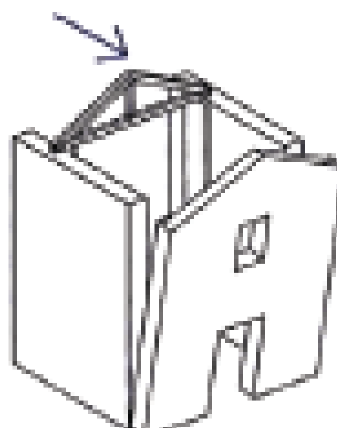
PARTIAL TO TOTAL COLLAPSE OF FACADES

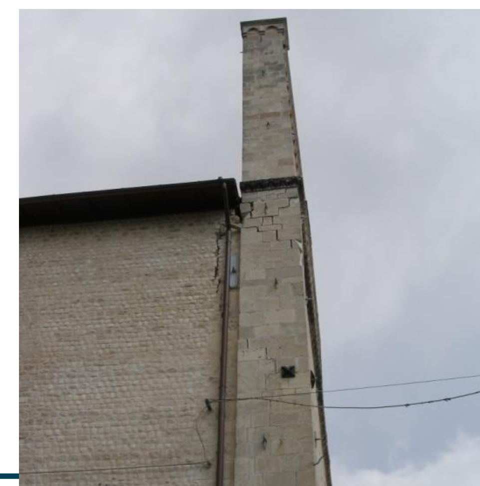
Chile

New Zealand

Philippines

L'Aquila





NEED FOR A DIAGNOSTIC APPROACH

- Collaborative & interdisciplinary
- Visual interaction
- Easy-to-use

Onsite data collection ↓ Archival research

Preliminary Diagnosis

↓

Structural Analysis ⇄ Testing ⇄ Material characterisation

↓

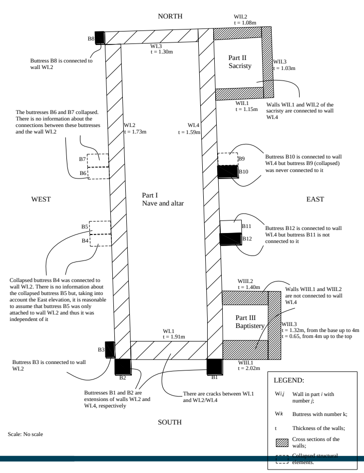
Detailed Diagnosis

↓

Strengthening

CRITERIA

Resilience | Interaction | Connections | Masonry Fabric | Deterioration



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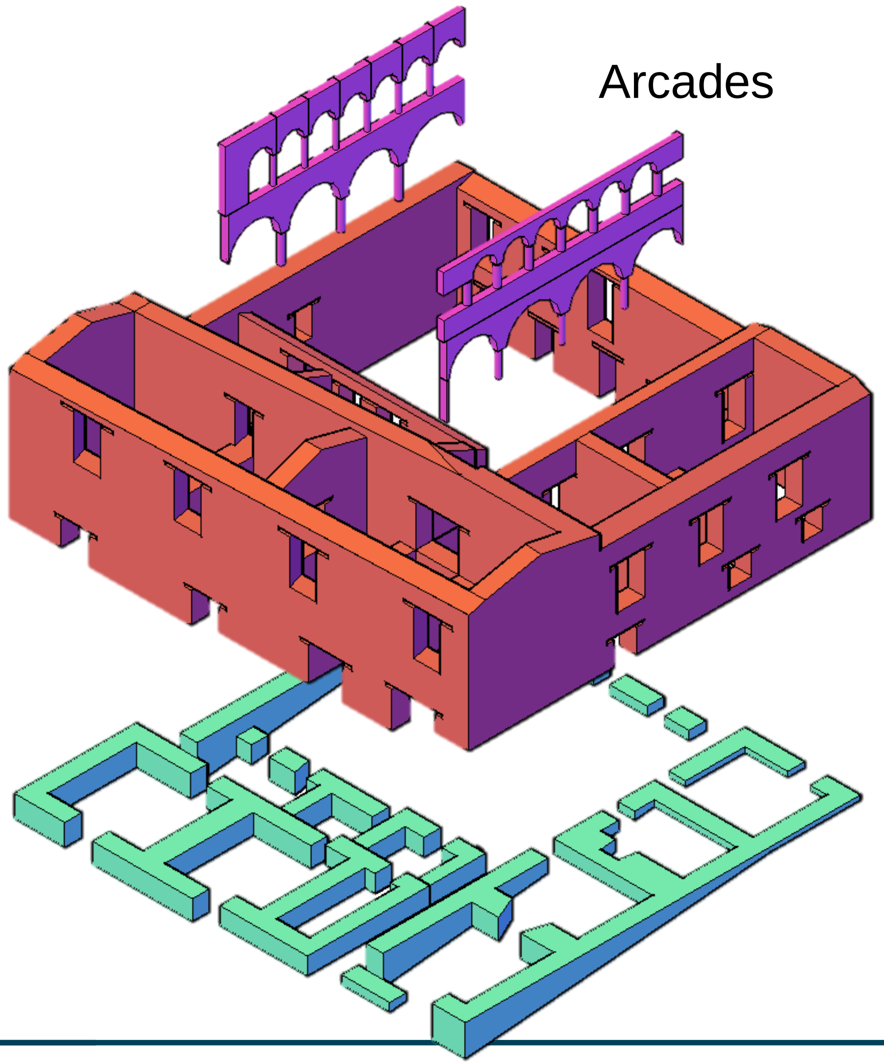
Division into Macroelements



Preliminary Diagnosis

Aims to give direct testing/modelling strategy

For each macroelement we look in turn at each variable:

- Relevance (how influential is the variable?)
- Nature of the variable (positive or negative)
- Level of confidence (percentage) in this judgement

MACROELEMENTS	VARIABLES				
	Resilience V1	Deterioration V2	Interaction V3	Connections V4	Masonry V5
Base Course	B + 70				
Arcades					
Tie Beams					
Floor					
Roof					
Adobe Walls					

D — Negligible influence

C — Influential but not significant

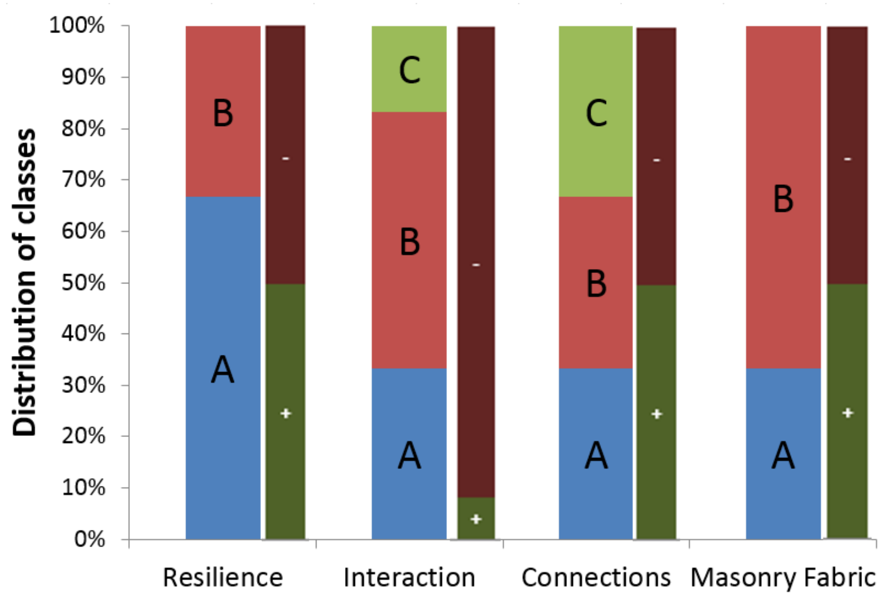
B — Significant

A — Critical

Results of Preliminary Diagnosis Casa Arones

MACROELEMENTS	VARIABLES					
	Resilience V1	Deterioration V2	Interaction V3	Connections V4	Fabric V5	
Base Course	B + 70	D - 80	A - 70		B +/- 80	Level of confidence (%)
Arcades	A + 70	C - 60	B - 40		A - 40	Level of confidence (%)
Tie Beams	B + 80	D - 60	A +/- 60	C + 60		Level of confidence (%)
Floor	A - 80	C - 75	B - 70			Level of confidence (%)
Roof	A - 80	D - 75	B - 75	B +/- 40		Level of confidence (%)
Adobe Walls	A - 80	D - 80	C - 80	A - 70	B + 80	Level of confidence (%)

Interaction between floor beams and adobe wall



Distribution of influential classes and their nature for Casa Arones

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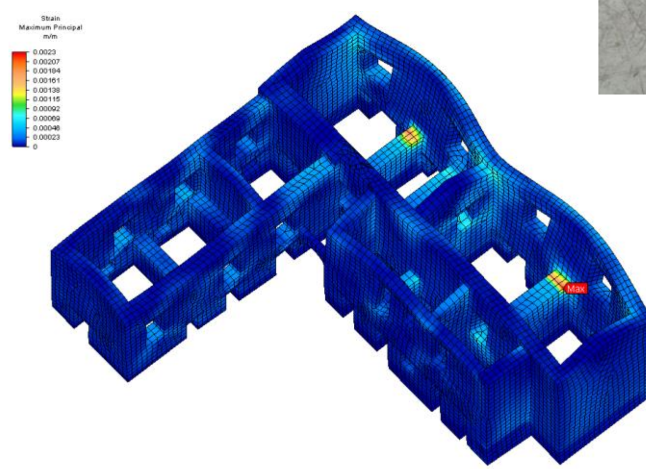
Detailed Diagnosis

Using data from;

- Numerical models;
- Analytical methods;
- Experimental tests;
- Non-destructive/Semi-destructive testing;
- On-site observations.



