Preservation of Historic Structures: Methodology, Safety Assessment and Practice

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Introduction

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Cultural heritage

Identity

- Conservation of cultural heritage buildings is a demand from society
- No memory, no identity; no identity, no nation, A.D. Smith, LSE, 1995
- We shape our buildings; thereafter they shape us, W. Churchill, 1943

Economy

- Europe: tourism is 10% of the GDP and 12% of the employment
- Europe is the world's no. 1 tourist destination (50% of tourist arrivals)
- 45% of the UNESCO World Heritage sites are within Europe



Heritage at risk

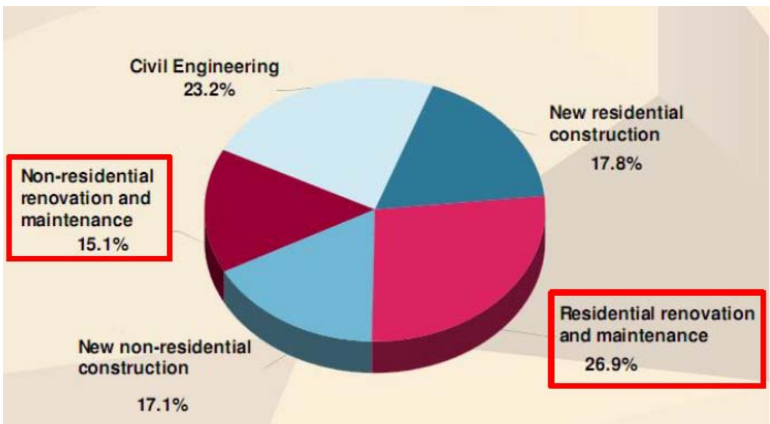
- **European Charter of the Architectural Heritage - 1975**
- Artº 6: This heritage is in danger.
- It is threatened by ignorance, obsolescence, deterioration of every kind and neglect. Urban planning can be destructive when authorities yield too readily to economic pressures and to the demands of motor traffic. Misapplied contemporary technology and ill-considered restoration may be disastrous to old structures. Above all, land and property speculation feeds upon all errors and omissions and brings to nought the most carefully laid plans.

SAHC MSc in Structural Analysis of Monuments and Historical Constructions

- ❑ Almost 500 alumni and 75 countries
- ❑ 10 years funding from EC
- ❑ Running for 16 years
- ❑ Practice & Research
- ❑ Europa Nostra Award 2017: *“allows students to view structural systems in different cultural contexts…an invaluable international perspective”*
- ❑ European Year of Cultural Heritage 2018: *“an inspirational example of what can be achieved when education, training and youth work meet cultural heritage”*
- ❑ Students from leading international universities
- ❑ 3 Robert Silman Fellows & 10 GCI internships
- ❑ Consultants (Arup, Cowi, Rambol, WJE,…)
- ❑ Awards for MSc theses and papers
- ❑ Selection for PhD programs worldwide

Importance

Construction Market in Europe



Buildings do not last forever

Lack of maintenance, deterioration & errors

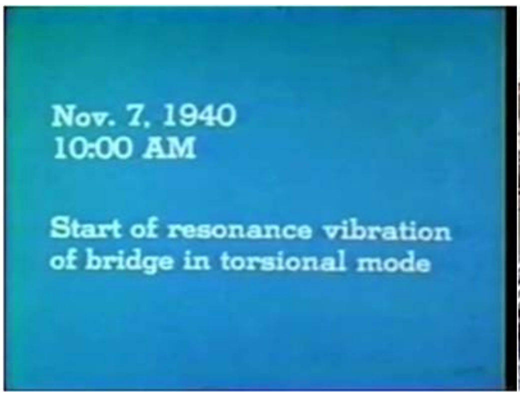
Buildings cost money!

Estimate for the US government: Average value of 6% of annual building cost, with 35% of this value for operation, 46% for preventive maintenance, repair and replacement of parts, and 19% for recapitalization

Extreme events

Some conceptual errors and Code changes

Ronan Point, 1968
Disproportionate collapse



Tacoma Narrows Bridge, 1940
Flutter instability
July 1 – November 7, 1940

Millennium Bridge, 2020
Lateral frequency modes

Prestressed bridge ban in UK, after several post-tension bridges collapsed in a short period of 10 years

25 September 1992: Department of Transportation banned post-tensioned grouted duct techniques from UK bridge construction. Lifted after 4 years and 10 M£ study

Timber bridge in Norway ‘built to last 100 years’ collapses after a decade

Bridge was inspected along with other wooden truss bridges in 2016 following the collapse of Perkolo Bridge, another timber crossing in Norway

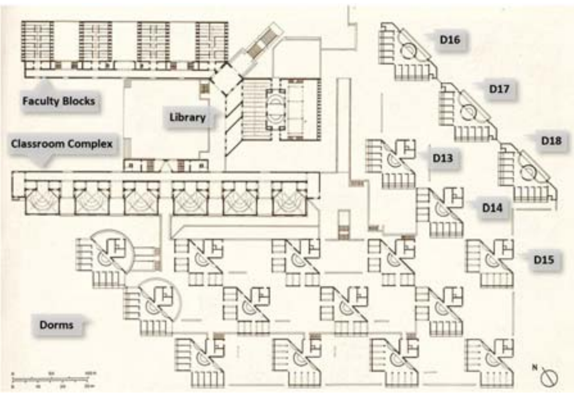
I-35 bridge over the Mississippi River

The National Transportation Safety Board (NTSB) identified a design flaw and inadequate inspections as the primary causes of the collapse. The tragedy led to increased awareness of the importance of regular inspections and maintenance of aging infrastructure

Durability

Louis Khan (USA, 1901-1974)
IIMA, Ahmedabad, India, 1962-1974

You say to brick, "What do you want, brick?" Brick says to you, "I like an arch." if you say to brick, "arches are expensive and I can use a concrete lintel over an opening. What do you think of that, brick?" Brick says: "I like an arch." —Louis Kahn



"I'm now wiser from that time. Now I can say that reinforcement was a recipe for a disaster" Architect MS Satsangi from the team in Ahmedabad, 2015

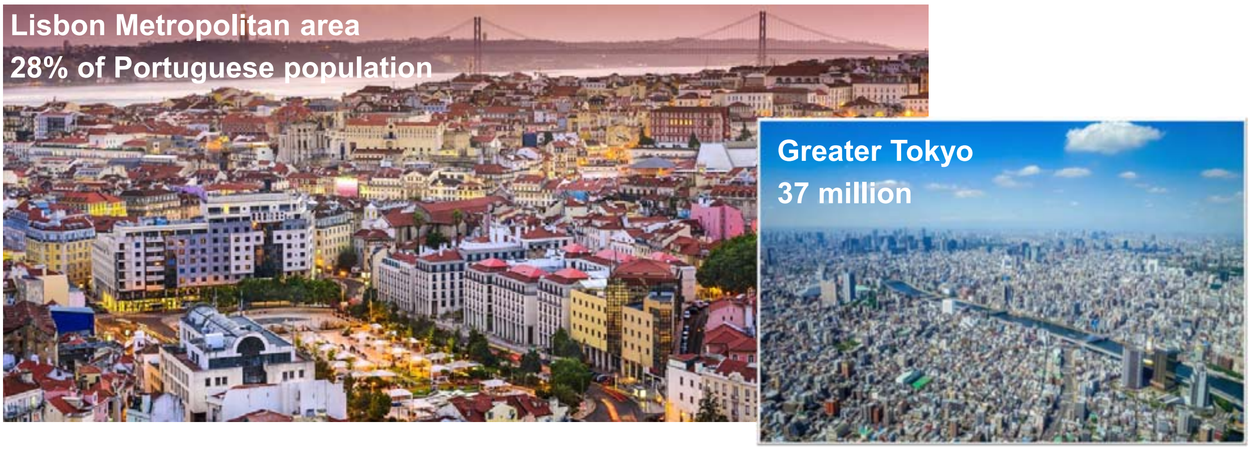
Reinforced masonry walls

RC slabs and staircases

Hazards: Natural and made-made

- ❑ Climate change (and non-deliberate human action)
- ❑ Deliberate human action

Growing value at risk



- ❑ The U.S. National Academy of Sciences projected for the next 50 years the human population to increase in ±50% with ±40% more life expectancy. This means >100% the demand for housing
- ❑ Half of the global population lives in cities, and by 2050 two-thirds (2100, 85%) is expected to live in urban areas (UN, World Urbanization Prospects)

Risk assessment

- **Risk evaluation for the built environment is associated with the level of hazard, building vulnerability and level of exposure**

- Within this holistic approach, building vulnerability is the most important, not only because of the physical consequences in a disaster, but because it is where engineering can intervene, reducing the level of vulnerability and consequently the level of physical damage, life loss and economical loss

Risk assessment

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Earthquakes

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The seismic problem

1755, Lisbon

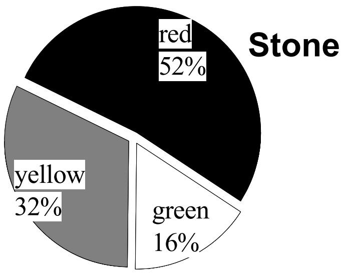
A perfect disaster: tsunami with 10 m, fire for 5 days, 85% of the buildings destroyed, up to 90.000 deaths = 30% of population, Enlightenment – Kant / Voltaire)

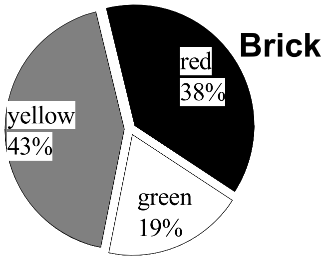
…, 2009, 2012, 2016, 2017, Italy

2011, Spain

Existing masonry: Churches in New Zealand (EQs 2010-11)

- Red: unsafe building with access forbidden
- Yellow: safety compromised but urgent access allowed
- Green: no restrictions



