cinpar2020

XVI INTERNATIONAL CONFERENCE ON
STRUCTURAL REPAIR AND REHABILITATION
PORTO | PORTUGAL 13-15 JULY 2020
ONLINE CONFERENCE

Activities in support of structural rehabilitation.

An overview of FEUP contributions

António Arêde

CONSTRUCT (LESE) – Faculty of Engineering of University of Porto (aarede@fe.up.pt)

LESE
Laboratório de Engenharia Sísmica e Estrutural

INSTITUTO DA CONSTRUÇÃO
U.PORTO FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO
CONSTRUCT
UNIVERSIDADE ESTADUAL VALE DO ACARAÚ

Outline

- **MOTIVATION & SCOPE**
- **DIAGNOSIS** (KNOW THE PROBLEM & FIND THE PROBLEMS)

  TESTING (CHECK CONDITIONS & INCREASE KNOWLEDGE)

  MONITORING (CHECK THE NEED FOR INTERVENTION)
- **ILUSTRATIVE CASE STUDIES**
- **TESTING FOR REHABILITATION**
- **MAJOR DEVELOPMENTS AND HINTS FOR THE FUTURE**

MOTIVATION & SCOPE

- STRUCTURAL REHABILITATION REQUIRES **KNOWLEDGE**

  - about the construction in general and its structure in particular
  - on its history and state of conservation or degradation
  - about its heritage, historic and cultural value

- BASED ON THIS **KNOWLEDGE**, the **INTERVENTION** is CHOSEN:

  - *CONSERVATION* and/or *REHABILITATION* and/or
  - *STRENGTHENING* or
  - *RECONSTRUCTION* or *DEMOLITION* + *NEW CONSTRUCTION*

- This KNOWLEDGE can involve

  - **DIAGNOSIS** and/or **TESTING** and/or **MONITORING**

DIAGNOSIS, TESTING and MONITORING

COLLECTING KNOWLEDGE → THE **DIAGNOSIS**

- Use of appropriate in-situ survey strategies and techniques.
- Consider heterogeneity and complexity of some existing constructions
- Cross-use of different diagnosis and auxiliary complementary techniques

SOMETIMES DIAGNOSIS IS NOT ENOUGH → **TESTING** (IN-SITU / LAB)

- Additional characterization of materials, components and/or structure, making use of more demanding techniques, tools and resources
- Parameters (strength, deformability, frequencies, …) can be obtained to “feed” numerical analysis tools and/or infer about “structural stability”

DIAGNOSIS, TESTING and MONITORING

Besides **TESTING**, the decision on “WHAT TO DO?” may not be EASY!

- In such cases, may be it’s better “**Wait and see**” → **MONITORING**

  - Short term, periodic, long term, continuous, local observation, remote.

  - Identify whether the damages/movements still develop or stabilized

  - Help on deciding about intervention: yes or not ? Which in type?

- **DIAGNOSIS** ←→ **TESTING** ←→ **MONITORING**

  - Can co-exist, combine, interact and complement each other

  - A few case studies are overviewed to illustrate possibilities, outputs, etc

DIAGNOSIS & TESTING - Tools / Techniques

Concrete

- FerroScan
- Phenolphthalein
- Schmidt sclerometer
- Thermography
- Load tests
- Dynamic tests
- Sonic tests
- Core sampling
- Material survey
- Pull-Off / Pull-Out
- GeoRadar

Wood

- Resistograph
- Moisture contents
- Thermography
- Load tests
- Dynamic tests
- Sonic tests
- Core sampling
- Material survey
- Videoscopy

Masonry

- Moisture contents
- Thermography
- Load tests
- Dynamic tests
- Sonic tests
- Core sampling
- Material survey
- Videoscopy
- GeoRadar
- Ménard Pressuremeter
- Flat jacks

Ilustrative case studies: BOLHÃO MARKET

- Requalification project to keep the same function of the building (dating to 1914)

Objectives:

To assess the current state of the building structure

To obtain technical data for the designers in charge of the requalification project

BOLHÃO MARKET

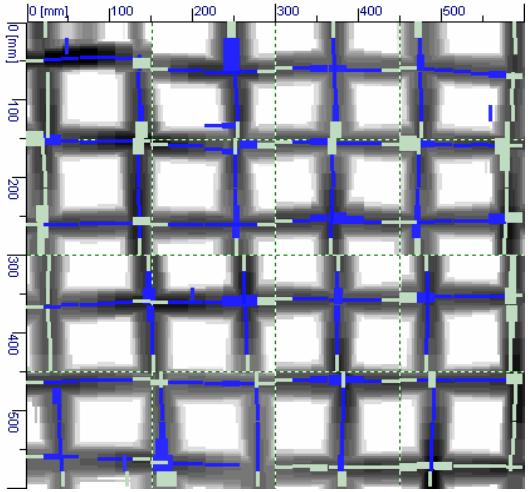
- Building survey and diagnosis

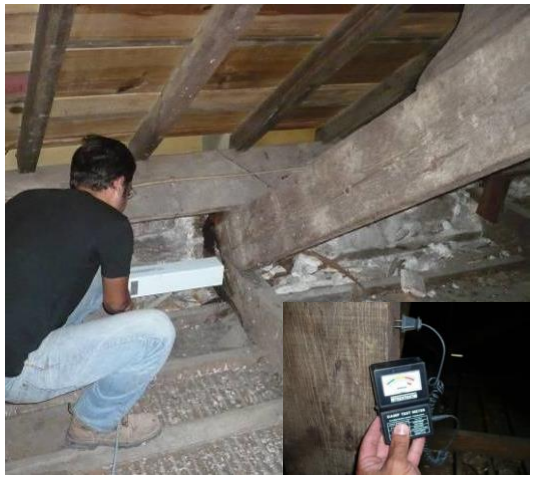
  The structure is made of several different materials :

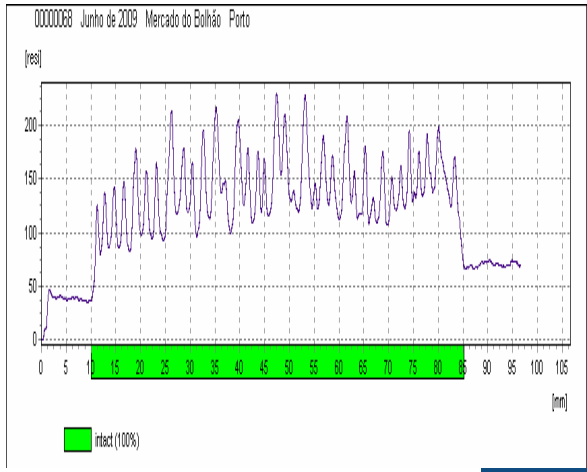
  Granite masonry → external walls;
  Reinforced concrete → floors;
  Timber → roofs;

  Material tests performed in situ:

  Opening-up survey works & rebar detection; Schmidt sclerometer & carbonation tests; RESISTOGRAPH® & moisture measurements

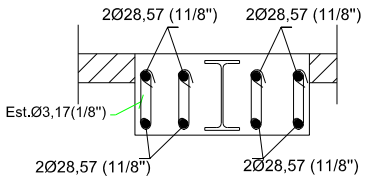
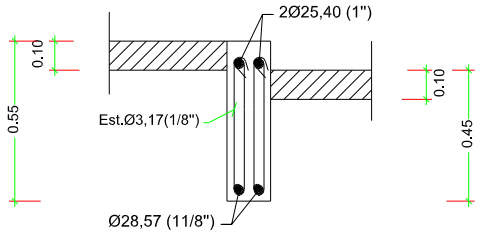
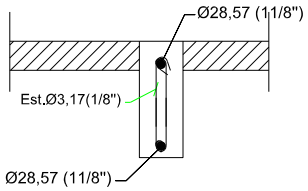






BOLHÃO MARKET

- Structural details obtained from the survey

Viga	b(m)	h(m)	Corte transversal (Esc. 1/20)	NOTAS
V1	0.60	0.28		- As armaduras foram identificadas através de inspecção visual. - O perfil metálico é semelhante ao actual IPE240.
V10	0.15	0.55		- As armaduras foram identificadas através de inspecção visual.
V33	0.15	0.40		- As armaduras foram identificadas com recurso ao pacómetro, pelo que o valor do diâmetro deve ser interpretado com alguma reserva.

Detail of the roof structure

Semi-destructive actions and tests

The <u>constructive system</u> that was found presents similarities with the *Coignet system*

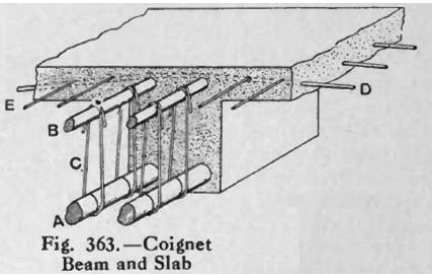
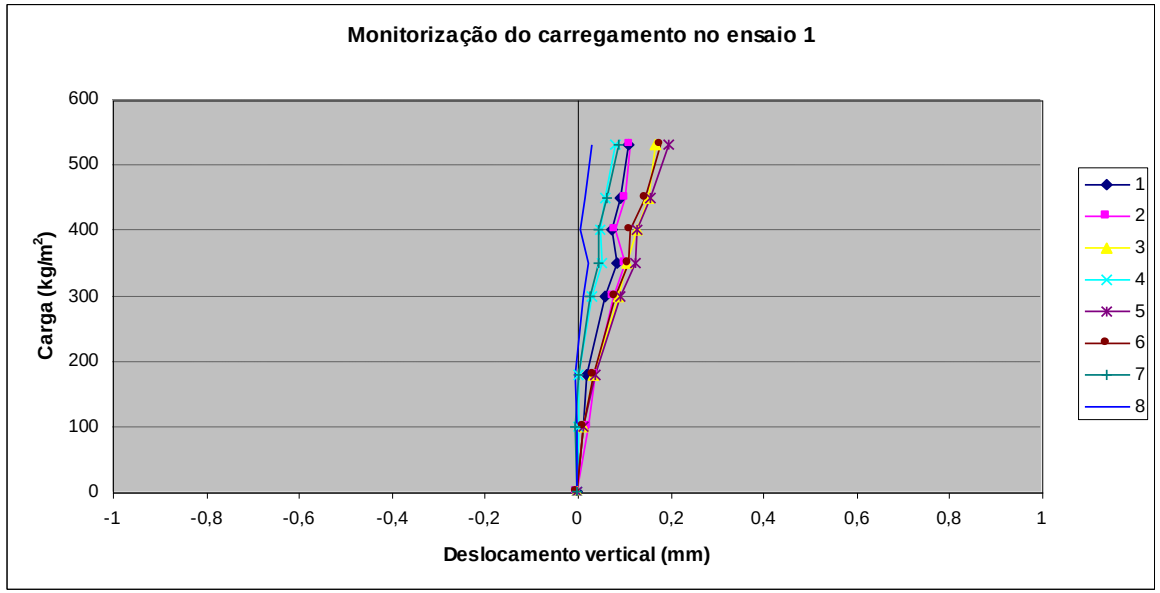


Fig. 363.—Coignet Beam and Slab

BOLHÃO MARKET

- Load test – up to 5 kN/m^2 on RC floors

Loading with water tanks



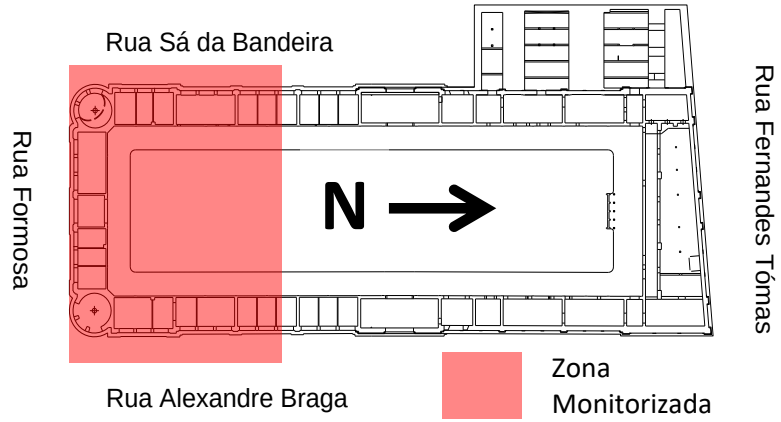
Linear behaviour and very small deflections

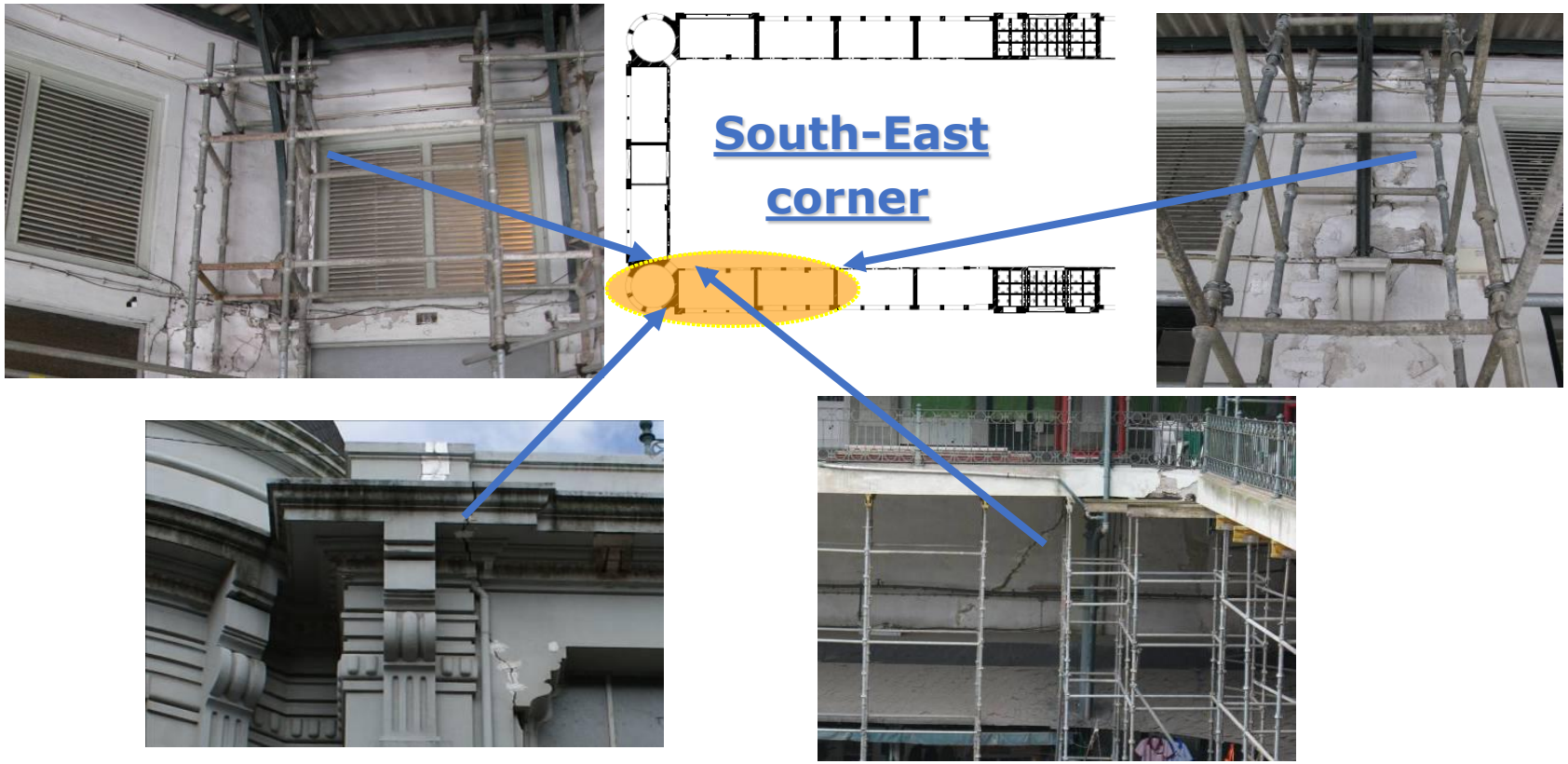
Continuous recording of deflections

BOLHÃO MARKET

- Structural long-term quasi-static monitoring

  Monitored zones where largest cracks were found:

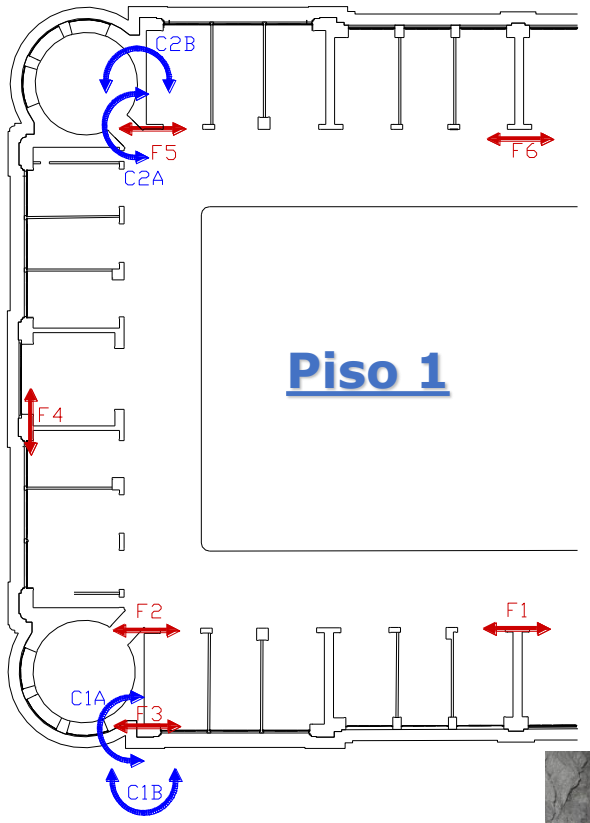




BOLHÃO MARKET

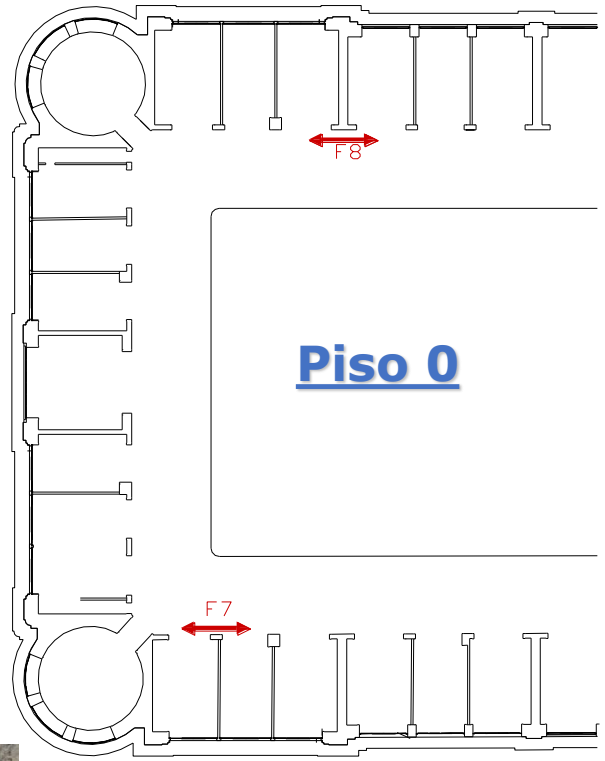
- Structural long-term quasi-static monitoring