Detailed Diagnosis

Global criteria

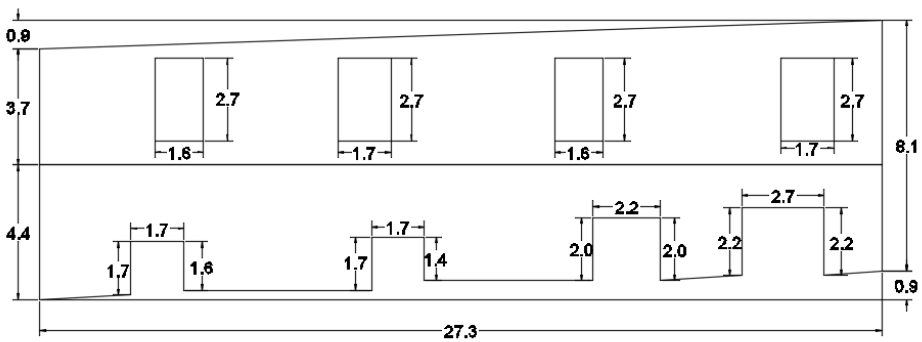
1. Regularity in elevation;
2. Regularity in plan;
3. In-plane and out-of-plane drift.

Resilience

Local criteria

1. Stability of the elements; — Resilience
2. Maximum stresses and strains at interfaces; — Interaction
3. Occurrence of cracking; — Resilience, Interaction
4. Layout of masonry fabric — Quality of the fabric
5. Failure of Connections — Connections

Global Criteria: regularity in elevation & plan



Peru Seismic Code E.030

TABLA N° 4
STRUCTURAL IRREGULARITIES IN HEIGHT

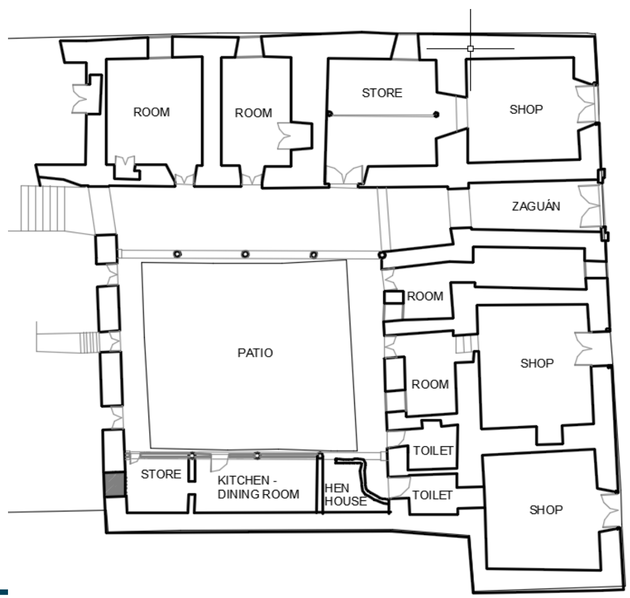
Stiffness Irregularities – Soft Floor
In each direction the sum of the transversal sections of the vertical elements resistant to shear in any story, columns and walls, is lower than 85% of the corresponding sum for the superior story, or is less than 90% of the average sum for the three consecutive stories. It is not applicable to basements. For buildings which have different story heights multiply the values mentioned above by (h_i/h_d), where h_d is the different story height and hi is the typical story height.

Mass Irregularity
It is considered that mass irregularity exists when a story mass is higher than 150% of the mass of the adjacent floor. It is not applicable to basements.

Vertical Geometric Irregularity
The dimension in plan of the structure resistant to lateral loads is higher than 130% of the corresponding dimension in an adjacent floor. It is not applicable to basements or rooftops.

Discontinuity in Resistant Systems.
Out of line in vertical elements, due to orientation change or by a displacement with a higher magnitude than the element dimension.

FEMA 365
ASCE 41-06



4.2.3.2 Criteria for regularity in plan

(1)P For a building to be categorised as being regular in plan, it shall satisfy all the conditions listed in the following paragraphs.

(2) With respect to the lateral stiffness and mass distribution, the building structure shall be approximately symmetrical in plan with respect to two orthogonal axes.

(3) The plan configuration shall be compact, i.e., each floor shall be delimited by a polygonal convex line. If in plan set-backs (re-entrant corners or edge recesses) exist, regularity in plan may still be consi... backs do not affect the floor in-pla... between the outline of the floor and ... not exceed 5 % of the floor area.

(4) The in-plan stiffness of the fl... the lateral stiffness of the vertical s... floor shall have a small effect on ... structural elements. In this respect, th... examined, notably as concerns the ... comparable to that of the central part... The application of this paragraph sh... building.

EN 1998-1, 2004

NZEE URM Code, 2006

Table 3.4: Guide to severity of critical structural weaknesses

Critical structural weakness	Effect on structural performance: Severe	Significant	Insignificant
Plan irregularity			
L-shape, T-shape, E-shape	Two or more wings length/ width > 3.0, or one wing length/width >4	One wing length/width > 3.0	All wings length/width ≤ 3.0
Long narrow building where spacing of lateral load resisting elements is ...	> 4 times bldg. Width	> 2 times bldg. Width	≤ 4.0 times bldg width
Torsion (Corner Building)	Mass/centre of rigidity offset > 0.5 width	Mass/centre of rigidity offset > 0.3 width	Mass/centre of rigidity offset < 0.2 width or effective torsional resistance available from elements orientated perpendicularly.
Ramps, stairs, walls, stiff partitions	Clearly grouped, clearly an influence	Apparent collective influence	No or slight influence
Vertical irregularity			
Soft storey	Lateral stiffness varies > 150%	Lateral stiffness varies 100–150%	Lateral stiffness varies < 100%

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Global Criteria: in-plane and out-of-plane drift