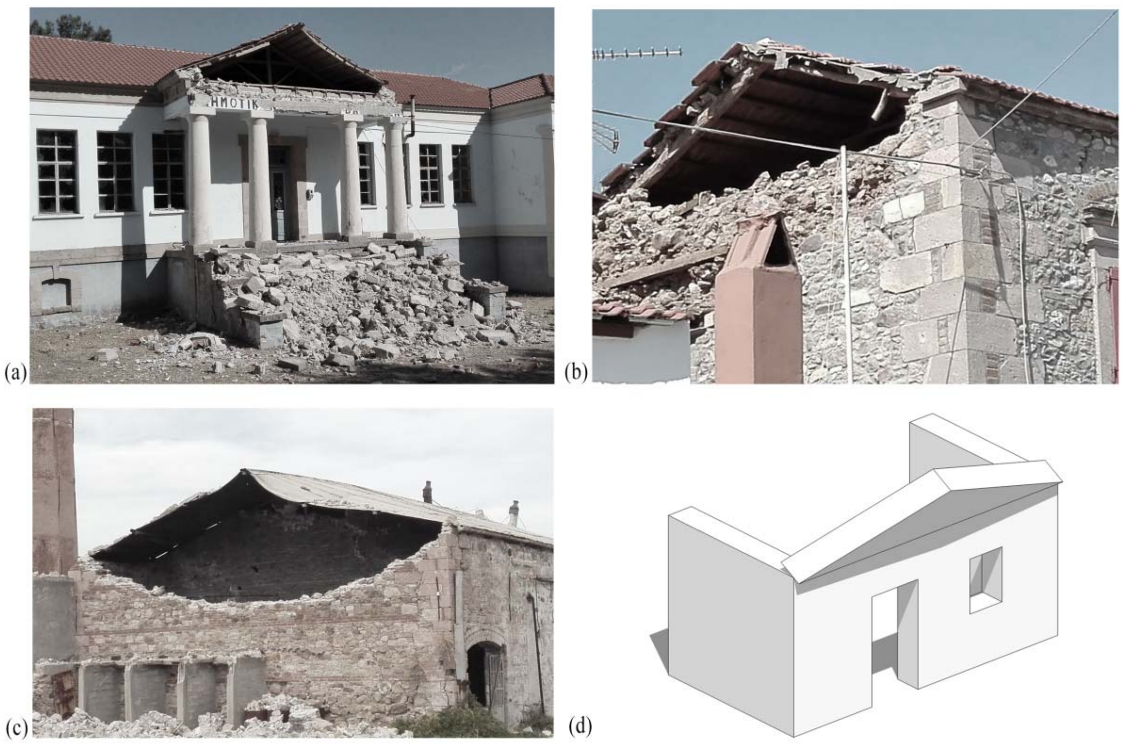


Learning from failure: 2017 Lesvos Earthquake (Greece)

12th of June 2017, at 12:28 GMT, a shallow earthquake with magnitude Mw=6.3 struck SSE of Lesvos Island

Damage and Failure Patterns: Mostly out-of-plane

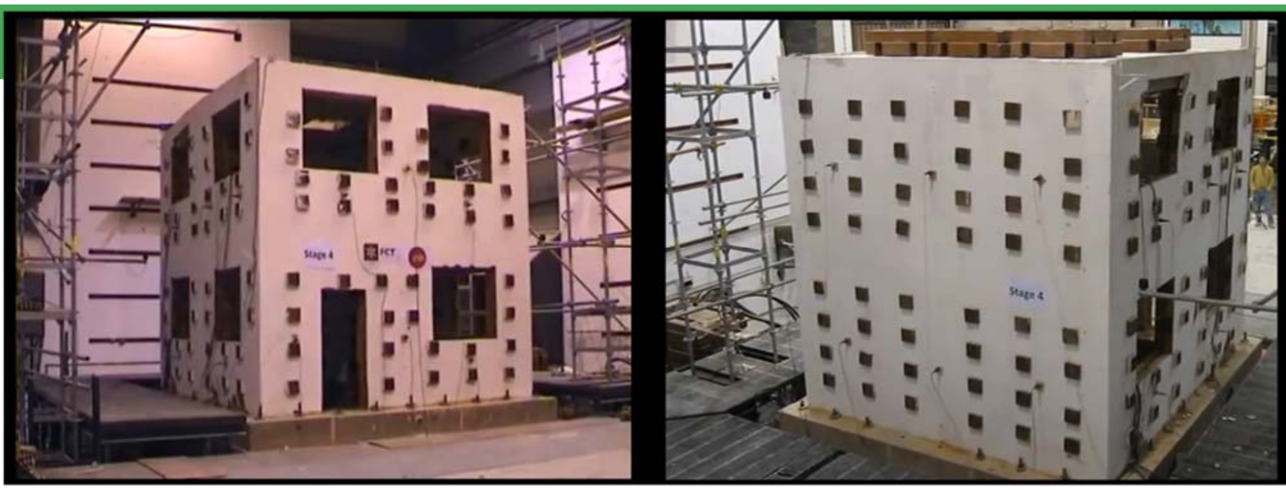
Local failures of the external leaf due to wall disintegration



Gable end wall overturning

Corner mechanism

Typical out-of-plane failures under one-way and two-way bending

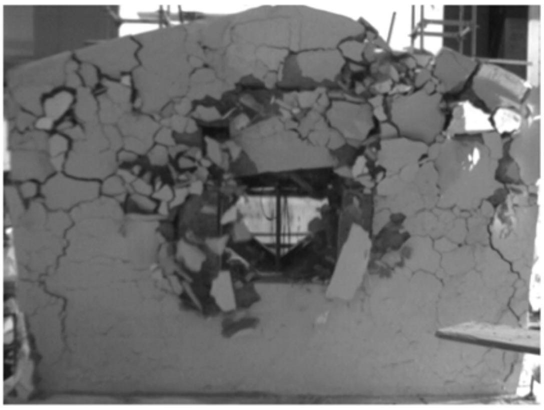


Earthquakes: Unacceptable Response

Earthquakes: Acceptable vs. Unacceptable

- Existing buildings are usually rather vulnerable: (a) fragile materials; (b) heavy construction; (c) inadequate connections; (d) inadequate design and construction; (e) lack of maintenance
- Simple and moderate cost measures can make drastically change the situation

Earthquakes: Existing vs. New



- Worst case scenario in modern masonry: embedded ring beam + unfilled vertical joints
- Minor damage for design earthquake in Lisbon (rock)
- Significant damage but very ductile response for 2.5 times the Lisbon design earthquake (rock)

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Blast & Impact

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Context

Terrorism

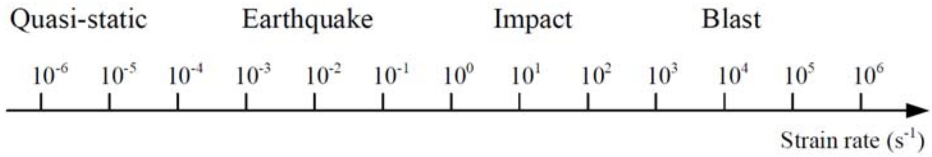
Gas explosions

Context

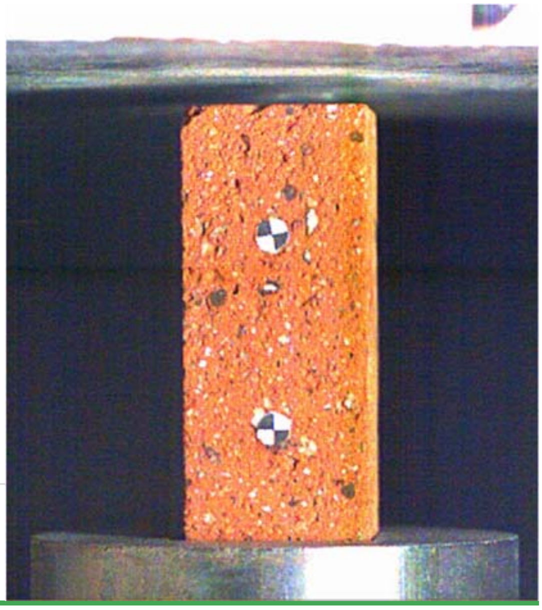
Impact

War

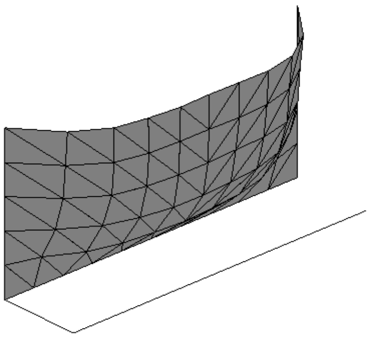
Blast: Behavior

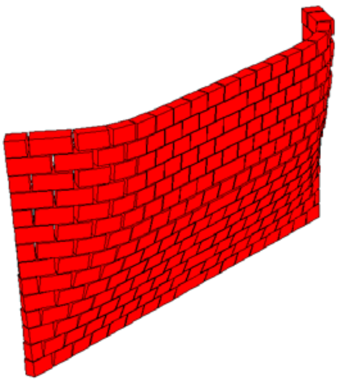


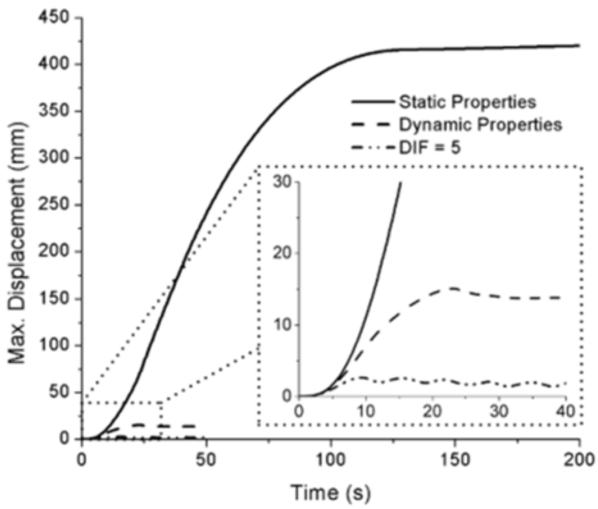
- ❑ Material properties change: Dynamic Increase Factor (DIF)
- ❑ Fast dynamics: Usually explicit analysis
- ❑ Much information for concrete & steel. Almost none for masonry



Simulation







DIF Influence

Results

Other Hazards

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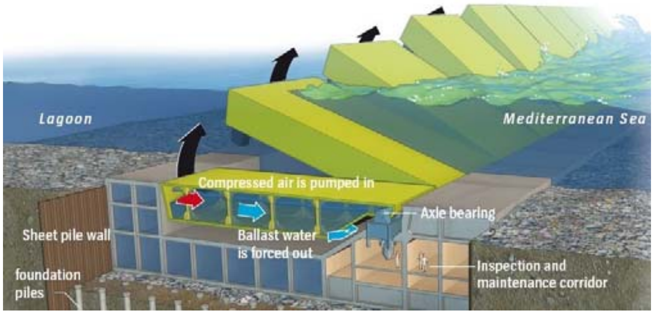
Natural and made-made hazards