Monitored motions and sensores:



Rotations:
Clinometers
- C1A, C1B
- C2A, C2B

Cracks:
Crackmeters
- F1 a F8



BOLHÃO MARKET

- Structural long-term quasi-static monitoring

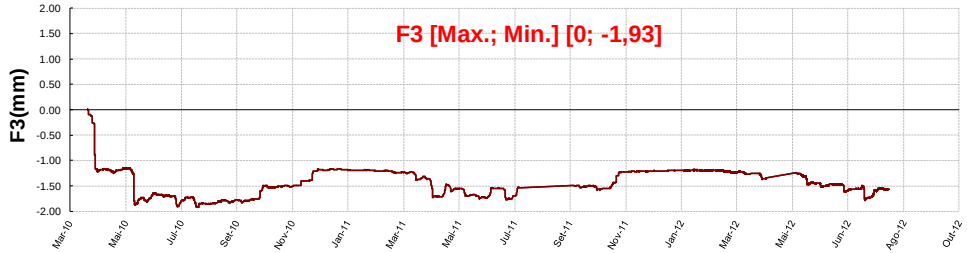
2,5 years monitoring duration

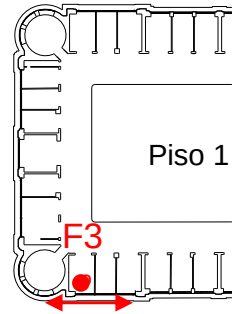
South-East Zone: Floor 1 / External wall

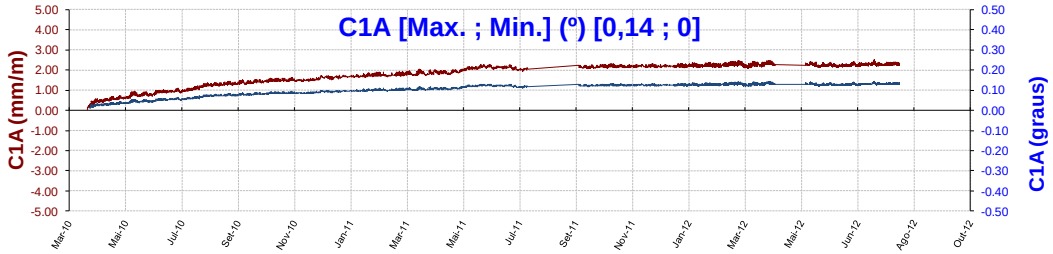
F3 crackmeter: after an initial sudden closing jump, the evolution follows the thermic cycle

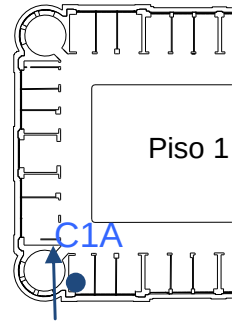
Rotations are increasing to the interior of the market, but with very reduced values

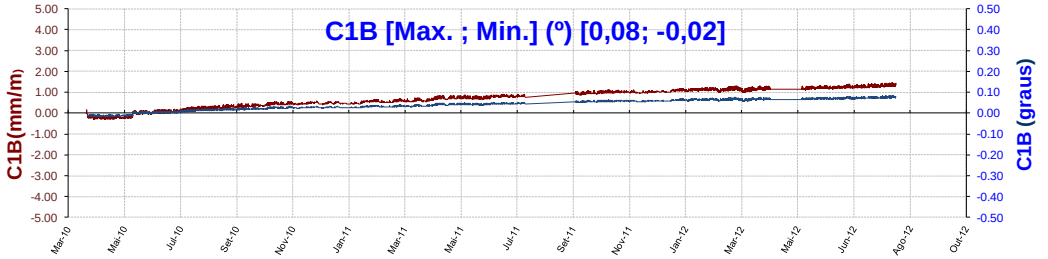
Temperature monitoring for thermal corrections

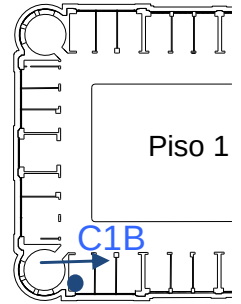


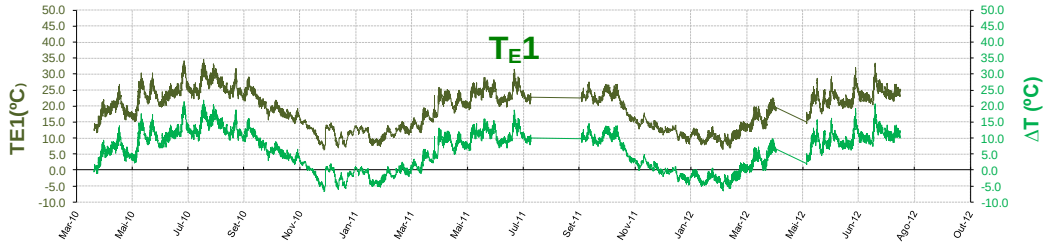


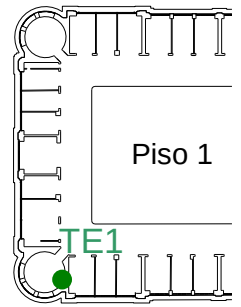








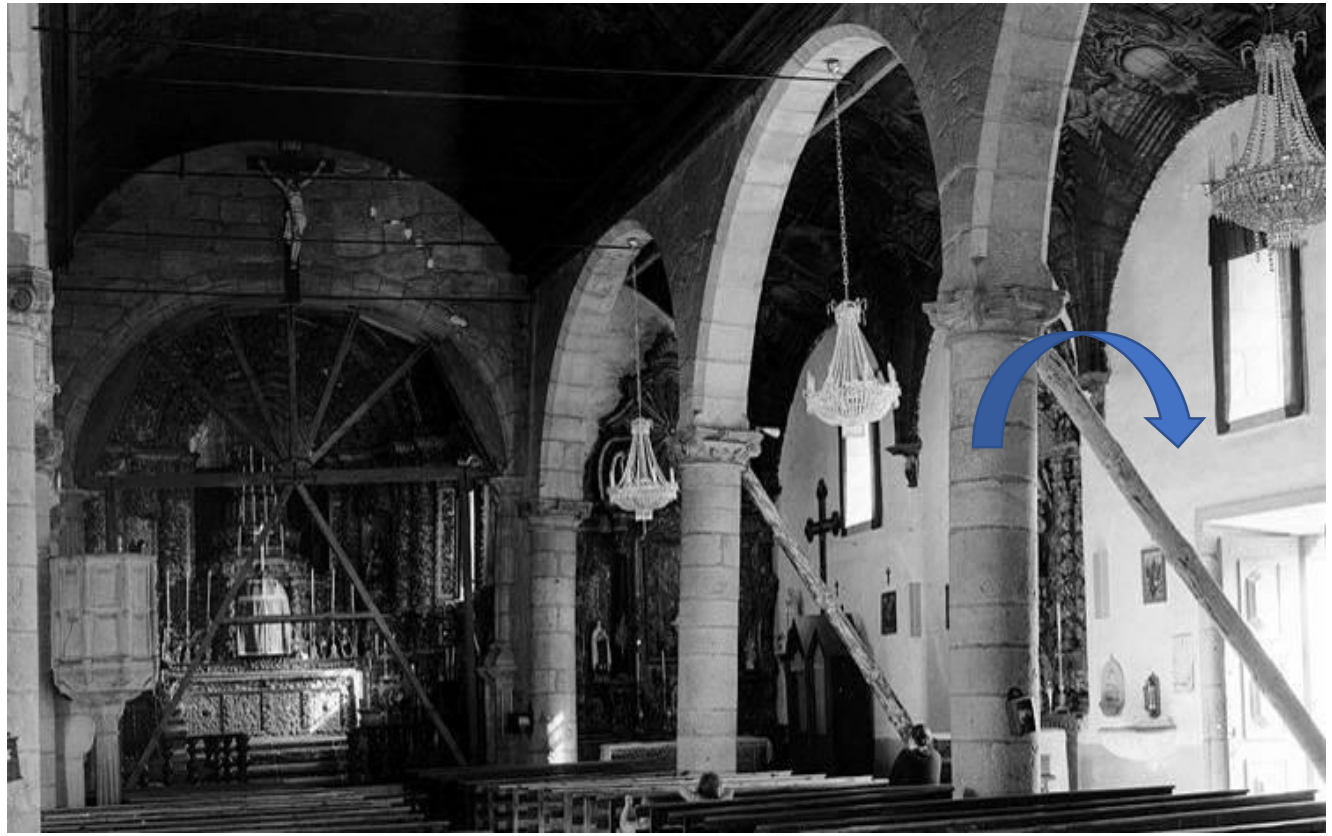




FOZ CÔA CHURCH - Monitoring

- Impressive damage!

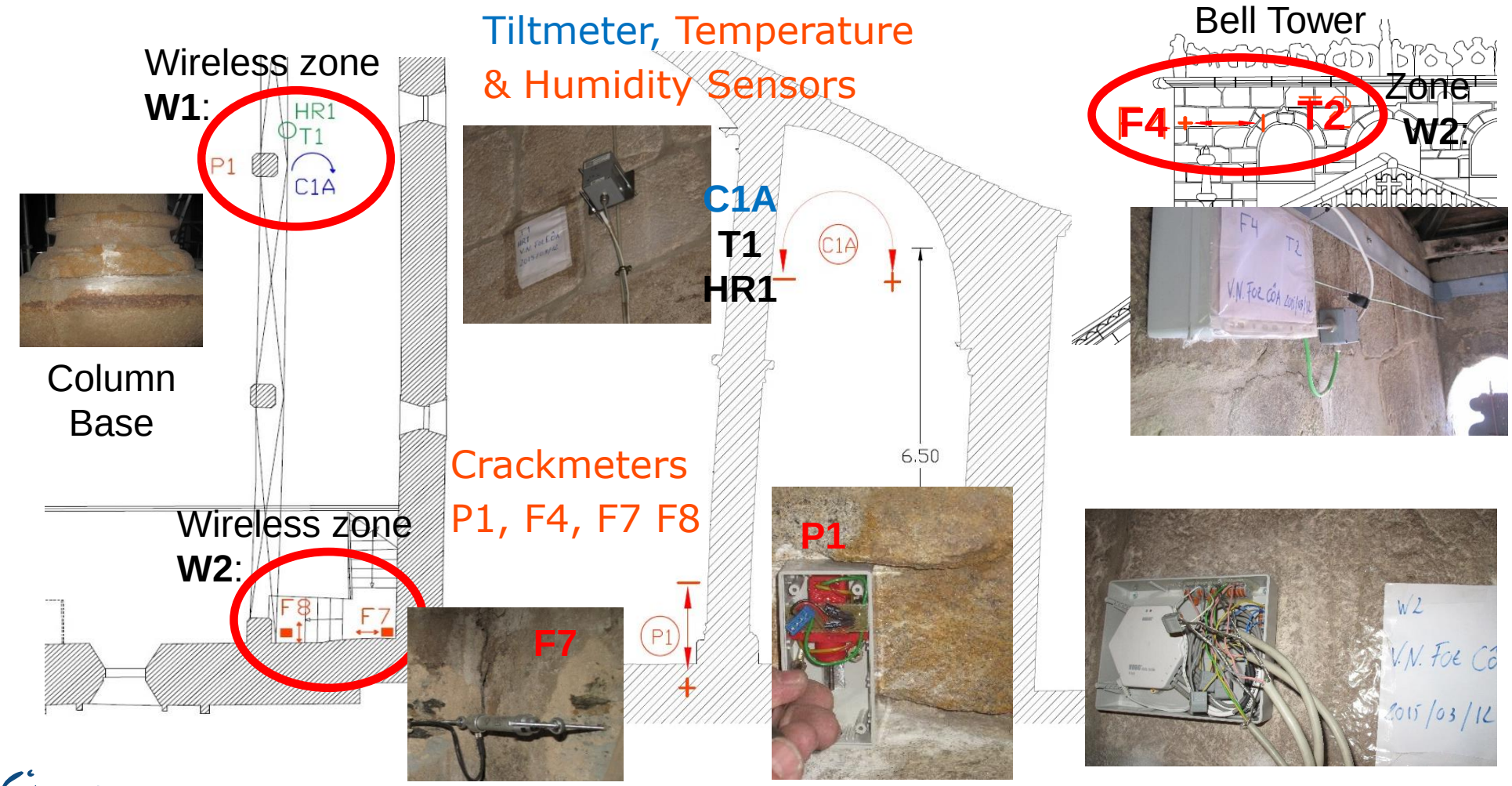
Very large out-of-plane deformation and crack developments.



60 cm deflection in the top !

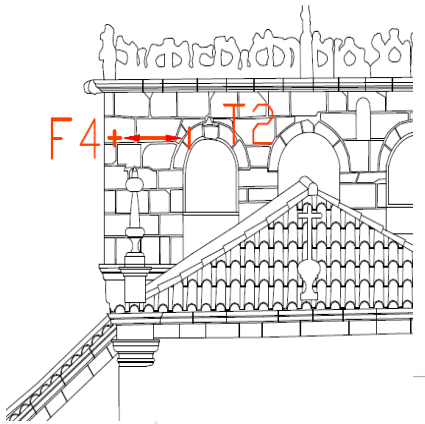
FOZ CÔA CHURCH - Monitoring

- Monitoring layout (2015) - the first wireless system installed

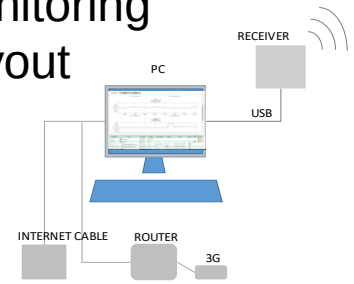


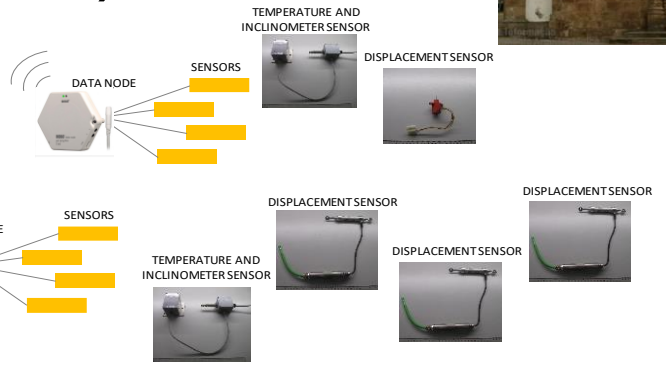
FOZ CÔA CHURCH - Monitoring

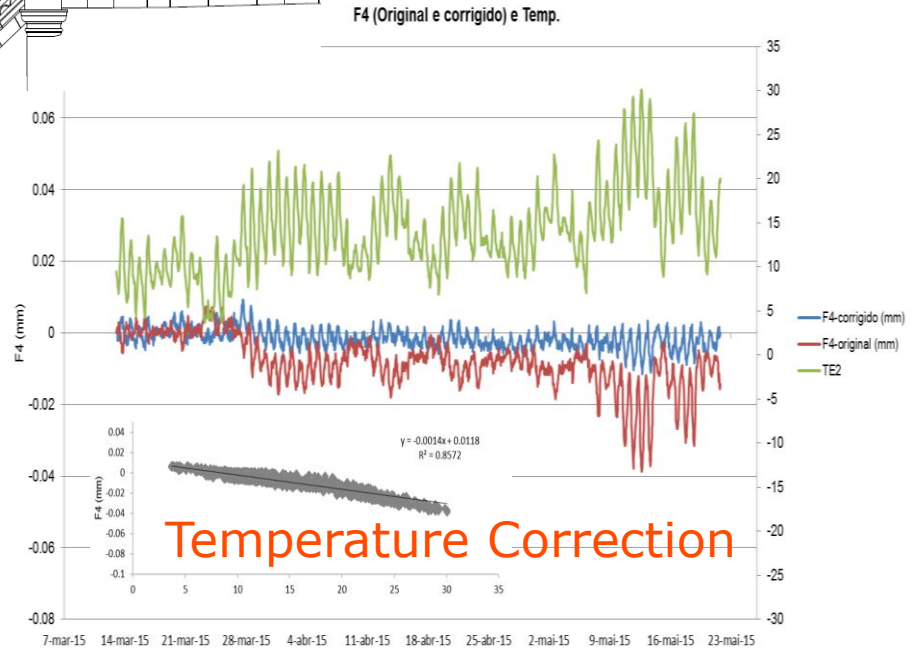
- Wireless monitoring results (9 months sample period)

