2018 ANNO EUROPEO DEL PATRIMONIO CULTURALE #EuropeForCulture

TRA GEOLOGIA E GEOFISICA
XV WORKSHOP DI GEOFISICA
VI GIORNATA DI FORMAZIONE

"Il nostro patrimonio:
dove il passato incontra il futuro"

Rilievo, Diagnostica e caratterizzazione dei Beni culturali: quali le competenze e le professioni coinvolte?

6-7 Dicembre 2018, VI Giornata di Formazione

IL RUOLO DELLA CONOSCENZA NELLE VALUTAZIONI DI SICUREZZA STRUTTURALE DEL PATRIMONIO ARCHITETTONICO

Prof. Ing. Claudio Modena

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Il progetto di interventi di carattere strutturale sul costruito storico è prima di tutto e soprattutto un lungo, incessante e faticoso lavorio – che inizia con i rilievi e le indagini preliminari ma continua sul cantiere sino alla fine dei lavori – teso al riconoscimento e all'interpretazione di possibili meccanismi resistenti propri della preesistenza, del loro ruolo nell'ambito della risposta strutturale d'insieme della specifica costruzione storica cui appartengono, e quindi delle loro potenzialità e dei loro eventuali punti deboli.

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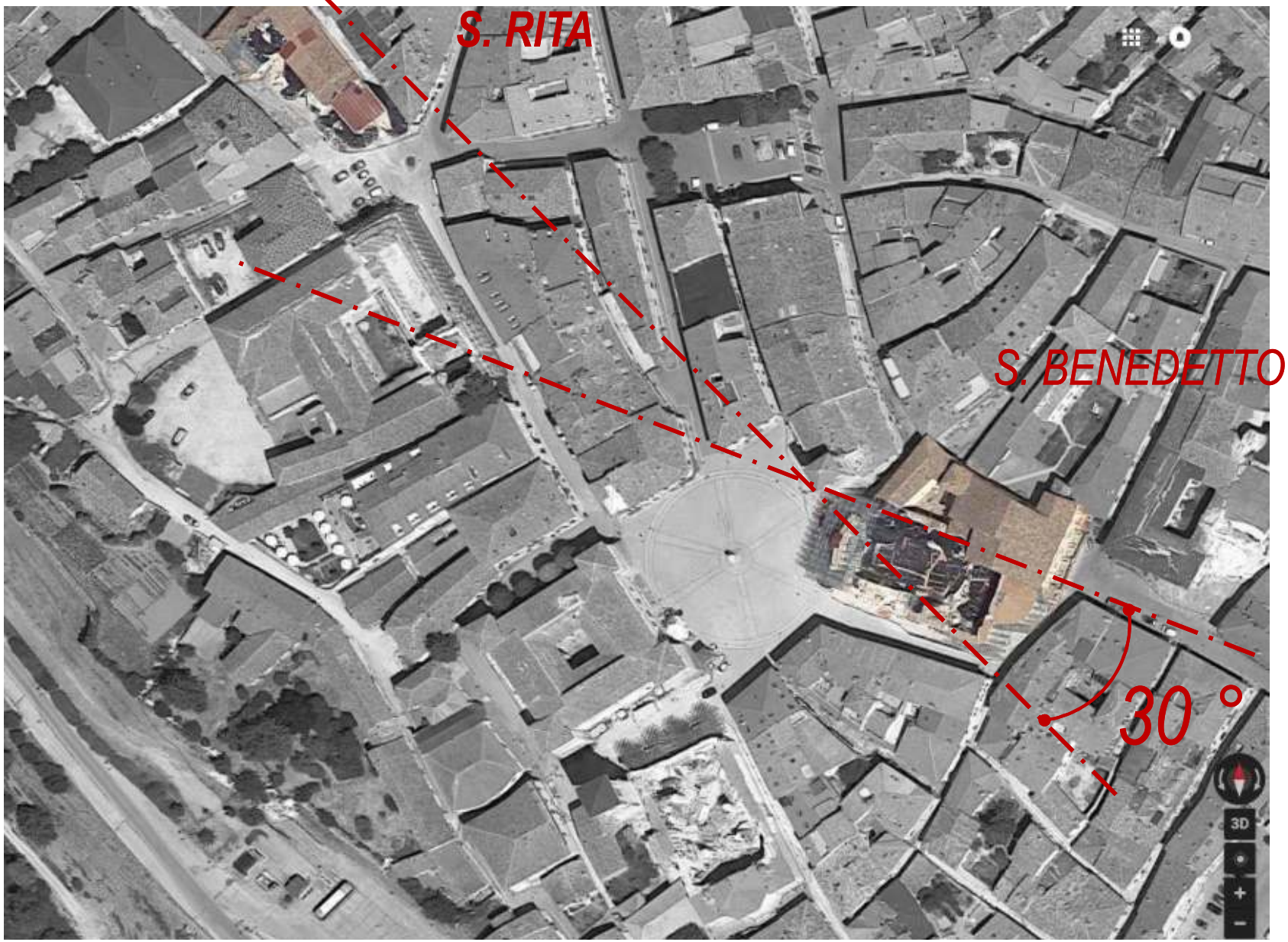

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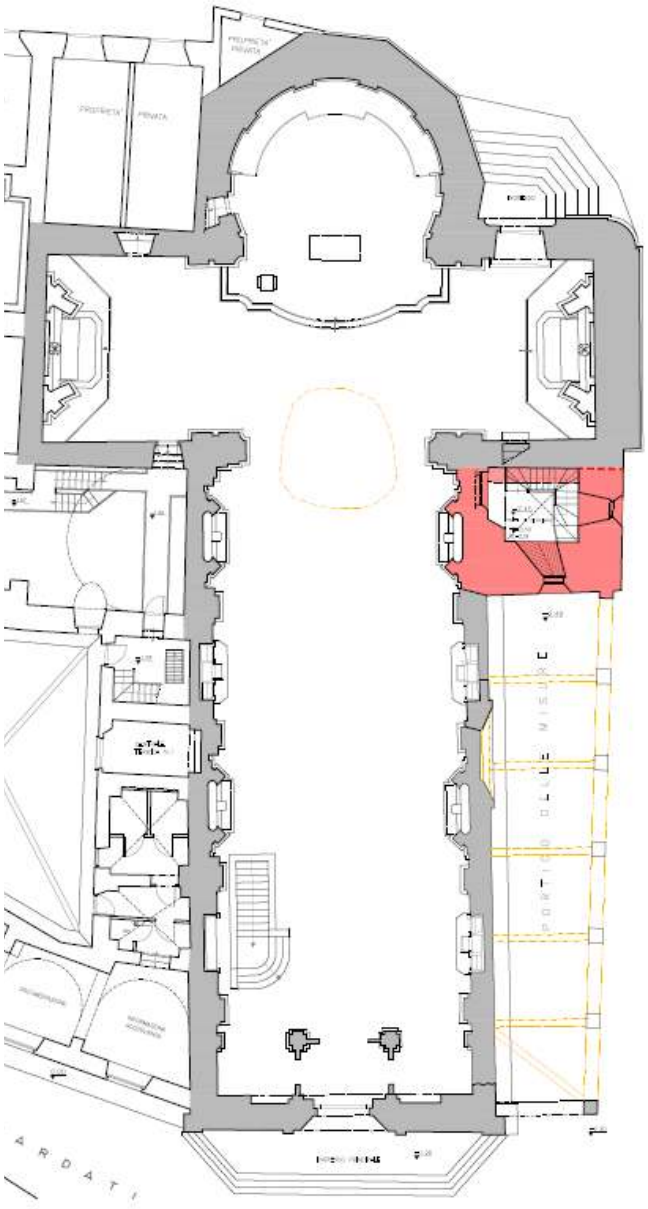
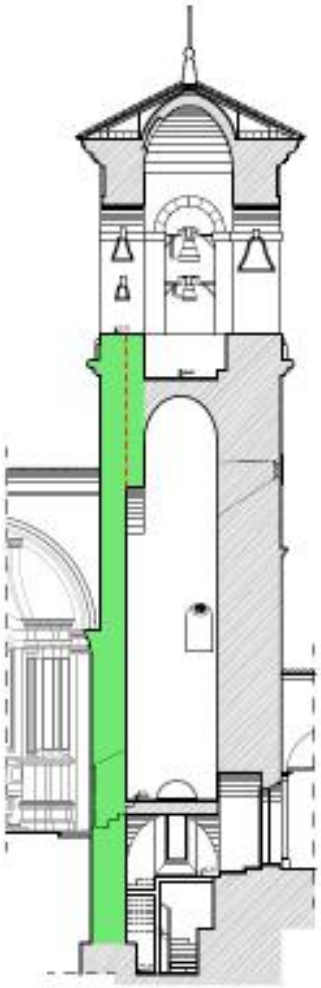
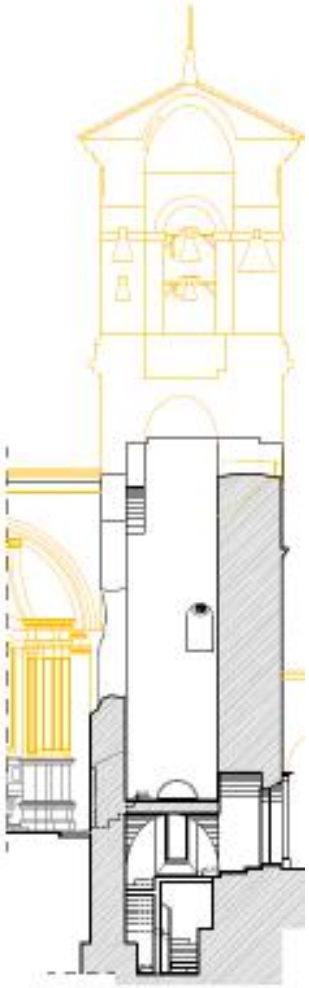
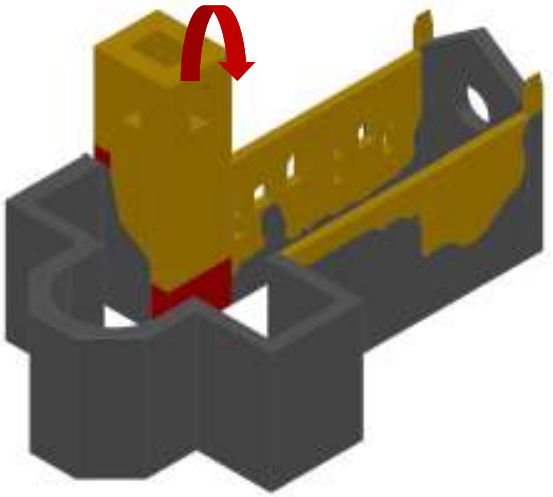


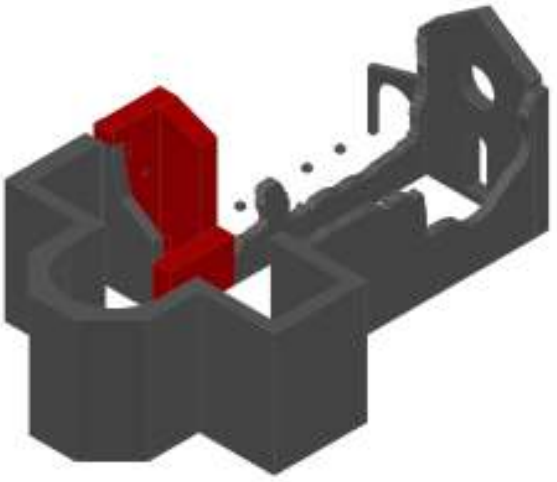


Sezione B-B PRE-SISMA



Sezione B-B POST-SISMA





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Solo in seguito intervengono attività progettuali di carattere più "convenzionale", quali la scelta delle tecniche di intervento e il loro "dimensionamento" e verifica, in un contesto tuttavia ancora di grande apertura verso la possibilità di scelte alternative, che devono essere poste a confronto per valutarne i possibili impatti, e di adattamenti, con modifiche anche sostanziali rispetto alle scelte originarie di progetto, alle situazioni reali di cantiere.

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C8 COSTRUZIONI ESISTENTI

- A quanto detto si è aggiunta la consapevolezza che, per l'Italia, il principale problema della protezione antisismica è oggi rappresentato dalle costruzioni esistenti e che il renderle sufficientemente antisismiche, senza peraltro snaturarle, è questione non facile da affrontare e risolvere, sostanzialmente legata a una approfondita conoscenza delle peculiarità dell'oggetto su cui si interviene.
- **Alla conoscenza della costruzione esistente si è dedicata, dunque, particolare attenzione, riducendo l'importanza attribuita alla conoscenza dei materiali impiegati per concentrarsi sui particolari costruttivi e sulle indicazioni progettuali dell'epoca di costruzione, maggiormente responsabili del reale comportamento della costruzione a fronte di azioni sismiche.**

C1.1 LOGICA DELLA NORMA

- Recuperare l'incertezza del "livello di conoscenza" propria del modello di calcolo (incertezza usualmente espressa attraverso un coefficiente moltiplicativo dell'azione) ricorrendo a un coefficiente riduttivo della resistenza dei materiali, come da Norma, può enfatizzare eccessivamente l'importanza delle indagini sui materiali.
- Ciò porta a sottostimare l'importanza delle indagini relative ai dettagli costruttivi, alla connessione dei vari elementi tra loro, alle loro modalità di interazione e di collasso; questi elementi sono invece fondamentali per identificare le criticità presenti e irrinunciabili per individuare il modello di calcolo globale (che descrive il comportamento d'insieme della costruzione) e i modelli di calcolo dei meccanismi di collasso locali.
- *Gli aspetti che definiscono i livelli di conoscenza sono: geometria della struttura, dettagli costruttivi, proprietà dei materiali, connessioni tra i diversi elementi e loro presumibili modalità di collasso.*

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C1.1 LOGICA DELLA NORMA

- La sostanziale unitarietà del processo progettuale, purché la conoscenza sia quella effettivamente necessaria nel senso prima evidenziato, non è turbata neppure dai vincoli di carattere storico-artistico-conservativo cui le costruzioni esistenti debbono, a volte, sottostare.
- Le costruzioni storiche, giunte a noi attraversando i secoli, sono frutto di lunghi e complessi processi di trasformazione, adattamento, danneggiamento e riparazione/ricostruzione (anche a seguito di terremoti di intensità non inferiore a quella che, di norma, ha una limitata probabilità di verificarsi durante la "vita utile" di una nuova costruzione); ogni volta si è intervenuti con i metodi di cui la tradizione costruttiva del tempo e del luogo disponeva (non necessariamente analitici, ma non per questo meno efficaci e determinanti). Sono maturate così le condizioni per cui i tentativi di migliorare il rapporto capacità/domanda modificando il "comportamento delle costruzioni esistenti" hanno prodotto "risultati deludenti".
- Approcci progettuali basati invece sul riconoscimento, mediante adeguati e rigorosi processi di conoscenza, di tutti i possibili fattori di vulnerabilità di una costruzione storica e su interventi volti a ridurli, se non del tutto eliminarli, modificando il meno possibile il comportamento strutturale della costruzione esistente, sono non solo più rispettosi dei criteri di conservazione di valori storico-artistici ma anche più affidabili ed efficaci dal punto di vista della sicurezza strutturale, come evidenziato anche dalle esperienze maturate in occasione dei più recenti terremoti.

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Conclusione

L'approccio "conservativo" alla sicurezza strutturale del patrimonio architettonico storico - entrato ormai nella prassi professionale avendo trovato uno specifico inquadramento a livello normativo con l'introduzione del criterio di progetto cosiddetti per «interventi locali» e di "miglioramento" - presenta criticità in grado di comprometterne l'efficacia soprattutto legate ad inevitabili e decisivi aspetti di discrezionalità.

Il "giudizio" di esperti di diverse discipline lascia inevitabilmente spazio a scorciatoie non adeguatamente motivate:

- sia nella concreta applicazione in questo contesto di concetti inerenti alla "conservazione";
- sia nella attribuzione di capacità prestazionali meccanico-strutturali a particolari materiali e tecnologie, tradizionali o innovative che siano (come dimostrano gli esiti spesso negativi dei recenti terremoti in aree dove, con le migliori intenzioni, erano stai eseguiti interventi con l'intento di aumentare la sicurezza strutturale).

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È del tutto evidente che in tale contesto il progetto deve uscire dalle condizioni di spesso umiliante subalternità, se non di irrilevanza, che gli vengono riservate da cattive prassi che hanno preso il sopravvento nel mondo delle costruzioni, per tornare ad essere l'operazione centrale di ogni intervento sul costruito storico.

Il progetto deve essere un'operazione di alto profilo culturale, svolta con profondo senso di responsabilità e professionalità, che rifiuta tutte le "scorciatoie" per immergersi in un lungo e faticoso processo di conoscenza – in cui la storia va a pari passo con i più avanzati strumenti di indagine ed algoritmi di calcolo – in grado di elaborare e adattare al singolo contesto le sollecitazioni, e le suggestioni, che provengono sia dalla tradizione sia dal mondo accattivante delle moderne tecnologie.

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6-7 Dicembre, Rovereto

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INTERNATIONAL GUIDELINES FOR RESTORATION AND CONSERVATION







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Safety standards for historical structures

Codes

- **ISO 13822** – bases for design of structures – assessment of existing structures (first edition 2001)
- **Italian Building Code** for design, assessment and seismic retrofitting – Chapter 8: existing buildings (NTC 2008)
- **prEN 1998-3 Eurocode 8** – Design of structures for earthquake resistance Part 3: assessment and retrofitting of buildings

Guidelines

- **ISCARSAH** Recommendations for the analysis, conservation, and structural restoration of architectural heritage
- **Italian Guidelines** for the assessment and the reduction of seismic risk of cultural heritage (2006)

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Rules for study, diagnosis and safety evaluation (I)

ISO 13822

- The continued use of existing structures is of great importance because the built environment is a huge economic and political asset, growing larger every year. The **assessment of existing structures** is now a major engineering task.
- The structural engineer is increasingly called upon to devise ways for extending the life of structures whilst observing tight cost constraints.
- The establishment of **principles for the assessment of existing structures** is needed because it is based on an approach that is substantially different from the design of new structures, and requires knowledge beyond the scope of design codes.
- The ultimate goal is to **limit construction intervention to a strict minimum**, a goal that is clearly in agreement with the principles of sustainable development.

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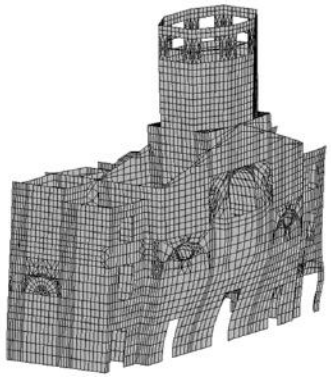
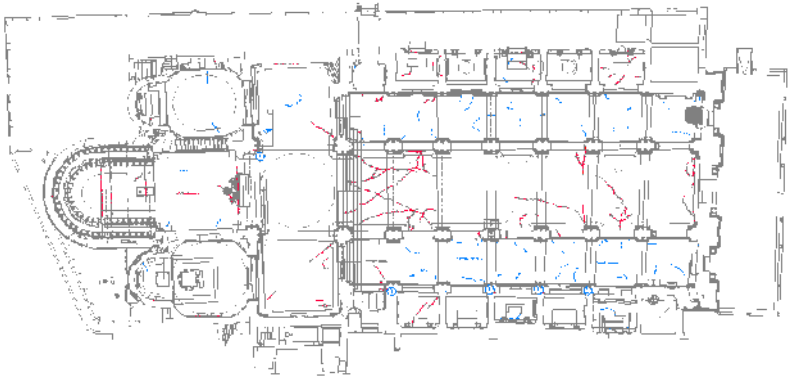
Rules for study, diagnosis and safety evaluation (II)

ISO 13822 – § 7.4

The conclusion for the assessment shall withstand a **plausibility check**. In particular, discrepancies between the results of structural analysis (e.g. insufficient safety) and the real structural condition (e.g. no signs of distress or failure, satisfactory structural performance) shall be explained.

Note: many engineering models are **conservative** and cannot always be used directly to explain an actual situation.





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International Council on Monuments and Sites
Conseil International des Monuments et des Sites

Recommendations for the analysis, conservation and structural restoration of architectural heritage

Guidelines

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Guidelines for the assessment and the reduction of seismic risk of cultural heritage

- CHAP. 1: OBJECT OF THE GUIDELINES
- CHAP. 2: SAFETY AND CONSERVATION REQUIREMENTS
- CHAP. 3: SEISMIC ACTION
- CHAP. 4: BUILDING KNOWLEDGE
- CHAP. 5: MODELS FOR SEISMIC SAFETY ASSESSMENT
- CHAP. 6: SEISMIC IMPROVEMENT AND INTERVENTION TECHNIQUES CRITERIA
- CHAP. 7: RESUME OF THE PROCESS

Sequence of the collapse of the vault of the Assisi Basilica during the 1997 earthquake

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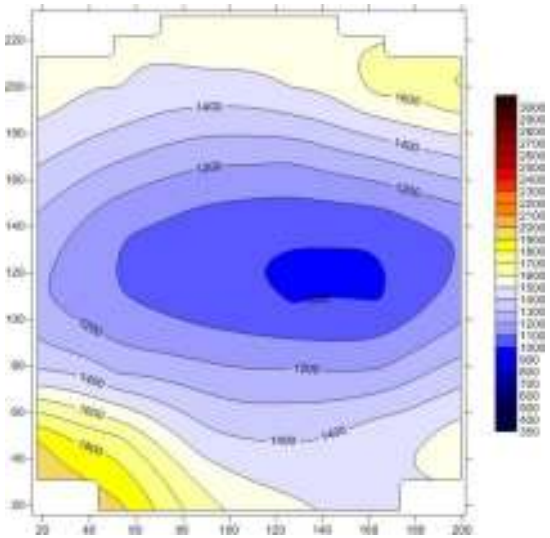
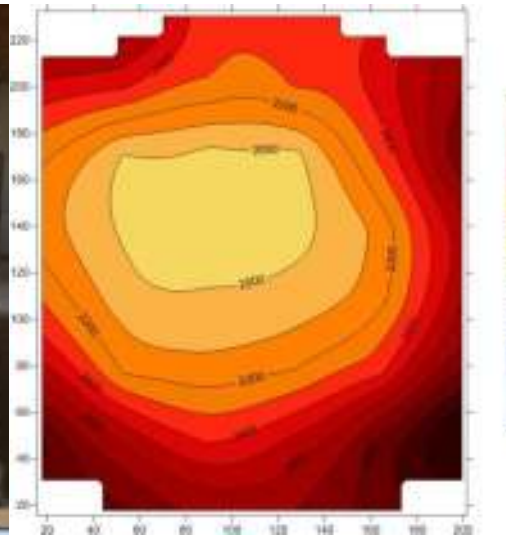
KNOWLEDGE





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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)

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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

7. MONITORING STRATEGIES

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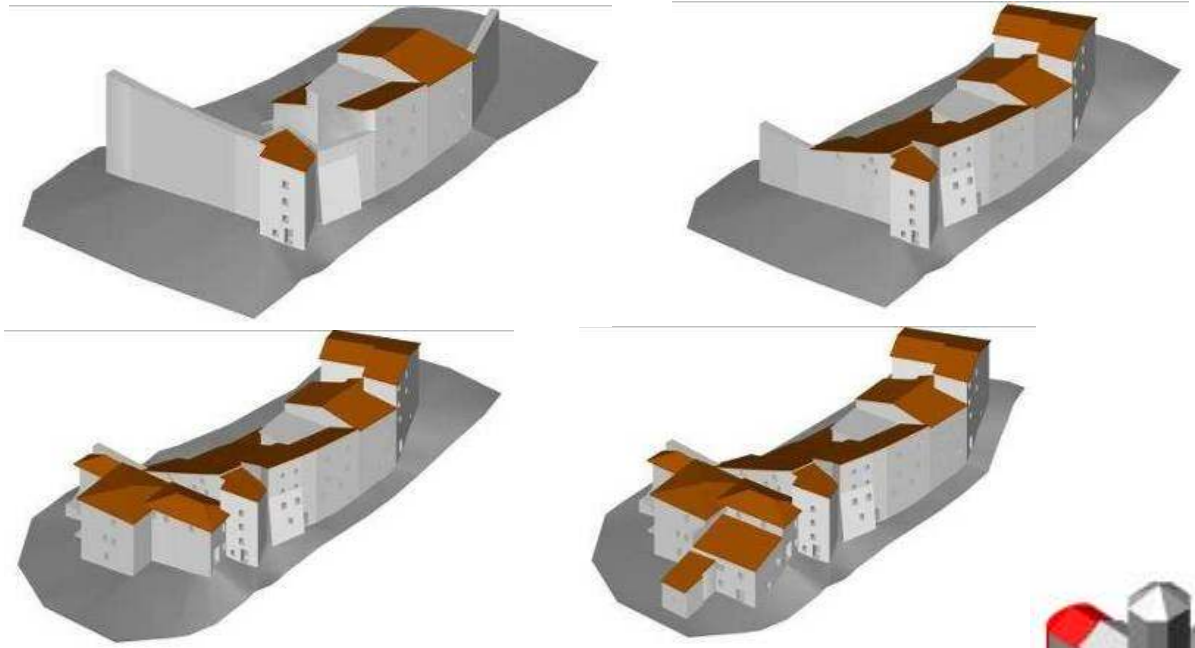
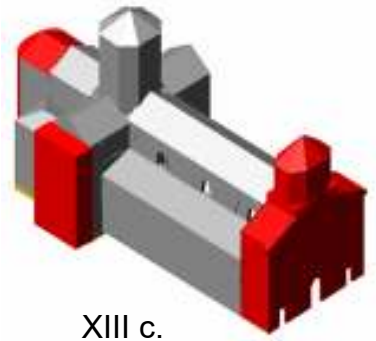
HYPOTHESYS ON THE BUILDING EVOLUTION





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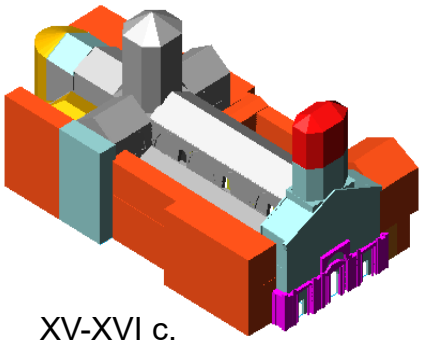

XV-XVI c.

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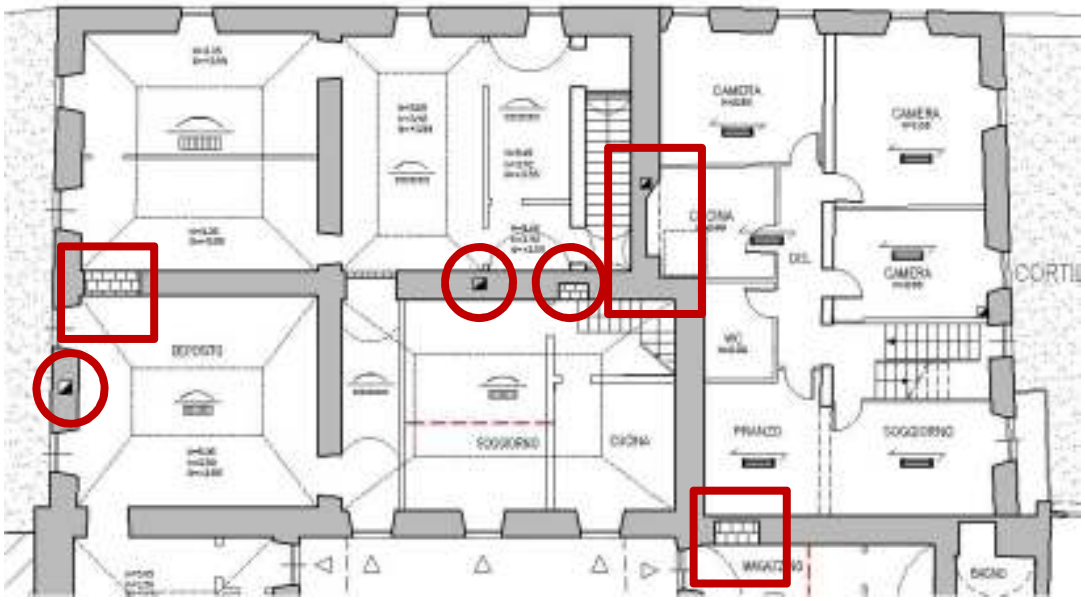
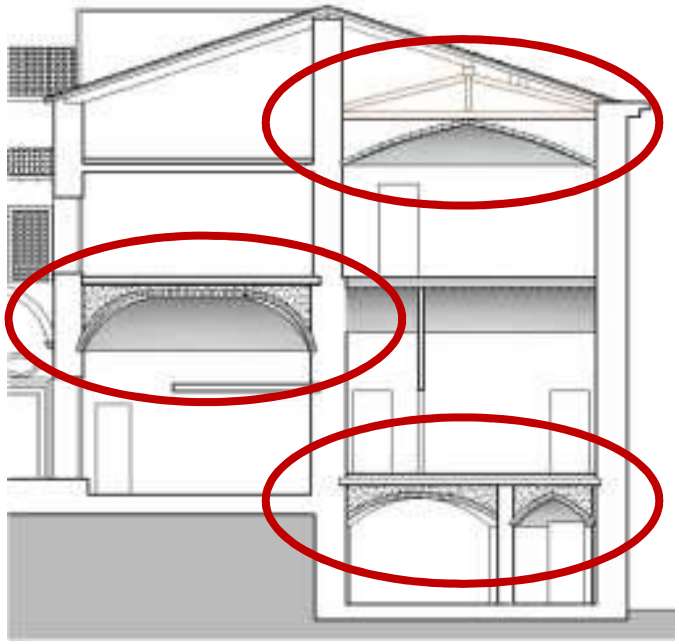
GEOMETRY

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





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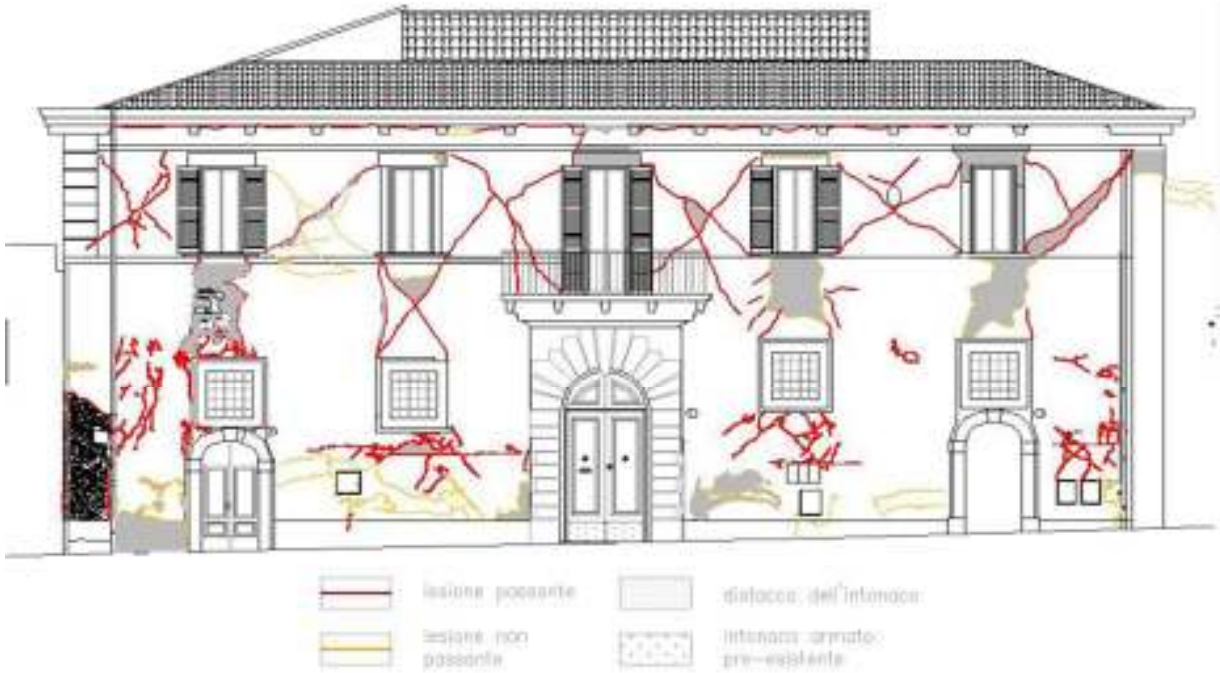
GEOMETRY

Survey and representation of eventual crack and deformation pattern.



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CONSTRUCTION DETAILS

a) quality of connections between walls;
b) type and quality of connections between horizontal diaphragms and walls;
c) type and efficiency of lintels above openings;
d) presence and efficiency of elements to counteract horizontal trusts;
e) Presence of structural or non structural elements with high vulnerability;
f) type of masonry

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CONSTRUCTION DETAILS

This 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.*

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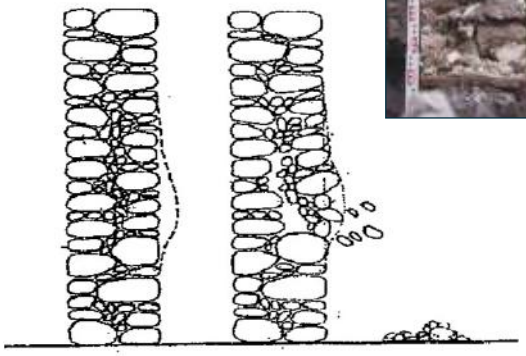
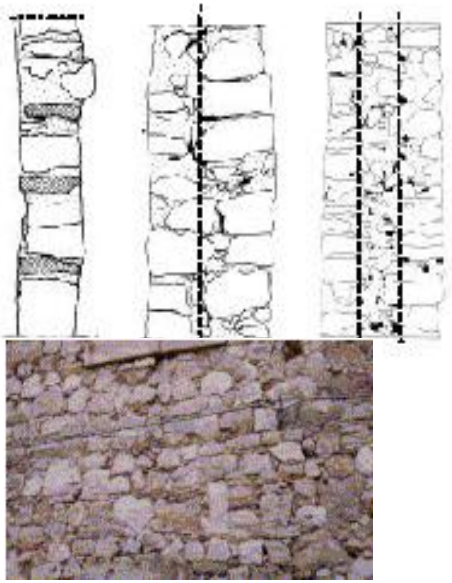
CONSTRUCTION DETAILS: MASONRY TYPOLOGY

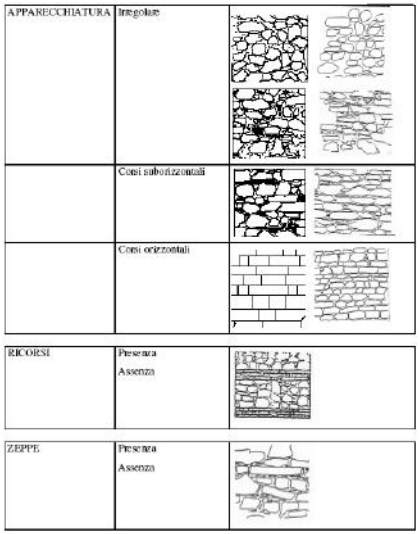
It Is possible to refer to abaci for the evaluation of the quality and bearing capacity of **masonry typologies**

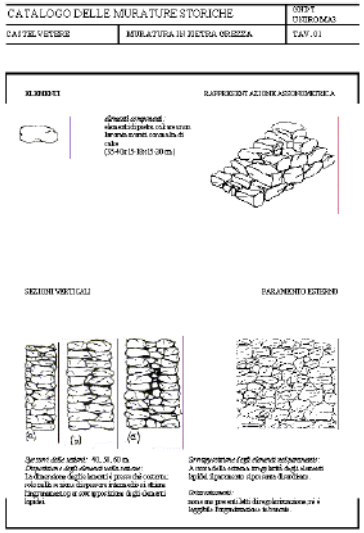
Heterogeneous masonry built up with poor materials, presence of voids, irregularities, multi-leaf sections, absence of connections





Out-of-plane brittle collapses





Survey forms: frequent local masonry typologies

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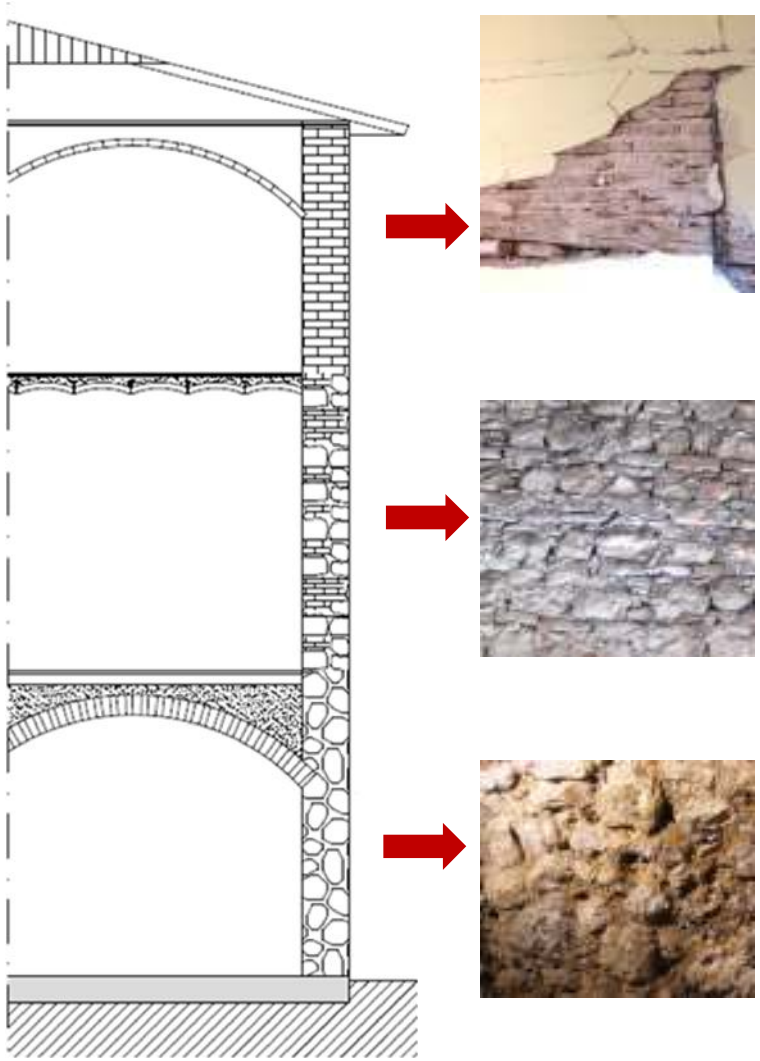
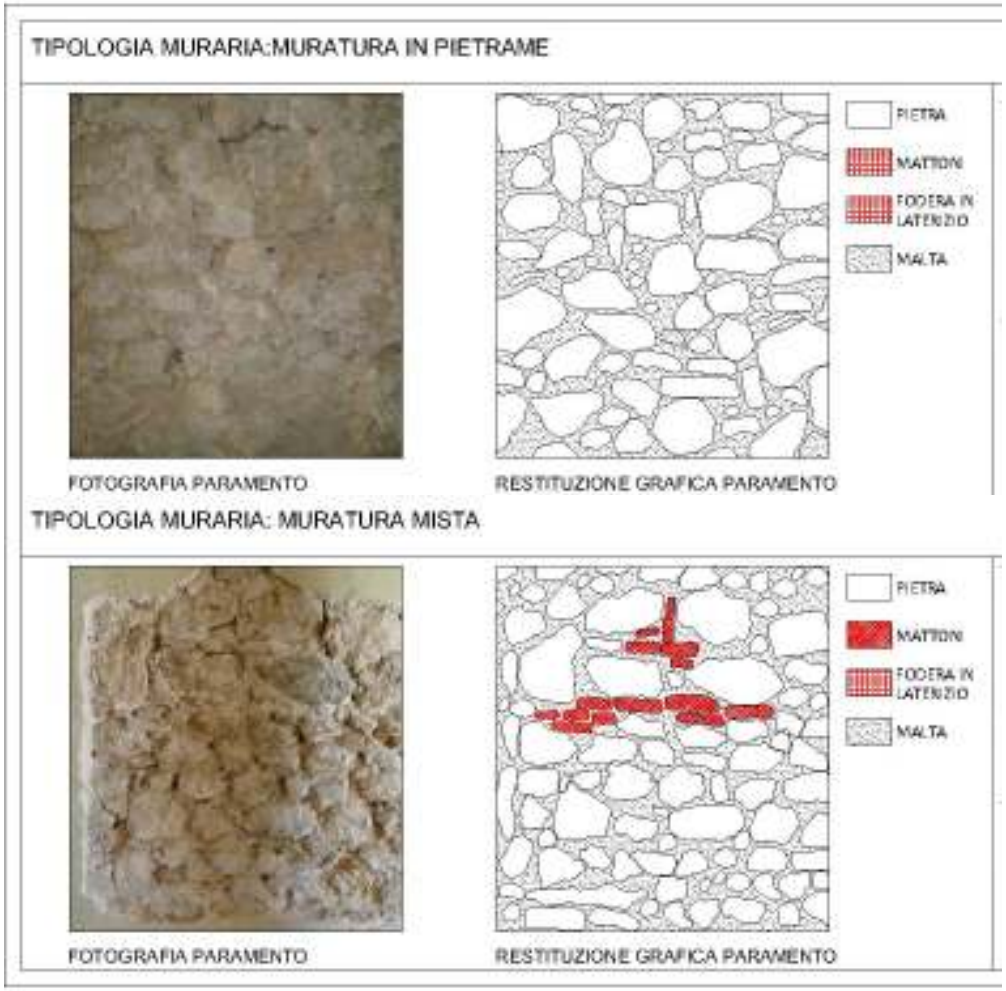
CONSTRUCTION DETAILS: MASONRY TYPOLOGY





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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

7. MONITORING STRATEGIES

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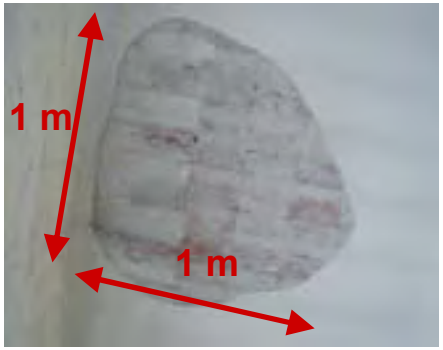
MATERIAL PROPERTIES

Limited on-site investigations:

Information on the material properties, in order to determine the masonry typology. They are based on visual examinations on the masonry surface.



Extended on-site investigations:

Tests with double flat jack and characterization tests of the mortar and of stones or bricks. Non-destructive tests (sonic tests, etc…).

Comprehensive on-site investigations:

Quantitative information on the material resistance through on-site or laboratory tests (diagonal compression tests on panels or combined tests of vertical compression and shear). Non-destructive tests can be employed in combination, but not in place of the ones above described.

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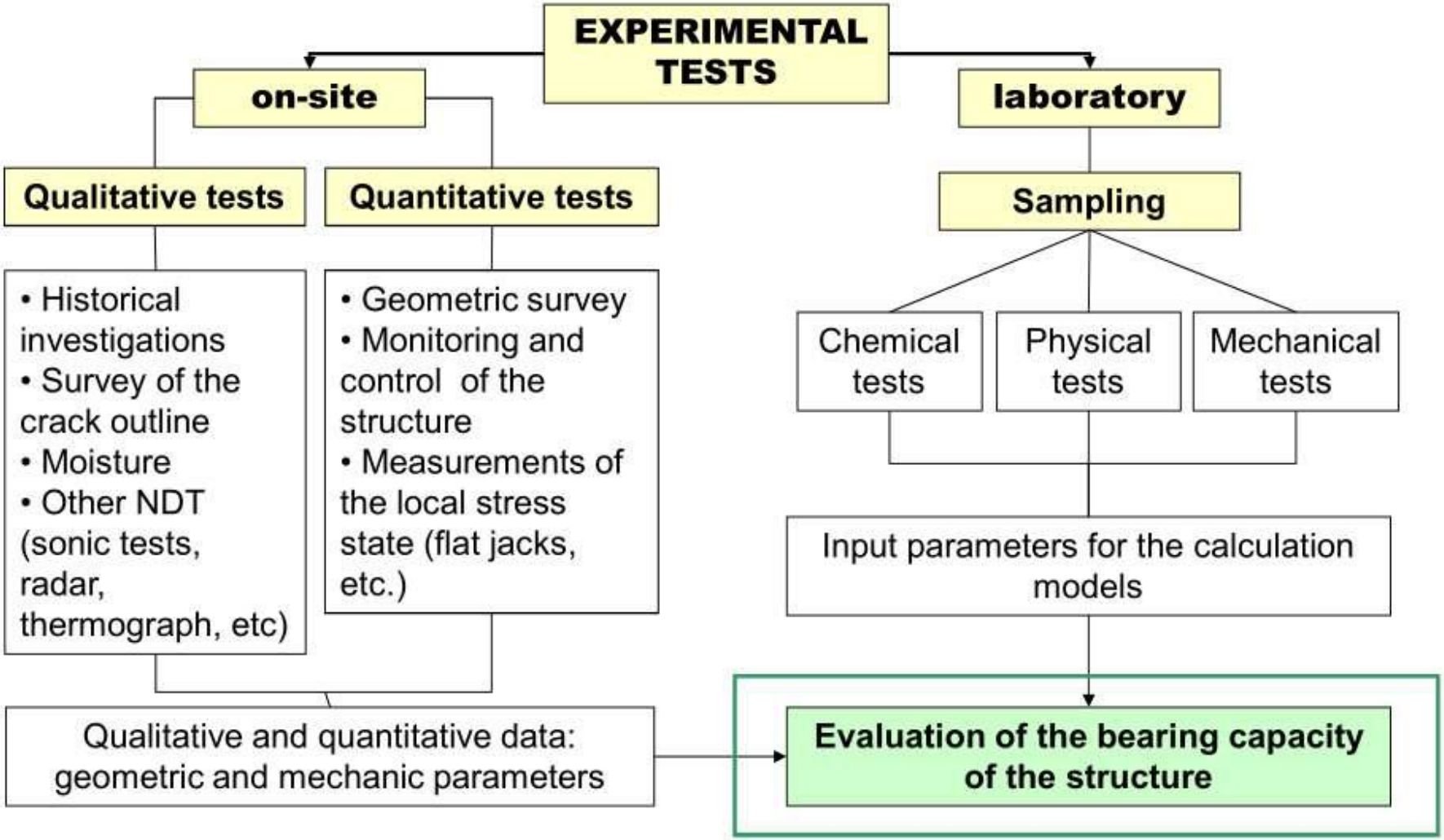

(Binda, 1994)

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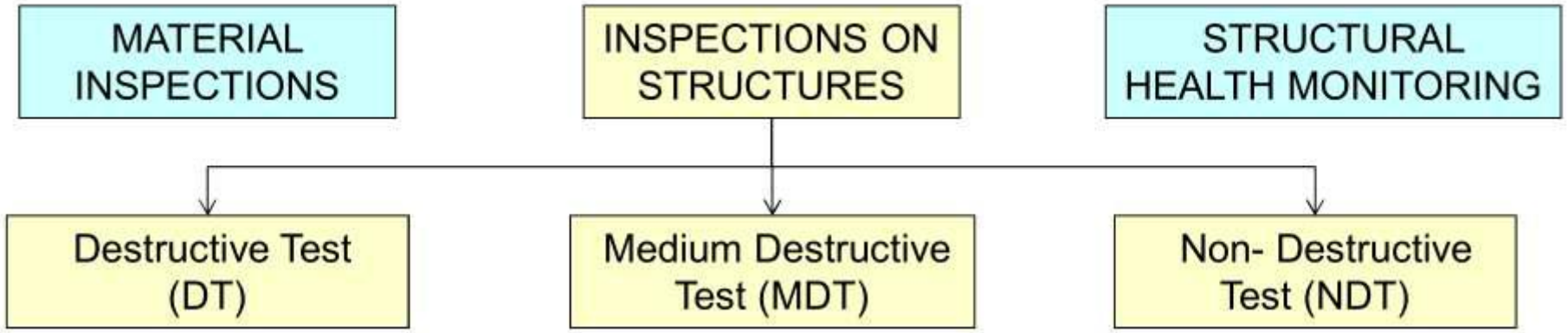

•Destructive Tests provide direct information on the mechanical properties of materials. Nevertheless, the main problem is the obtrusiveness of the investigation procedure.

•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.

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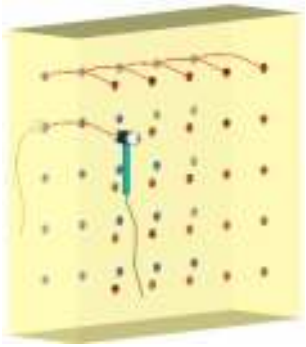
INVESTIGATION TECHNIQUES FOR KNOWLEDGE AND CONTROL OF REPAIRS

Non destructive tests (NDT):

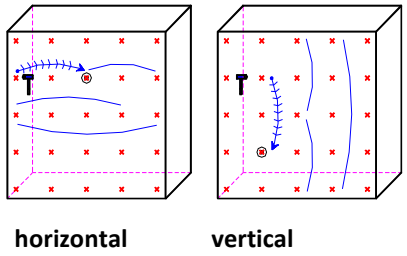
NDT can be helpful in finding hidden characteristics (internal voids and flaws and characteristics of the wall section) which cannot be known otherwise than through destructive tests.

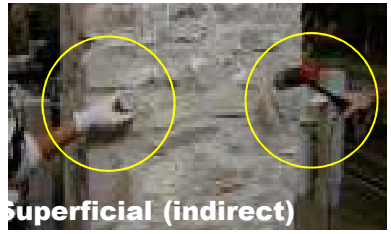


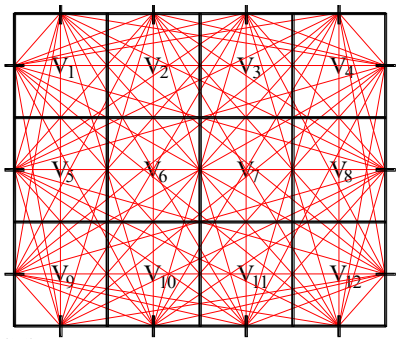
Sonic pulse velocity test

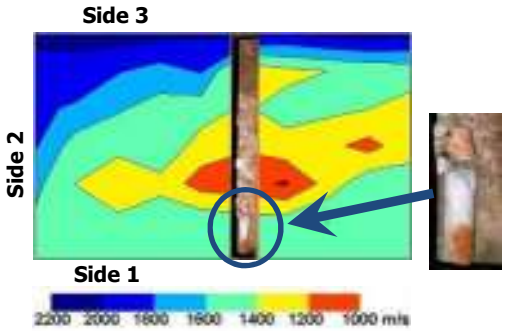
The use of sonic tests has the following aims:

- 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.









Sonic Tomography

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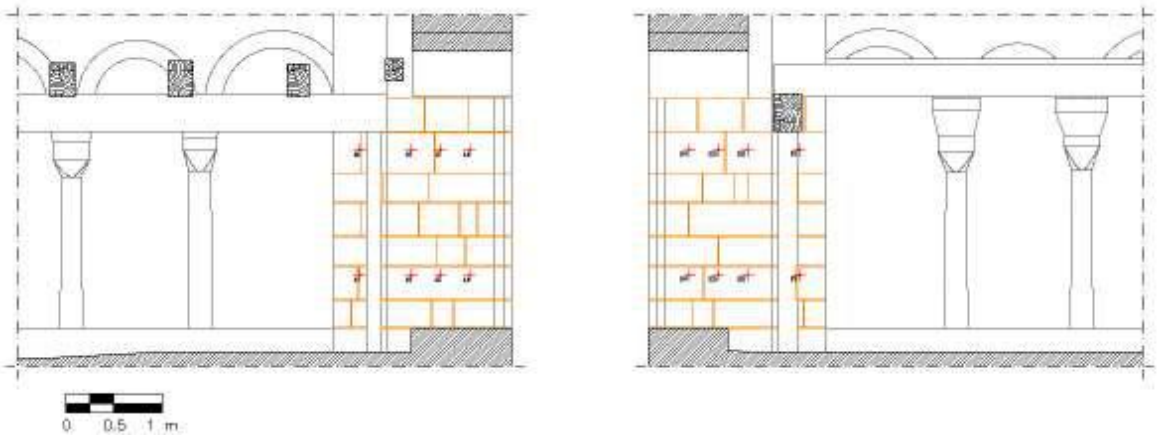
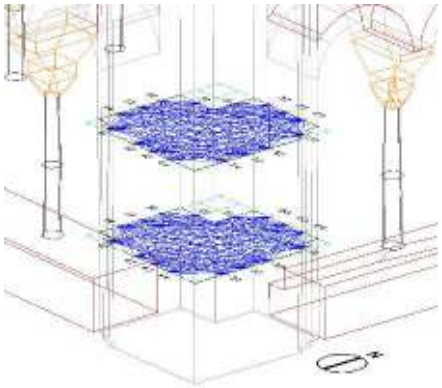
Examples of sonic tomography and coring (Example of San Zeno bell tower)

NDT

The inner part of the pillar is composed by a masonry with reduced masonry consistency/different composition respect the external area, being this denounced by the different velocities emerged from the analysis (avg. velocity of the inner and outer areas corresponding respectively to approximately 1800 and 2500 m/s in the lower cross section and 1600/2600 m/s in the higher).