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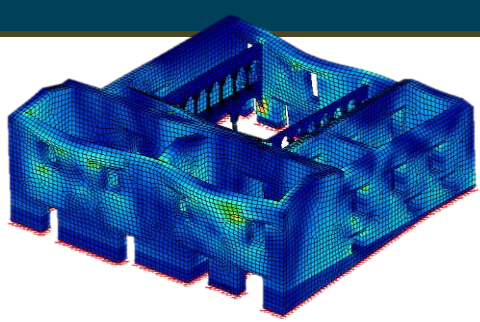
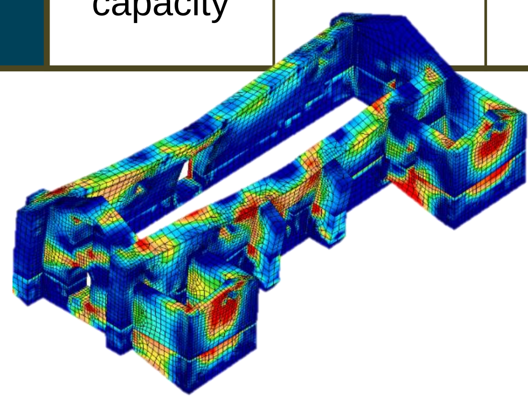
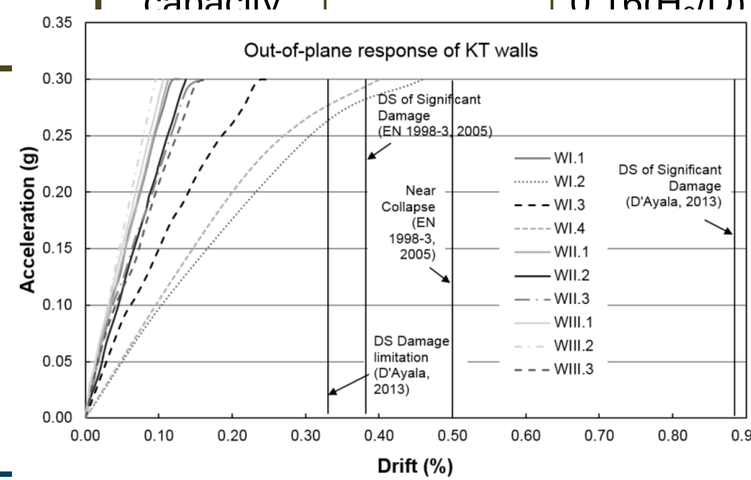
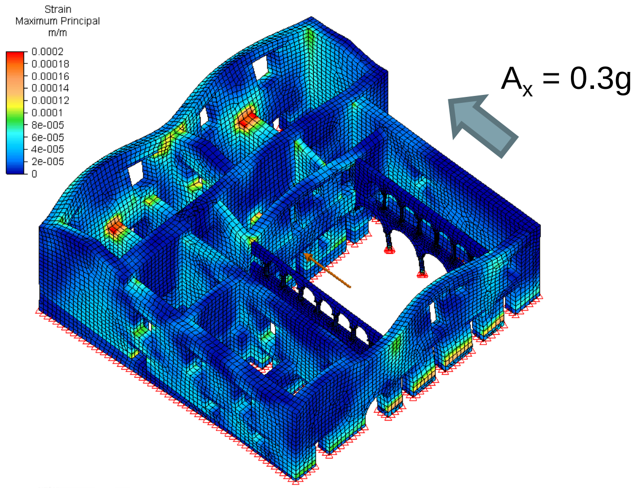
Source	In-plane drift (%)			Out-of-plane drift (%)		
	Damage Limitation	Significant Damage	Near Collapse	Damage Limitation	Significant Damage	Near Collapse
D'Ayala (2013) (Masonry Walls) Results for combined behaviour of the FaMIVE procedure.	-	-	-	0.030-0.168	0.099-0.582	0.198-1.401
D'Ayala (2013) Based on review of experimental work	0.18-0.23	0.65-0.90	1.23-1.92	0.33	0.88	2.3
Eurocode 8, Part 3 (EN 1998-3, 2005)	Shear force capacity	0.4-0.6	0.533-0.8	Shear force capacity	$0.008(H_0/D)$ to 0.012	$0.011(H_0/D)$ to $0.16(H_0/D)$







Local Criteria: maximum stresses & strains



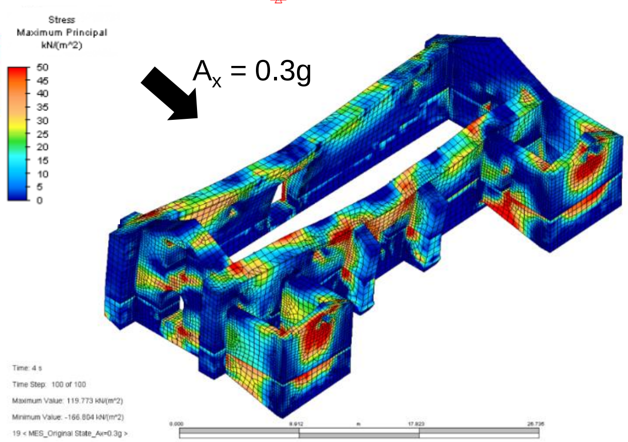


Image: E. Vicente

Image: E. Vicente

Local Criteria: connections

Image: PUCP

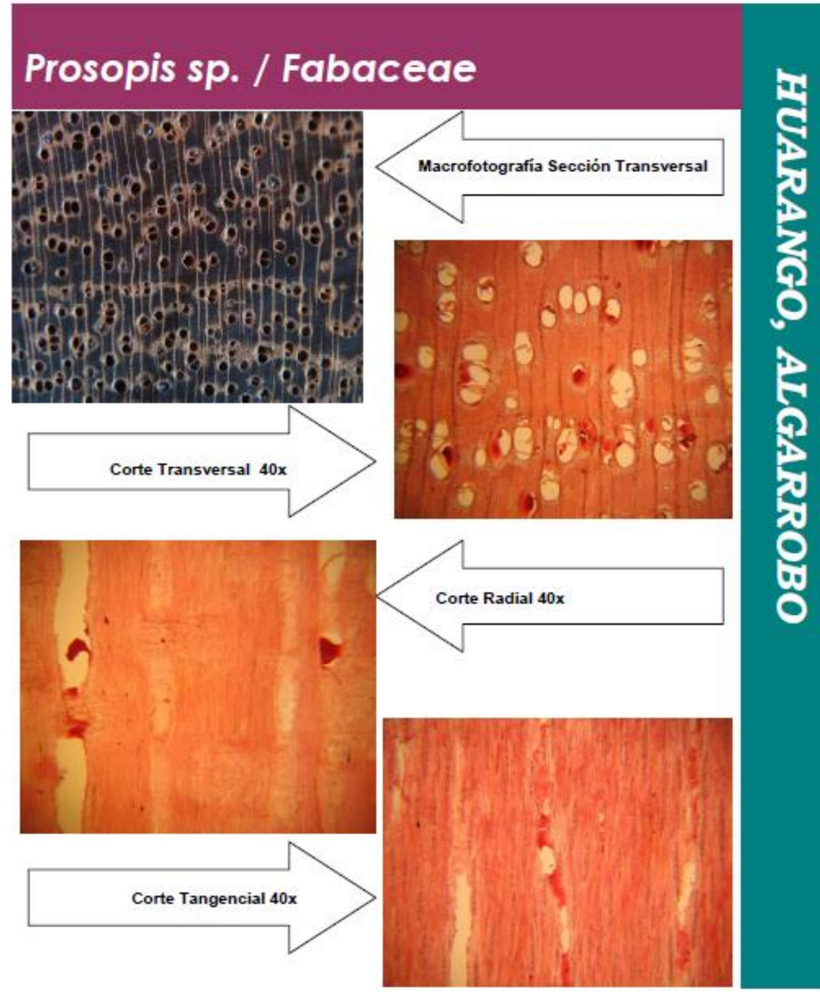


Image: Universidad La Molina

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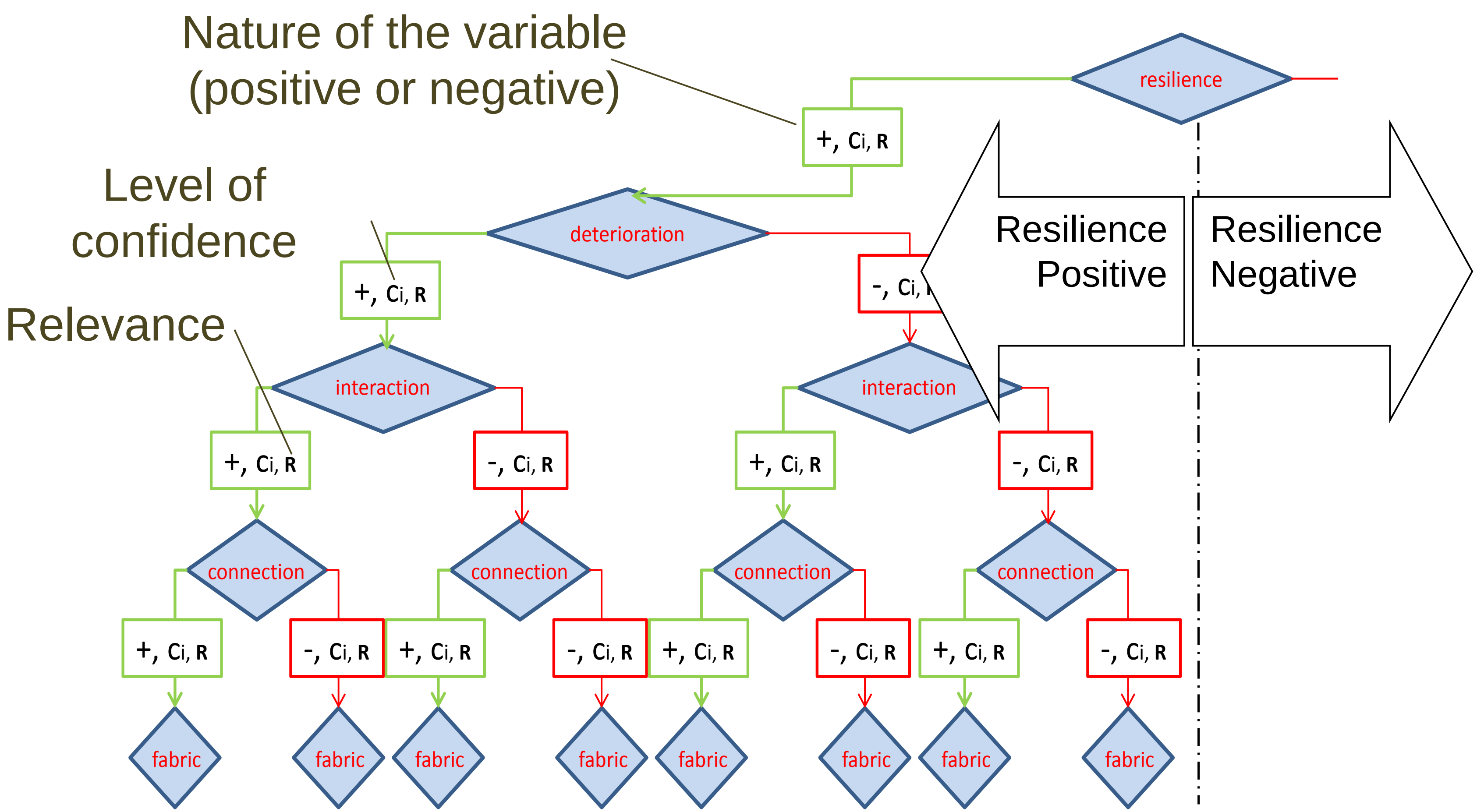
Local Criteria: quality of the masonry fabric