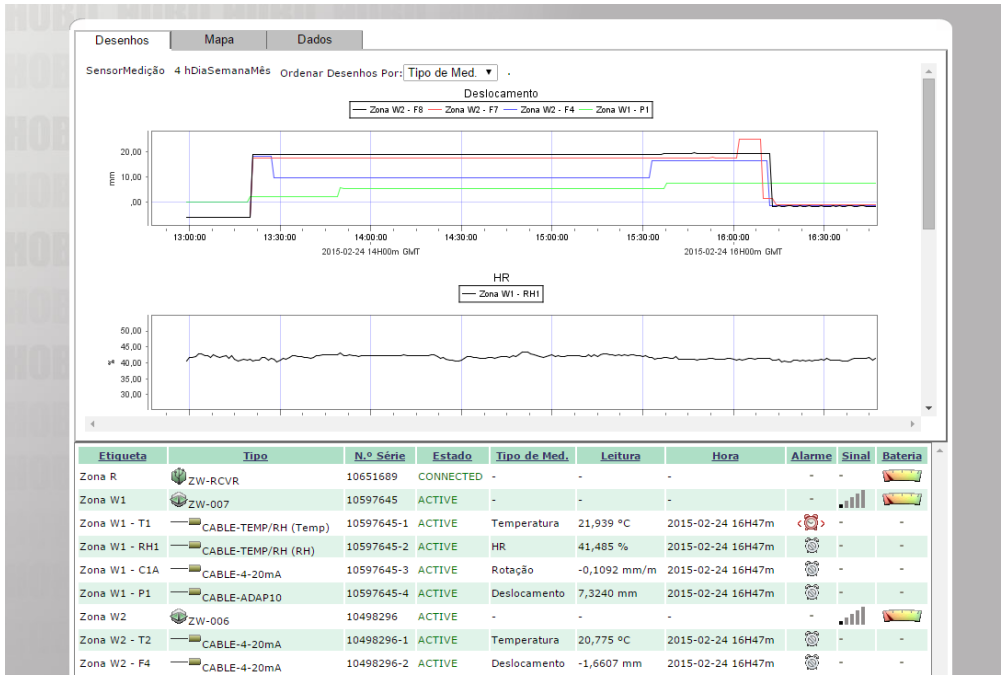


Monitoring Layout





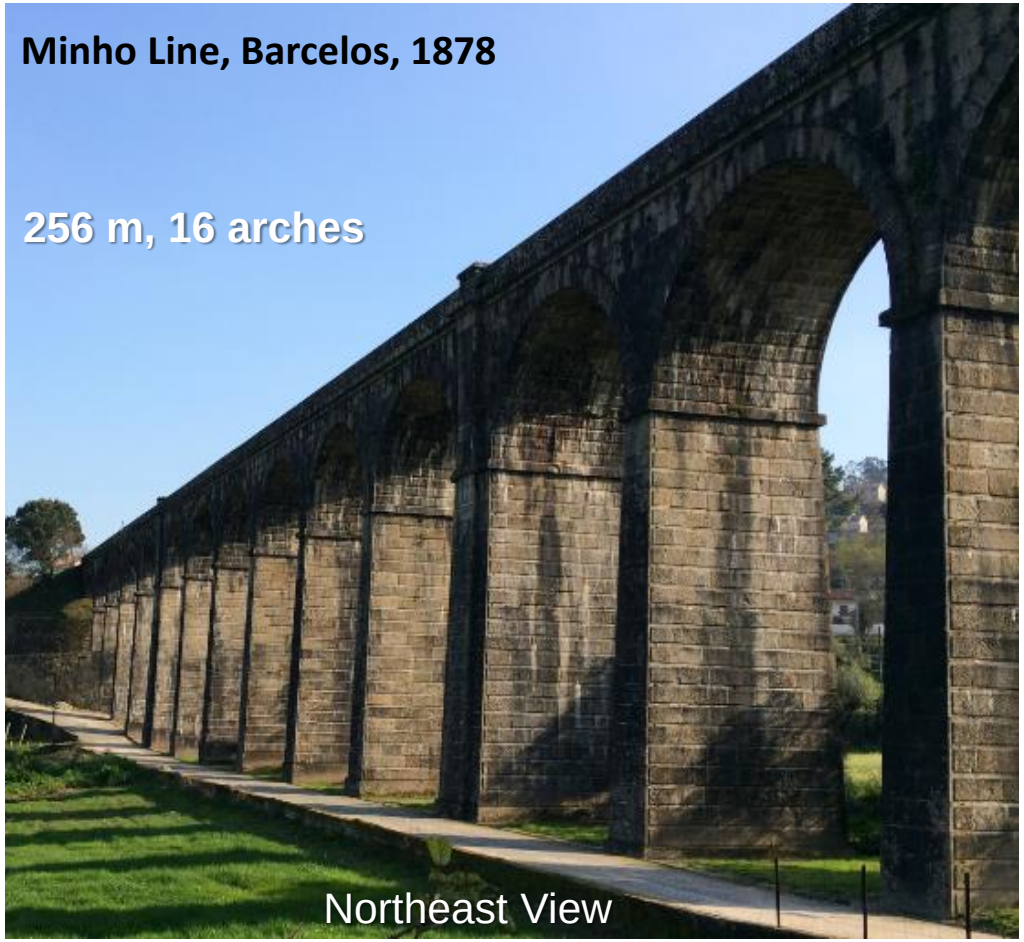


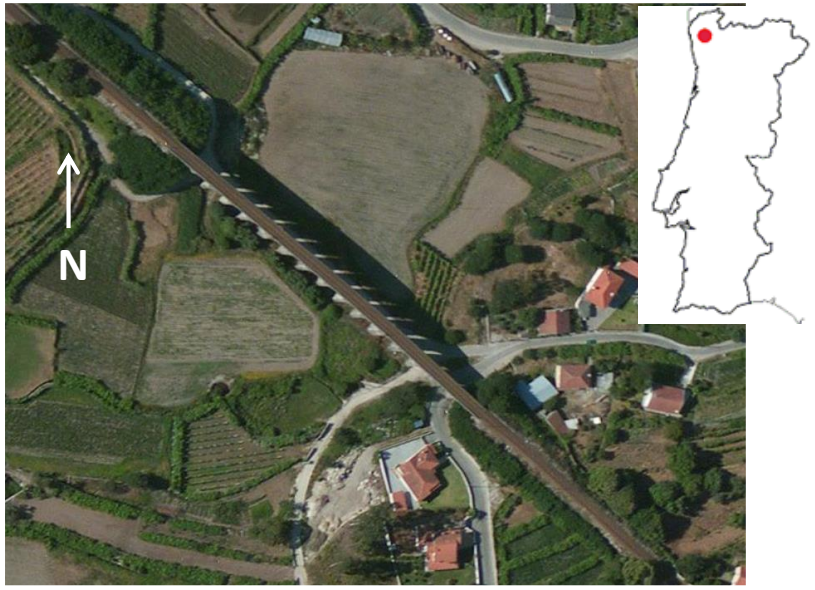


Remote Monitoring Interface Panel

Durrães Railway Bridge

- Experimental campaign for structural and material characterization

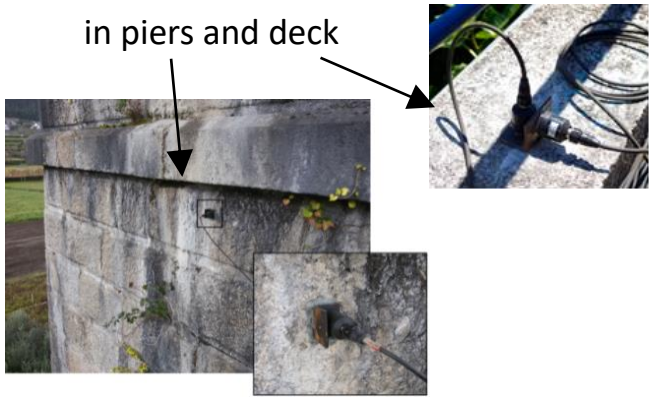




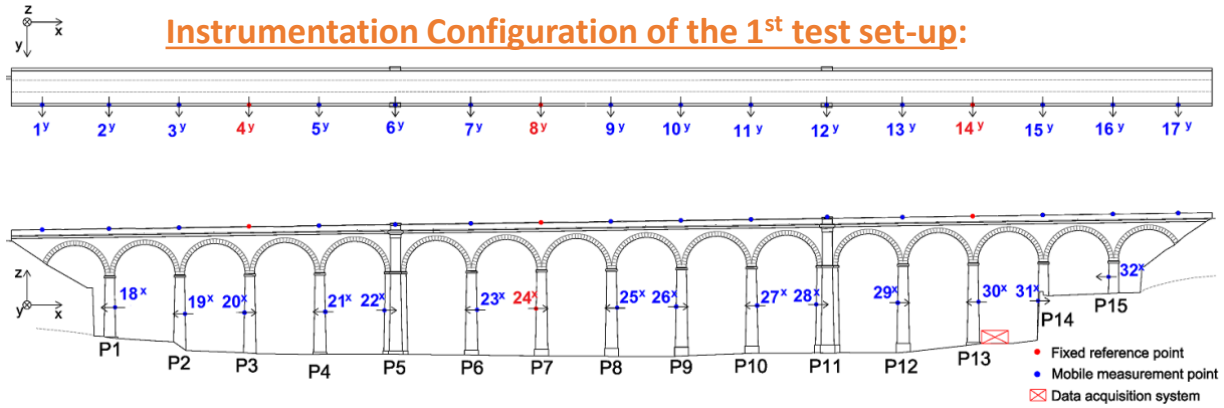
Durrães Railway Bridge

- Experimental campaign – Dynamic characterization tests

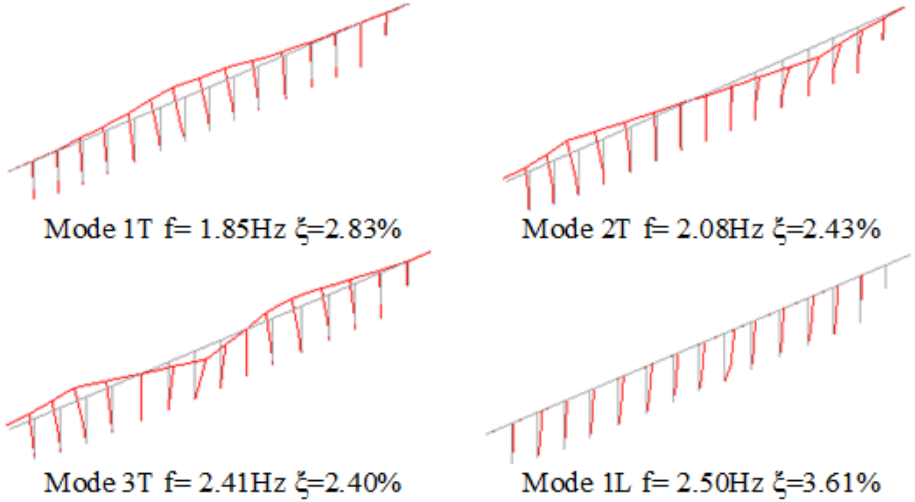
Accelerometers in piers and deck



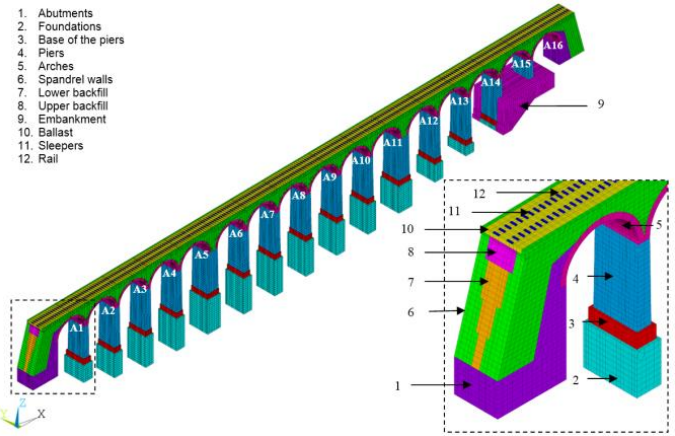
Instrumentation Configuration of the 1st test set-up:



Vibration frequencies and modal shapes



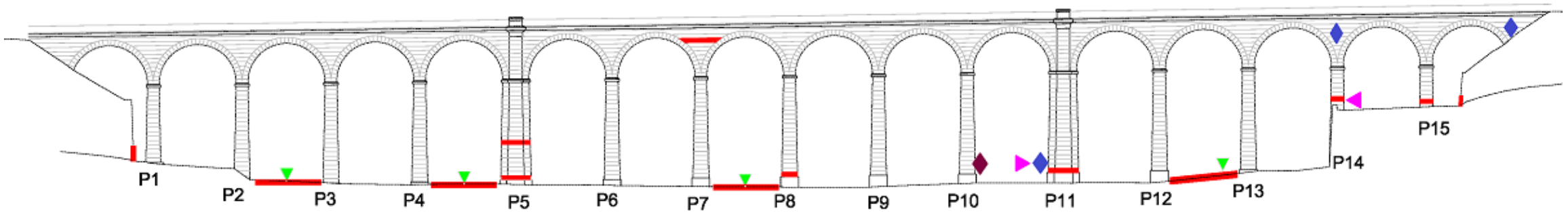
Estimate stiffness characteristics by zones, using optimization genetic algorithms



Durrães Railway Bridge

- Experimental campaign – In-situ tests for material characterization

  - Georadar (GPR) records
  - Dynamic Probing Super Heavy (DPSH) tests in the foundation ground
  - Core sampling and extraction
  - Ménard Pressuremeter tests
  - Flat-jack tests



Localization of all the tests for bridge material and foundation ground characterization

Durrães Railway Bridge

- Experimental campaign – In-situ GPR e DPSH tests

GPR test (Georadar):

25 radargrams allowing identifying
- thickness of the facing stones of structural components (columns and spandrel walls)
- the constituent layers of the foundation ground

2 antenna types: 250 MHz and 500 MHz

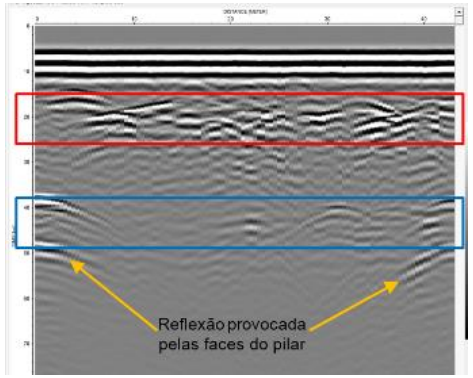
DPSH (Dynamic Probing Super Heavy) Tests:

- 4 locations in the span between the piers
- to confirm the depth of bedrock

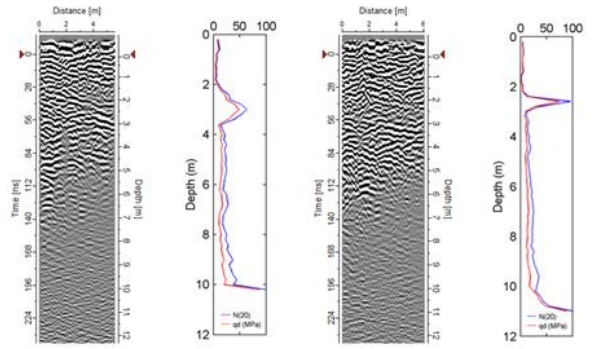
Results:

Geometry of P8 cross section

Recorded radargram

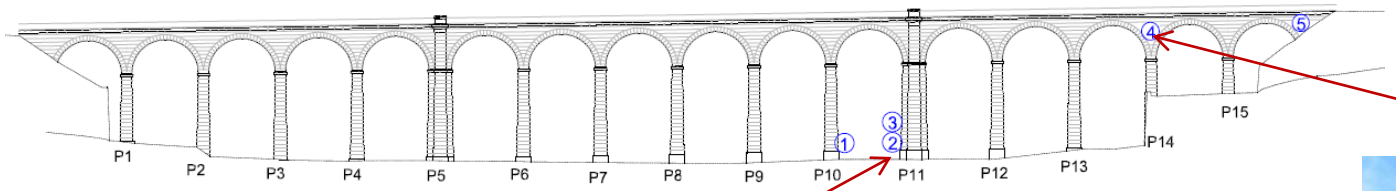


Ground foundation profiles



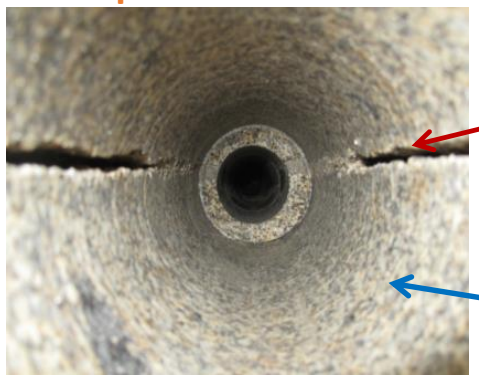
Durrães Railway Bridge

- Experimental campaign – In-situ core sampling and extraction



stone joint infill

Extracted material (core samples) replaced afterwards:

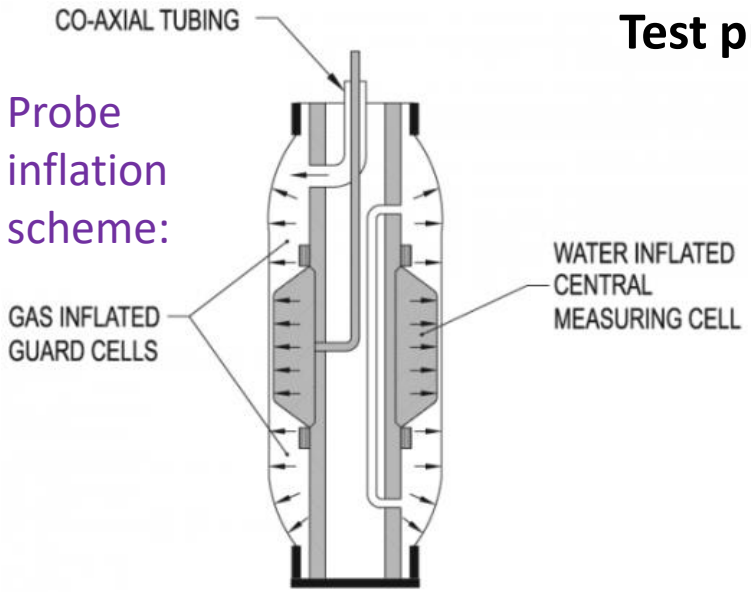


stone joint infill

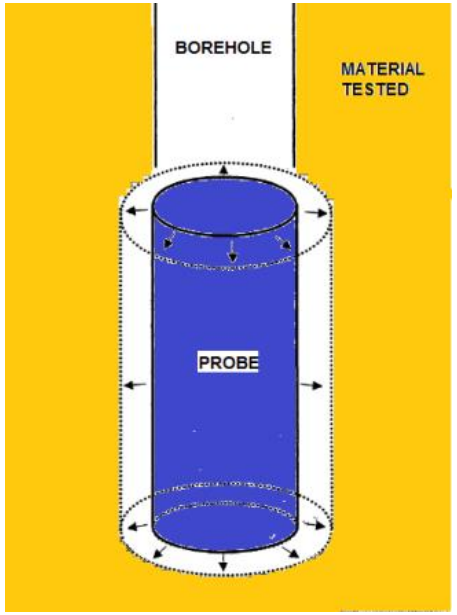
Durrães Railway Bridge

- Experimental campaign – In-situ local pressuremeter tests

Probe inflation scheme:



