ועדת ההיגוי הבין-משרדית להיערכות לרעידות אדמה
National Steering Committee for Earthquake Preparedness

International Seminar

Assessment and improvement of structural safety under seismic actions of existing constructions: Reinforced Concrete Structures and Historical buildings

SCE - Shamoon College of Engineering, Beer Sheva - 29 November 2015

International Conservation Center, Citta' di Roma, Old Acre - 1 December 2015

Investigation methodologies and techniques: historical investigations, surveys, in-situ and laboratory tests, monitoring

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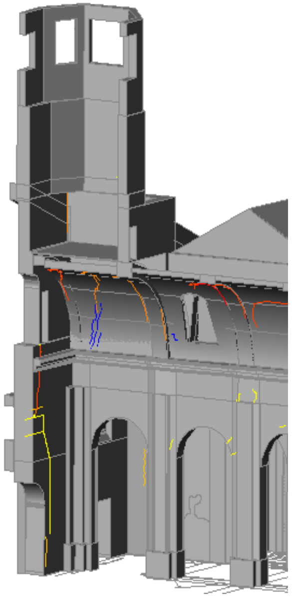
INVESTIGATION FOR KNOWLEDGE

Existing buildings are affected by many uncertainties concerning various aspects detectable with diagnosis investigations:

- Geometry
- Materials
- Structural system and configuration (conceptual design)
- Structural component typology
- Constructive details
- Effect of deterioration and damage
- Influence of interventions
- Interaction with soil



Preservation of historic buildings:

- In-situ low-obtrusive procedures
- Combination of techniques for cross-checking (complementarity)

Objectives:

- Improve knowledge
- Minimize interventions
- Calibration and validation of assessment models

STRUCTURAL CODES APPROACH

<u>Iscarsah Guidelines</u> - Recommendations for the analysis, conservation, and structural restoration of architectural heritage

This **knowledge** can be reached by:

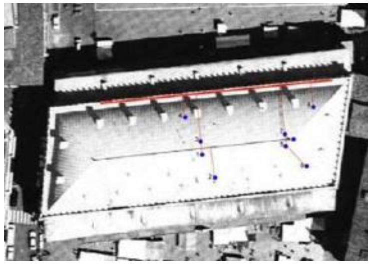
- description of the structure's **geometry** and construction;
- definition, description and understanding of building's **historic and cultural significance**;
- description of the original **building materials and construction techniques**;
- historical research covering the entire life of the structure including both changes and any **previous structural interventions**;
- description of the present state including identification of **damage, decay and possible progressive phenomena**, using appropriate types of test;
- description of the **actions** involved, **structural behaviour** and types of materials;
- a survey of the **site**, soil conditions and environment of the building.

Italian Standard & Guidelines – Building knowledge

The **knowledge of the masonry historical building**, using particular techniques of analyses and interpretation, is the basis for a reliable appraisal of the seismic safety and for the choice of an effective improvement.

Steps:

- **Building identification**
- **Functional characterisation of the building**
- **Geometrical survey**
- **Historical analyses of events and past interventions**
- **Material and structural survey and conservation state**
- **Mechanical characterization of materials**
- **Ground and foundations**
- **Monitoring**

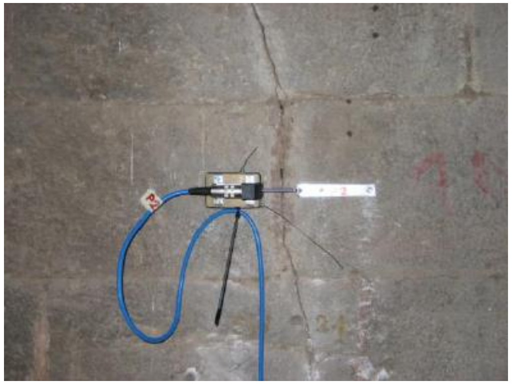


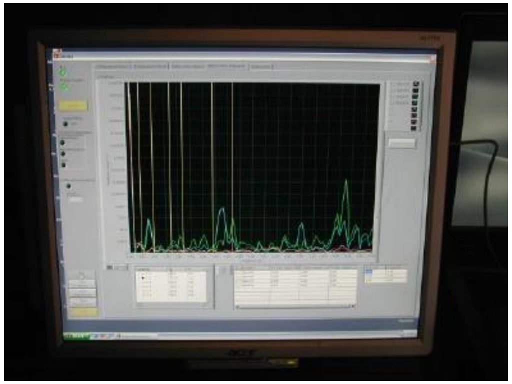
Different knowledge levels and confidence factors CF

MONITORING FOR MAINTENANCE

Monitoring allows to evaluate the behaviour of the structure during its life, enabling the scheduling of **maintenance** works, and indicating the possible necessity of strengthening or repair interventions.

Monitoring start with basic **visual inspection**, to evaluate macroscopic changes in the structure (damage pattern onset, widening of existing cracks…), up to more sophisticated electronic controls on significant mechanical or physical parameters.





Italian Guidelines – Building knowledge

To evaluate the capacity of structural elements, the **material properties** have to be divided by the **confidence factor**, obtained on the basis of the gained **level of knowledge**: an higher knowledge level means higher mechanical properties that can be considered for the materials.

If the considered model for seismic safety assessment does not consider mechanical properties of the material, the confidence factor is used to **reduce the acceleration corresponding to the particular limit state**.

The **confidence factor** is determined as: $F_C = 1 + \sum_{k=1}^{4} F_{Ck}$

Geometrical survey	Material and constructive details inspection	Materials mechanical properties	Ground and foundations
Full geometrical and structural survey $F_{C1} = 0.05$	Limited material and constructive details on site inspection $F_{C2} = 0.12$	mechanical properties obtained from old data $F_{C3} = 0.12$	Limited inspections on ground and foundation, absence of geological data $F_{C4} = 0.06$
Full geometrical and structural survey, with crack and deformation patterns $F_{C1} = 0$	Extended material and constructive details on site inspection $F_{C2} = 0.06$	Limited on site testing on material mechanical properties $F_{C3} = 0.06$	Limited inspections on ground and foundation, presence of geological data $F_{C4} = 0.03$
	Comprehensive material and constructive details on site inspection $F_{C2} = 0$	Extended on site testing on material mechanical properties $F_{C3} = 0$	Extended and comprehensive inspections on ground and foundation $F_{C4} = 0$

KNOWLEDGE ASPECTS

Italian Guidelines – Building knowledge

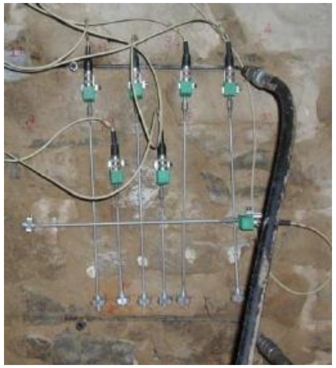
To carry out the structural analyses, it is necessary to gain **proper knowledge** by means of surveys, historical researches, in-situ and laboratory tests:

BUILDING GEOMETRY → geometry, particular elements (such as chimneys, niches, etc), crack pattern & out of plumbs

- by means of surveys

CONSTRUCTIVE DETAILS → connections, lintels, elements to counteract thrusts, vulnerable elements, masonry tipology

- limited *in situ inspection*
- extended & comprehensive *in situ inspection*



MATERIAL PROPERTIES → particularly aimed at the mechanical characterization of masonry, through inspections, NDT, MDT & DT

- limited *in situ testing* (inspections)
- extended *in situ testing* (MDT & NDT)
- comprehensive *in situ testing* (DT)

INVESTIGATION PLAN

1. HYPOTHESYS ON THE BUILDING EVOLUTION

2. IDENTIFICATION OF PLAN-ELEVATION CHARACTERISTICS

3. INTERPRETATION OF CRACK AND DEFORMATION PATTERNS

4. IDENTIFICATION AND CHARACTERIZATION OF CONSTRUCTION DETAILS/ELEMENTS

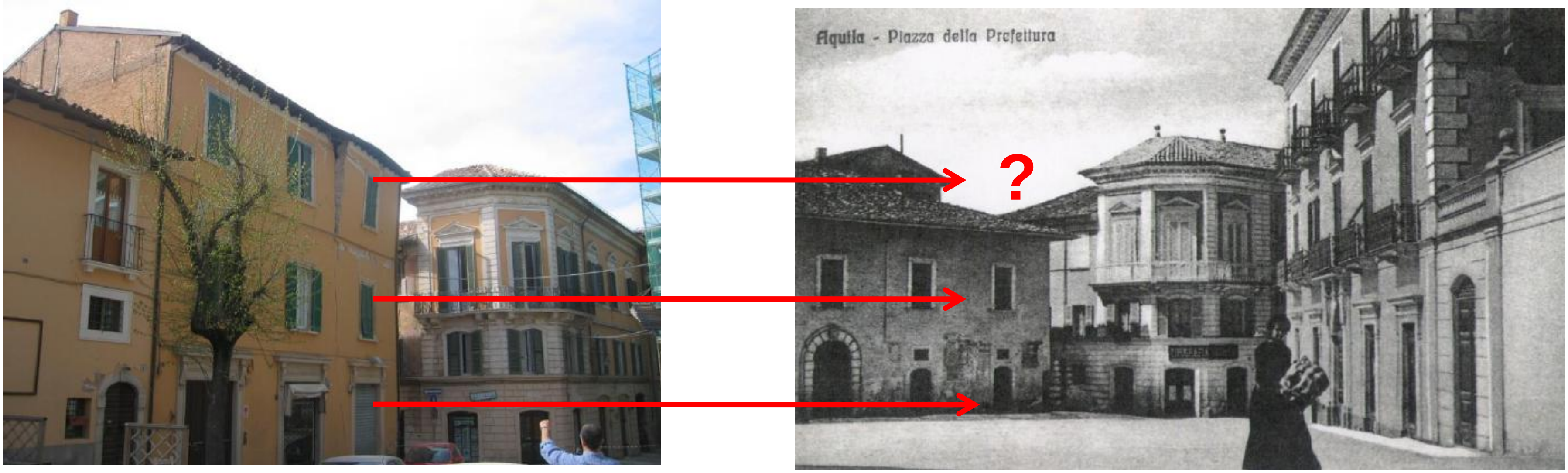
5. MASONRY TIPOLOGY

6. MATERIALS CHARACTERIZATION

↓

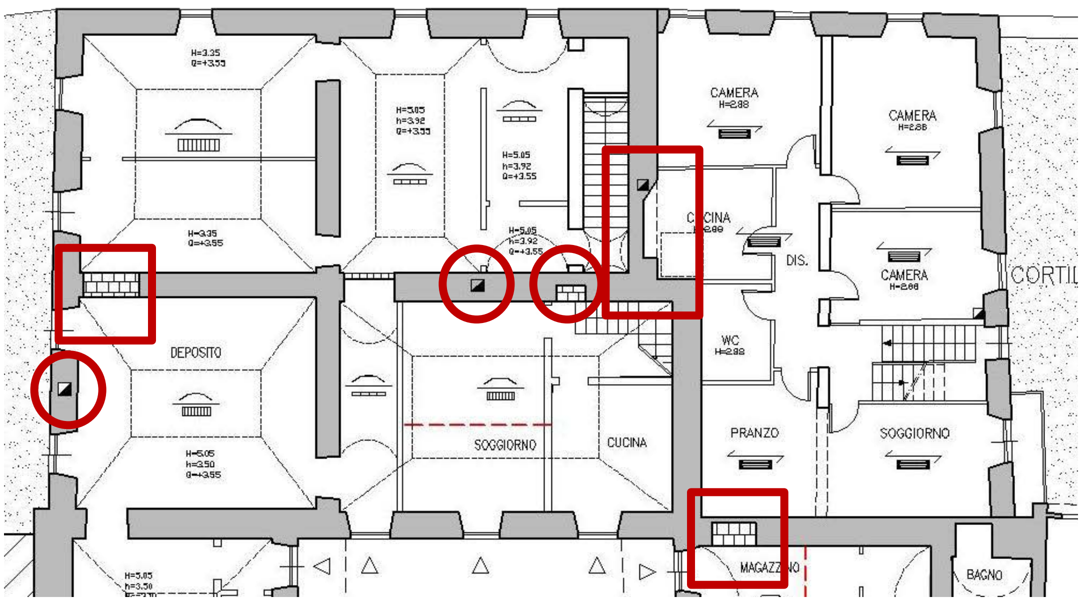
IDENTIFICATION OF RESISTING STRUCTURAL SCHEME, DEFINITION OF ACTIONS AND MECHNICAL PARAMETERS

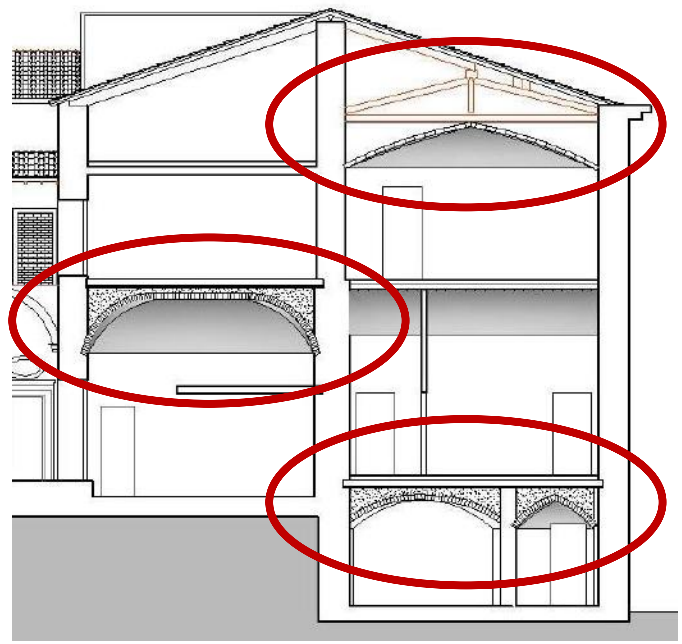
HISTORIC SURVEY



GEOMETRY

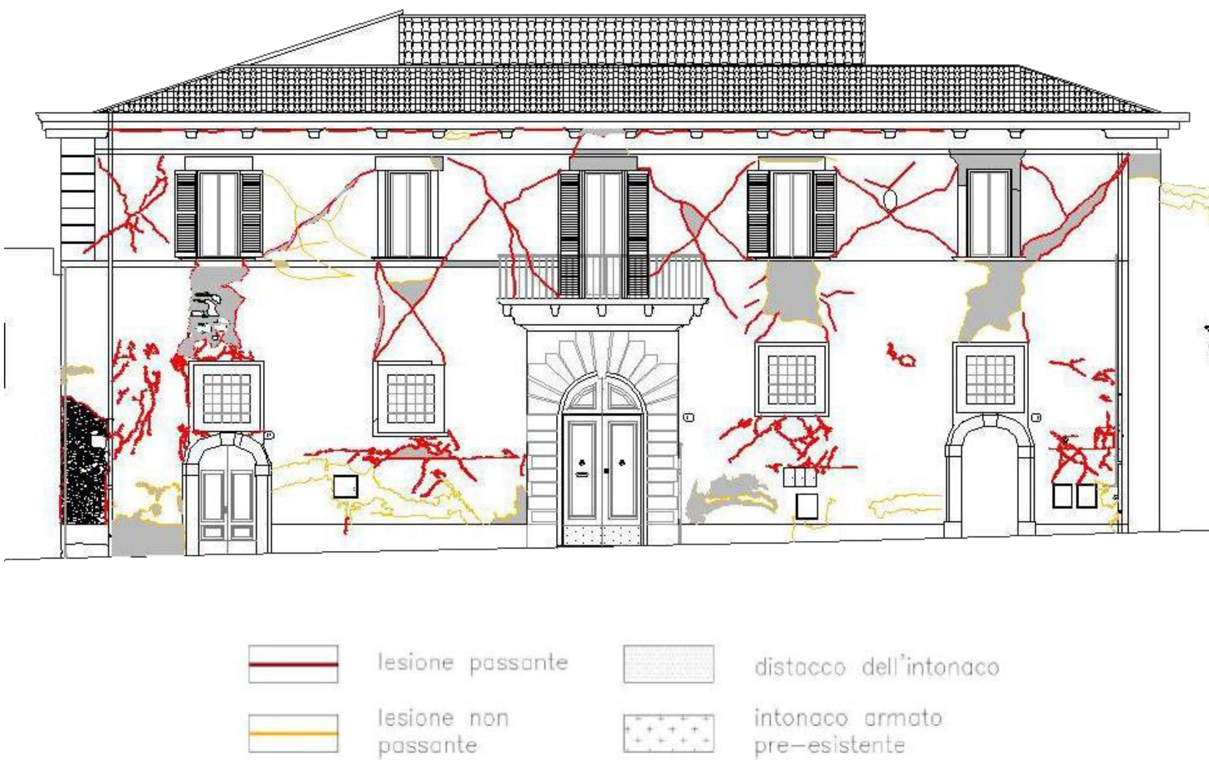
Geometrical survey includes: survey at each floors of all masonry elements and eventual niches, voids, chimneys, vault survey, floors, roofing, stairs, definition of loads, foundations.