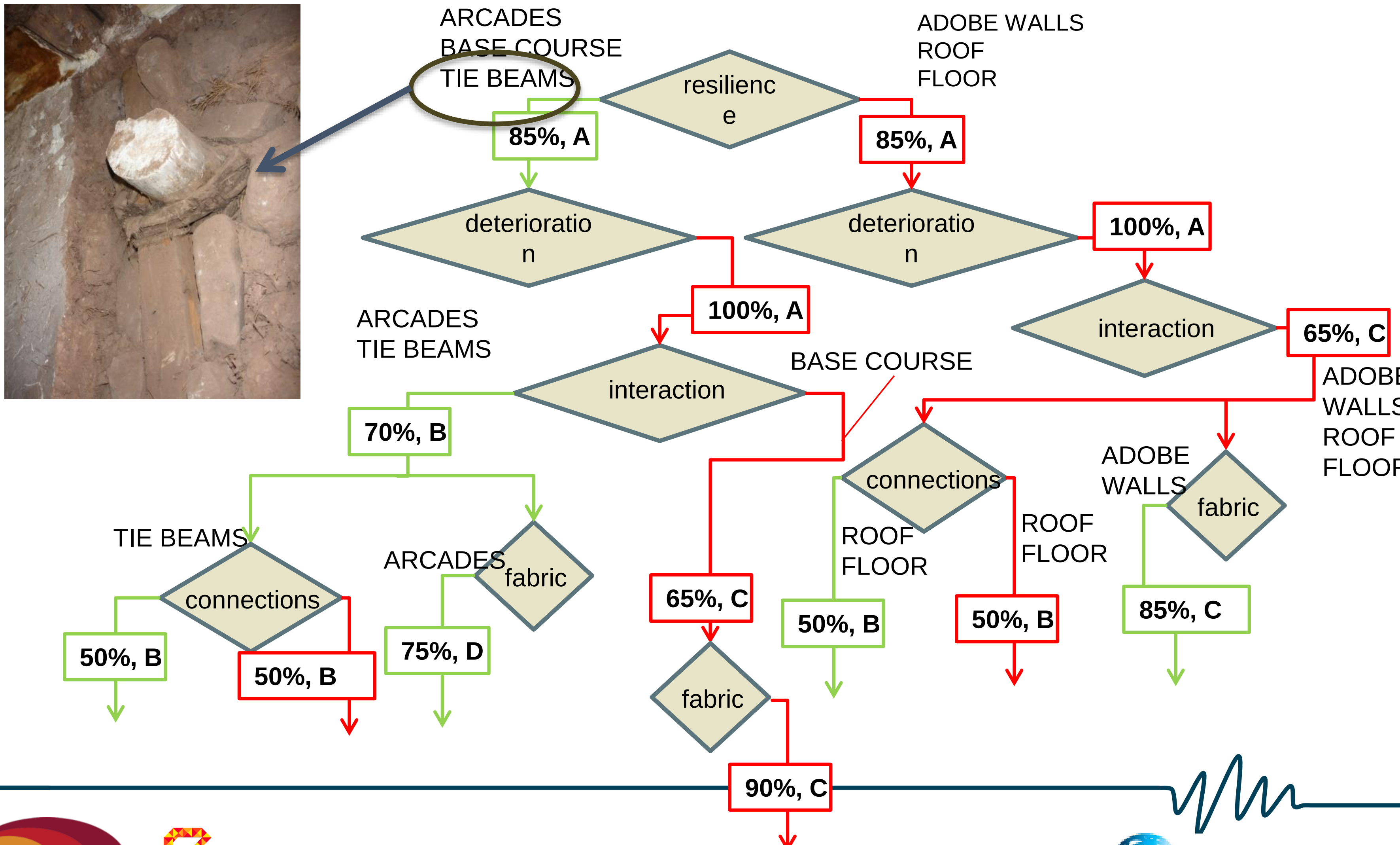
- Homogeneity of the fabric;
- Shape ratios of units;
- Overlapping of units;
- Thickness and filling of the joints and quality of the mortar.