Test principle



Expansion of probe in the borehole:

- A cylindrical probe, with 2 flexible and expansible rubber covers (1 internal and 1 external), is introduced in a borehole;
- Gas pressure is applied by the probe onto the borehole surface and the material deformation is measured by recording the changes in water volume readings;
- Tests are performed in accordance with French standard *NF14 P94-110* ;

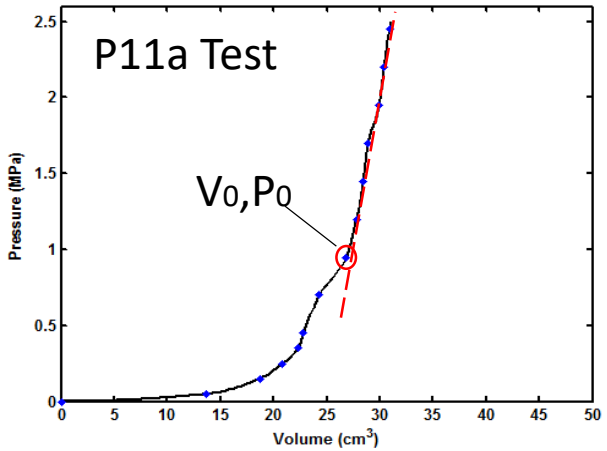
Durrães Railway Bridge

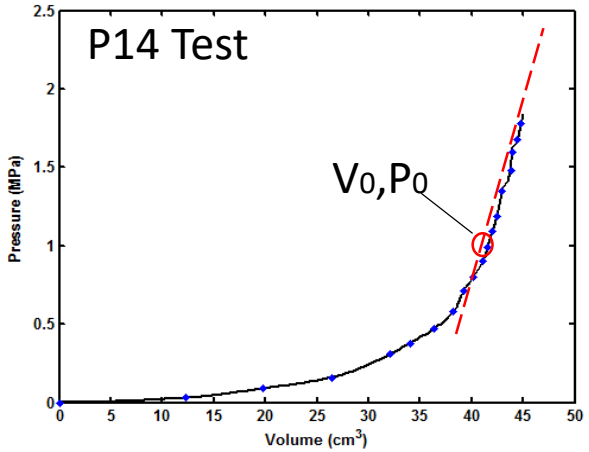
- Experimental campaign – In-situ local pressuremeter tests

Operation – probe insertion

Recording results

Obtained Pressure-Volume Curves





Global results:

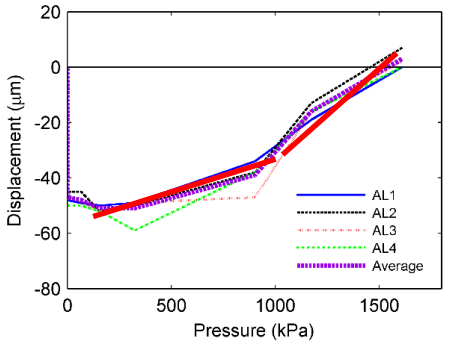
Location	G_{PMT} Mean (MPa)	E_{PMT} Mean (MPa)	E_{PMT} [(Min-Máx)] (MPa)
Pier P11a	226	588	490-735
Pier P11b	206	537	524-550
Spandrel P14	135	350	300-438
Abutment	140	363	208-513

Durrães Railway Bridge

- Experimental campaign – In-situ local Flat-jack tests

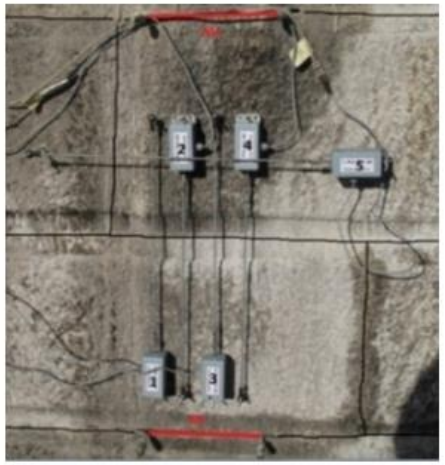
Single flat-jack tests

Example of one curve obtained:

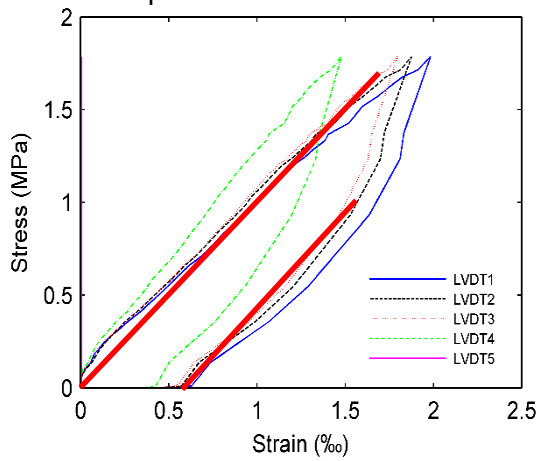


Equipment

Double flat-jack tests



Example of one curve obtained:



Overall results:

In-situ stress [MPa]	In-situ deformability of masonry, E [GPa]
1.5	7 to 23

Durrães Railway Bridge

- Experimental campaign – Lab tests

Stone **sample tests**
Compressive strength
Elastic modulus in compression
Tensile splitting strength

Stone

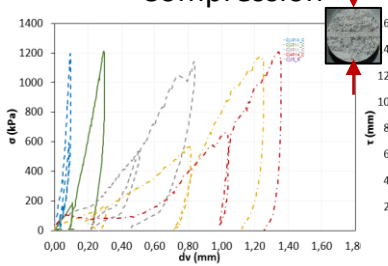
Parameter	Mean values
Compressive strength (MPa)	34,8 – 59,4
Compressive Elastic modulus (GPa)	20,0 – 23,5
Tensile strength (MPa)	3,7 – 5,4

Global Results:

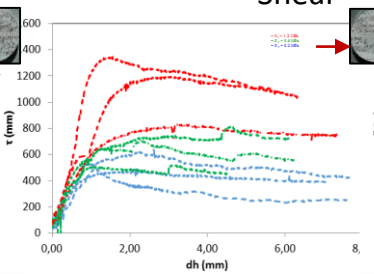
Stone-to-stone *joint* tests
Direct Shear-box tests
Normal Compression tests

Joints

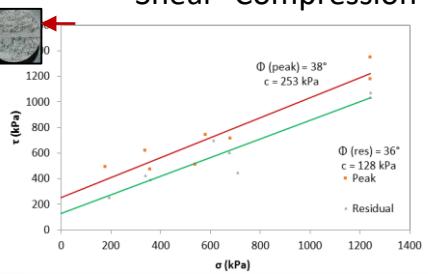
Compression



Shear



Shear- Compression



Mohr Coulomb envelopes (peak ; residual)

Parameter	Mean values
Normal stiffness (MPa/mm)	0,83 – 1,8
Shear stiffness (MPa/mm)	0,63 – 0,83

Caminha Tower

- Experimental campaign for structural and material characterization – Sonic tests

Sonic testing basics

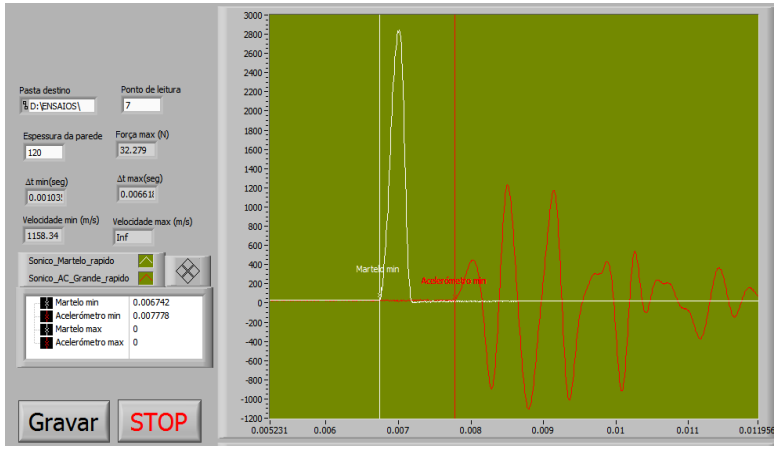
Impact application by an instrumented hammer and measurement of impact wave departure from a given point.

Wave reception and measurement, by an accelerometer fixed at another point a certain distance apart.

Measurement of wave travel time and computation of wave velocity.

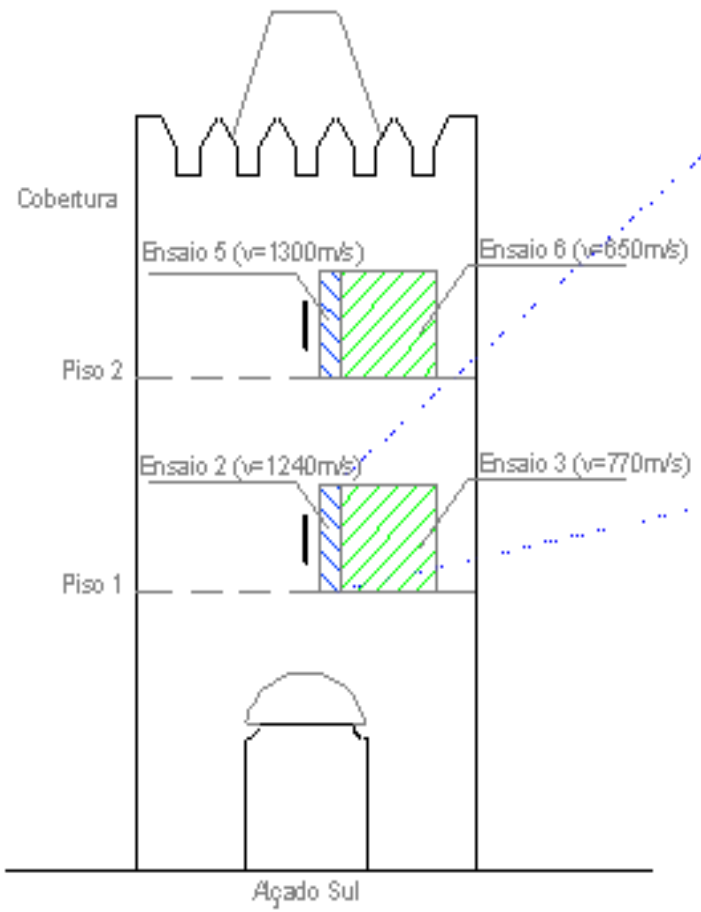
Instrumented hammer

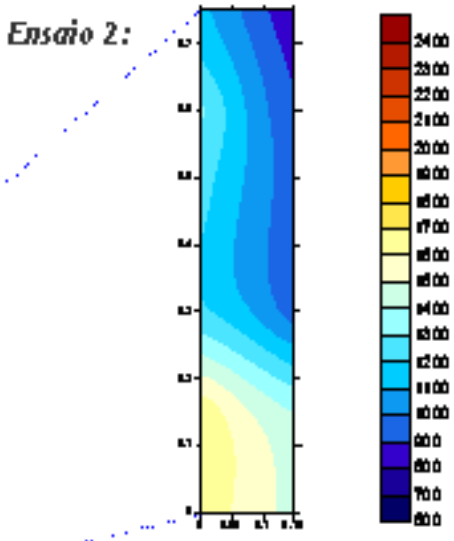
Wave recording



Caminha Tower

- Experimental campaign for structural and material characterization – Sonic tests





Wave velocity contour map.

Ensaio	Espessura (m)	N° de Pontos	$V_{média}$ (m/s)
2	1.2	12	1222 - 1249
3	2.0	36	765
5	1.2	12	1297
6	2.0	12	646

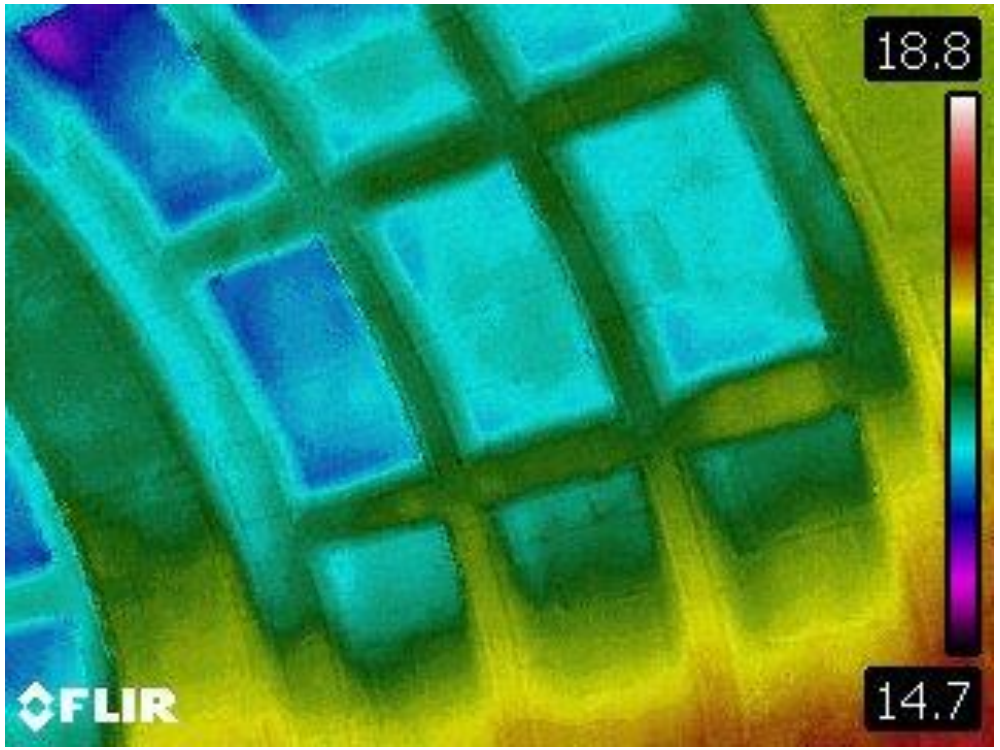
The existence of low cohesion material in the interior of walls, was evidenced by a clear reduction of the wave velocity in portions of walls with infill material.

Grilos Church

- Experimental identification of different structural materials – Thermography

Structural view of vault

Thermographic picture



From Diagnosis and Analysis to Intervention

- Santo António Church in Viana do Castelo

Serious damage exhibiting large deformations, excessive out-of-plumb of columns and significant opening of cracks and joints in the left side chapels.

Intense moisture in the whole building, mainly in the left side.

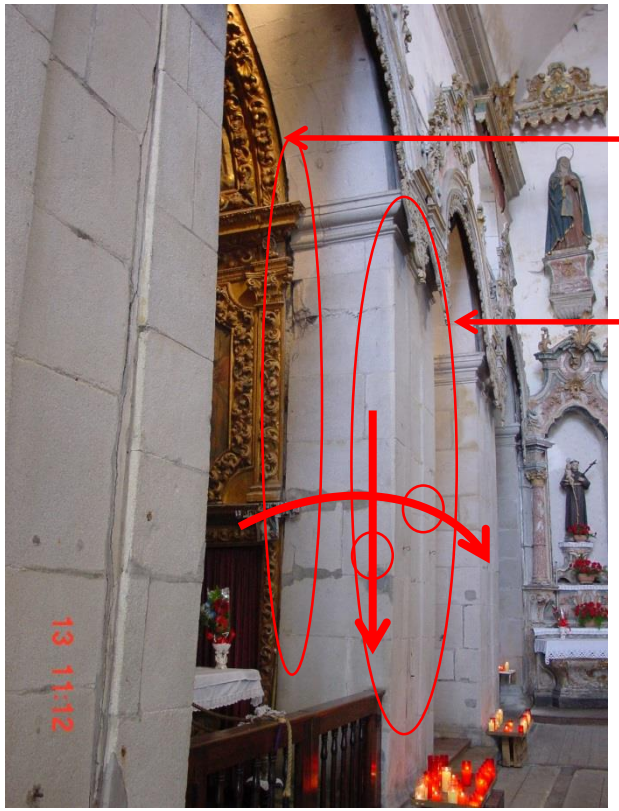
After a long waiting period, the rehabilitation works started in 2013, having also included archeological activities.

Diagnosis → Intervention – S. Antonio Church (Viana)

- 1st step - **Structural survey …. in 2002** !!

Main visible damages:

Left wall deformation and main vault cracks



Diagnosis → Intervention – S. Antonio Church (Viana)

- 1st step - **Structural survey …. in 2002** !!

Crack and joint opening in the left Chapels

Cracks in the main vault (transversal and longitudinal)

Diagnosis → Intervention – S. Antonio Church (Viana)

- 2nd step - **Urgent structural intervention proposal - 2006**
- 3rd step - **Structural strengthening design – 2010**
- 4th step - **Structural strengthening intervention – 2013-2014**

Lateral chapel walls, columns and vaults consolidated with confining rods and mortar injection.

Diagnosis → Intervention – S. Antonio Church (Viana)

- 4th step - **Structural strengthening intervention – 2013-2014 (cont.)**

Foundation soil consolidation (after repair of walls, columns & vaults).

Adopted solution: voids filling with stones and mortar, materializing an "impermeable" curtain and to allow making soil injection at low pressure.

Diagnosis → Intervention – S. Antonio Church (Viana)

- 4th step - **Structural strengthening intervention – 2013-2014 (cont.)**

Roof structure repair: consolidation of assumed wood structure,
… that did not show-up!!!....

Roof directly placed on rubble filling material, supported in the vault !!!....

Highly permeable!