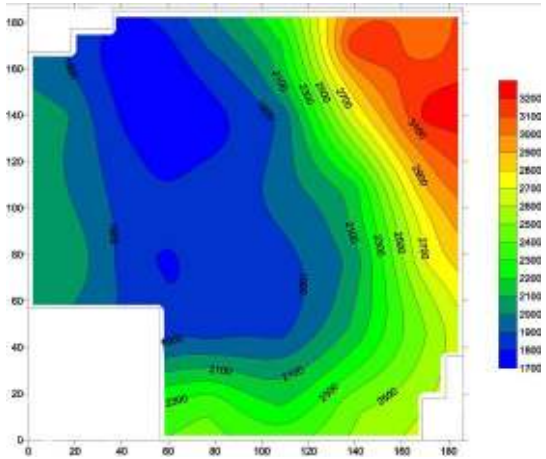


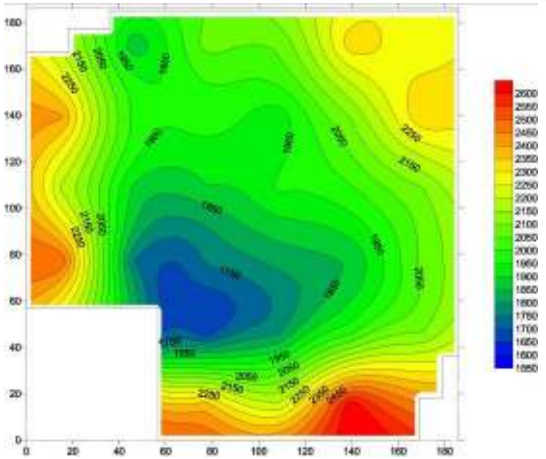
Sonic tomographies



Velocity maps

Lower cross section





Higher cross section

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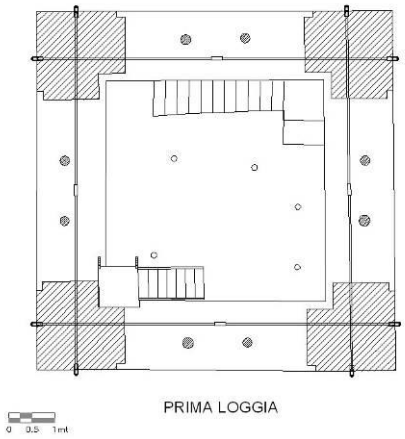
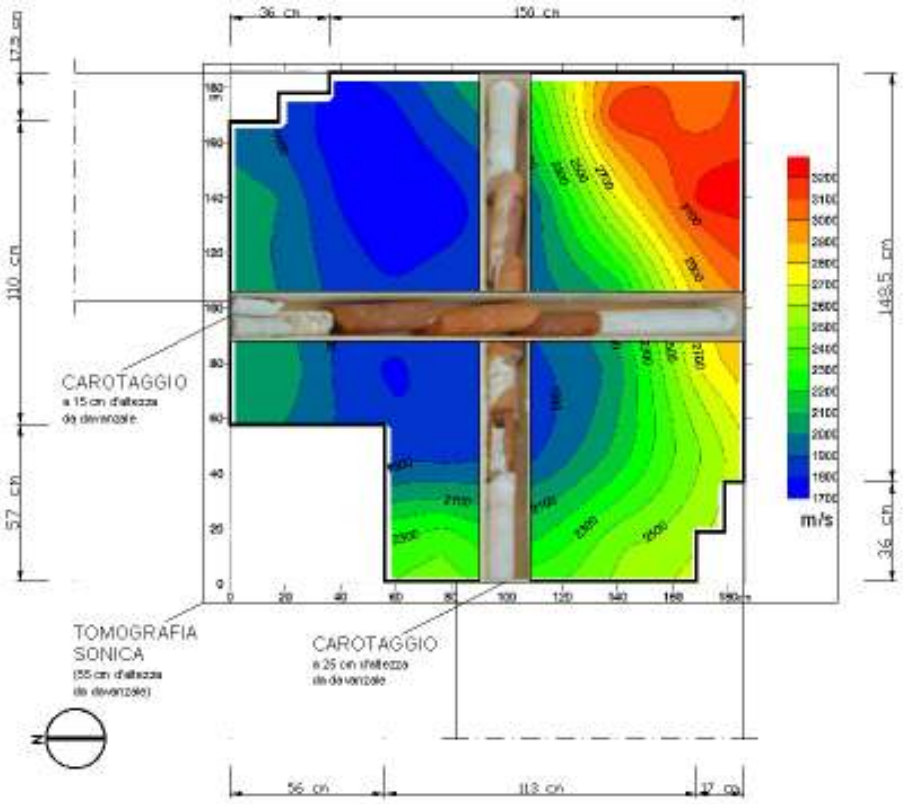
Examples of sonic tomography and coring (Example of San Zeno bell tower)

NDT

Results were confirmed by the successive extraction of core samples in the area of execution of the tests (brickwork masonry in the inner part, presenting a velocity that generally denotes a material with fair/good mechanical characteristics, and an outer masonry composed by well arranged sandstone masonry blocks).



core samples



Overlapping: sonic tomography – core samples

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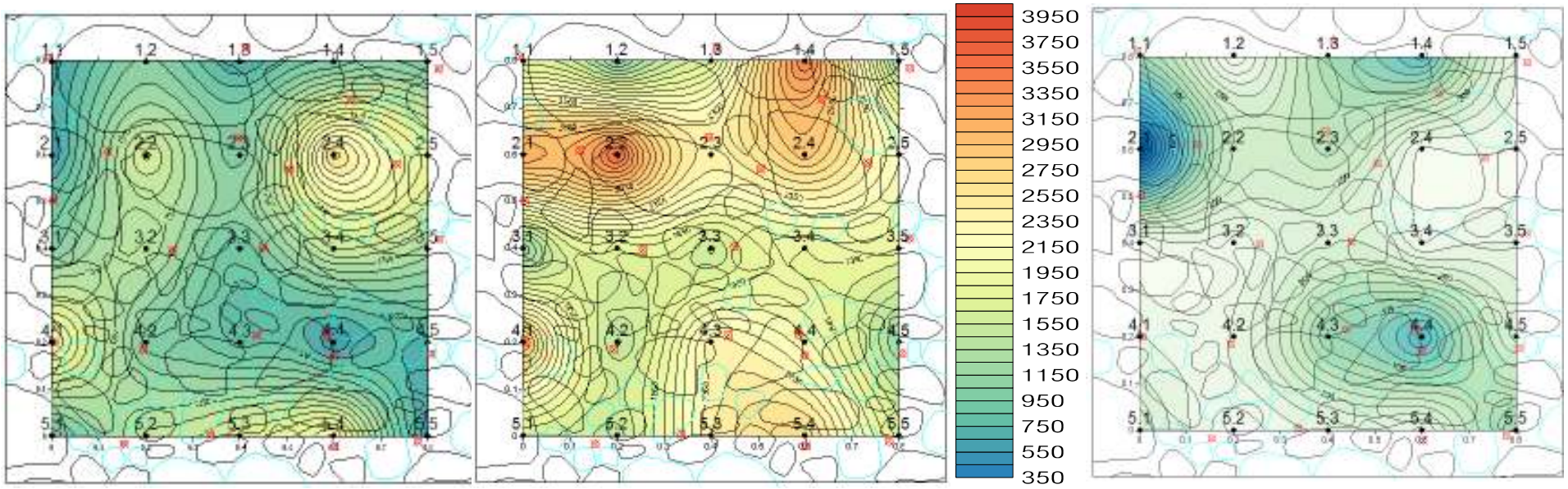
NDT

Examples of sonic (Control of injection)

The **sonic tests** are adopted in situation pre and post injection in order to evaluate their efficacy analysing:

- Average increment of velocity
- Distribution of the injection in the investigated area



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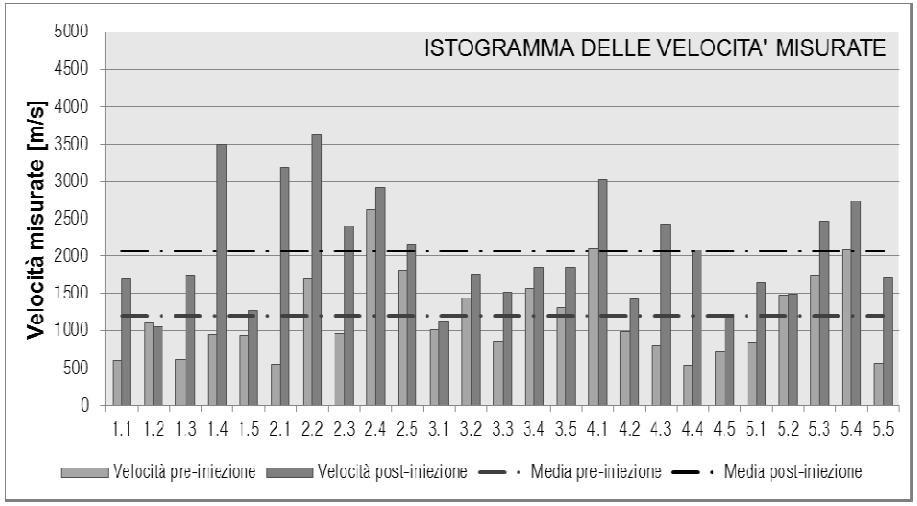
Examples of sonic (Control of injection)

NDT

PROVA SONICA DIRETTA - POST INIEZIONE						
Percorso	Spessore Muratura [m]	Tempo di volo (sec) T_A [sec]	T_B [sec]	T_C [sec]	T_m [sec]	V_m [m/s]
1.1	0.36	2.19E-04	2.39E-04	1.82E-04	2.13E-04	1689
1.2	0.36	3.32E-04	3.35E-04	3.61E-04	3.43E-04	1051
1.3	0.36	2.09E-04	2.10E-04	2.05E-04	2.08E-04	1730
1.4	0.36	9.29E-05	1.04E-04	1.12E-04	1.03E-04	3490
1.5	0.36	2.64E-04	3.02E-04	2.85E-04	2.84E-04	1269
2.1	0.36	1.26E-04	1.07E-04	1.06E-04	1.13E-04	3182
2.2	0.36	9.17E-05	9.57E-05	1.10E-04	9.92E-05	3630
2.3	0.36	1.35E-04	1.75E-04	1.40E-04	1.50E-04	2399
2.4	0.36	1.25E-04	1.25E-04	1.20E-04	1.23E-04	2915
2.5	0.36	1.73E-04	1.43E-04	1.86E-04	1.67E-04	2154
3.1	0.36	3.15E-04	3.21E-04	3.18E-04	3.18E-04	1132
3.2	0.36	1.82E-04	2.05E-04	2.32E-04	2.06E-04	1746
3.3	0.36	2.44E-04	2.34E-04	2.34E-04	2.37E-04	1516
3.4	0.36	1.99E-04	1.84E-04	2.02E-04	1.95E-04	1847
3.5	0.36	1.99E-04	1.81E-04	2.04E-04	1.95E-04	1851
		1.11E-04	1.37E-04			



PRE-INJECTION

Average speed	1195	m/s
Standard deviation	555	m/s
Coefficient of variation	46.41 %	

POST-INJECTION

Average speed	2072	m/s
Standard deviation	729	m/s
Coefficient of variation	35.17 %	

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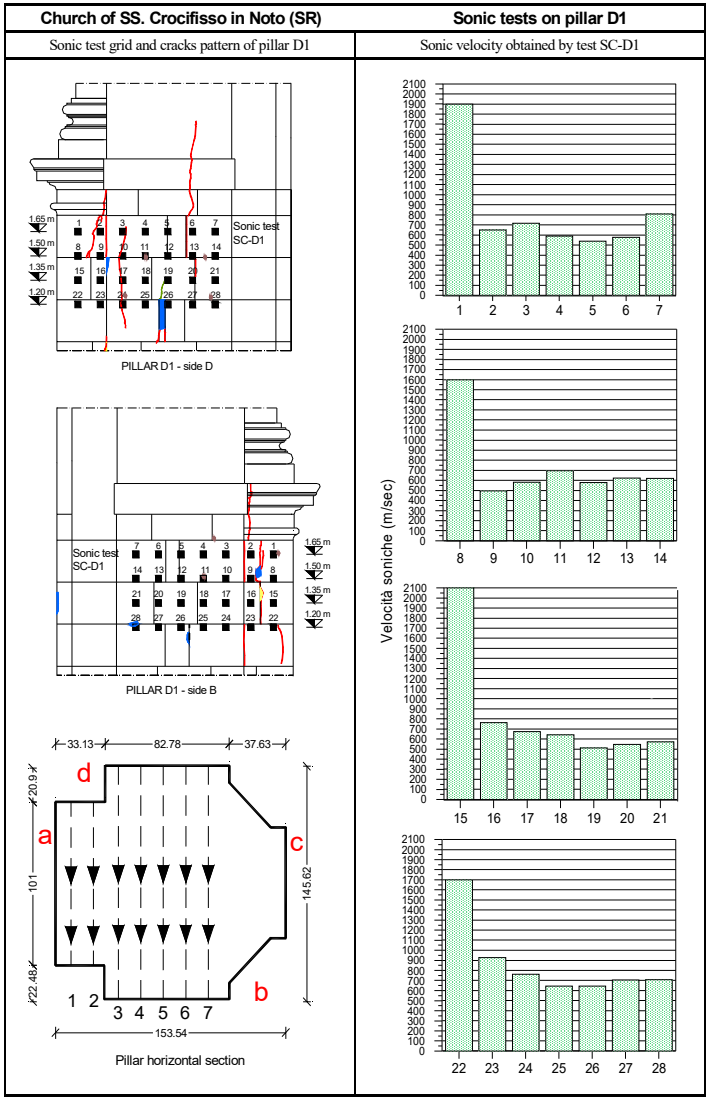
INVESTIGATION TECHNIQUES FOR KNOWLEDGE AND CONTROL OF REPAIRS

Non destructive tests (NDT): 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)

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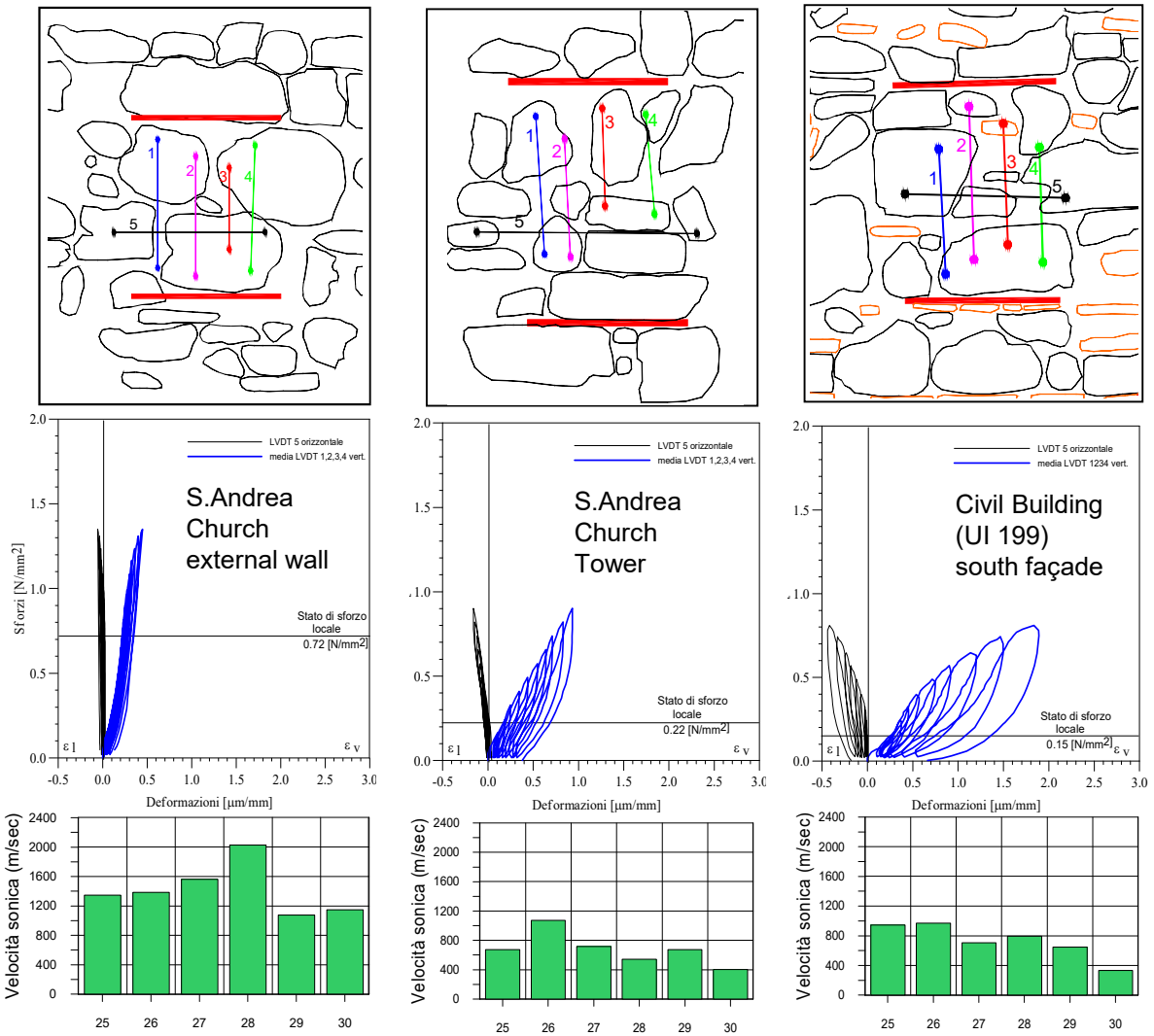
INVESTIGATION TECHNIQUES FOR KNOWLEDGE AND CONTROL OF REPAIRS



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

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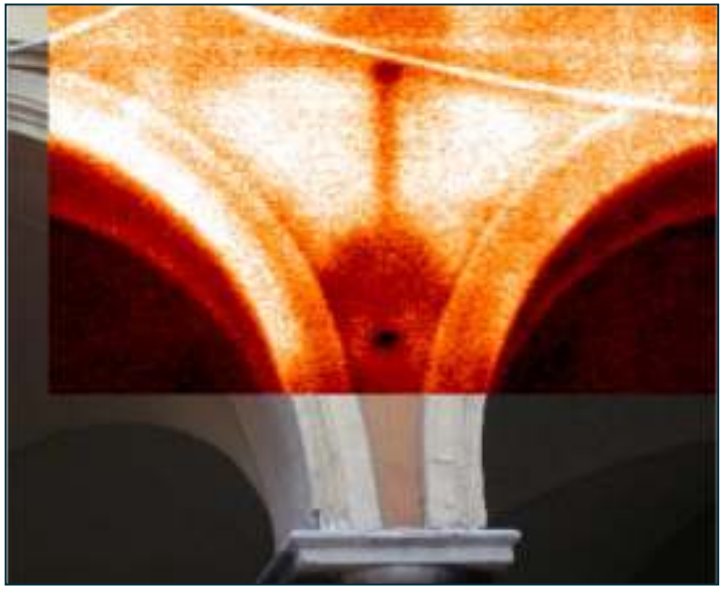
INVESTIGATION TECHNIQUES FOR KNOWLEDGE AND CONTROL OF REPAIRS

Non destructive tests (NDT): Thermovision

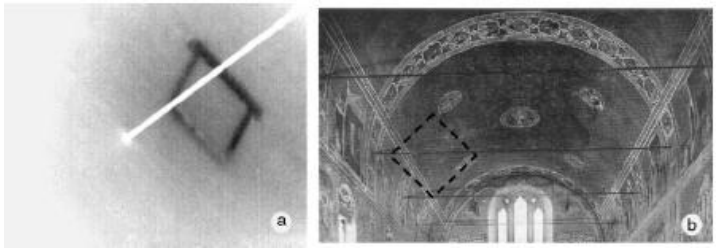
The **thermographic analysis** is based on the thermal conductivity of a material and may be passive or active. The passive application analyses the radiation of a surface during thermal cycles. If the survey is active, forced heating to the surfaces analyzed are applied

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.



Investigation on hidden steel tie rods



Detention of a modified opening

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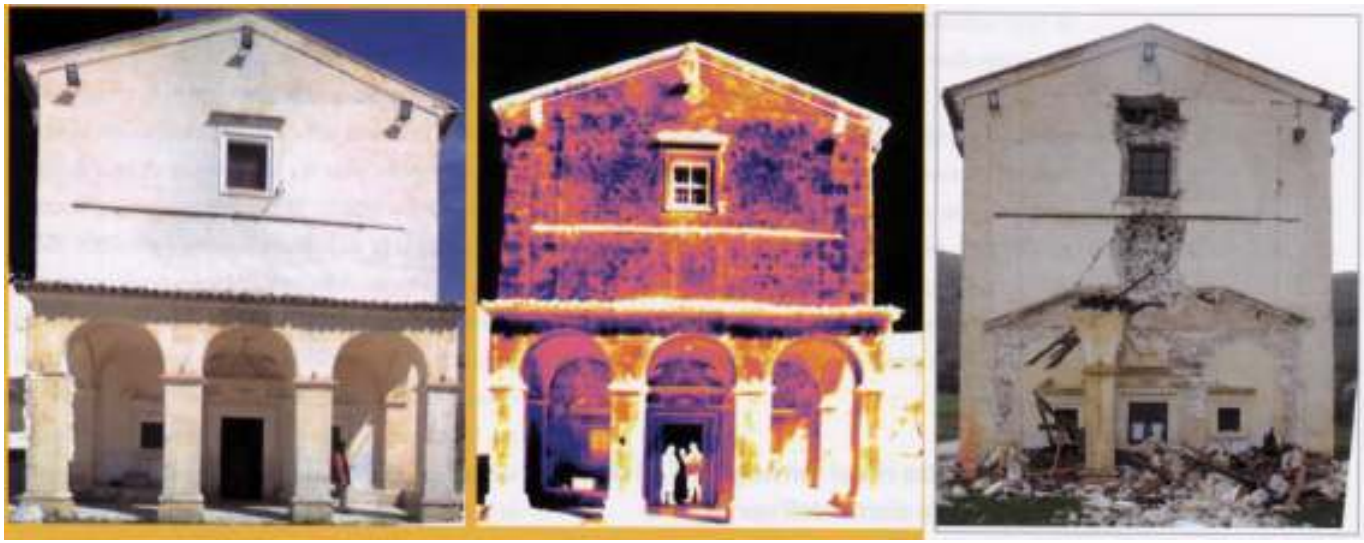
NDT

Thermographic analysis

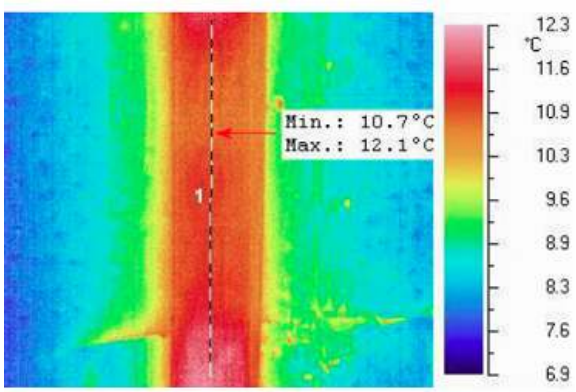
Passive use

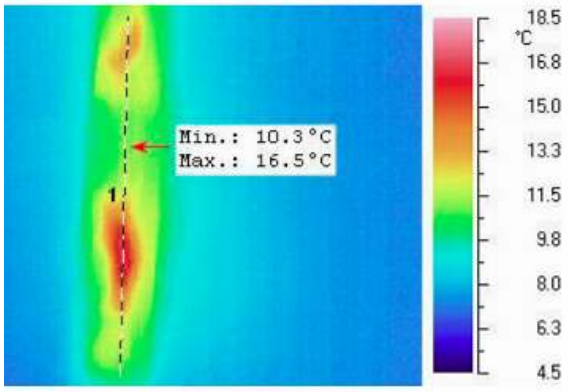


Comparison between IR termography and damages occurred on the façade of S. Stefano's church [Grinzato 2009]

Active use

Control in application of FRP





Termography profile, fairly uniform (left) and non uniform (rigth) temperature [Niker 2012]

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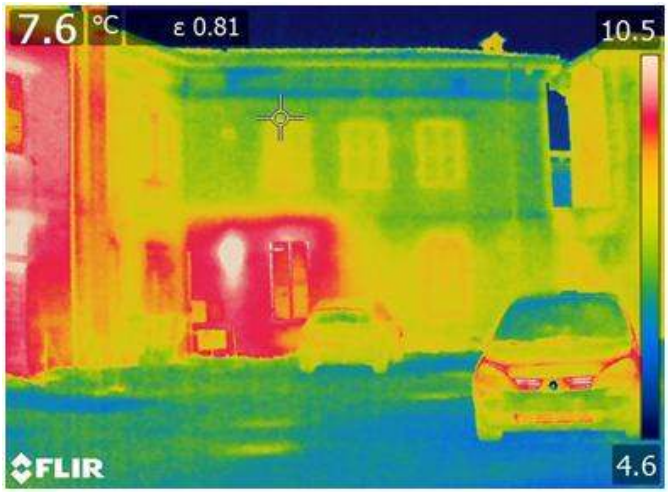
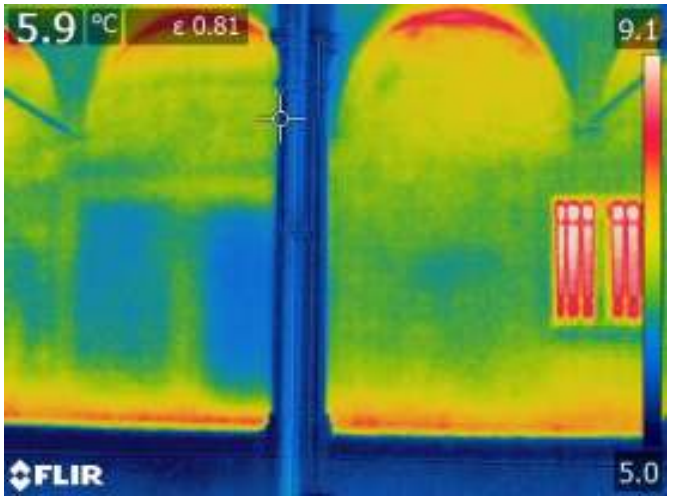
Thermographic analysis

(Cescatti, 2016)

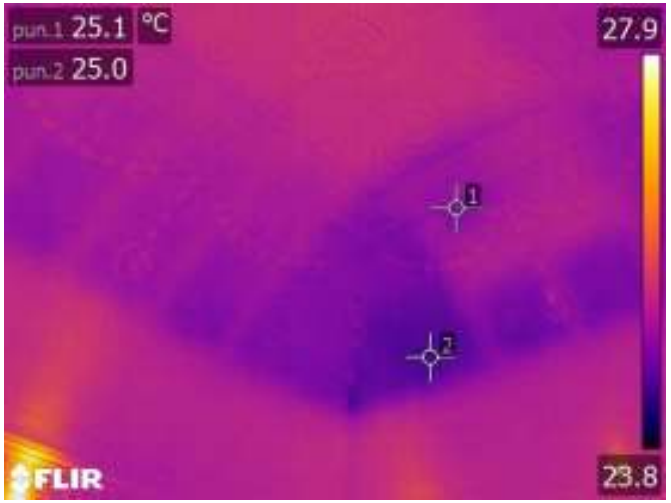
NDT

Identification of different structural elements, concrete stringcourse (left) and infill door (right)





Identification of material and typologies: ceilings (wattle, L) and roofs (concrete, R)



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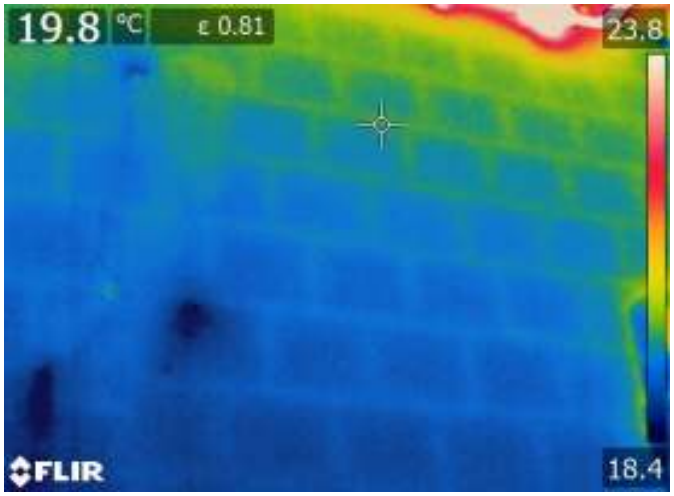
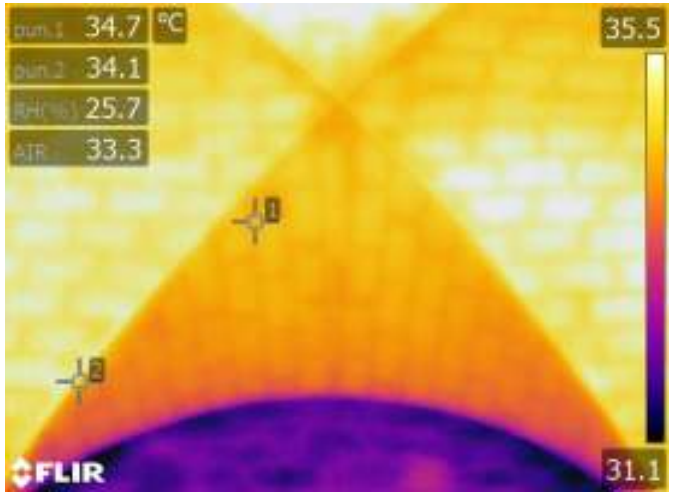
Thermographic analysis

(Cescatti, 2016)

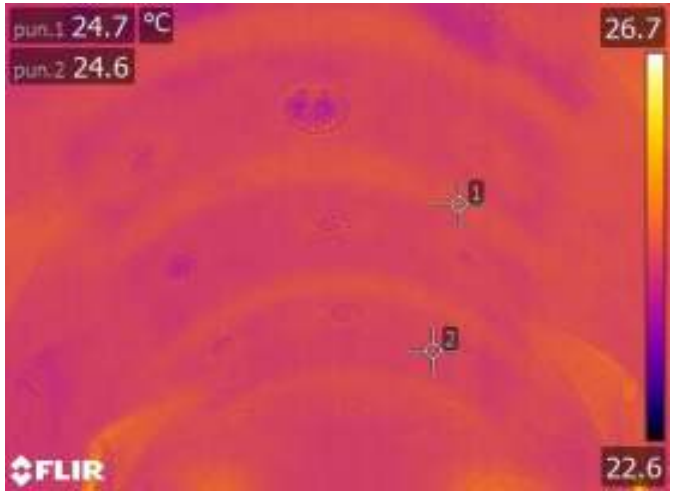
NDT

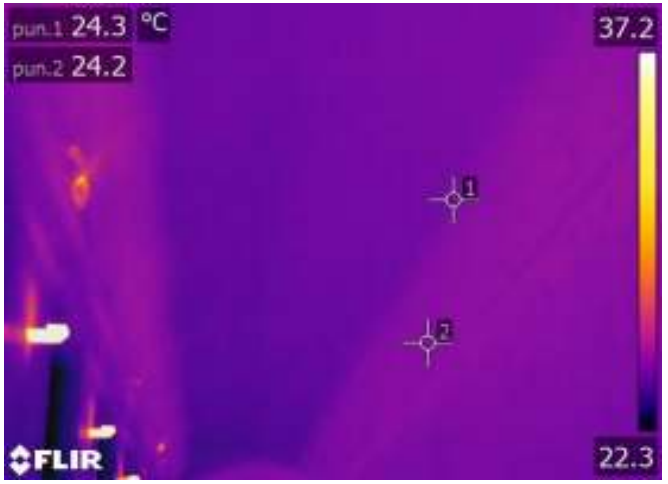
Identification of unit texture on walls (left) and vaults (right)





Identification of thickness distribution and detachements





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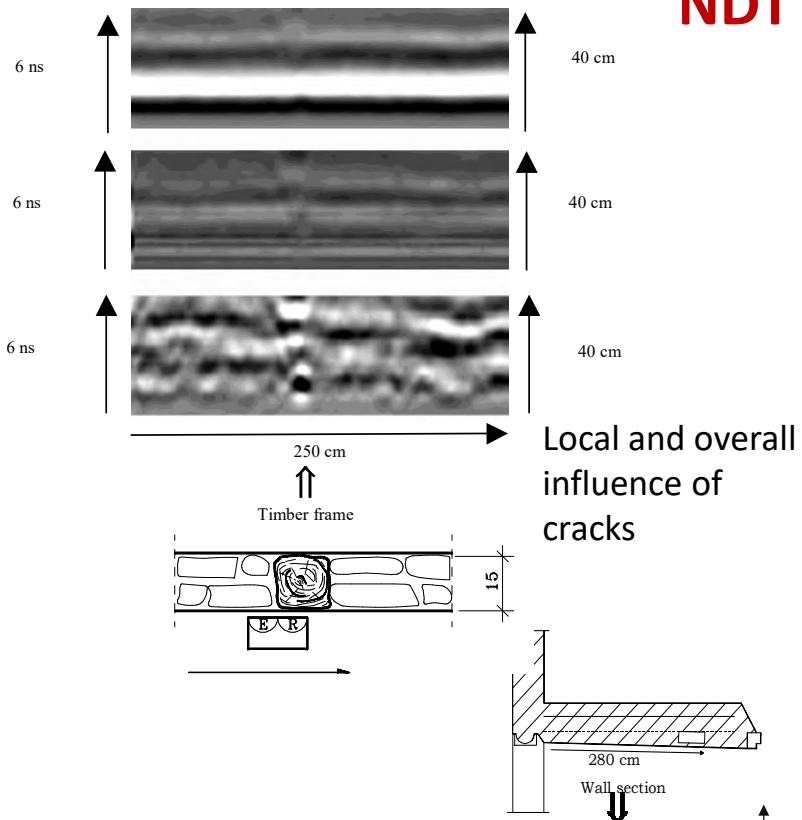
NDT

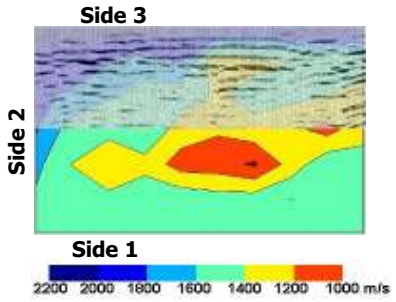
Non destructive tests (NDT): Georadar

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

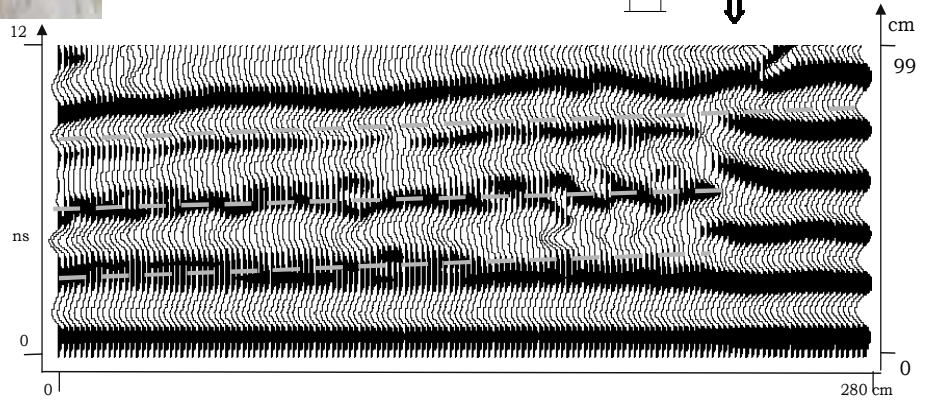
- to locate the position of large voids and inclusions of different materials, like steel, wood, etc.;
- to qualify the state of conservation or damage of the walls;
- to define the presence and the level of moisture;
- to detect the morphology of the wall section in multiple leaf masonry.



Local and overall influence of cracks



Radar vs Sonic



Radargram of the wall section at the Malpaga Castle

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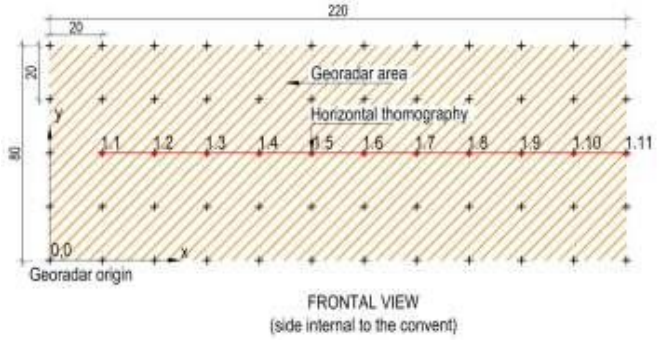
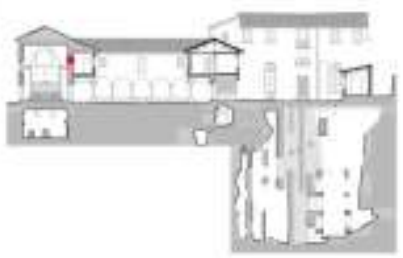
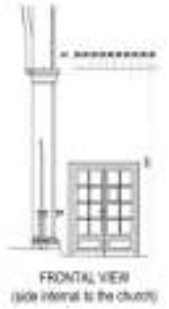
(Cescatti Modena , 2015) **NDT**

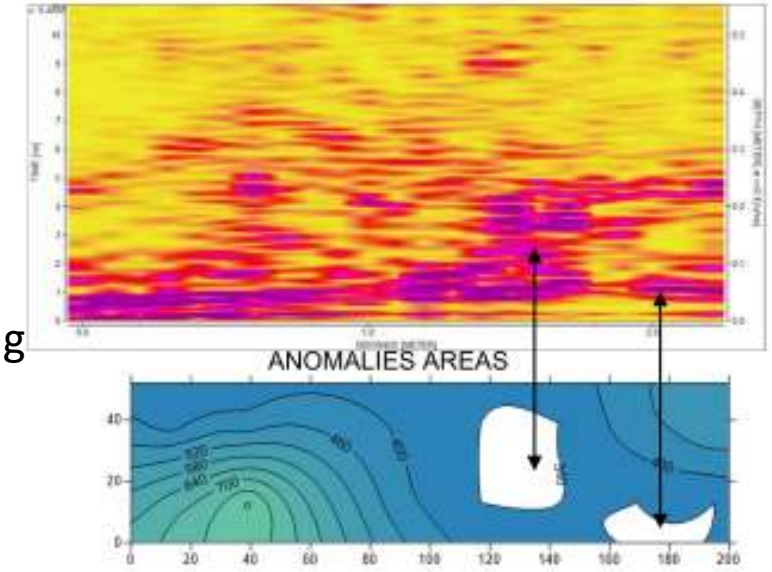
Comparison between Georadar and Sonic test

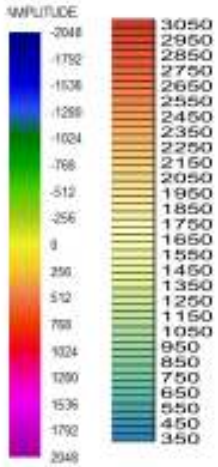






- Comparison among different NDT techniques
- GPR and Sonic demonstrates to be more reliable
- Confirmation of anomalies detecting during restoration and by both methodologies





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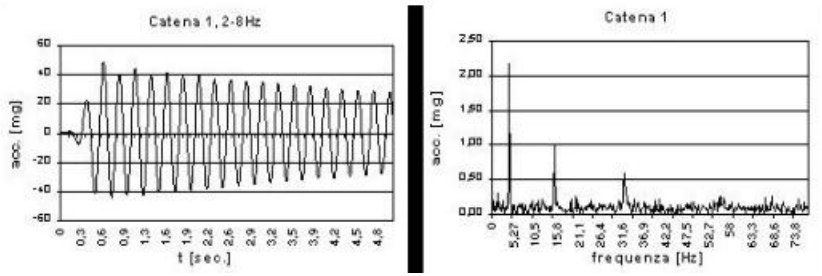
NDT

ANALYSIS OF AXIAL STRESS IN TIES

Palazzo del Bo',
University

Palazzo della Ragione



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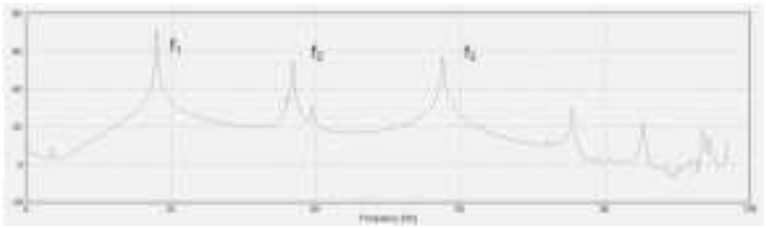
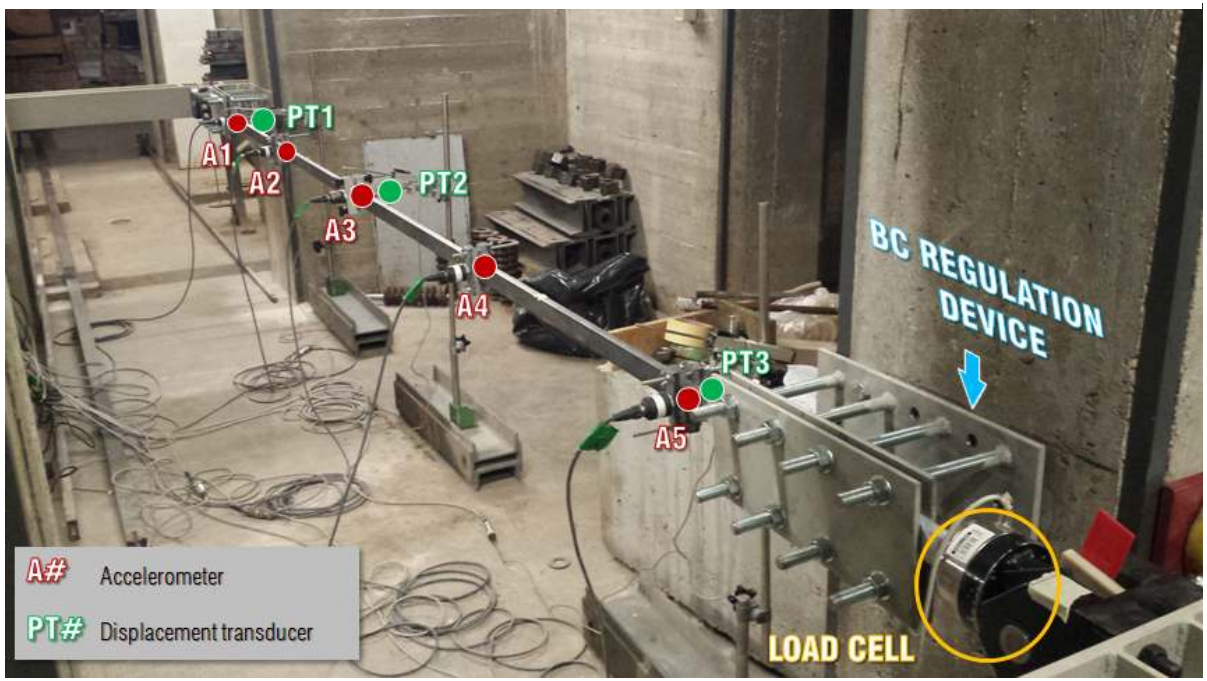
EXPERIMENTAL ASSESSMENT OF THE IDENTIFICATION TECHNIQUE

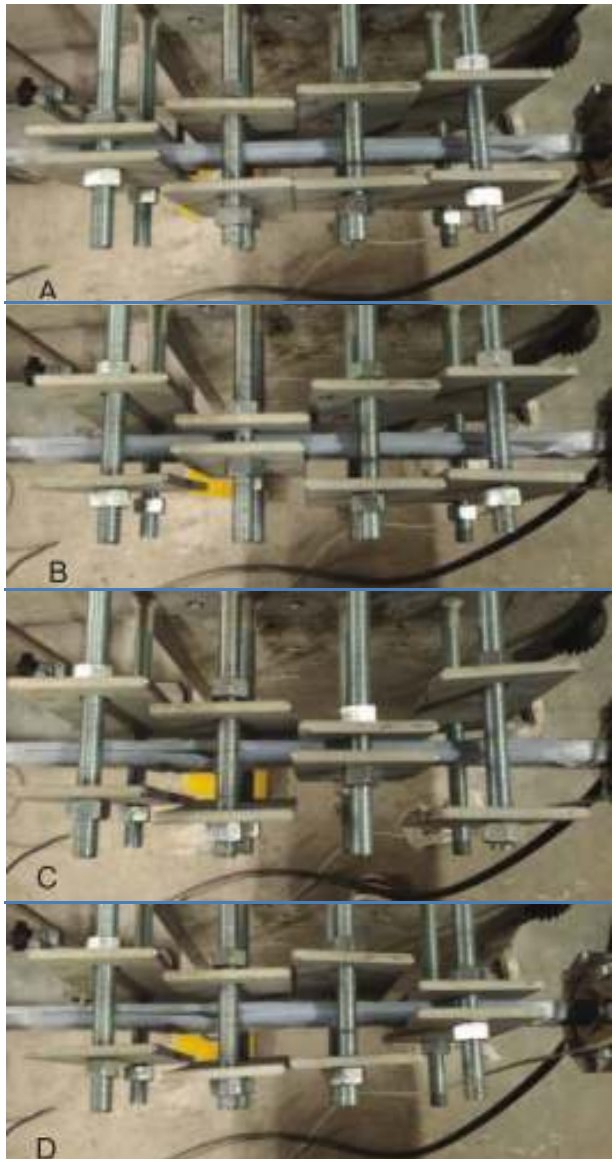
NDT

Tullini Laudiero [2008]

$$\frac{v_1 + v_3}{v_2} = \frac{1 + 2\cos(q_1/4)\cos(q_2/4)}{\cos(q_1/4) + \cosh(q_2/4)}$$







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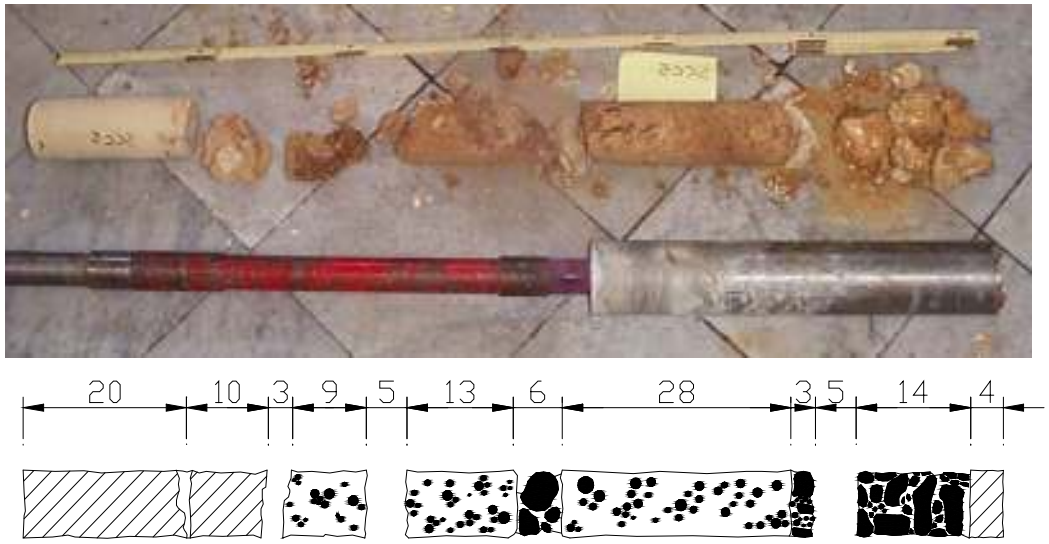
INVESTIGATION TECHNIQUES FOR KNOWLEDGE AND CONTROL OF REPAIRS

Minor destructive tests (MDT):

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 should be 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 can be used:
- the **Schmidt hammer** rebound test;
- the **penetration tests** proposed in different ways, like probes, drillers, etc. correlate the depth of penetration to the material mechanical properties;
- the **pull-out tests** can only be used on bricks and stones.