Decision Tree Approach

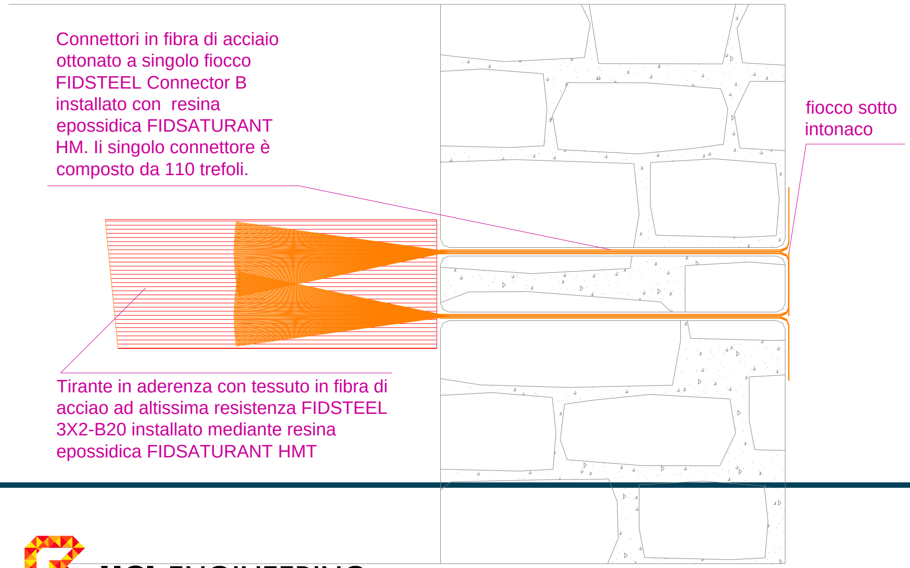


Results of Detailed Diagnosis of Casa Arones

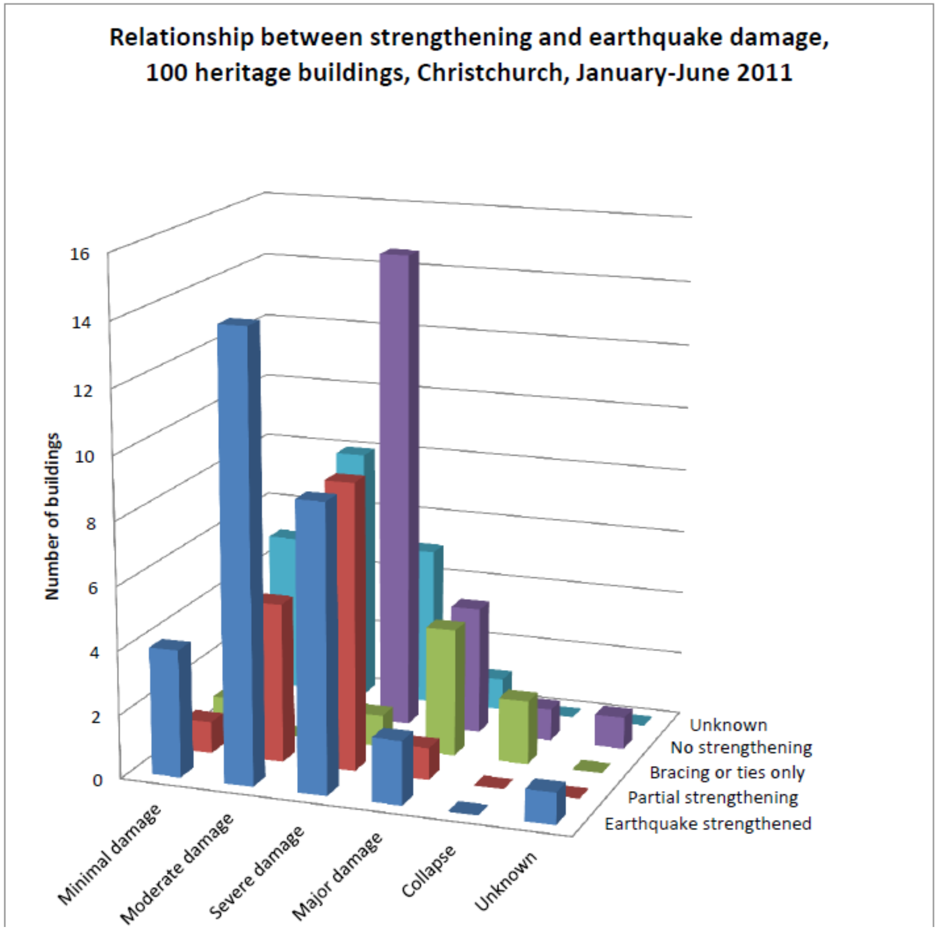


ITALIAN GUIDELINES: OPCM 2008-2011

- **Out-of plane failure prevention**. Ties and anchors in two orthogonal directions to connect orthogonal walls, floors to walls, vaults to walls. Ring beams: conventionally in reinforced concrete, but reinforced masonry or steel preferred. External wrapping and confinement using FRP can be seen as an alternative. Anchorage is a problem.
- **In-plane strengthening and stiffening.** Grouting to improve integrity and coherence of walls. Reinforced core grouting only in extreme cases of very poor coherence of the wall’s leafs. Shotcreting should also be avoided
- **Improving diaphragm action**. In timber floor and roofs by means of double layers of planks or thin mortarcrete topping and connection of joists to walls by anchors. Vaults should be strengthened by including spandrel walls. Extradossal use of FRP strips is acknowledge but not recommended



- **In-plane strengthening** – i.e. concrete shear walls and facings, concrete frames, braced steel frames, infilling w openings, plywood faced shear walls.
- **Face-load strengthening** – i.e. Floor, roof and ceiling l ties, rosehead washers, mullion supports, parapet bracin cantilever columns, composite fibre flexural strips, butt or propping, helical steel through ties, concrete overlay
- **Combined face-load and in-plane strengthening** – i.e Vertical and/or horizontal post tensioning, deep drilling reinforcing of walls, grouting rubble filled walls, concre overlay walls.
- **Diaphragm strengthening** – i.e. plywood overlay diap boundary connections, chords, drag ties, steel flat overl concrete topping overlays, roof and ceiling diaphragms.
- **Chimney, towers and appendages** – i.e. securing chim and towers to diaphragms and/or walls, wire tying



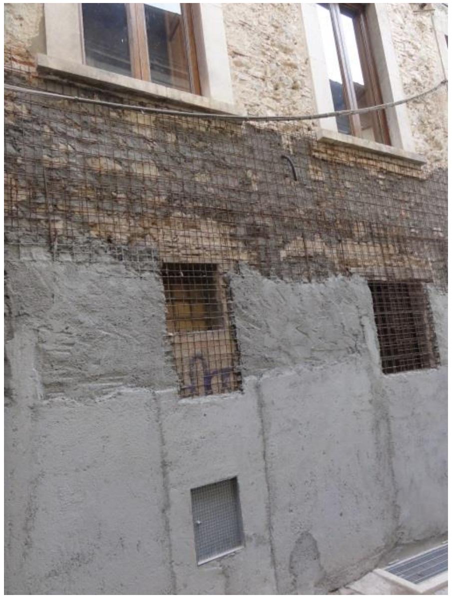
Heritage Buildings, Earthquake Strengthening and Damage, The Canterbury Earthquakes, September 2010-January 2012

EFFECTIVE TIES and PEGS

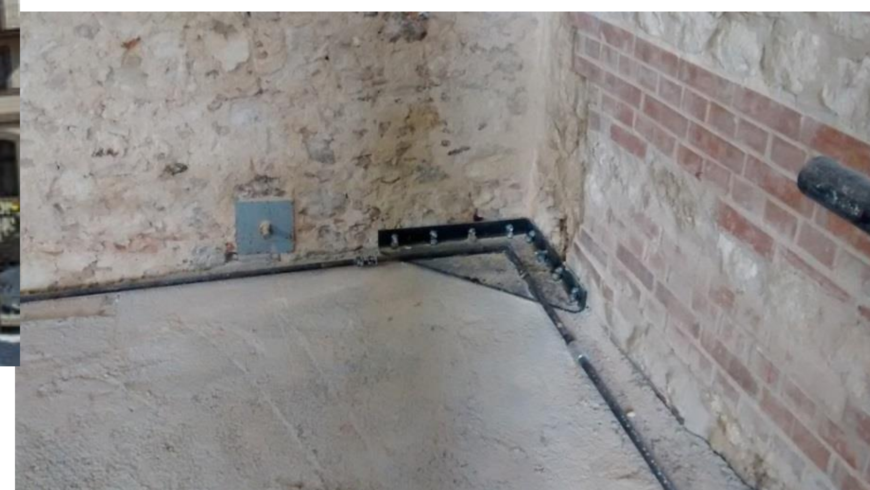
Philippines **L'Aquila**

EVIDENCE FROM THE FIELD: STRENGTHENING

- Fabric integrity
- Diaphragm action
- Box like behaviour
- Out of plane control



PALAZZO ARDINGHELLI IN L'AQUILA



BRACING OF ROOF DIAPHRAGM

SYSTEMIC USE OF STANDARD ANCHORS

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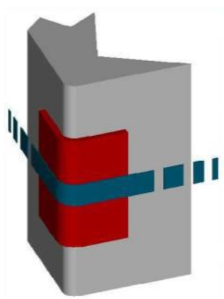
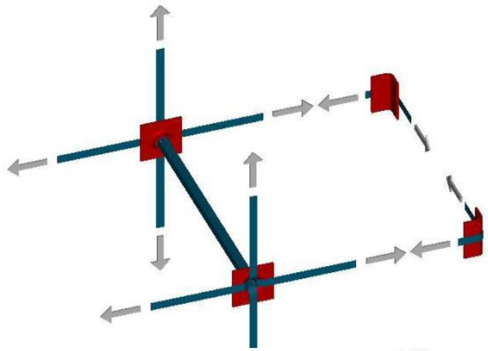
REINFORCED CORE GROUTING

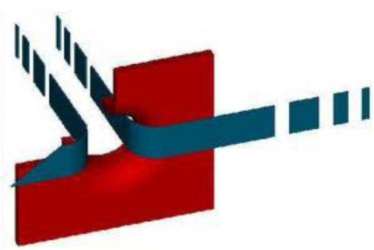
a)

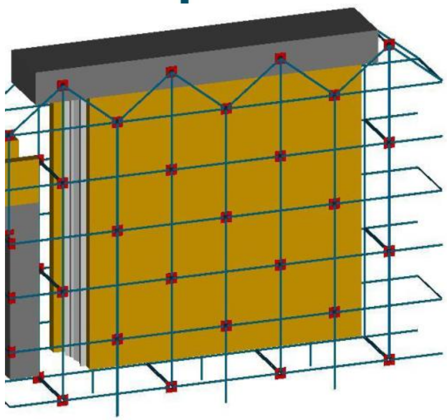
Active Masonry Confinement (CAM SYSTEM)

- As an alternative to shotcreting, more ductile, but very invasive, very labour intensive and non retractable