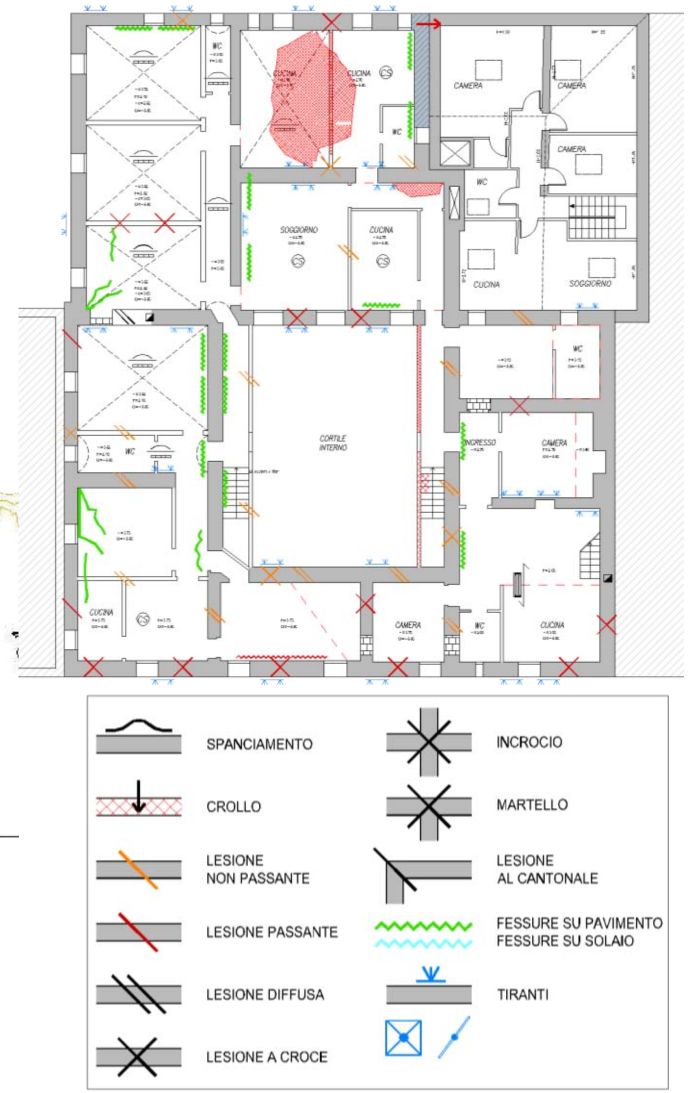




GEOMETRY

Survey and drawing of crack and deformation patterns

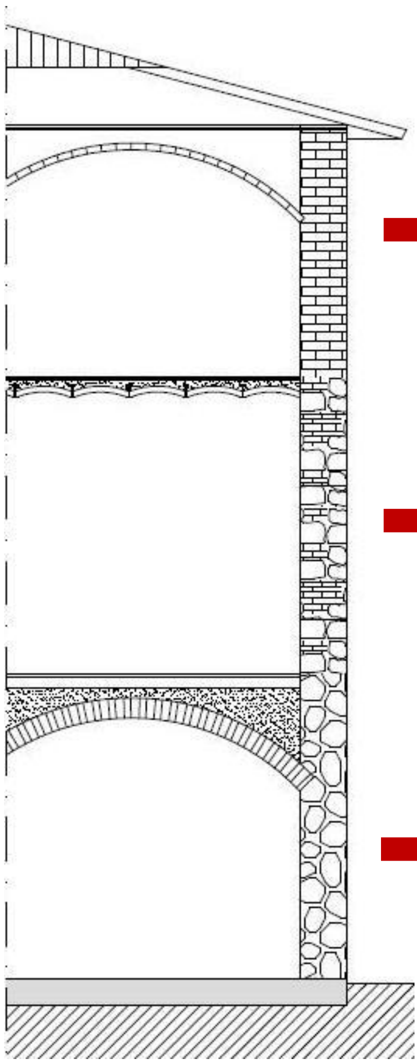


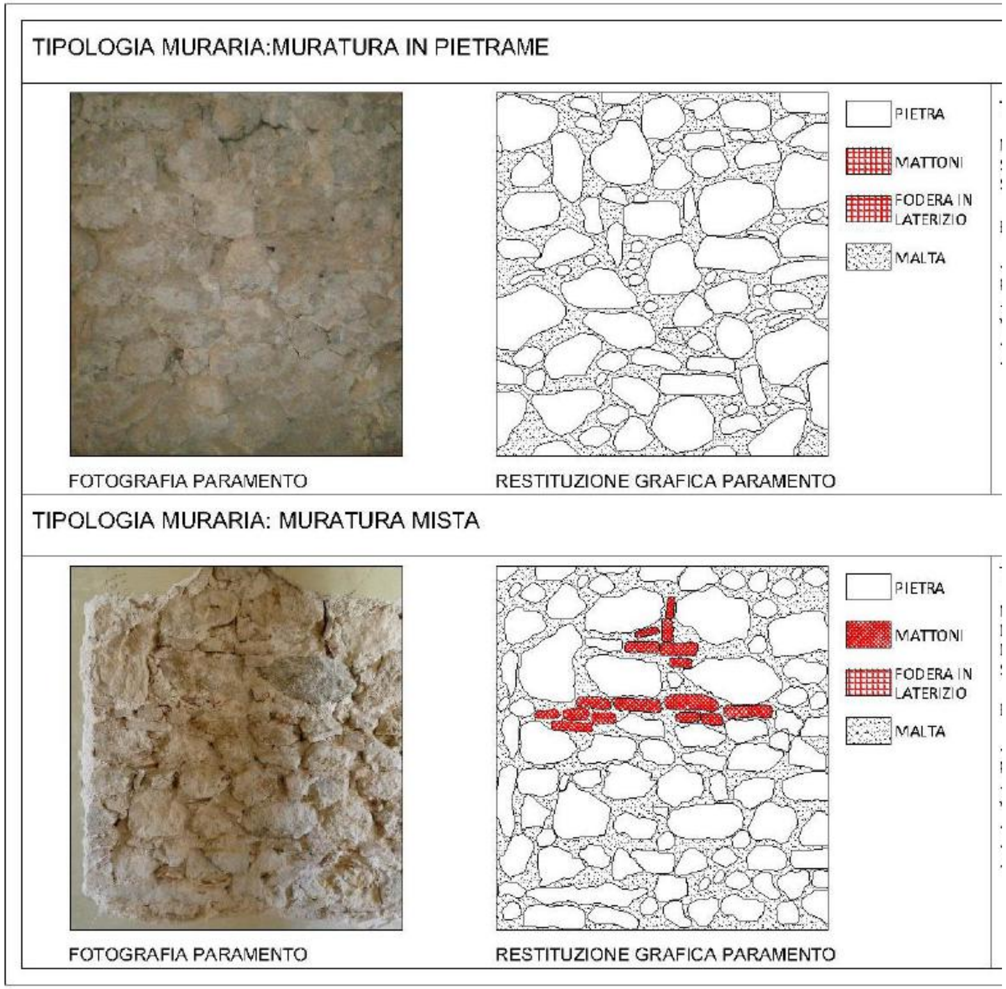


CONSTRUCTION DETAILS

- quality of connections between walls;
- type and quality of connections between horizontal diaphragms and walls;
- type and efficiency of lintels above openings;
- presence and efficiency of elements to counteract horizontal thrusts;
- presence of structural or non structural elements with high vulnerability;
- type and quality of masonry

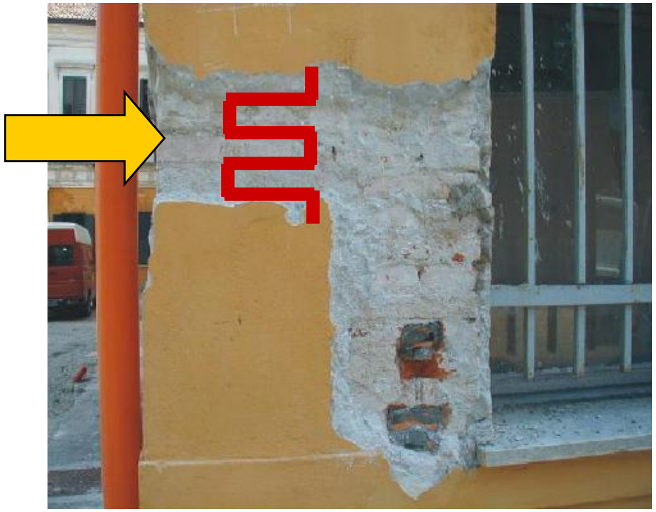
STRUCTURAL COMPONENTS TYPOLOGIES





CONSTRUCTION DETAILS

The critical analysis is carried out by means of visual inspections, by removing plaster and small masonry dismantling, in order to check both masonry texture and masonry in its thickness, considering also the connections between walls and between walls and floors.

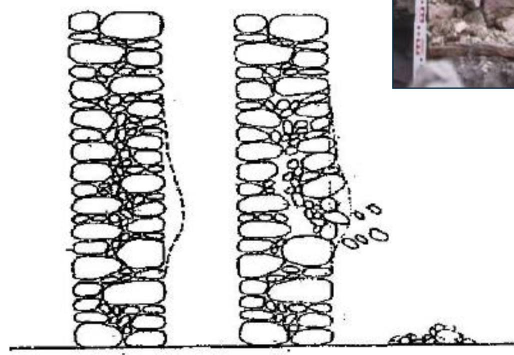


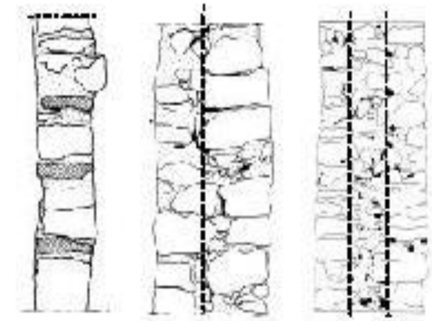
Limited on-site verifications: based on visual surveys, usually through tests on the masonry that lead to superficial examination

Extended and comprehensive on-site verifications: based on visual surveys, usually through tests on the masonry that lead to <u>both</u> superficial and deep examination, and of the connection between orthogonal walls.

MASONRY TYPOLOGIES

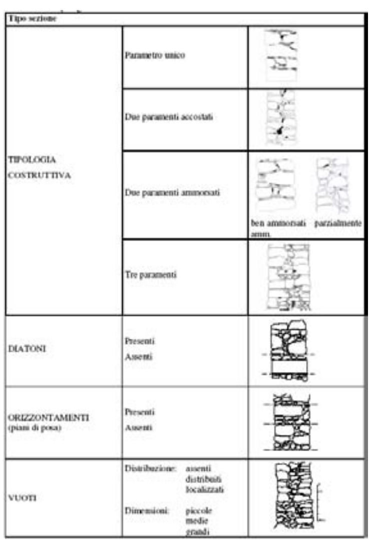
It Is possible to refer to abaci for the evaluation of the quality and bearing capacity of **masonry typologies**

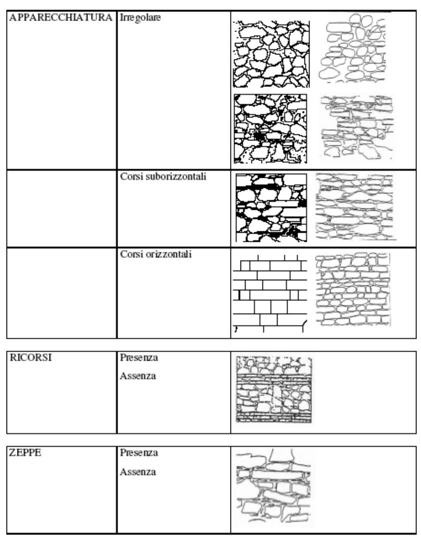


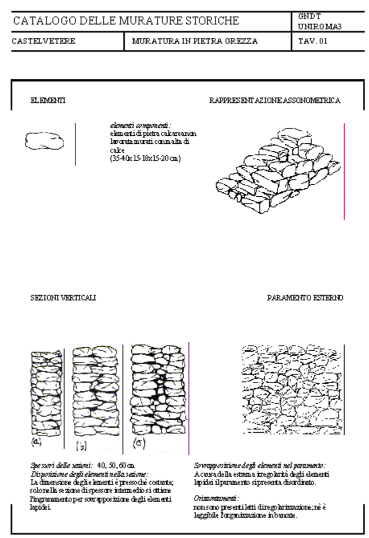


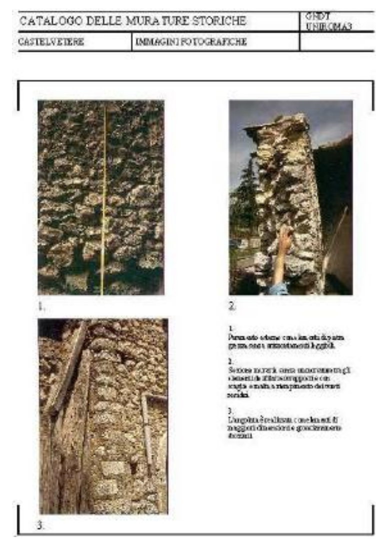
Heterogeneous masonry built up with poor materials, presence of voids, irregularities, multi-leaf sections, absence of connections

Out-of-plane brittle collapses







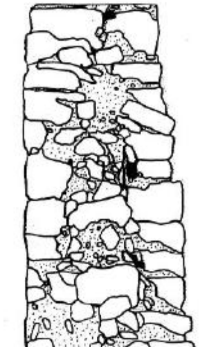


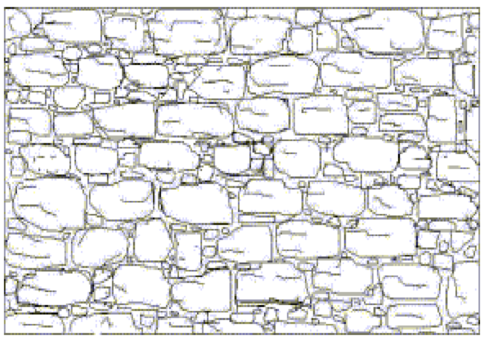
Survey forms: frequent local masonry typologies

MASONRY TYPOLOGIES

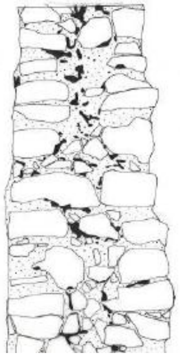
Montesanto di Sellano (PG) - Politecnico di Milano