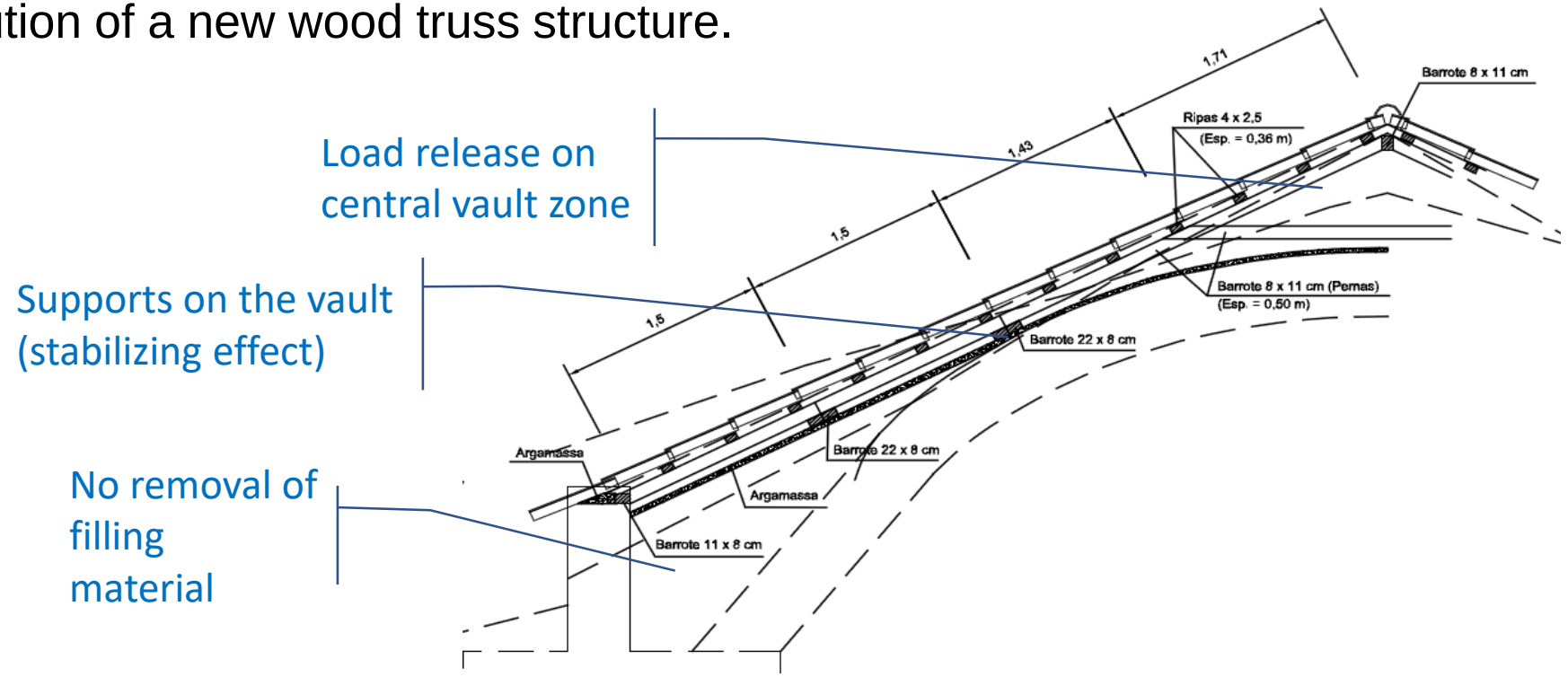
The excessive moisture was finally explained !!

Diagnosis → Intervention – S. Antonio Church (Viana)

- 4th step - **Structural strengthening intervention – 2013-2014 (cont.)**

Proposal for new roof structure solution:

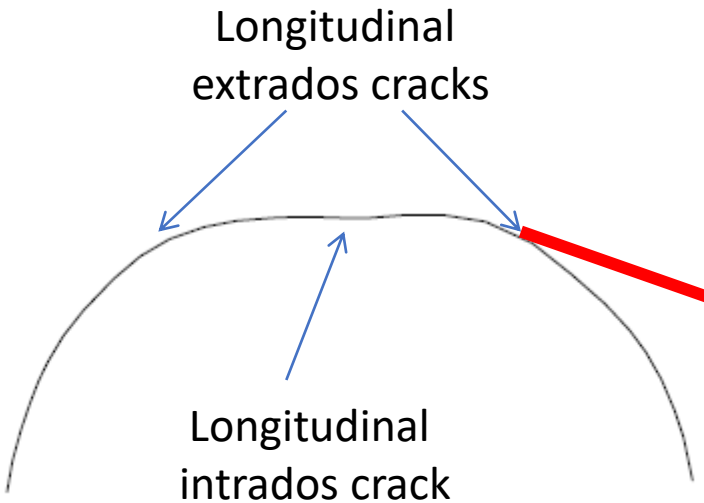
- removal of filling material from the central vault zone
- execution of a new wood truss structure.



Diagnosis → Intervention – S. Antonio Church (Viana)

- 4th step - **Structural strengthening intervention – 2013-2014 (cont.)**

But the **real scenario** was really **bad**, demanding further care!



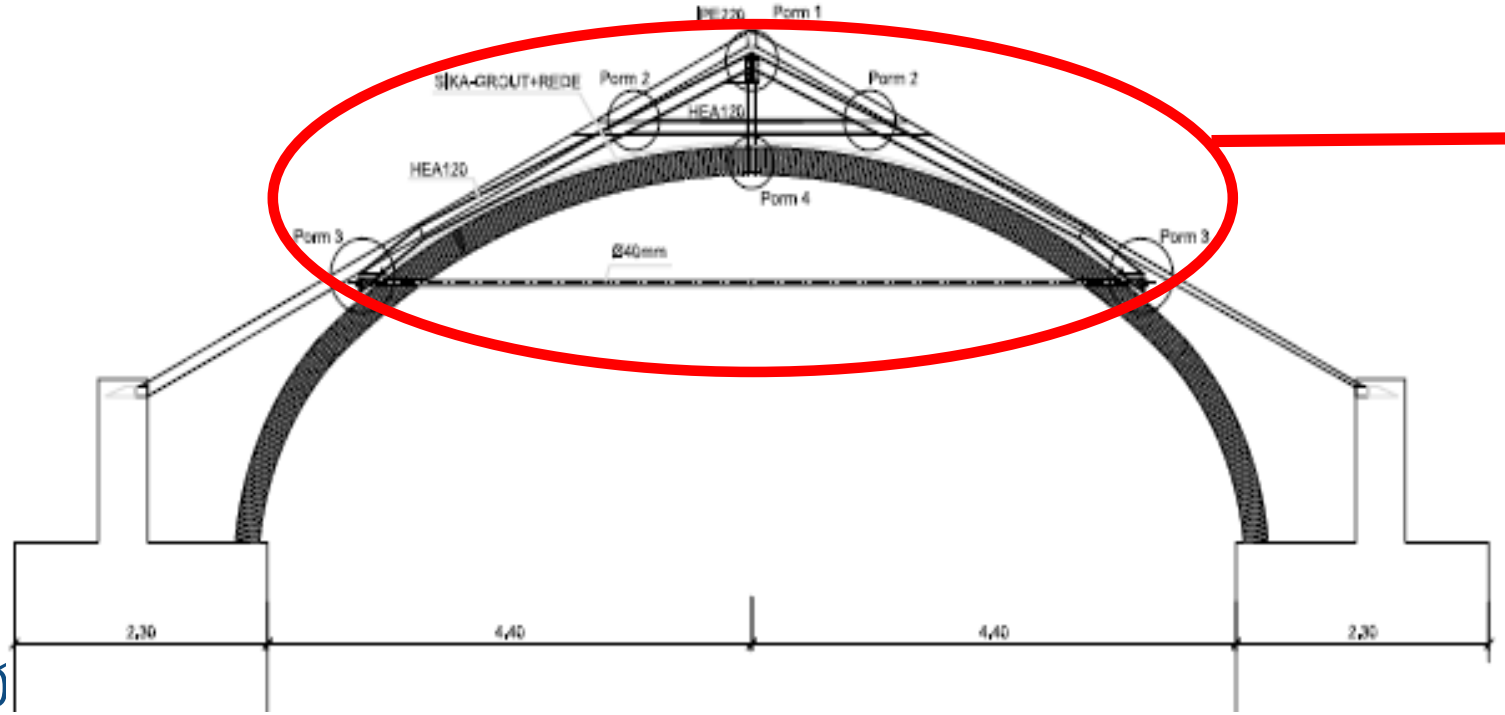
Observed vault profile

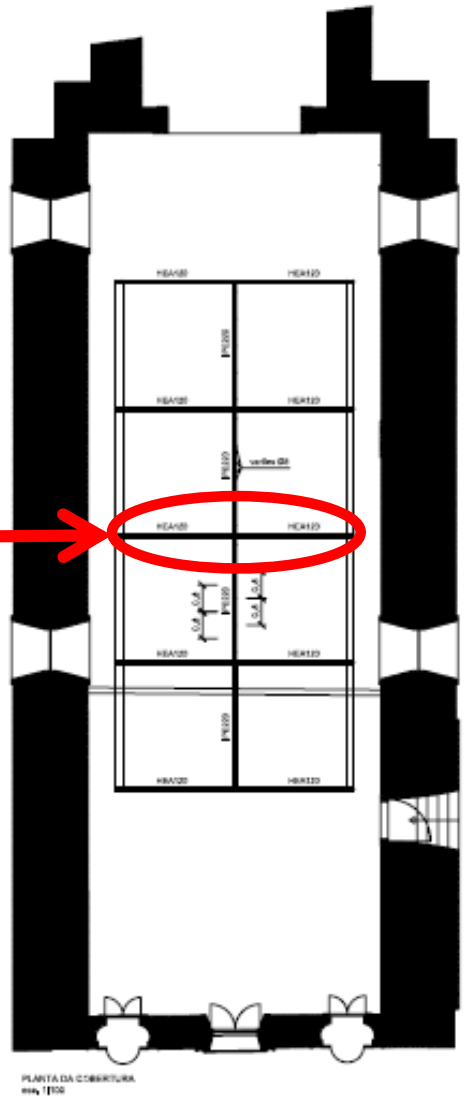
Diagnosis → Intervention – S. Antonio Church (Viana)

- 4th step - **Structural strengthening intervention – 2013-2014 (cont.)**

Improved strategy!

Self-equilibrated steel truss to suspend and strengthen the “deformed” central zone of the vault.





Diagnosis → Intervention – S. Antonio Church (Viana)

- 4th step - **Structural strengthening intervention – 2013-2014 (cont.)**

Vault strengthening - implementation:

- New steel trusses positioned;

- External cracks injected with mortar and stitched with rods.

Diagnosis → Intervention – S. Antonio Church (Viana)

- 4th step - **Structural strengthening intervention – 2013-2014 (cont.)**

Vault strengthening implementation:

→ a new mixed "**steel truss – masonry**" vault !

The final, external wood roof structure, totally independent of the steel trusses.

TESTING FOR REHABILITATION

- Traditional URBAN CONSTRUCTION SYSTEMS of Northern Portugal, e.g. Porto

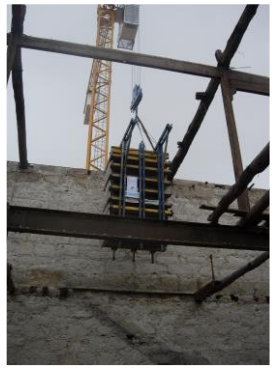
  - stone masonry walls (one-leaf lateral or multiple-leaves façades)

  - timber structure in floors and roofs

    - Walls made of medium to large granite stones (diagonals 50 to 90cm) along horizontal layers (mostly single leaf, 30 to 50cm thick).
    - Joints with many small stones (wedges), partially filled in with mortar (poor lime-based mortar).

TESTING for Rehabilitation – Stone Masonry Walls

- Testing Real Large Specimens – Single leaf / In-plane behavior / Laboratory
  - One-leaf granite real wall (30m long) available to cut into panels for **<u>compression tests</u>** (*<u>original state</u>* and after *<u>mortar injection</u>*) and **<u>shear-compression tests</u>**



4 to 6 ton !!

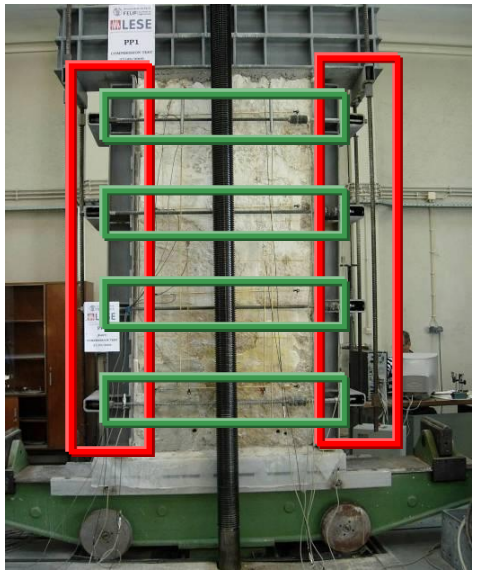
✓ **Uniaxial Compression**:
PP1; PP2 e PP3
(1.20mx2.50mx0.40m)

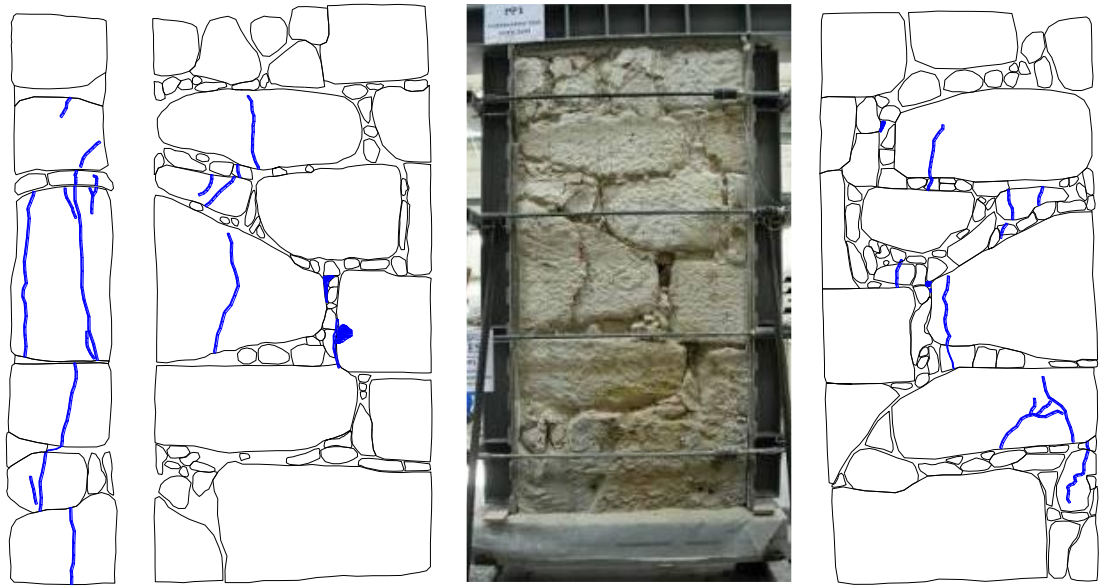
✓ **Diagonal Compression & Shear-Slidding**:
PP4 (1.20mx2.50mx0.40m)

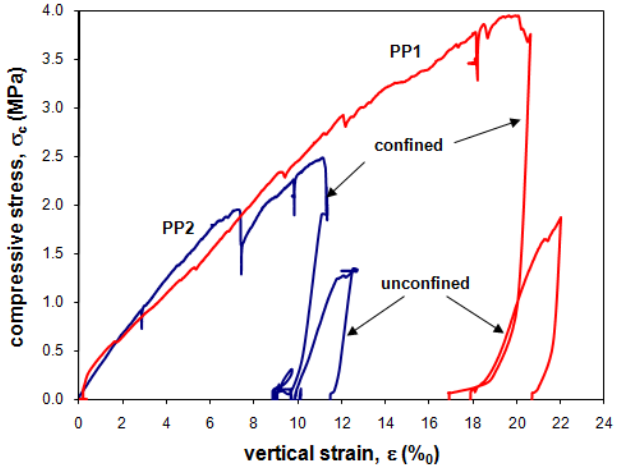
✓ Cyclic **shear- compression**:
PG1 (σ_0= 0.8 MPa); PG2 (σ_0= 0.4 MPa)
(1.60mx2.50mx0.40m)

TESTING Stone Masonry Walls – In plane / Lab

- COMPRESSION TESTS OF original WALL PANELS







Mainly vertical crack pattern: Most important stone damages

- Strength (lower bound estimates) within expected interval (PP1- **3.94** MPa; PP2- **2.5** MPa)
- Much larger deformability than expected (PP1- **0.22** GPa; PP2- **0.33** GPa)

$$E = 85\, f_c$$

TESTING Stone Masonry Walls – In plane / Lab

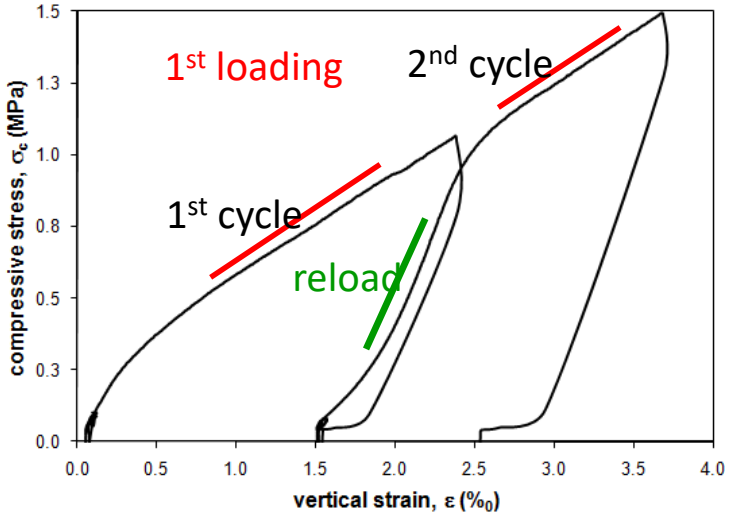
- COMPRESSION TESTS OF original WALL PANELS – why large deformability?