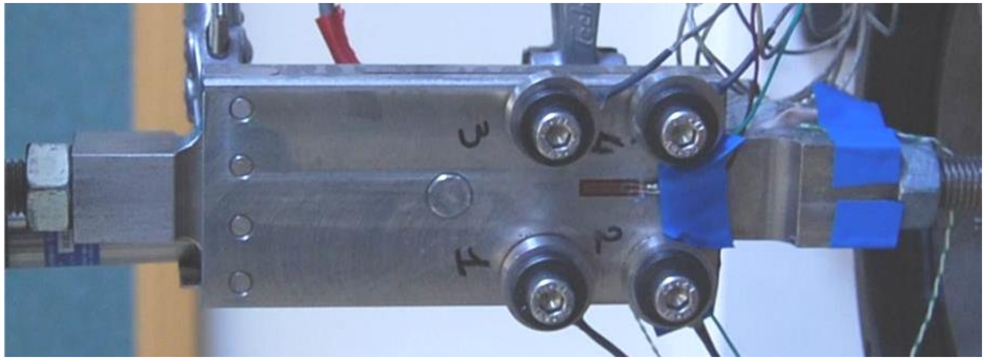


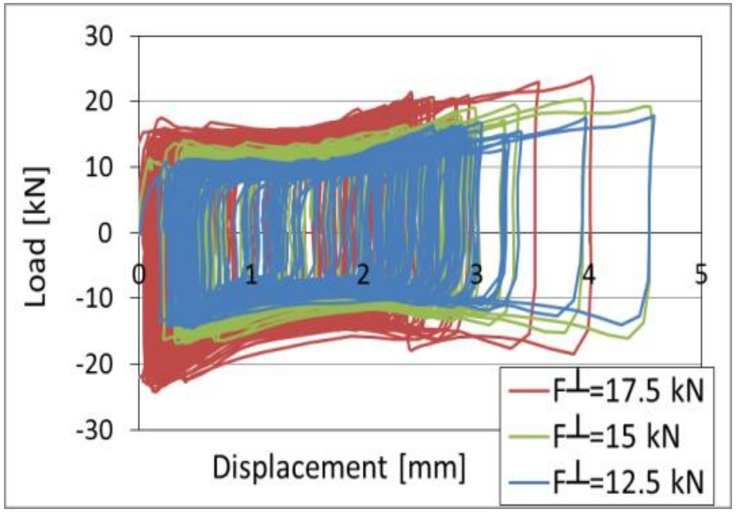


Ponzo et al. 2011., Proceedings of the Ninth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Society , Auckland New Zealand