- **84% of wildfires caused be humans (Boulder's Earth Lab, UColorado)**

Floods




Venice 2018


Reno floods


Porto Fino 2018

Landslides


El Salvador

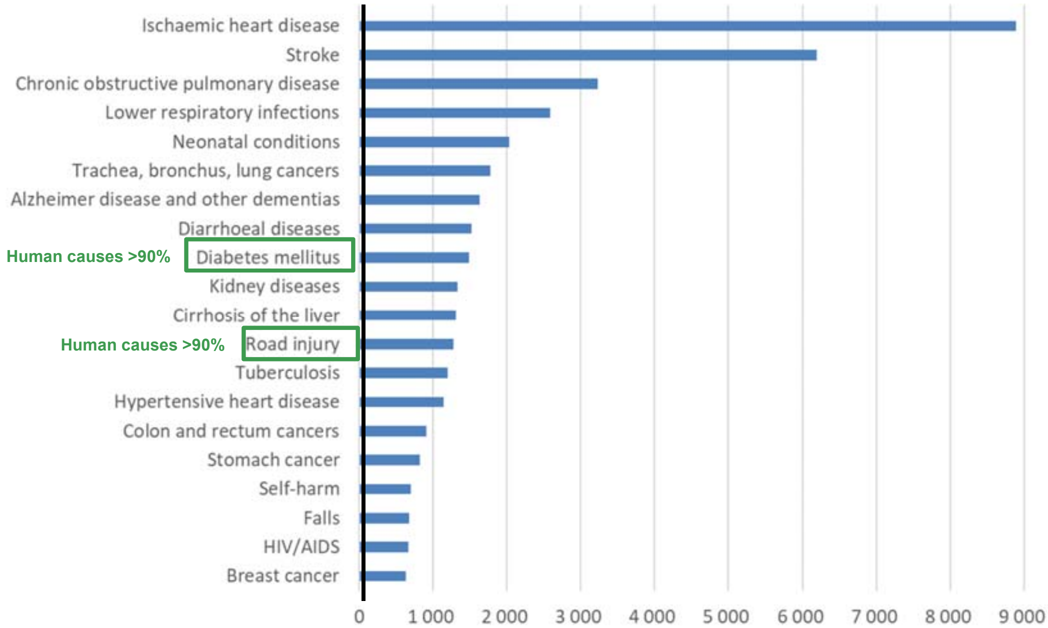

Norway 2020


France 2020


Japan, 2021

Risk. Perception and communication

- ❑ **Perception, WHO data 2019**

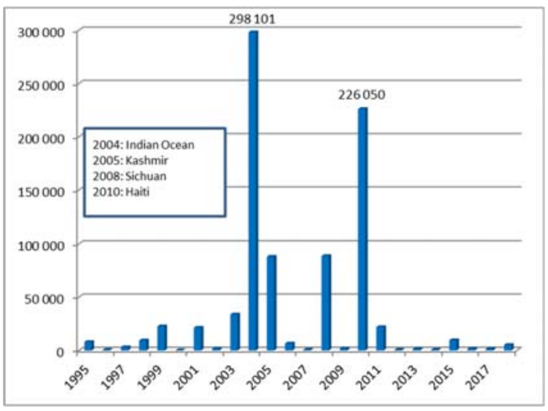


Natural disasters
60.000/year

Our World of Data

Earthquakes

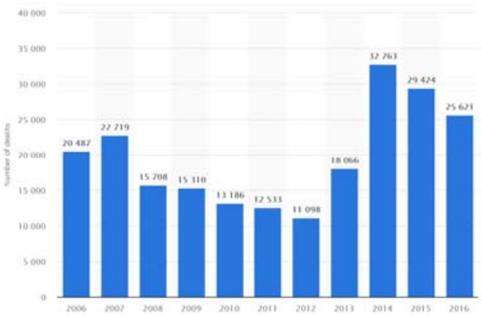
- ❑ **Since 1960, 40% of natural disaster deaths occurred as a result of earthquake events**
- ❑ **60% of these are due to masonry buildings (stone, clay, earth, lime,…)**
- ❑ **More than half of the built heritage is unreinforced masonry**



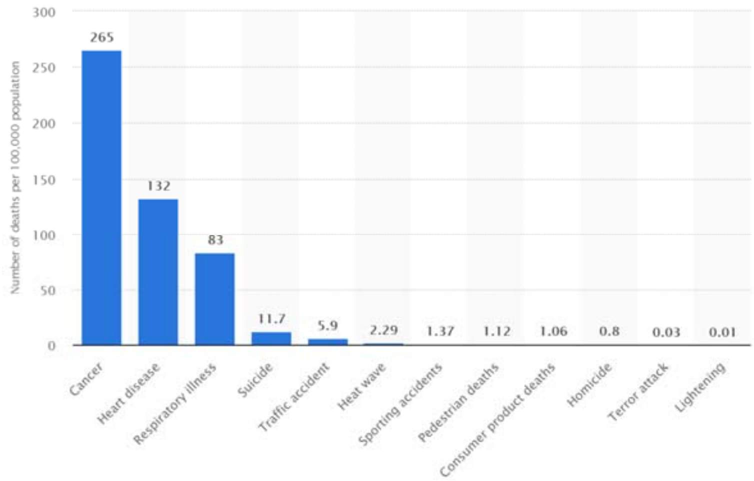
Eqs since 1995, 36.000 people/yr

Blast and terrorism

- **Eurobarometer: The risk of a terrorist attack is considered to be high by 40% of respondents in the EU (47% medium risk)**



World casualties
Blast, 20.000 people/yr



European casualties per 100.000

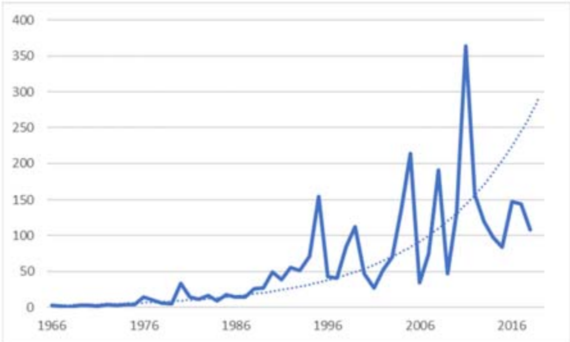
Natural Hazards Losses: Huge and Spread Worldwide (2011)

http://usatoday30.usatoday.com/weather/news/extremes/story/2012-01-04/world-disasters-costliest-earthquake-tsunami/52377642/1

$380 billion is the annual wealth produced by 15 million European. Statista: $540 billion in 2020 USD

Risk Management, Technical Experts and Society

- ❑ **Perception and communication**
- ❑ **Assessment and diagnosis**
- ❑ **Solutions, costs and implementation**



Our World of Data, current billion USD

In the last 50 years, costs increased exponentially

- ❑ ***How to solve the mathematical indeterminacy of huge consequences and low probabilities?***

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Available tools

Tools and methodology

Evaluation scales

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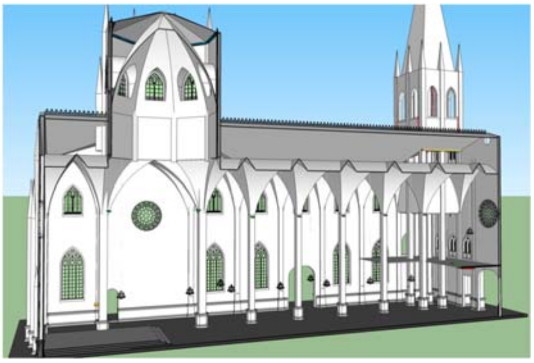
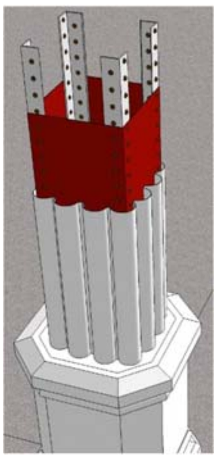
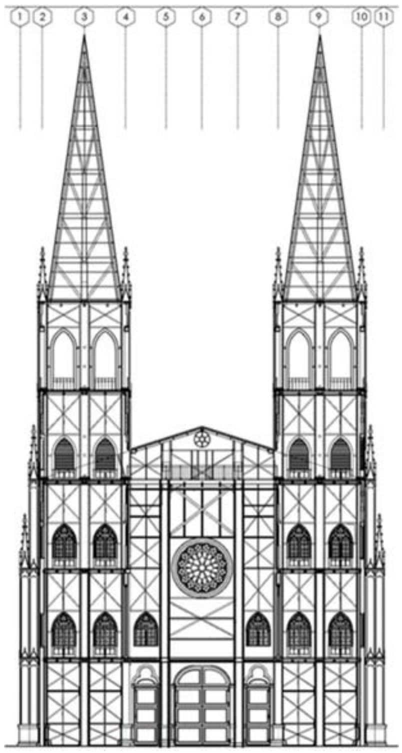
Examples at building level

San Sebastian Basilica, Manila, Philippines

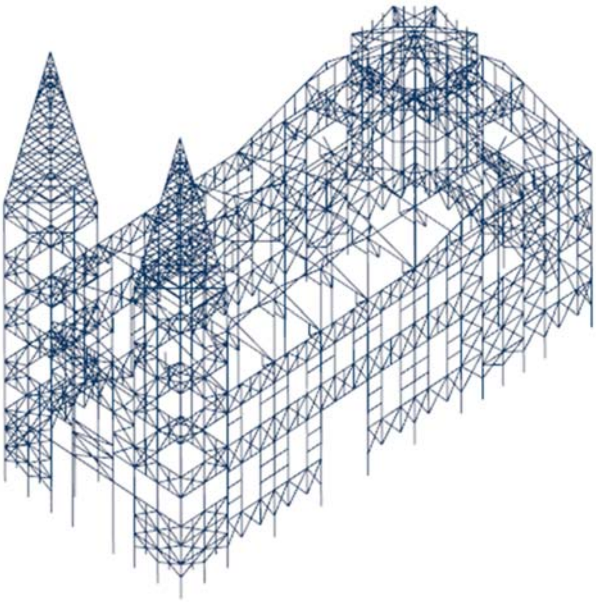


- Construction: 1890-1891
- Unique gothic metallic church. 9 steam boats from Belgium and 1500 ton
- 3 previous buildings (1639, masonry, fire and revolution), 1645 (earthquake), 1863 (masonry, earthquake), 1880 (timber, earthquake)