1st phase (compression in **original PP3):**
Two loading cycles (**1.0** and **1.5** MPa)

Deformability modulus :

- 1st loading
  0.36 GPa (1st cycle)
  0.39 GPa (2nd cycle)
- reload
  1.37 GPa

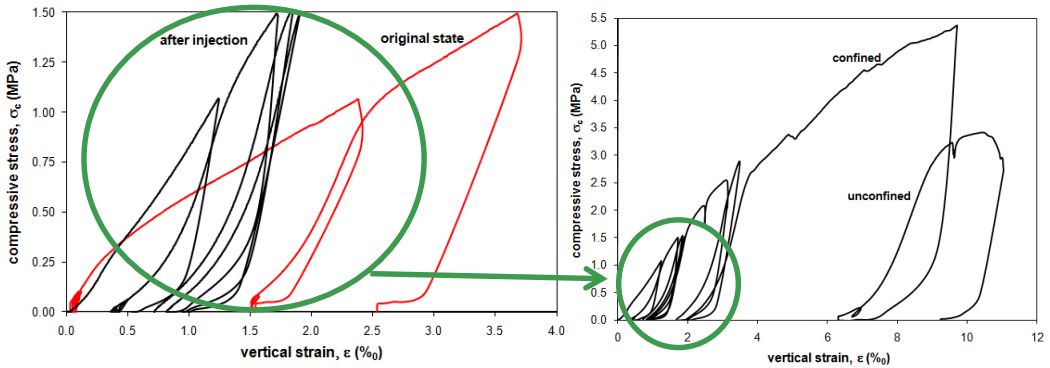
No visible damages



2nd phase Injection with *poor-quality* **fluid mortar** to **fill-in** existing **internal voids in PP3**

Considerable
Stiffness **increase**:
1.0 GPa (2.7x)
Strength **increase**:
5.4 MPa (1.7x)

$$E = 185\, f_c$$



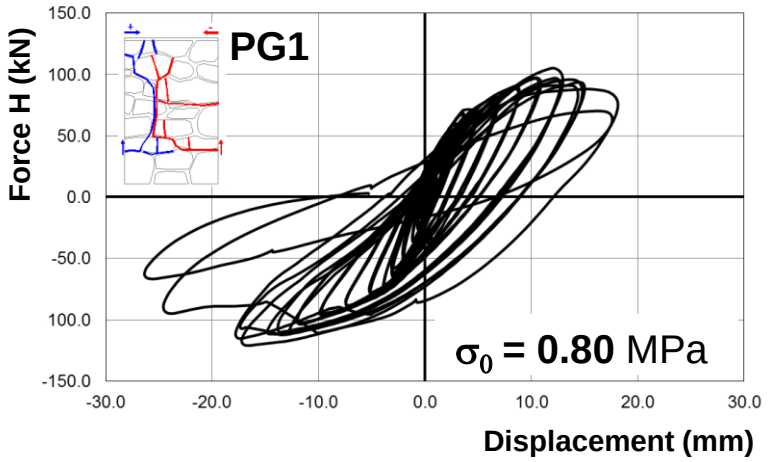
TESTING Stone Masonry Walls – In plane / Lab

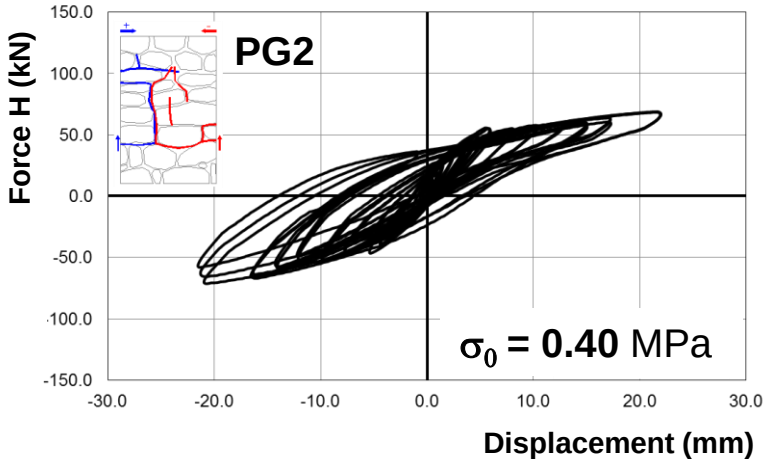
- SHEAR-COMPRESSION TESTS of 2 original WALL PANELS

Initial *vs.* damaged stages

Initial Final

Top force H / displacement plots





Behavior in both walls:

✓ Similar damage type (*shear and rocking).*

✓ Strength degradation more pronounced in **PG1**

*$H_{máx.}$ = 108 kN (**PG1**)*
*$H_{máx.}$ = 70 kN (**PG2**)*

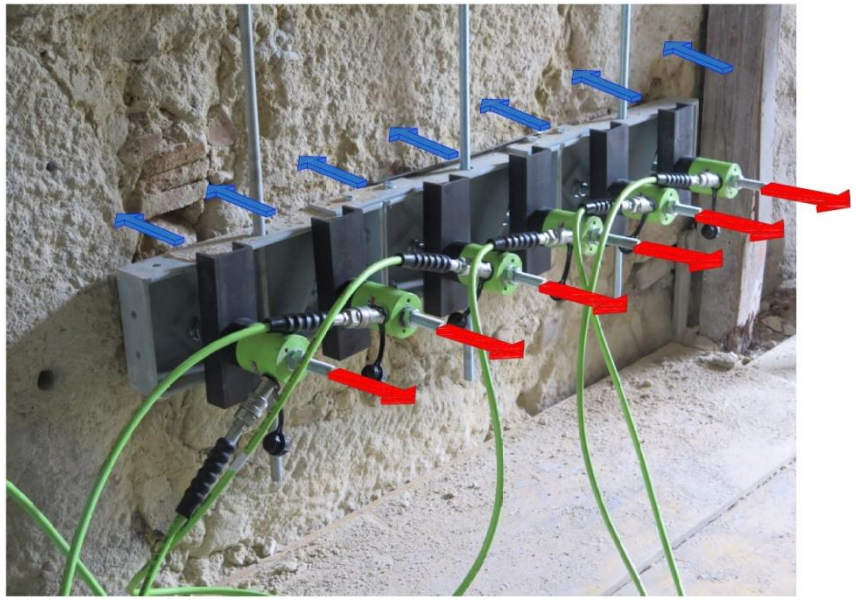
✓ "Máx. ductility (?)": ~4.0

✓ Max. *drift:* 0.85%.

✓ Equiv. damping ratio: 16%

TESTING Stone Masonry Walls: Compression / In situ

- A new light, modular, portable and self-equilibrated compression test set-up (2018)

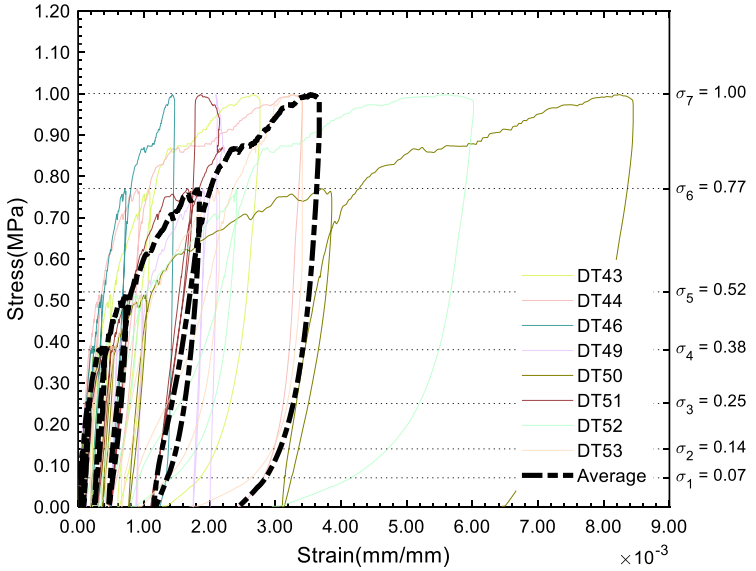


Set-up preparation (1-2 days)

Test execution < 1 day

Test results

Stress-Strain Curves



TESTING Stone Masonry Walls: Out-of-plane / In situ

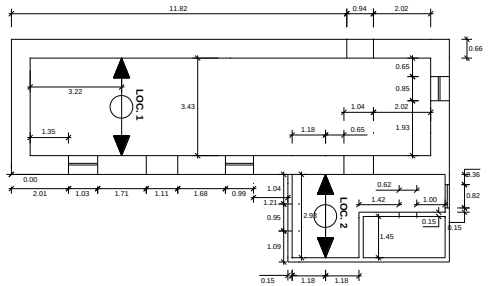
- Azores Island – Faial: testing campaign from 2007 to 2013

Tests on wall panels existing between openings of 3 houses and on the gable wall of 1 house

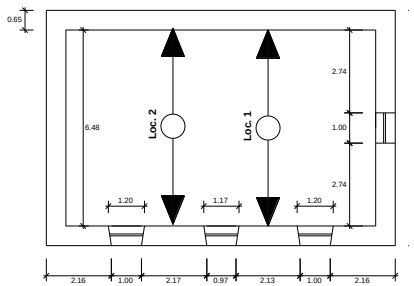
House 1

House 2

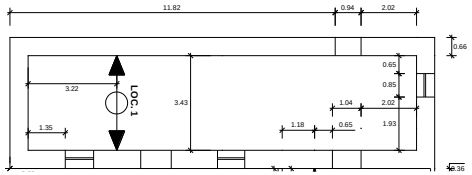
House 3



2 test locations



2 test locations

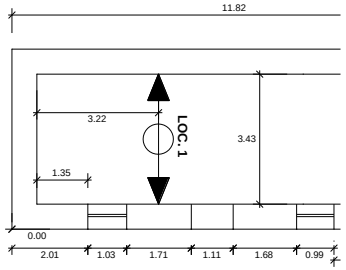


5 test locations

TESTING Stone Masonry Walls: Out-of-plane / In situ

- Azores Island – Faial: testing campaign from 2007 to 2013

Simultaneous testing two opposite walls, by applying horizontal forces one against the other



Top concentrated force

Pair of hydraulic actuators (250mm stroke):
- displacement controlled,
- quasi-static cyclic forces at the top of walls
Simulation of the roof horizontal action on walls.

Out-of-plane testing based on a self-equilibrated setup: easy implementation, reduced testing time and portable system.
Loading reaction provided by the "rear wall", thus not requiring any reaction structure external to the house itself.

"Reaction wall"

Marine plywood plank

Distributed loads using airbags

Tubular steel elements

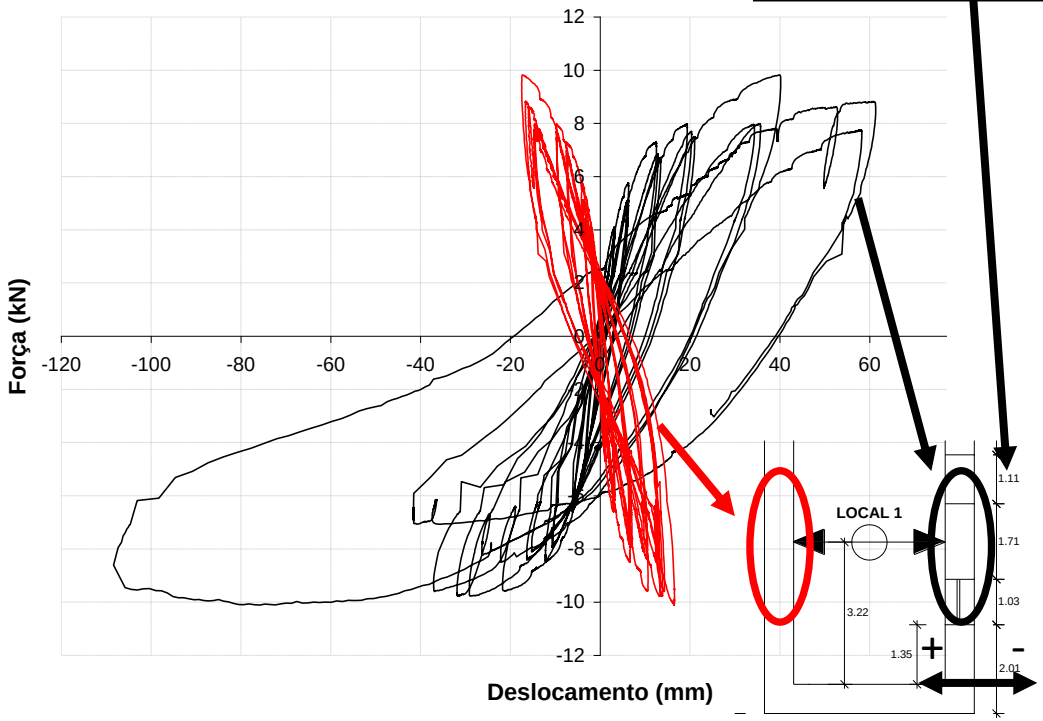
Pressurizing system

TESTING Stone Masonry Walls: Out-of-plane / In situ

- Azores Island – Faial: testing campaign from 2007 to 2013

1st Test: House 1, Location 1 (2007)

Weaker wallet after test 10 kN max.!!

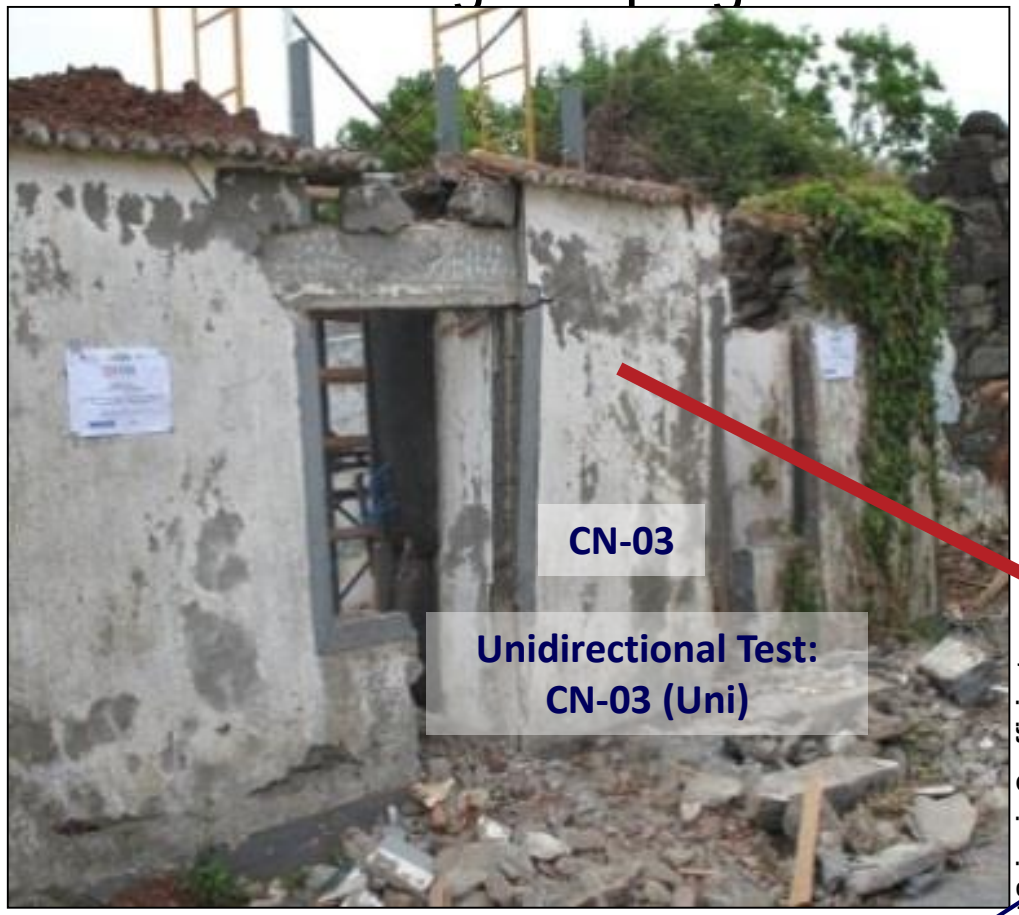


Global force-displacement diagrams (quasi-static tests)

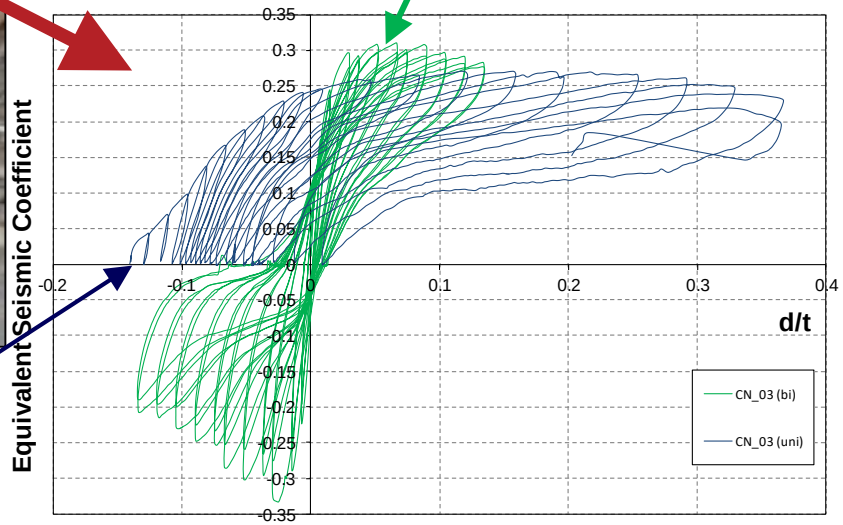
TESTING Stone Masonry Walls: Out-of-plane / In situ

- Azores Island – Faial: testing campaign from 2007 to 2013

Test in wallet of House 3, With Airbags (2011)



Previous Bidirectional Test: CN-03 (Bi)