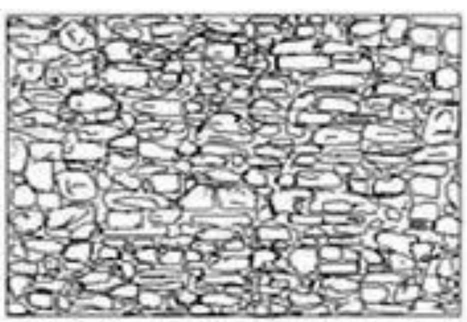
Regular texture



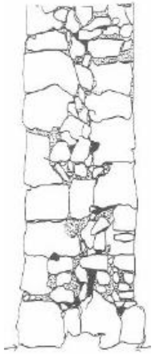


Texture with sub-horizontal courses



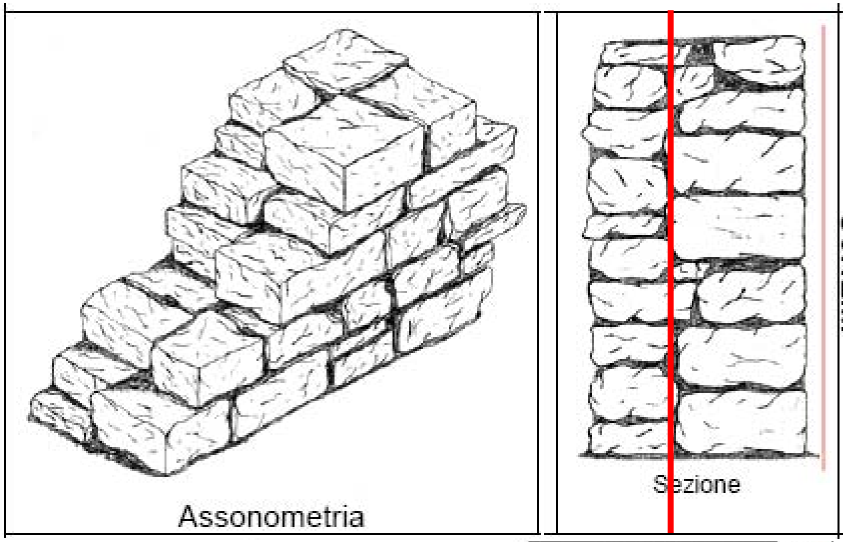


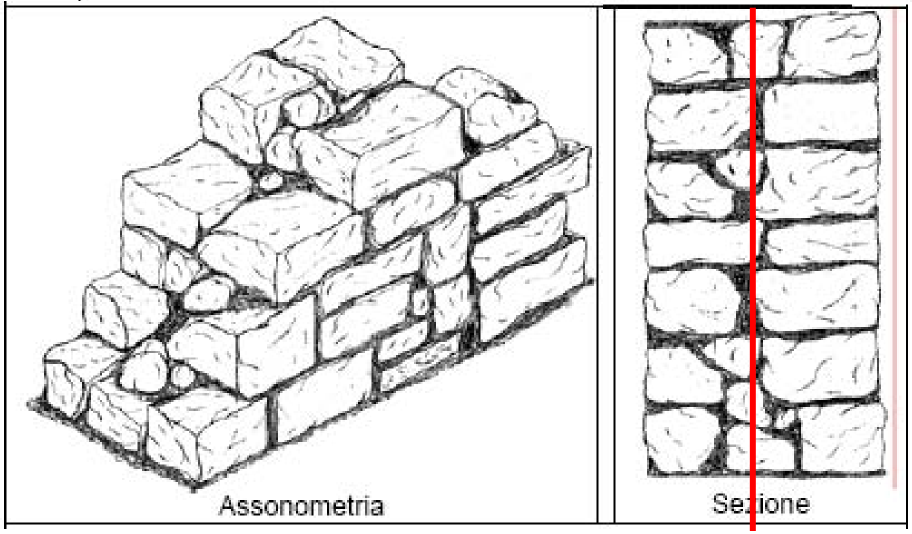
Irregular texture



MASONRY MORPHOLOGY

TWO-LEAF WALLS

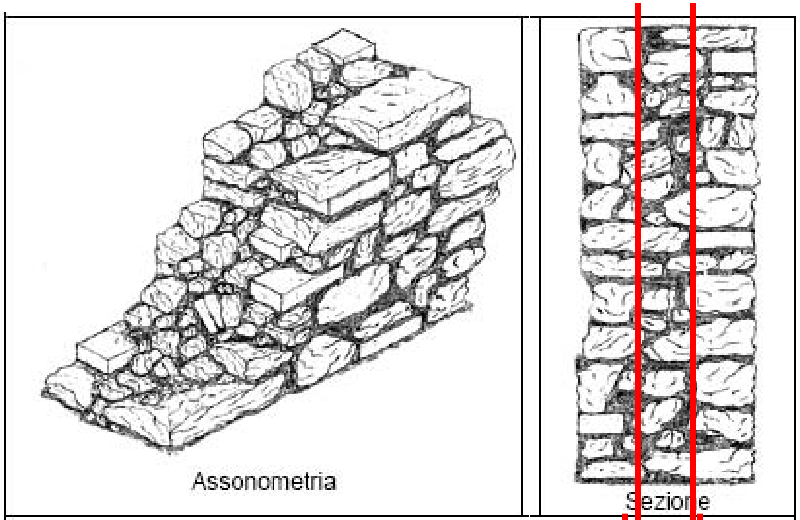


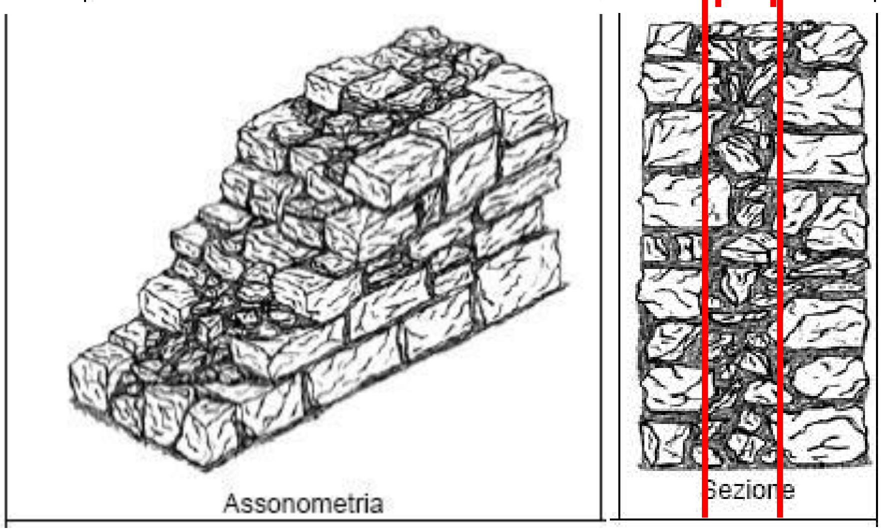


Progetto esecutivo Reluis 2005-2008; Allegato 3b.1_UR06_2

MASONRY MORPHOLOGY

THREE-LEAF WALLS





Progetto esecutivo Reluis 2005-2008; Allegato 3b.1_UR06_2

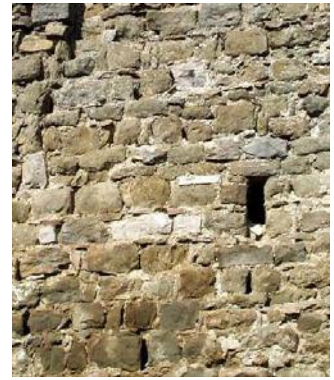
MASONRY QUALITY

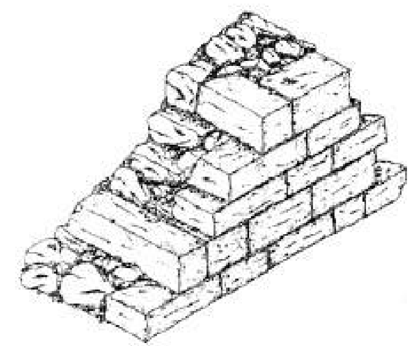
MASONRY QUALITY EVALUATION

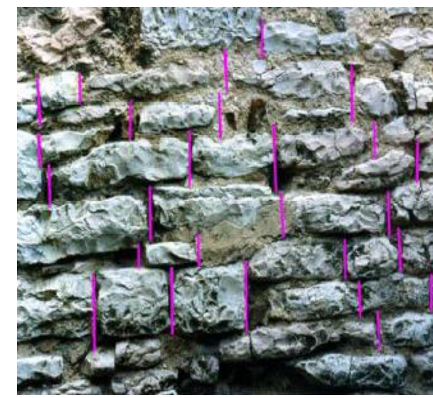
Local constructive rule parameters:

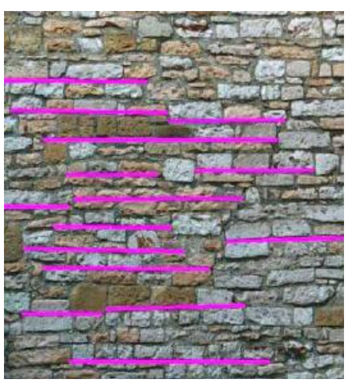
- mortar quality
- presence of transverse connecting elements
- elements shape
- elements dimension
- staggering vertical joints
- horizontality of the courses
- units strength
- wedges

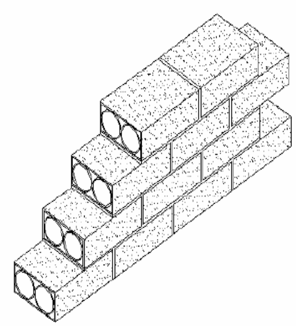
(University of Perugia)



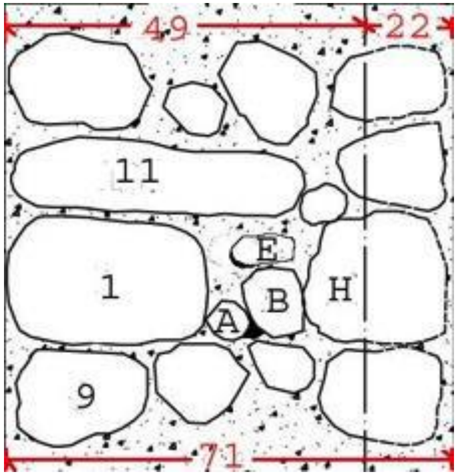


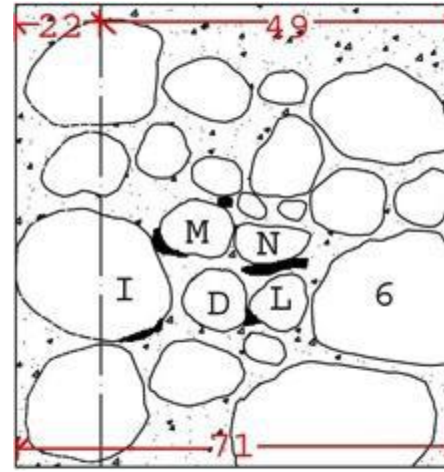




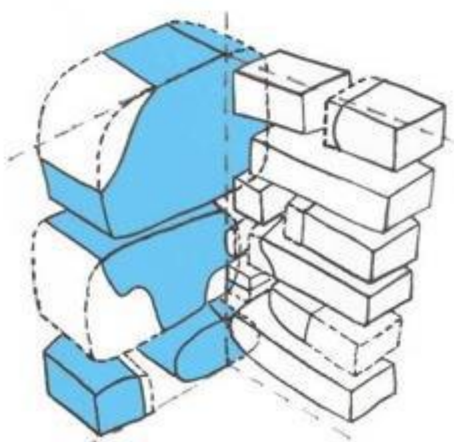


CONSTRUCTION DETAILS

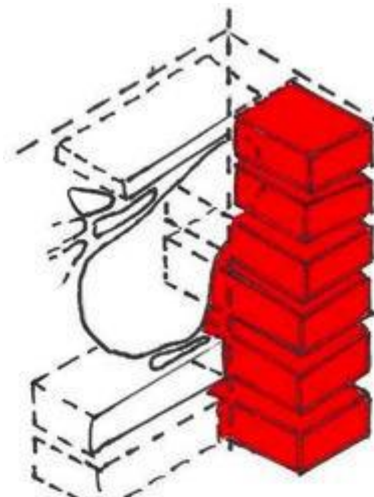




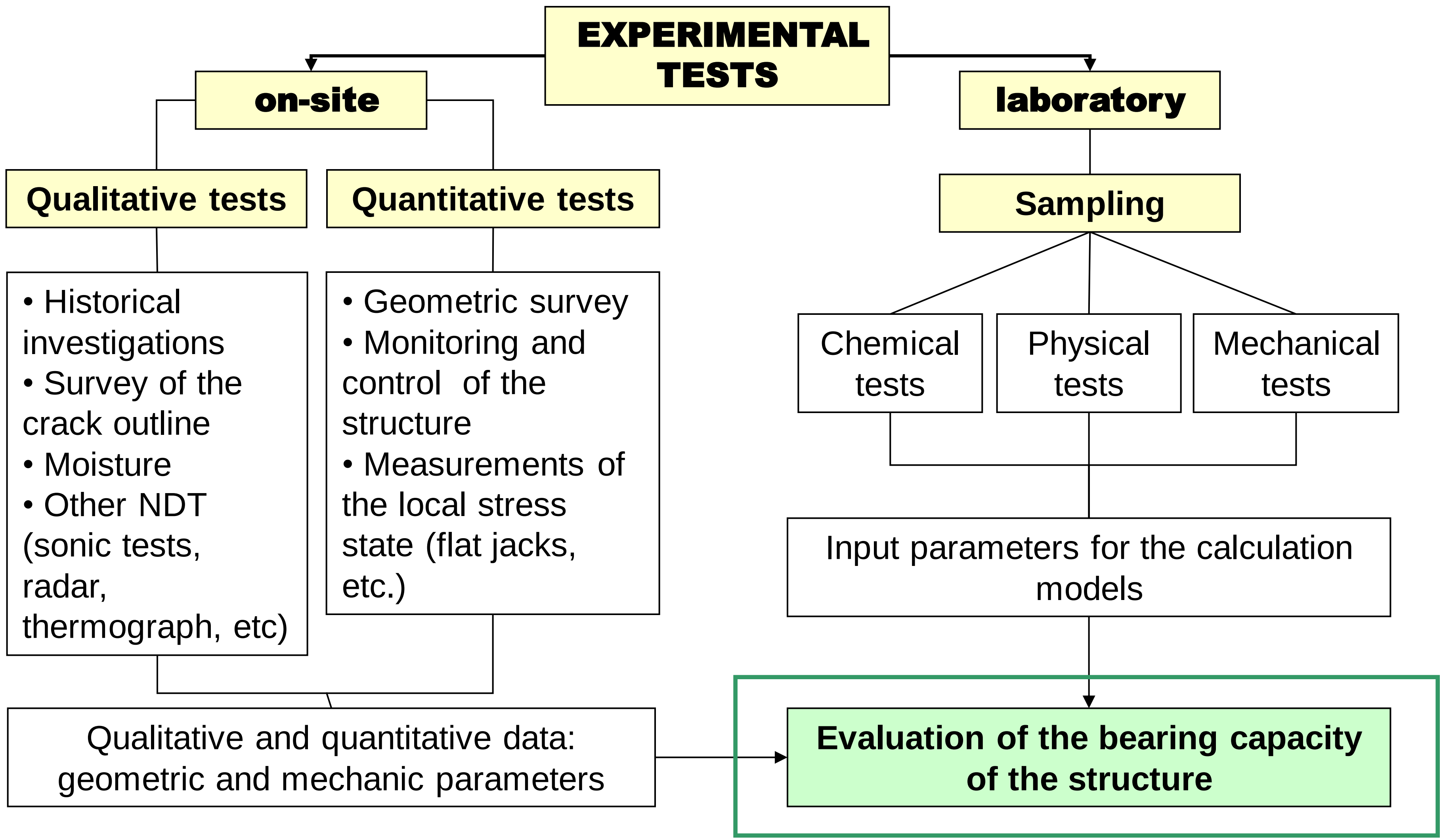
Local dismantling and recontruction of the inner morphology of the wall



(Binda, 2011)



EXPERIMENTAL TEST PROCEDURES



(Binda, 1994)

EXPERIMENTAL TEST PROCEDURES

MATERIAL INSPECTIONS

INSPECTIONS ON STRUCTURES

STRUCTURAL HEALTH MONITORING

Destructive Test (DT)

Medium Destructive Test (MDT)

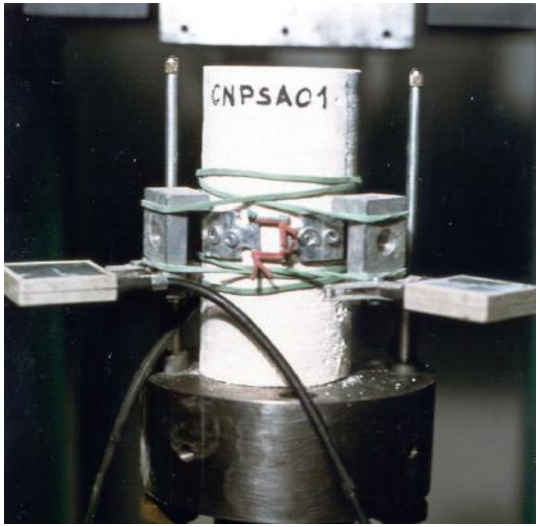
Non- Destructive Test (NDT)

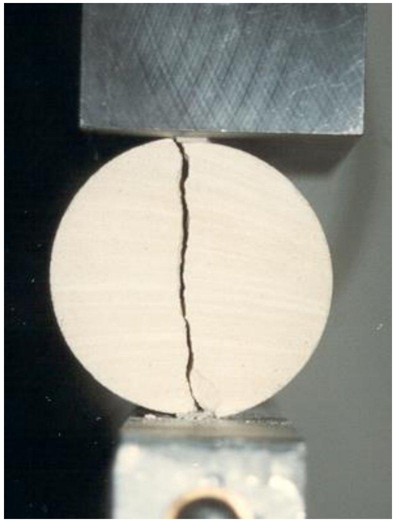
- Destructive Tests provide direct information on the mechanical properties of materials. Nevertheless, the main problem is the obtrusiveness of the investigation procedure.