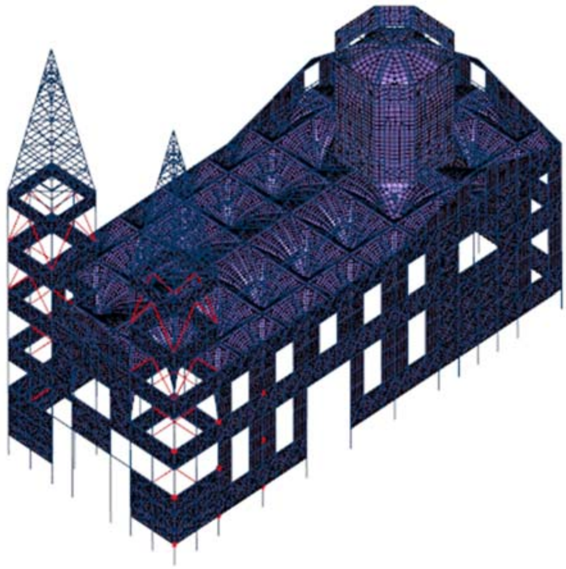


Complex structure. Important corrosion



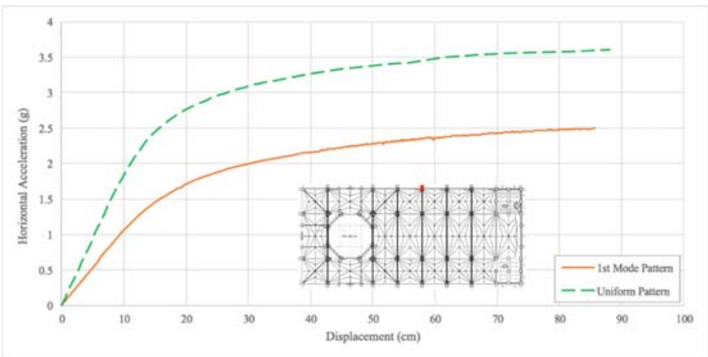
Beam elements: 54 905
Total DOF: 645 198

Model 1…

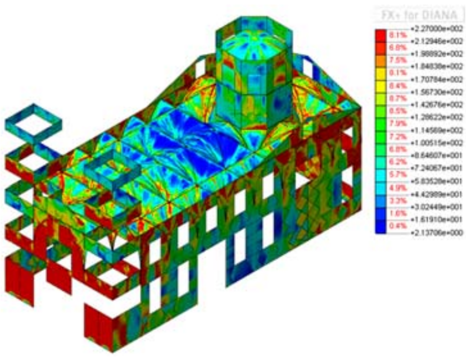


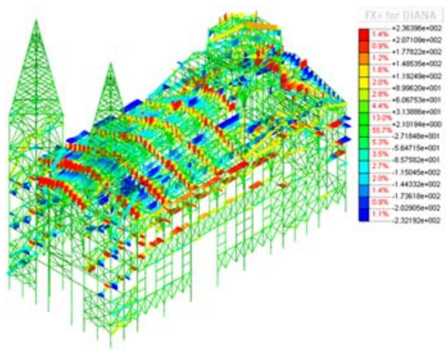
Beam elements: 56 452
Shell elements: 50 555
Springs elements: 9
Total DOF: > 1 000 000

…Model 5



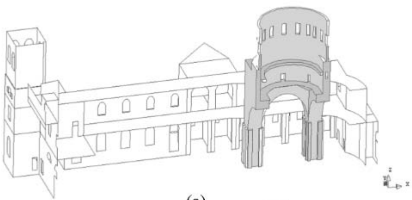
Damaged model. Safety still acceptable



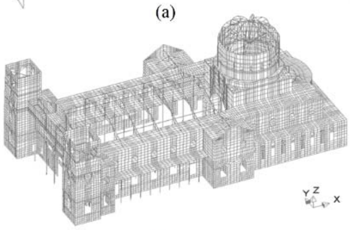


Blessed Sacrament Cathedral, Christchurch, NZ

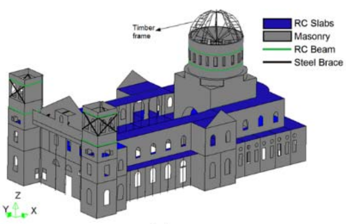
- ❑ Construction 1901-1905
- ❑ Seismic strengthening: 2004
- ❑ Major damage in EQs 2010-11



(a)



(b)



(c)

Justify damage & incorrect past strengthening

Examples at territorial level

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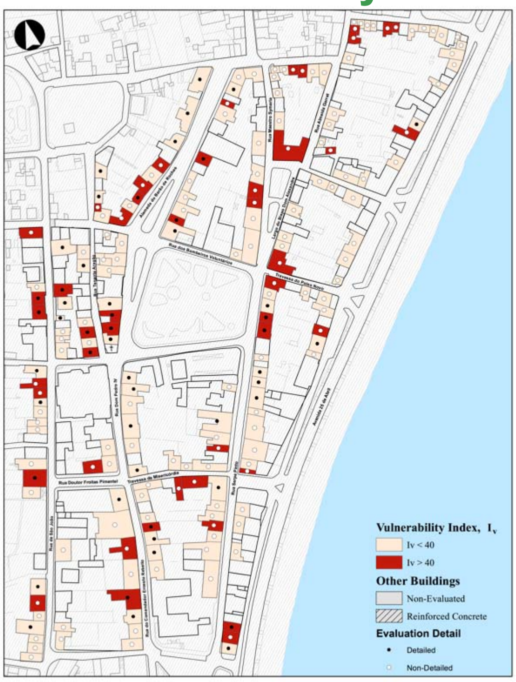
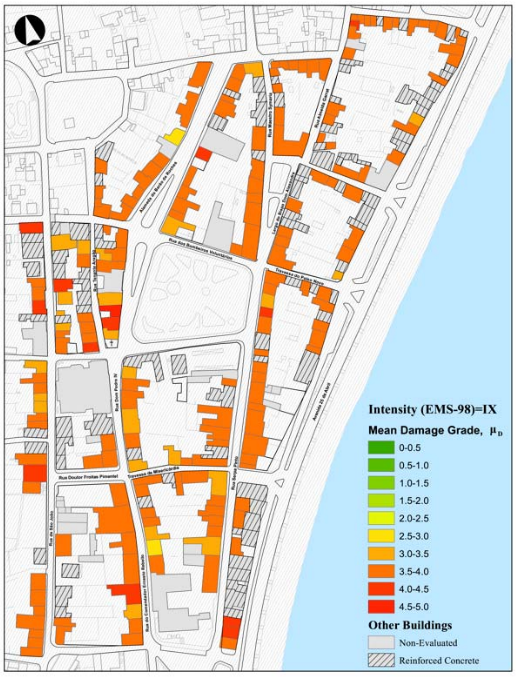
Seismic vulnerability assessment and scenarios



Global vulnerability distribution and identification of the buildings with I_v values over 45



Damage scenarios for macroseismic intensities I_{EMS-98}= IX.

Simple forms and indicators

Parameter		Class C_{vi} A	B	C	D	Weight p_i	Relative weight over I_v
1. Structural building system							
P1	Type of resisting system	0	5	20	50	0.75	
P2	Quality of resisting system	0	5	20	50	1.00	
P3	Conventional strength	0	5	20	50	1.50	46/100
P4	Maximum distance between walls	0	5	20	50	0.50	
P5	Number of floors	0	5	20	50	1.50	
P6	Location and soil conditions	0	5	20	50	0.75	
2. Irregularities and interactions							
P7	Aggregate position and interaction	0	5	20	50	1.50	
P8	Plan configuration	0	5	20	50	0.75	27/100
P9	Height regularity	0	5	20	50	0.75	
3. Floor slabs and roofs							
P10	Facade wall openings and alignments	0	5	20	50	0.50	
P11	Horizontal diaphragms	0	5	20	50	1.00	15/100
P12	Roofing system	0	5	20	50	1.00	
4. Conservation status and other elements							
P13	Fragilities and conservation status	0	5	20	50	1.00	12/100
P14	Non-structural elements	0	5	20	50	0.50	

Seismic vulnerability assessment and scenarios

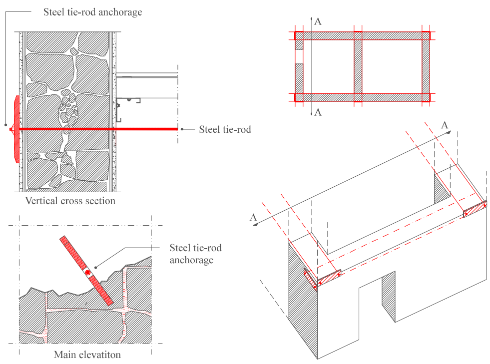
Total number of buildings: 192	Macroseismic intensity, I_{EMS-98} VII	VIII	IX	X
Collapsed	0	0	15 (7.7%)	101 (52.7%)
Unusable	3 (1.8%)	33 (17.3%)	93 (48.2%)	72 (37.3%)

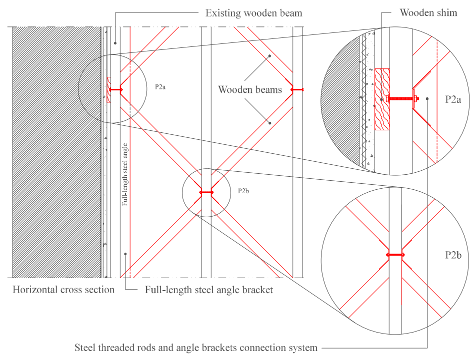
Total number of inhabitants: 1596	Macroseismic intensity, I_{EMS-98} VII	VIII	IX	X
Dead and severely injured	0	0	37 (2.3%)	252 (15.8%)
Homeless	29 (1.8%)	278 (17.4%)	856 (53.7%)	1184 (74.2%)

Example of seismic retrofitting

RP1

Retrofitting Package 1 (RP1): Improvement of the connections and floor stiffening (35€/m^2)