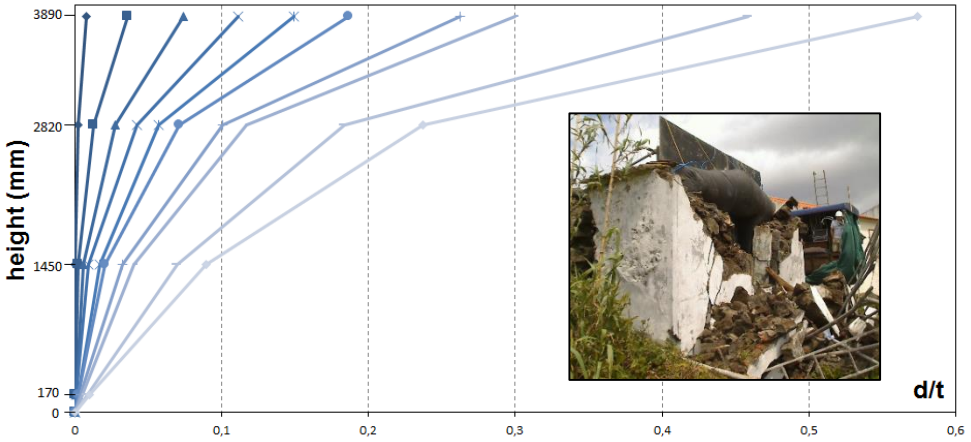


CN-03 (Uni) test:
Restarted at residual displacement (null force) of the previous CN-03 (Bi) test

TESTING Stone Masonry Walls: Out-of-plane / In situ

- Azores Island – Faial: testing campaign from 2007 to 2013

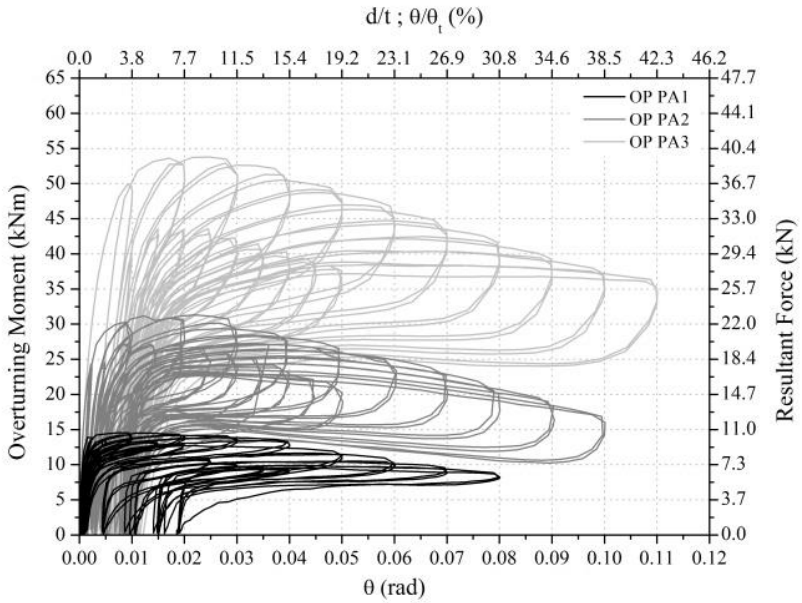
Last Test: House 3, Gable wall (2013)



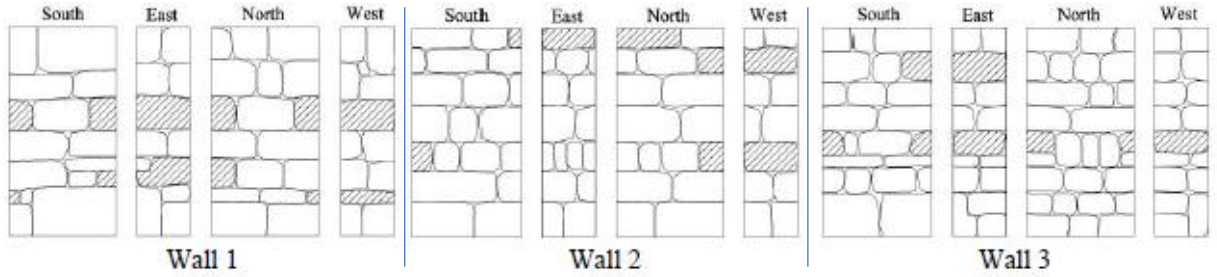
TESTING for Rehabilitation: Stone Masonry Walls

- Stone-masonry walls: out-of-plane performance

Airbags tests Distributed force



3 levels vertical stress at the base: 0.05 MPa, 0.11 MPa, 0.22 MPa



TESTING for Rehabilitation: Stone Masonry Walls

- Stone-masonry walls: out-of-plane performance improvement

  Repair / Strengthening using **low-cost** solutions (reinforced plaster)

Reahabilitation after tests

Strengthened with PP polymer mesh

Experimental campaign to validate the **efficiency** of this technique to improve the walls' capacity and to test their behaviour under **cyclic loadings**

TESTING for Rehabilitation: Stone Masonry Walls

- Stone-masonry walls: out-of-plane performance improvement

Repair / Strengthening using **low-cost** solutions (reinforced plaster)

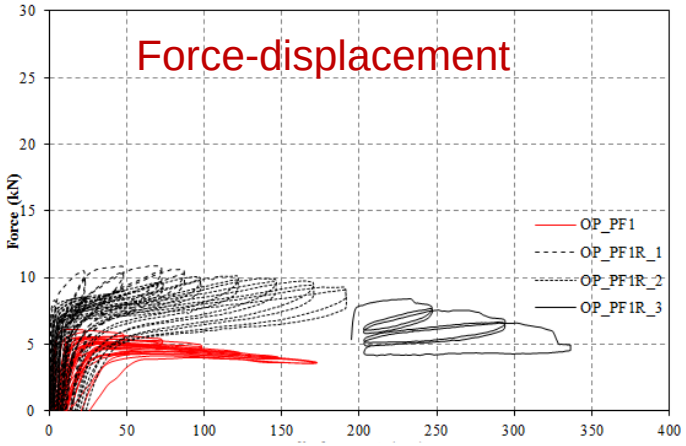
Before strengthening

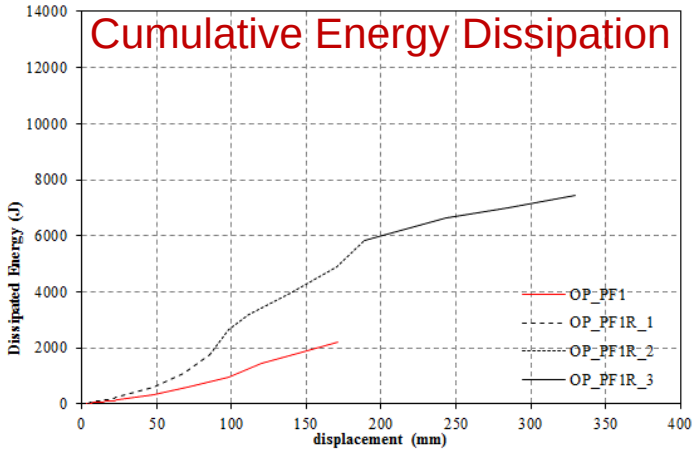
After strengthening

Strength: ***+77%***

Displacement: ***+95%***

Energy: ***+311%***

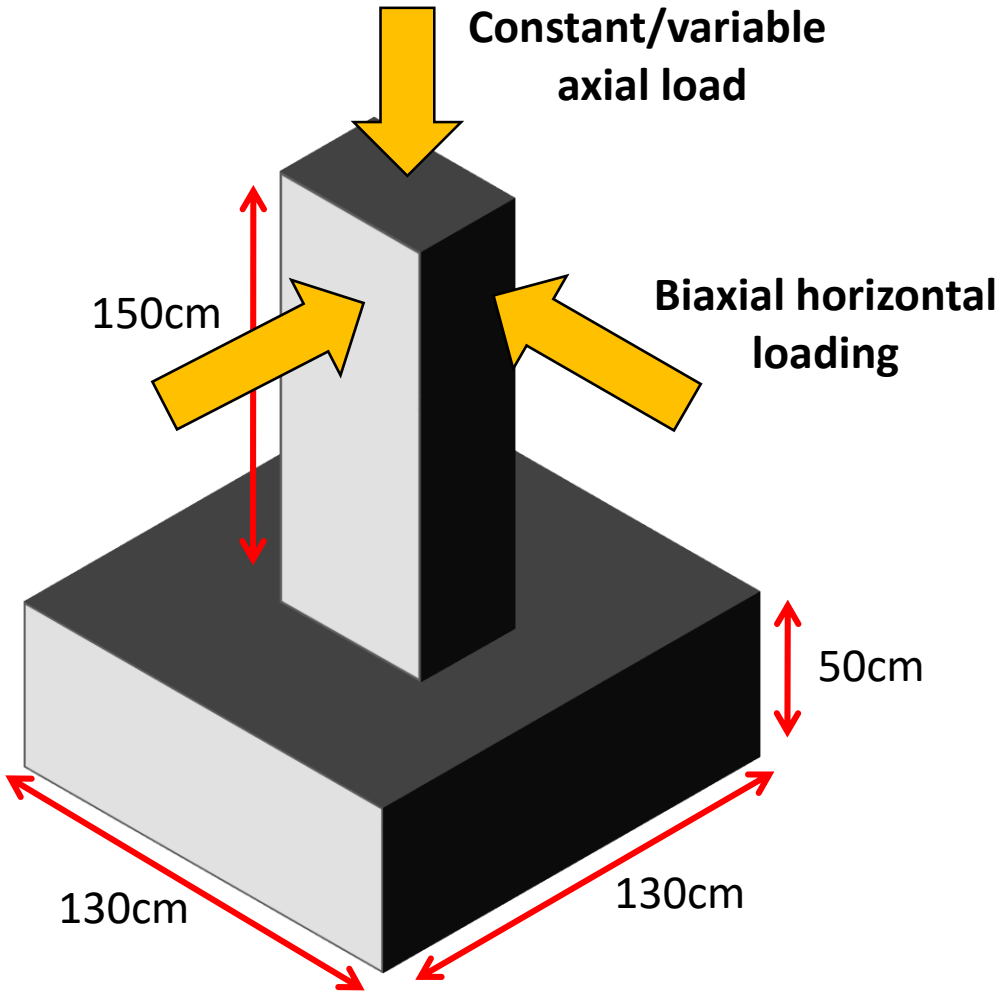




TESTING for Seismic Rehabilitation - Columns

- Reinforced concrete columns under lateral loading (1D or 2D):

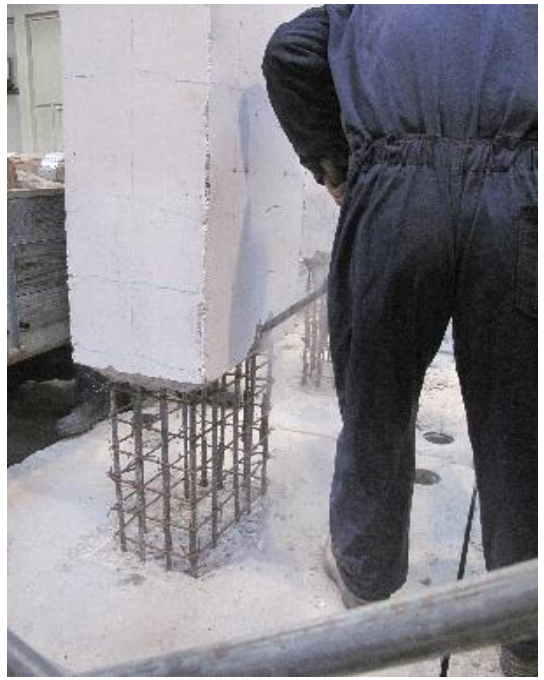
Test setup



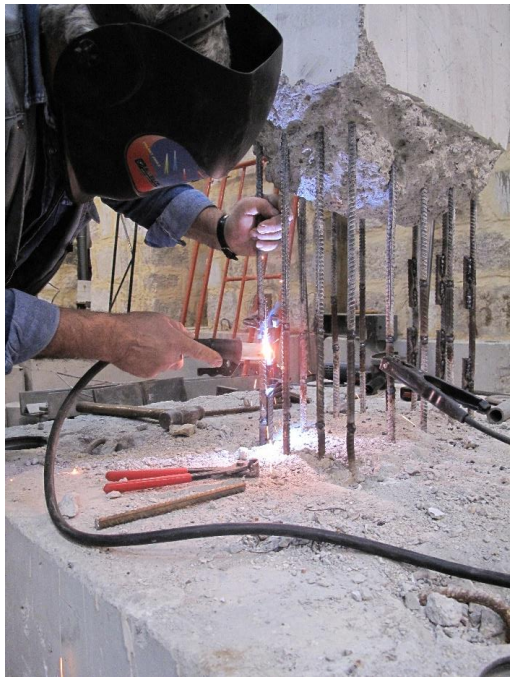
2004 →

TESTING for Seismic Rehabilitation - Columns

- Reinforced concrete columns: repair and/or strengthening



Demolition and cleaning of the damaged concrete



Cut damaged (buckled) rebars and weld new rebar segments

Replace transverse reinforcement

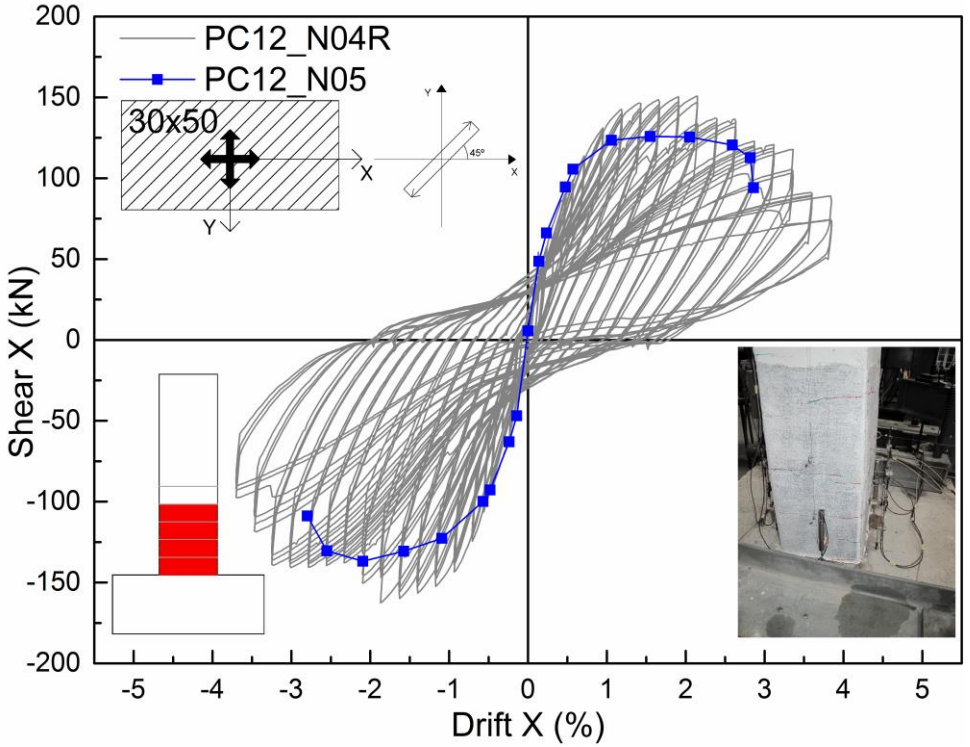
Re-cast with new micro-concrete

TESTING for Seismic Rehabilitation - Columns

- Reinforced concrete columns: repair and/or strengthening

Final repaired critical zone

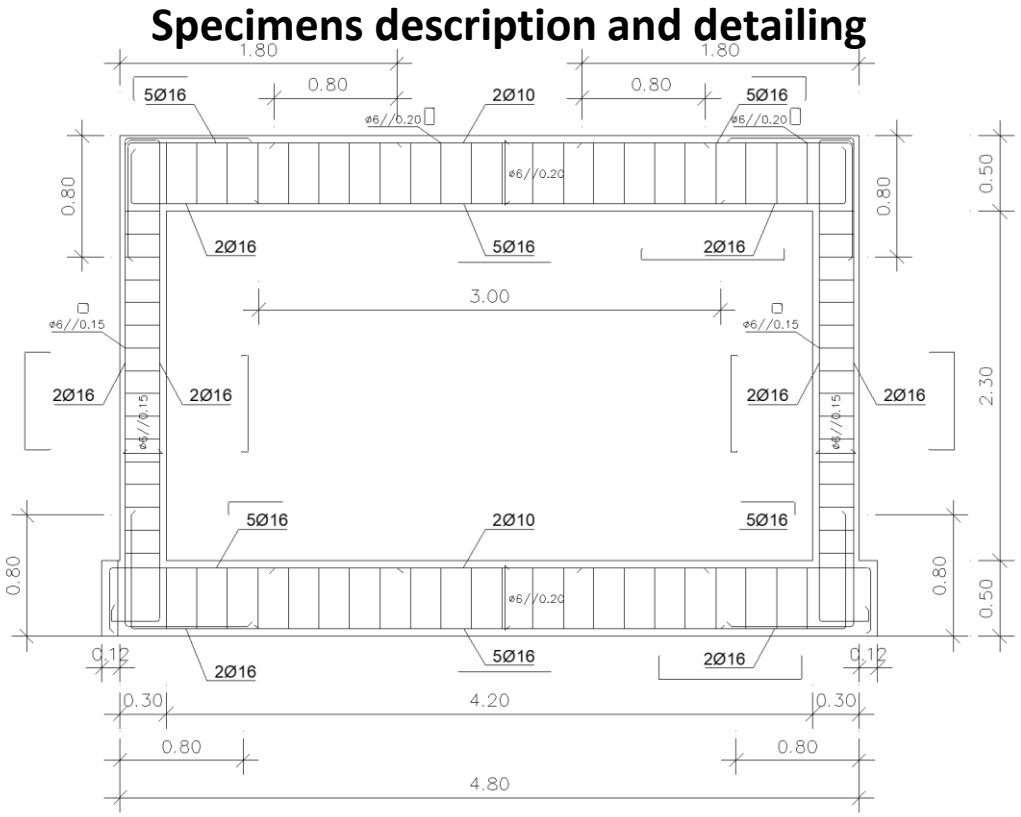
Strengthen with external jacketing (eg.: CFRP)

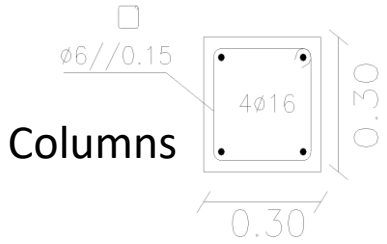


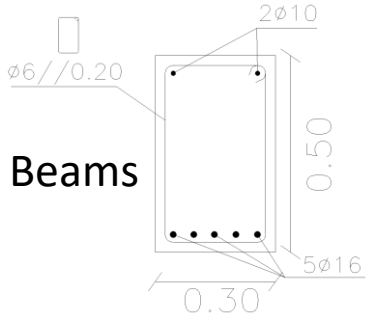
Re-test again and compare with original results. Performance reestablished and even improved