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INVESTIGATION TECHNIQUES FOR KNOWLEDGE AND CONTROL OF REPAIRS

Minor destructive tests (MDT): Flat jack test

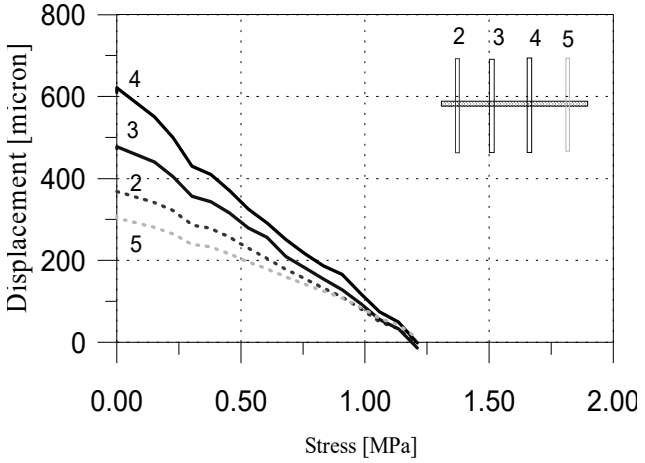
The determination of the **state of stress** is based on the stress relaxation caused by a cut perpendicular to the wall surface; the stress release is determined by a partial closing of the cutting, i.e. the distance after the cutting is lower than before. A thin **flat-jack** is placed inside the cut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

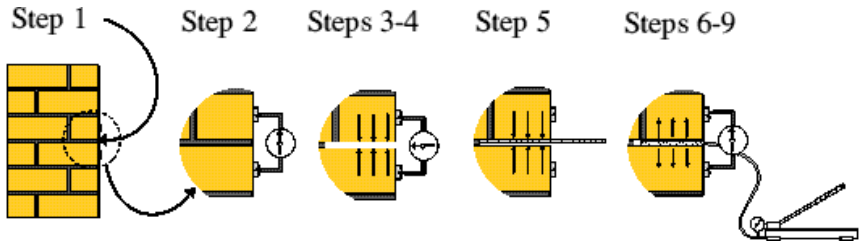
The equilibrium relationship is the fundamental requirement for all the applications where the flat-jack are currently used (ASTM, 1991):

$$S_f = K_j K_a P_f$$

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

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





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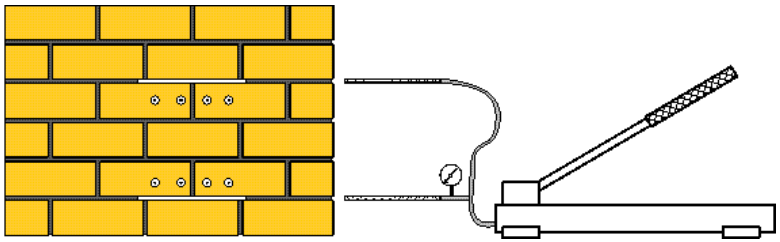
INVESTIGATION TECHNIQUES FOR KNOWLEDGE AND CONTROL OF REPAIRS

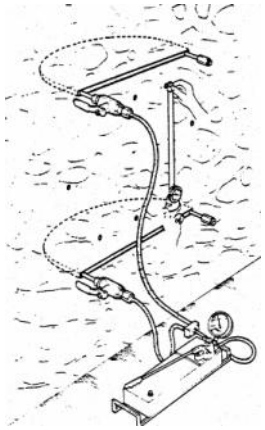
Minor destructive tests (MDT): Flat jack test

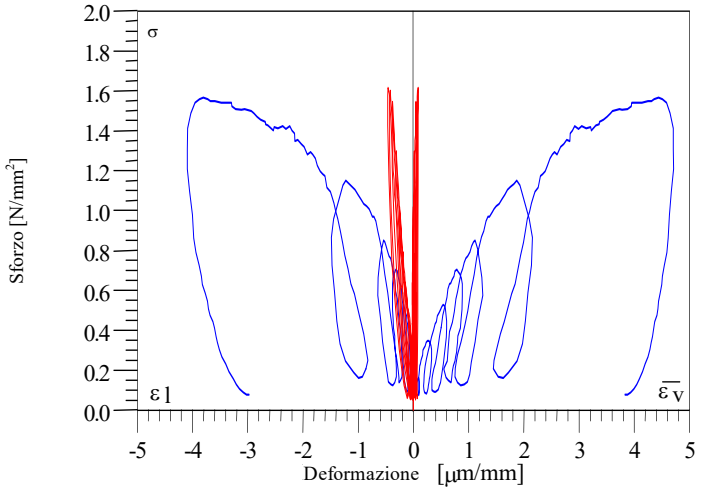
The test described can also be used to determine the **deformability characteristics** of a masonry. A second cut is made, parallel to the first one and a second jack is inserted, at a distance of about 40 to 50 cm from the other. The two jacks delimit a masonry sample of appreciable size to which a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





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MDT

DOUBLE FLAT JACK

ADVANTAGES

ON – SITE TECHNIQUE

- MDT (suggested by NTC 2008, ASCE 41-13)
- More reliable than extracted specimens
- Many experimental campaigns and confirmations since eighties [Maier 1983], Abrams et al 1989]
- Calibrations tests [Gregorczyk 2000, Dalla Benetta 2012]

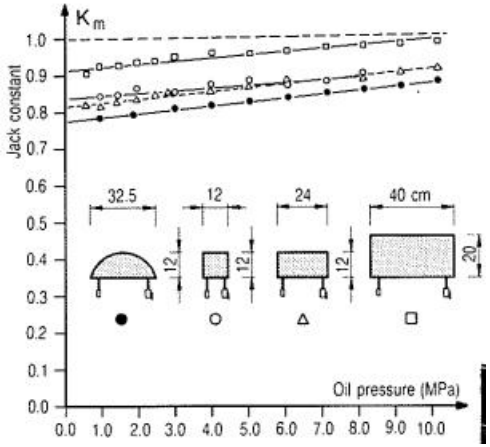
SHORTCOMINGS

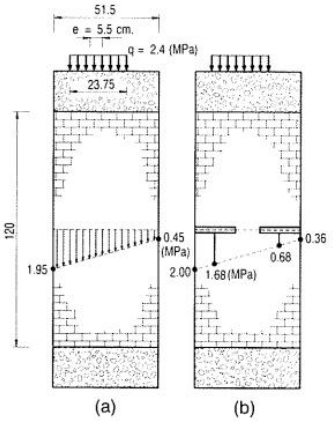
APPLICATION - PROCEDURE

- Low stress acting
- Very irregular masonry

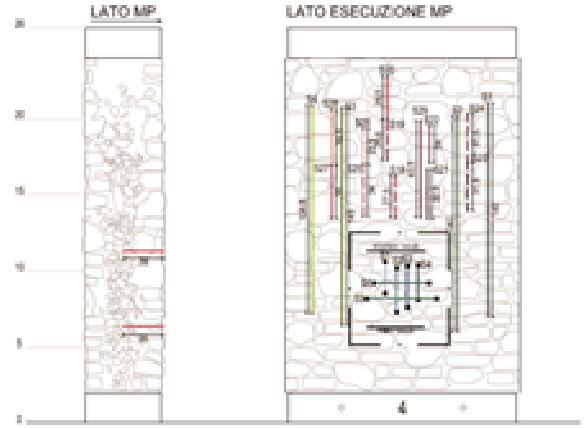
INTERPRETATION

"the test can create subjective interpretation according to the operator expertise bringing to possible different values" [Binda 2007]





Maier, L.B. ;Rossi, P.P.; Landriani, G.S. 1983



Dalla Benetta M. 2012

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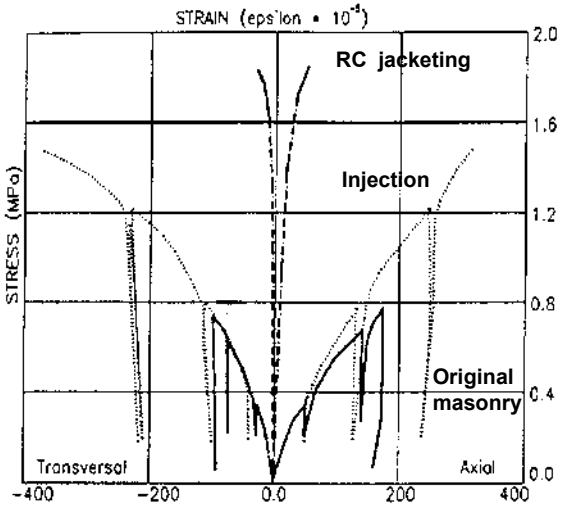
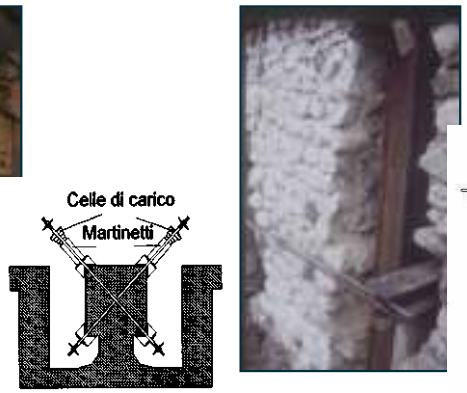
INVESTIGATION TECHNIQUES FOR KNOWLEDGE AND CONTROL OF REPAIRS

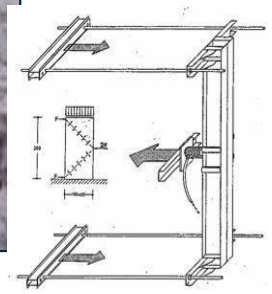
Destructive tests (DT) realised before and after strengthening intervention

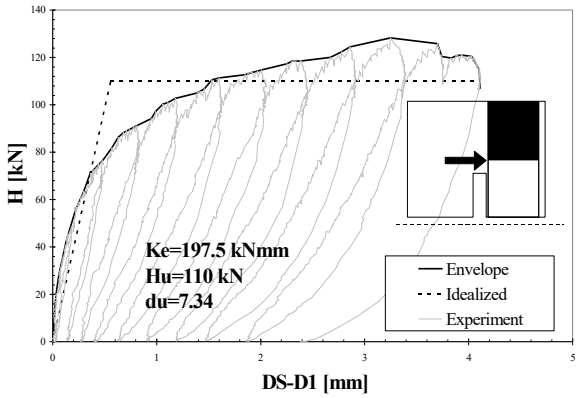
Mechanical characteristics for vertical actions



Mechanical characteristics for horizontal and vertical actions







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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

7. MONITORING STRATEGIES

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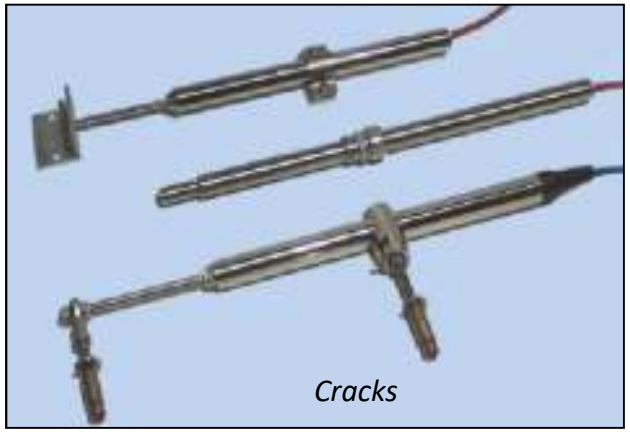
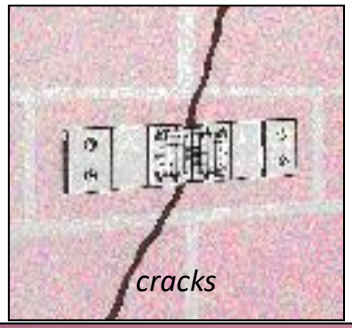
cracks



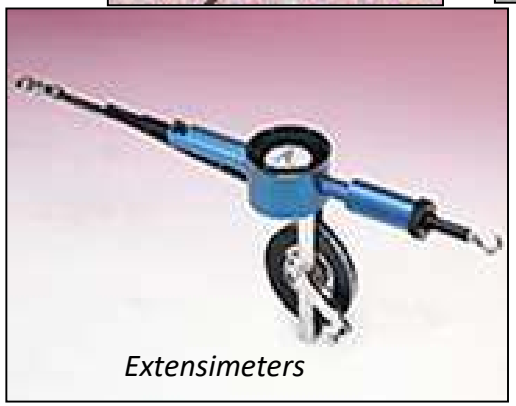
Cracks

Tilting



cracks

data-logger



Extensimeters

Heavy masses monitoring

Piezometers

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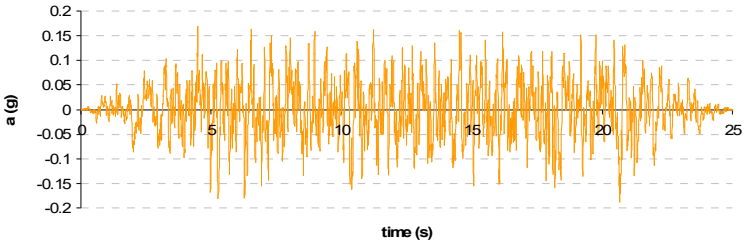
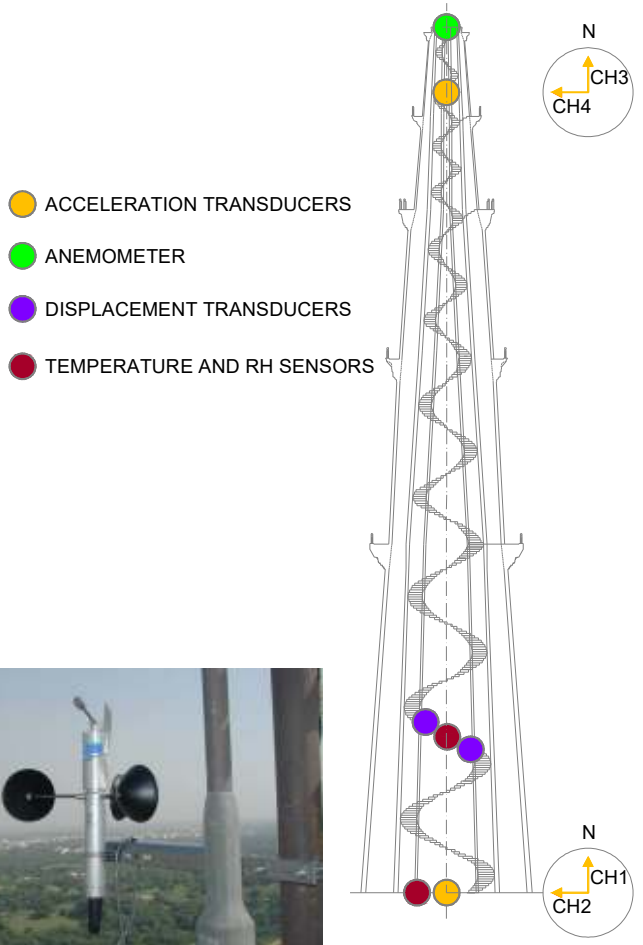
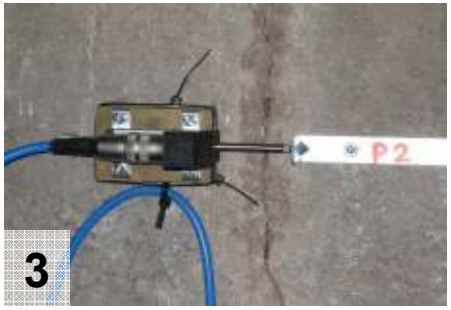
Qutb Minar – New Delhi (India)

- 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



EU-India Research Project





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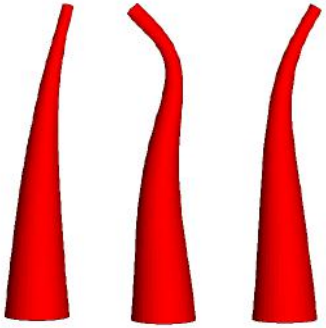
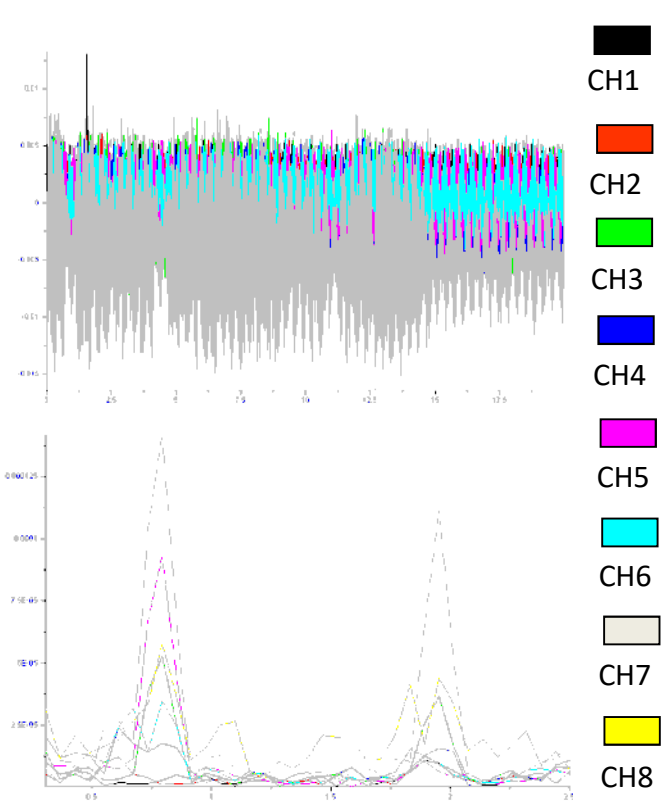
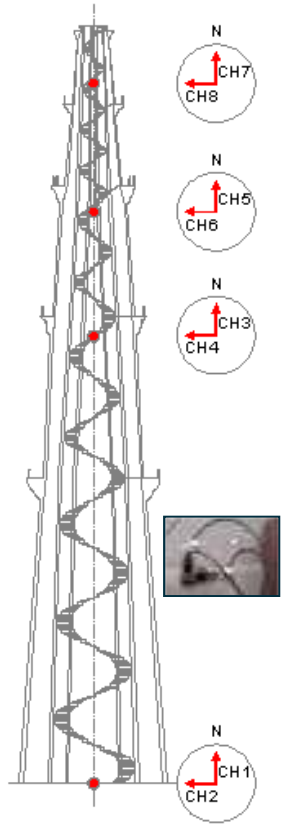
Example of a dynamic monitoring system: Qutb Minar – New Delhi (India)

Where an important crack pattern is detected and its progressive growth is suspected due to soil settlements, temperature variations or to excessive loads, the measure of displacements in the structure as function of time has to be collected.







Pakistani seismic event:

- time history recorded by the monitoring system – 09:29:20, 8th Oct /2005 CPU time
- **Fourier transform**
- positioning of the accelerometers in the Qutub Minar

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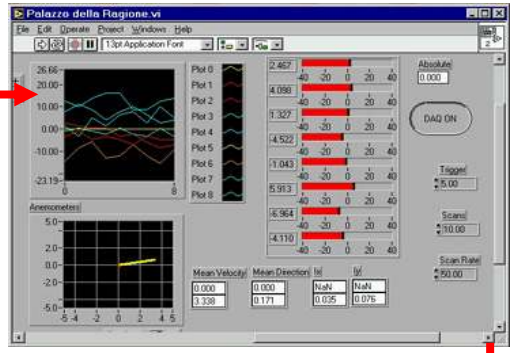
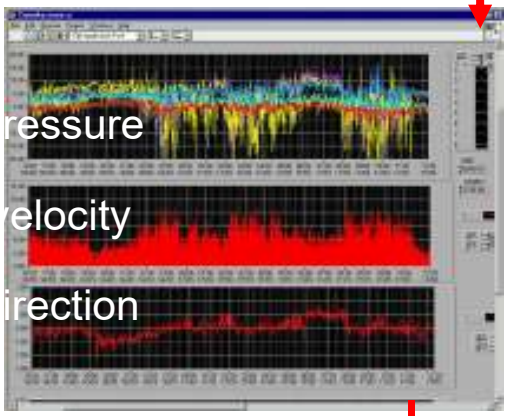
Palazzo della Ragione (Padua, XIII-XV c.)

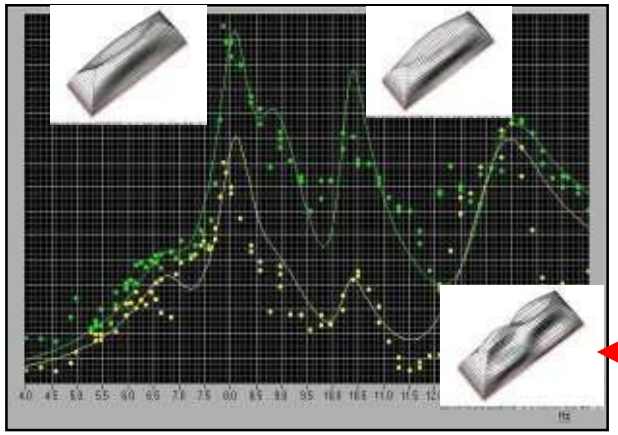
Idea:
- wind effects monitoring
- stepped sine test
- FE modeling
- modal identification
- www data management



Data acquisition



Modal analysis



www database

Web monitoring home page

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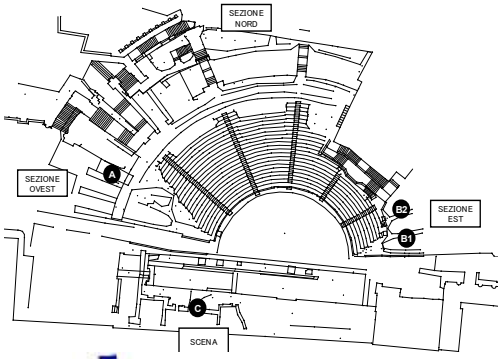
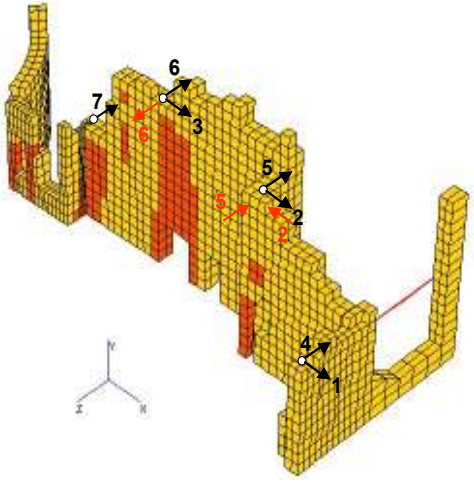
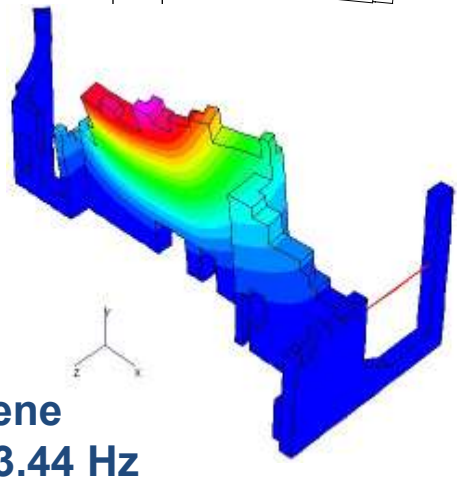
Roman Theatre (Verona)

- **shock test**
- **stepped sine test**
- **modal identification**

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







Scene
f_1=3.44 Hz

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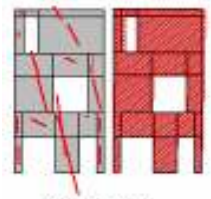
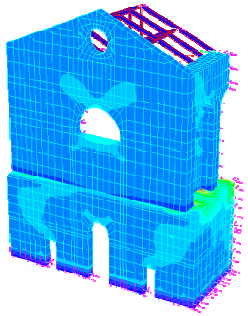
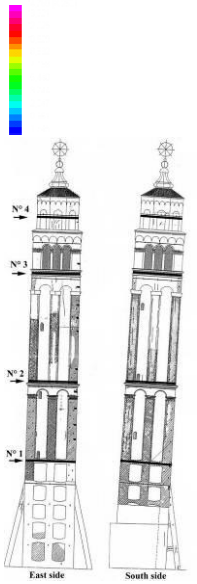
Structural modelling and seismic analysis methods

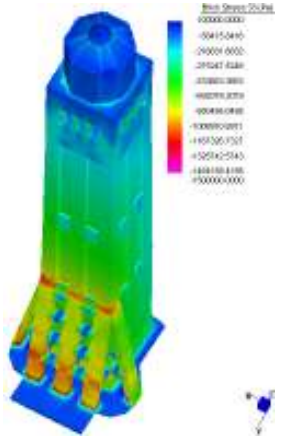
For existing masonry buildings it is possible to consider **various analysis methods**, according to the considered **appropriate model** which describe the structure and its seismic behaviour.
It is possible to consider:

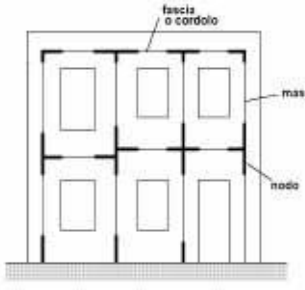
- **Macro-elements models**
- **Equivalent frame models**
- **Finite elements models**

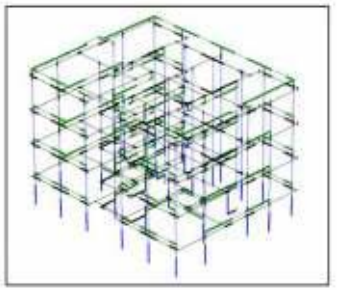












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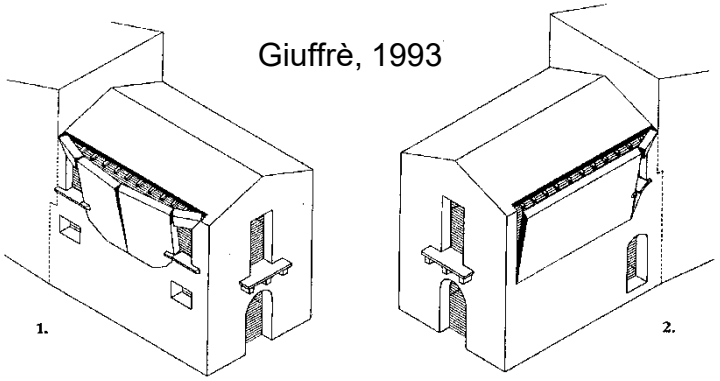
Structural modelling and seismic analysis methods

The **effective response of an existing masonry building to horizontal actions** can be hardly defined, in the majority of cases, by just considering the global behaviour of the structure

Main causes:

- Lack of connection between walls
- Lack of connection between walls and floors
- Reduced in plane stiffness of floors
- Masonry composition
- Existing crack pattern



Giuffrè, 1993

Salò-Garda lake
earthquake (24/11/2004)

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VERONA SHM NETWORK

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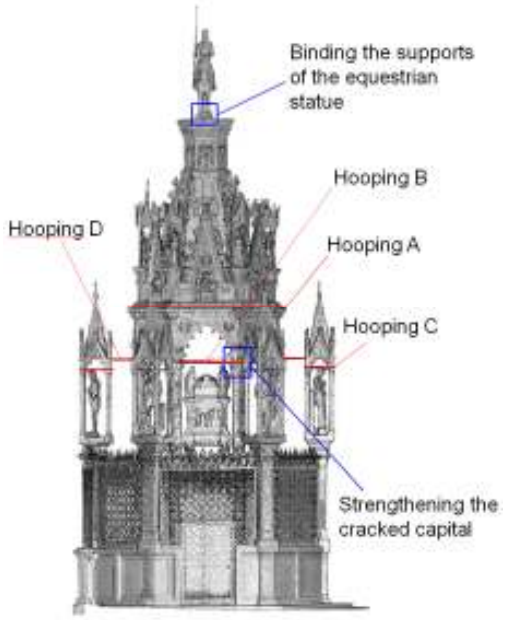
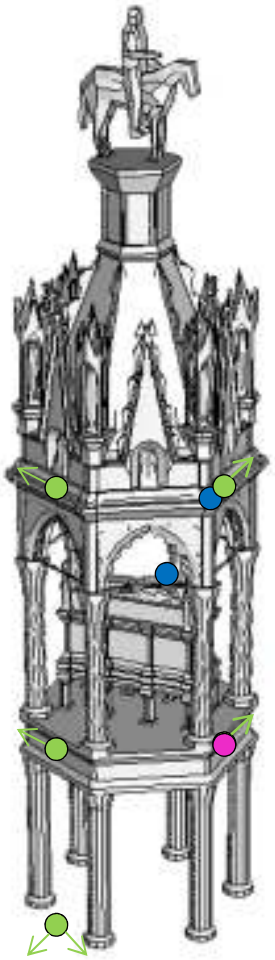
SHM NETWORK: CANSIGNORIO STONE TOMB





DYNAMIC MONITORING

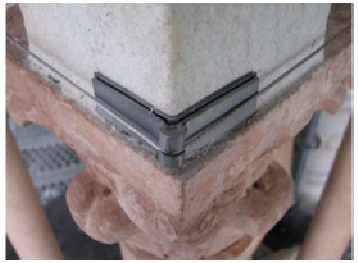
4 SINGLE-AXIS ACCELEROMETERS

STATIC MONITORING

2 DISPLACEMENT TRANSDUCERS

ENVIRONMENTAL MONITORING

1 TEMPERATURE/RH



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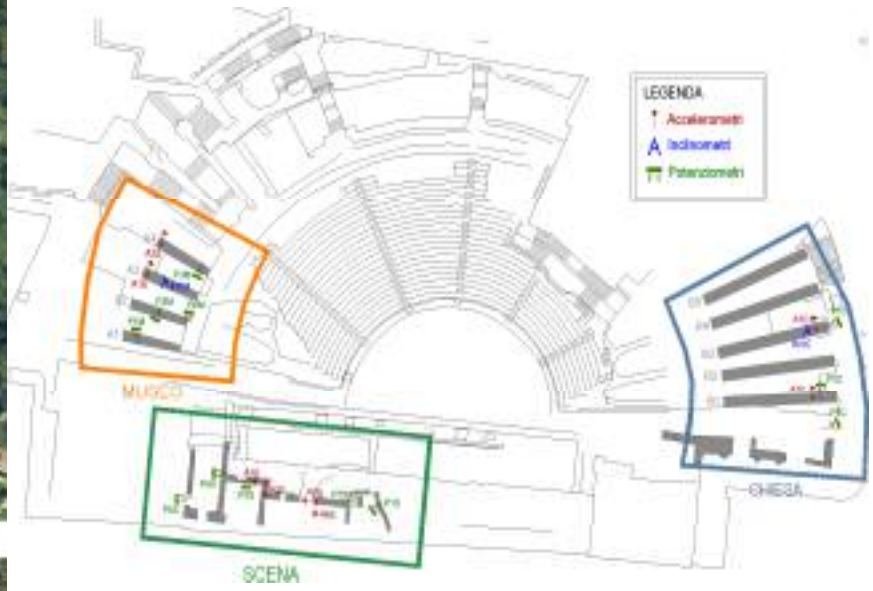
SHM NETWORK: ROMAN THEATER



3 SISTEMI INDIPENDENTI

TEATRO - FIUME	
Unità acquisizione	1
Accelerometri	4
Potenziometri	4

TEATRO - CHIESA	
Unità acquisizione	1
Accelerometri	2
Potenziometri	3
Temperatura/Umidità	1
Inclinometro	1

TEATRO - MUSEO	
Unità acquisizione	1
Accelerometri	4
Potenziometri	4
Temperatura/Umidità	1
Inclinometro	1

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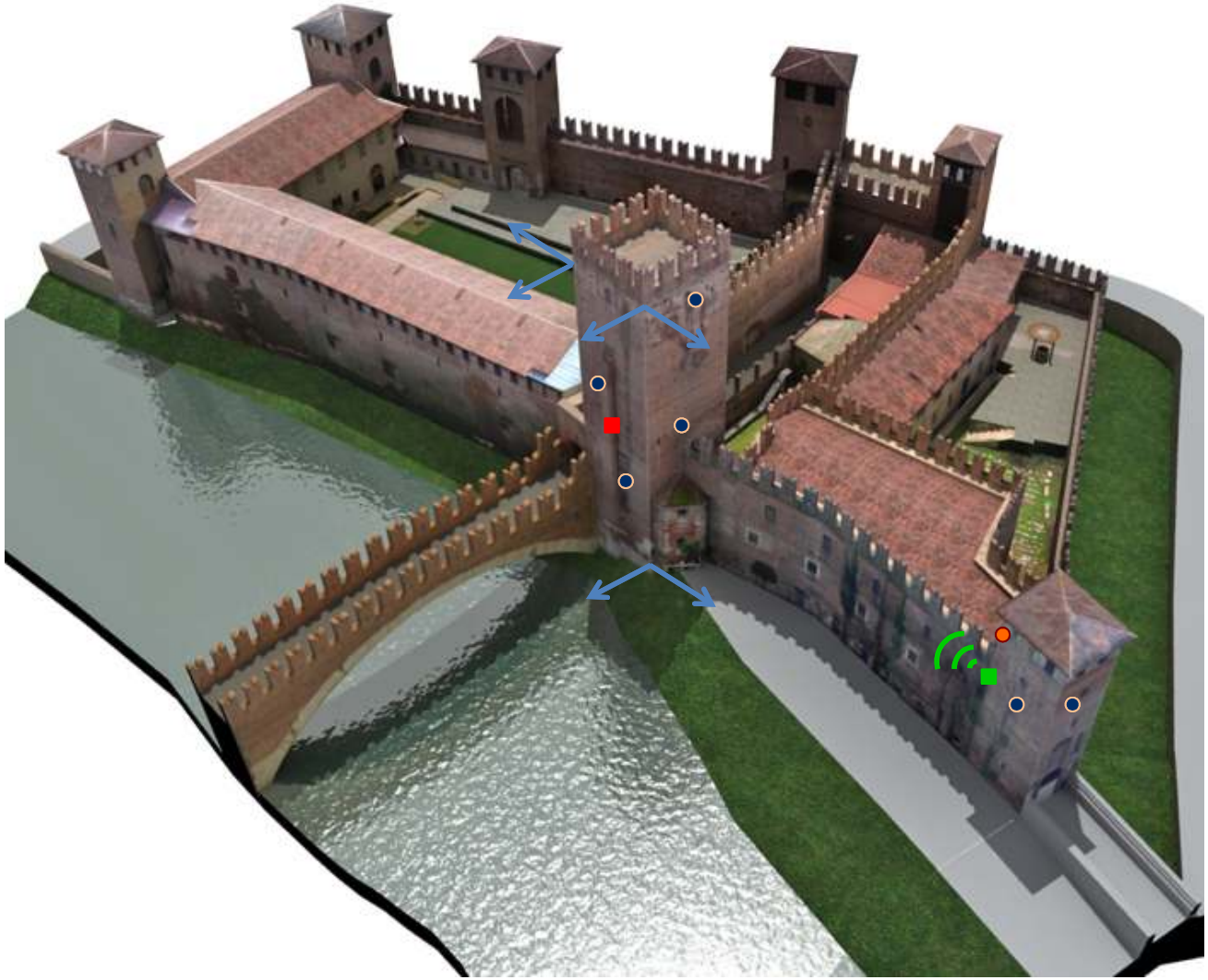
SHM NETWORK: CASTELVECCHIO



MONITORING SYSTEM

- 6 DISPLACEMENT TRANDUCERS
- 1 TEMPERATURE/RELATIVE HUMIDITY SENSOR
- 6 ACCELEROMETERS
- 1 MASTER
- 1 WIRELESS SENSORS NODE

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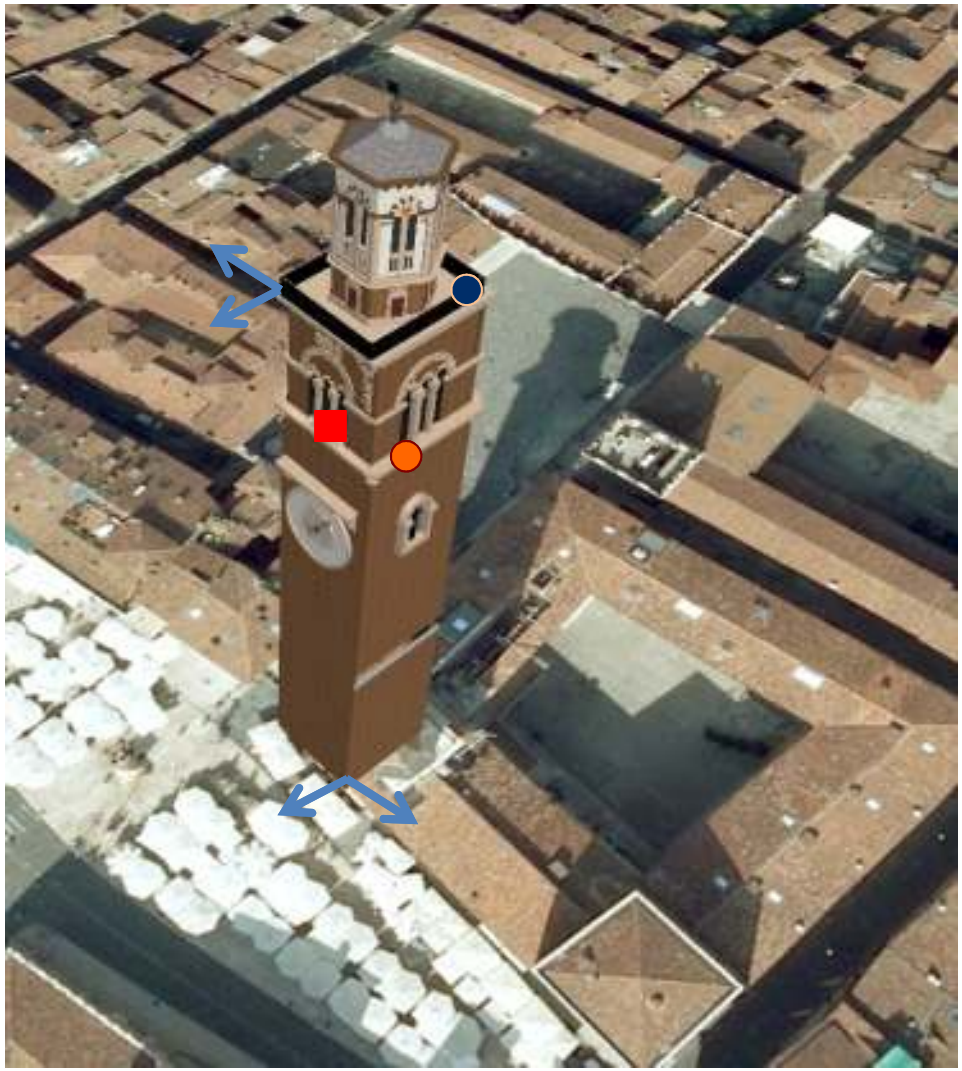
SHM NETWORK: LAMBERTI TOWER



MONITORING SYSTEM

- 1 ANEMOMETER
- 1 TEMPERATURE/RELATIVE HUMIDITY SENSOR
- 4 ACCELEROMETERS
- 1 MASTER

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Assessment and analysis of Cultural Heritage: CHURCHES




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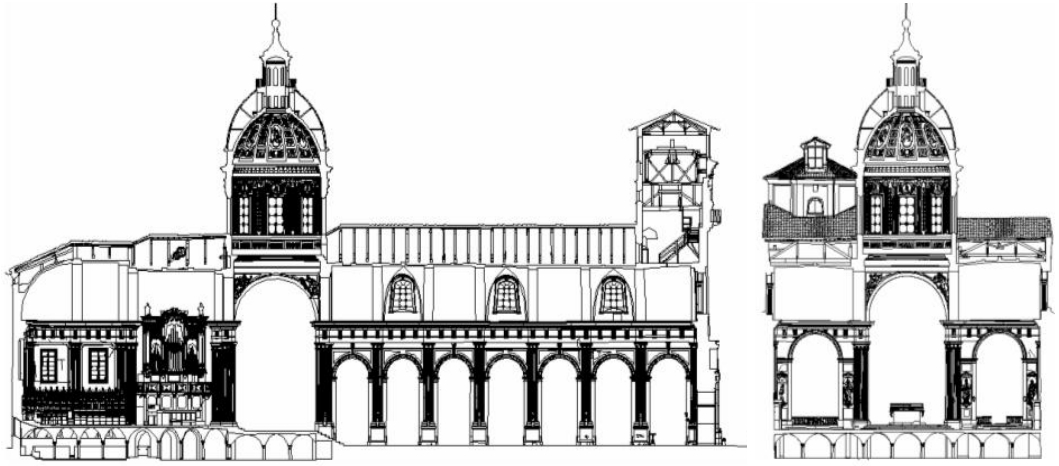
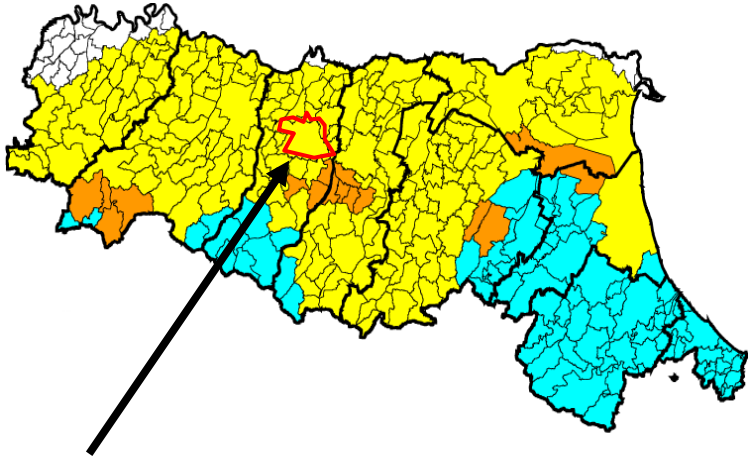
THE CATHEDRAL OF REGGIO EMILIA (Italy)



The length of the church is 77,40 m, the width is 33,80 m, the span of the main nave is 10,15 m, the span of the two lateral naves is 6,50 m. The maximum height is reached at the top of the dome, with 44,60 m; the height of the front lantern is 33,80 m and the height of the roof above the central nave is 22,25 m.

The seismicity of the area is well documented: medium-moderate seismic events are typical of the region.
In the last centuries, the earthquakes that struck the Reggio Emilia area never exceeded the VIII degree on the MCS scale. In particular, the principal seismic events recorded happened in 1465 (VI-VII), in 1547 (VIII) in 1996 (VII MCS - 6.1 Richter) and in 2000 (VI-VII MCS - 5.4-6.1 Richter).
Following the earthquake of 1832 the reconstruction of the wall of the façade lantern was necessary. The last significant seismic sequence appeared in 1996 and 2000, causing detachment of plaster and opening of fissures.



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THE CATHEDRAL OF REGGIO EMILIA (Italy)

Roman mosaics under the crypt

Main façade

Main nave

The dome (view from the bottom

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THE CATHEDRAL OF REGGIO EMILIA (Italy)

The structures of the Cathedral are generally composed by clay brickwork masonry. The diversified constructive phases comported the use of different materials, and some structural elements or parts (e.g. Romanesque pillars, lower façade veneers) are made of stone.

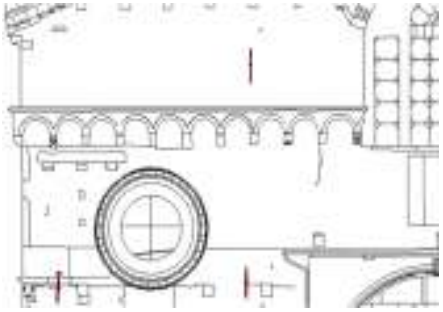




The façade presents towards the church square a rough and heterogeneous external aspect.



The masonry walls of the clerestory present a strongly composite aspect, being subject to past interventions comporting remarkable size windows closing.




The Cathedral is generally provided with connective systems (metallic tie-beams), present in the central nave and in the aisles, in the arches connecting the dome sustaining pillars, in the transept, in the apses, in the dome lantern and in façade.

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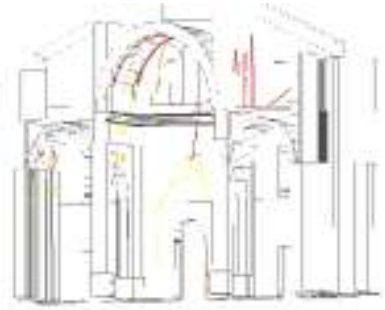
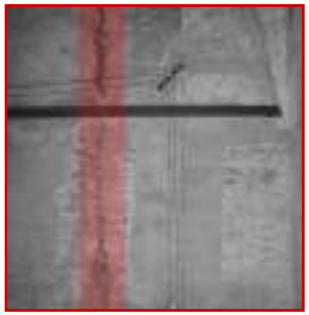
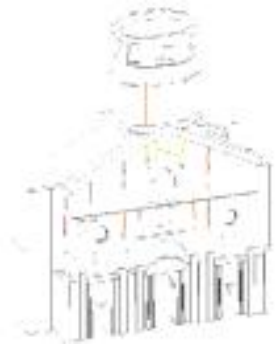
THE CATHEDRAL OF REGGIO EMILIA (Italy)

The present damage pattern shown by the Cathedral is highly indicative of the structural response of the building, and denounces the areas manifesting higher seismic vulnerability.

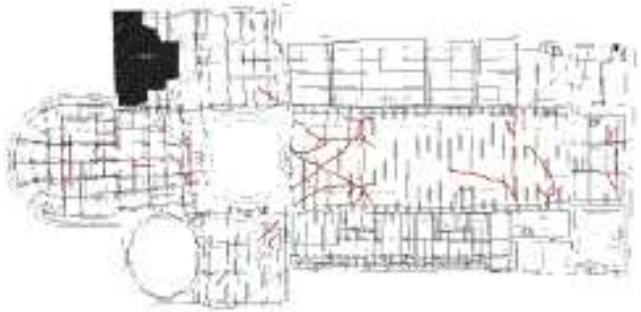
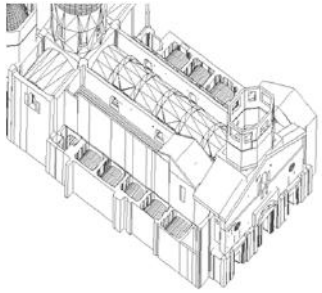









Façade


Nave vaults

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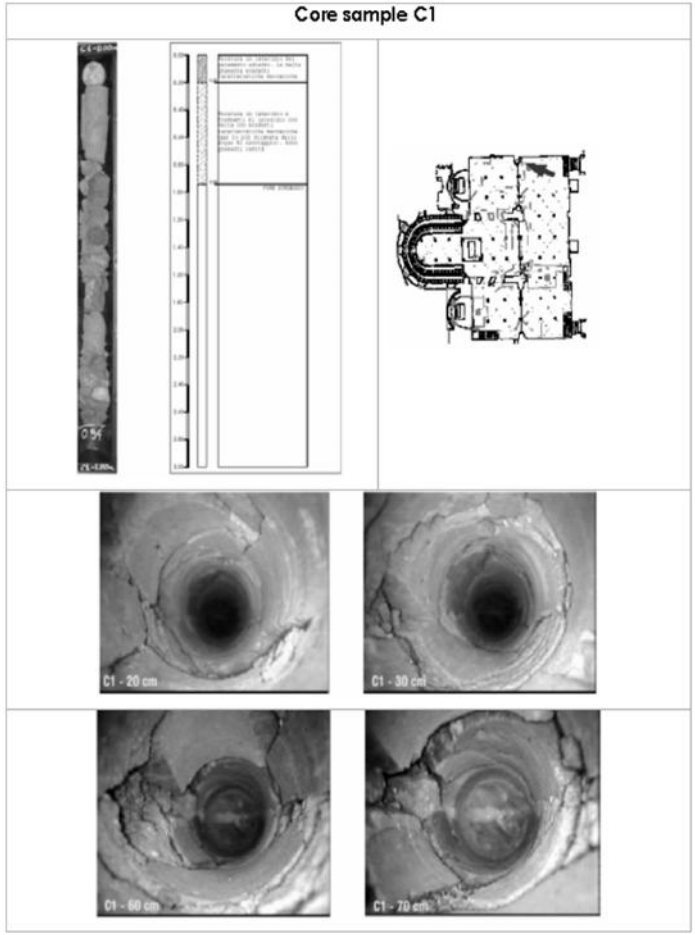
THE CATHEDRAL OF REGGIO EMILIA (Italy)

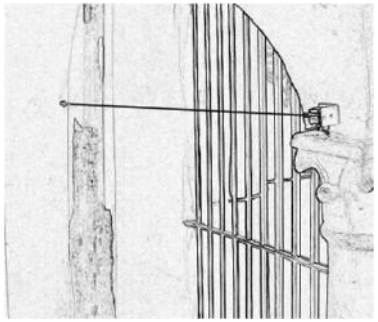
EXPERIMENTAL INVESTIGATIONS

- Core samples;
- endoscopy.

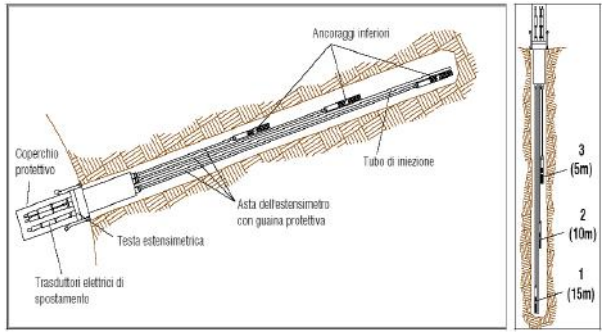


Static monitoring:

- relative displacements between the vertical structures;
- eventual variations in the openings on the main cracks;
- settlements of the foundation soils below the crypt's two main pillars;
- air temperature control.

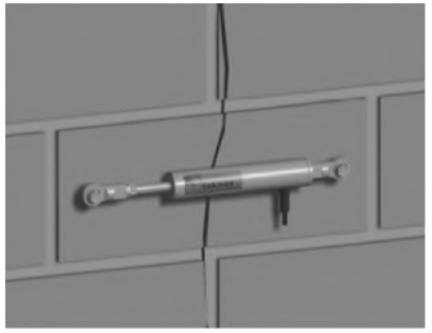


Extensometer cables



Multi-base extensometer

Electrical extensometer



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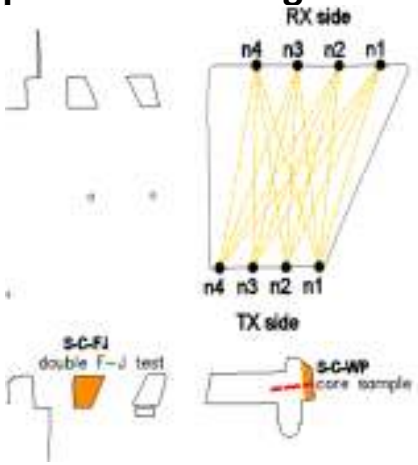
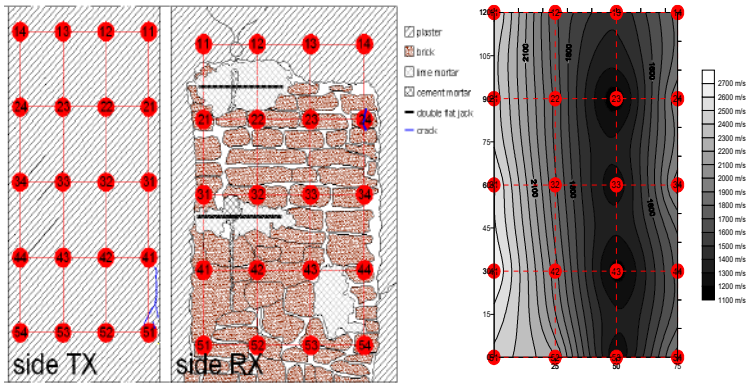
THE CATHEDRAL OF REGGIO EMILIA (Italy)

EXPERIMENTAL INVESTIGATIONS

Several investigation procedures have been implemented; the attempt is to use non destructive techniques (NDT) as much as possible. With the exception of few MDT investigation techniques that can provide information about quantitative characteristics of materials and structural elements, most of the procedures can give only qualitative results .



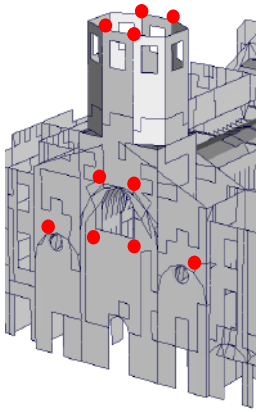
Sonic testing

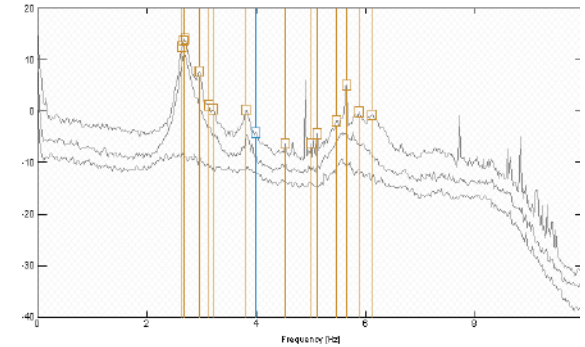


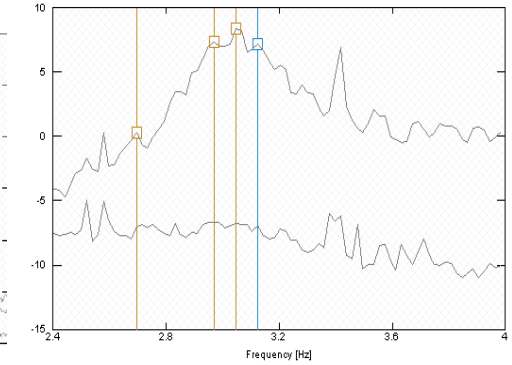
Dynamic testing

dome

façade







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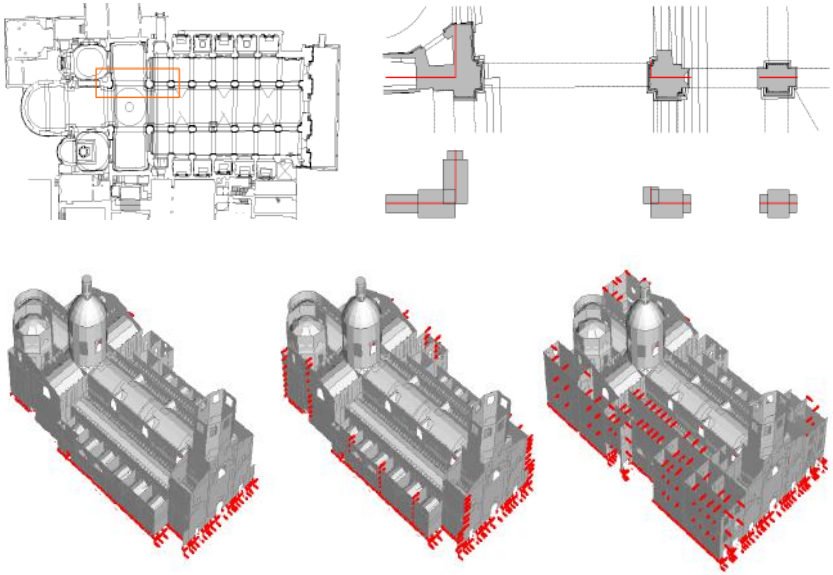
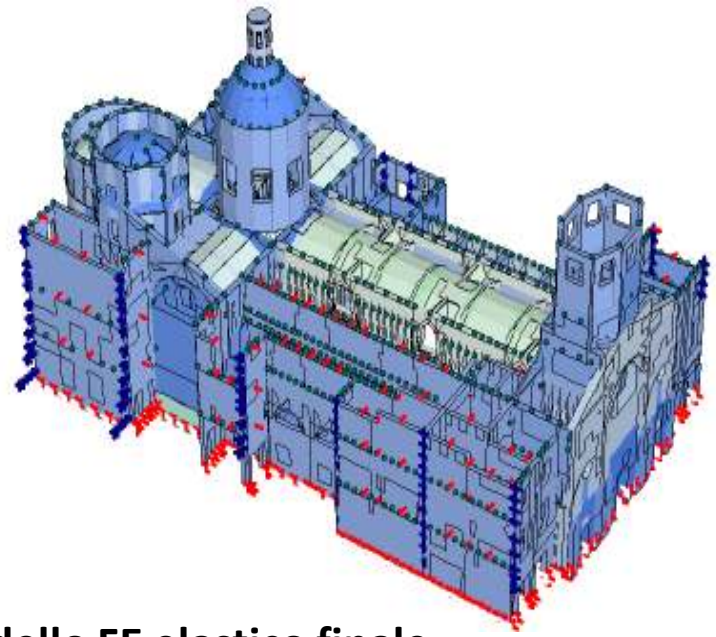
THE CATHEDRAL OF REGGIO EMILIA (Italy)

The numerical simulation of Reggio Emilia Cathedral considered in the first instance several linear elastic Finite Element models. All of them represented the global Cathedral's structure, since the overall dynamic response can not be evaluated by considering partial models.
From the first model, considering the structures of the Cathedral as disconnected from the other adjacent buildings, several refinement were introduced, subsequently applying lateral constraints and then adding portions of the surrounding structures: the final model can be considered acceptable for dynamic identification purposes.



a) **b)** **c)**



Modello FE elastico finale

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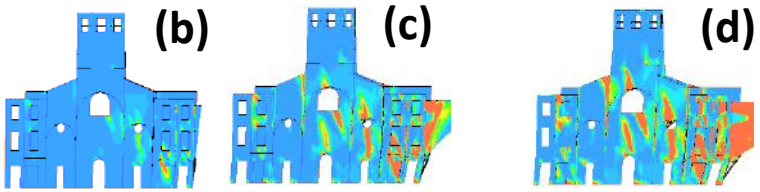
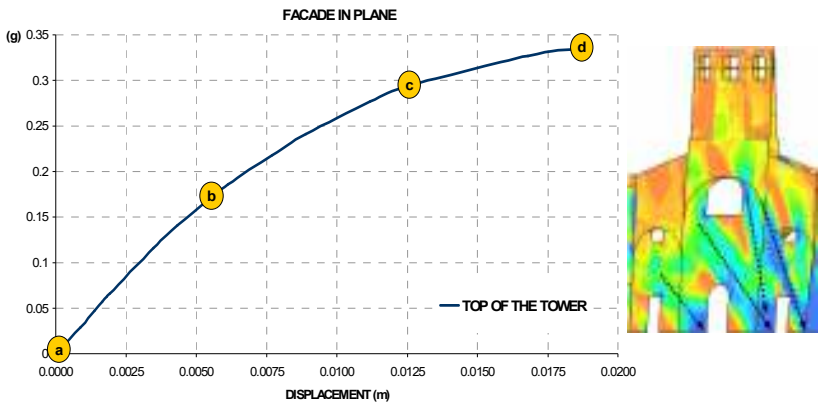
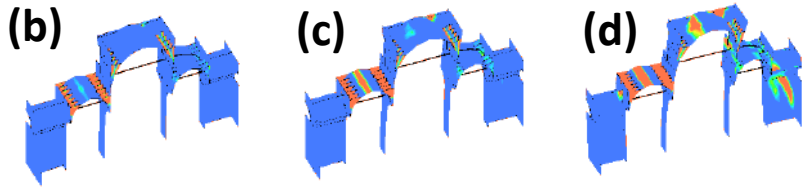
THE CATHEDRAL OF REGGIO EMILIA (Italy)

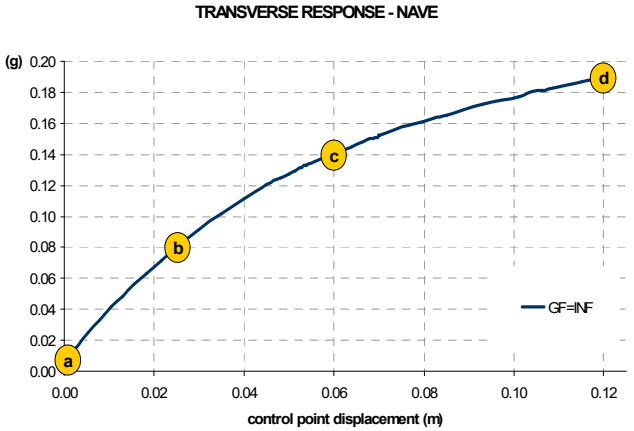
MODEL FT



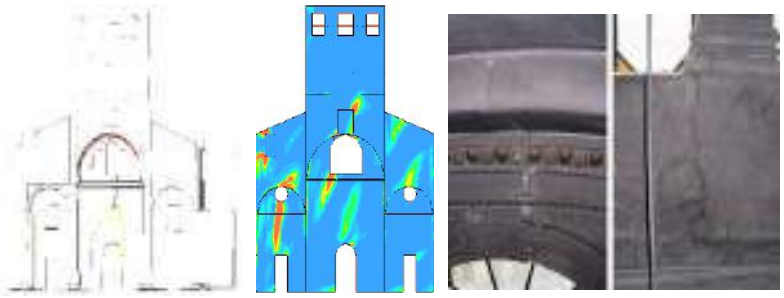


MODEL NT

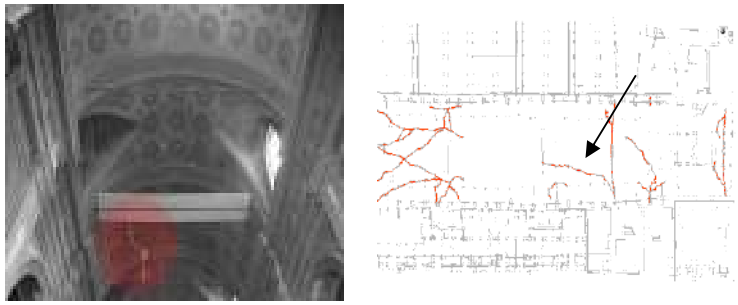




Damage identification



Damage identification



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THE CATHEDRAL OF REGGIO EMILIA (Italy)

General interventions were carried out by using traditional techniques, devoted to give back to the structure its integrity and continuity, to reestablish connections between structural elements and to substitute damaged structural elements. The typology of these interventions are:

- **the traditional "scuci-cuci" (substitution of damaged elements with new ones);**
- **mortar repointing and grout injections, especially in the cracked vaulted system.**

Other strengthening interventions were carried out at the roof level:

- **restoration of the wooden truss structure;**
- **reestablishment of the connections between wooden structural elements.**

Roof wooden trusses: (a) metallic "T" shaped connection elements; (b) substitution of the old wooden trusses of the left nave with new elements, with stainless steel tie beams. Roof level: (c) a "scuci-cuci" intervention.