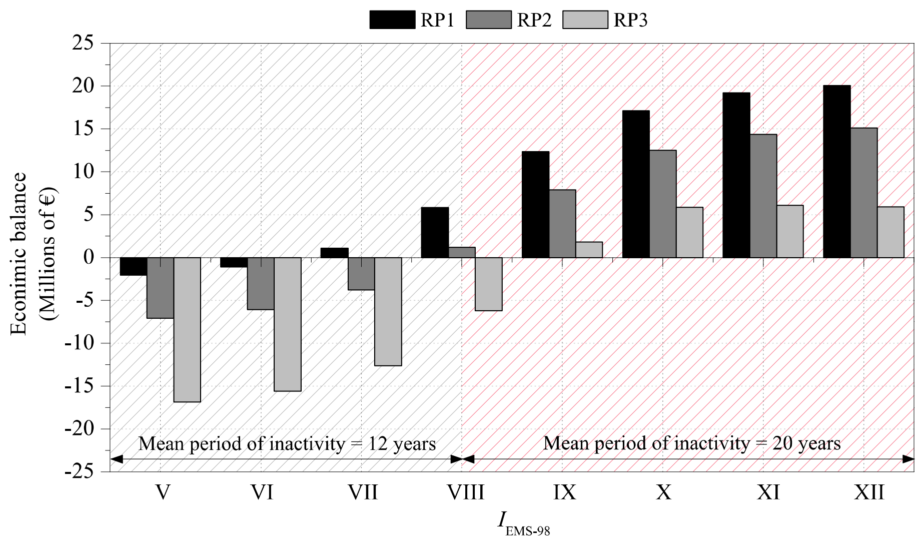




WALL-TO-WALL CONNECTION IMPROVEMENT THROUGH TIE-RODS

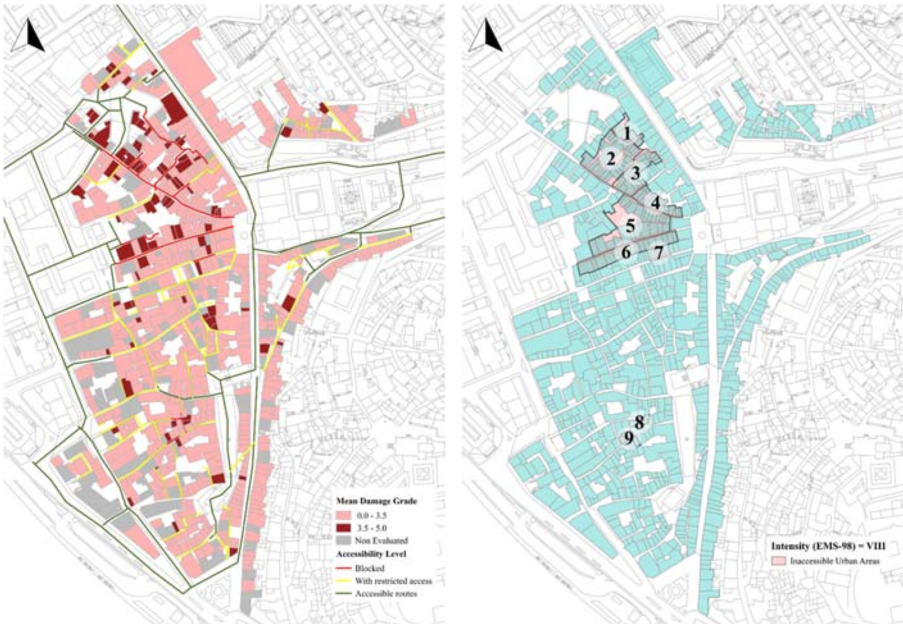
FLOOR STIFFENING WITH DIAGONAL BRACING AND TIMBER PLANKS

Impact of seismic retrofitting (cost-benefit analysis)



Retrofitting package	Intensity, I_{EMS-98}							
	V	VI	VII	VIII	IX	X	XI	XII
RP1	-	-	1.08 M€	5.85 M€	12.24 M€	17.15 M€	19.23 M€	20.10 M€
RP2	-	-	-	1.20 M€	7.89 M€	12.53 M€	14.39 M€	15.13 M€
RP3	-	-	-	-	1.80 M€	5.86 M€	6.12 M€	5.91 M€

Emergency planning: Evacuation routes / inaccessible areas



Definition of evacuation routes for a scenario of $I_{EMS\text{-}98}$=VIII and possible inaccessible areas

Methodology: International Recommendations for Cultural Heritage

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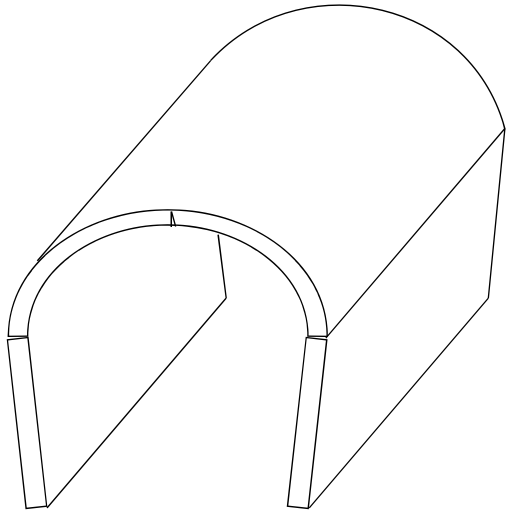
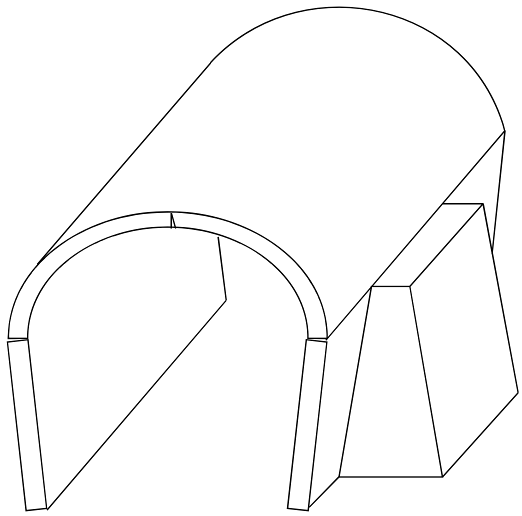
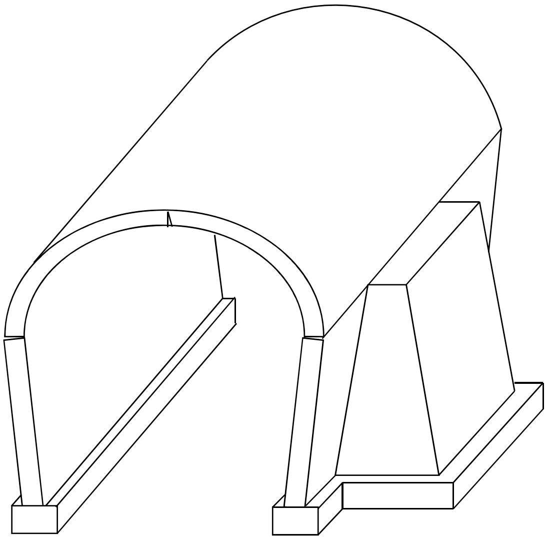
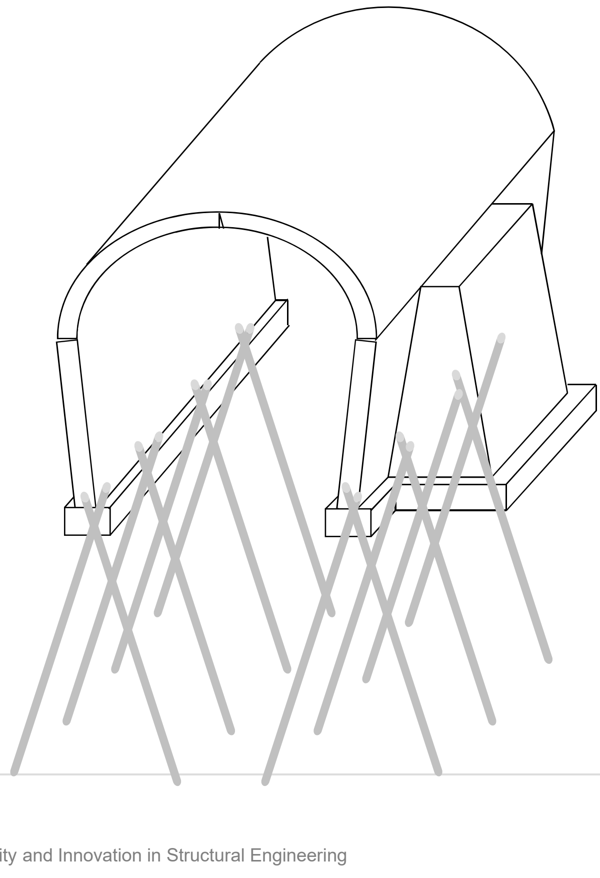
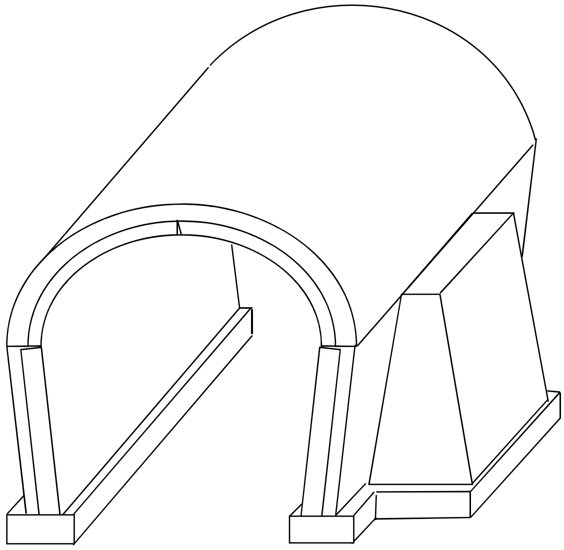
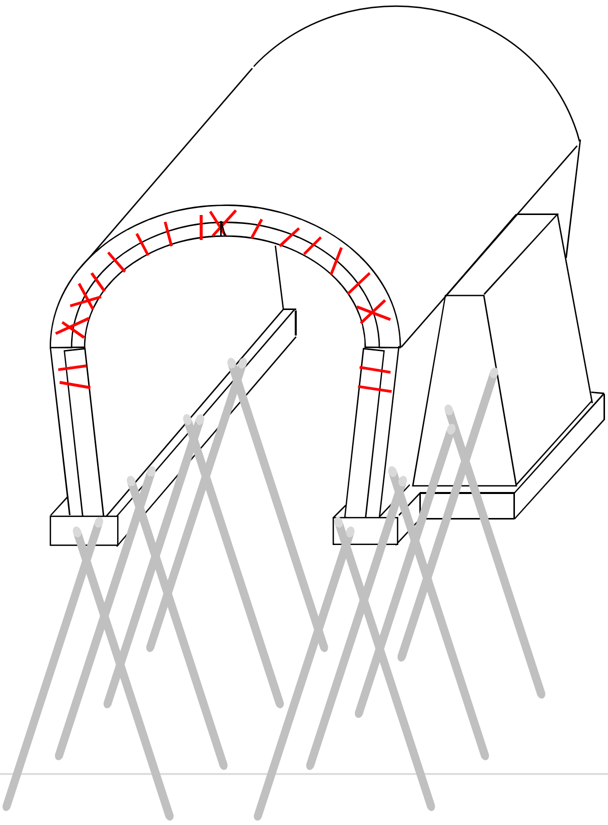