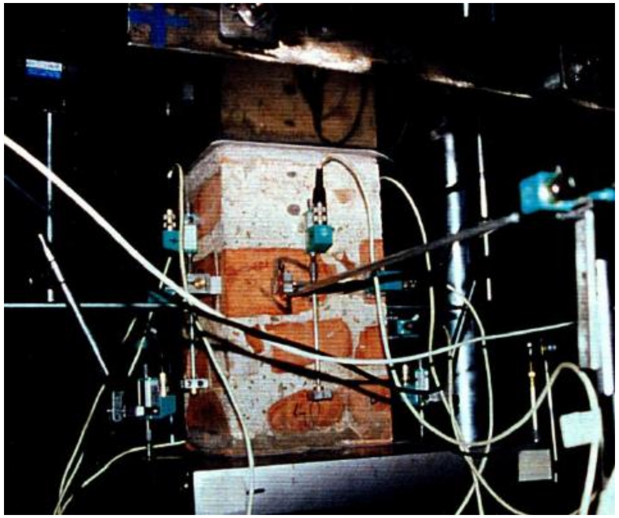
- Non-Destructive Tests are indicated as a complement to Destructive / Medium Destructive Tests. The combined use of NDT and DT / MDT and the cross-check of the results can induce more "quantitative“ significance to the NDT results, through a calibration at local level.

- NDT tests extended in large areas may address MDT for the best optimization of the experimental campaign and the exploitation of the resources, to improve the knowledge of the structure.

INNER INSPECTIONS AND TESTING ON SAMPLES







(Politecnico di Milano)

INVESTIGATION METHODS FOR MASONRY BUILDINGS

INVESTIGATIONS ON MATERIALS

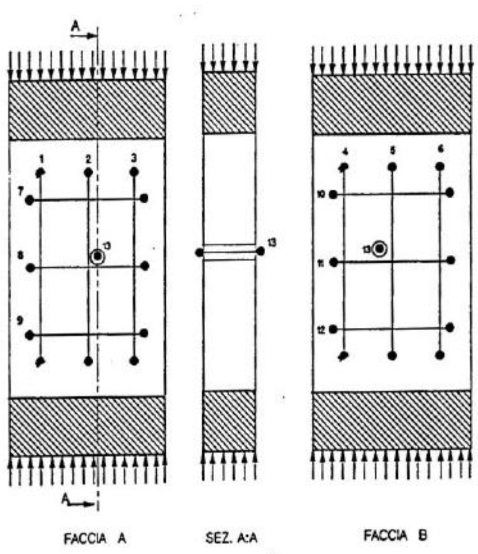
INVESTIGATIONS ON MASONRY

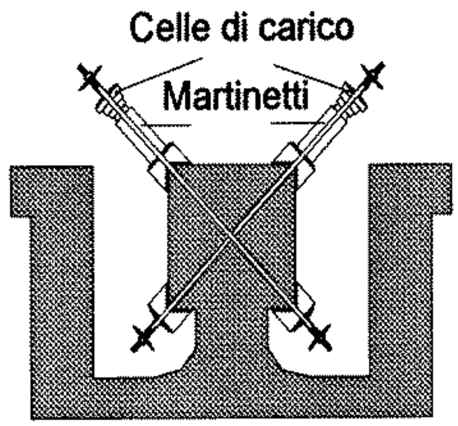
MONITORING AND CONTROL OF THE STRUCTURES

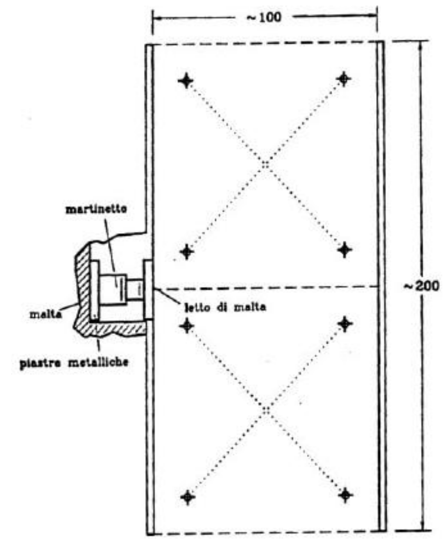
Destructive tests
- Laboratory
- On-site
  - mono-axial direct compression
  - diagonal compression
  - shear-compression

Minor destructive tests (MDT)
- direct inspections, endoscopies, core boring
- single flat jacks
- double flat jacks
- shove test
- pull-out test
- dilatometer

Non-destructive tests (NDT)
- passive
  - surveys and maps
  - pictures
  - displacements measurements
  - spontaneous phenomena (magnetometers)
- active
  - sonic and ultrasonic tests
  - radiography, georadar
  - thermographs
  - sclerometer
  - dynamic tests







UNIAXIAL COMPRESSION

DIAGONAL COMPRESSION

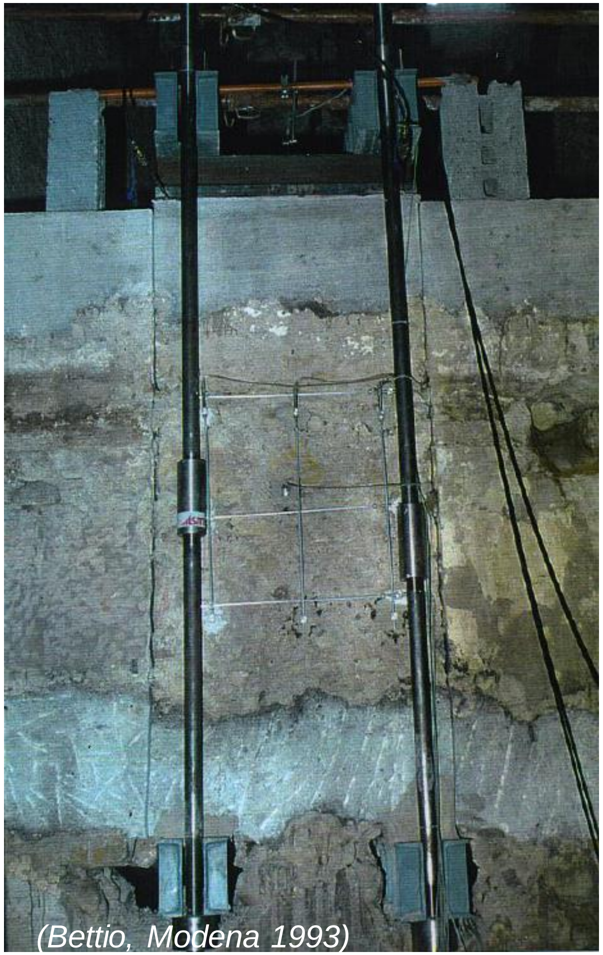
SHEAR-COMPRESSION

Direct evaluation of mechanical properties

- strength
  - compression
  - shear
- deformability
  - elastic modulus
  - shear modulus
  - Poisson coefficient

DESTRUCTIVE TESTS

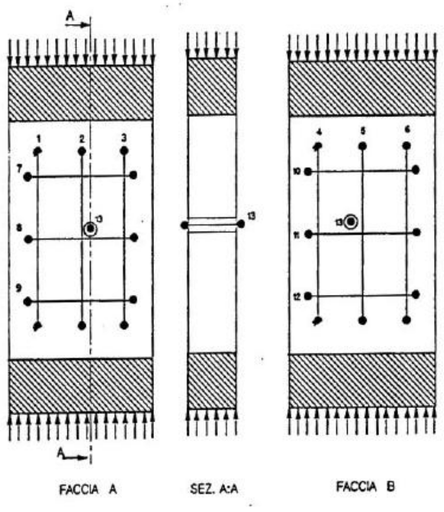
Strength of masonry walls: compression



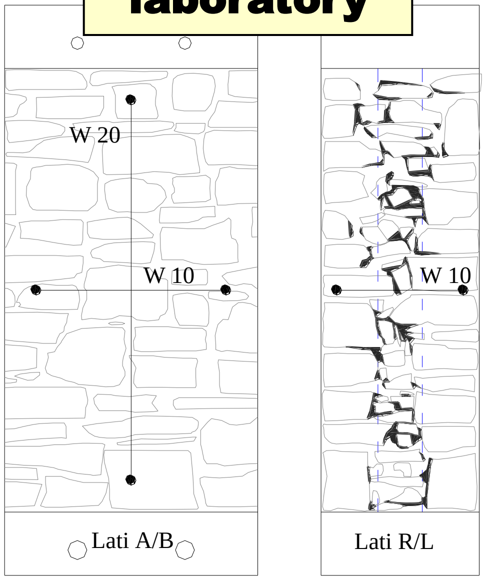
(Bettio, Modena 1993)

Mechanical properties of the original masonry and after consolidation interventions (E, ν, f_m) through experimental tests

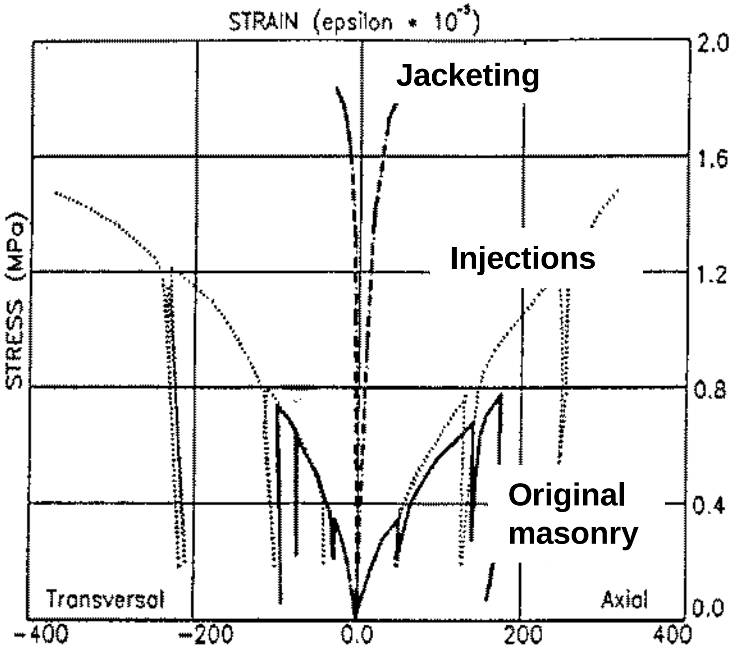
On-site



laboratory



Strength of masonry walls: compression

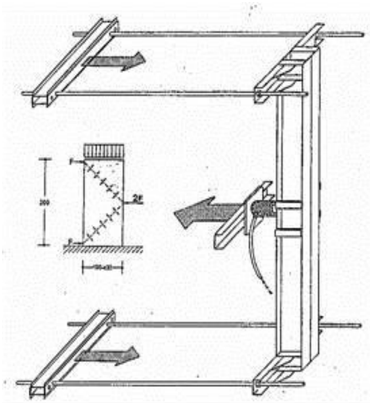


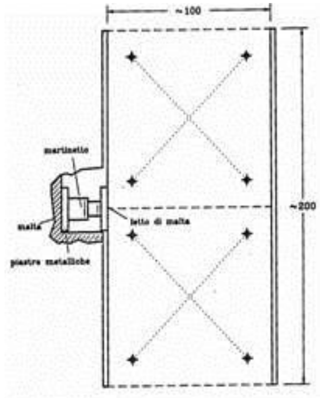
The compression behavior shows the differences in terms of resistances and stiffness brought from different kinds of intervention.

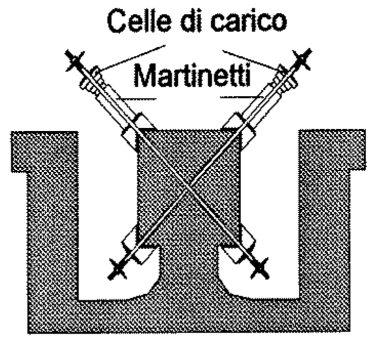
DESTRUCTIVE TESTS

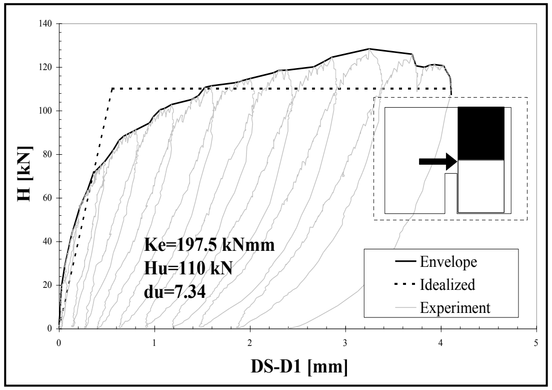
On site compression and shear

On site diagonal-compression



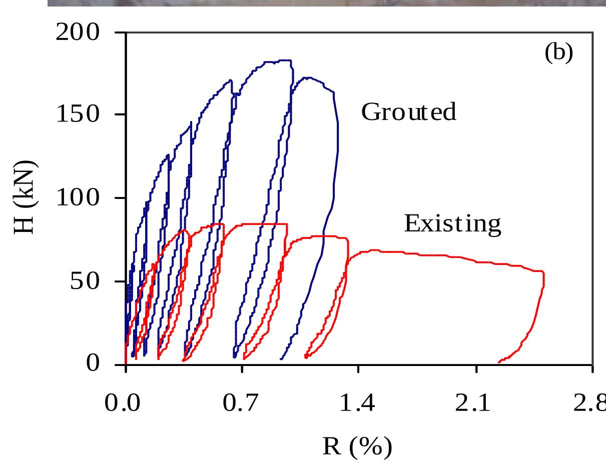






DESTRUCTIVE TESTS

Mechanical properties of the original masonry and after consolidation interventions (τ_0, G) with experimental tests



MINOR DESTRUCTIVE TESTS

INVESTIGATIONS ON MATERIALS

INVESTIGATIONS ON MASONRY

MONITORING AND CONTROL OF THE STRUCTURES

Destructive tests

- Laboratory
- On-site

• mono-axial direct compression
• diagonal compression
• shear-compression

Minor destructive tests (MDT)