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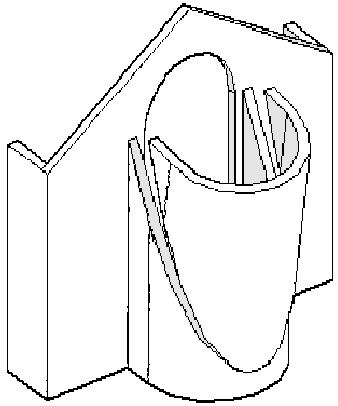
THE CATHEDRAL OF REGGIO EMILIA (Italy)

Specific strengthening interventions are conceived to improve the seismic behavior of the portions of the complex manifesting higher vulnerability rather than to modify the overall structural response of the structure:

- **walls of the lateral apses;**
- **lantern at the top of the dome;**
- **vaults of the central apse;**
- **vaults of the main nave;**
- **façade area.**

Lateral apses



Lantern

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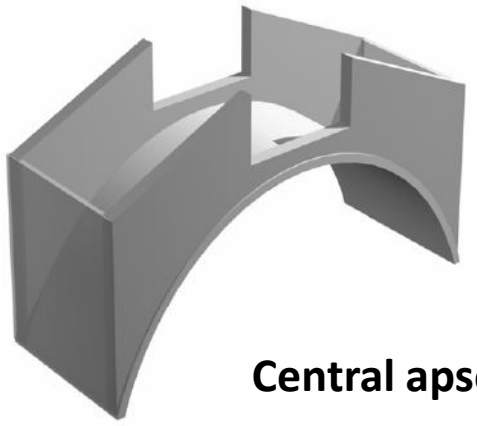
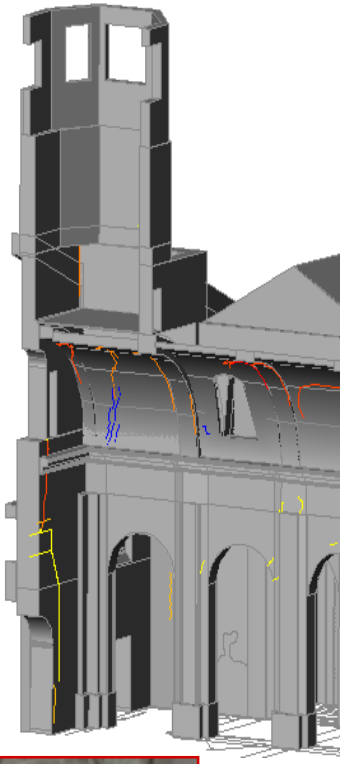
THE CATHEDRAL OF REGGIO EMILIA (Italy)



Central apses

Vaults of the main nave

Façade



TRA GEOLOGIA E GEOFISICA - XV WORKSHOP DI GEOFISICA
IL RUOLO DELLA CONOSCENZA NELLE VALUTAZIONI DI
SICUREZZA STRUTTURALE DEL PATRIMONIO ARCHITETTONICO
6-7 Dicembre, Rovereto

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Assessment and analysis of Cultural Heritage: TOWERS




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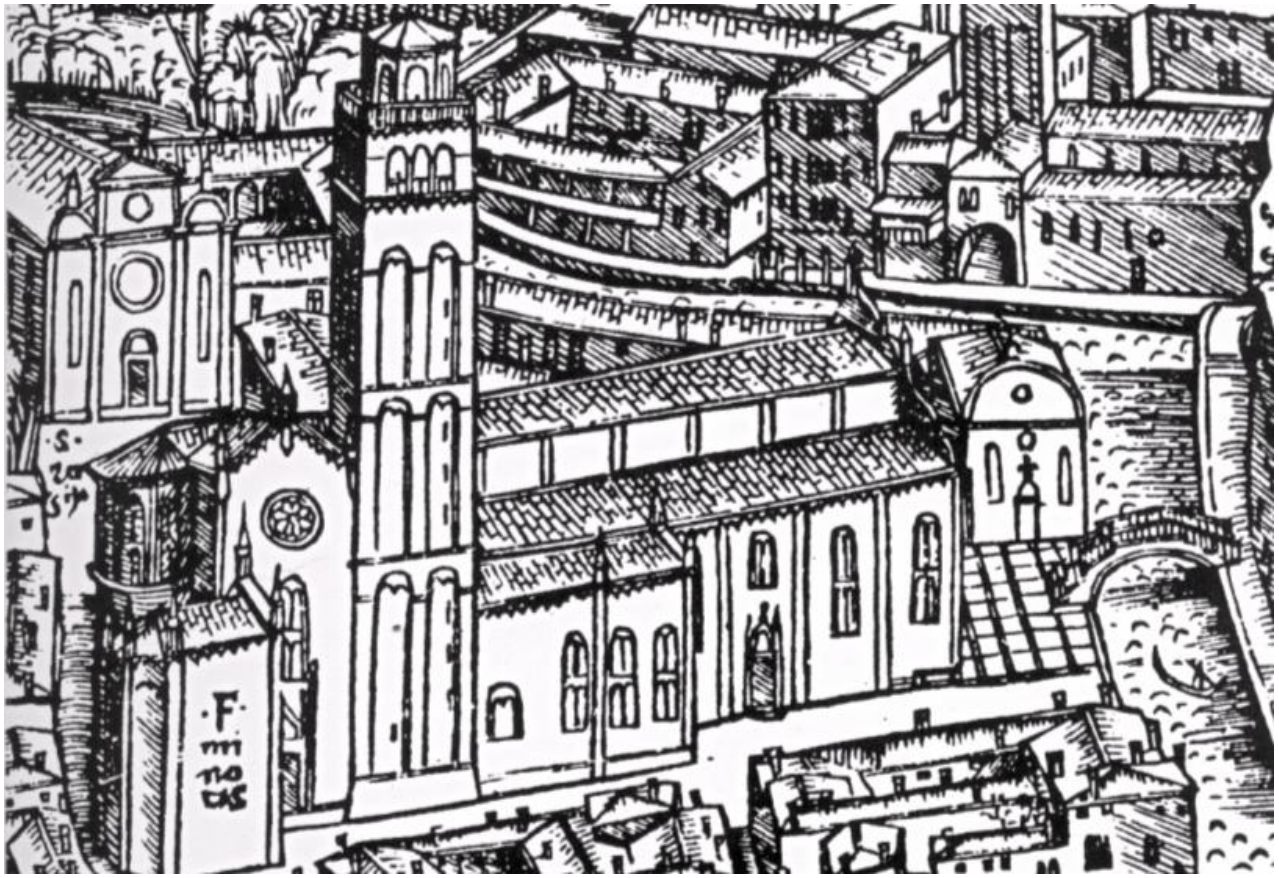
Investigation and monitoring for the design of a strengthening intervention on the Frari Basilica – Venice



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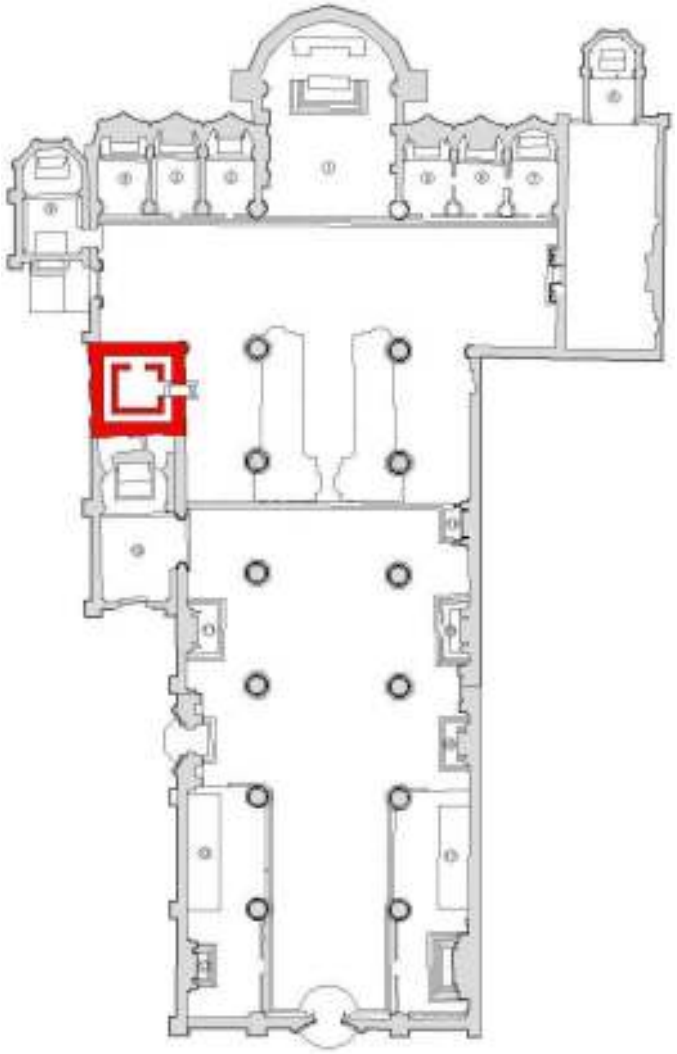
Basilica dei Frari (Venice)



1st PHASE (1361-1396): CONSTRUCTION OF THE BELL TOWER

The tower, built next to the church between 1361 and 1396, was originally conceived as a completely independent structure

It is 65 m tall, has a square base of about 9.5m and shows a double pipe brick masonry structure, supporting the internal staircase.

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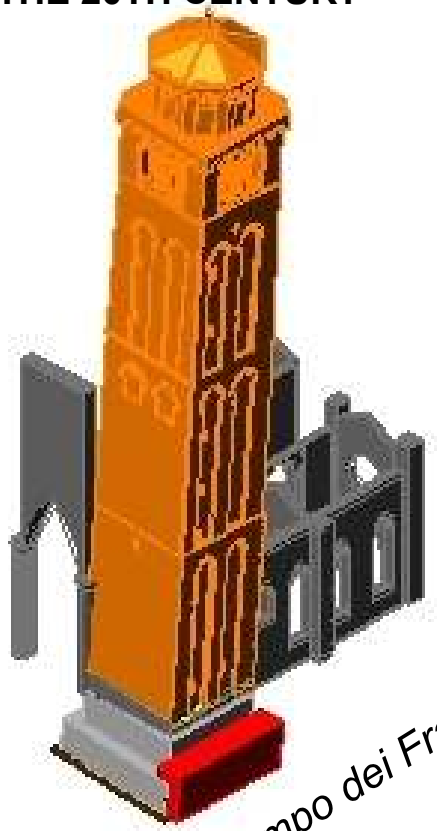
Basilica dei Frari (Venice)

1902: COLLAPSE OF THE BELL TOWER OF THE ST. MARK BASILICA

STRUCTURAL INTERVENTION IN THE 20TH CENTURY



Campo dei Frari

Monitoring of the venetian towers, including the "Frari" bell tower

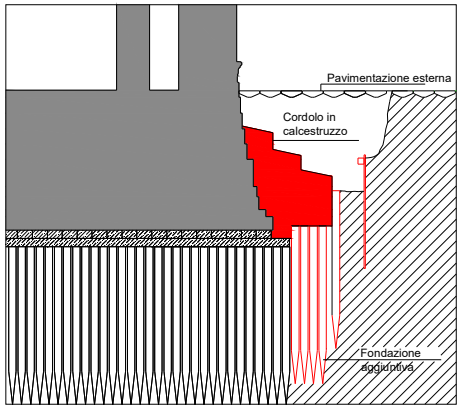
RESULTS OF THE MONITORING:

- **DIFFERENTIAL SETTLEMENT BETWEEN CHURCH AND TOWER: 30 cm**
- **OUT-OF-PLUMB: 76cm ON A HEIGHT OF 42.5m**

1903: Intervention on tower's foundations

CONSEQUENCES:

- **Reverse of tower's rotation toward the church**
- **The new structural configuration caused the formation of widespread cracks and extensive damages on structural elements of the church directly connected to the bell tower**



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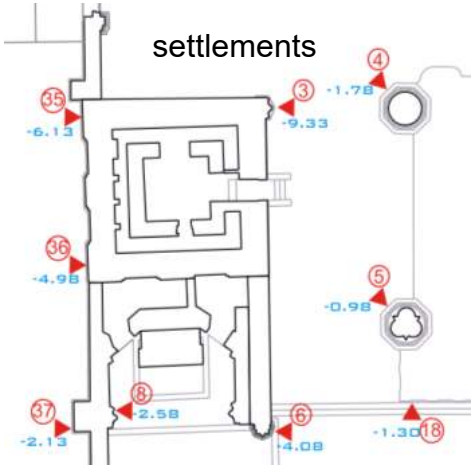

Experimental investigations and monitoring

1990
- fotogrammetric survey;
- geotechnical investigations on the foundation's soil;
- endoscopies;
- single and double flat-jack tests on the masonry elevation structures;
- sonic tests on steel ties;
- monitoring of the main cracks, by means of extensometers;
- positioning of clinometers (detection of rotations of the bell-tower).

⇓

discrete stability of the tower structure; out of plumb of about 0.8 m

2000
- worrying sign of structural deterioration (new crack patterns; widening of already existing fissures; falling of small portions of plaster and bricks from the vaults).
- survey of differential settlements in different points of the complex

⇓

disconnectedness of the stone ashlars of the aisle arch adjacent to the bell-tower (differential settlement of the arch supports) → **installation of a timber prop**

average subsidence of the **structure of the church:** **- 10 ÷ - 20 mm**
average subsidence of the **area of the bell-tower base:** **- 49.8 mm East corner**
- 61.3 mm South corner
- 93.3 mm West corner

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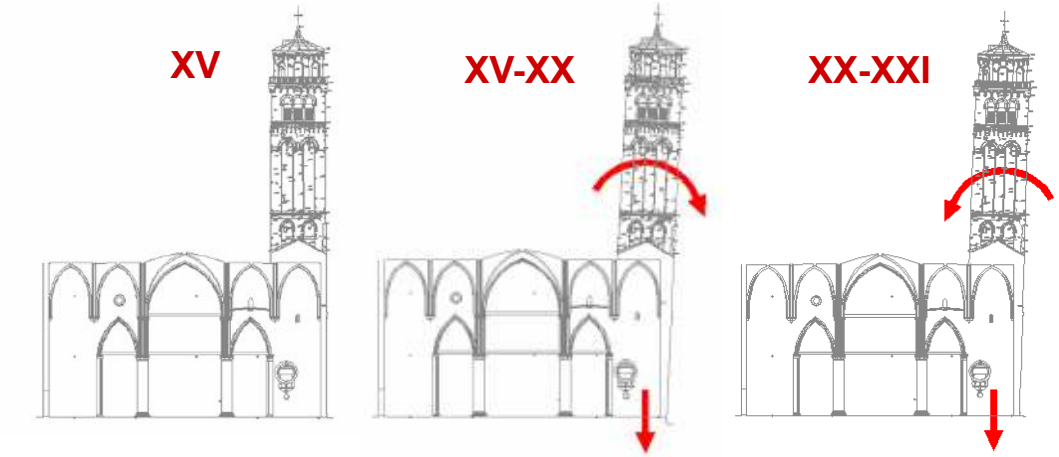
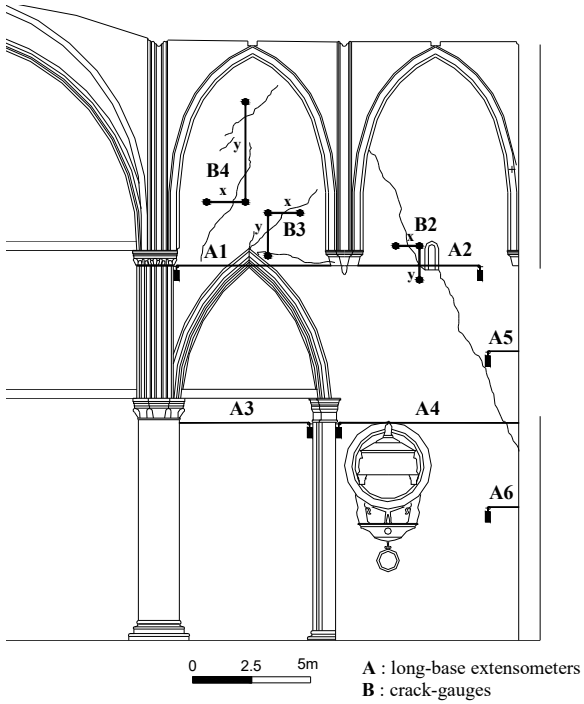


The differential settlements and the comparison between the fotogrammetric survey of 1995 and 2000, indicated that **the bell-tower is tilting in the opposite direction respect the "historical" tendency**, meaning that it is going back towards its vertical.



2001 automatic **monitoring system** (check of the deformations):

- **6 long base extensometers** relative displacements between the walls of the bell-tower and the adjacent structures of the basilica;
- **8 crack-gauges** installed on the main cracks of the South-West side of the bell-tower and of the wall above the stone arch.

⇓

the opening of the cracks is only partly caused by the settlement noticed at the foundations level

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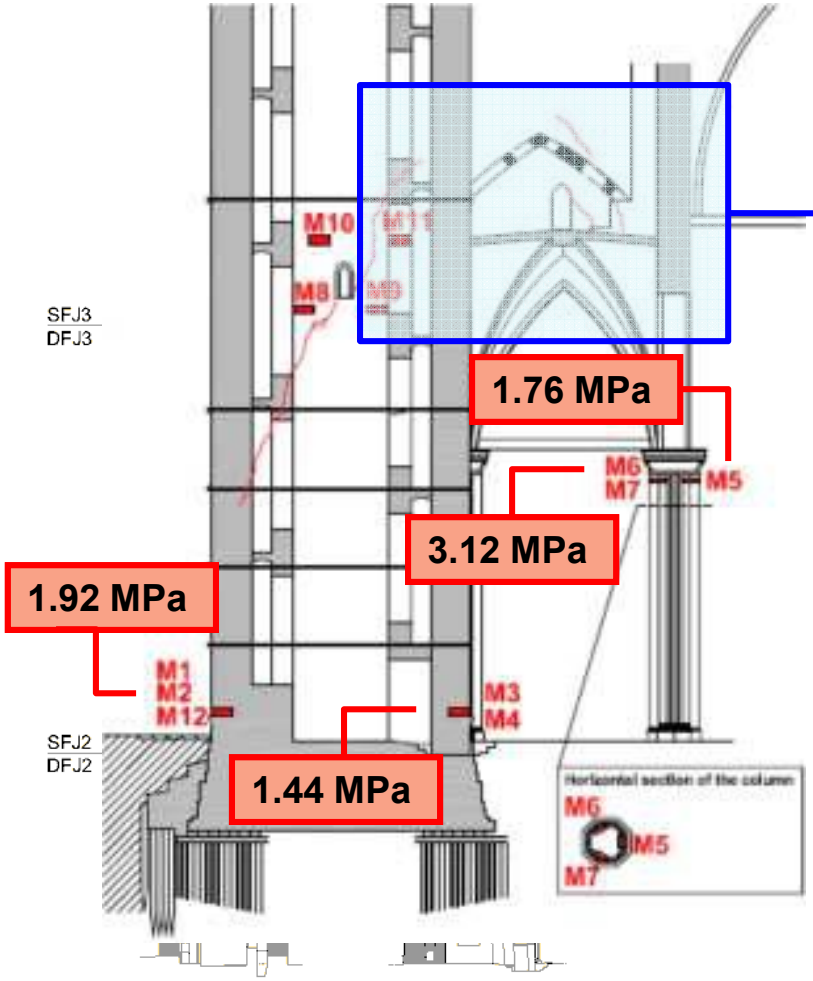
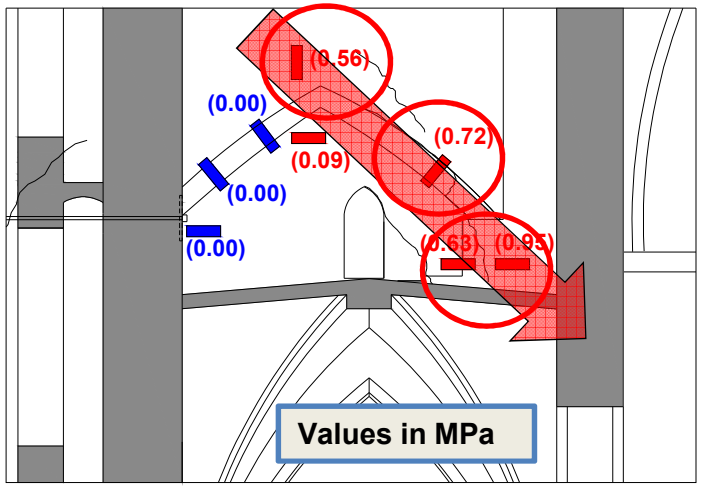
Basilica dei Frari (Venice): 2003 investigation campaigns

ANALYSIS OF THE STATE OF STRESS: FLAT JACK TESTS

Second Test Campaign



Third Test Campaign



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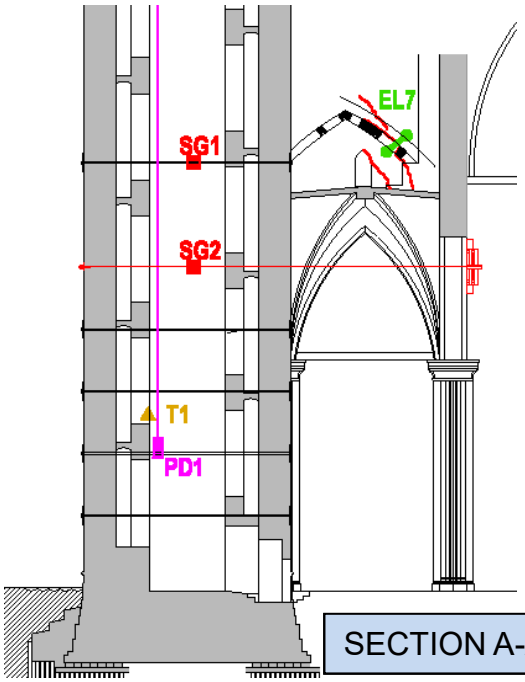
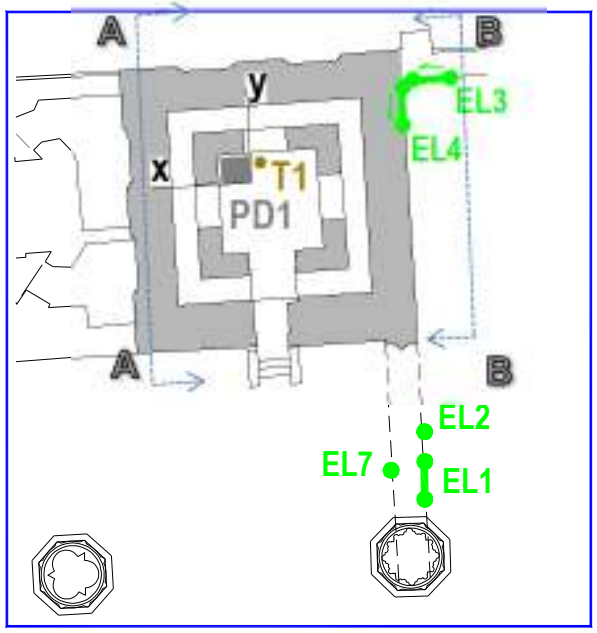
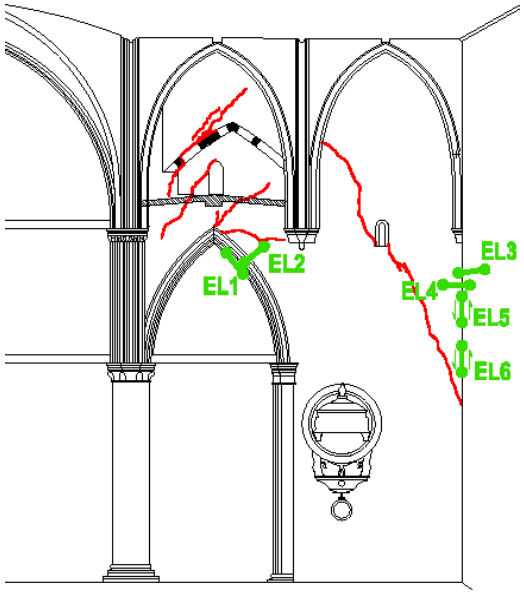
Basilica dei Frari (Venice) – 2003 extension of the automatic monitoring system

- Direct Pendulum
- Crack-gauges
- Strain Gauges
- Temperature sensors



SECTION A-A





SECTION B-B

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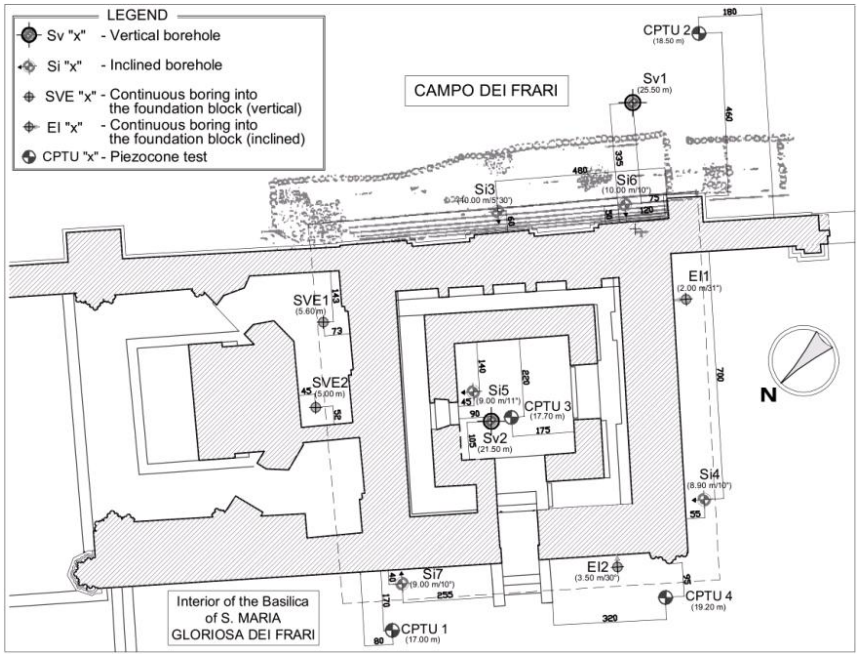
2003 extensive geotechnical investigation campaign

- analysis of the **subsoil stratigraphy and geotechnical properties**;
- exploration of the exact geometry and typology of the **foundation block**;
- definition of an accurate **geotechnical model** of the foundation finally completed;
- **in situ tests**:



- 2 **vertical boreholes**: outside the church, to a depth of 25.50 m and inside the bell-tower, to a depth of 21.50 m;
- 5 **inclined boreholes**;
- 4 continuous **borings** into the foundation block:
  - EI1 and EI2 inclined of 30°, drilled for length of 4 m and located inside the basilica;
  - SVE1 and SVE2 short vertical borings, carried out on the NE side of the bell-tower;
- 4 **static penetrometer tests** with monitoring of pore water pressure (piezocone tests – CPTU) pushed to variable depths (17.00 ÷ 19.20 m);
- **Standard Penetration Tests** (SPT), in boreholes;
- **Extractions** of soil and foundation samples.

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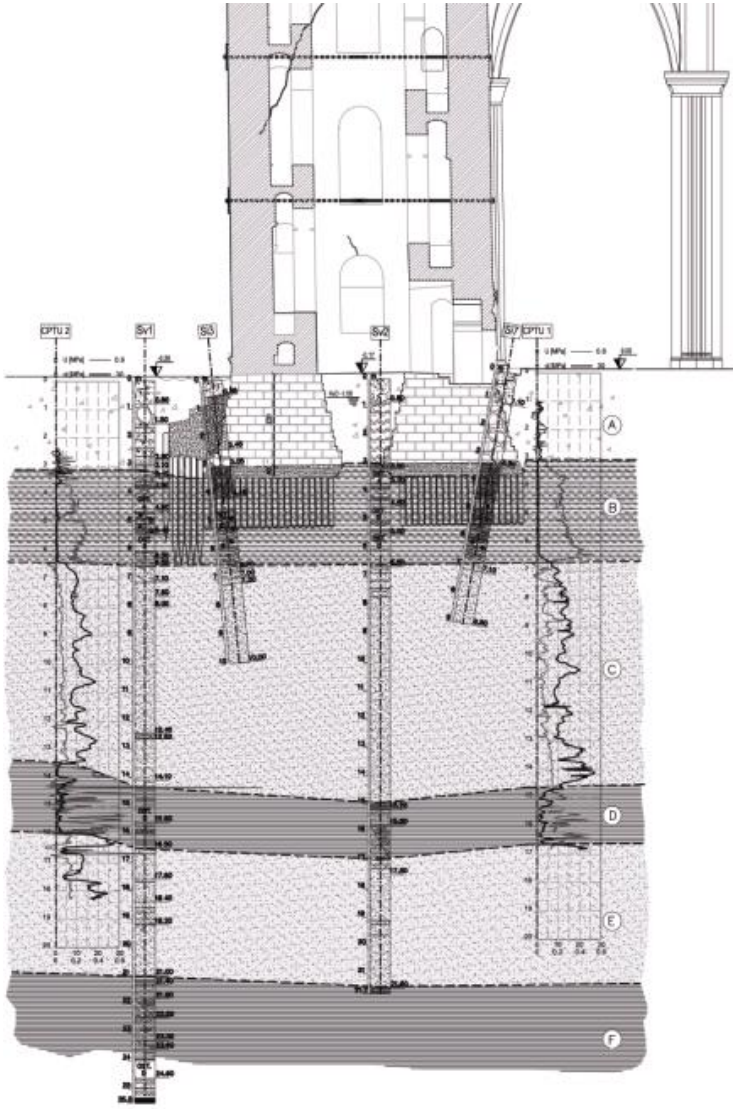
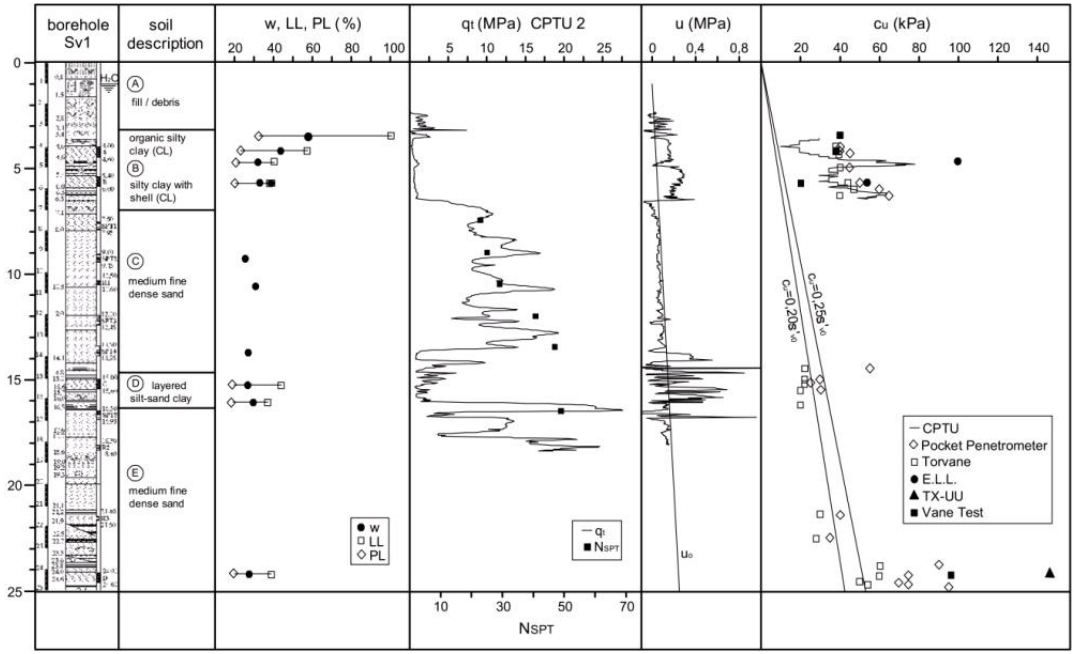
Geotechnical section and foundation geometry





Origin of continuous settlements and stability problems

Some **progressive failure of the soft silty clay layer**, squeezed between the piles end and the unit C, must be taken into account.

In addition, a **possible increasing decay of the mechanical characteristics of the wooden piles** under the foundation block could also be seen as concomitant cause.

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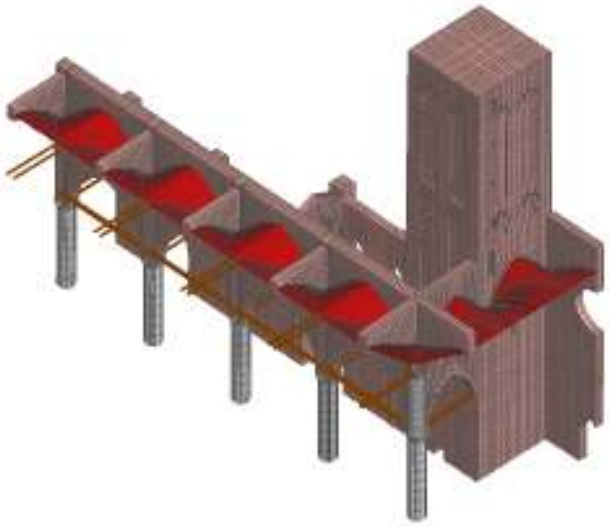

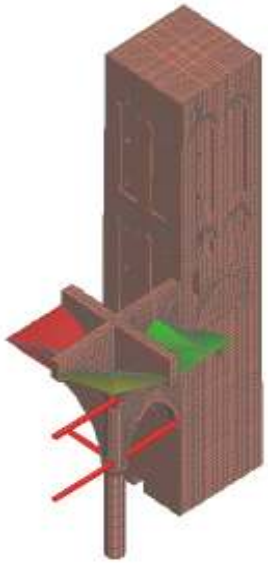

Structural modeling

The modelled portion of structure includes the **bell-tower and the adjoining parts of the church** that were mostly affected by the interaction with the tower

The only load condition considered is the **self weight**. The load corresponding to some parts of the real structure not modelled (timber structure roof of the basilica, belfry), was imposed as external forces; the crossed vaults' filling was included as surface load.

The **mechanical properties** chosen to describe the materials arise from the results of previous tests performed on the masonry structures. In particular:

- **elastic modulus** E = 3300 MPa (average of the results of double flat jack tests performed on the bell-tower masonry)
- **density** ρ = 2000 kg/m^3

The material is considered homogeneous and isotropic, and the analyses performed are linear elastic.

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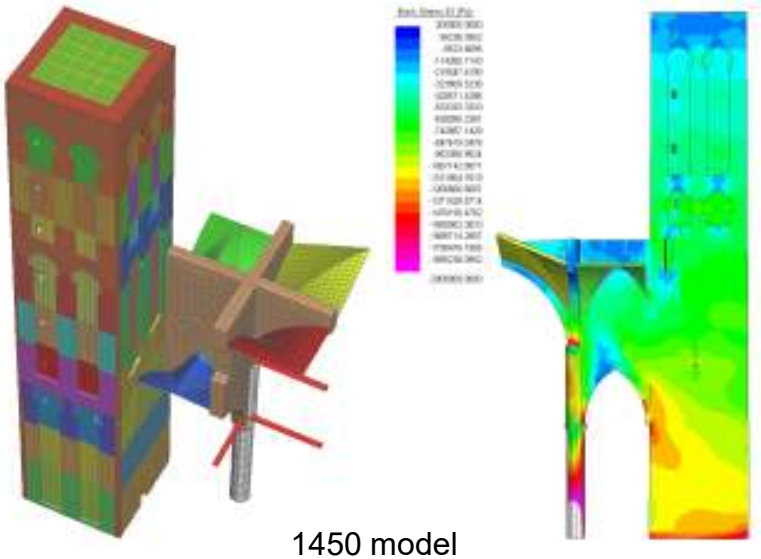
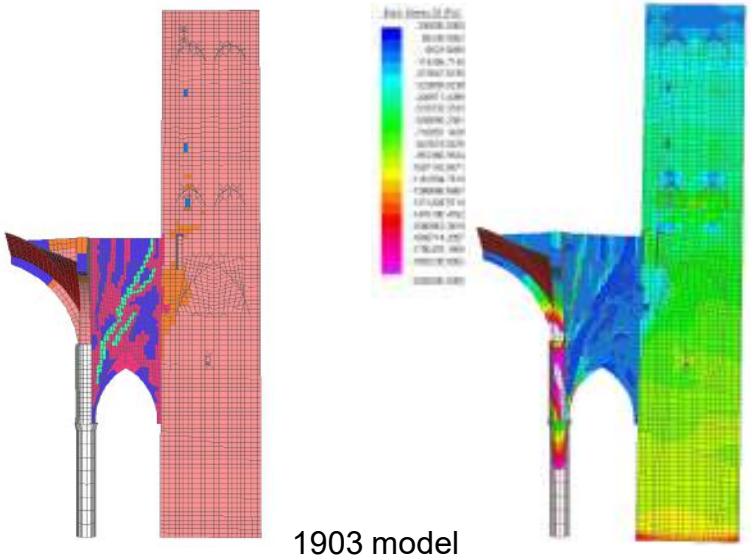


1450 model



1903 model

Two **previous models**, calibrated with the available experimental data (historical drawings, surveys, monitoring and on site tests), were analyzed before implementing the actual one, by means of imposed rotations and translations at the base of the bell-tower:

- after the construction (1450);
- before the strengthening intervention on the bell-tower (1903).

In each model, after running the analysis, a higher deformability was assigned to the elements subjected to an excessive tension respect the assumed strength of the material, in the successive analysis.

A **tensile stress concentration** appeared in the model where a **real crack pattern** is evident. The propagation of some principal cracks was followed by the subsequent iterative process.

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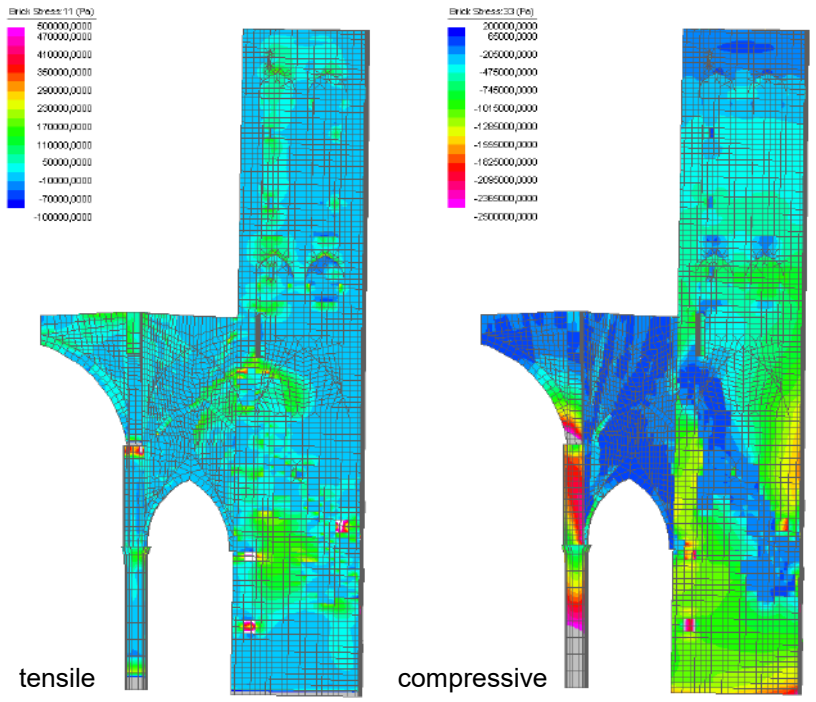
The **final model** reflects the tendency of the XX century. An “inverted” rotation was imposed to the bell-tower, with an average settlement of 84 mm.

Results:



2002 model

- preferential channels of **compressive stress** localized inside the masonry wall above the propped arch;
- high **tensile stresses** found in the same masonry wall, due to the settlements of the bell-tower → wide crack patterns and loss of shape of the stone arch;
- **high stress** found below the capital of the column → horizontal thrust determined by the movements of the bell-tower;
- **tensile stress** in correspondence of the bell-tower window opening on the transept → presence of the main fissure on the external pipe of the bell-tower.

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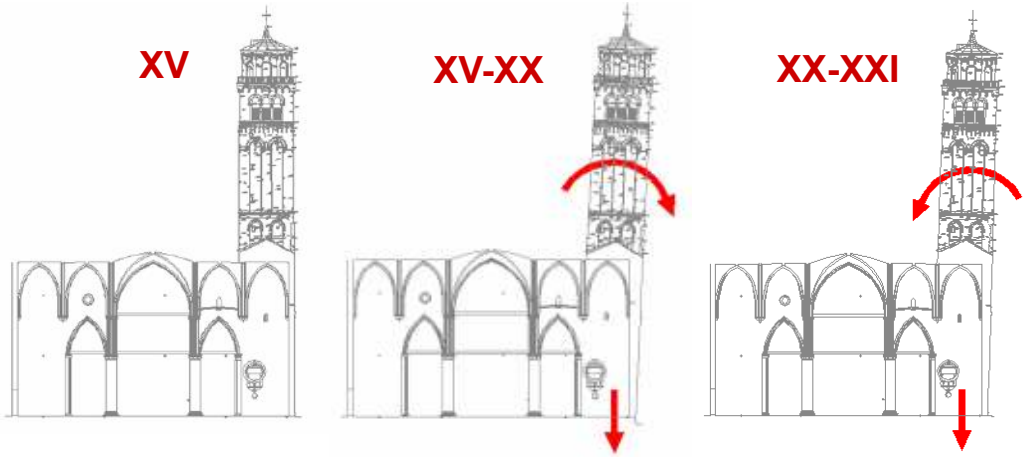

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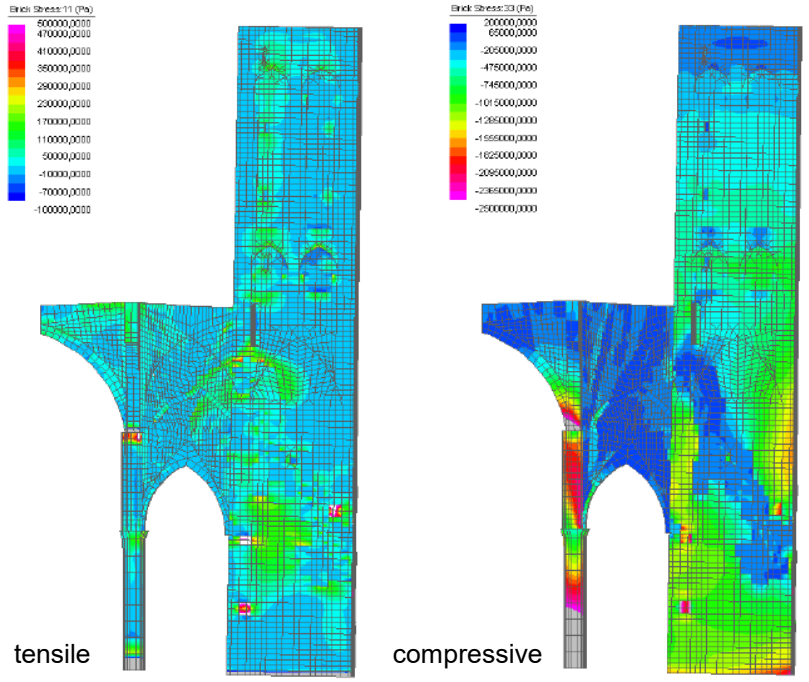

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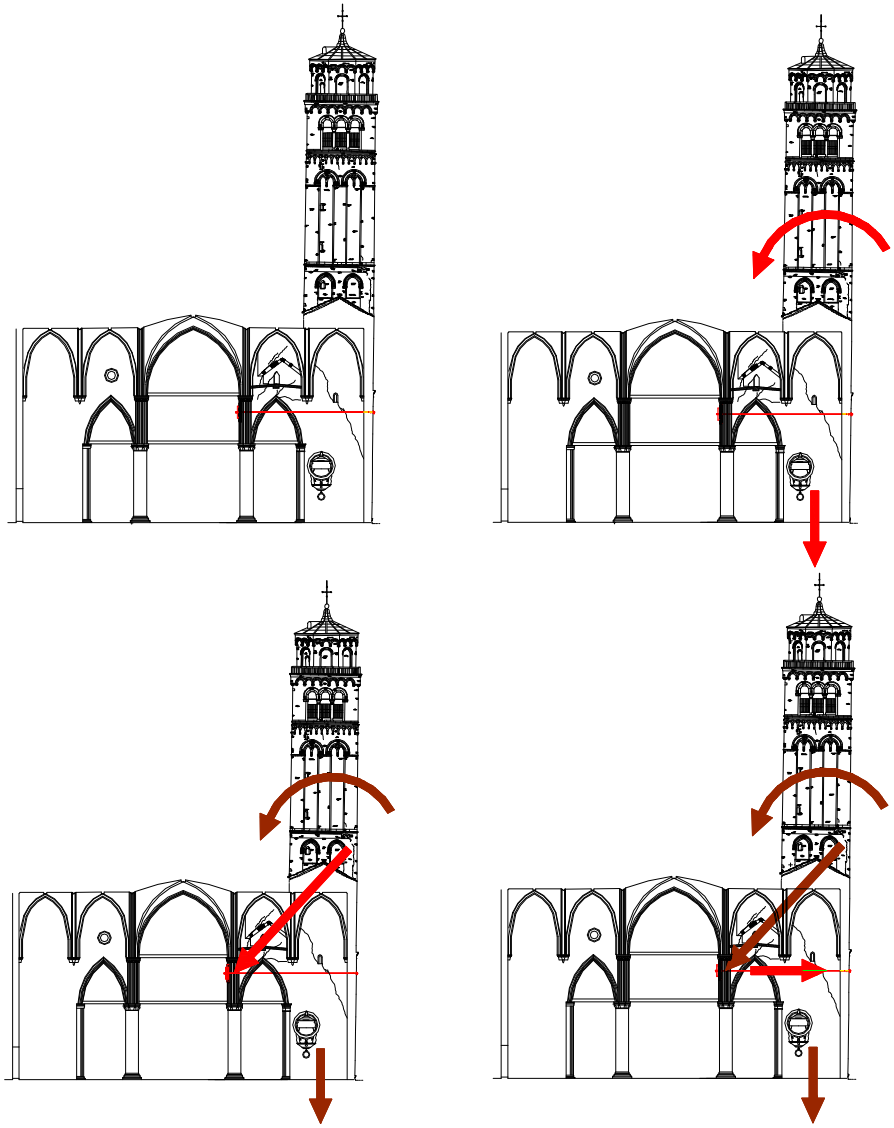
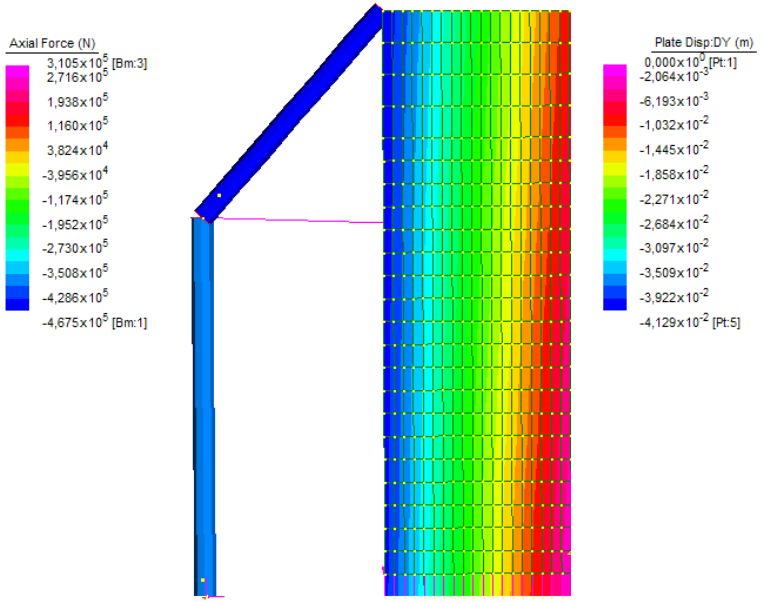
Realization of a provisional intervention for static control



Structural schemes considered for the design of the intervention



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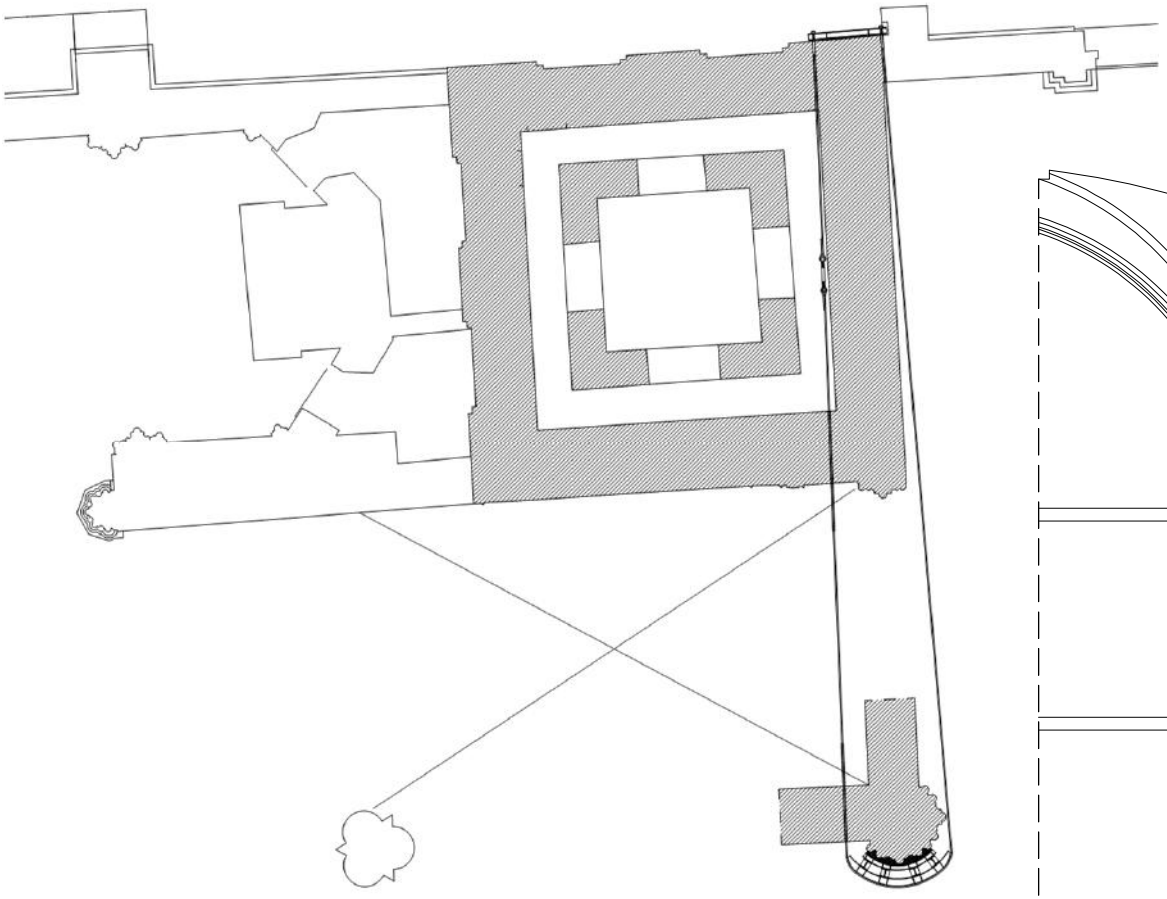