TESTING for Seismic Rehabilitation - Infills

- Brick masonry infills: in-plane, out-of-plane response and strengthening







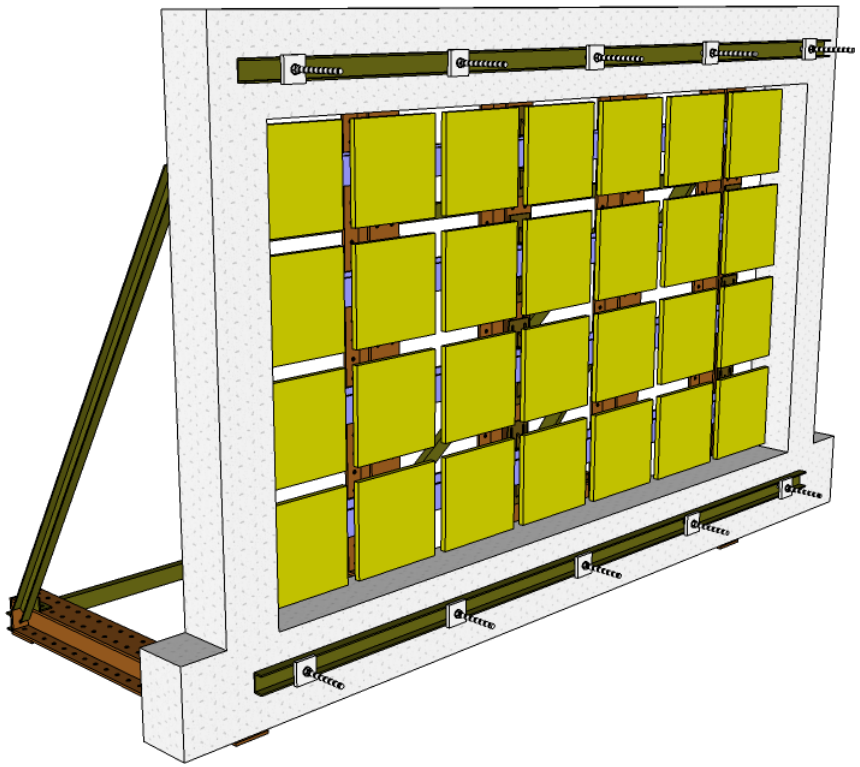
Full scale specimens representative of the Portuguese building stock according to:

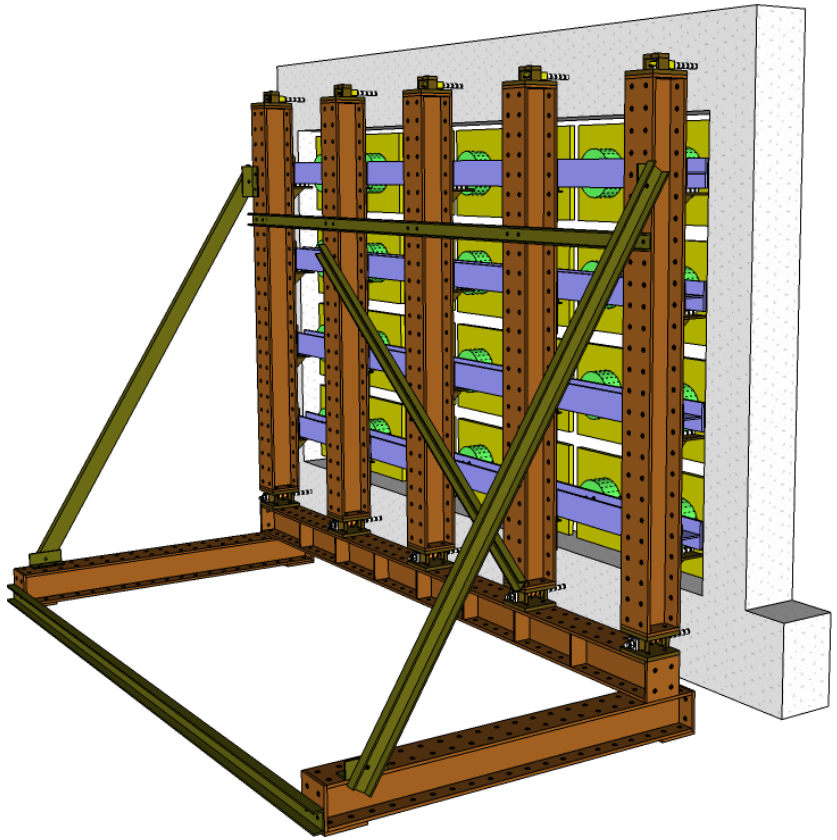
A. Furtado, H. Rodrigues, A. Arêde, C. Costa (2016), “Geometric characterization of Portuguese RC buildings with masonry infill walls”, European Journal of Environment and Civil Engineering

TESTING for Seismic Rehabilitation - Infills

- Brick masonry infills: in-plane (IP), out-of-plane (OOP) response and strengthening

A new upgraded platform (2017 → present) **for OOP tests and extensible to IP+OOP testing**





- self-equilibrated set-up

- 4x7 pneumatic actuators (aprox. max. 60 kPa OOP surface load in the infill panel)

TESTING for Seismic Rehabilitation - Infills

- Brick masonry infills: in-plane (IP), out-of-plane (OOP) response and strengthening

A new upgraded platform (2017 → present) **for OOP tests and extensible to IP+OOP testing**

Side view

Rear view

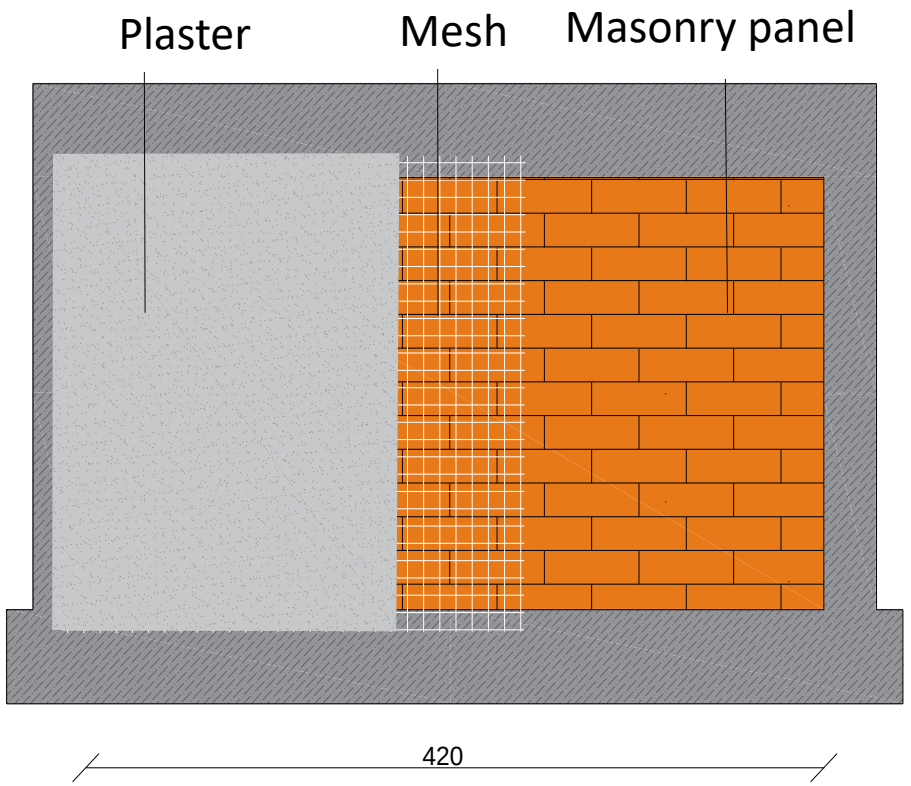
ng

TESTING for Seismic Rehabilitation - Infills

- Brick masonry infills: in-plane (IP), out-of-plane (OOP) response and strengthening

Application and testing of retrofit strategies

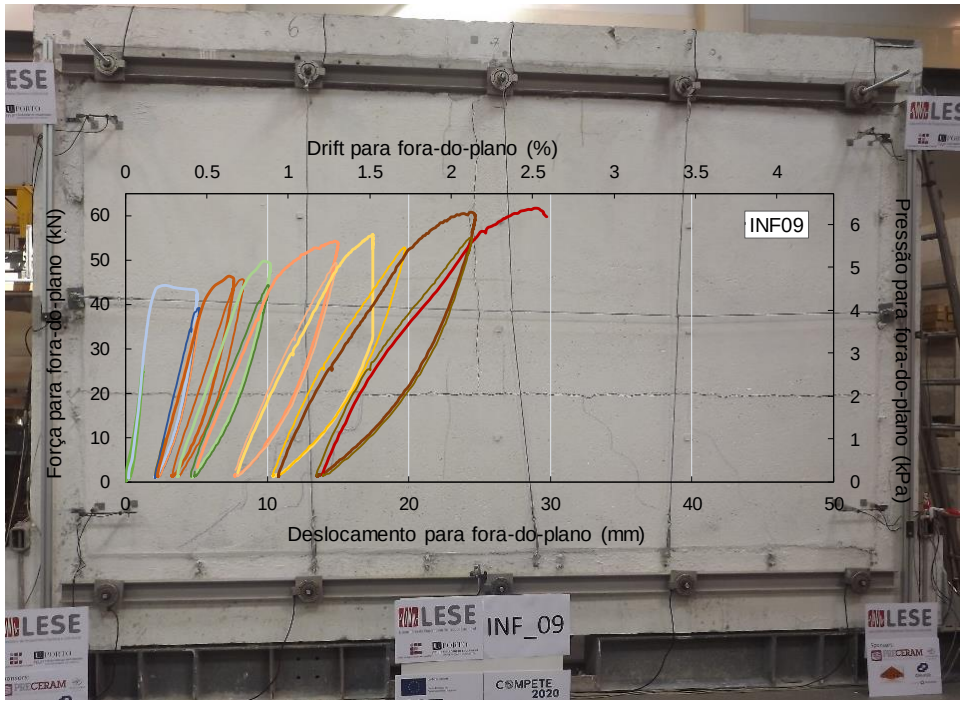
Textile reinforced mortars (TRM)
GFRP mesh with connectors



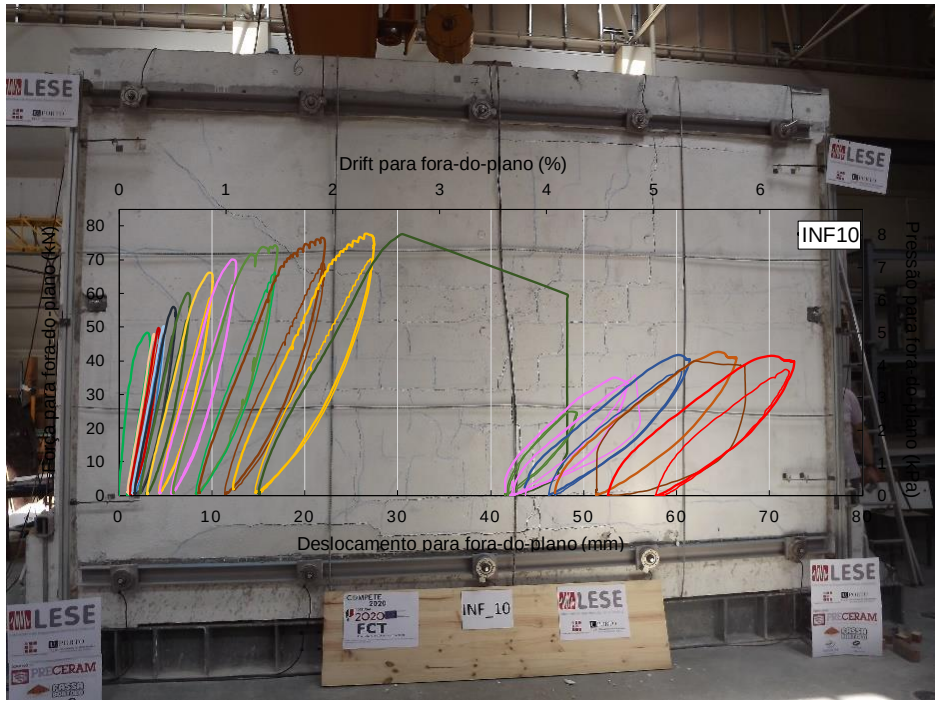
TESTING for Seismic Rehabilitation - Infills

- Brick masonry infills: in-plane (IP), out-of-plane (OOP) response and strengthening

Application and testing of retrofit strategies



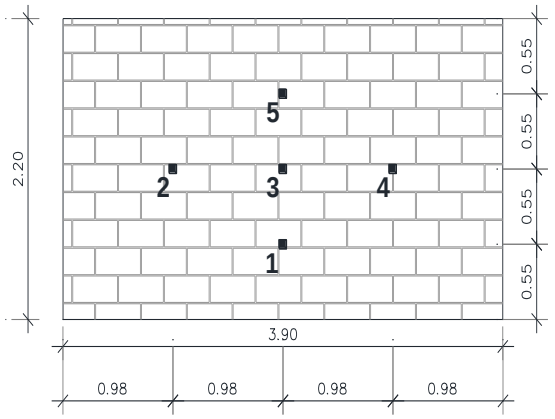
Inf_09 - As-Built specimen
Trilinear cracking pattern with horizontal cracks

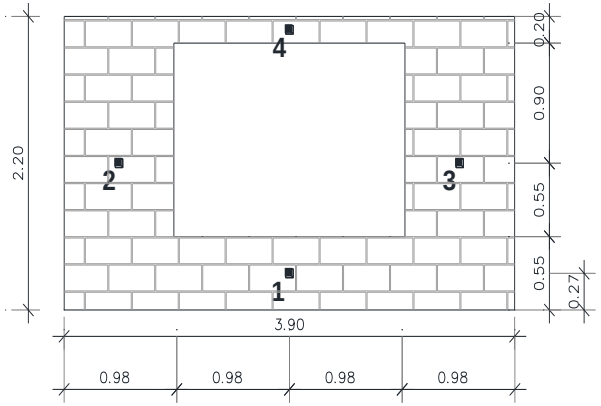


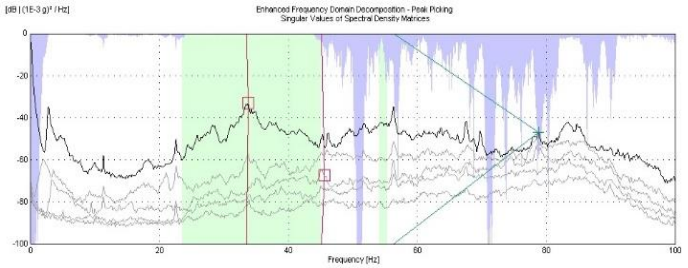
Specimen Inf_10 - Retrofitted specimen
Distributed damage with 5 line cracking pattern

TESTING for Seismic Rehabilitation - Infills

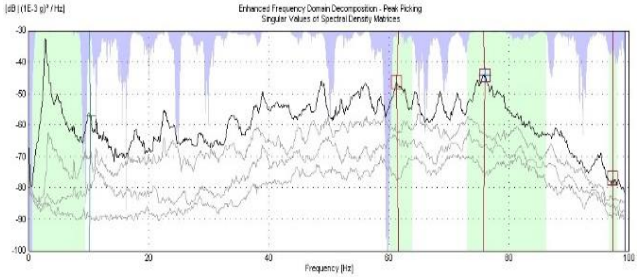
- Ambient vibration tests for OOP stiffness characterization - Influence of openings







Vibration Mode	Frequency (Hz)	Damping Ratio (%)
1	31.83	2.003
2	45.02	0.5108
3	79.91	0.1655



Vibration Mode	Frequency (Hz)	Damping Ratio (%)
1	10.07	5.170
2	61.39	1.491
3	135.3	0.129

The opening reduced the OOP first natural frequency by ~66%.

Data example taken from reconnaissance mission post Nepal earthquake (2015)

Major developments (projects)

1. SeismicPRECAST - Seismic performance **ASSessment** of existing Precast Industrial buildings and development of Innovative **Retrofitting** sustainable solutions (RUNNING, until 2021)
2. RIACT - Risk Indicators for the Analysis of Cultural **heritage** under Threat (RUNNING, until 2021)
3. SERA - Seismology and Earthquake Engineering Research Infrastructure Alliance for Europe (H2020)
4. SafEarth - Seismic **protection** of earthen construction **heritage** (2019)
5. ASPASSI: Safety evaluation and **retrofitting** of infill masonry enclosure walls for seismic demands (2019)
6. StonArcRail - Experimental and Numerical **Characterization** of Structural Behaviour of Stone Masonry Arch Bridges under Railway Traffic Loading (2015)
7. PRISE - Earthquake loss **assessment** of the Portuguese building stock (2015)
8. RetroInf – Innovative Solutions for Seismic **Retrofitting** of Masonry Infill Walls (2015)
9. Structural Assessment and **Strengthening** of Reinforced Concrete Columns Under Horizontal Bi-Axial Cyclic Loading (2013)
10. Field Experimental **Characterization** of Stone Masonry Constructions under Earthquake Actions (2013)
11. Structural Safety **Assessment** and **Retrofitting** of Bridges (2010)
12. Seismic **Protection** of Built **Heritage** (2005)

Hints for the future (submitted projects – April 2020)

1. Assessment and **retrofitting** of existing reinforced concrete building structures non-seismically conformed
2. Innovative procedures for mechanical characterization of stone masonry walls towards databases in support of structural **rehabilitation**
3. SEismic-Thermal Energy composite **upgrading** Solutions for infilled RC frames envelopes
4. Seismic Vulnerability **Assessment** of Stone Masonry Arch Bridges of the Portuguese Railway Network
5. Increased **Resilience** of Transport Infrastructure to Seismic and **Structural Degradation** Risk
6. Redefining Earthquake Safety by Integrating **Sustainable** Thinking

Thanks for your attention!

Obrigado!

Gracias!