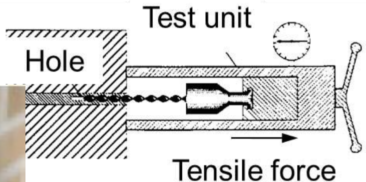
• direct inspections, endoscopies, core boring
• single flat jacks
• double flat jacks
• shove test
• pull-out test
• dilatometer

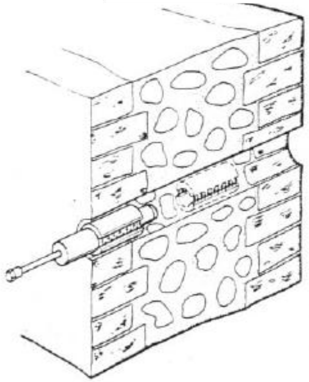
Non-destructive tests (NDT)

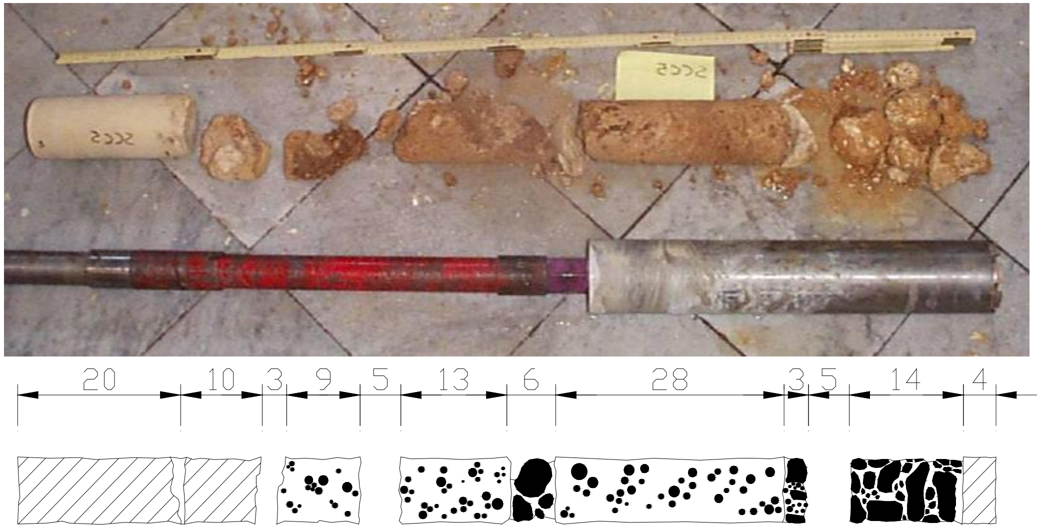
- passive
  • surveys and maps
  • pictures
  • displacements measurements
  • spontaneous phenomena (magnetometers)
- active
  • sonic and ultrasonic tests
  • radiography, georadar
  • thermographs
  • sclerometer
  • dynamic tests

CORING

To understand the morphology of a masonry wall it is important a **direct inspection**. Sometimes it could be performed by removing few bricks or stones.
Coring is commonly done with a rotary driller using a diamond cutting edge.
A small camera may be inserted into the borehole allowing a detailed study of its surface and try a reconstruction of the wall section.







Drilled core and reconstruction *(Binda, 2000)*

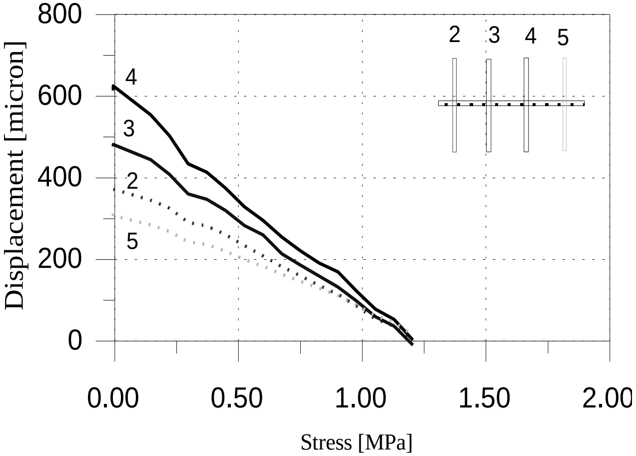
Other slightly destructive tests are:

- the **penetration tests** proposed in different ways, like probes, drillers, etc. correlate the depth of penetration to the mortar mechanical properties;
- the **pull-out tests** can only be used on bricks and stones
- the **dilatometer** can give deformability properties of inner cores

SINGLE FLAT JACK TEST

The determination of the **state of stress** is based on the stress relaxation caused by a cut perpendicular to the wall surface; the stress release is determined by a partial closing of the cutting, i.e. the distance after the cutting is lower than before. A thin **flat-jack** is placed inside the cut and the pressure is gradually increased to obtain the distance measured before the cut.

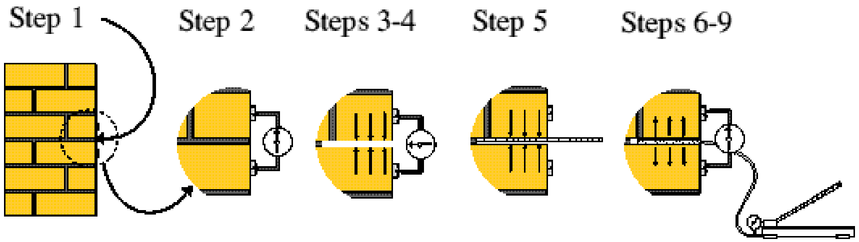
Single flat-jack test (detection of state of stress) carried out at the Monza Tower *(Binda, 1998)*



The equilibrium relationship is the fundamental requirement for all the applications where the flat-jack are currently used (ASTM, 1991):

$$S_f = K_j K_a P_f$$

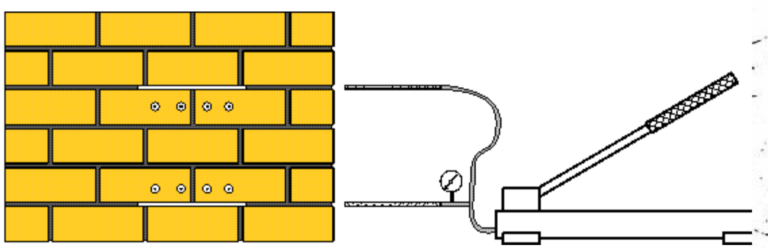
S_f = calculated stress value
K_j = jack calibration constant (<1)
K_a = slot/jack area constant (<1)
P_f = flat-jack pressure

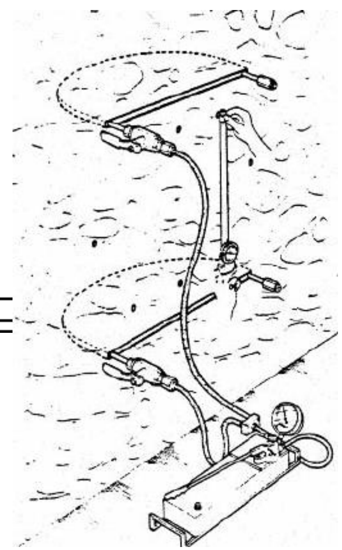


DOUBLE FLAT JACK TEST

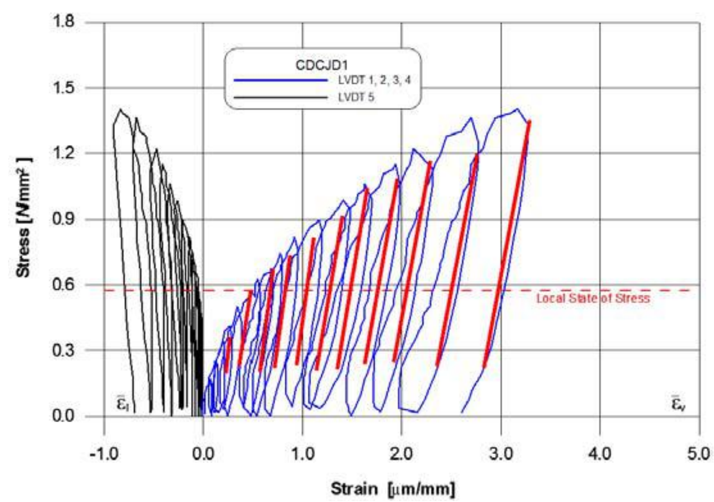
The test described can also be used to determine the **deformability characteristics** of a masonry. A second cut is made, parallel to the first one and a second jack is inserted, at a distance of about 40 to 50 cm from the other. The two jacks delimit a masonry sample of appreciable size to which a uni-axial compression stress can be applied.

Double flat-jack test (stress-strain behaviour) on West side of the Monza Tower *(Binda, 1998)*





Rilem committee MDT, 2003



NON DESTRUCTIVE TESTS

INVESTIGATIONS ON MATERIALS

INVESTIGATIONS ON MASONRY

MONITORING AND CONTROL OF THE STRUCTURES

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- On-site

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Non-destructive tests (NDT)

passive

- surveys and maps
- pictures
- displacements measurements
- spontaneous phenomena (magnetometers)

active

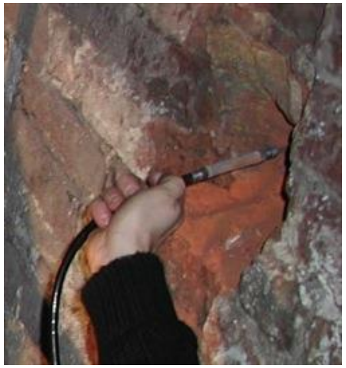
- sonic and ultrasonic tests
- radiography, georadar
- thermographs
- sclerometer
- dynamic tests

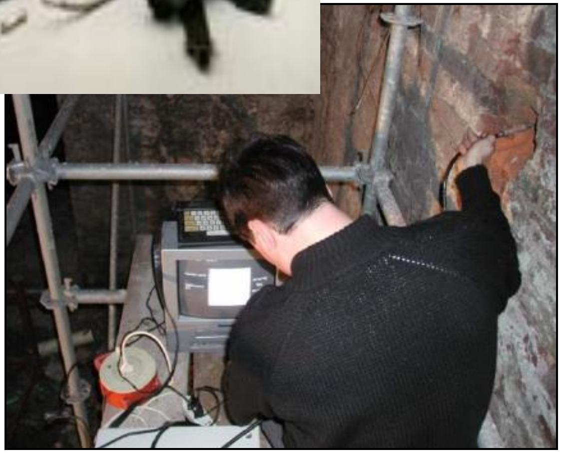
NON DESTRUCTIVE TESTS

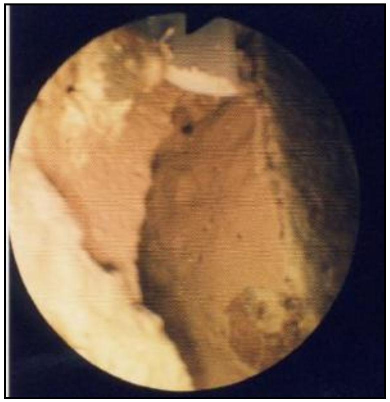
NDT can be helpful in finding hidden characteristics (internal voids and flaws and characteristics of the wall section) which cannot be known otherwise than through destructive tests.

BOREHOLE VIDEO-ENDOSCOPY

Usually integrate the coring inspection in order to detect the morphology of the wall section (or the structural component – also floors, roof, etc..), thickness, presence of voids, cracking, the effectiveness of interventions (e.g., injections), etc.





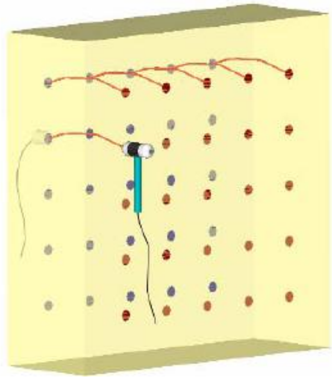


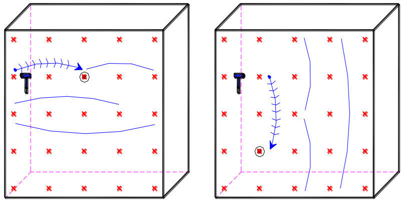
NON DESTRUCTIVE TESTS

SONIC PULSE VELOCITY TEST

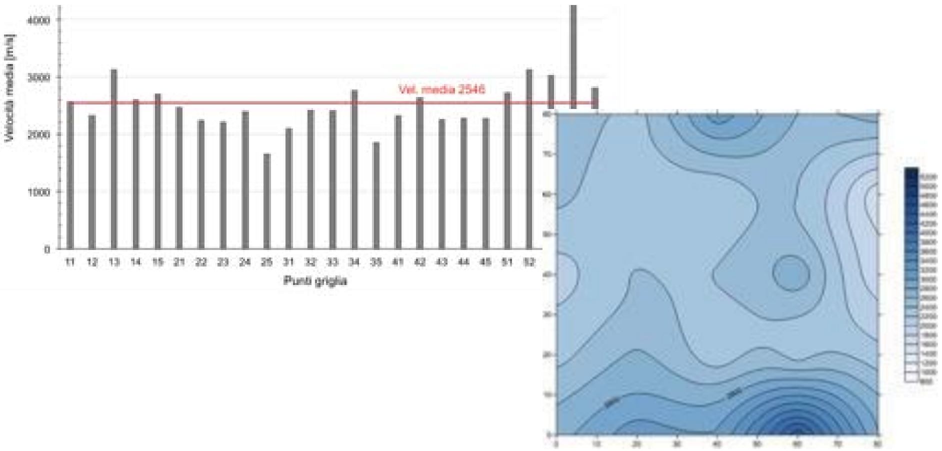
The use of sonic tests has the following aims:

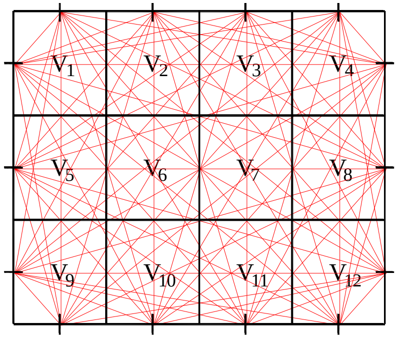
- to qualify masonry through the morphology of the wall section;
- to detect the presence of voids and flaws;
- to find crack and damage patterns;
- to control the effectiveness of repair by injection technique.