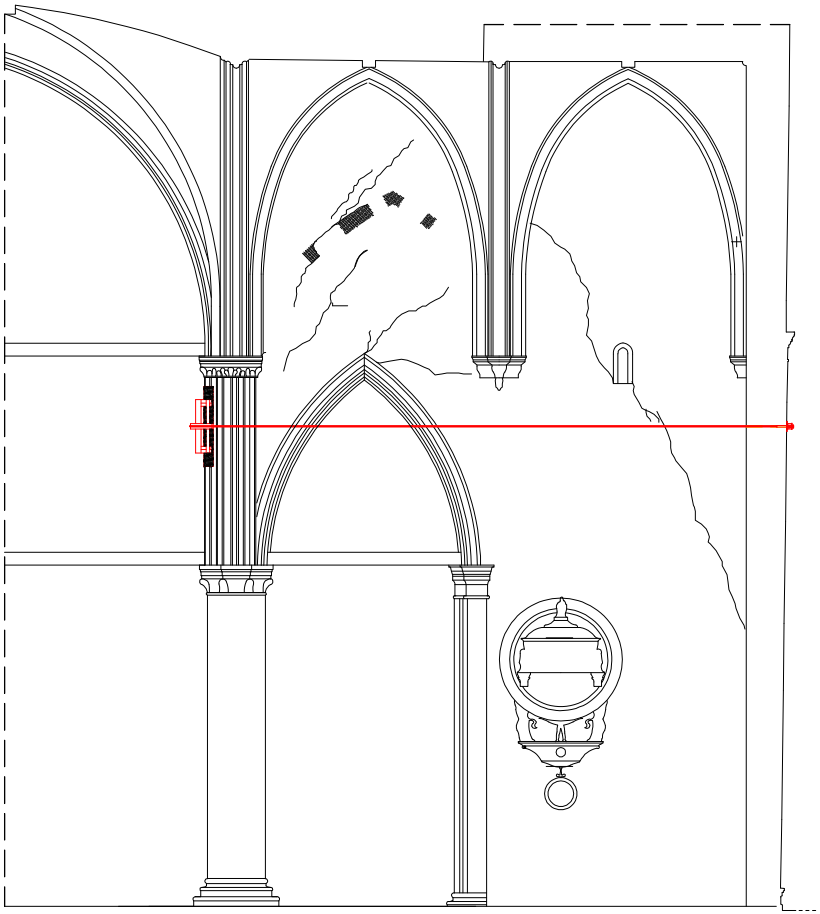

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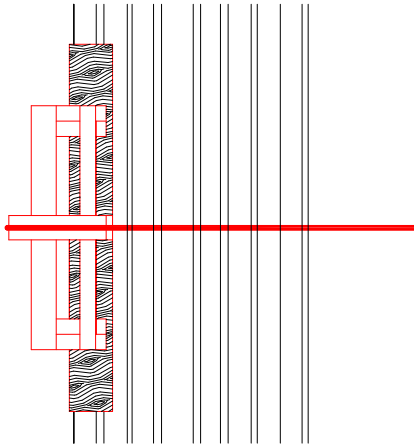

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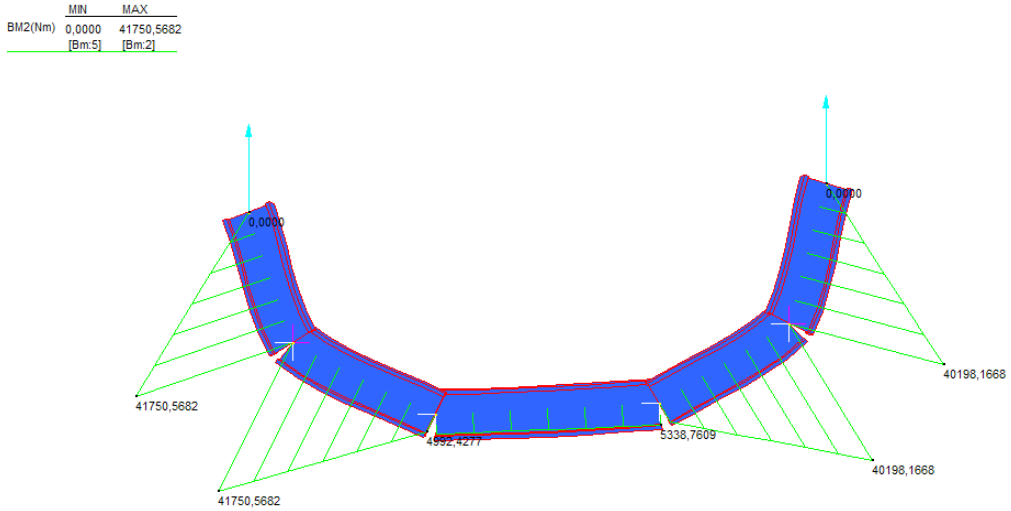

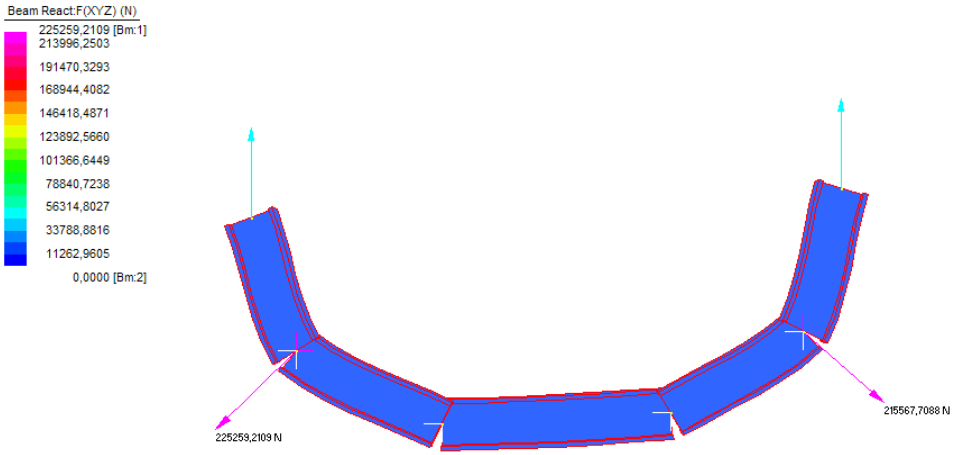

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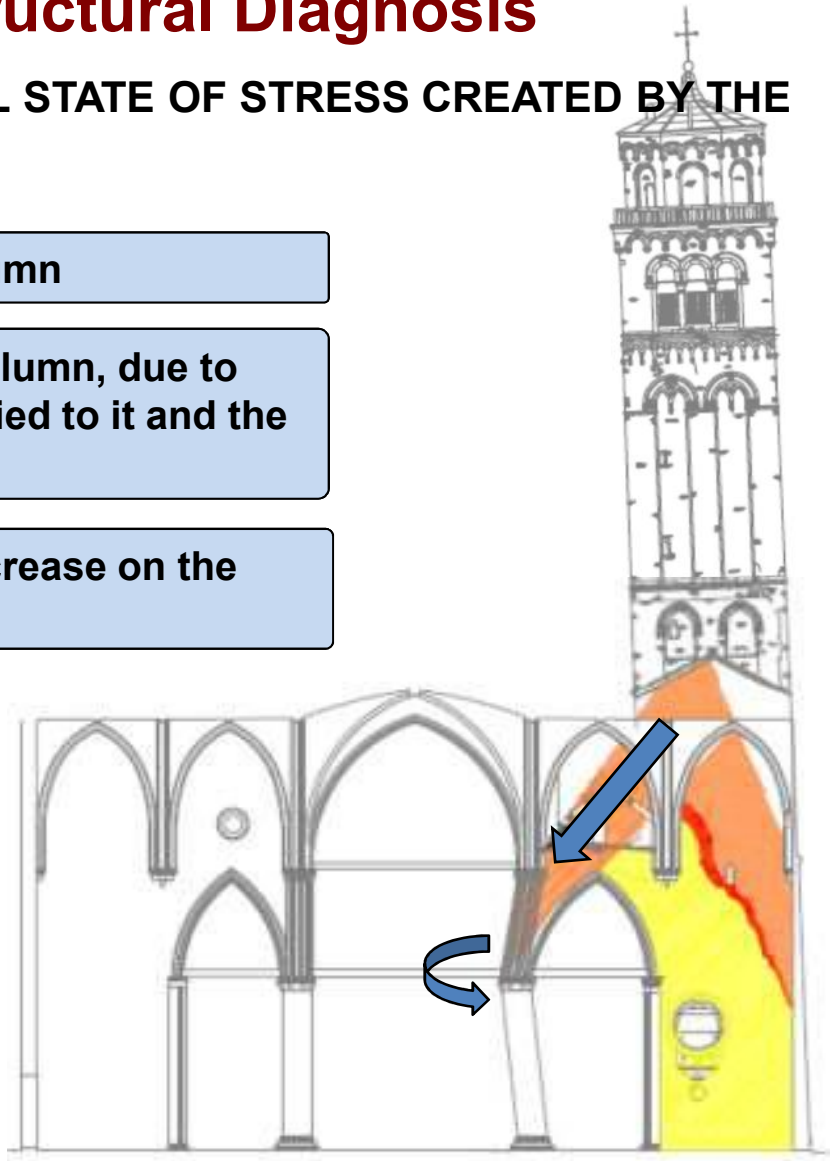
Basilica dei Frari (Venice) – Structural Diagnosis

CONSEQUENCES OF THE INTERNAL STATE OF STRESS CREATED BY THE MECHANICAL INTERACTION:

- **increase of the compression load on the column**
- **a strong transverse bending stress on the column, due to both the eccentricity of the vertical load applied to it and the horizontal component of the thrust**
- **decrease of the vertical load (equal to the increase on the column) on the tower**



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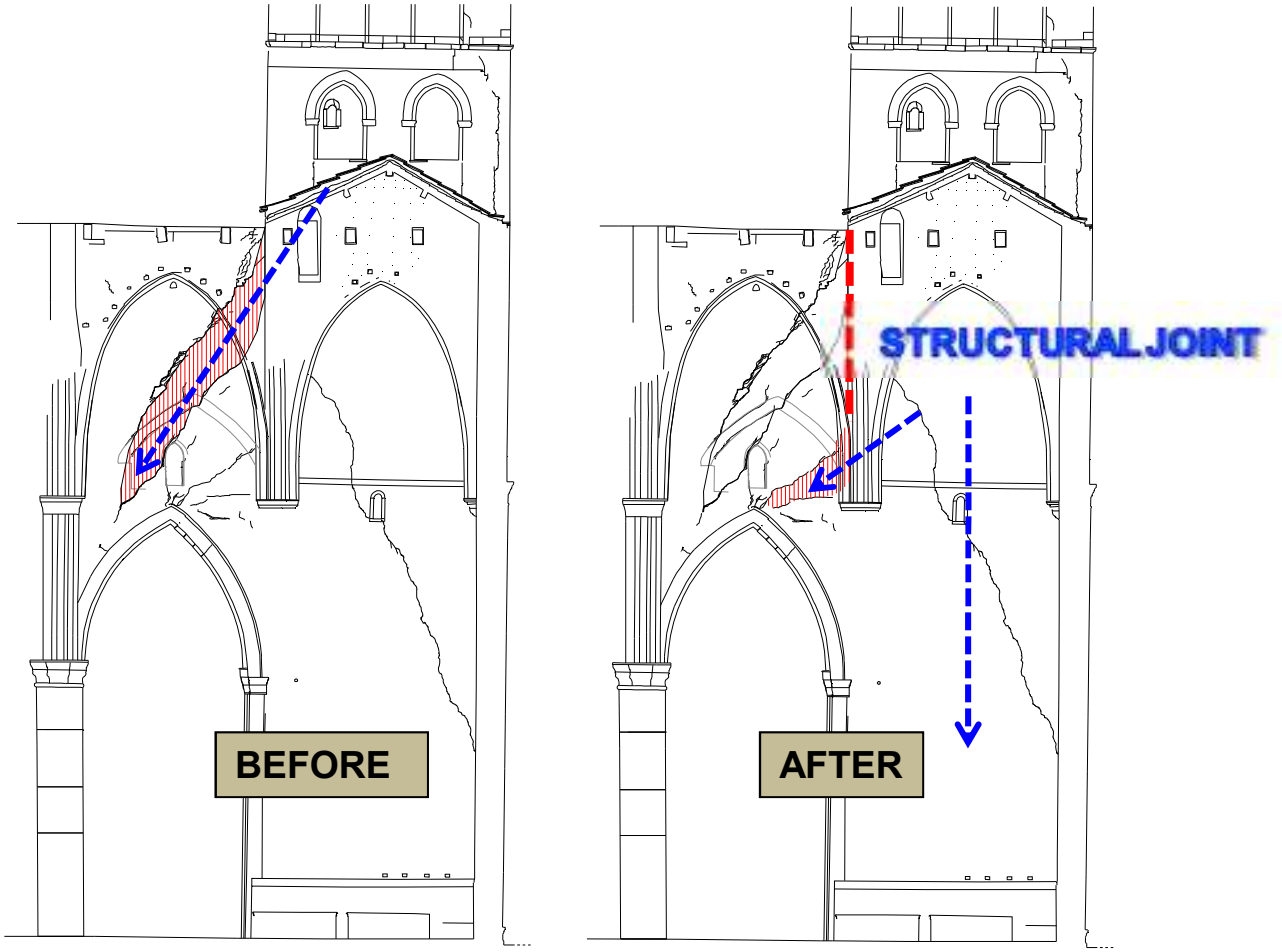
Basilica dei Frari (Venice) – Structural Diagnosis

BASIC PRINCIPLE OF THE INTERVENTION:

- Creation of a joint in order to separate the bell tower from the church and make them structurally more independent
- Reduction of the compressive forces that transfer part of the tower's self weight to the column



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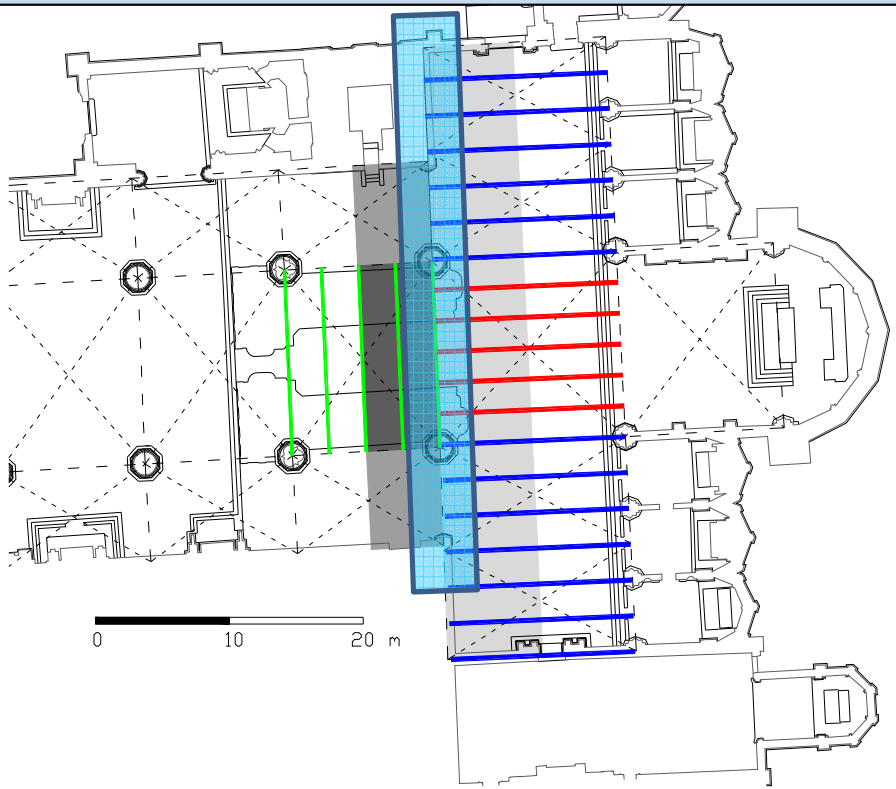
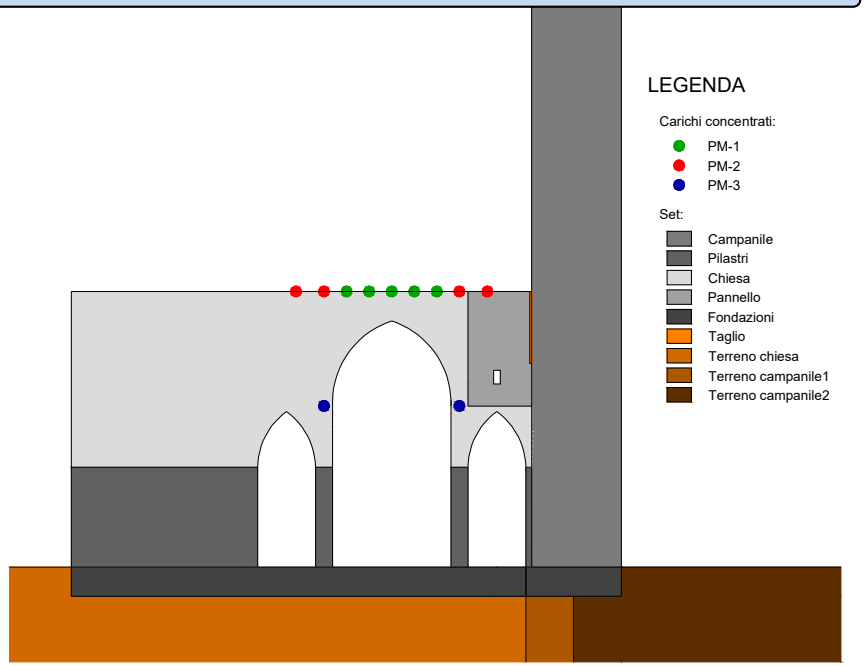
NUMERICAL MODELS

A 2D numerical model is created including the cross section of the church and considering parts of the structure and loading conditions that are relevant in relation to the structural problem.

Simulation of building's settlements during centuries through a non-linear phased analysis, varying the values of stiffness of the underlying soil.





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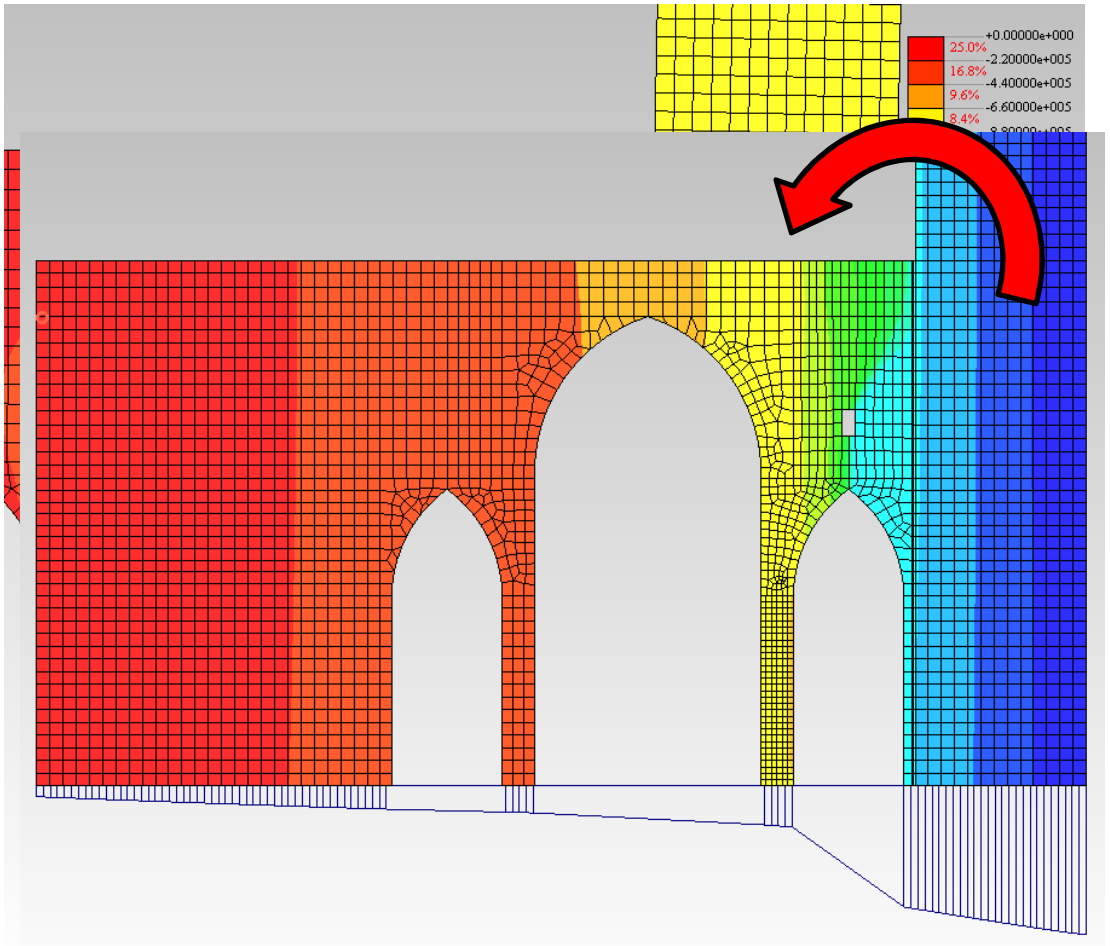
MAIN RESULTS

3RD PHASE: 1903-2008



Settlements during the 20th c.: reversal of tower's rotation toward the church after the intervention on foundations

Pre-intervention configuration

VERTICAL STRESSES DISTRIBUTION

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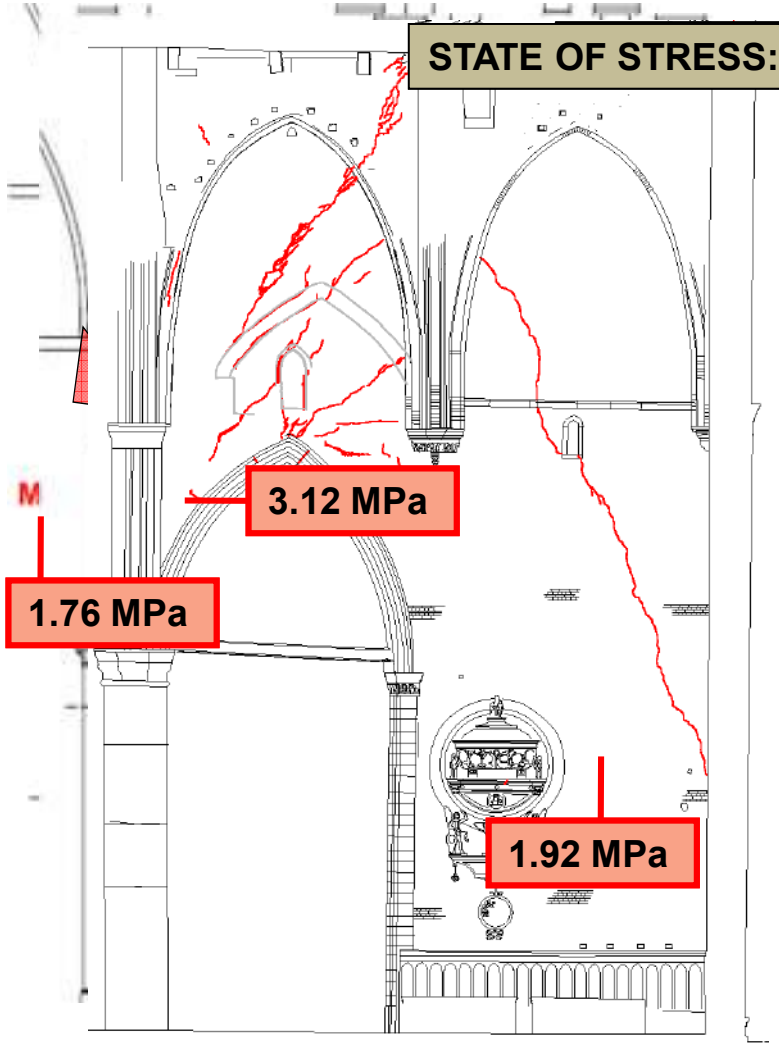
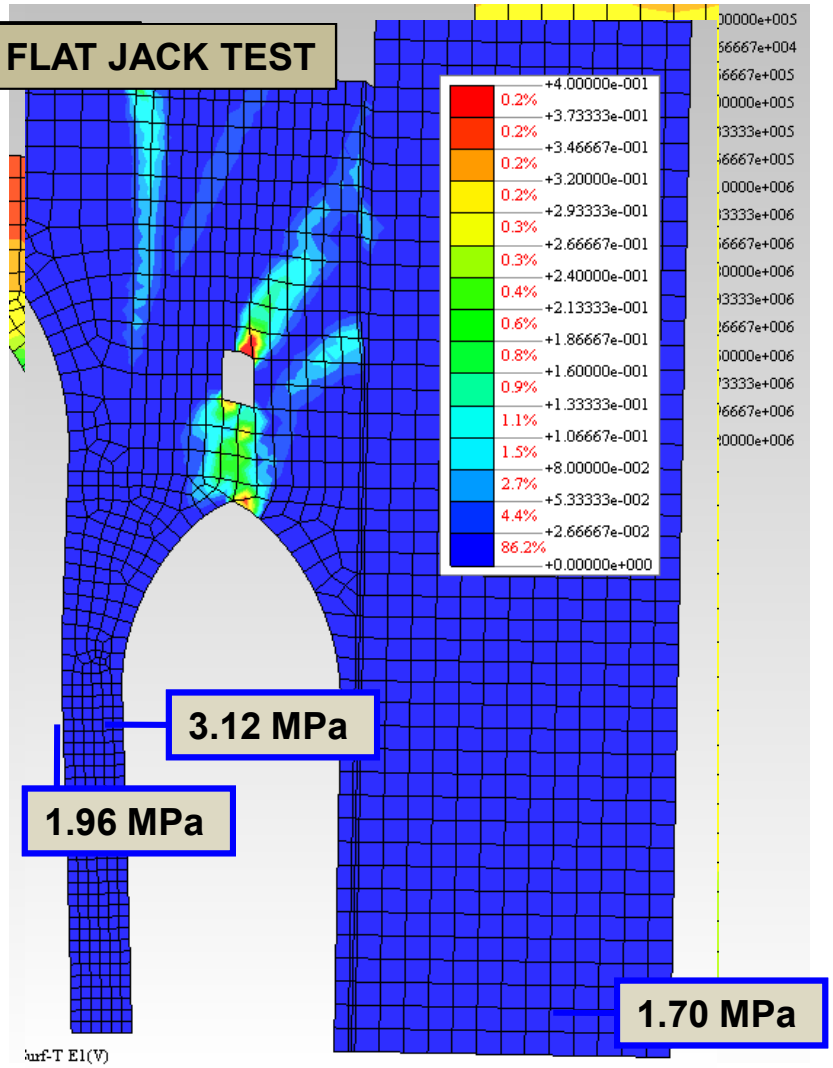
3RD PHASE: 1903-2008

COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

STATE OF STRESS: FLAT JACK TEST





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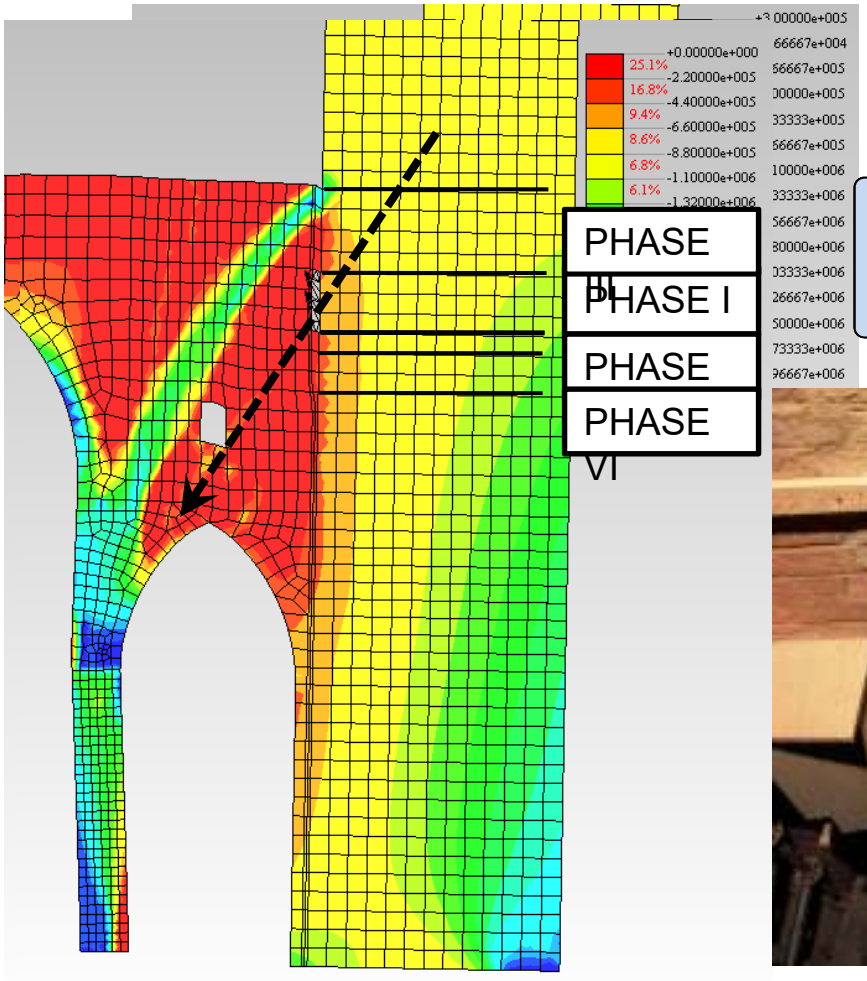
4TH PHASE: 1903-2008

STRUCTURAL INTERVENTION AUGUST-OCTOBER 2008

NUMERICAL SIMULATION OF THE INTERVENTION

PRE-INTERVENTION

POST-INTERVENTION



VARIATION OF THE STRESS PATTERN DURING THE FOUR INTERVENTION'S STAGES

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Examples of Conservation of Cultural Heritage: - palaces




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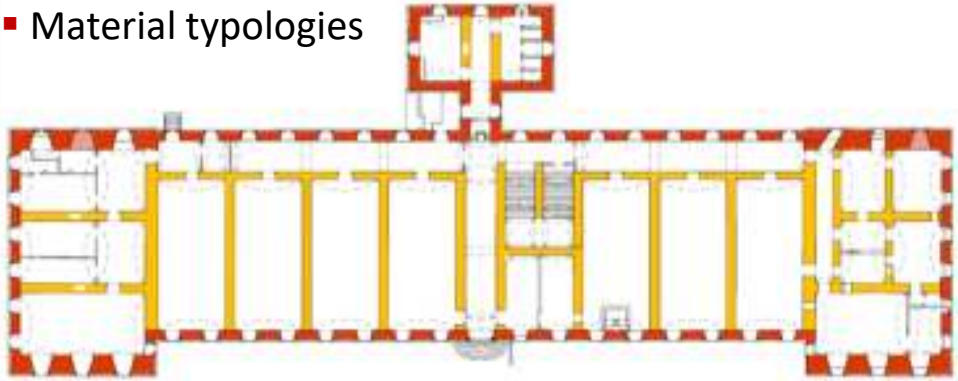
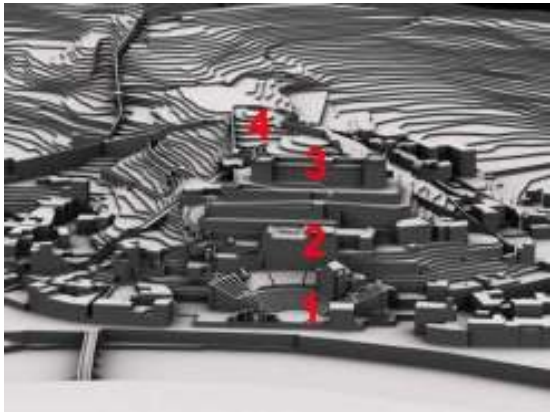
TEST ON VAULTS- IN SITU

(Cescatti Modena, 2016) **DT**

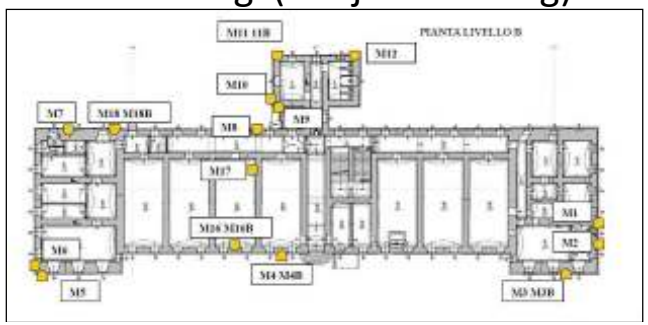
- Geometrical survey

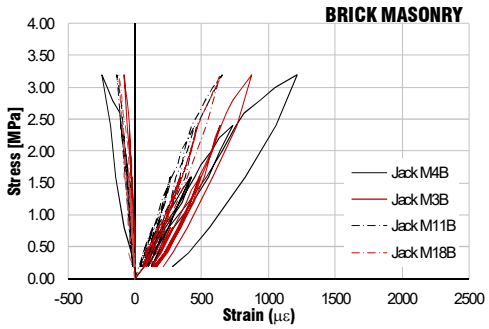
- Material typologies





- Material testing (flat jack - coring)





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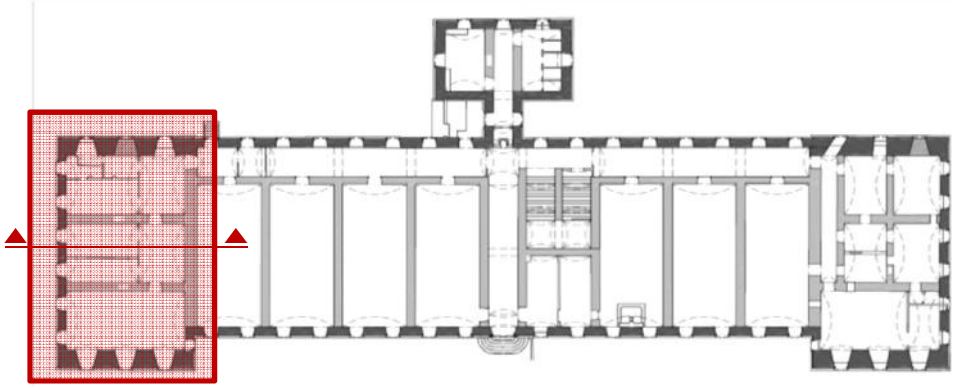
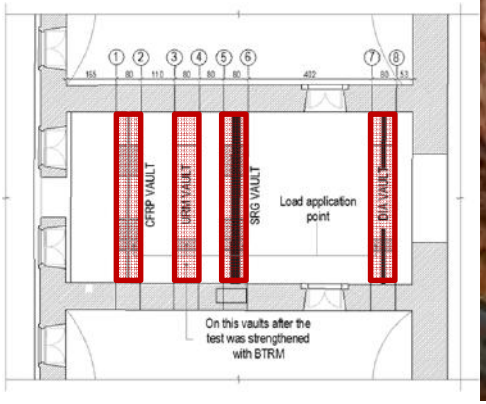
TEST ON VAULTS- IN SITU

(Cescatti Modena, 2016) **DT**





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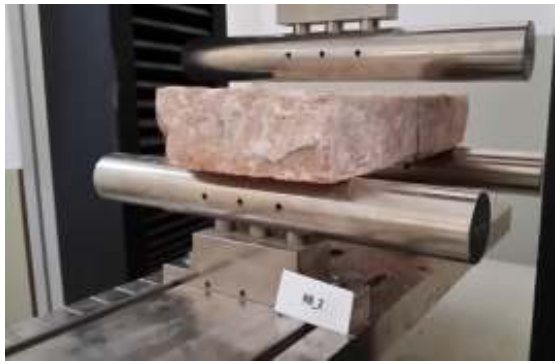
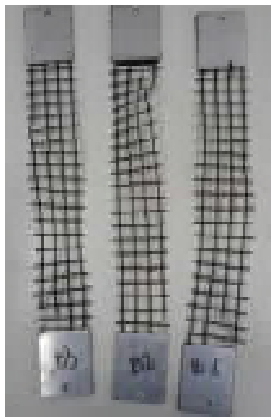
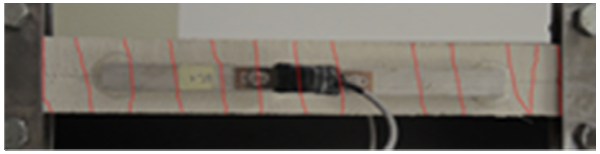
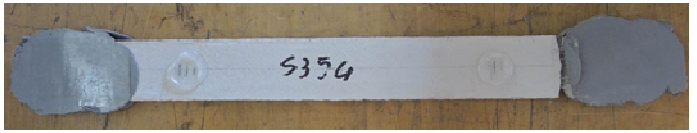
LABORATORY TEST ON BRICK AND MORTAR

Flexural tension *Splitting tension* *Compressive test* *Flexural tension*





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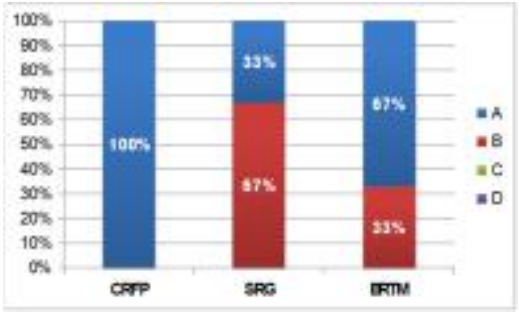
IN SITU EVALUATION OF INTERVENTION

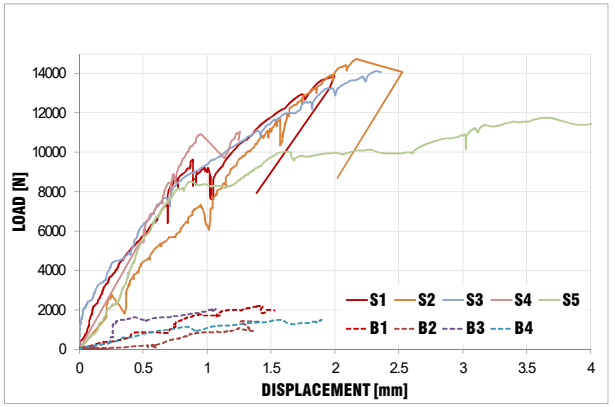
Orthogonal bond

- *Useful to survey the system quality of application*
- *Does not provide information on the system capacity*
- *Especially in case of FRCM the main failure is not **'A'** (failure on the substrate)*



Shear tests

- *Shear test on site helps to characterize the real response of the system*
- *Useful to assess the anchorage length*
- *No suitable information about the bond constitutive law*



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TEST ON VAULTS- IN SITU

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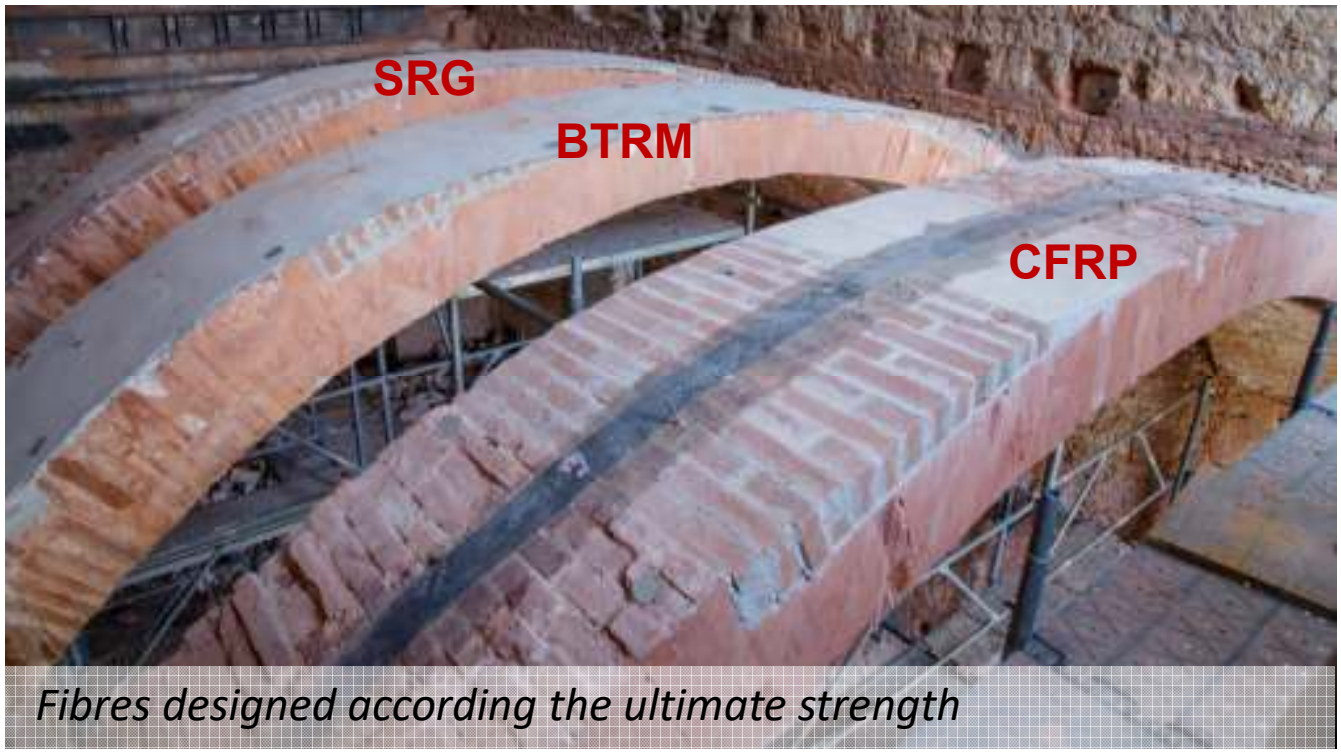

Fibres designed according the ultimate strength

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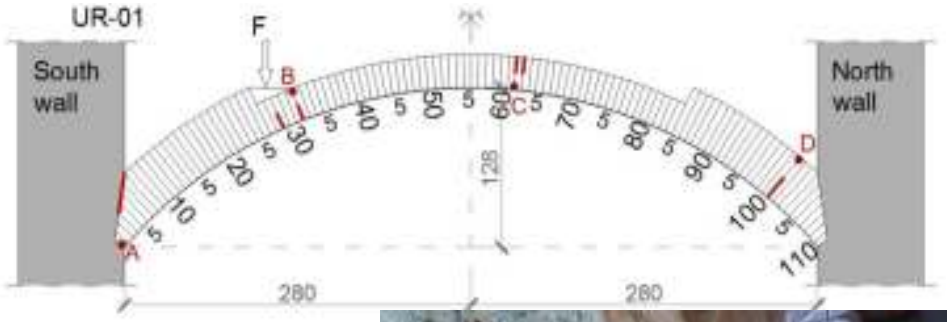
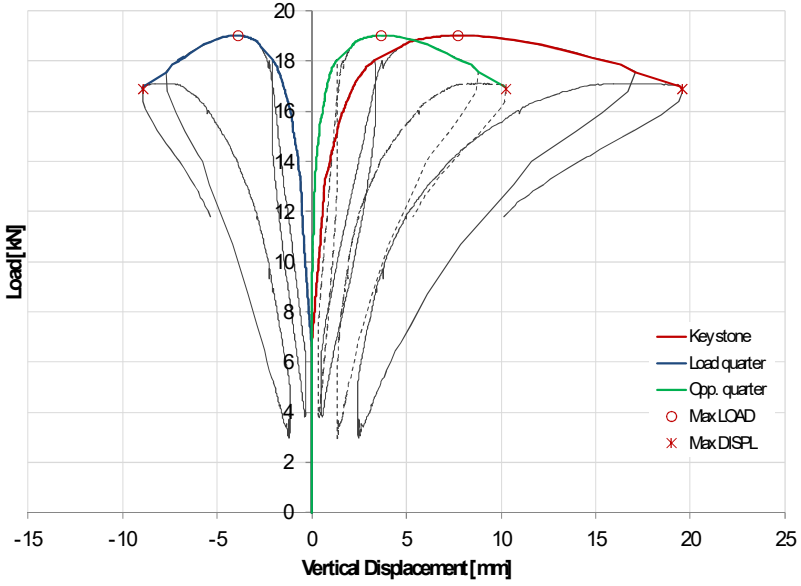
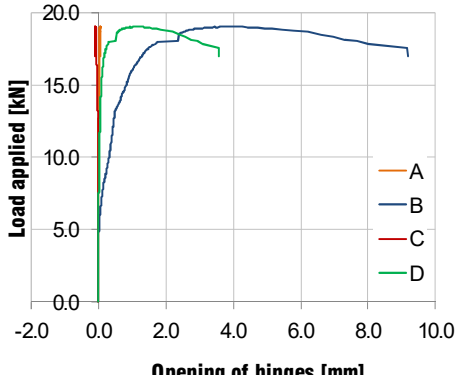
TEST ON VAULTS- IN SITU

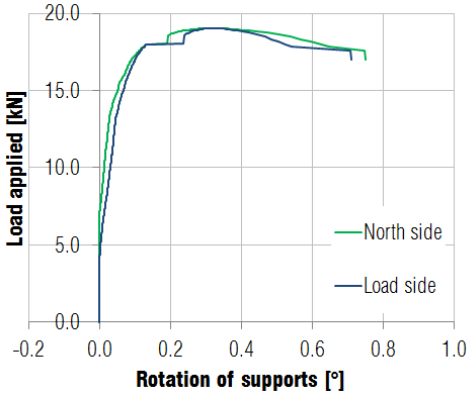
(Cescatti Modena, 2016) **DT**



	F_{max} [kN]	δ_{k-v} [mm]	$F_{\delta,max}$ [kN]	δ_{k-v} [mm]
01_URM	19.04	7.69	16.91	19.54







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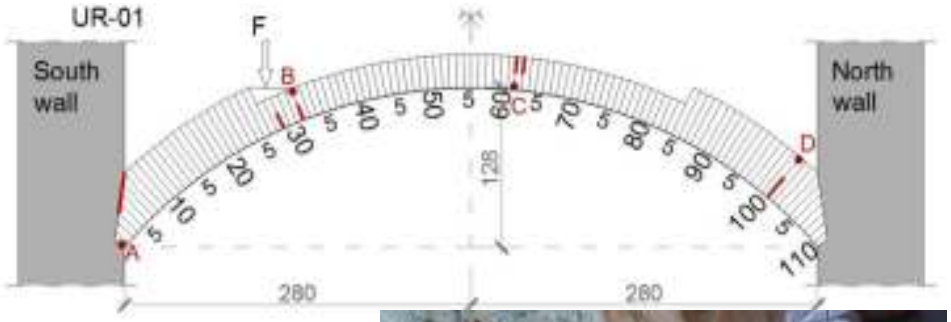
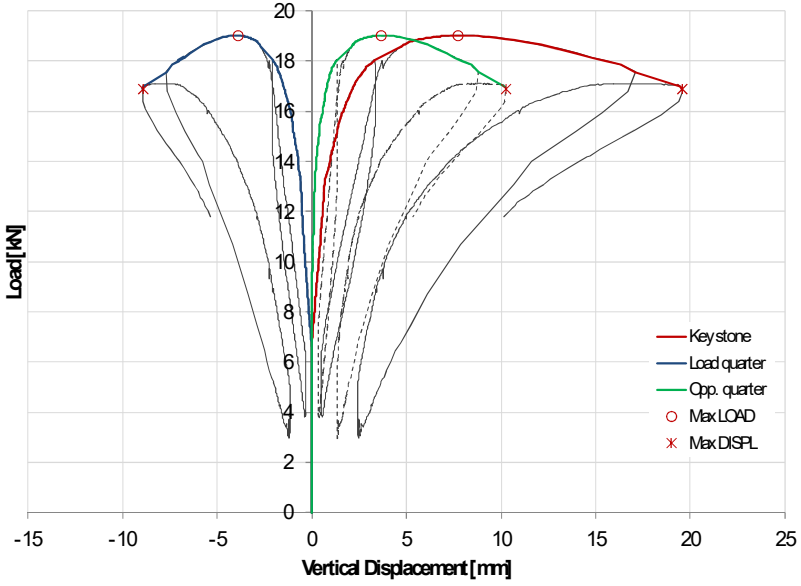
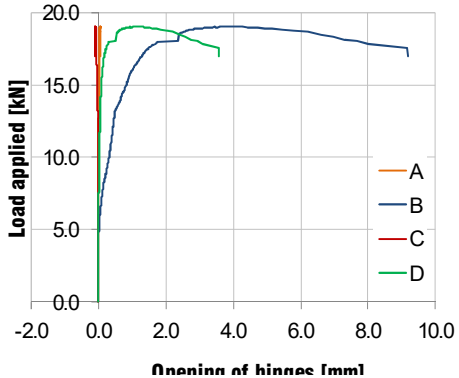
TEST ON VAULTS- IN SITU

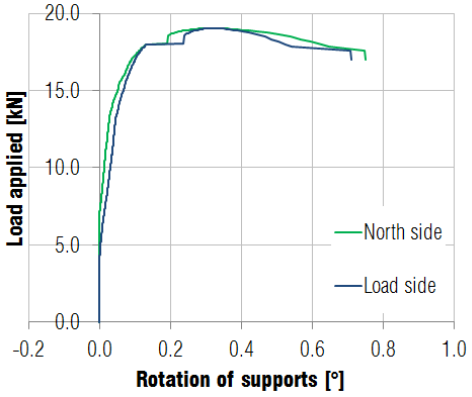
(Cescatti Modena, 2016) **DT**



	F_{max} [kN]	δ_{k-v} [mm]	$F_{\delta,max}$ [kN]	δ_{k-v} [mm]
01_URM	19.04	7.69	16.91	19.54







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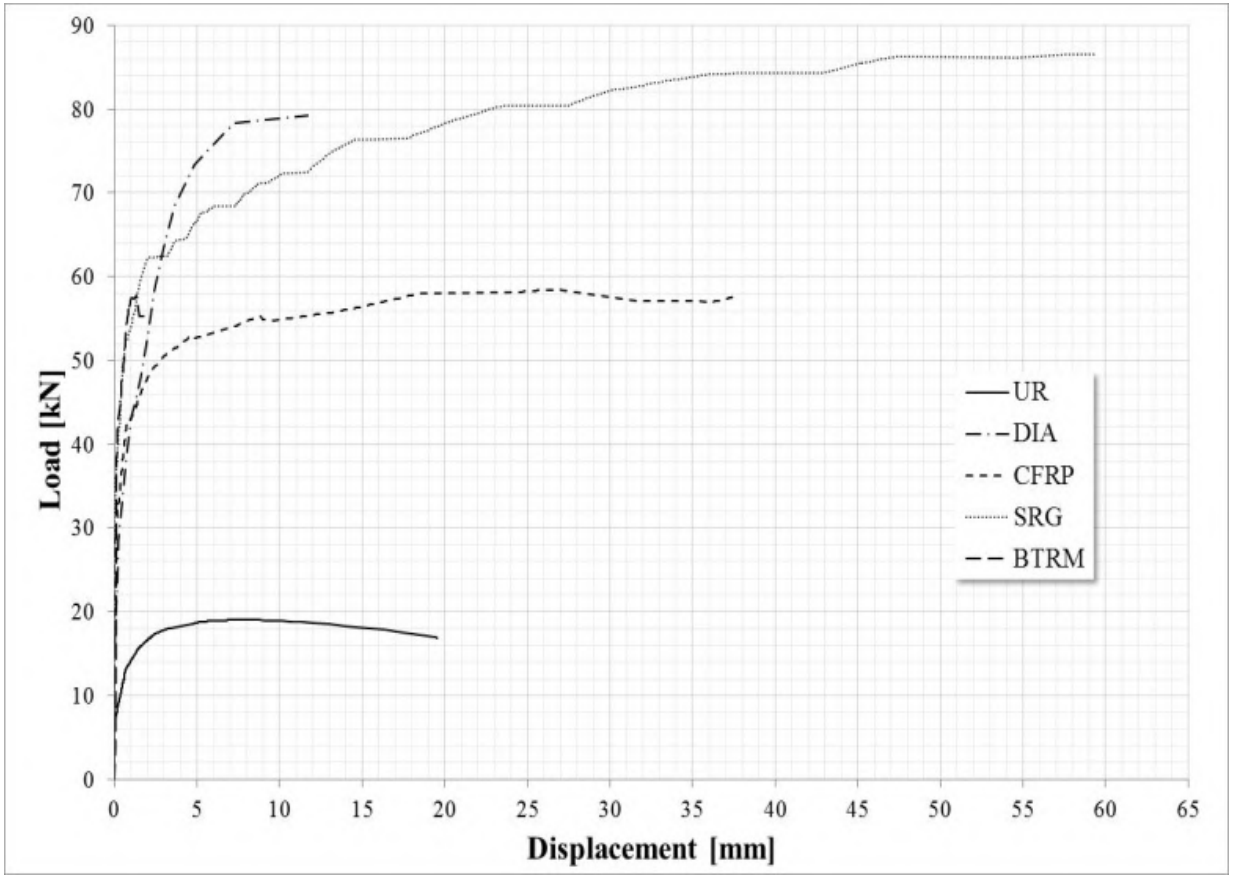
TEST ON VAULTS- IN SITU

- Major increase of maximum load of 86.6 kN, (4.55 times URM) by steel fibre with mortar
- Major displacement (F_{max}) 58.99 mm, (7.5 times URM) by steel fibre with mortar
- DIA load 79.18 kN could not be compared with EBR application (different load position with the respect of hinges)
- DIA provide extremely fragile response



VAULTS	F_{max} [kN]	d_{max} [mm]	F^*_u [kN]	d^*_u [mm]
UR	19.04	7.69	16.75	19.58
DIA	79.18	11.71	-	-
CFRP	58.48	26.76	56.88	37.67
SRG	86.64	58.99	37.65	63.05
BTRM	57.75	1.33	47.38	1.85

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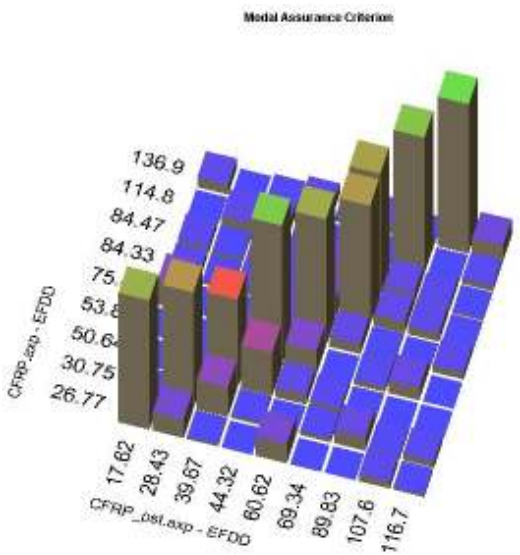
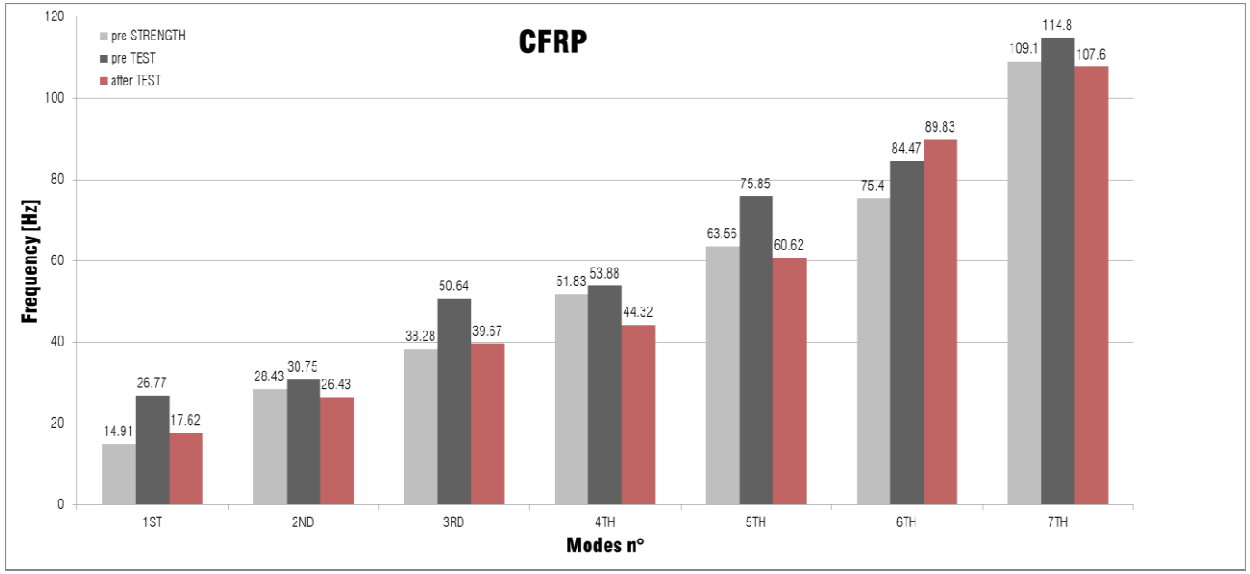
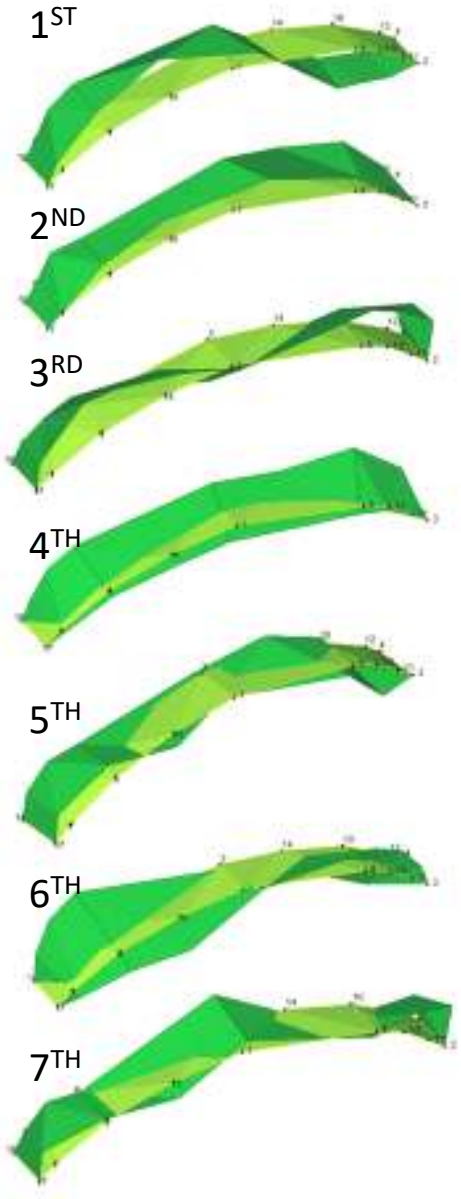
DYNAMIC TESTS







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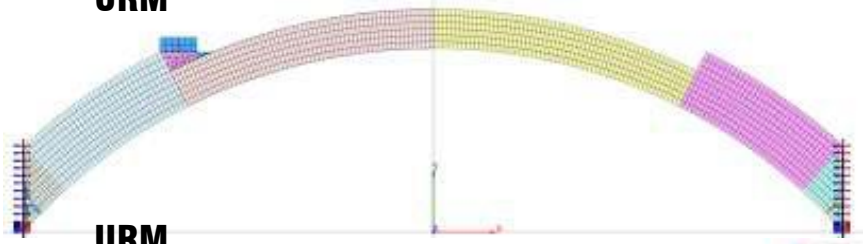
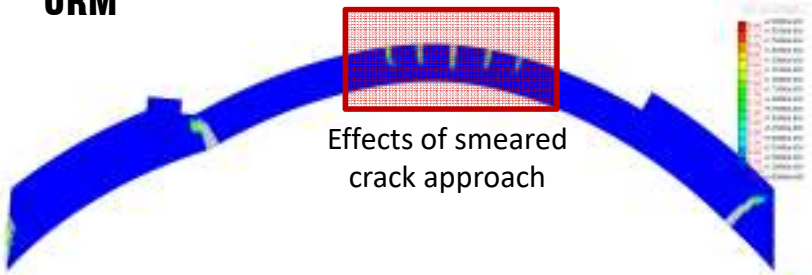
MACRO MODELLING – F.E.M.