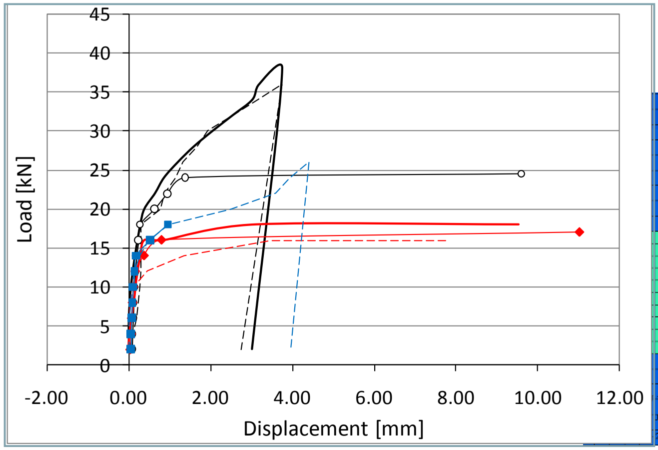
CAM System implemented on site

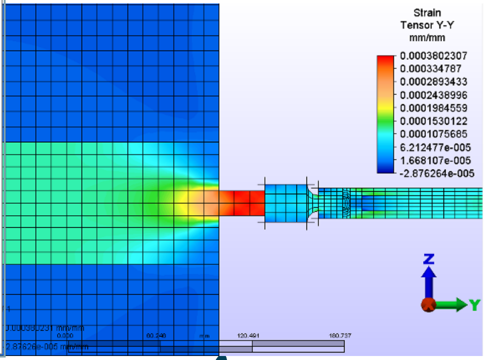
- Friction system



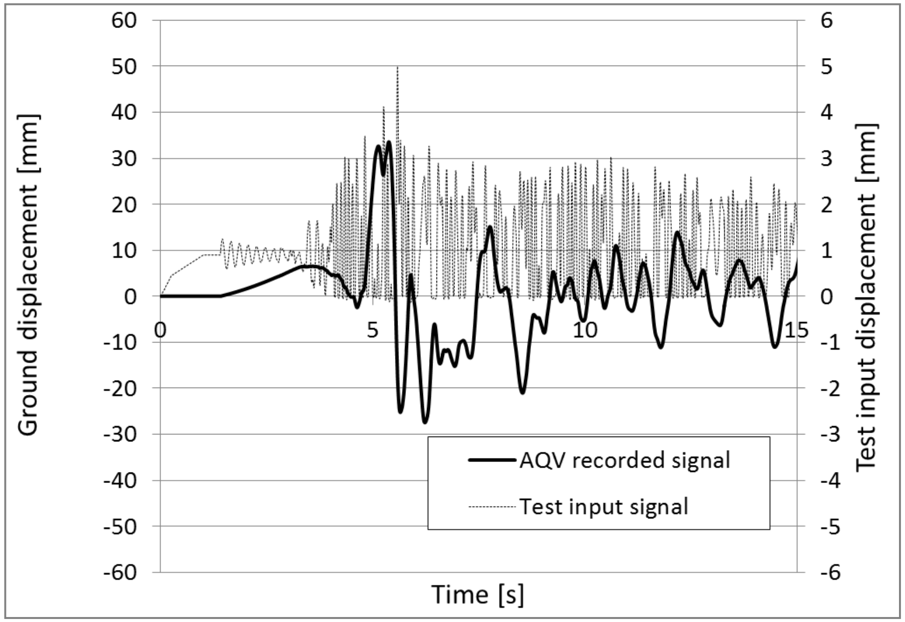


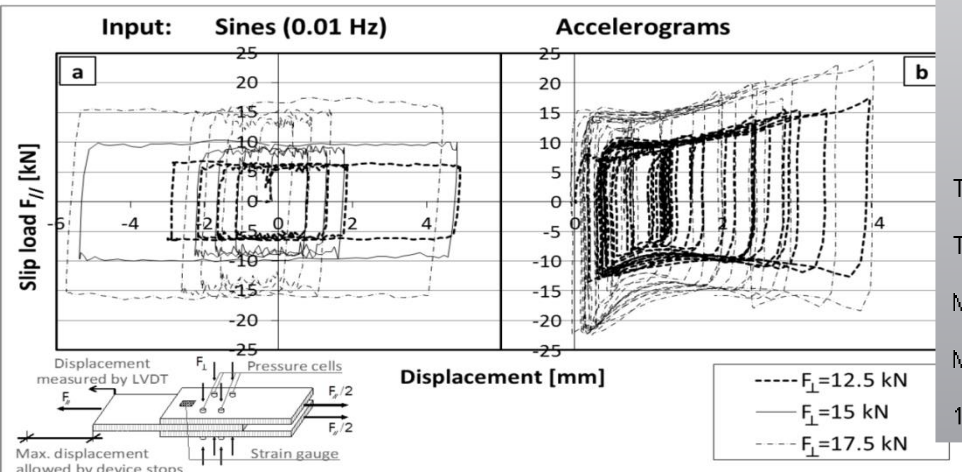
- Pull out

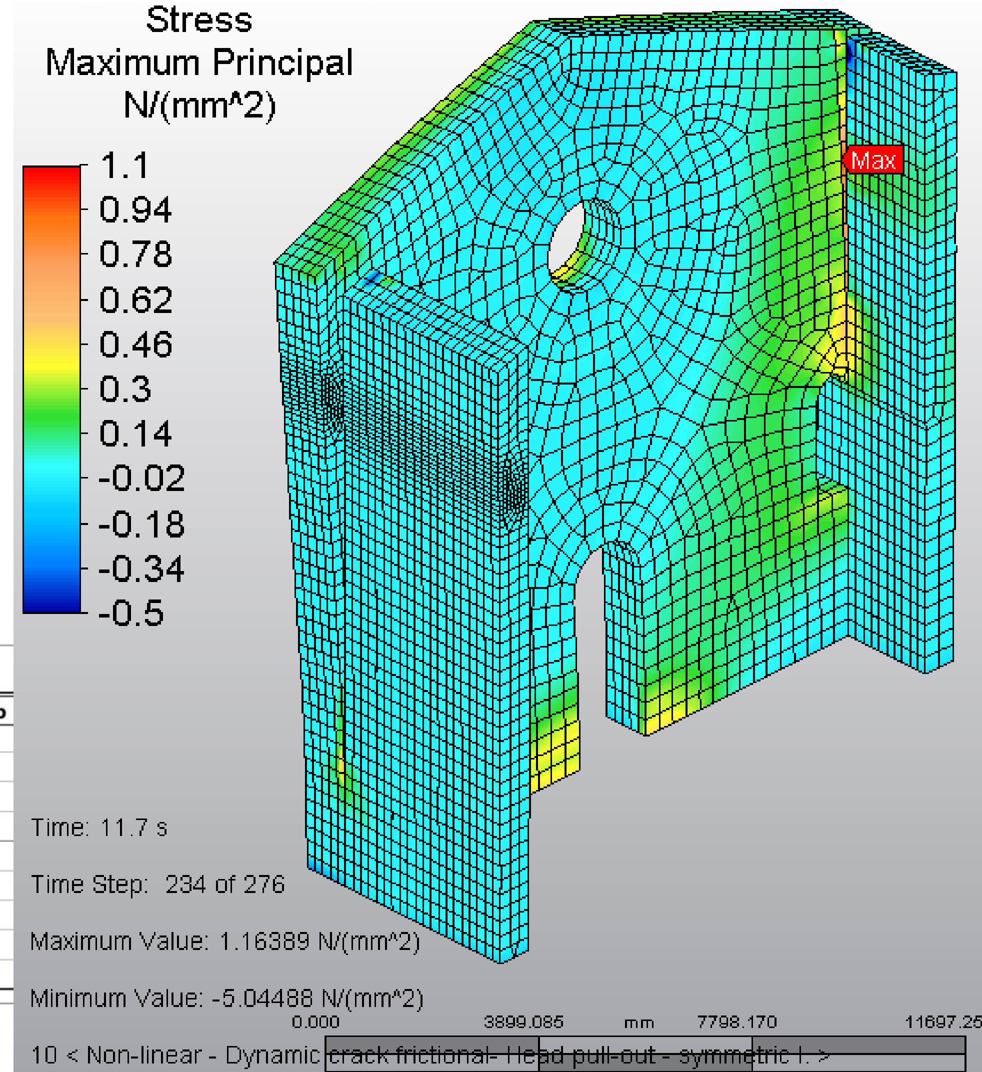




RESPONSE TO SEISMIC EXCITATION







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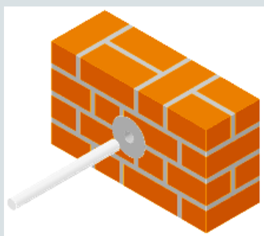
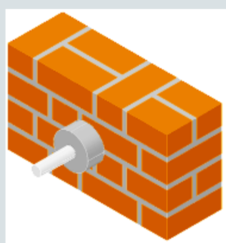
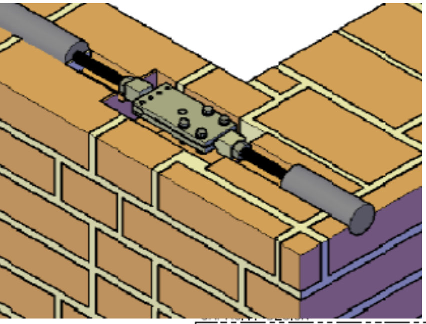
All fixed components are designed for **Near Collapse**

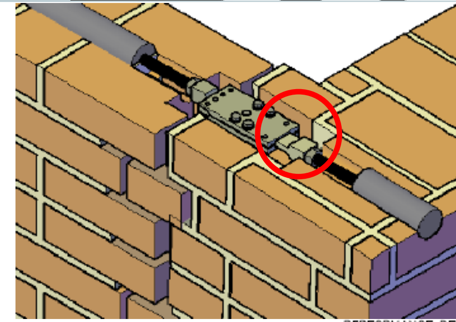
$$\mathrm{Min}(F_{steel}, F_{a/b\ bond}, F_{b/p\ bond}, F_{masonry}) > F_{DU}$$

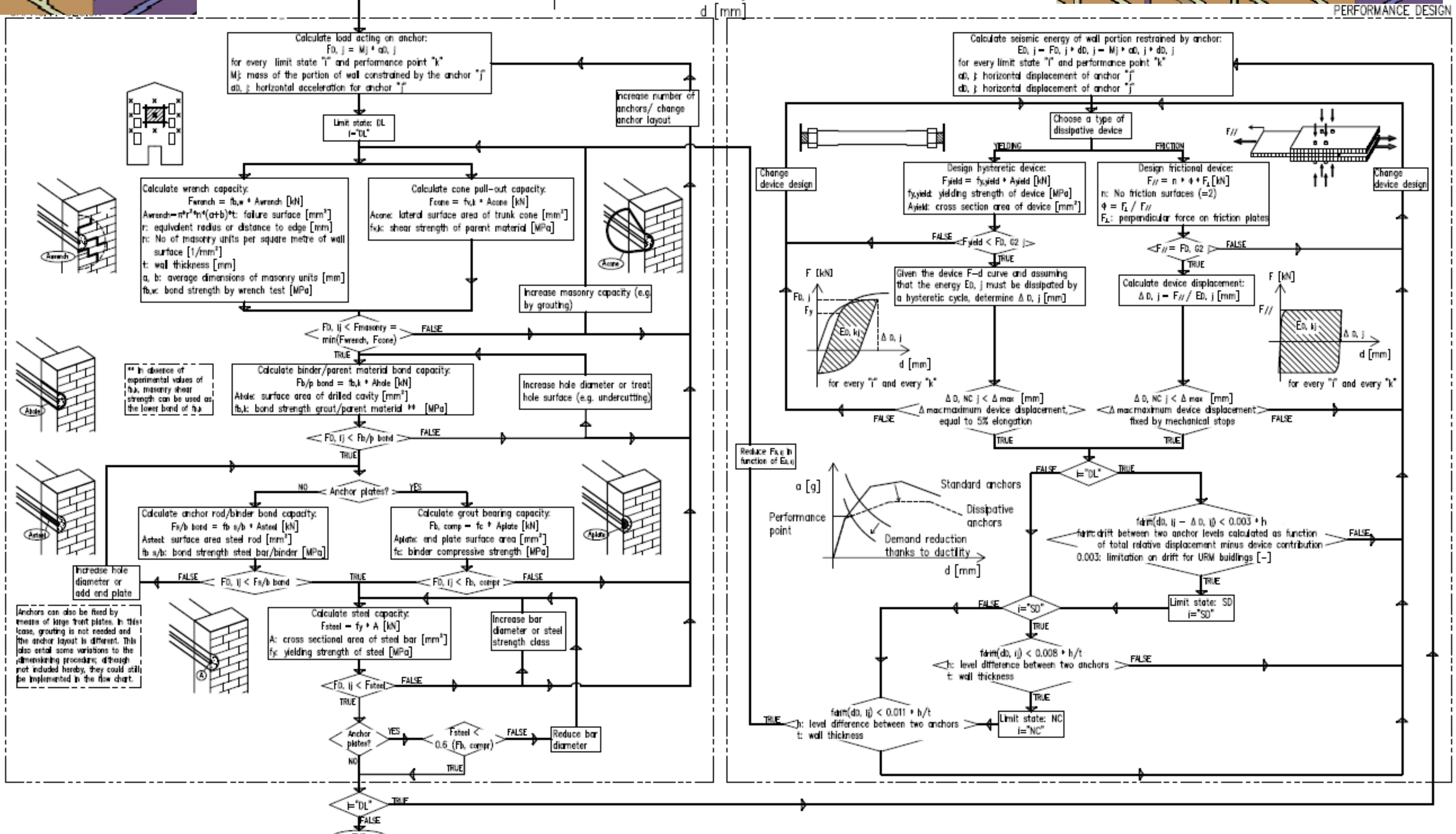
2) F_{steel}: tensile capacity of metallic bar at yielding [kN] 	F_{steel}=71 kN (for M16 threaded bar - values stated by producer)	F_{steel}=71 kN; calculated as: $F_{steel}=f_yA$ with f_y yielding strength of steel and **A** net cross sectional area of metallic profile (EN 1993-1-1:2005)
3) $f_{b\ a/b}$: bond strength anchor/binder [MPa] calculated on cylindrical surface of embedded bar 	Calculated as: $f_{b\ a/b}=F_{s/b\ bond}/A_{steel}$ with $F_{s/b\ bond}$ recorded load at failure and A_{steel} cylindrical lateral surface calculated as: $A_{steel}=\pi l d_{pitch}$ with **l** embedment length and d_{pitch} pitch diameter of steel bar. For pull-out tests of M16 threaded bars from 550 mm long grouted socks: $f_{b\ a/b}$=2.07 MPa (CoV 4%)	$f_{b\ a/b}$= 3.4 MPa – design value suggested in BS 5268-2 for tested binder, bar diameter and type of bar; 2 MPa – design value suggested in EN 1996-1-1:2005 for tested binder and type of application
4) $f_{b\ b/p}$: bond strength binder/parent material [MPa] calculated on cylindrical surface of grouted socket 	Calculated as: $f_{b\ b/p}=F_{b/p\ bond}/A_{hole}$ with $F_{b/p\ bond}$ recorded load at failure and A_{hole} inner cylindrical surface of drilled hole of length **l**. For pull-out tests with vertical load on masonry specimens σ_d:	Calculated as: $f_{b\ b/p}=f_{vk}=f_{vk,0}+0.4\sigma_d$ with $f_{vk,0}$ initial shear strength (calculated through experimental results) and σ_d vertical load (EN 1996-1-1:2005).