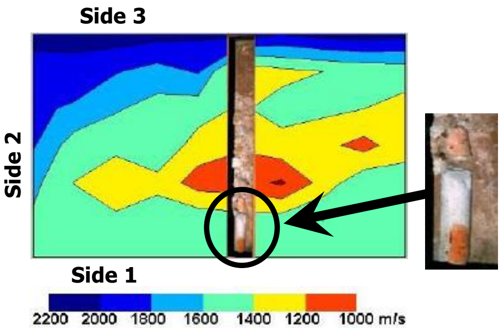




horizontal vertical



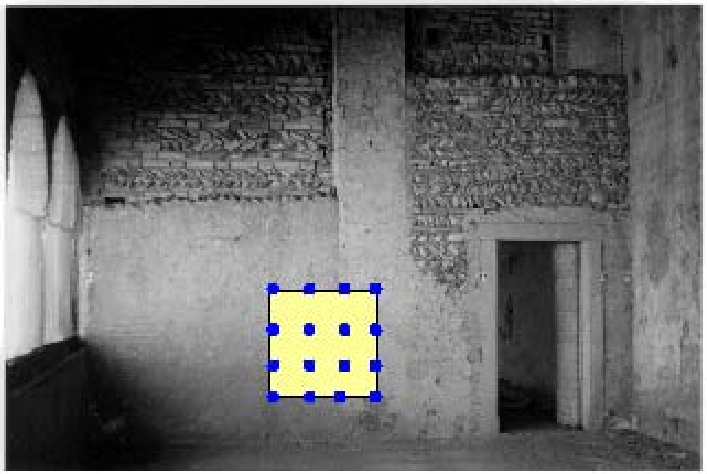




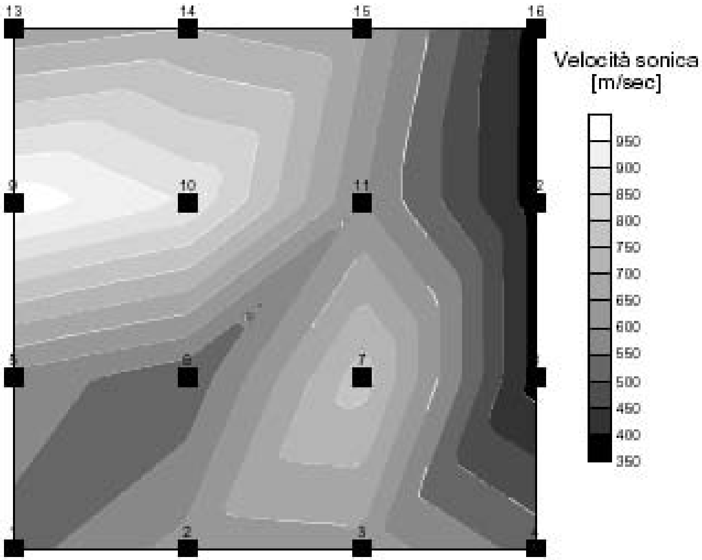
Sonic Tomography

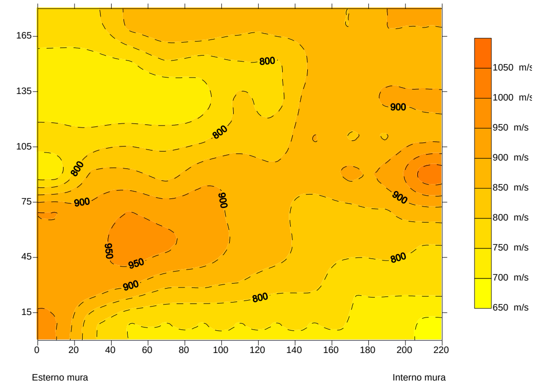
NON DESTRUCTIVE TESTS

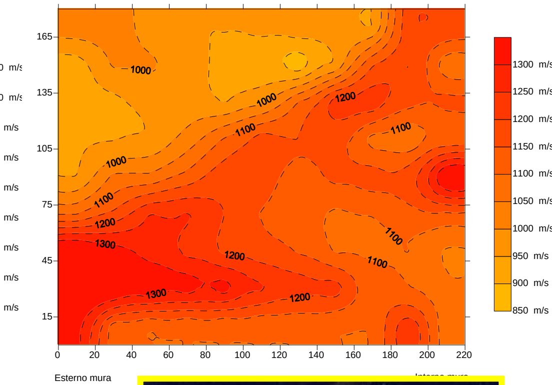
SONIC TEST: qualitative evaluation for masonry morphology and effectiveness of intervention (injections)

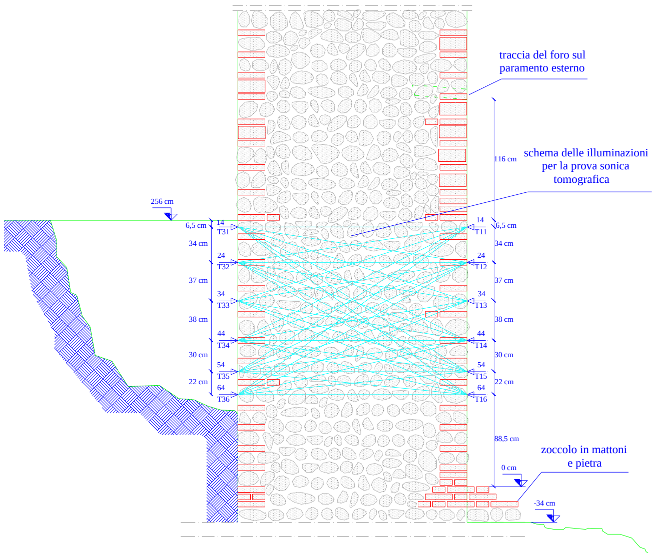


(Binda, 2000)

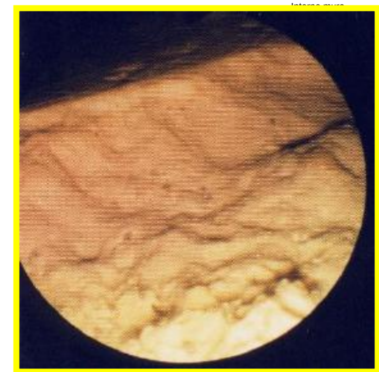








CINTA MURARIA DI CITTADELLA (PD)

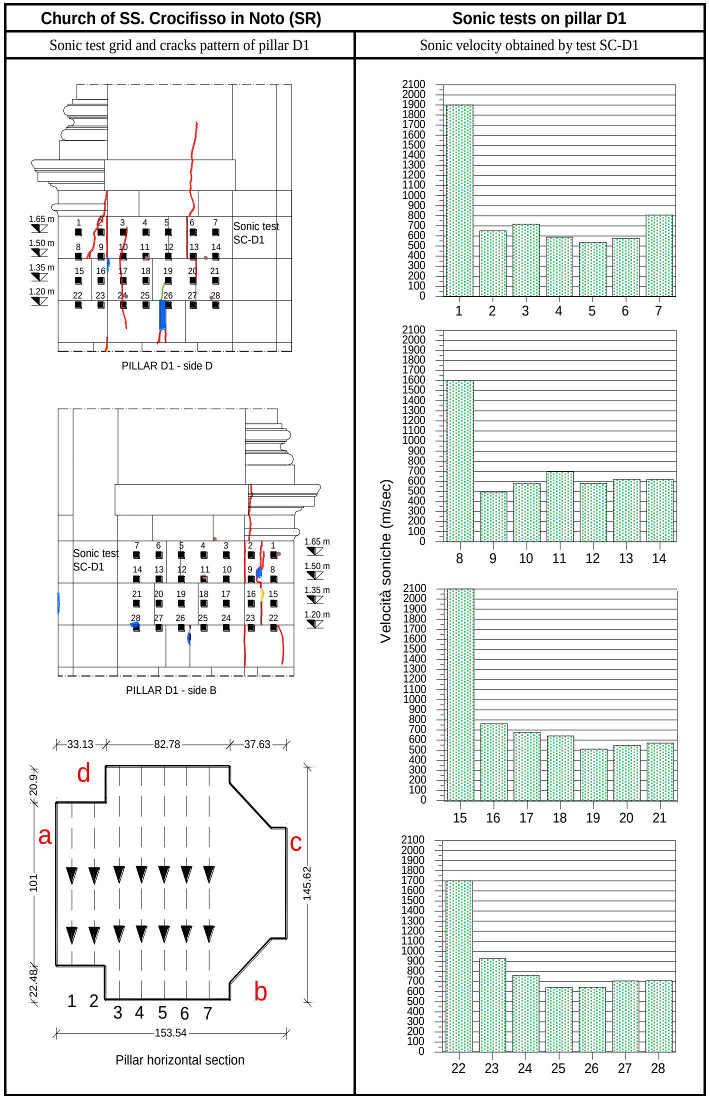


NON DESTRUCTIVE TESTS

SONIC TEST

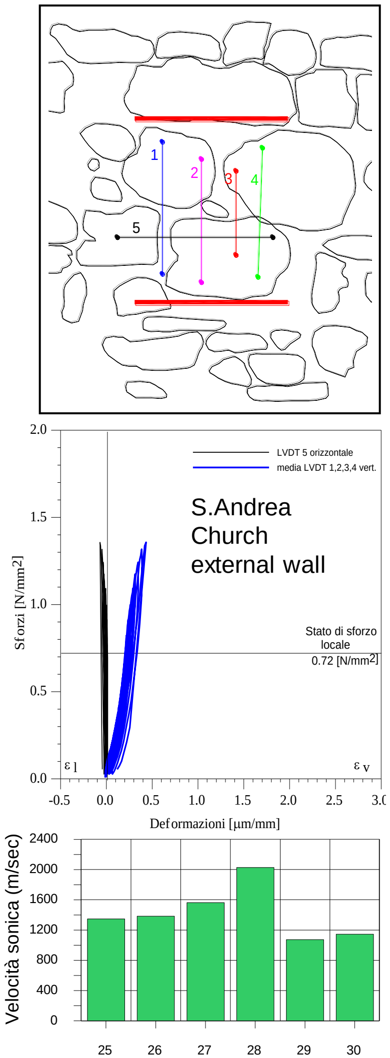
The velocity and waveform of stress waves generated by mechanical impacts can be affected by:

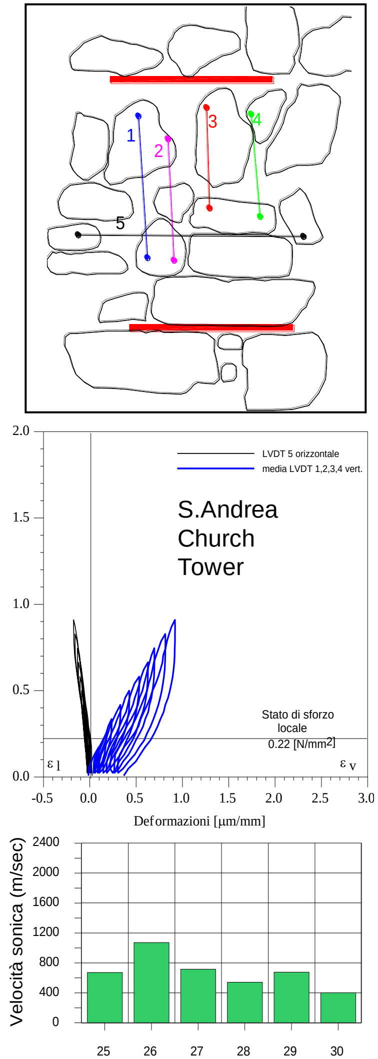
- Input frequency generated by different types of instrumented hammers and transducers;
- Number of mortar joints crossed from the source to the receiver location: the velocity tends to decrease with the number of joints;
- Local and overall influence of cracks.

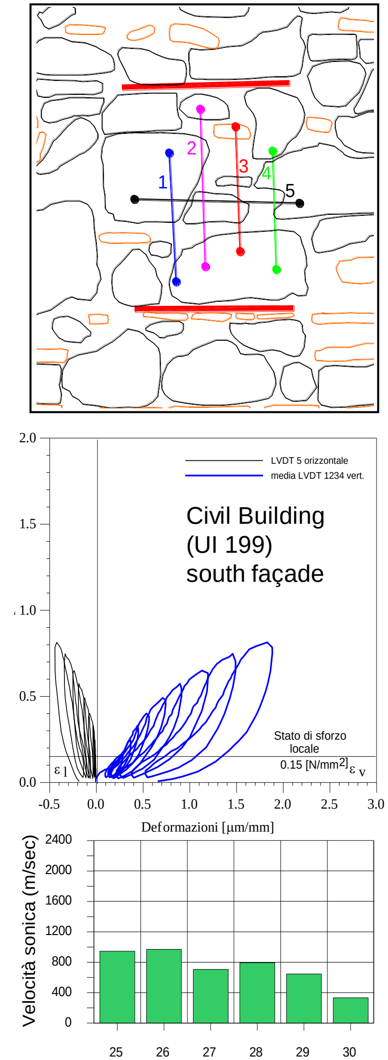


Local and overall influence of cracks: sonic tests on a pillar of the church of SS. Crocifisso in Noto - SR (Binda, 1999)

COMPLEMENTARITY OF IN SITU TESTS







Flat jack tests: some results obtained with single and double flat-jack tests on the external wall of a church, of a bell tower and of a civil building in Campi Alto di Norcia (PG)

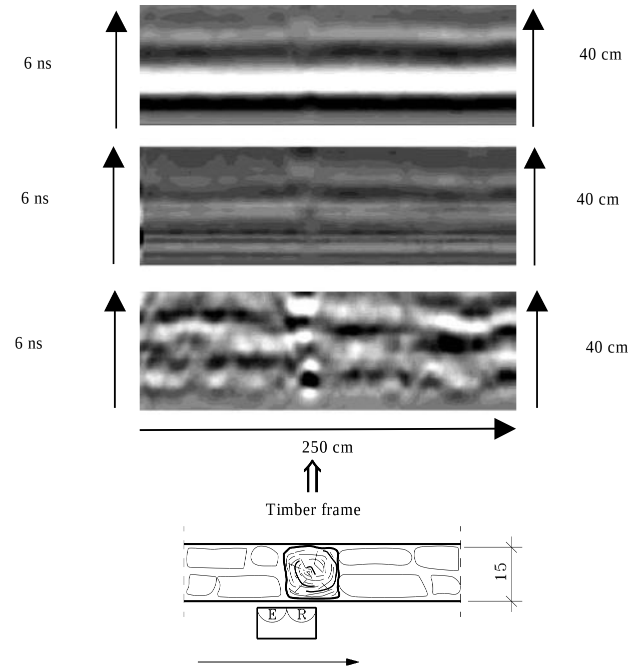
Sonic tests: representative results of the diagonal surface sonic measurements on the same walls

NON DESTRUCTIVE TESTS

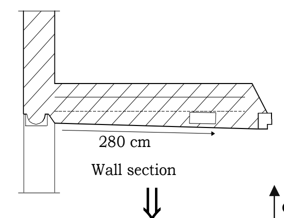
GEORADAR

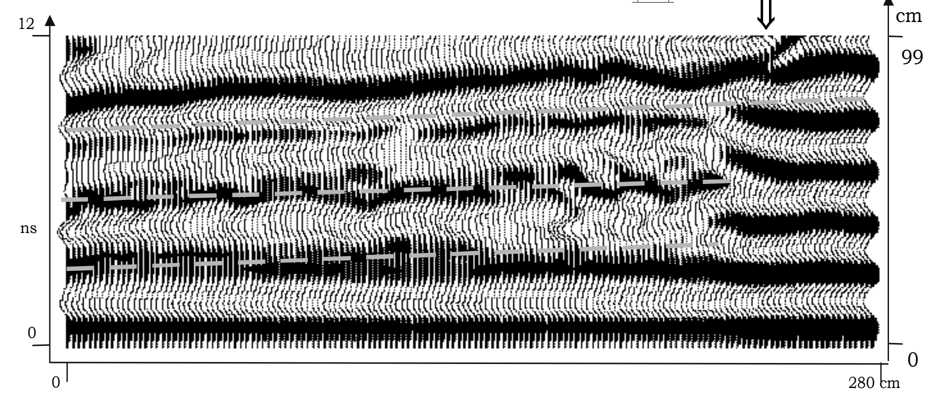
When applied to masonry, the applications of radar procedures can be the following:

- to locate the position of large voids and inclusions of different materials, like steel, wood, etc.;
- to qualify the state of conservation or damage of the walls;
- to define the presence and the level of moisture;
- to detect the morphology of the wall section in multiple leaf masonry.