URM



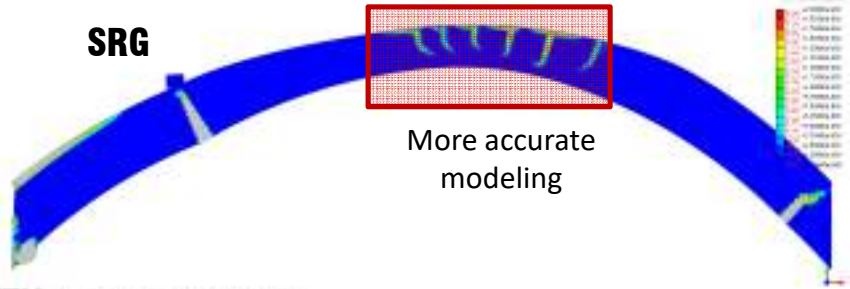
URM



Effects of smeared crack approach

URM

SRG



More accurate modeling

SENSITIVITY ANALYSIS

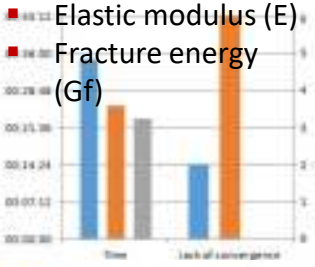
Evaluation of:

MODELING

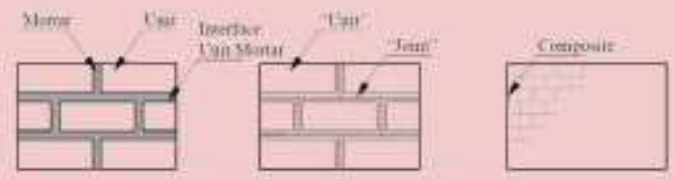
- Mesh sensitivity
- Step increment
- Solution method
- Time consuming
- Convergence criteria
- Geometrical non linearity

MATERIAL

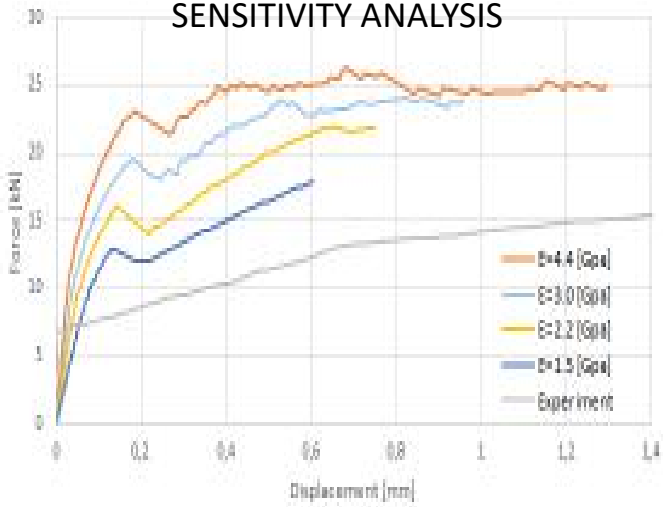
- Tensile behaviour (ft)
- Elastic modulus (E)
- Fracture energy (Gf)

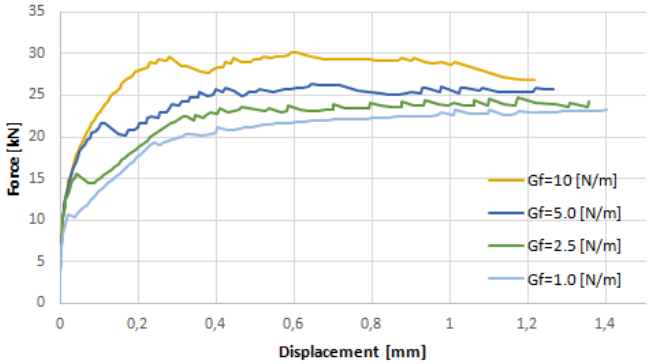


Possibile approaches



SENSITIVITY ANALYSIS





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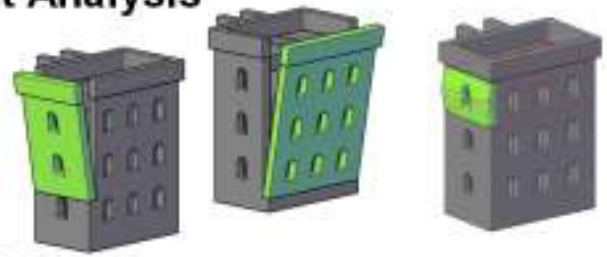
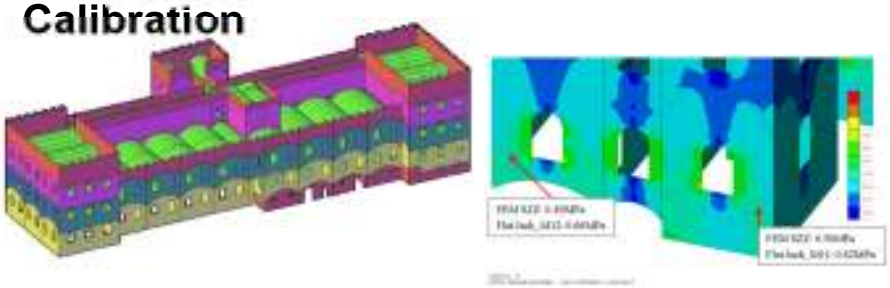
GLOBAL ANALYSIS

S. PIETRO CASTLE

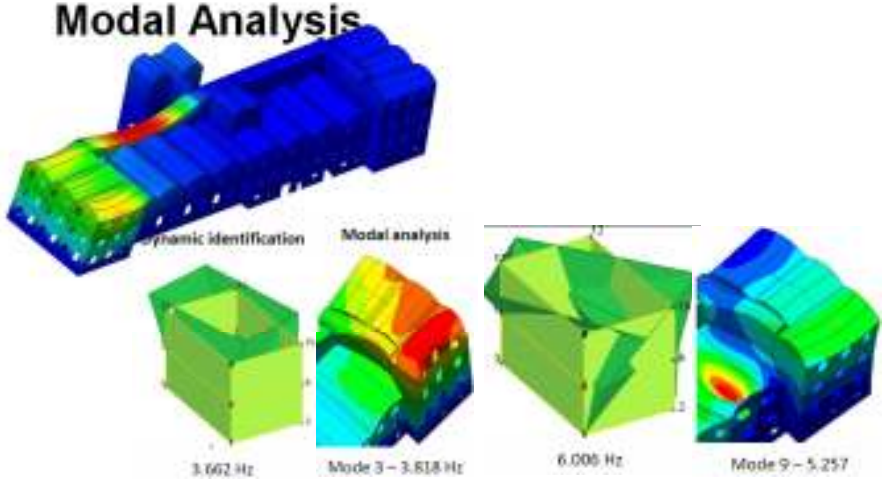
Limit Analysis



Calibration

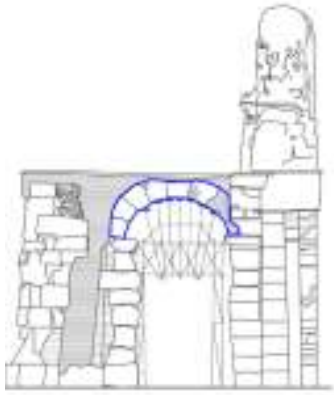


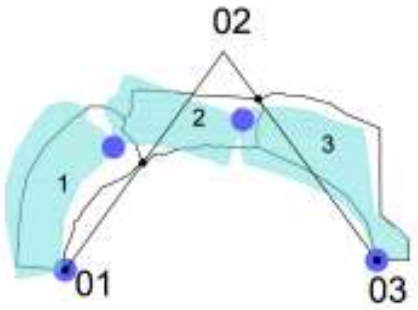
Modal Analysis



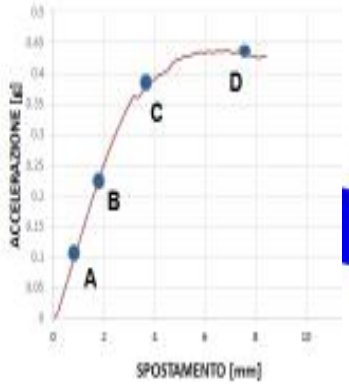
ROMAN THEATRE

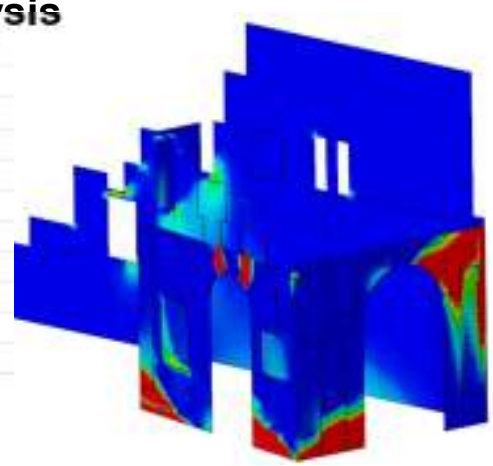
Limit Analysis





Pushover analysis





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Examples of Conservation of Cultural Heritage: ARCHAEOLOGICAL SITES




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THE ROMAN AMPHITHEATRE (ARENA) OF VERONA

Arena of Verona
The Roman Amphiteatre or “Arena” represents the most important roman monument in Verona.

The monument was erected between the 2nd and 3rd decades of the 1st century AD, on a site which was then beyond the late-republican city walls.

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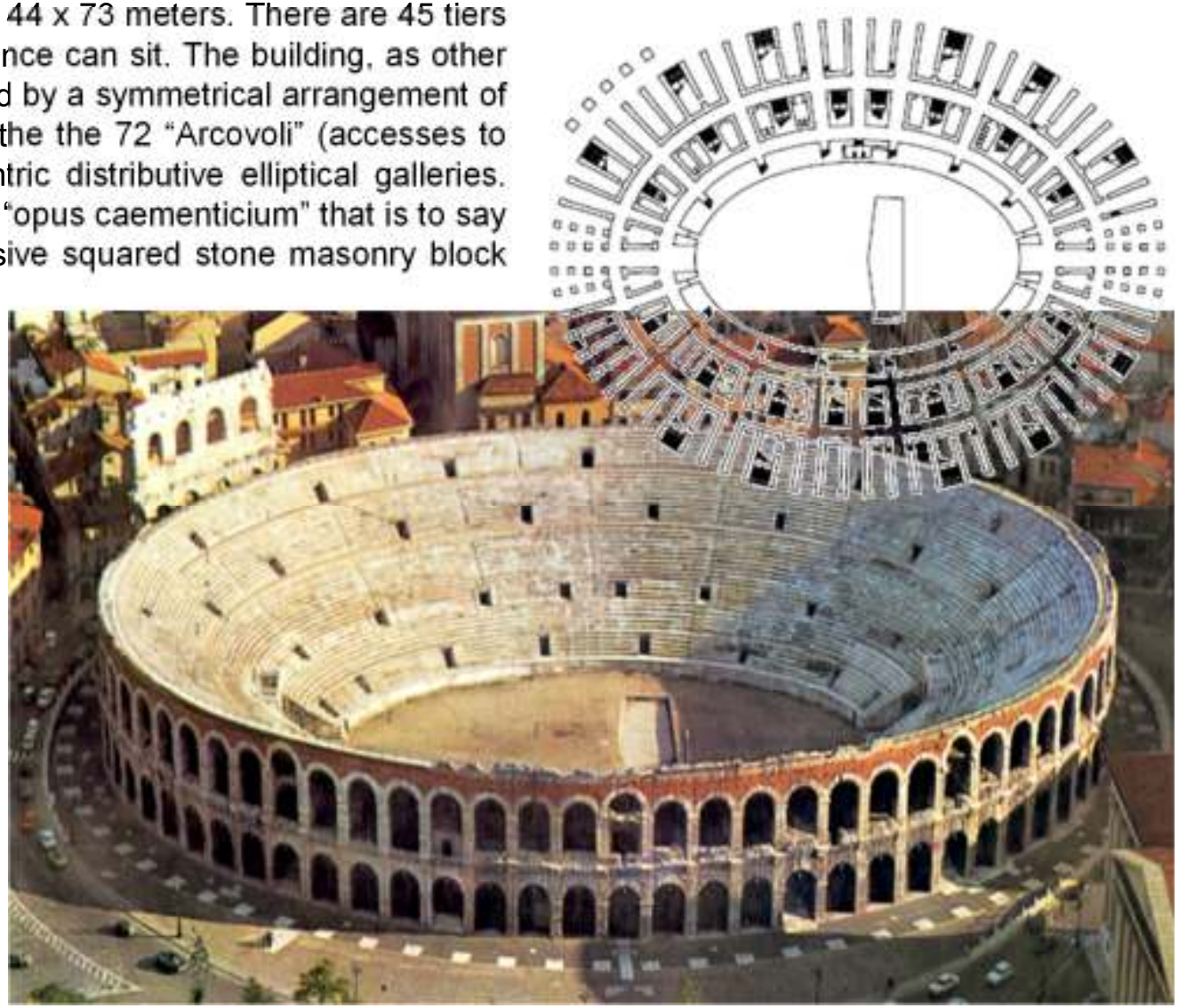
The Arena dimensions are about 138 x 109 meters on the outside while the inner elliptic pit is about 44 x 73 meters. There are 45 tiers of steps wherein the opera audience can sit. The building, as other structures of its kind, is composed by a symmetrical arrangement of radial masonry walls separating the the 72 "Arcovoli" (accesses to the courtyard) and three concentric distributive elliptical galleries. Main employed materials are the "opus caementicium" that is to say the roman concrete, and a massive squared stone masonry block masonry.



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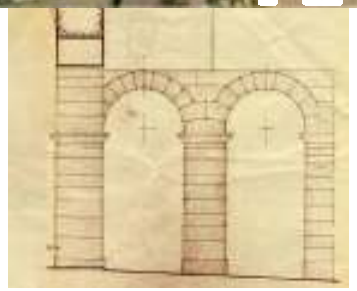
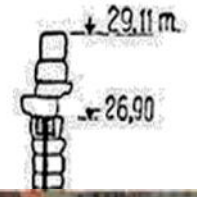
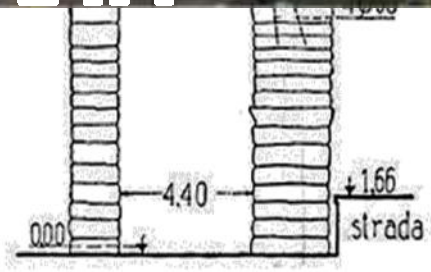
The **monument was subjected** to several natural and man induced actions, like the **flooding** of 589 AD, the **earthquakes** of 1116 and 1117, leading to the almost complete collapse of the outer ring of the Arena, the collapse of 5 arcades on Bra square in 1579, and the continuative **stealing of stones** and material for re use in other constructions, until being treated like an “historical” monument, with archeological excavations, starting from the XVIII century.

XX century structural interventions and induced damages are documented more in detail: in 1939, both the need of intervening on the external “Ala” for manifest tilting and the necessity of protecting the same structural portion from the possible damages induced by the II w.w. consequences, rendered necessary the construction of massive buttresses , removed after the end of the war by an intervention of post tensioned tendons vertically positioned within the pillars (1956).







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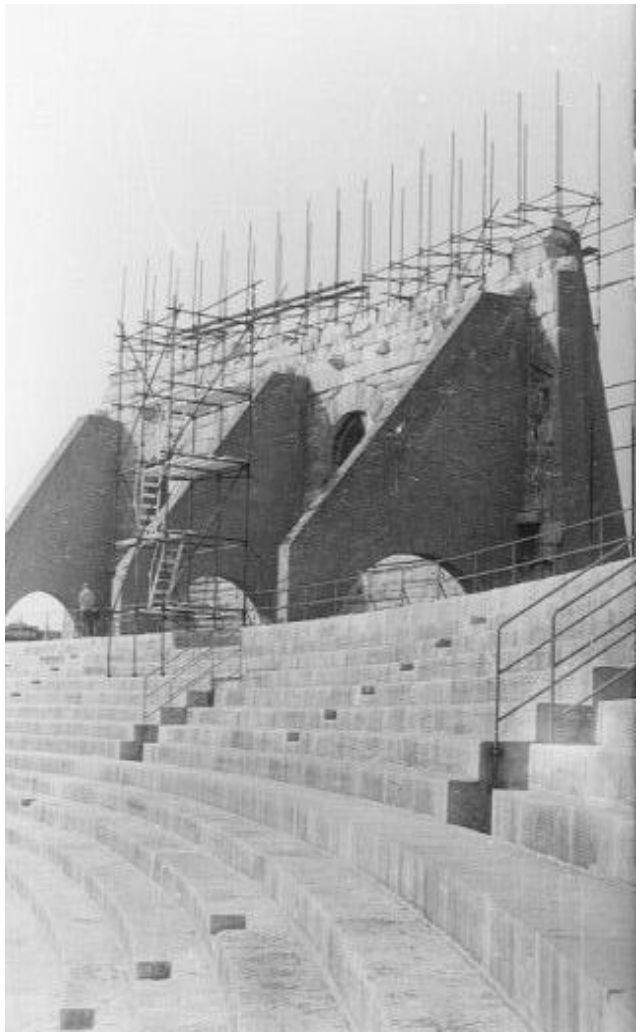
STRUCTURAL INTERVENTION (ENG. MORANDI, 1956)



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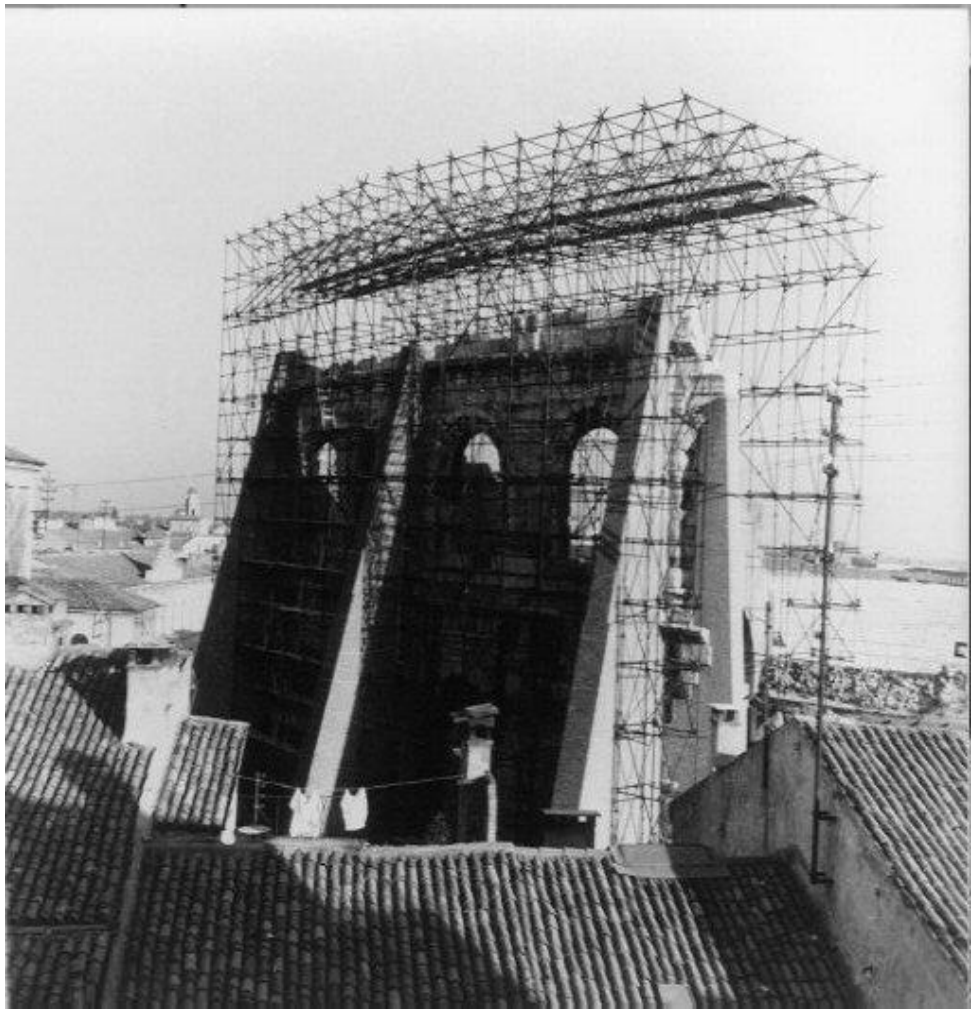
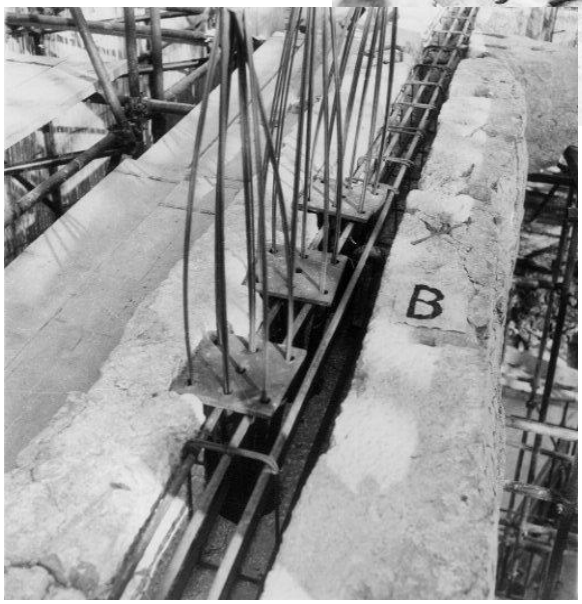
STRUCTURAL INTERVENTION (ENG. MORANDI, 1956)





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STRUCTURAL INTERVENTION (ENG. MORANDI, 1956)

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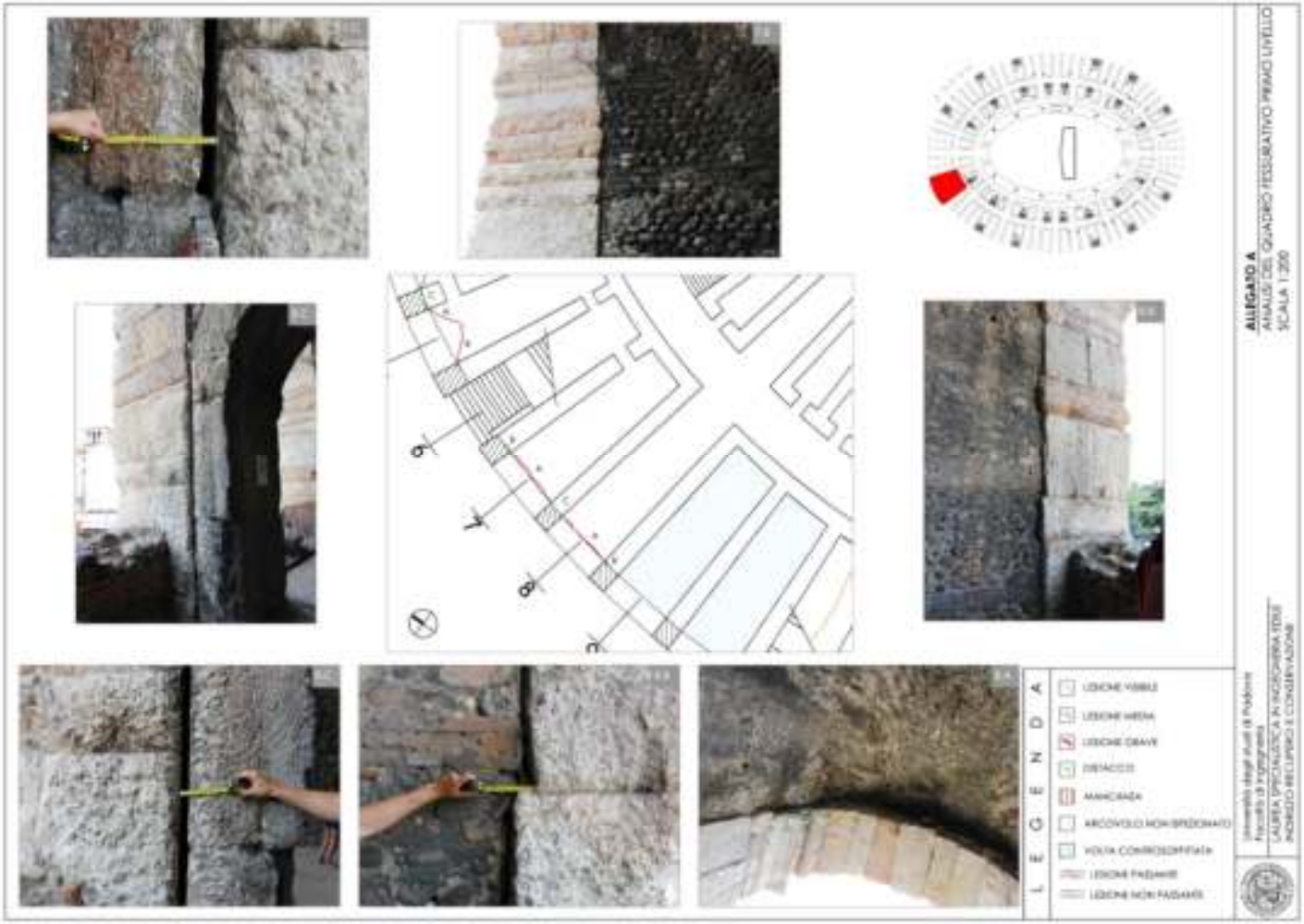
DIAGNOSIS: VISUAL INSPECTIONS

DAMAGE PATTERN SURVEY



Damage survey forms

SHM (Structural Health Monitoring) OF HISTORICAL STRUCTURES: DYNAMIC AND STATIC ANALYSIS OF THE ARENA IN VERONA – Beccaro, Milan 2012

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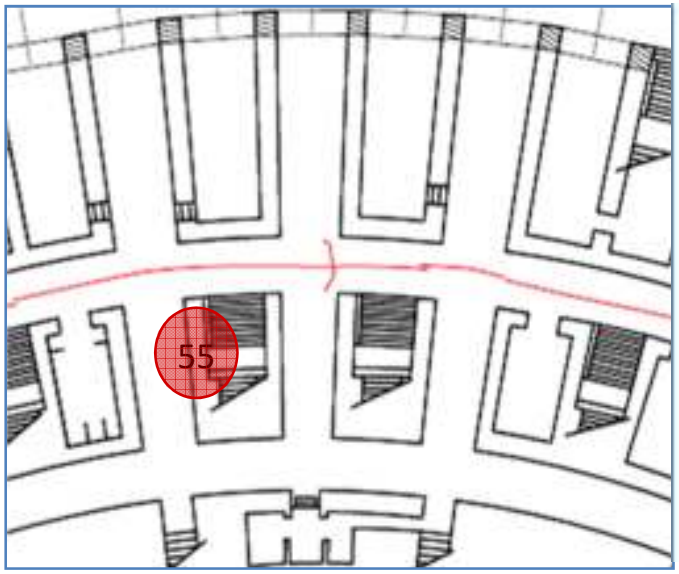
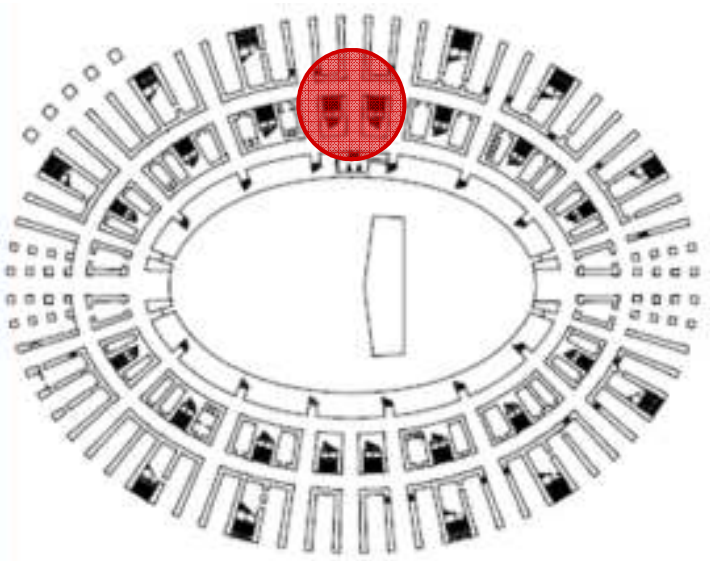
DAMAGE PATTERN SURVEY





Gate 55

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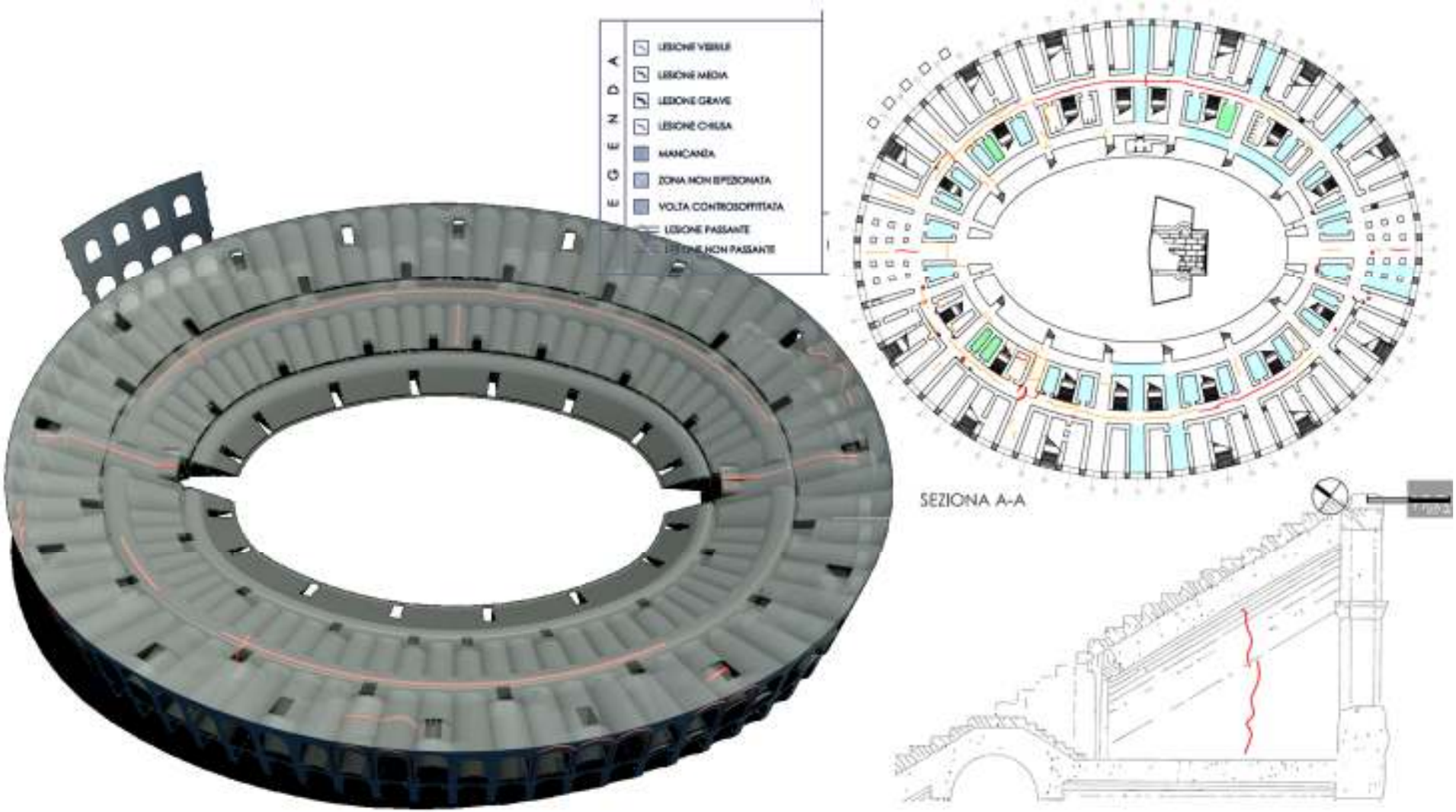
DIAGNOSIS: VISUAL INSPECTIONS



Damage survey forms

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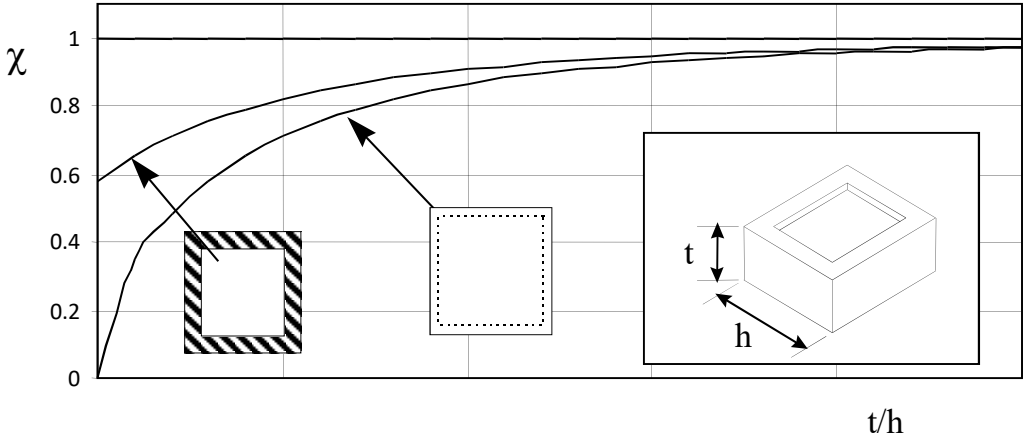
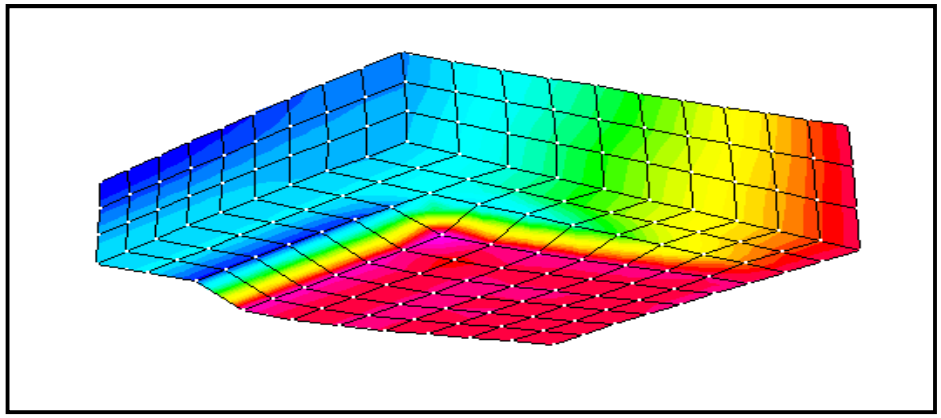
DIAGNOSIS: STUDY OF THE COSTRUCTION TECHNIQUE





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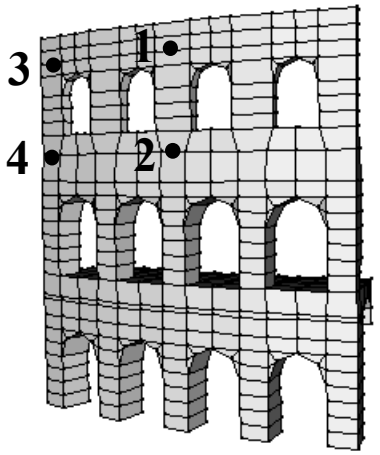
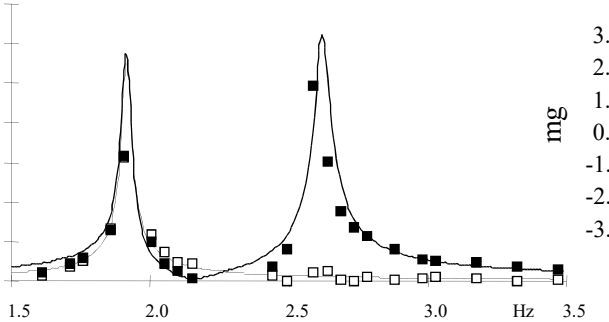
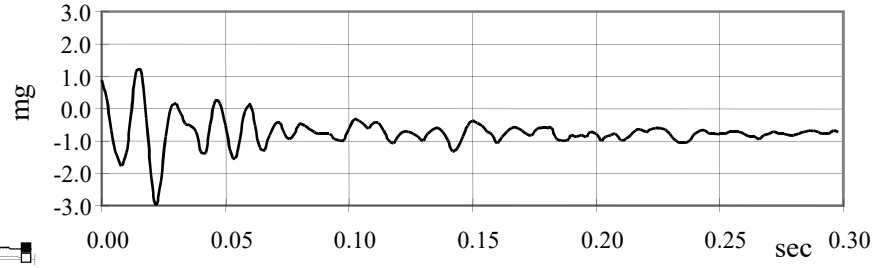
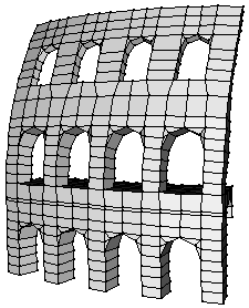
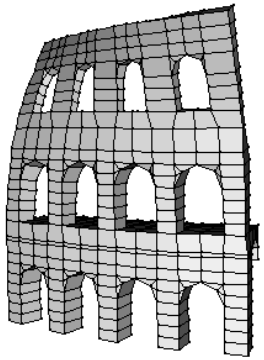
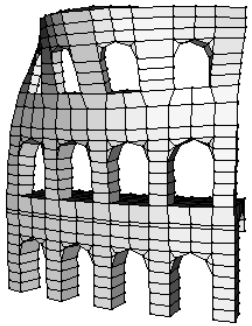
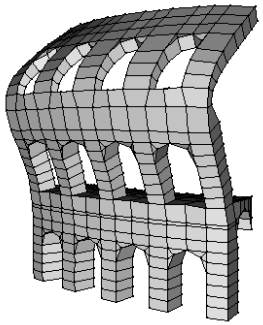
DIAGNOSIS: AMBIENT VIBRATIONS TEST







	f_1 = 1.92 Hz				f_2 = 2.61 Hz			
	1	2	3	4	1	2	3	4
Real	1	0.36	1	0.36	0.06	-	1	0.32
Theoretical	1	0.37	1	0.37	0	0	1	0.34

				
Real	1.91	2.61	4.83	5.87
Theoretical	1.92	2.63	5.01	5.85

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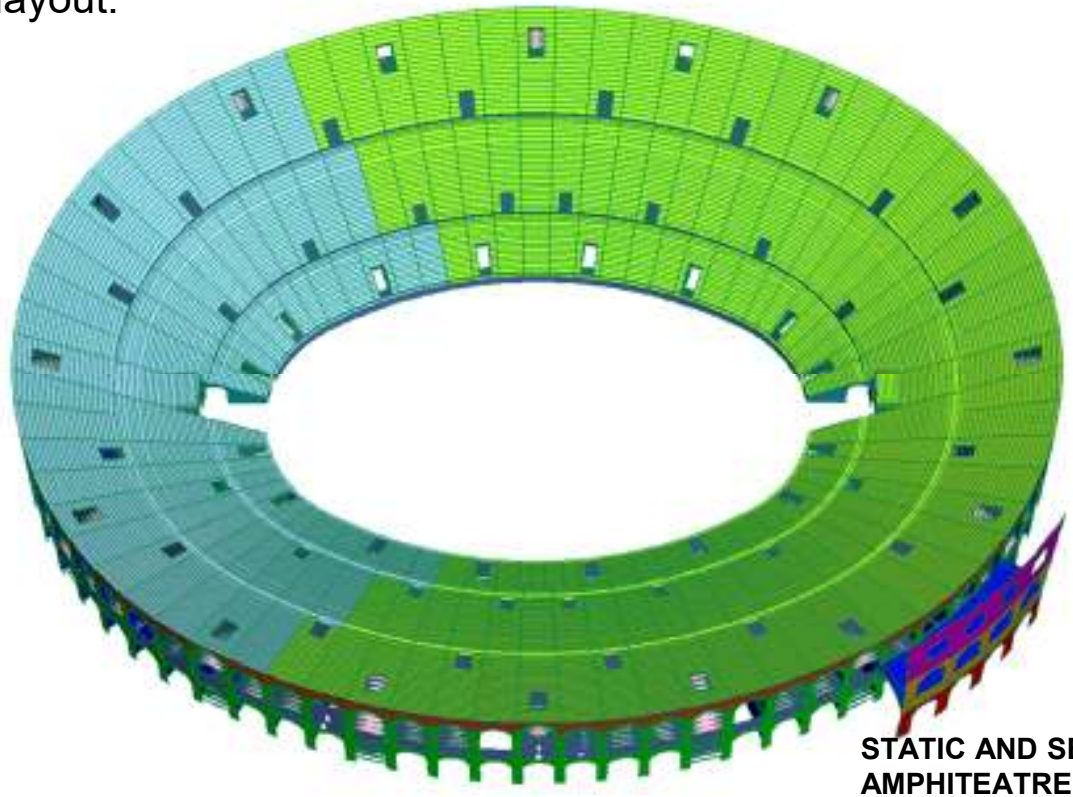
STRUCTURAL ANALYSIS: NUMERICAL MODELS

Because of the complexity and huge dimensions of the monument, for simplification reasons the masonry was modeled as a isotropic, homogeneous and continuum material, with linear elastic constitutive law.
3-4 nodded 2D elements were employed (plates): such approximation was considered the most appropriate since the structural elements of the Arena (walls and vaults) have a prevailing 2D layout.



STATIC AND SEISMIC ANALISYS OF THE ROMAN AMPHITEATRE OF VERONA - Bertini, 2008

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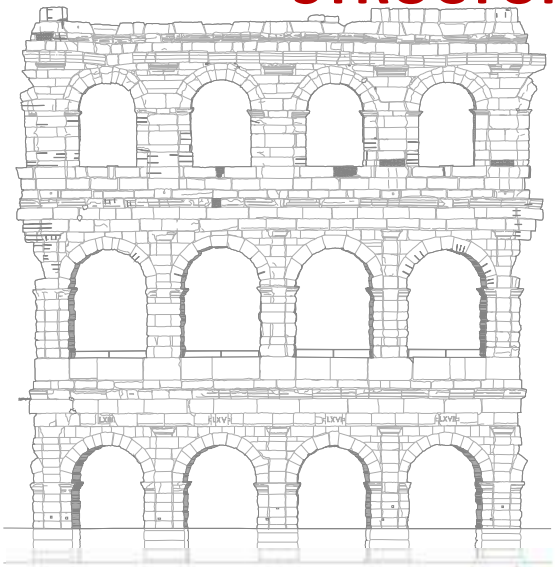
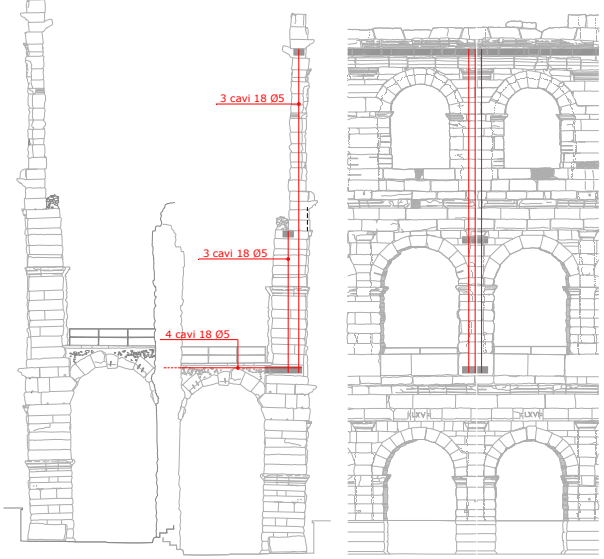
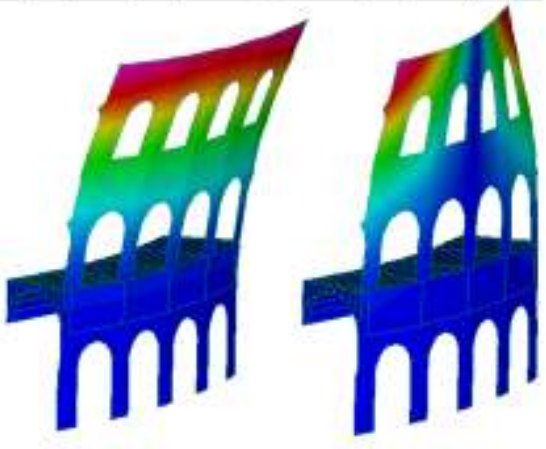
STRUCTURAL ANALYSIS: MODEL CALIBRATION

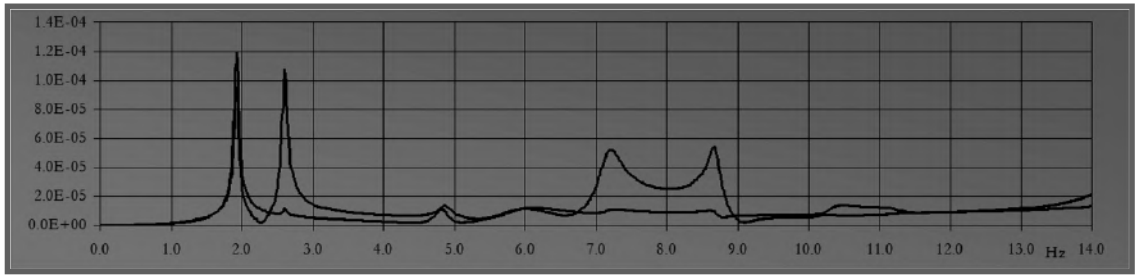




MODE n°	EXP FREQ [Hz]	FEM FREQ [Hz]
1	1,92	1,68
2	2,61	2,42
3	4,83	4,91
4	5,87	5,89
5	6,10	6,20
6	7,10	7,18



VULNERABILITY ANALISYS OF THE WING OF THE ARENA - Faretina, 2008



The so called “wing” of the Arena must however studied more in detail

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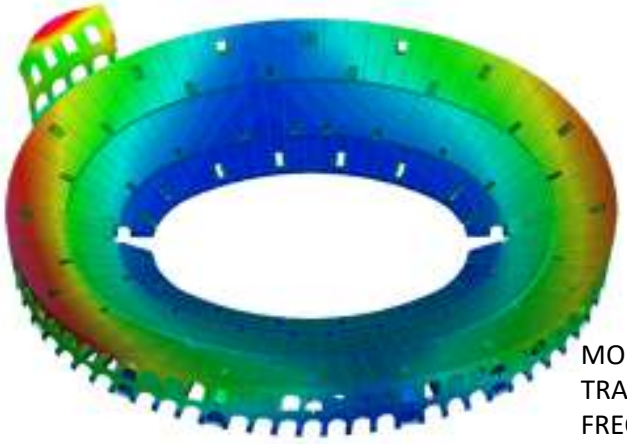
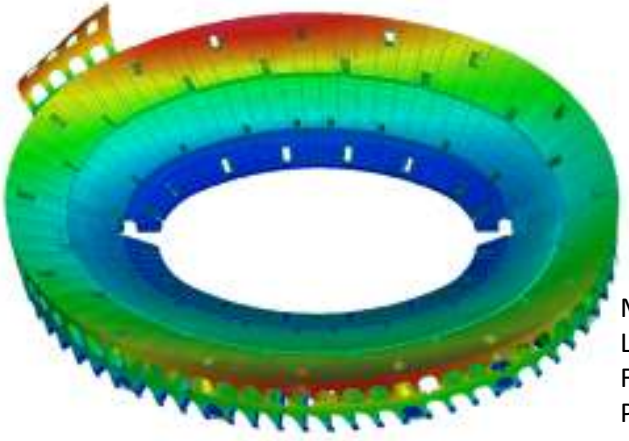
STRUCTURAL ANALYSIS: VULNERABILITY ASSESSMENT

Natural Frequency Analysis was considered in order to assess the eigenmodes and values, and subsequently to Spectral Response Analysis. Safety requirements are met for the walls resisting skeleton of the Arena.