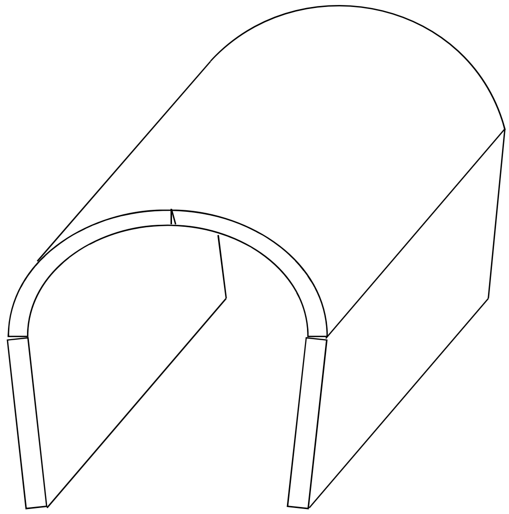


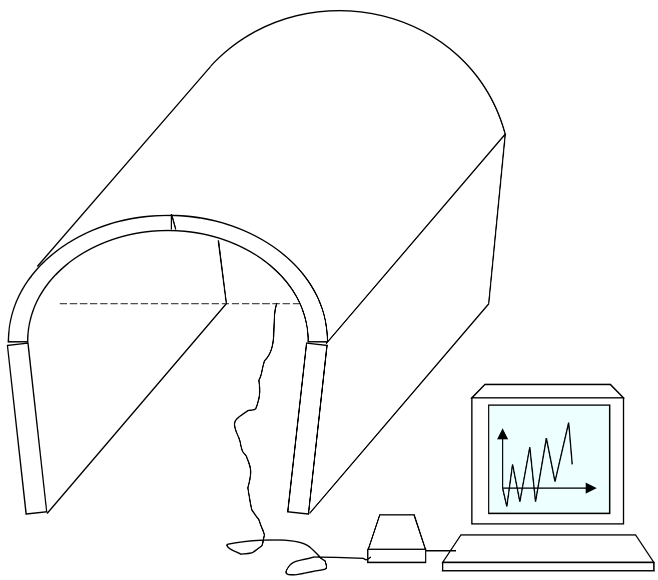


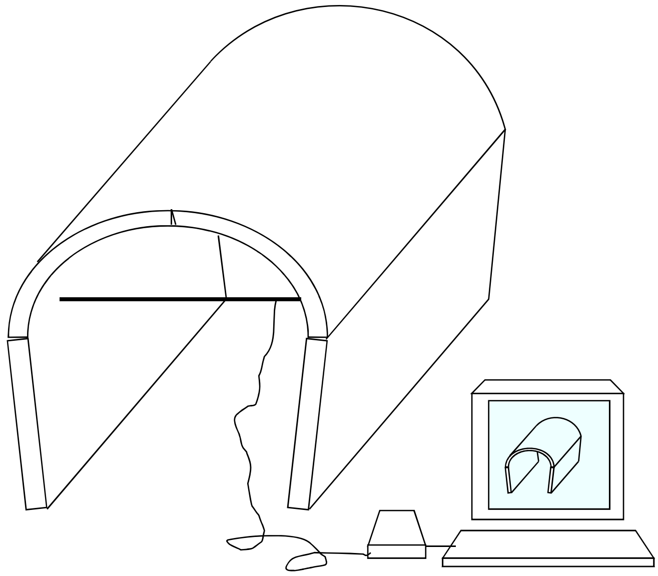


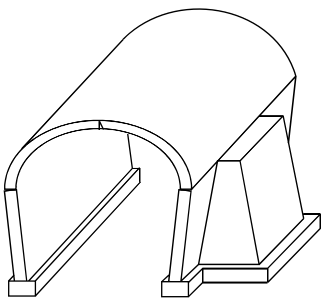












Past understanding

"Conservation" is warranted by the powerfulness of the intervention

Blind confidence in modern materials and technologies

Mistrust towards original or ancient materials and original resisting resources of the building

The value of original / ancient structure and structural principles is not recognized

The importance of previous studies is not fully recognize

Significant negative experience accumulated

Athens Charter (1931)
Recommends the use of concrete and other modern material and techniques for restoration purposes. Added materials and components should be hidden to avoid altering the historical aspect of the building.

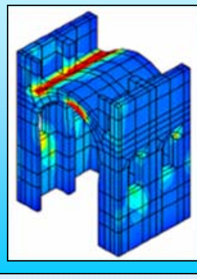
ICOMOS Methodology

HISTORY

INSPECTION
PRESENT CONDITION

MONITORING

STRUCTURAL ANALYSIS



EMPIRICAL EVIDENCE

HYPOTHESES

Conclusions on building condition and adequate remedial measures

The phases of the study

Diagnosis — Identify causes of damage and decay

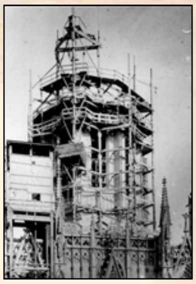
Safety evaluation — Determine acceptability of safety levels by analyzing present condition of structure and materials

Design of remedial measures — Lay-out repair or strengthening actions to ascertain the required safety

Diagnosis and safety evaluation of the structure are two consecutive and related stages on the basis of which the effective need for and extent of treatment measures are determined. If these stages are performed incorrectly, the resulting decisions will be arbitrary: poor judgement may result in either conservative and therefore heavy-handed conservation measures or inadequate safety levels.

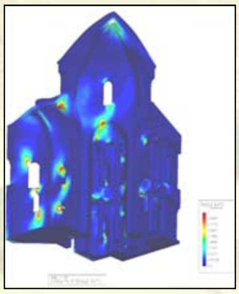
METHODOLOGICAL CONSISTENCY

DIAGNOSIS




SAFETY ASSESMENT



DESIGN OF REMEDIAL MEASURES

The peculiarity of heritage structures, with their complex history, requires the organisation of studies and analysis in steps that are similar to those used in medicine. Anamnesis, diagnosis, therapy and controls, corresponding respectively to the condition survey, identification of the causes of damage and decay, choice of the remedial measures and control of the efficiency of the interventions.

We have it all ☺

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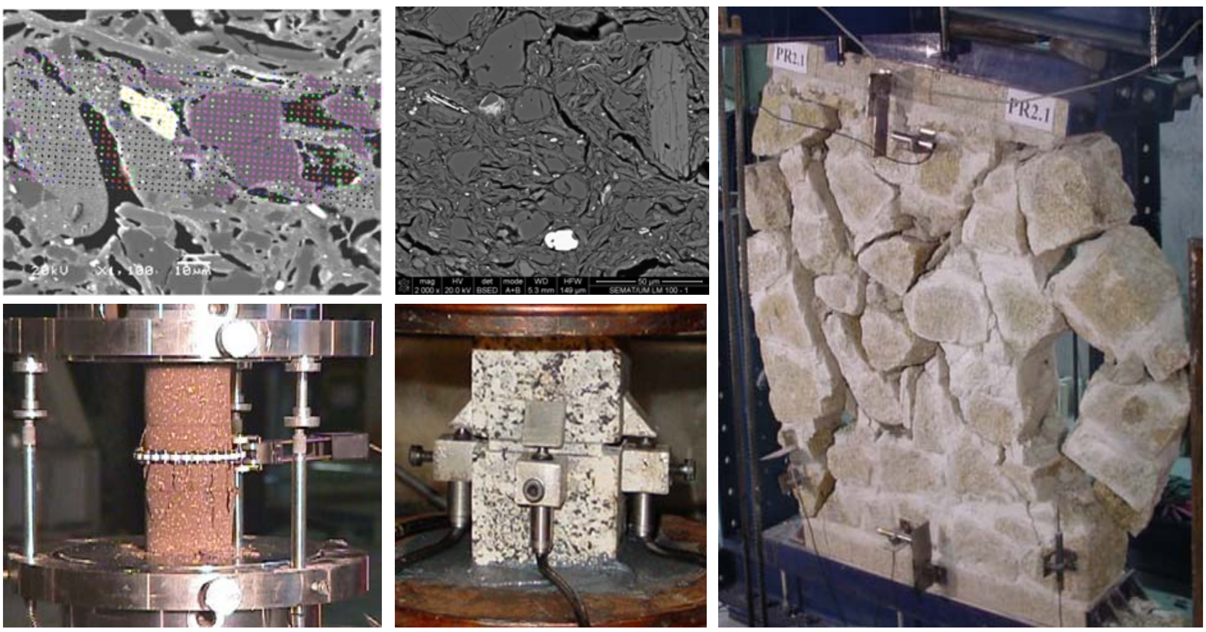
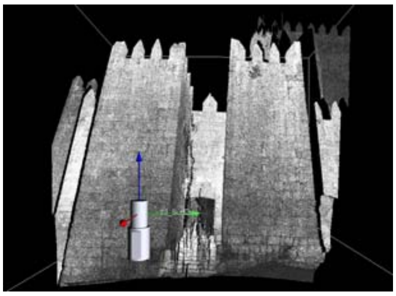
Experimental characterization