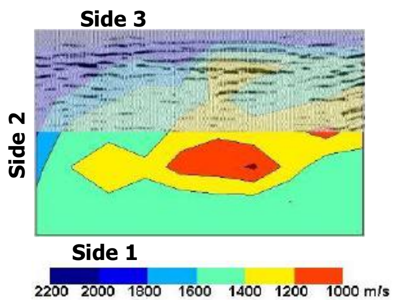


Local and overall influence of cracks





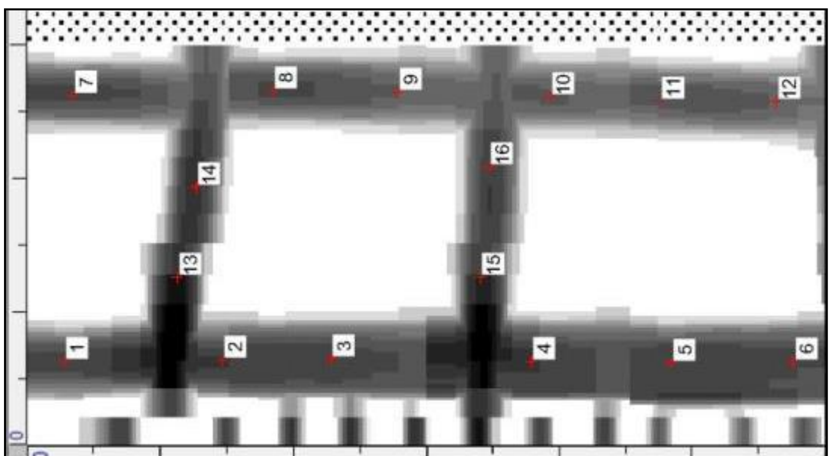
Radargram of the wall section at the Malpaga Castle



Radar vs Sonic

NON DESTRUCTIVE TESTS

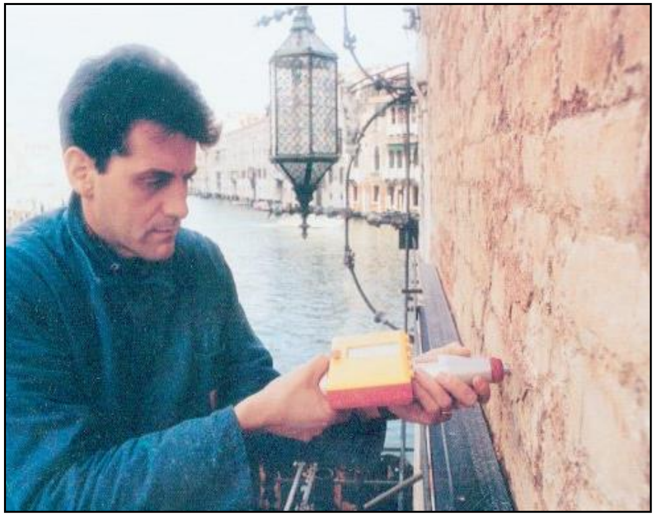
Detector of ferromagnetic materials
materials

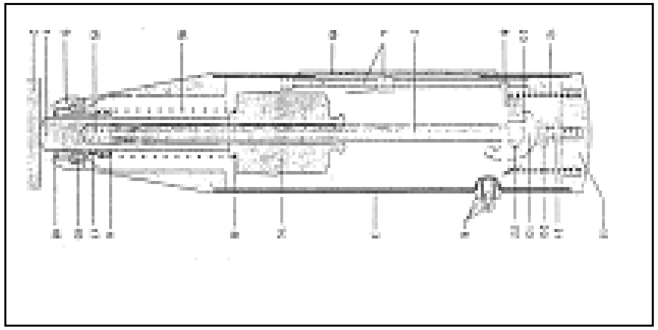


Detection of metals inside materials (ferromagnetic materials) – usually used as covermeter.

Eddy current principle: the induced magnetic field is dissipated when meets a conductive material

Schimdt rebound hammer





Surface hardness methods are based on the relation between the surface hardness and the compressive strength of material (concrete), selection of pointing mortars or quality control (masonry)

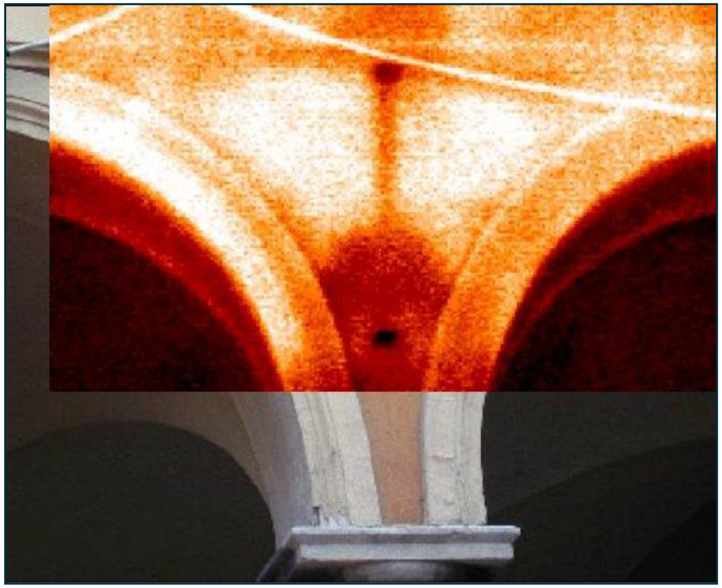
Class	Hardness	Indicative quality
0 (zero)	<15	Very soft
A	15-25	Soft
B	25-35	Moderate
C	35-45	Normal
D	45-55	Hard
E	55	Very hard

THERMOVISION

The **thermographic analysis** is based on the thermal conductivity of a material and may be passive or active. The passive application analyses the radiation of a surface during thermal cycles. If the survey is active, forced heating to the surfaces analyzed are applied

Thermovision can be very useful in diagnostic:

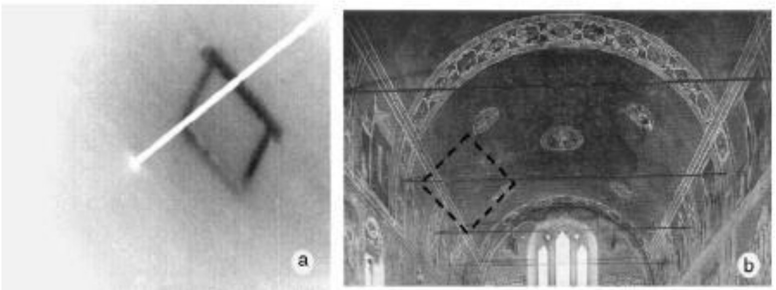
- to identify areas under renderings and plasters,
- to survey cavities,
- to detect inclusions of different materials,
- to detect water and heating systems,
- to detect moisture presence.

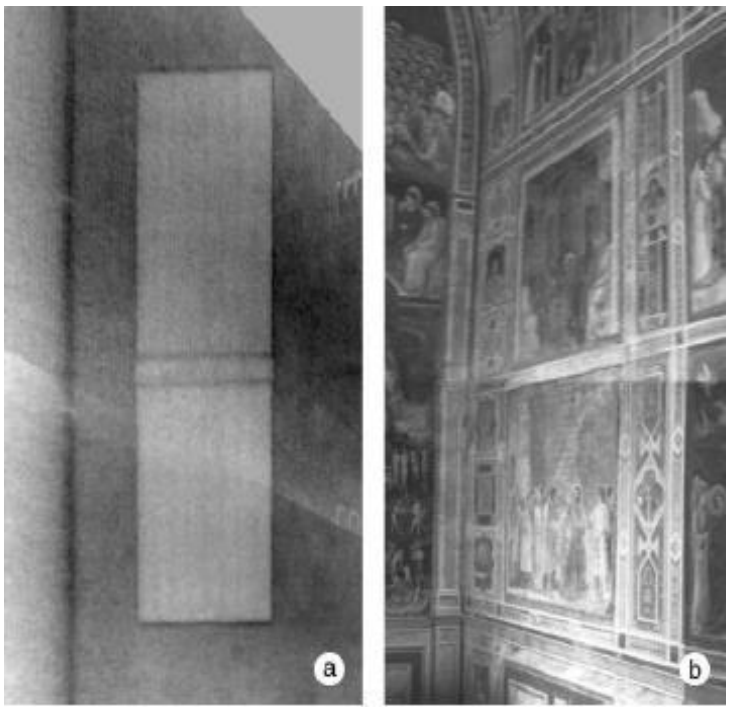


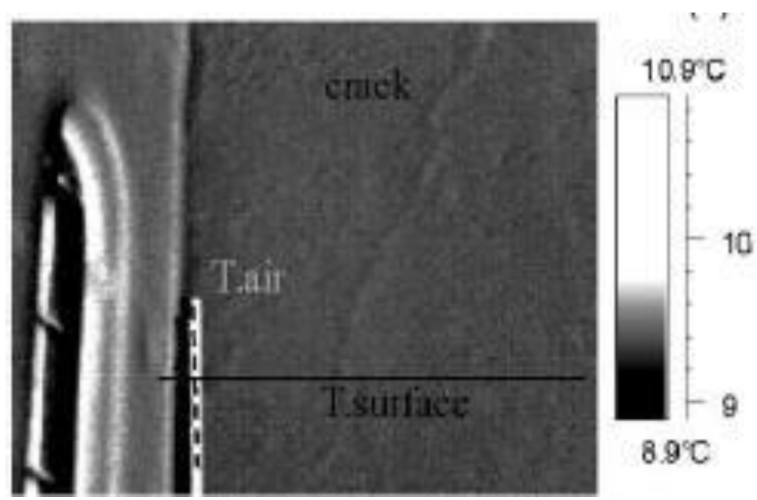
Detection of hidden steel tie rods

NON DESTRUCTIVE TESTS

THERMOVISION: Investigation in the Giotto's Chapel (Padua)



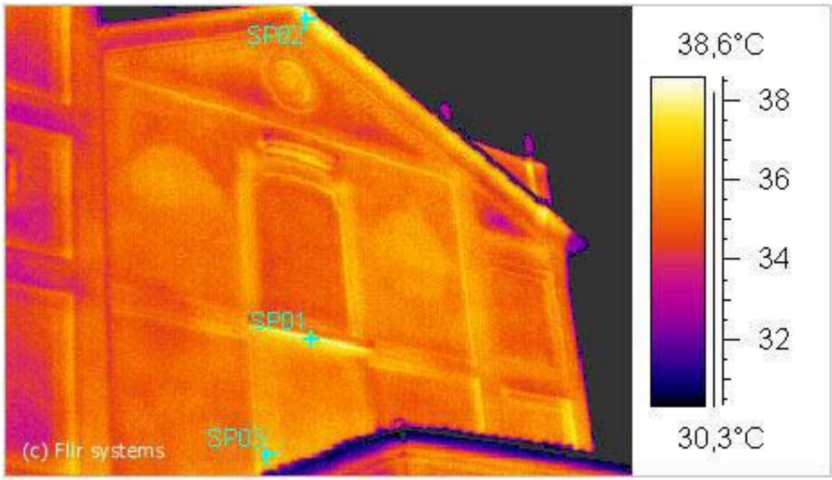




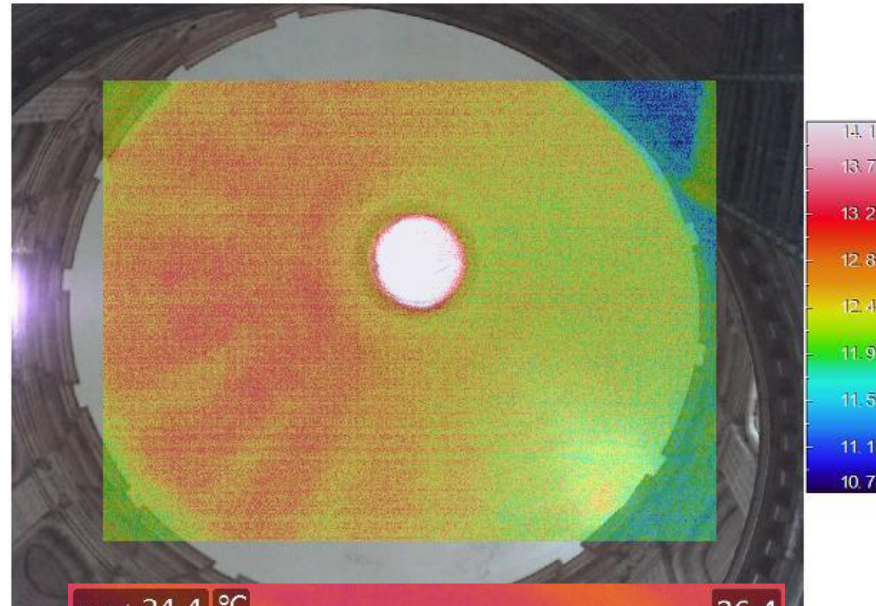
(Grinzato et al., 2002)

NON DESTRUCTIVE TESTS

THERMOVISION:
detection of modifications due to interventions
detection of structural systems

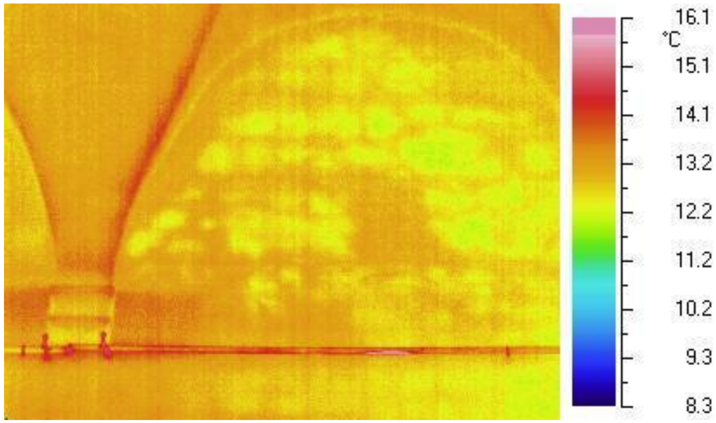


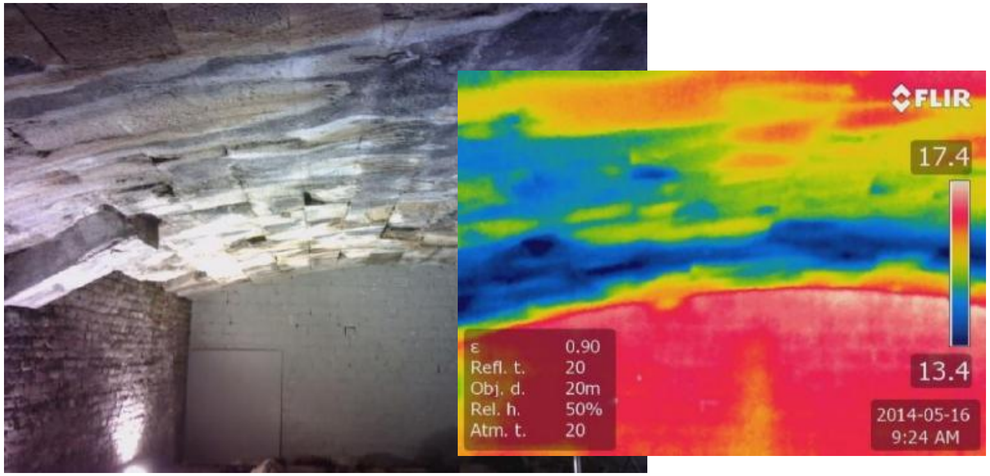
Label	Value
SP01	38,1°C
SP02	37,5°C
SP03	36,9°C