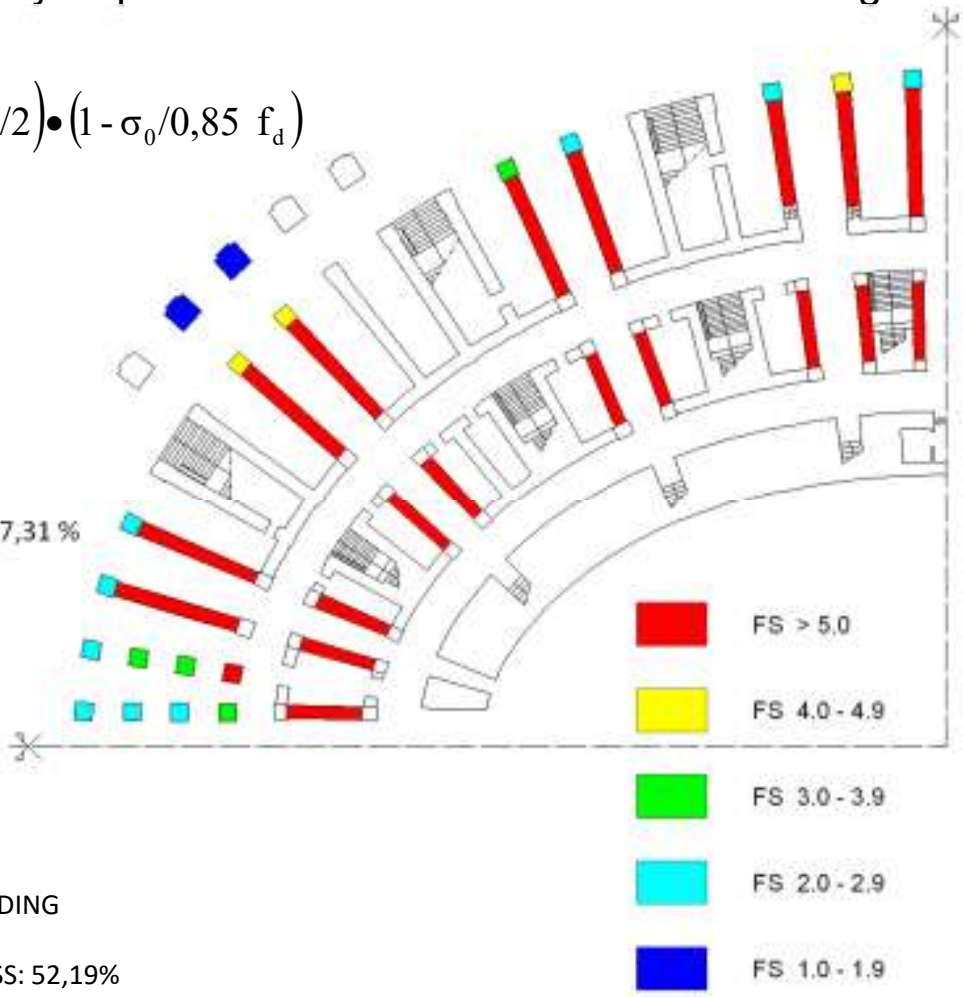


MODE 5
TRANSVERSE BENDING
FREQ: 5,30 Hz
PARTICIPATING MASS: 37,31 %



MODE 6
LONGITUDINAL BENDING
FREQ: 5,56 Hz
PARTICIPATING MASS: 52,19%

$$M_u = \left(l^2\ t\ \sigma_0/2\right) \bullet \left(1 - \sigma_0/0{,}85\ f_d\right)$$



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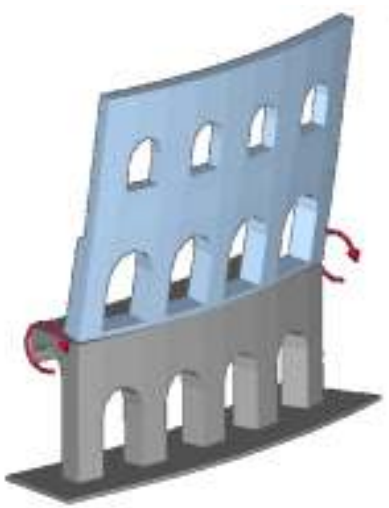
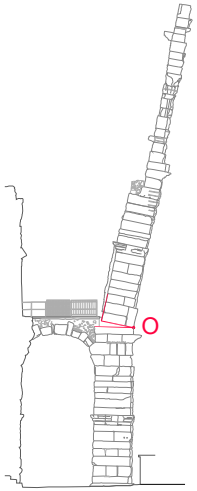
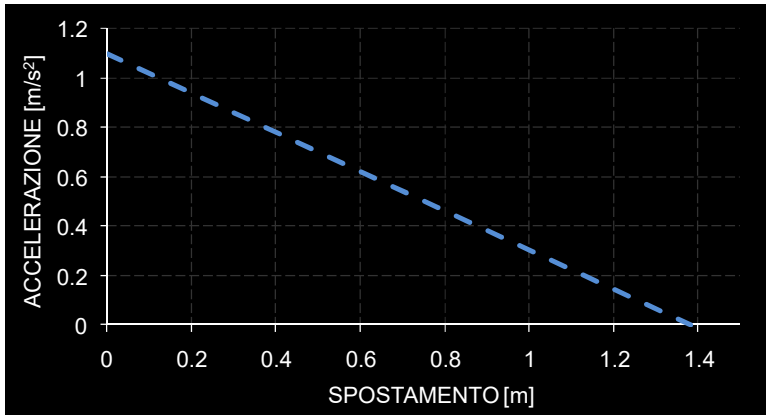
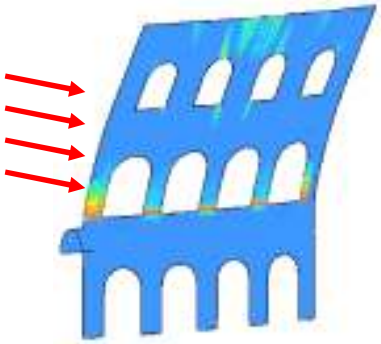
STRUCTURAL ANALYSIS: VULNERABILITY ASSESSMENT



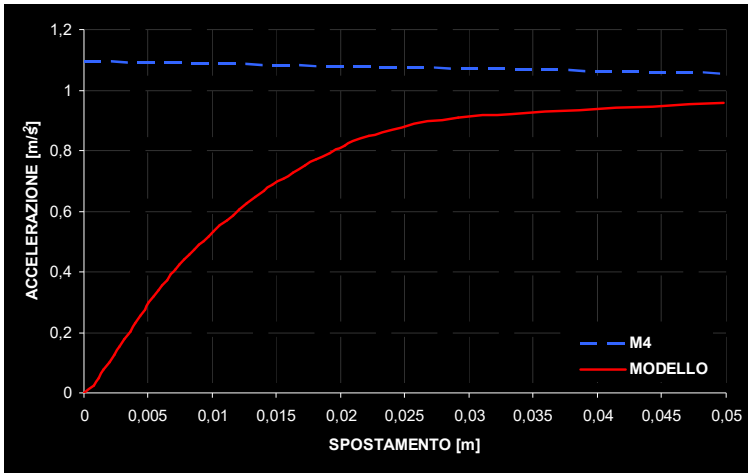




KINEMATIC MODEL



FE NON LINEAR



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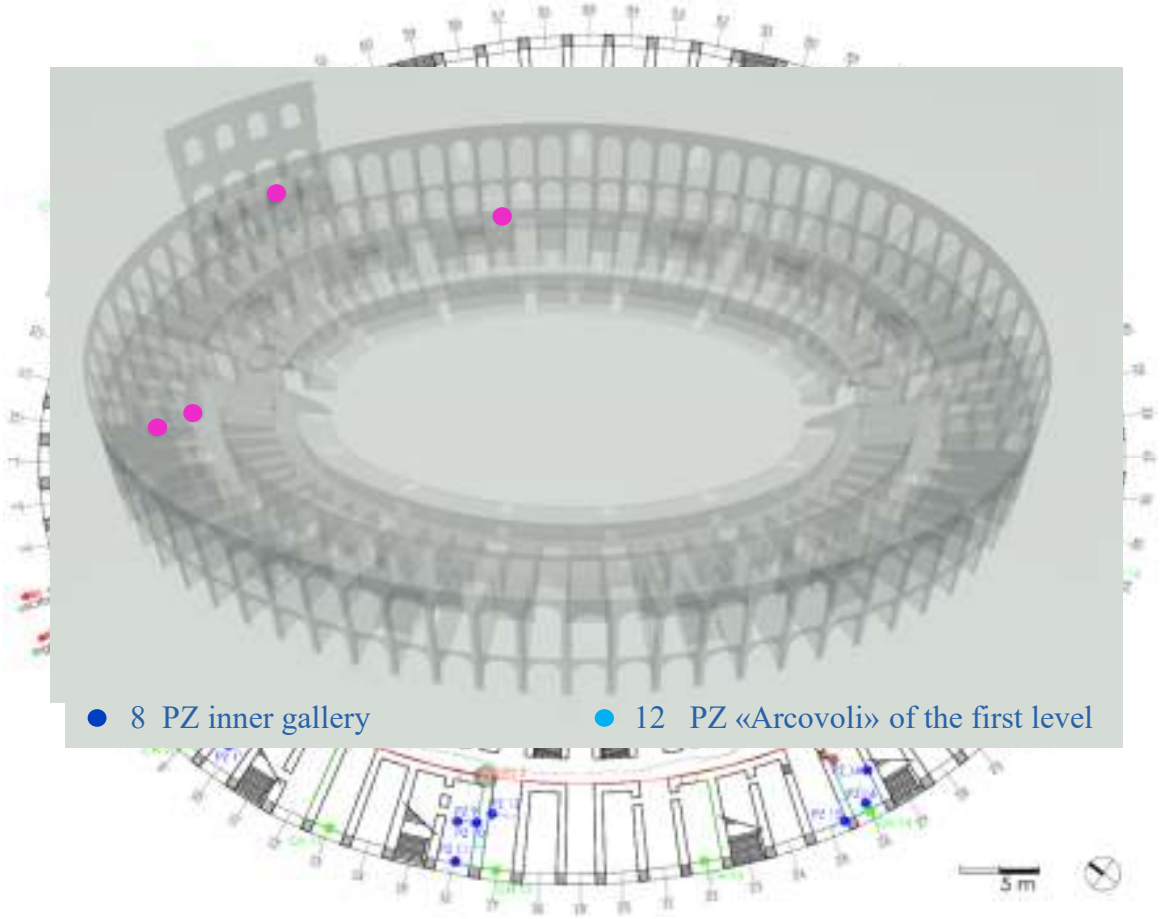
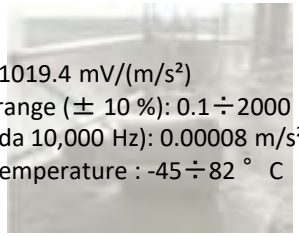
STRUCTURAL HEALTH MONITORING



- 8 PZ inner gallery
- 12 PZ «Arcovoli» of the first level

DYNAMIC MONITORING:

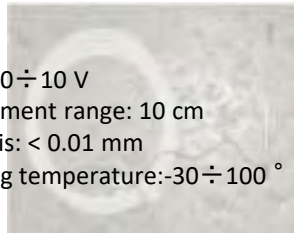
16 SINGLE-AXIS ACCELEROMETERS



Sensitivity: 1019.4 mV/(m/s²)
Frequency range (± 10 %): 0.1÷2000 Hz
Resolution(da 10,000 Hz): 0.00008 m/s²
Operating temperature : -45÷82 ° C

STATIC MONITORING:

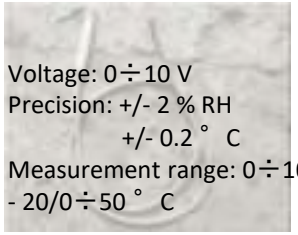
20 DISPLACEMENT TRANSDUCERS



Voltage: 0÷10 V
Measurement range: 10 cm
Hysteresis: < 0.01 mm
Operating temperature:-30÷100 ° C

ENVIRONMENTAL MONITORING:

4 TEMPERATURE/RH



Voltage: 0÷10 V
Precision: +/- 2 % RH
+/- 0.2 ° C
Measurement range: 0÷100% RH
- 20/0÷50 ° C

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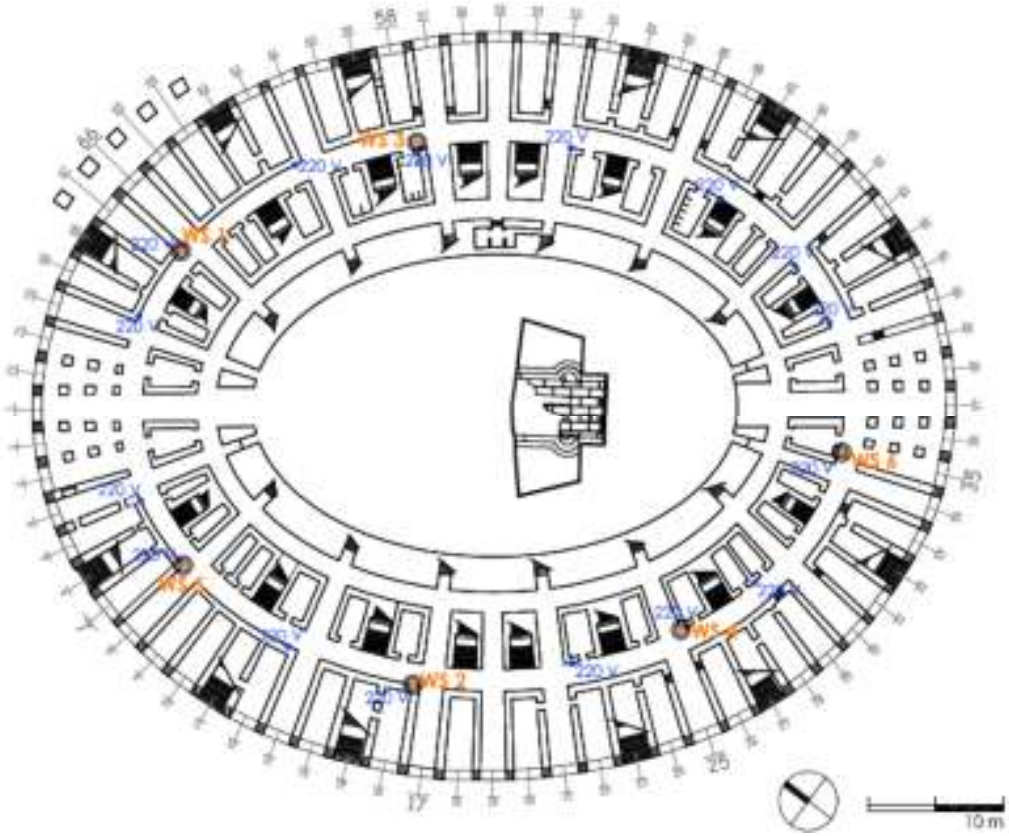
STRUCTURAL HEALTH MONITORING

Static sensors



Wireless Node	Corresponding gate nr
WS 1	66
WS 2	17
WS 3	58
WS 4	25
WS 5	7
WS 6	35

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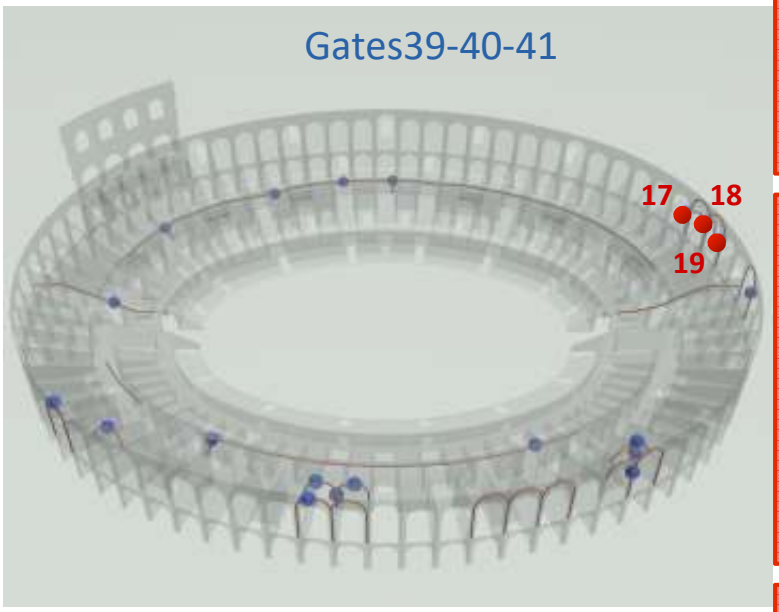
STRUCTURAL HEALTH MONITORING

Static sensors



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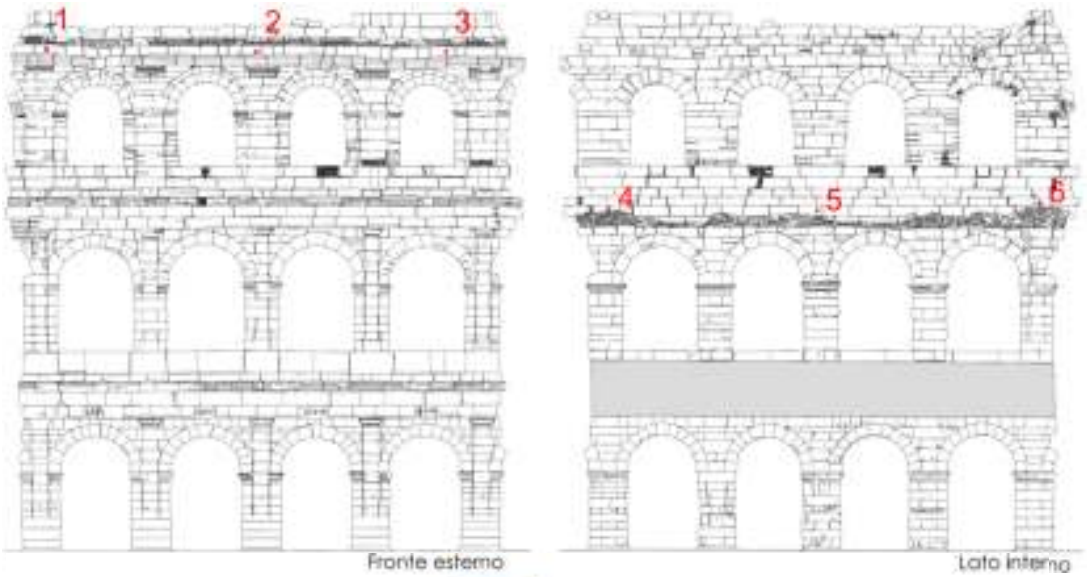
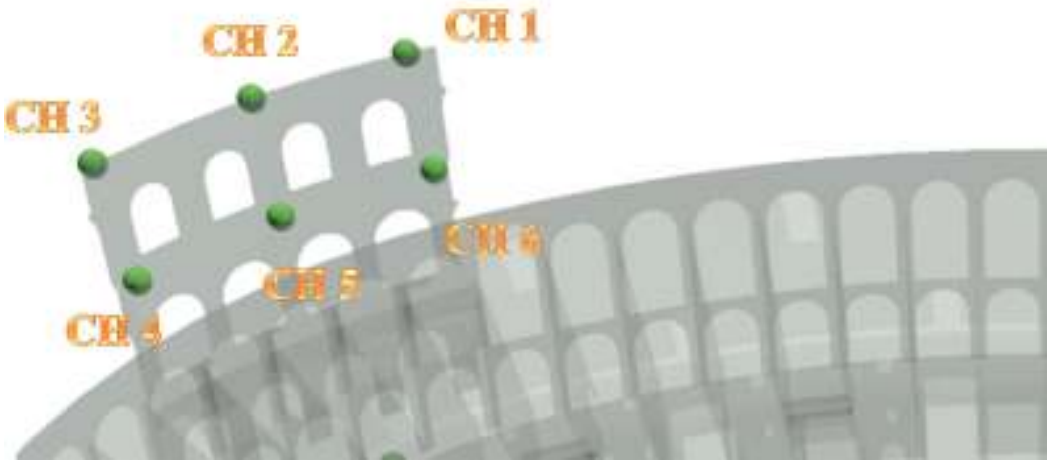
SHM SYSTEM - Dynamic sensors





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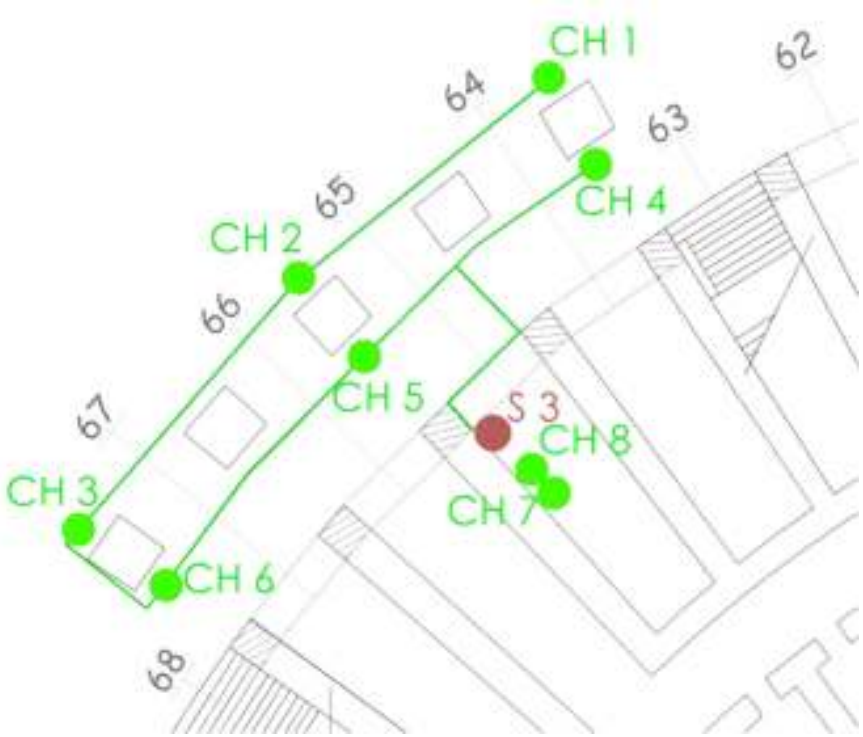
SHM SYSTEM - Dynamic sensors



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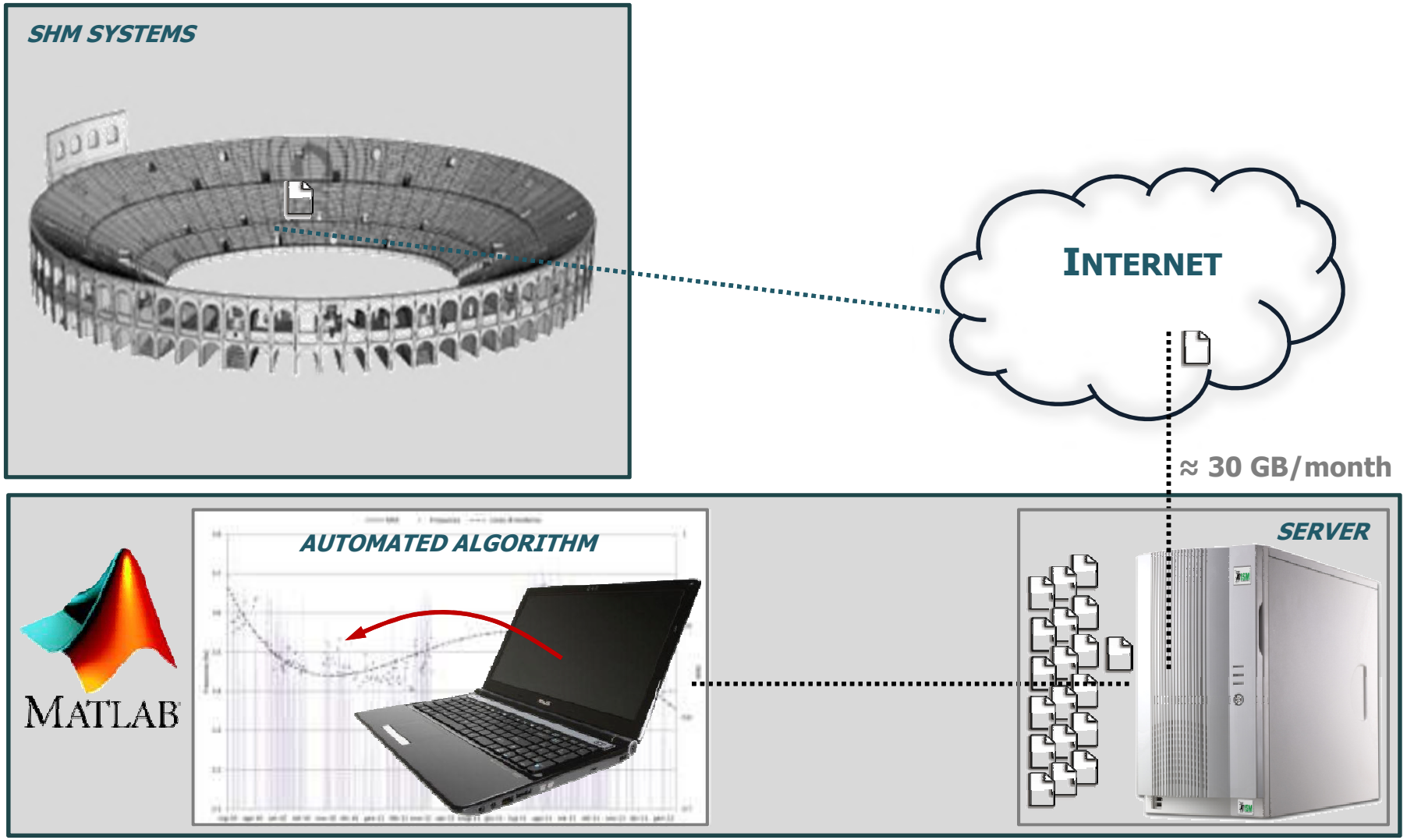
SHM SYSTEM - DATA PROCESSING



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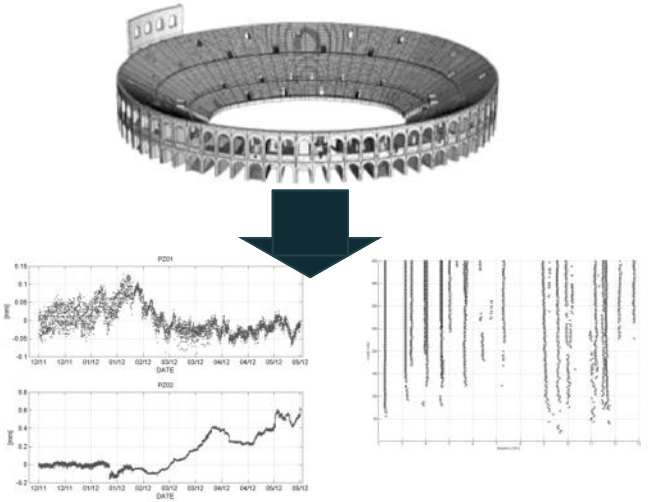
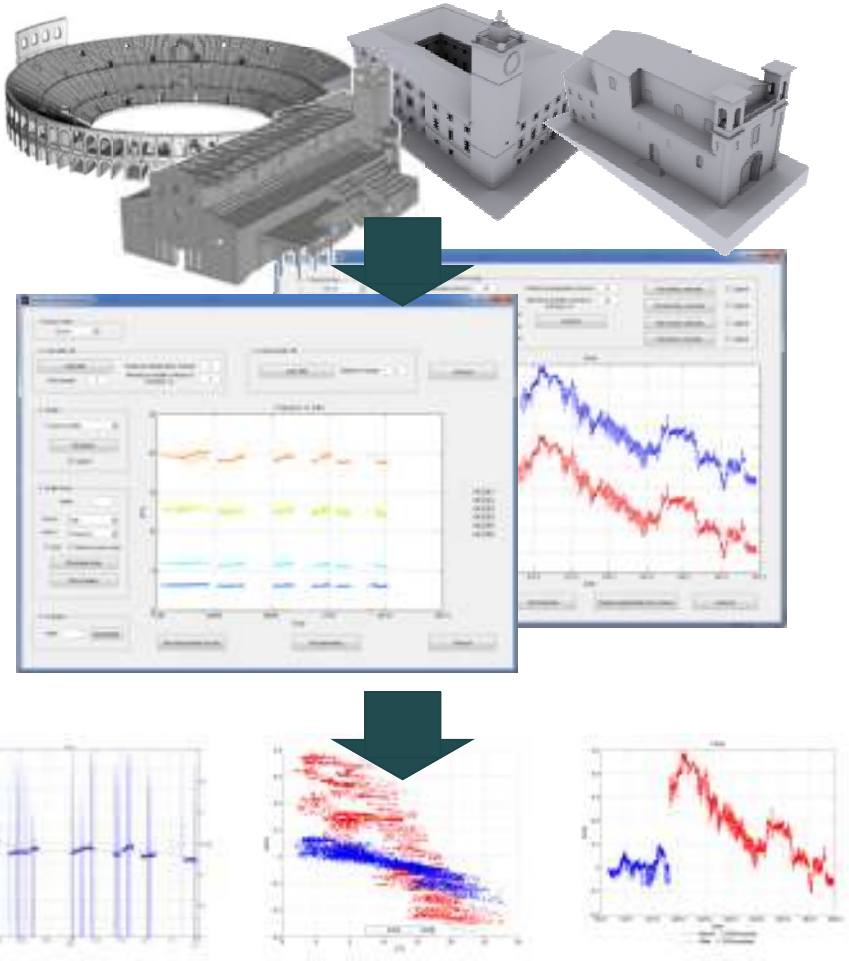
AUTOMATED ALGORITHMS FOR SHM

AUTOMATIC SUBROUTINE (NO USER-INTERACTION)



- EARLY WARNING MESSAGES
- AUTOMATIC PLOT OF RESULTS
- DETECTION OF SYSTEM OR SENSOR MALFUNCTION

GRAPHICAL USER INTERFACE (GUI)



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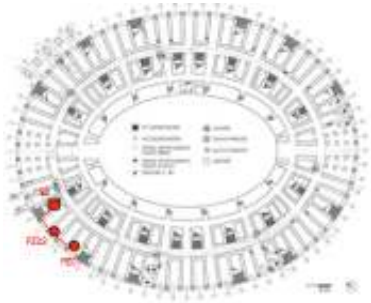
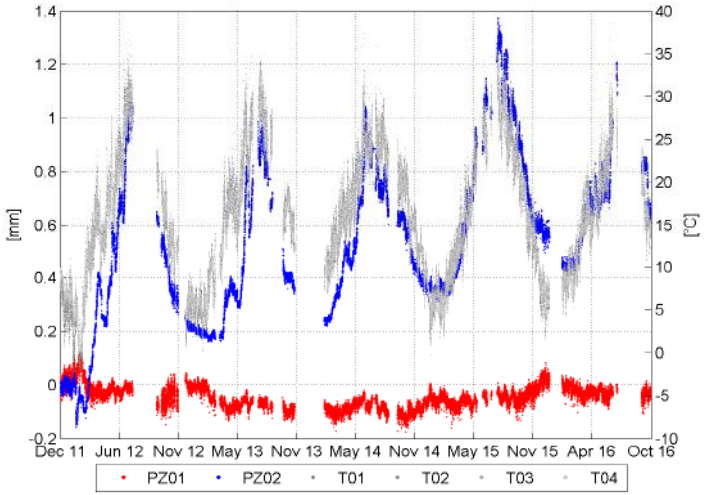
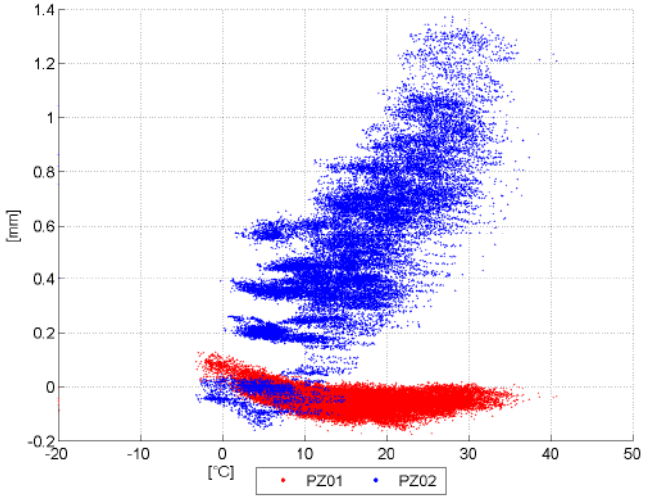
STATIC MONITORING RESULTS

GROUP 1







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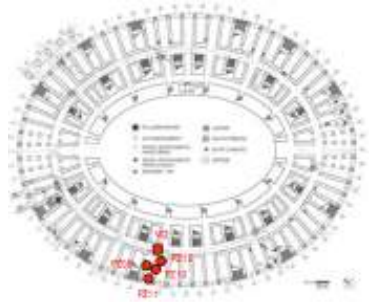

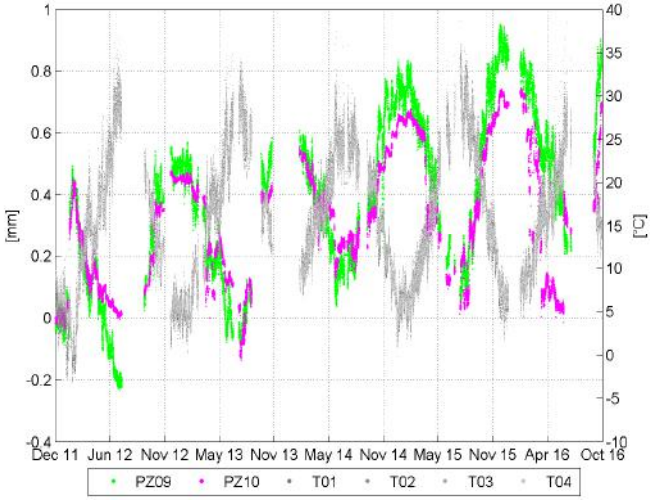

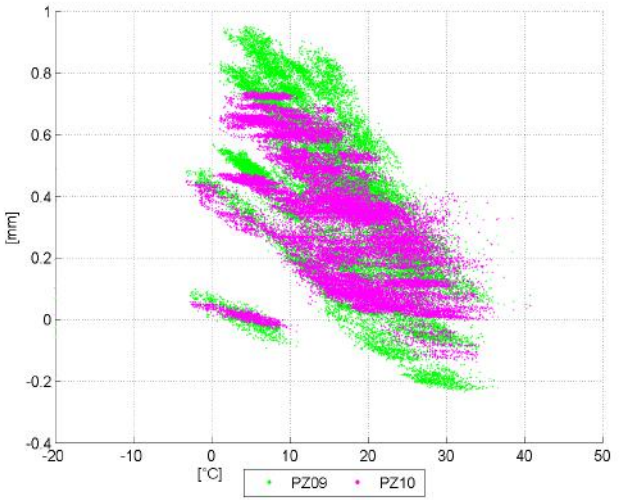

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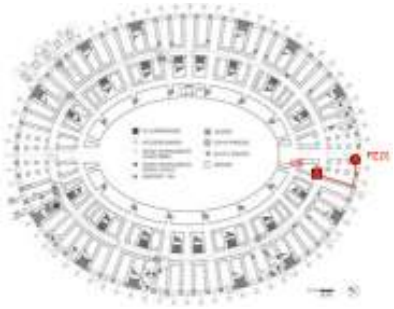
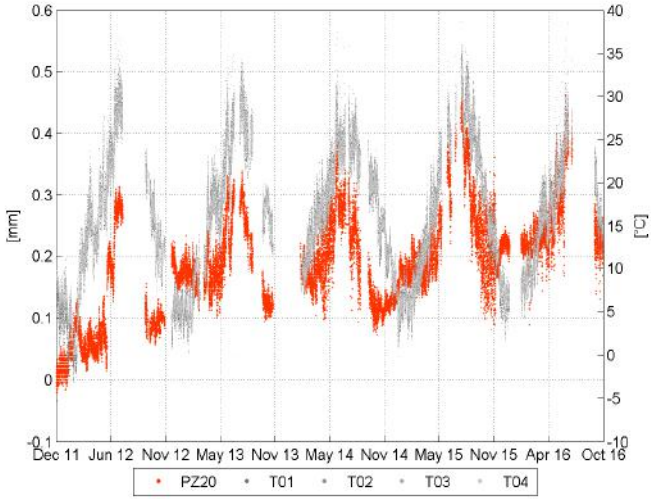
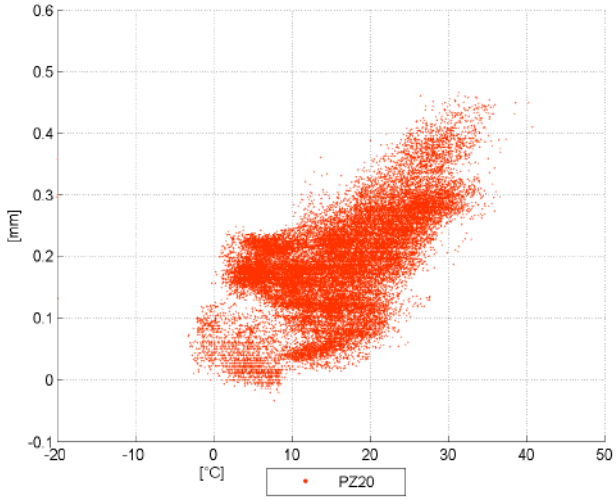
STATIC MONITORING RESULTS

GROUP 3







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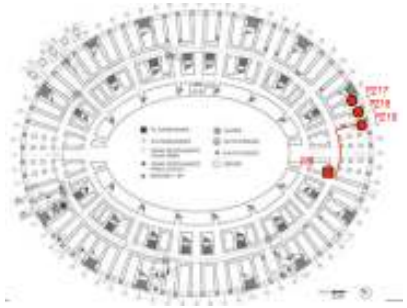

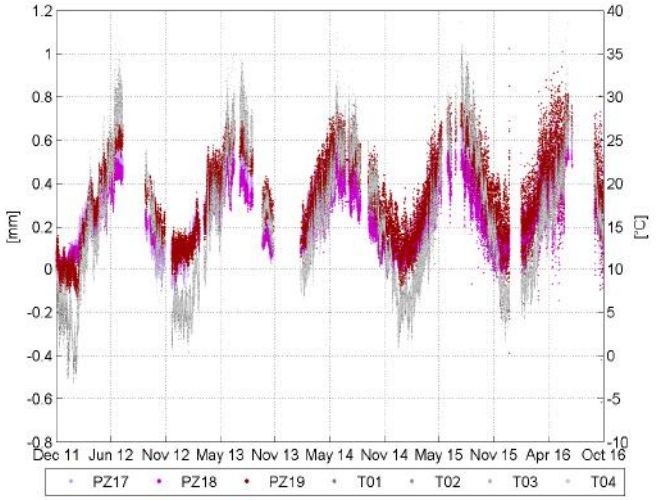

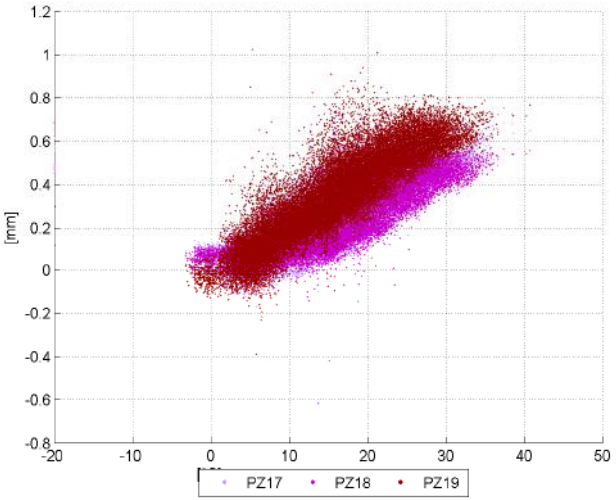

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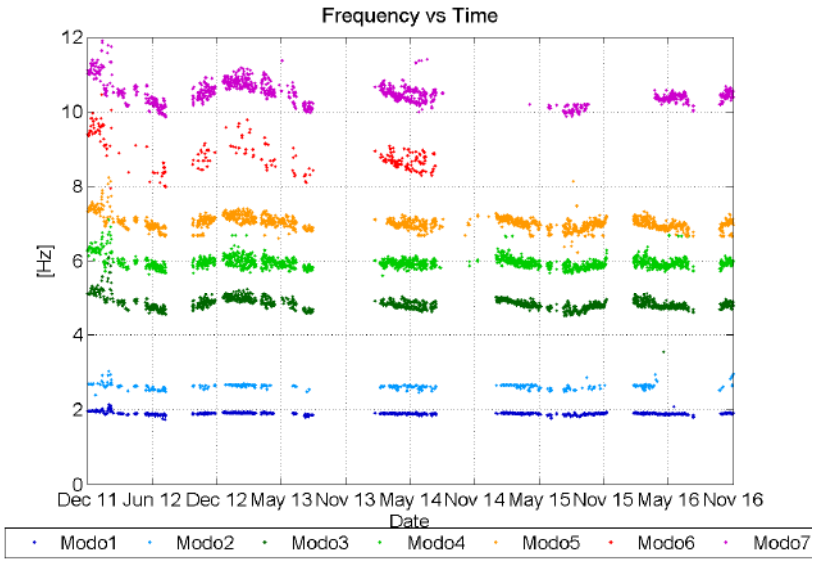
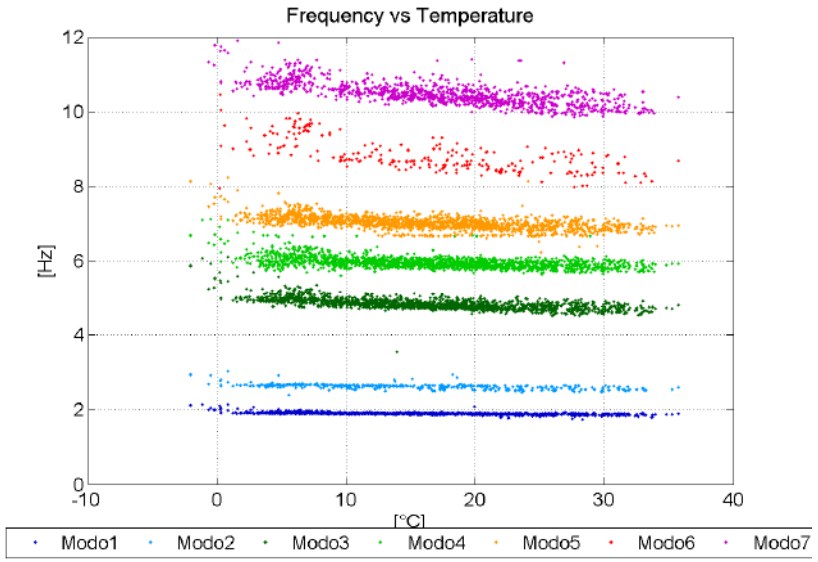
DYNAMIC MONITORING RESULTS

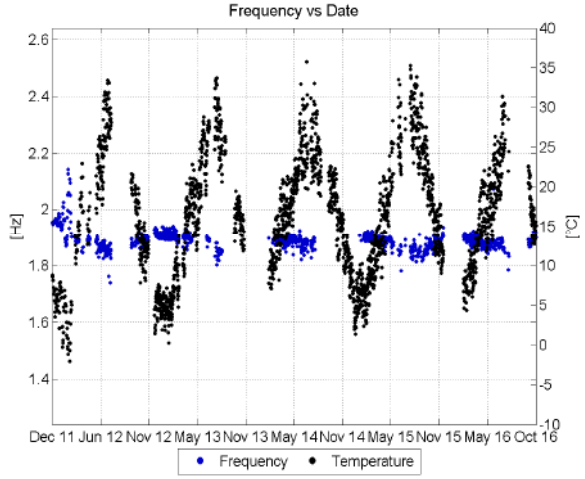
FREQUENCY VS. TIME



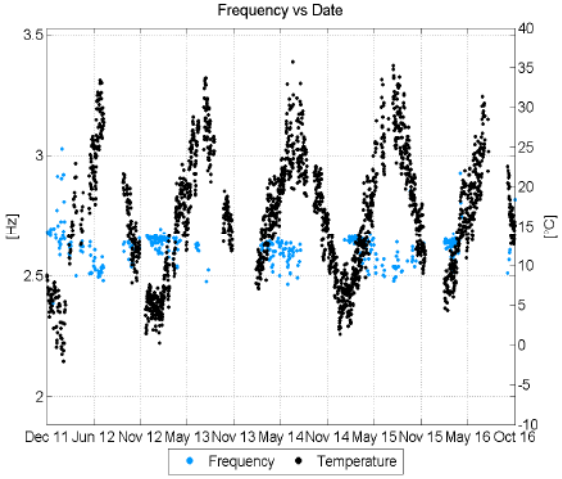
FREQUENCY VS. TEMPERATURE



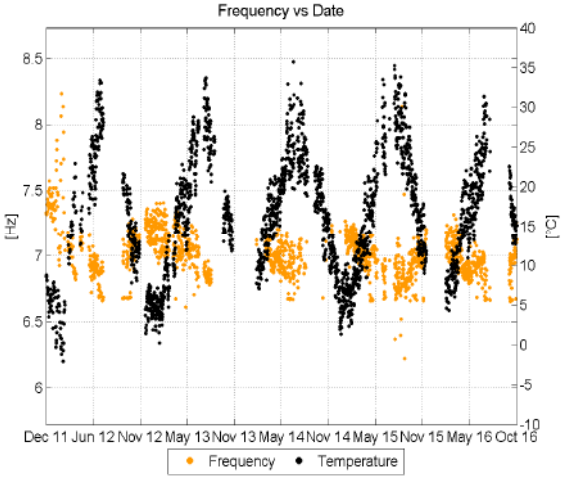
1st MODE



2nd MODE



3rd MODE



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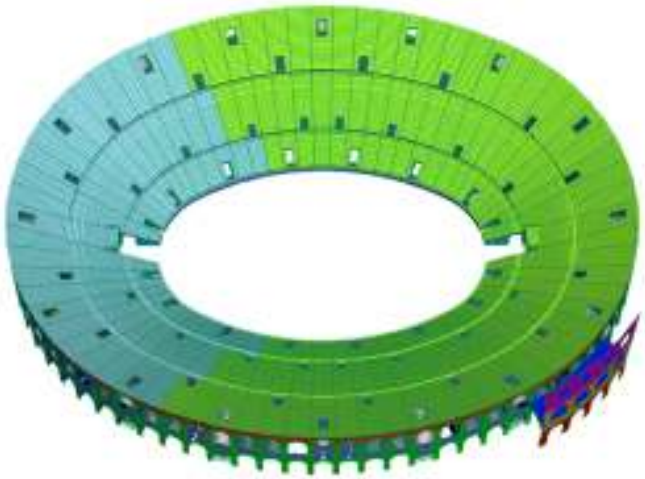
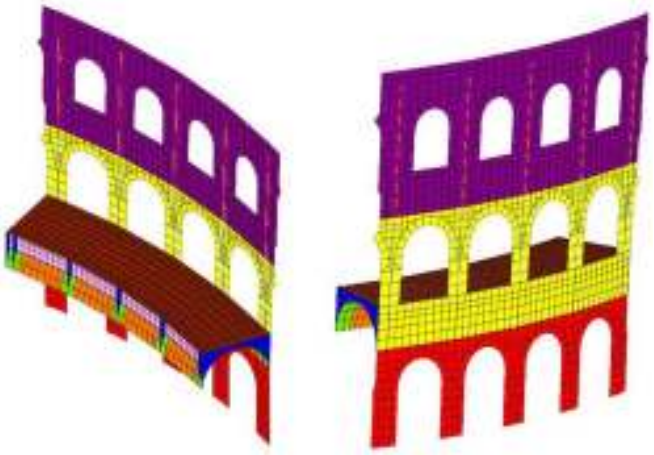
SHM SYSTEM - Model updating

- Model driven approach → exploit SHM and dynamic identification results to calibrate and validate reference numerical models
- Implementation of modal matching procedures
- Model updating targets: material properties, geometry, morphology, connections, boundary conditions, soil-structure interaction, damage distribution, ect.