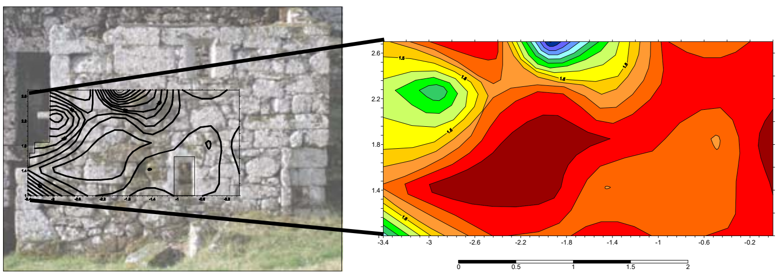


Survey and visual inspection

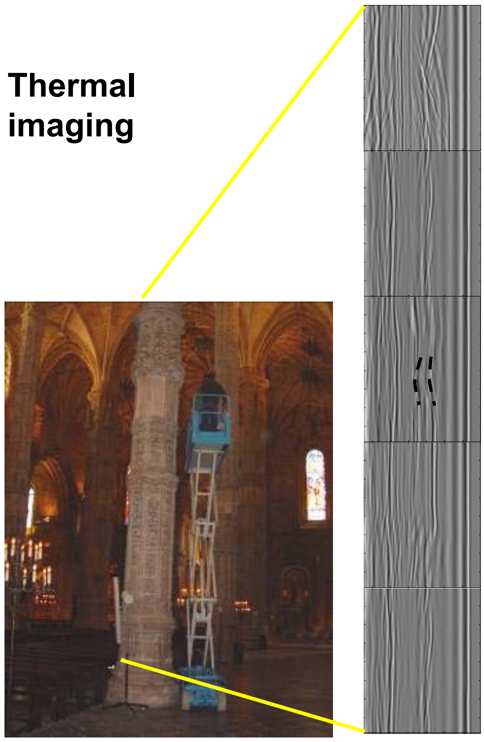


Non-destructive Testing

Thermal imaging

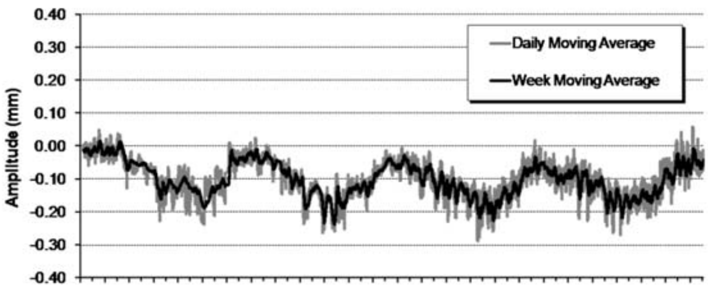


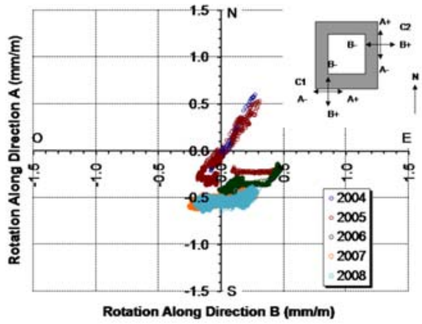
Sonic tomography



GPR testing

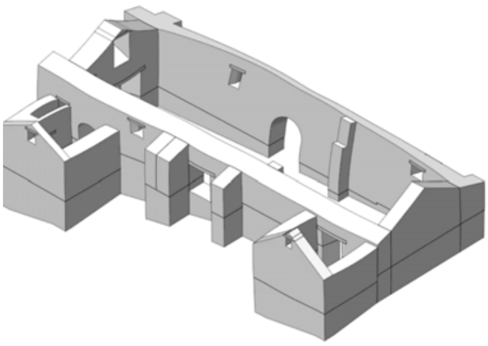
Monitoring

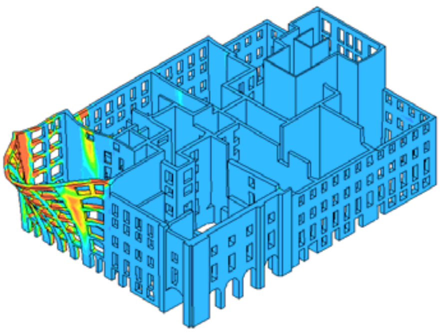


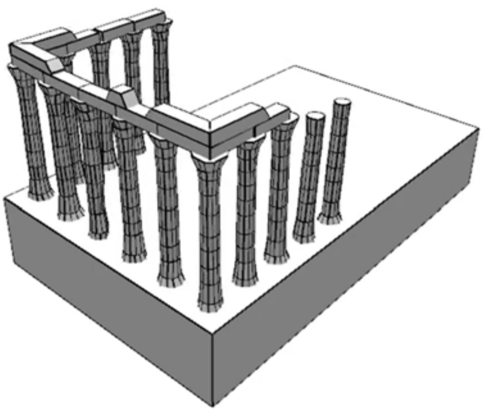


Crack opening and tilting, Cathedral of Porto

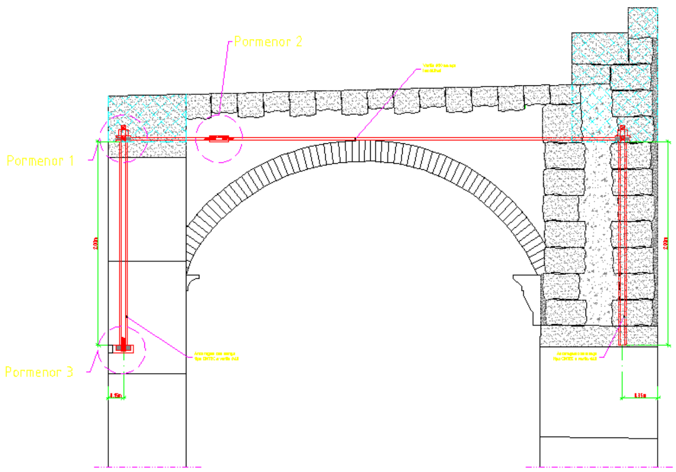
Computer Simulation

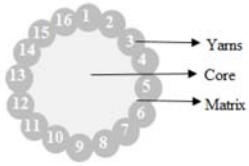






Remedial Measures

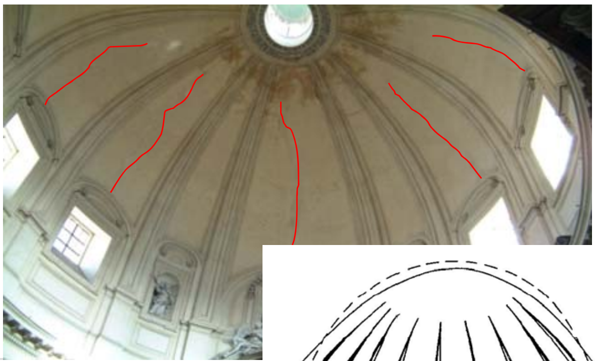


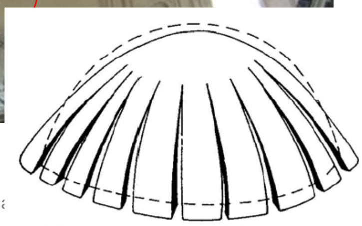


In short…

- ❑ Scientific approach
- ❑ Combination of different sources and approaches
- ❑ Methodological consistency
  Using similar approaches for diagnosis, safety evaluation and design of intervention
- ❑ Subjectivity is still possible
- ❑ Importance of personal judgment
  Recognize the need for experts and the value of their personal judgment

What not to do (I)?





The need to understand materials, structural arrangements and construction techniques from existing buildings

What not to do (II)?

It is necessary to adopt adequate safety evaluation procedures (history, quantitative analysis, qualitative analysis, experimental analysis)

Case studies

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Swimming Pools at Leça da Palmeira, Portugal, by Álvaro Siza

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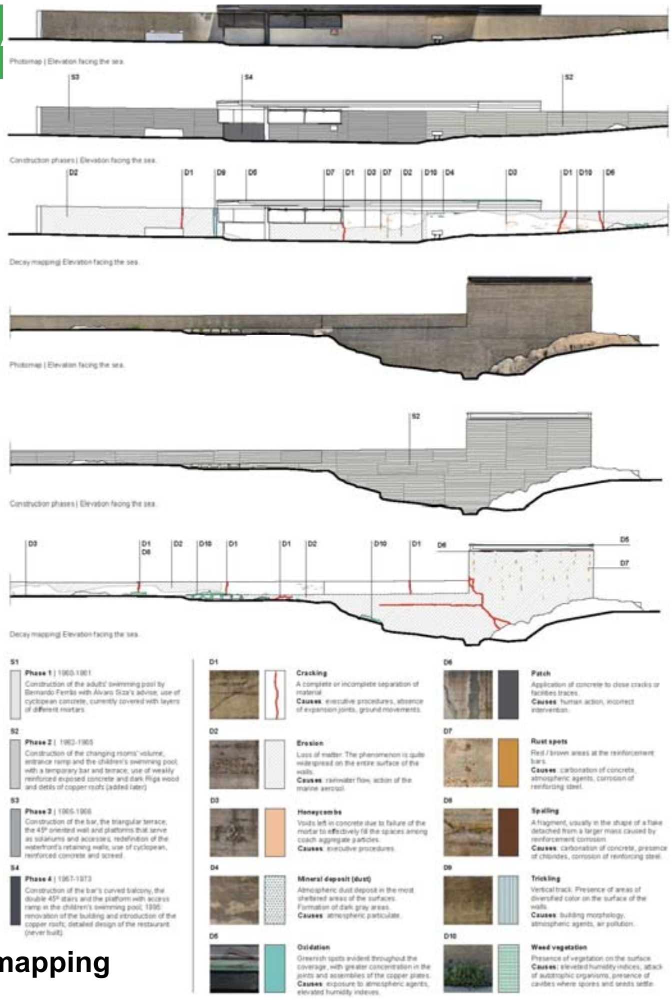
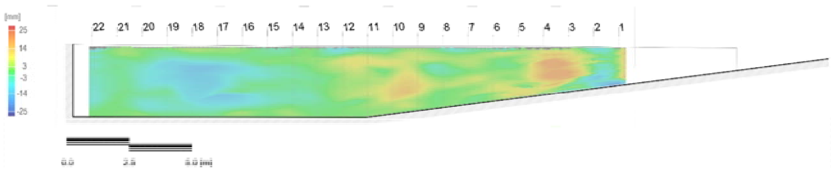
Some of the works done (i)

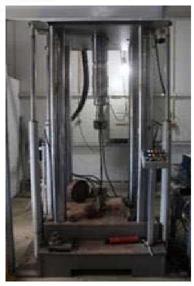


Damage mapping

Some of the works done (ii)



Laser scanning and deformation measurements

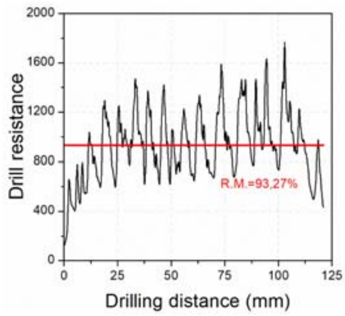


Concrete and steel strength testing

Non-destructive testing: Sonic, chloride content, water penetration

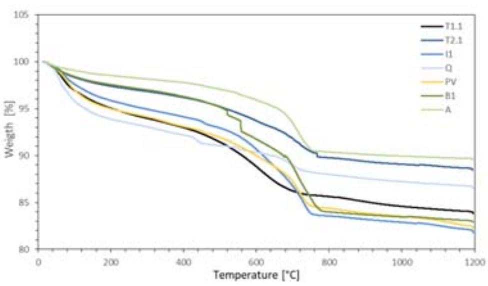
Some of the works done (iii)

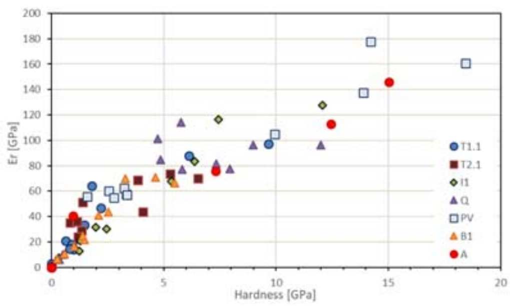
Non-destructive testing: Schmidt hammer and color analysis