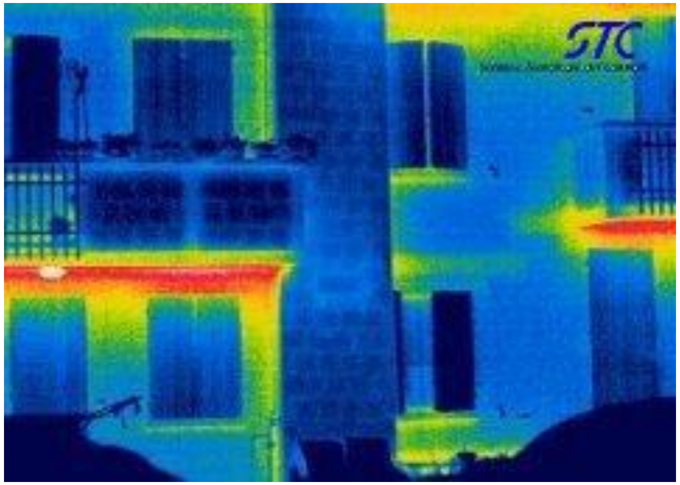


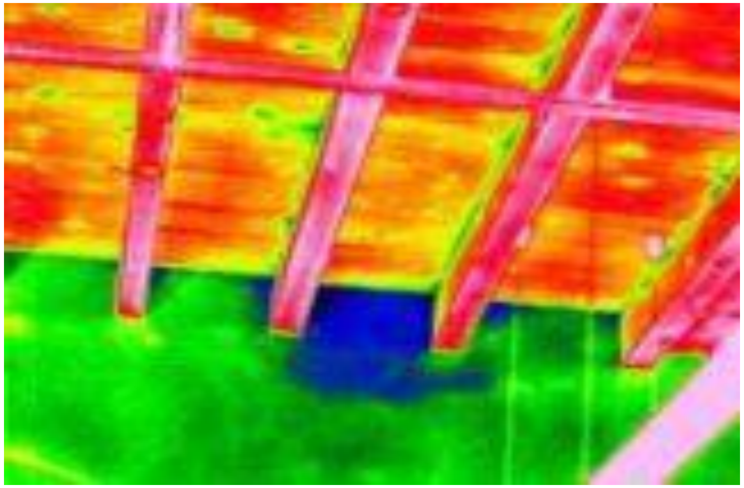
NON DESTRUCTIVE TESTS

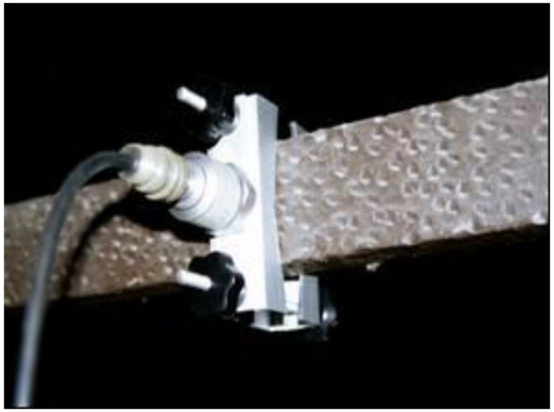
THERMOVISION:
Detection of texture and deterioration, thermal dispersion, humidity content

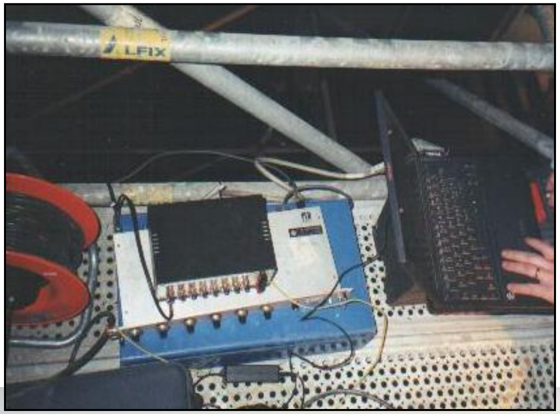






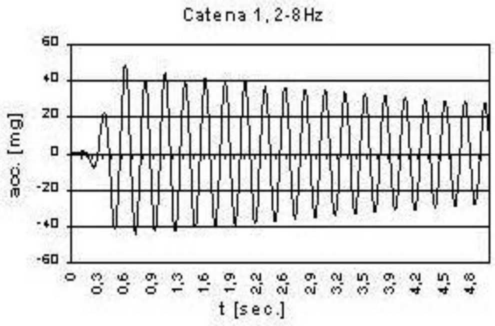


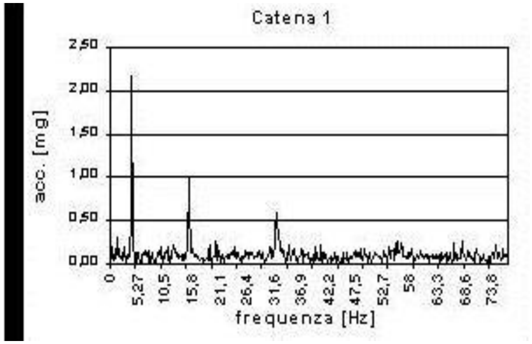




Dynamic tests on ties

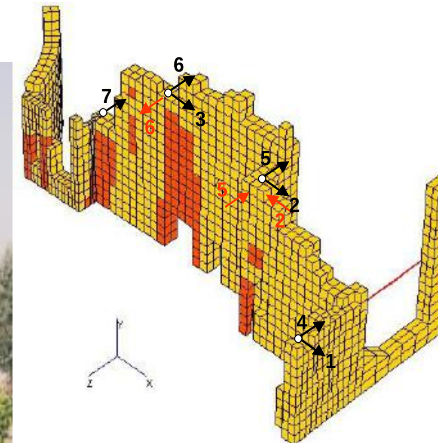
$$T=(f * \lambda)^2 * \mu$$



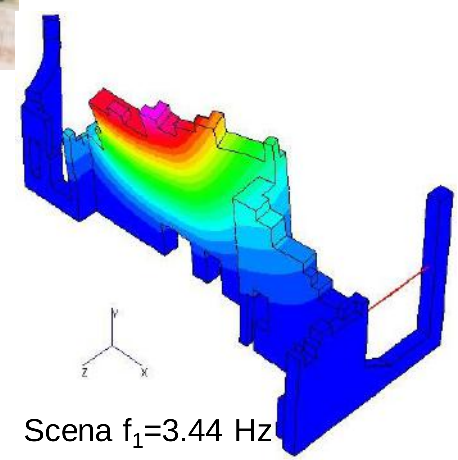


Catena	Sezione			peso specifico	lunghezza libera	frequenza propria	Tiro
	mm			kg/m	m	Hz	kg
1	30	x	60	14,148	17	4,102	6879,93
2	30	x	60	14,148	17	3,906	6238,17
3	30	x	60	14,148	17	3,125	3992,94
4	30	x	60	14,148	17	4,102	6879,93
5	30	x	60	14,148	17	3,516	5054,64

Dynamic identification tests



Proprietà 1	**E**	**1.2E+03**	**MPa**
	ρ	**1.3E+03**	**kg/m³**
Proprietà 2	**E**	**3.2E+03**	**MPa**
	ρ	**1.3E+03**	**kg/m³**
Proprietà 3	**E**	**1.2E+03**	**MPa**
	ρ	**1.5E+03**	**kg/m³**



Scena f_1=3.44 Hz

MONITORING AND STRUCTURAL CONTROL

MONITORING AND CONTROL OF STRUCTURES

- **continuous** → Measure of Increasing parameters → *Crack patterns, stress states, etc.*
- **discontinuous** → Measure of variation of parameters compared to a stationary state → *Dynamic excitation, static loadingi, etc.*
- **static** → Measure of parameters related to quasi-static effects of actions → *Displacement, deformations, stresses, temperature, cracks, out-of-plumb, tilting, damage, etc*
- **dynamic** → *Time-history* measurement of vibrations → *accelerations, velocity, time-displacements*
- **periodic** → Measurement at regular time intervalls
- **permanent** → Measurement at very frequent time intervals → *MONITORING SYSTEMS*

MONITORING AND STRUCTURAL CONTROL

Cracks

Tilting

data-logger

Extensimeters

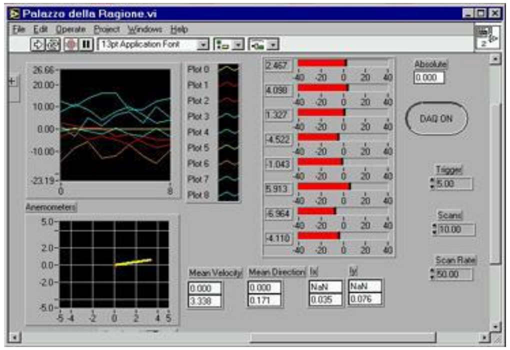
Heavy masses monitoring

Piezometers

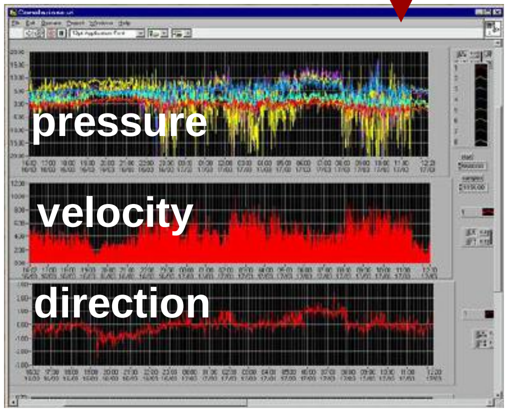
MONITORING AND STRUCTURAL CONTROL

Example of monitoring: Palazzo della Ragione (Padova, XIII-XV cen.)

- Wind effect moniting
- stepped sine test
- FE modelling
- modal identification
- on-line data management

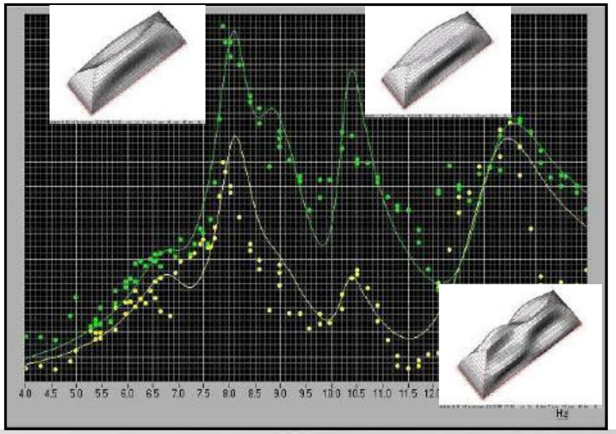


Data acquisition

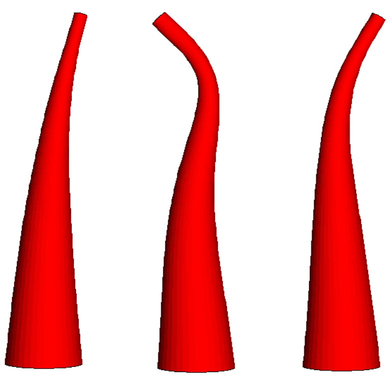


www database

Web monitoring home page



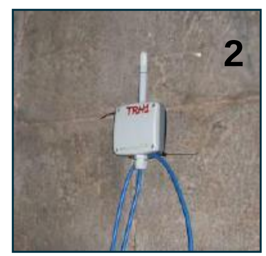
Modal Analysis

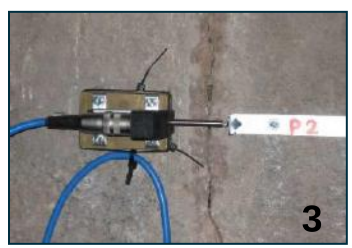


0.62 Hz 1.96 Hz 3.82 Hz

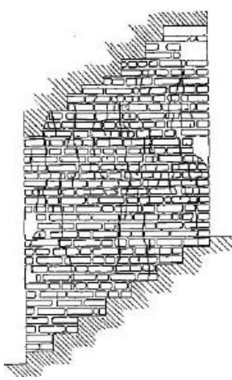
Example of a monitoring system for the control of the behavior: Qutb Minar – New Delhi (India)

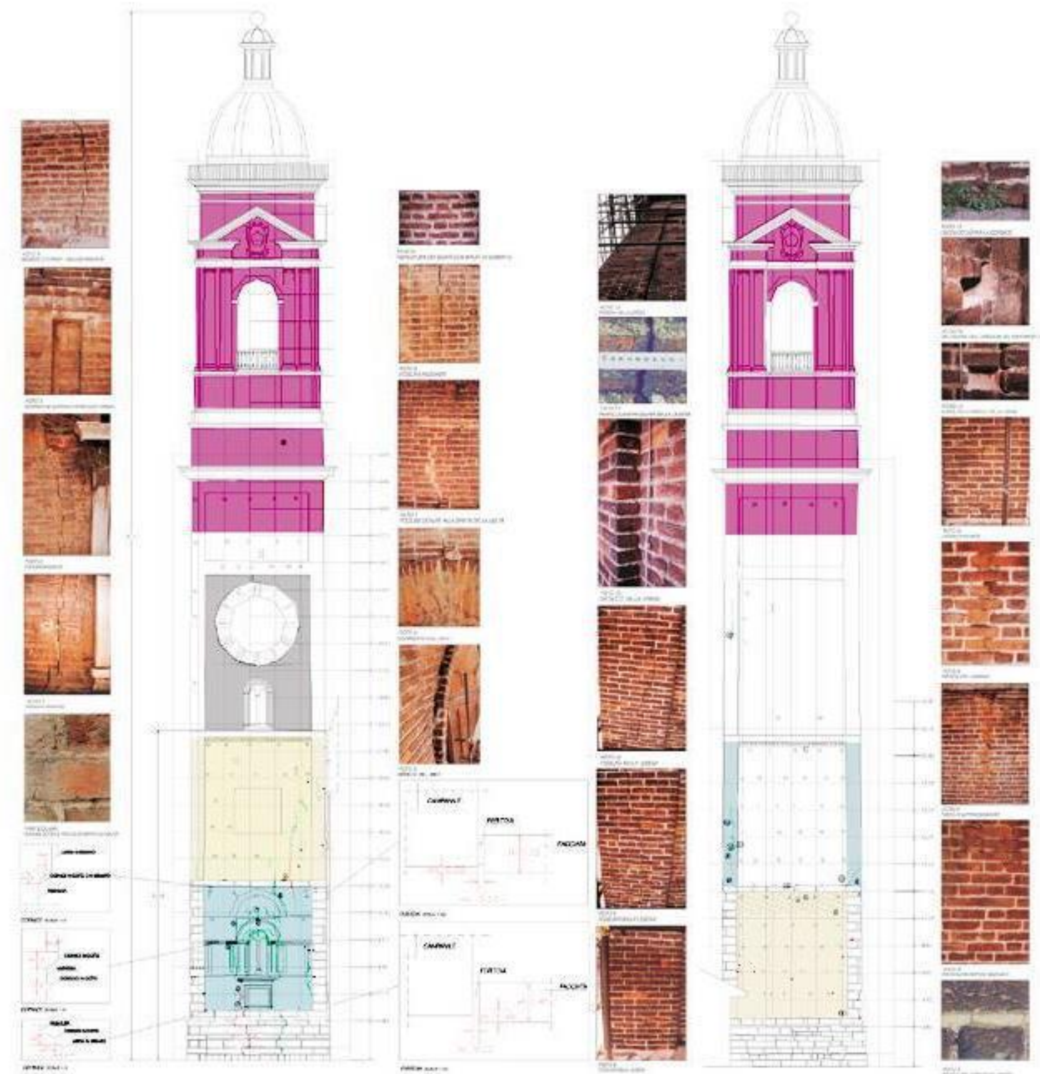
- Positioning of **sensors**:
  1 - acceleration transducers
  2 - temperature and R.H. sensor
  3 - displacement transducer
  4 - wind velocity and direction transducer
- Data acquisition and analysis



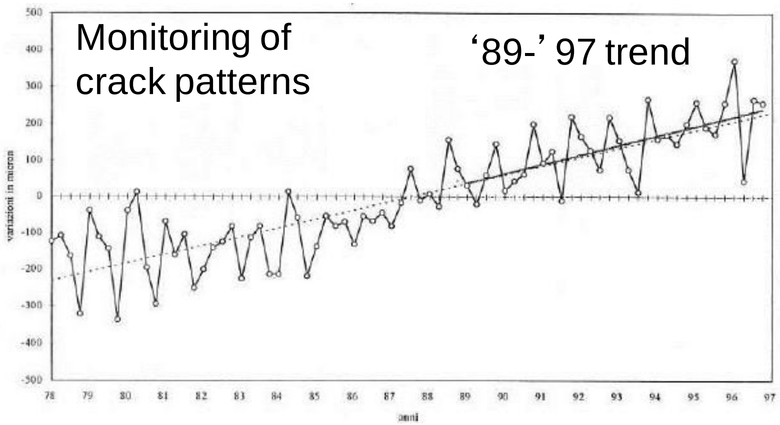


Example of monitoring: Monza Bell Tower XVI cen.)





MONITORING AND STRUCTURAL CONTROL



International Seminar

Assessment and improvement of structural safety under seismic actions of existing constructions: Reinforced Concrete Structures and Historical buildings

SCE - Shamoon College of Engineering, Beer Sheva - 29 November 2015

International Conservation Center, Citta' di Roma, Old Acre - 1 December 2015

Investigation methodologies and techniques: historical investigations, surveys, in-situ and laboratory tests, monitoring

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THANKS FOR YOUR ATTENTION