FE MODEL OF THE ARENA'S WING



CALIBRATION PROCEDURE

- Identification of morphology and materials
- Definition of initial values of elastic mechanical properties
- Iterative variation of mechanical properties/boundary conditions within a predefined range until reaching the final calibration

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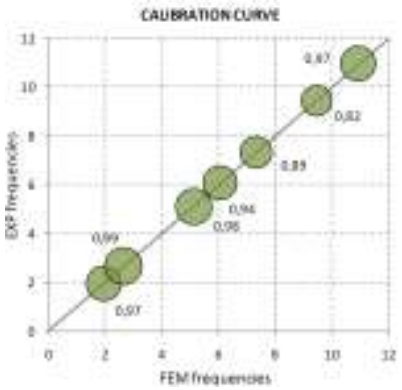
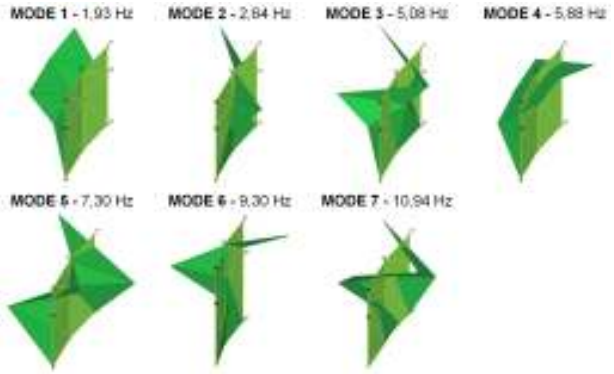
SHM SYSTEM - Model updating

MODAL MATCHING: EXP/FEM RESULTS

MODE	Type	f_{EXP} [Hz]	f_{FEM} [Hz]	Average error ε [%]	MAC $(\{\psi^{EXP}\},\{\psi^{FEM}\})$
1	1st out-of-plane bend.	1,924	1,924	|0,01|	0,973
2	1st torsional	2,666	2,640	|1,00|	0,993
3	2nd torsional	5,103	5,122	|0,36|	0,984
4	2nd out-of-plane bend.	6,086	6,054	|0,53|	0,936
5	3rd torsional	7,308	7,323	|0,20|	0,886
6	4th torsional	9,434	9,464	|0,32|	0,821
7	5th torsional	10,970	10,944	|0,24|	0,973

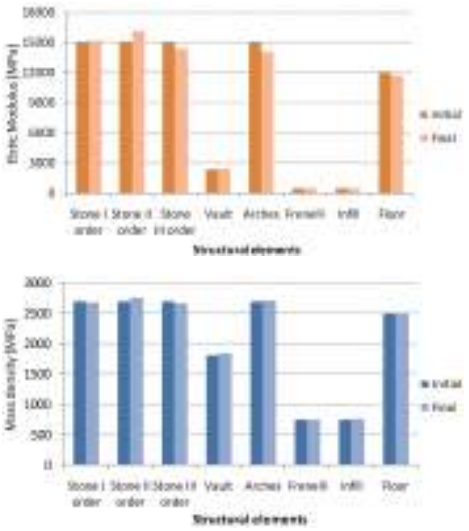


EXPERIMENTAL MODE SHAPES

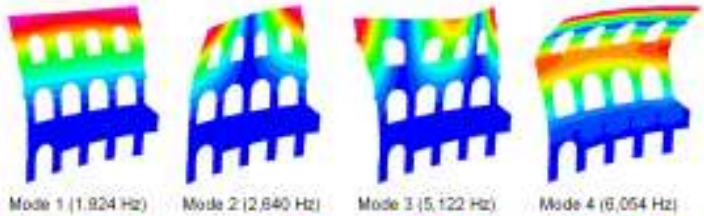


VARIATION OF UPDATING PARAMETERS

Structural element	ELASTIC MODULUS [MPa]			MASS DENSITY [kg/m³]		
	Initial	Final	Diff. [%]	Initial	Final	Diff.[%]
Stone I order	15000	15223	1.49	2700	2687	-0.48
Stone II order	15000	16174	7.82	2700	2752	1.92
Stone III order	15000	14443	-3.71	2700	2658	-1.56
Vault	2400	2479	3.27	1800	1830	1.64
Arches	15000	14096	-6.03	2700	2703	0.12
Frenelli	500	477	-4.63	750	750	-0.04
Infill	500	483	-3.48	750	757	0.92
Stone floor	12000	11723	-2,31	2500	2509	0.36



NUMERICAL MODE SHAPES



* in-plane bending mode not identified during AVT and dynamic monitoring

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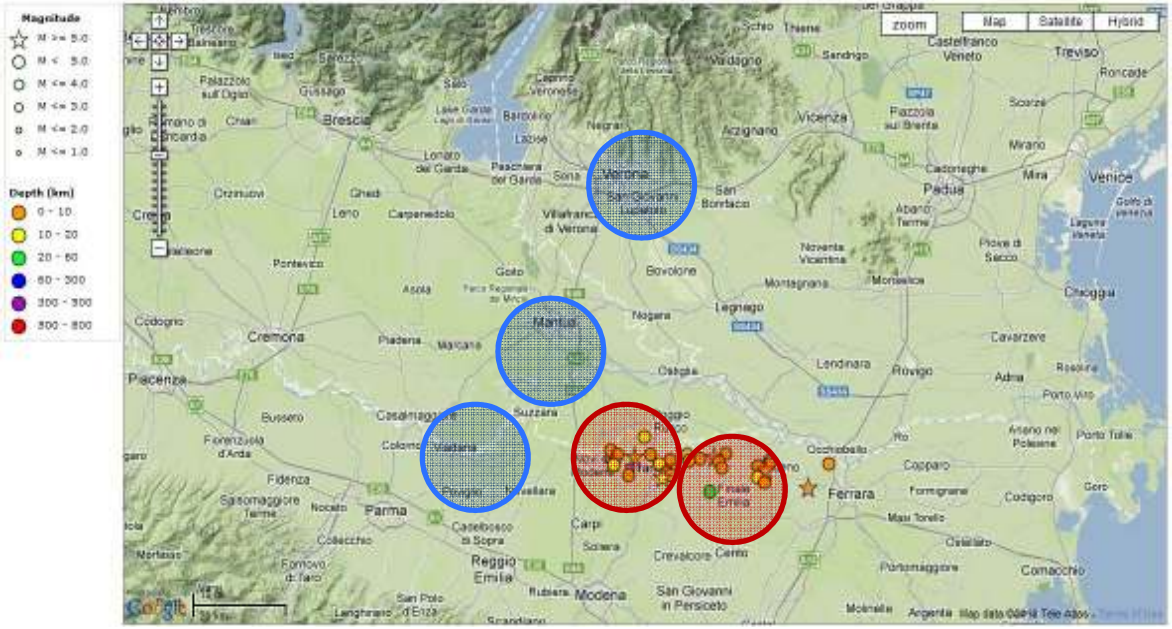
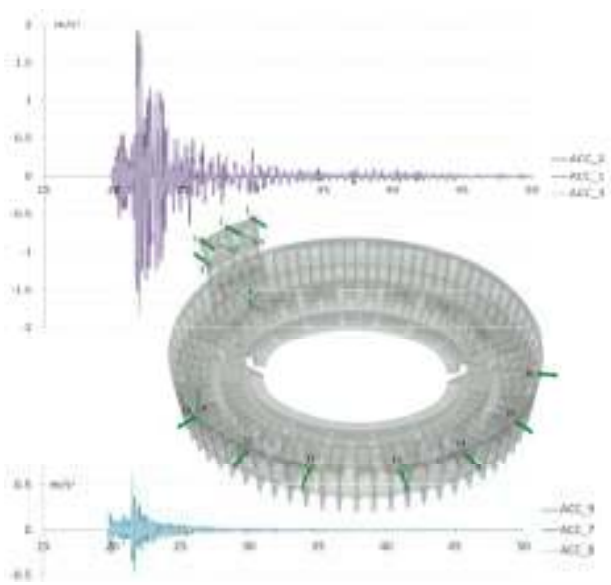
SHM SYSTEM - Exceptional events

5 Main seismic events (with several aftershoks) recorded from January to May 2012:

1. Prealpi Venete
2. Reggio Emilia province
3. Parma province
4. Emilia-Romagna: Finale Emilia
5. Emilia-Romagna: Medolla

Seismic events	UTC	Magnitude	Depth	GPS Coordinates	
				Latitude	Longitude
1	2012-01-24 23:54:46	4.2	10.3	45.541	10.973
2	2012-01-25 08:06:36	4.9	33.2	44.854	10.538
3	2012-01-27 14:53:13	5.4	60.8	44.483	10.033
4	2012-05-20 02:03:53	5.9	6.3	44.890	11.230
5	2012-05-29 07:00:03	5.8	10.2	44.851	11.086





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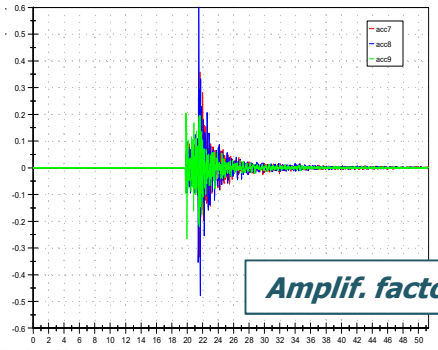
SHM SYSTEM - Exceptional events

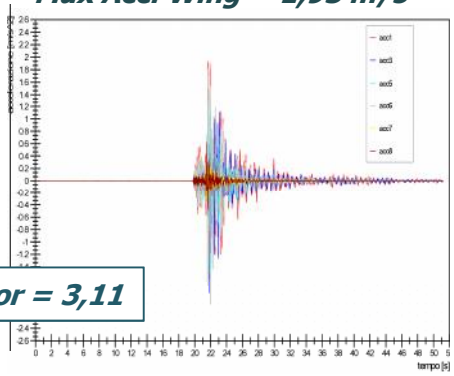
MAIN SHOCK: 25 JANUARY 2012

Prealpi Venete (VR) 2012-01-24 23:54:46
Magnitude: 4.2
Depth 10.3 Km
Distance: 11,5 Km

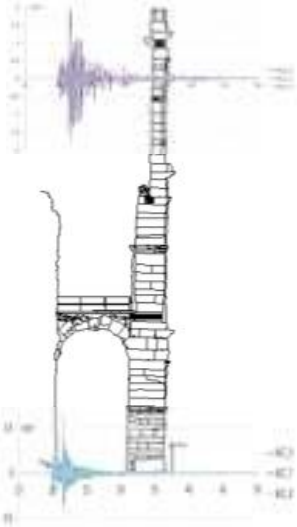
Max. Acc. Base = 0,62 m/s²



Max Acc. Wing = 1,93 m/s²



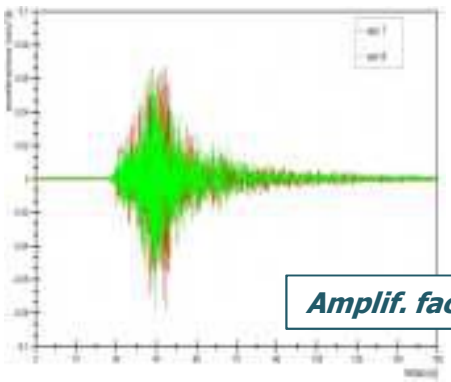
Amplif. factor = 3,11



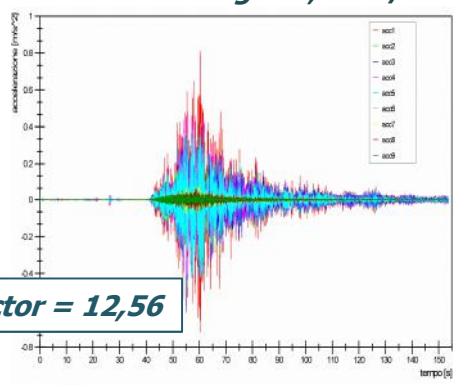
MAIN SHOCK: 29 MAY 2012

Pianura Padana-Emiliana (MO) 2012-05-29 07:00:03
Magnitude: 5.8
Depth 10.2 Km
Distance: 75 Km

Max. Acc. Base = 0,08 m/s²



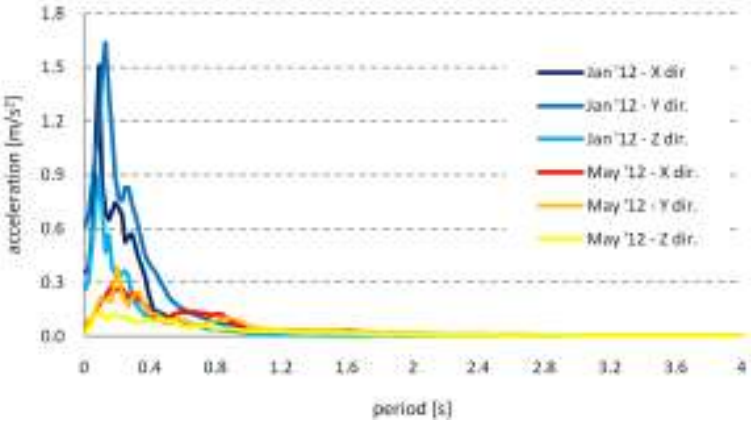
Max Acc. Wing = 0,98 m/s²



Amplif. factor = 12,56

COMPARISON: MAX. ACCELRATIONS, AMPLIFICATION FACTORS AND ELASTIC RESPONSE SPECTRA

Seismic event	BASE	TOP WING		TOP AMPHITHEATER	
	PGA [m/s²]	Max. Acc. [m/s²]	Amplif. factor	Max Acc. [m/s²]	Amplif. factor
25/01/2012	0,619	1,93	3,11	1,251	2,02
29/05/2012	0,078	0,98	12,56	0,40	5,13



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SHM SYSTEM - Exceptional events

MAIN SHOCK: 25 JANUARY 2012 → Dynamic identification of modal parameters before, during and after the seismic event

OMA TECHNIQUES NOT RELIABLE

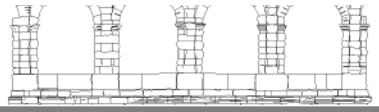
- INPUT IS NOT A WHITHE NOISE STOCHASTIC PROCESS
- EARTHQUAKE IS A NONSTATIONARY SIGNAL
- FREQUENCY SPECTRUM OF THE TRANSIENT INPUT BIASES MODAL PARAMETER ESTIMATION

→ **OMAX COMBINED OMA/EMA**

DATA-DRIVEN REFERENCE-BASED DETERMINISTIC-STOCHASTIC SUBSPACE IDENTIFICATION (CSI/REF) METHOD

FREQUENCY VARIATIONS							
MODE	BE [Hz]	MS [Hz]	PP [Hz]	AE [Hz]	f change (BE-MS)	f change (BE-AE)	MAC $(\{\psi^{BE}\},\{\psi^{MS}\})$
1	1,98	1,66	1,73	1,89	-16,28%	-4,44%	0,9998
2	2,75	2,24	2,35	2,62	-18,63%	-5,11%	0,9664
3	5,31	n.i*	4,50	4,97	/	-6,94%	/
4	6,44	4,52	5,29	6,07	-29,77%	-6,09%	0,9933
5	7,57	5,59	6,28	7,10	-26,15%	-6,55%	0,9372
6	10,00	n.i.*	n.i*	9,18	/	-8,89%	/
7	11,40	8,62	9,71	10,67	-24,34%	-6,78%	0,9581

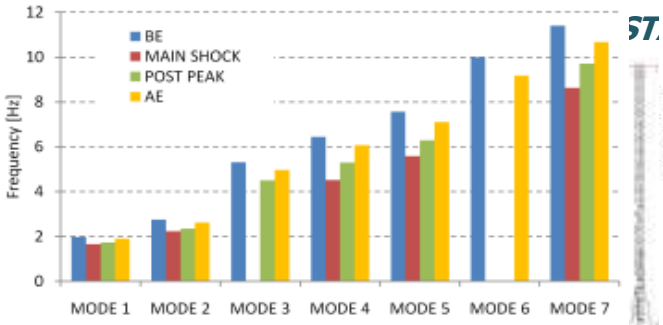
*not identified

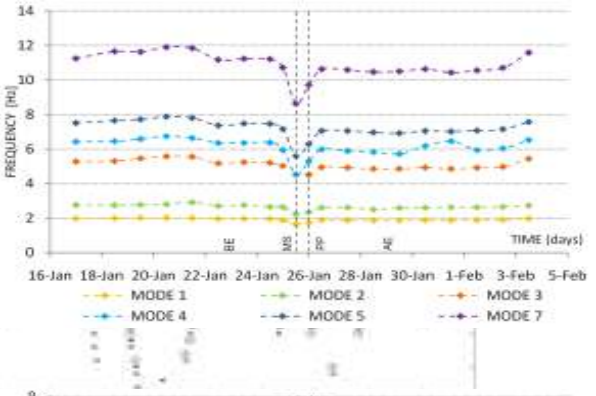


DAMPING RATIO VARIATIONS						
MODE	BE [%]	MS [%]	PP [%]	AE [%]	ξ change (BE-MS)	ξ change (BE-AE)
1	1.17	2.71	2.18	0.96	+131.47%	-22.25%
2	1.11	5.11	2.67	0.82	+361.43%	-35.21%
3	1.03	n.i*	1.30	0.96	/	-7.10%
4	6.44	1.97	3.75	4.87	-69.45%	-32.23%
5	2.81	6.64	4.38	2.30	+136.19%	-22.44%
6	0.95	n.i*	n.i*	0.99	/	+3.71%
7	1.34	3.57	1.93	1.19	+166.63%	-12.51%

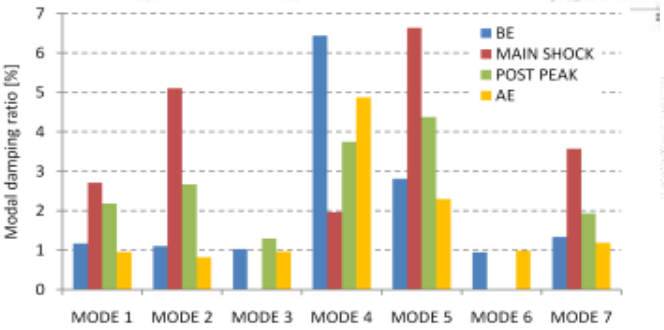
*not identified

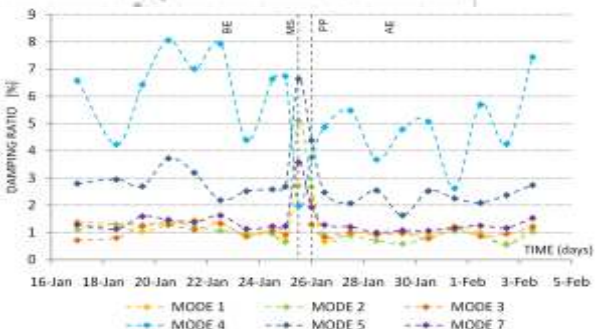
NATURAL FREQUENCIES VARIATION





MODAL DAMPING VARIATION





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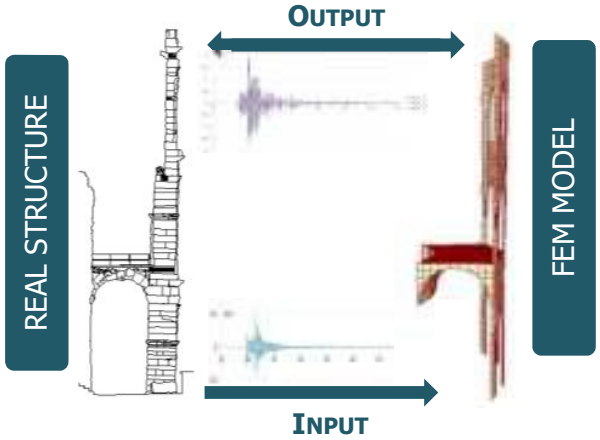
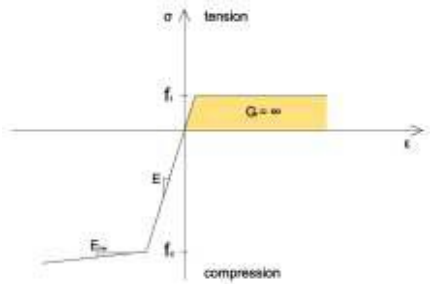
SHM SYSTEM - Exceptional events



- FE simulation on the main shock of the 25/01/2012 earthquake
- Type of analysis: linear and non-linear dynamic
- Aims:
  a) Compare the actual response (experimentally recorded) with the model response (numerically predicted)
  b) Refine the calibration of the reference FE model: modification of the elastic properties and of the damping coefficients, accurately estimated during a real earthquake

NON-LINEAR CONSTITUTIVE MODEL OF MASONRY

Material	Tensile strength f_t [MPa]	Fracture energy G_f [N/mm]	Compressive strength f_c [MPa]	Elastic Hardening E_{har} [MPa]
Stone blocks masonry	0,13	∞	3,00	3,00
Opus coementicium (vaults and arches)	0,13	∞	3,00	3,00
Infill of vaults	linear elastic			
Stone floor	linear elastic			



DAMPING COEFFICIENT CALIBRATION

From dynamic identification during the earthquake

DAMPING RATIO VARIATIONS						
MODE	BE [%]	MS [%]	PP [%]	AE [%]	ξ change (BE-MS)	ξ change (BE-AE)
1	1.17	2.71	2.18	0.96	+131.47%	-22.25%
2	1.11	5.11	2.67	0.82	+361.43%	-35.21%
3	1.03	n.i*	1.30	0.96	/	-7.10%
4	6.44	1.97	3.75	4.87	-69.45%	-32.23%
5	2.81	6.64	4.38	2.30	+136.19%	-22.44%
6	0.95	n.i*	n.i*	0.99	/	+3.71%
7	1.34	3.57	1.93	1.19	+166.63%	-12.51%

*not identified

Reyleigh damping: $\zeta = aM + bK$

a, b Reyleigh coefficients calculated on the estimated damping ratio ξ

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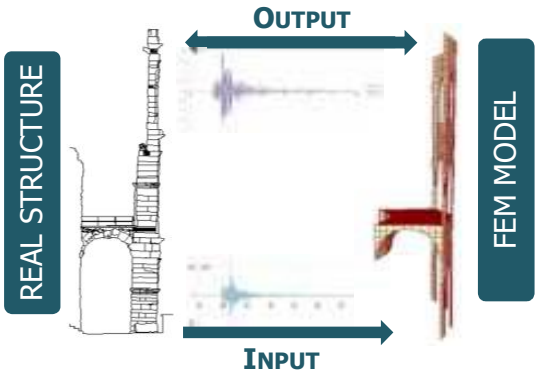
SHM SYSTEM - Exceptional events



Model	III order		II order	
	Max Acc. 1 [m/s²]	Max Acc. 3 [m/s²]	Max Acc. 5 [m/s²]	Max Acc. 6 [m/s²]
Experimental	1,934	1,840	1,670	1,817
FE linear	2,253	2,06	1,330	2,130
FE non linear	1,702	1,86	1,252	1,195

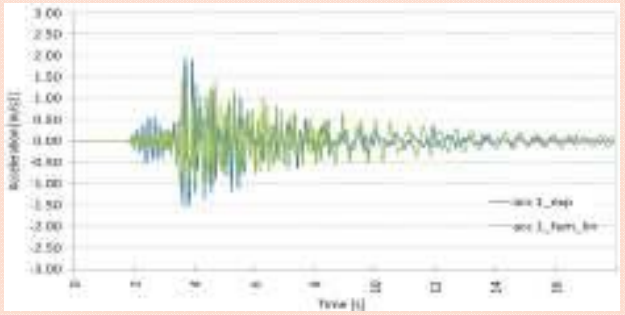
Max. accelerations comparison EXP/FEM

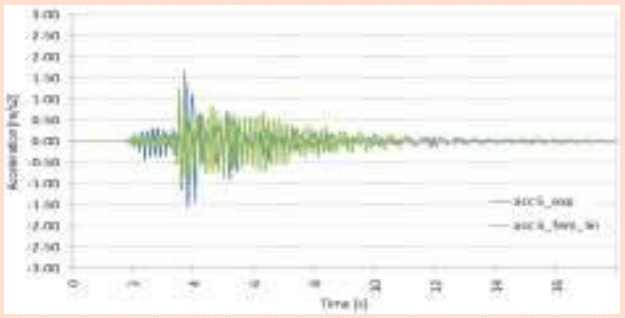
Position	FE model type	Time history	2-10 sec	2-8 sec
Acc. 1	Linear	41,32	37,49	36,37
	Non linear	45,18	45,09	45,76
Acc. 3	Linear	67,60	62,77	60,70
	Non linear	76,53	77,17	78,02
Acc. 5	Linear	46,26	46,30	45,18
	Non linear	47,57	47,23	46,52
Acc. 6	Linear	34,11	33,76	32,67
	Non linear	58,19	58,33	58,52

Fit index comparison EXP/FEM

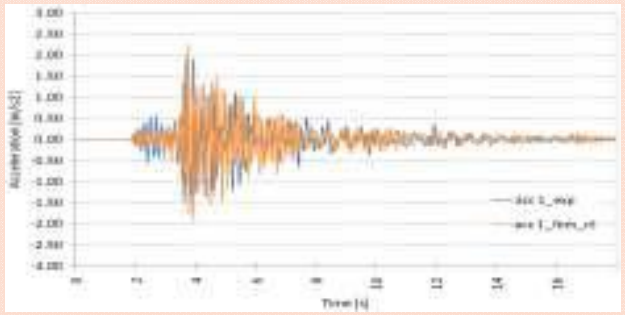
$$fit = 100\frac{1 - norm(y_{fem} - y_{exp})}{norm(y_{exp} - \bar{y}_{exp})}$$

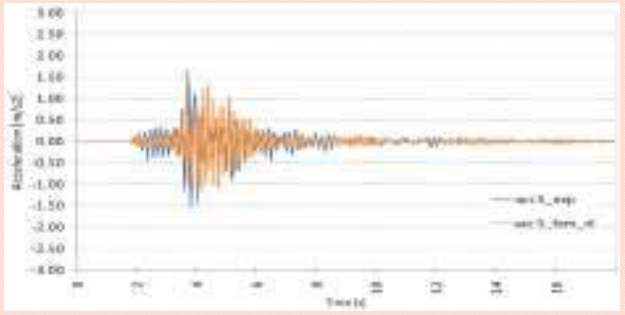
LINEAR MODEL

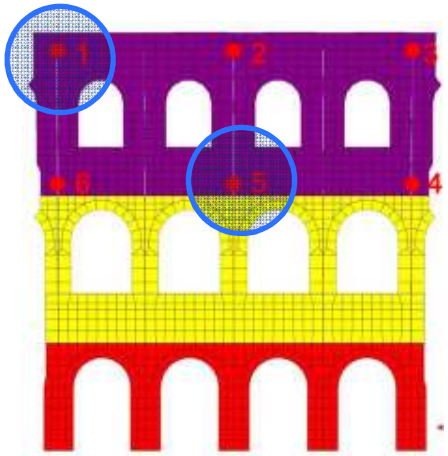




NON-LINEAR MODEL







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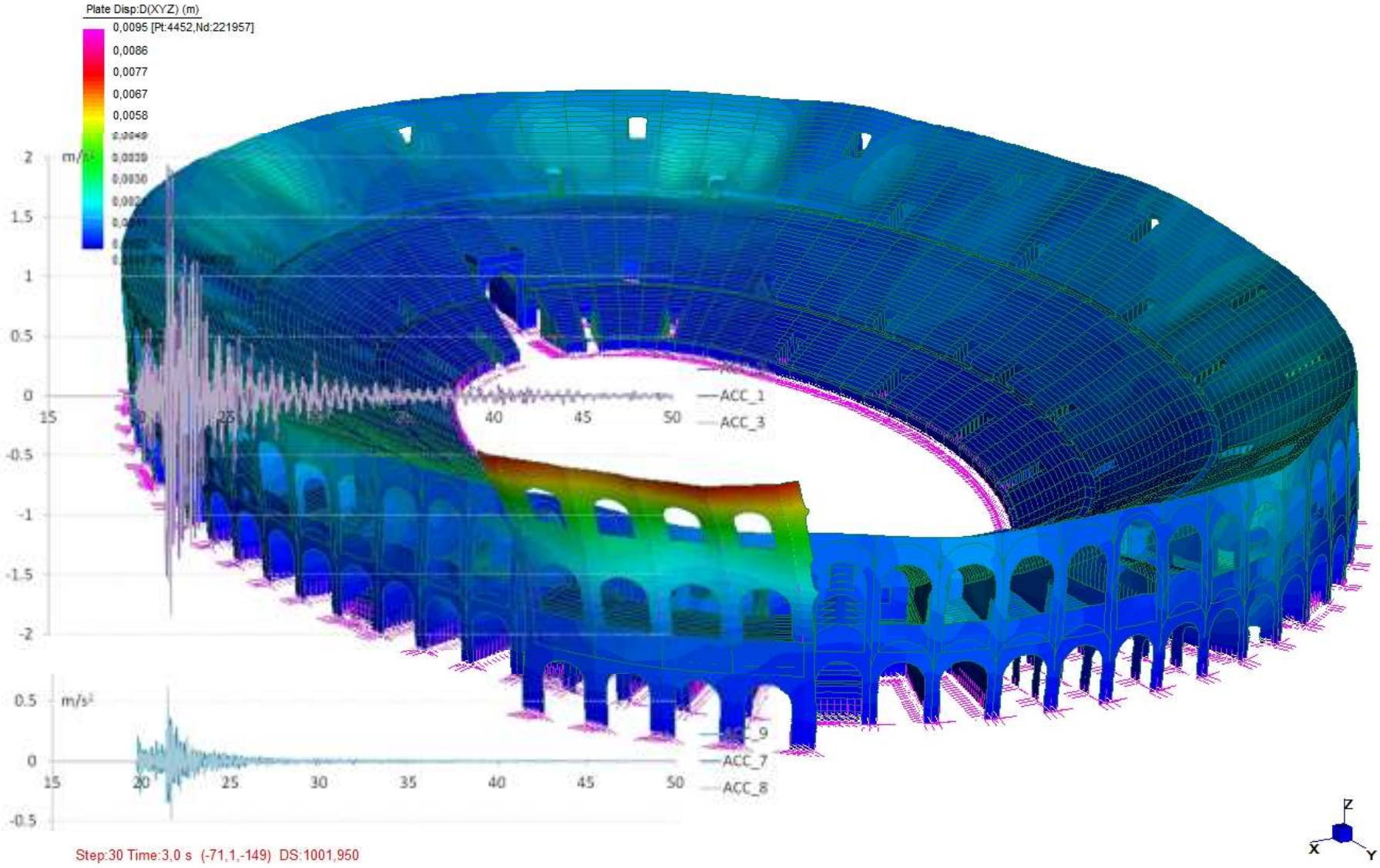
SHM SYSTEM - Exceptional events



TRA GEOLOGIA E GEOFISICA - XV WORKSHOP DI GEOFISICA
IL RUOLO DELLA CONOSCENZA NELLE VALUTAZIONI DI
SICUREZZA STRUTTURALE DEL PATRIMONIO ARCHITETTONICO
6-7 Dicembre, Rovereto

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Examples of Conservation of Cultural Heritage: 20th Reinforced Concrete Buildings




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ISSUES IN ASSESSMENT AND CONSERVATION OF EARLY 20th CENTURY HERITAGE REINFORCED CONCRETE BUILDINGS

- MATERIAL DECAY
- INADEQUATE STRUCTURAL DETAILS
- INADEQUATE SAFETY LEVELS
- MODIFIED USES
- CONSERVATIVE ASPECTS
- REUSE AND VALORIZATION

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PROCEDURES FOR SAFETY ASSESSMENT AND DESIGN: KNOWLEDGE STEPS

INFORMATION FOR STRUCTURAL ASSESSMENT

- available documentation specific to the building in question
- relevant generic data sources (e.g. contemporary codes and standards)
- field investigations

↓ in-situ and/or laboratory measurements and tests

↓

cross-checks should be made between the data collected from different sources to minimise uncertainties

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HISTORICAL AND CRITICAL ANALYSIS → HISTORY OF BUILDING, CHANGES, PAST EVENTS

- historical and archival investigations

GEOMETRY → GEOMETRY, DETAILS, CRACK PATTERNS AND DEFORMATIONS

- in-situ surveys

DETAILS → CONNECTIONS, NO. OF REINFORCEMENT BARS, etc.

- in situ checking

MATERIAL PROPERTIES → MECHANICAL CHARACTERISATION OF CONCRETE AND REBARS

- in-situ and lab testing

KNOWLEDGE LEVEL AND CONFIDENCE FACTORS

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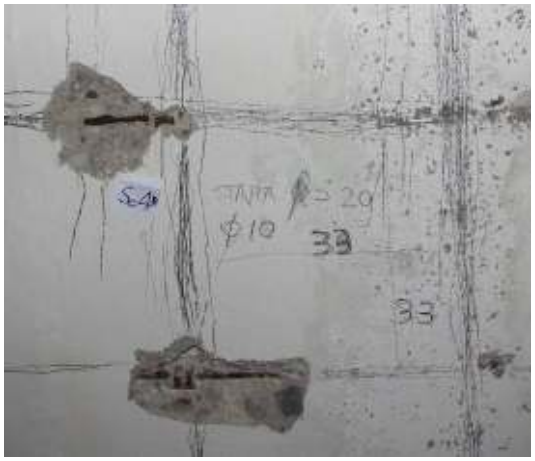
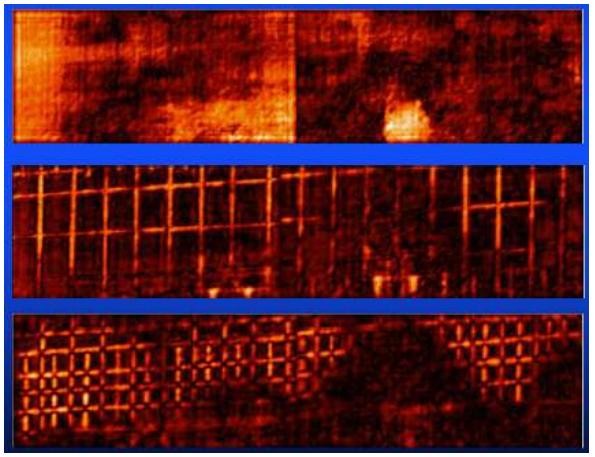
DETAIL CHARACTERIZATION

- local scarifications
- survey of reinforcement bars by direct inspection
- survey of reinforcement bars by NDT test:
  - Ground Penetration Radar
  - Ferroscan - analysis of magnetic fields

Ferroscan



Local scarifications



RADAR

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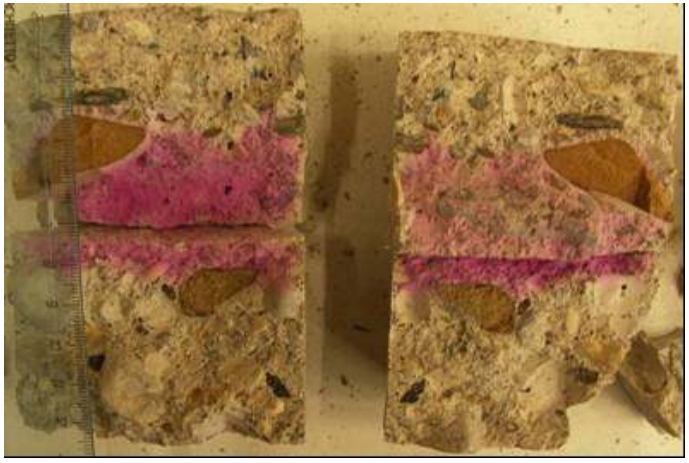
MATERIAL CHARACTERIZATION

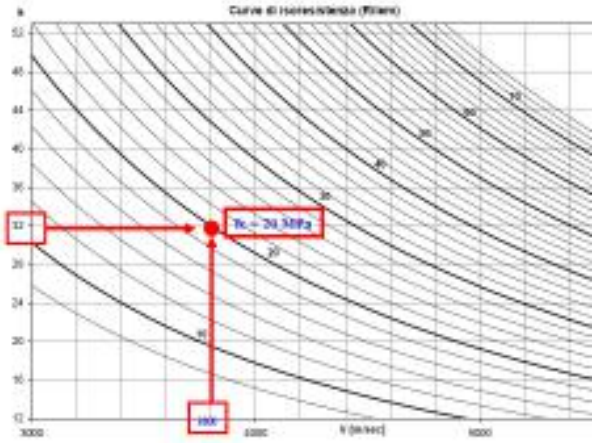
- carbonation depth measurement test
- tensile test of reinforcement bars
- sampling of reinforcement bars
- sampling of concrete corings
- Schmidt rebound hammer test
- Ultrasonic tests and combination with Rebound (SONREB)

Sclerometer



Carbonation test on concrete

Coring and tests



SONREB

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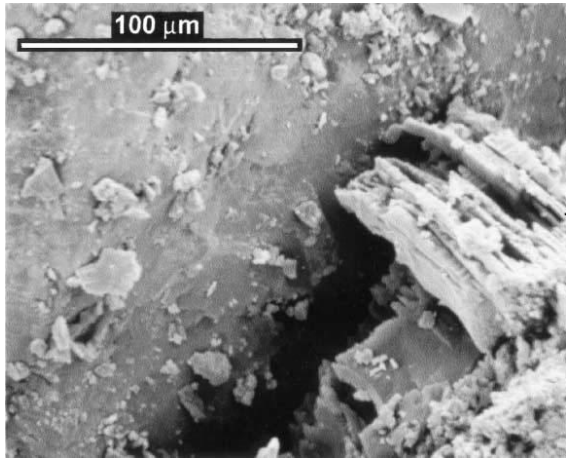
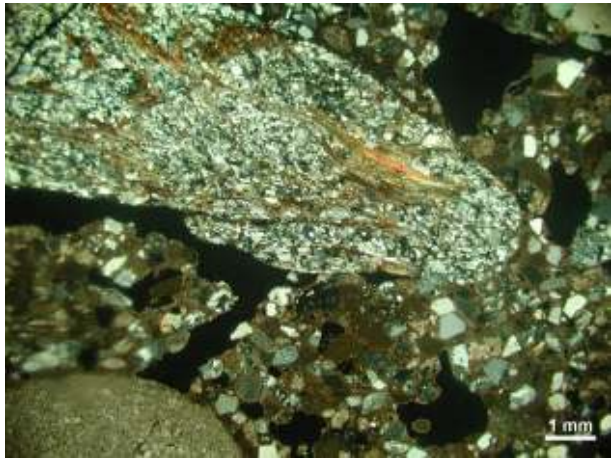
DECAY AND ITS CHARACTERIZATION

- aggregate characterisation
- porosity study
- compositional ratio identification
- alteration phenomena identification

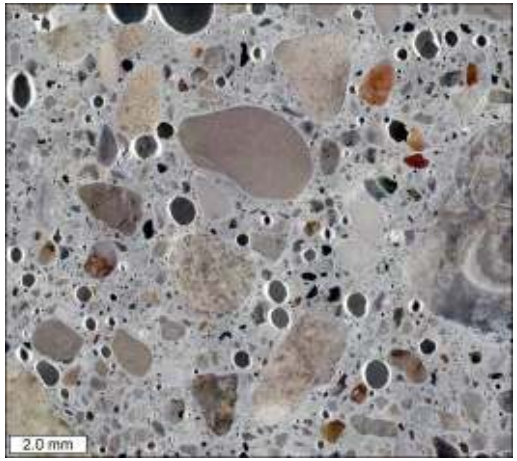
Compositional visual analysis



BSE image of secondary gypsum



Porosity study



Scanner image of a polished surface

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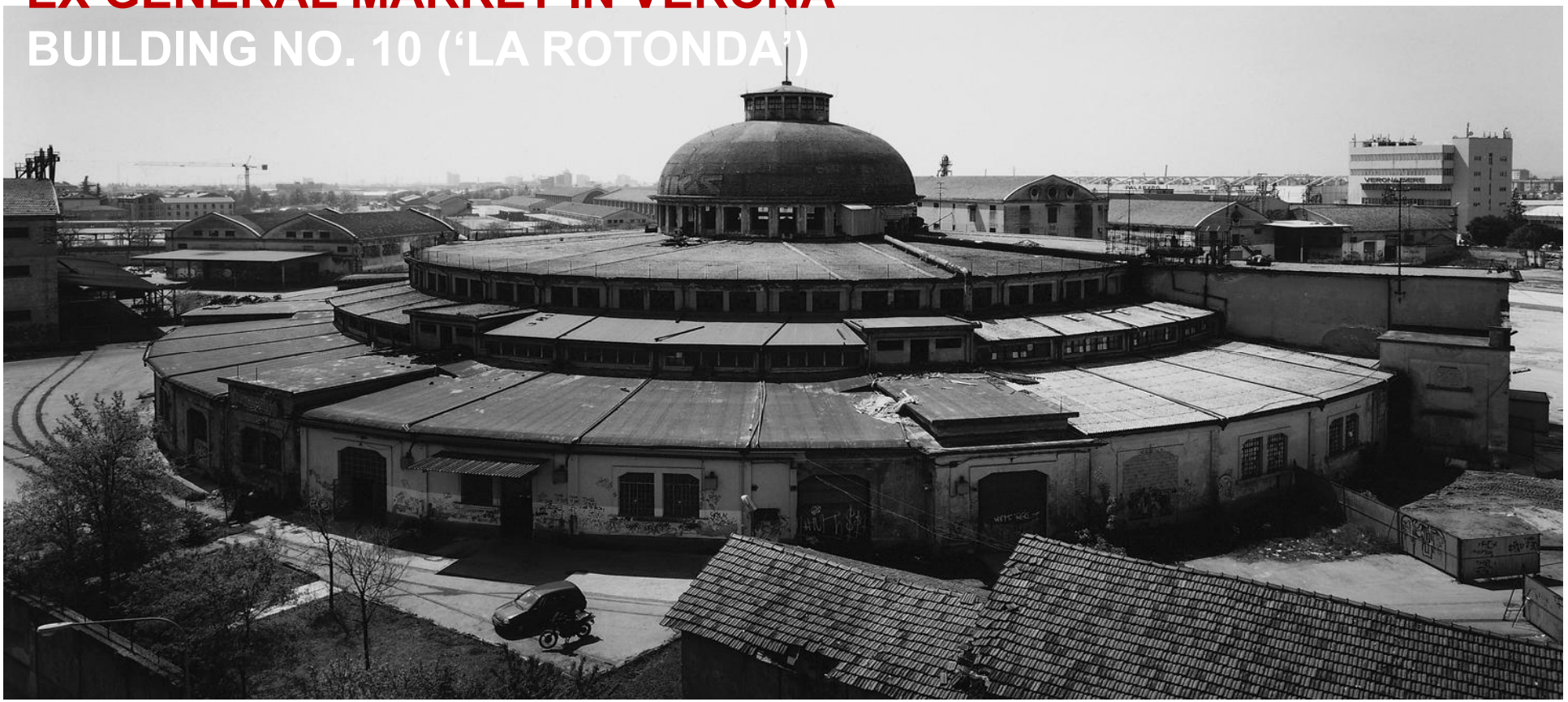
EX GENERAL MARKET IN VERONA
BUILDING NO. 10 ('LA ROTONDA')



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- NDT – MDT – DT tests on URM
- NDT – MDT – DT tests on concrete and steel
- Chemical characterizations
- Laser scanner survey

MAIN DATA

• DESIGNED BY	PIO BECCHIERLE
• INAUGURATED IN	1930
• EXTERNAL DIAMETER	100 m
• DOME's DIAMETER	25 m
• HEIGHT OF THE EXTERNAL RING	7.15 m
• HEIGHT OF THE INTERNAL RING	13.8 m
• TOTAL HEIGHT	26 m

Typical steel reinforcement in columns

General deterioration of the rc dome.

Roof degradation on the external ring

Degradation of the slab and beams of the first floor at the access tunnels

Steel roof degradation on the external ring

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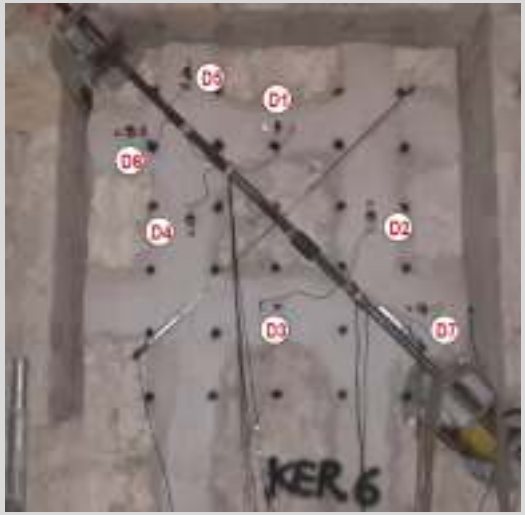
Tests on R.C. structures

- Diffuses carbonatation tests
- N.10 Compression tests on cores
- N. 4 tensile tests on rebars
- N. 28 direct sonic tests before and after consolidation
- N. 3 Brinell tests



Tests on masonry

- N.6 Video endoscopy
- N.2 Single flat jack and 4 Double flat jacks
- N. 5 direct sonic tests
- N. 8 direct sonic tests before and after consolidation
- N. 8 Diagonal compression test

NIKER

Sviluppo di metodologie integrate e basate sulla conoscenza per la protezione dei Beni Culturali dal rischio sismico, sulla base dell'ottimizzazione e minimizzazione degli interventi.

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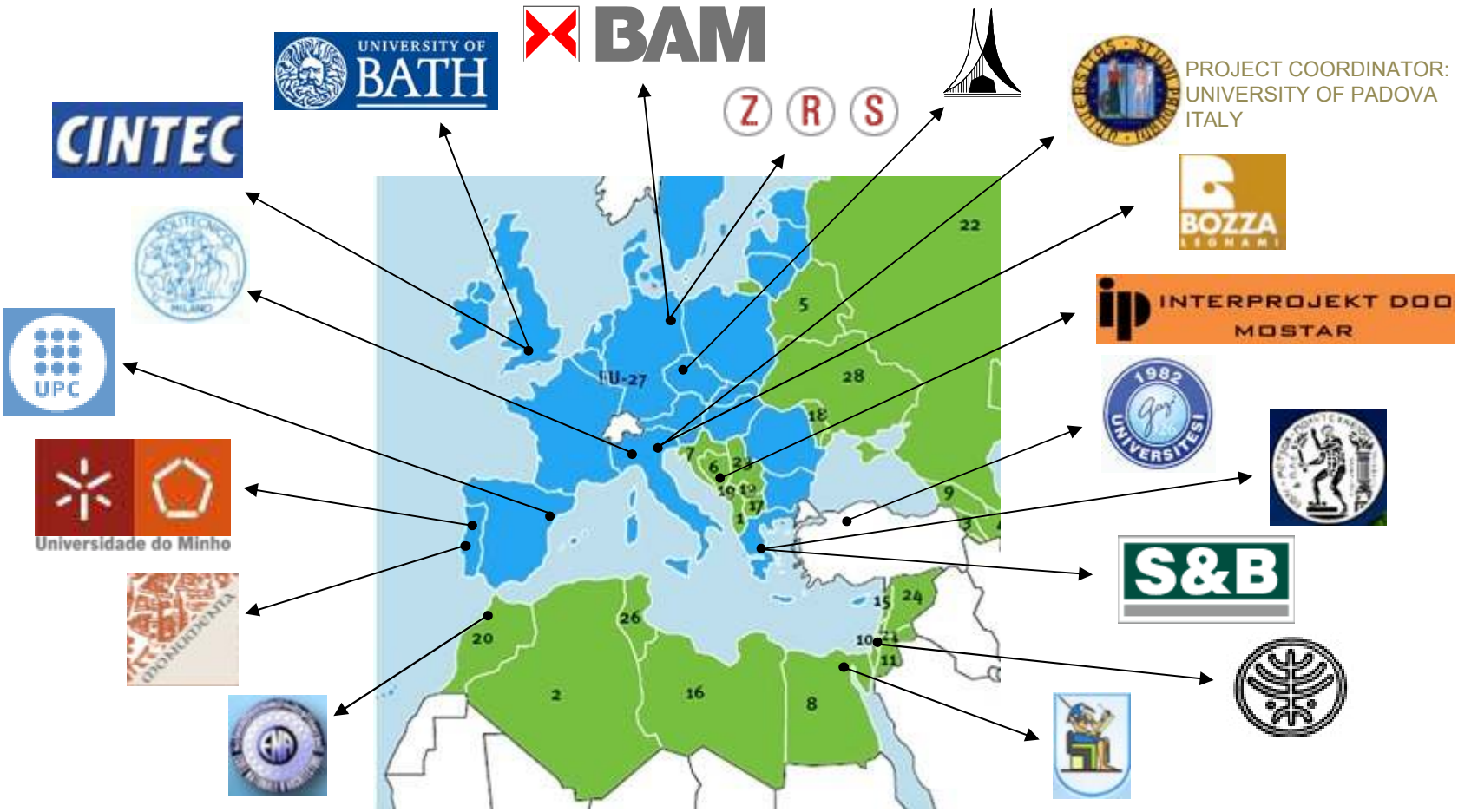
- Materiali e tecniche per gli interventi
- Studi e tecniche per i collegamenti
- Metodi di prova per elementi e sotto-strutture
- Approccio di ‘ottimizzazione’ per i BC
- Sistemi di monitoraggio ed early warning
- Approccio integrato, multidisciplinare per i BC
- Standardizzazione



PROJECT COORDINATOR:
UNIVERSITY OF PADOVA
ITALY

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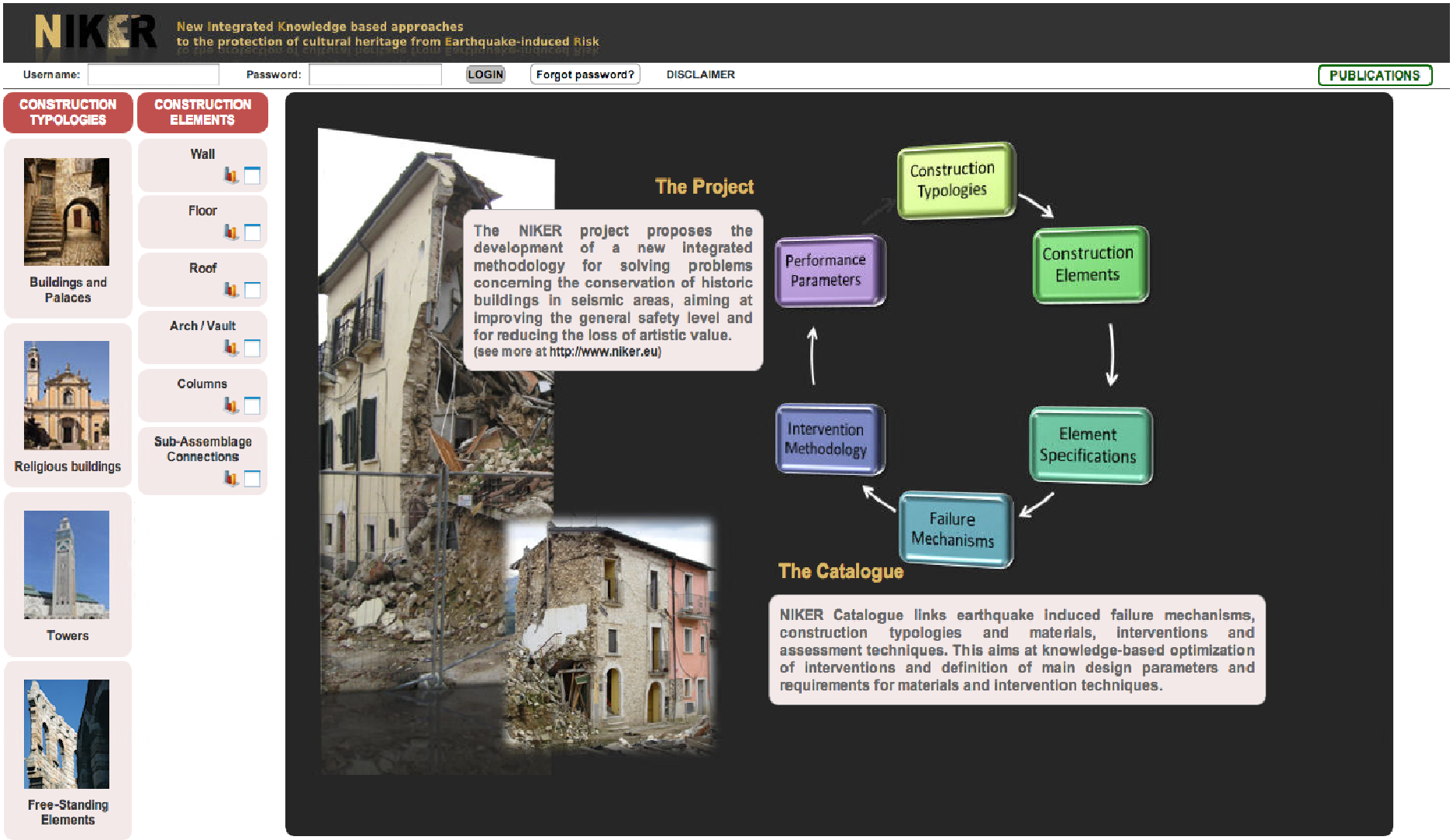

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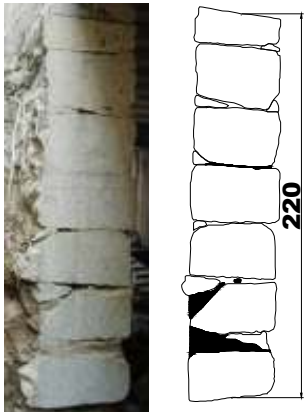
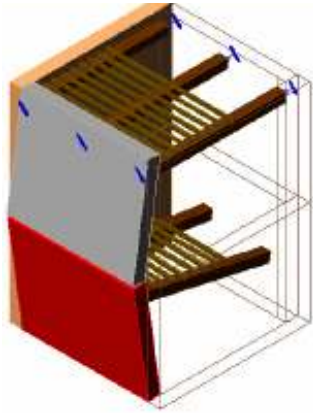
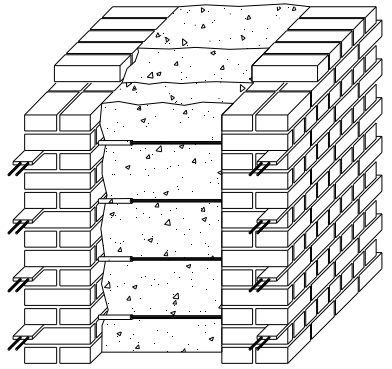
CATALOGO

- Tipologie costruttive
- Materiali da costruzione
- Meccanismi di collasso
- Tecniche di intervento







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CONSTRUCTION TYPOLOGIES

Buildings and Palaces

Religious buildings

Towers

CONSTRUCTION ELEMENT	MATERIAL	TYPOLOGY
WALL	EARTH MASONRY	ADOBE
		RAMMED
		COB
	STONE MASONRY	SINGLE-LEAF
		MULTI-LEAF
	BRICK MASONRY	SINGLE-LEAF
		MULTI-LEAF
FLOOR		
ROOF		
ARCH/VAULT		
CONNECTION		
SUB-ASSEMBLY		

FAILURE MECHANISMS			
IN-PLANE FAILURE	OUT OF PLANE OVERTURNING	OUT-OF-PLANE FLEXURE	LAYER SEPARATION
INTERVENTION 1 INTERVENTION 2	INTERVENTION 1 INTERVENTION 2	INTERVENTION 1 INTERVENTION 2	
INTERVENTION 1	INTERVENTION 1 INTERVENTION 2	INTERVENTION 1	
INTERVENTION 1	INTERVENTION 1	INTERVENTION 1	
INTERVENTION 1 INTERVENTION 2	INTERVENTION 1	INTERVENTION 1	INTERVENTION 1 INTERVENTION 2
INTERVENTION 1	INTERVENTION 1 INTERVENTION 2	INTERVENTION 1	INTERVENTION 1 INTERVENTION 2
INTERVENTION 1 INTERVENTION 2	INTERVENTION 1	INTERVENTION 1	INTERVENTION 1
INTERVENTION 1 INTERVENTION 2	INTERVENTION 1	INTERVENTION 1 INTERVENTION 2	INTERVENTION 1

PARAMETRI PRE-INTERVENTO

Property	Symbol [Units]	Description	Range of values
Apparent density	ρ [kg/m3]		
Elastic Modulus	E [N/mm^2]		
Shear modulus	G [N/mm^2]		
Compressive strength	f_c [N/mm^2]		
Initial shear strength	f_{v0} [N/mm^2]		
Tensile strength	f_t [N/mm^2]		
….	…		

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CONSTRUCTION ELEMENT	MATERIAL	TYPOLOGY
WALL		
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ARCH/VAULT		
CONNECTION		
SUB-ASSEMBLY		
	EARTH	ADOBE
		RAMMED
		COB
	STONE	SINGLE-LEAF
		MULTI-LEAF
	BRICK	SINGLE-LEA
		MULTI-LEA

FAILURE MECHANISM

IN-PLANE FAILURE	**OUT OF PLANE OVERTURNING**	OUT-OF-PLANE FLEXURE	LAYER SEPARATION
INTERVENTION 1 INTERVENTION 2	INTERVENTION 1 INTERVENTION 2	INTERVENTION 1 INTERVENTION 2	
INTERVENTION 1	INTERVENTION 1 INTERVENTION 2	INTERVENTION 1	
INTERVENTION 1	**INTERVENTION 1**	INTERVENTION 1	
INTERVENTION 1 INTERVENTION 2	INTERVENTION 1	INTERVENTION 1	INTERVENTION 1 INTERVENTION 2
INTERVENTION 1	INTERVENTION 1 INTERVENTION 2	INTERVENTION 1	INTERVENTION 1 INTERVENTION 2

PARAMETRI POST-INTERVENTO

INTERVENTION 1			
Property	Symbol [Units]	Description	Range of values
Apparent density	ρ [kg/m3]		
Elastic Modulus	E [N/mm^2]		
Shear modulus	G [N/mm^2]		
Compressive strength	f_c [N/mm^2]		
Initial shear strength	f_{v0} [N/mm^2]		
Tensile strength	f_t [N/mm^2]		
…			
Performance indicator		Description	
Section monolithism			
…			