	l [mm]	σ_d [MPa]	$f_{b\ b/p}$ [MPa]	σ_d [MPa]	$f_{b\ b/p}$ [MPa]
Brick masonry, f_c=6.7 MPa, f_w=0.7 MPa	350	0.70	0.67 (CoV 8%)	0.7	0.52
		0.07	0.57 (CoV 18%)	0.07	0.27
Brick masonry f_c=3.1 MPa, f_w=0.33 MPa	220	0.10	0.26 (CoV 34%)	0.10	0.08
		0.05	0.4	0.05	0.06

PBD OF DISSIPATIVE SYSTEM COMPONENTS

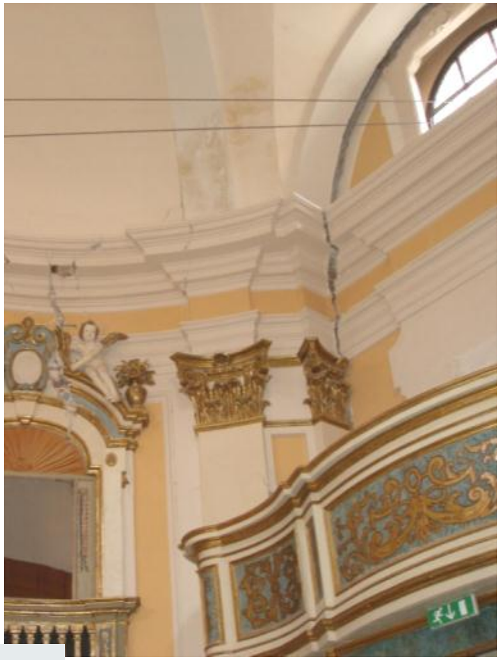


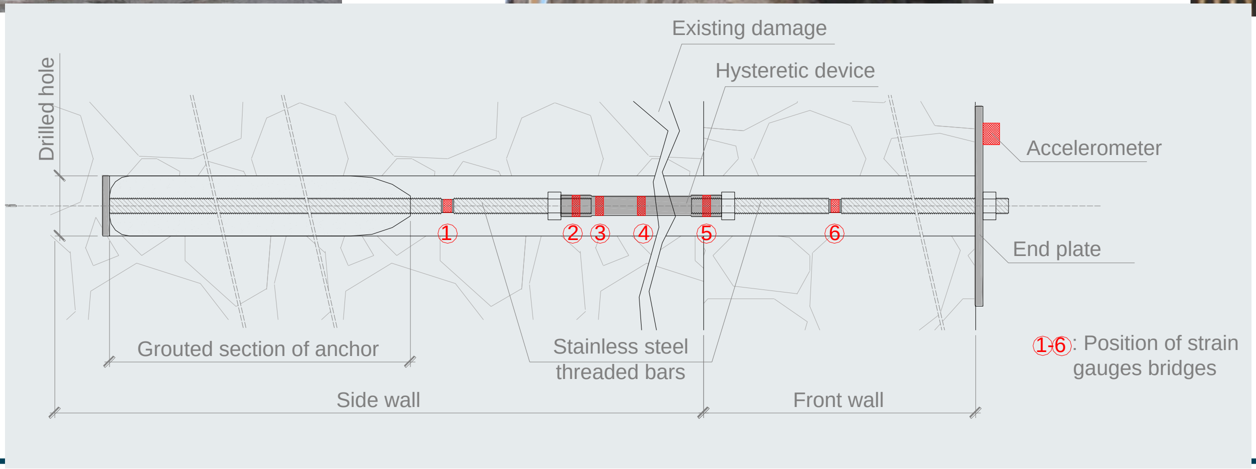




PERFORMANCE MONITORING

The oratory of S. Giuseppe dei Minimi in L'Aquila Italy





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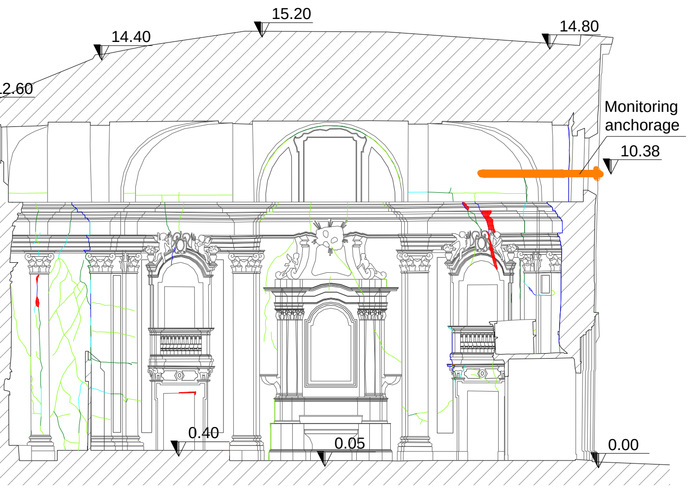
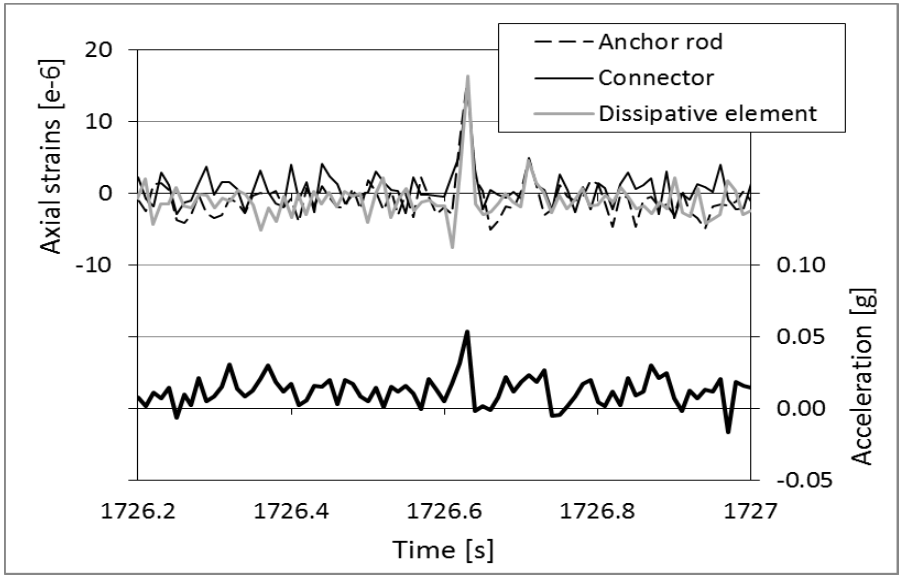
RESPONSE OF INSTRUMENTED ANCHOR





CONCLUSIONS

- The earthquake engineering community has shown increased sensitivity towards the importance of preservation promoting research in new assessment and strengthening methods
- Public cultural differences exist and cannot be ignored when devising policies.
- Recent initiatives such as the ICOMOS New Zealand Charter 2010 (ICOMOS 2010) show a change in perspective and perhaps a different acceptance of risk.
- Much training and education of professional engineers is needed to ensure that the shift in design emphasis from force to energy and displacement requirements is fully understood. Similar training is also needed for contractors
- In the field still far too often upgrading is pursued in terms of increasing strength and stiffness and some assessment criteria are far too conservative.
- The economics of developing and installing dissipative devices, can be overcome, as shown by the prototype devices which can be manufactured in small sizes and at costs which is affordable in the retrofit of heritage buildings, as well as more prestigious landmark.

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