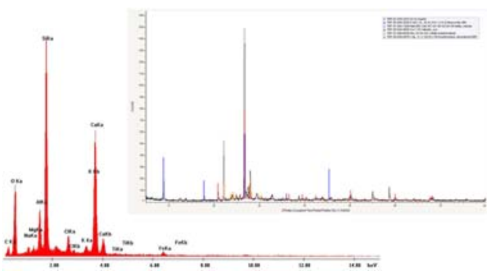


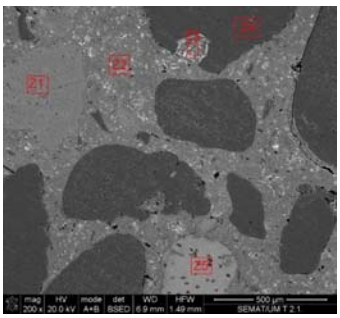
Timber characterization

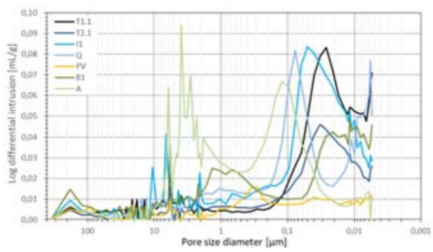
Some of the works done (iv)





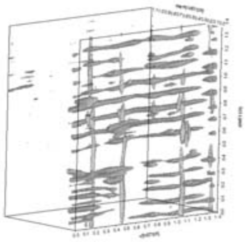


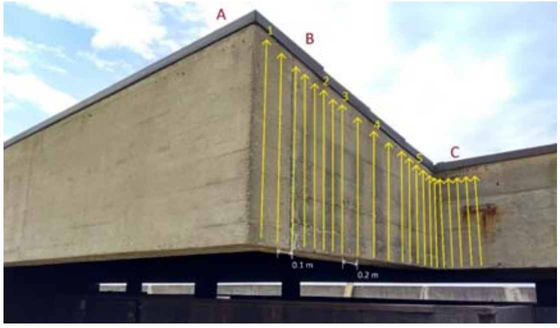


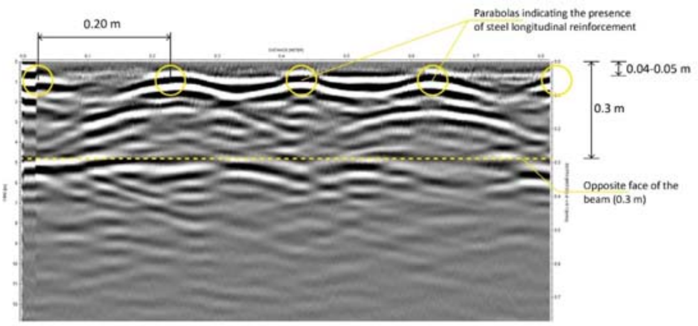


Cement paste characterization: Thermogravimetry, nanoindentation, X-ray analysis and diffraction, scanning electron microscopy, mercury intrusion porosimetry

Some of the works done (v)







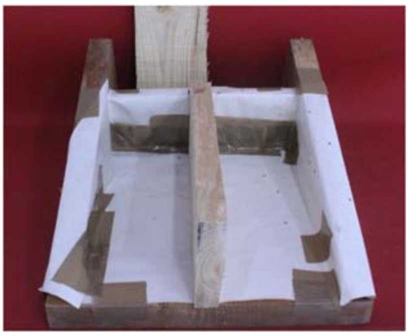
GPR testing

Repair approach #1 (i)

Displaced fragment, volume loss and biological colonization

Large volume loss and shrinkage / thermal movement

Repair approach #1 (ii)



Wooden molds

Materials: Sand, gravel, yellow granite powder, black limestone powder, pigments, natural and Portand cement

Replicating original formwork

Repair approach #1 (iii)

Selection of the sample by Arch. Álvaro Siza

Repair approach #1 (iv)

Cleaning and biocide

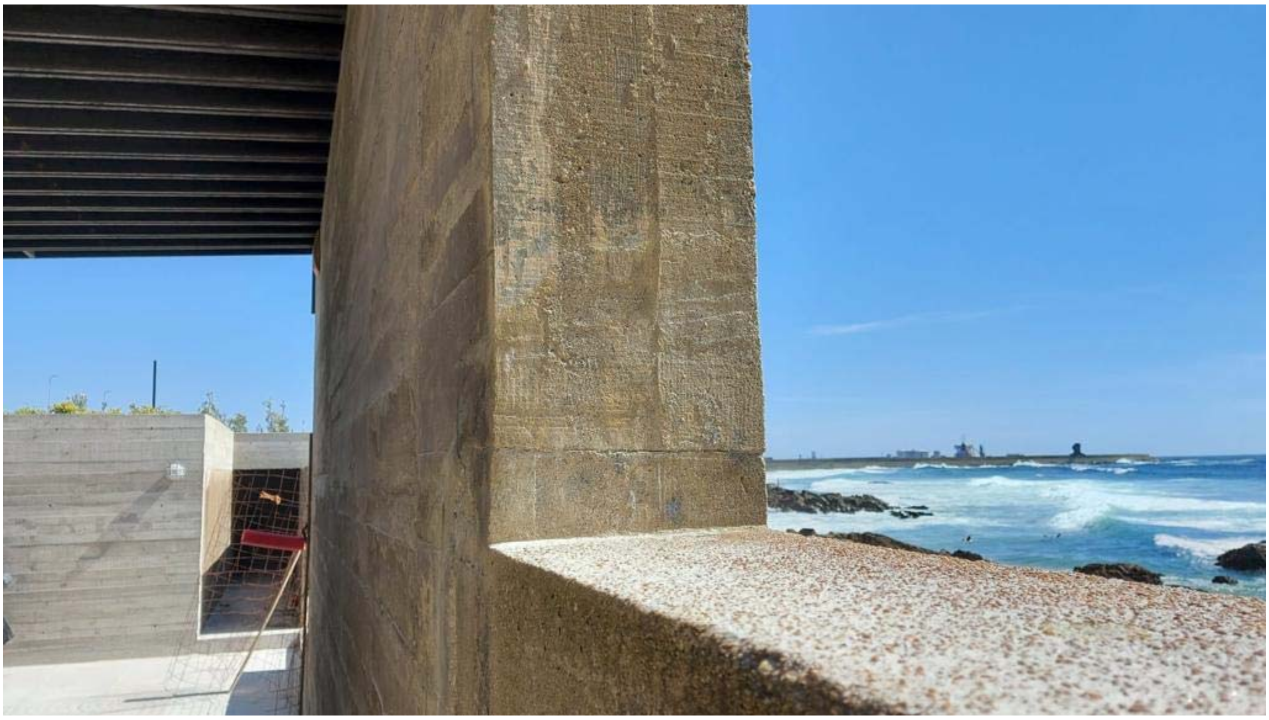
Repair approach #1 (v)

Stainless steel installation

Repair approach #1 (vi)

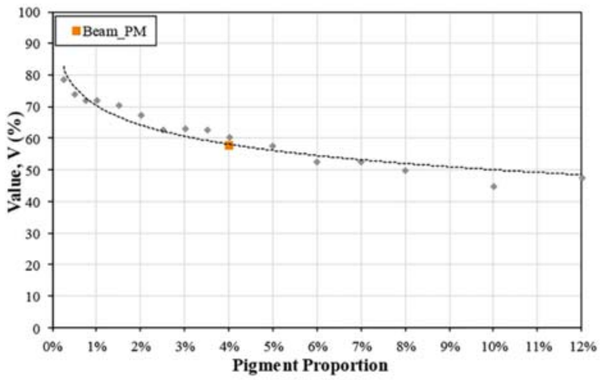
Mold, silicon paper and mortar filling

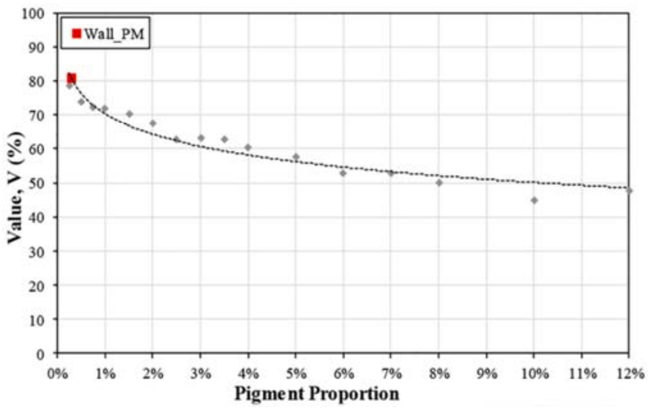
Repair approach #1 (vii)



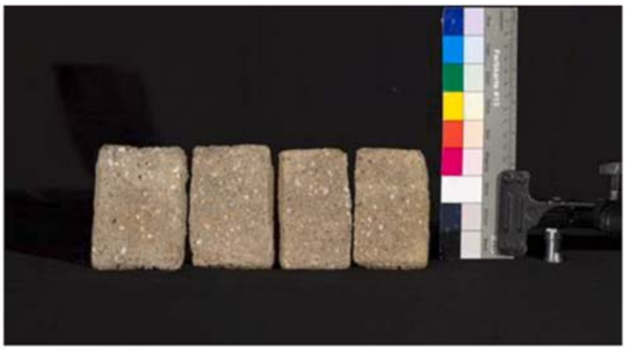
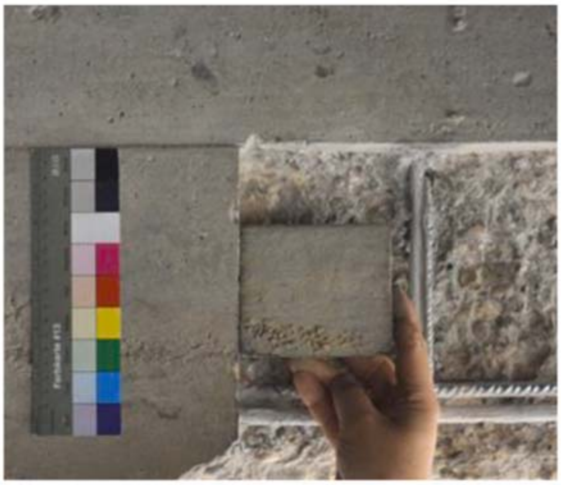
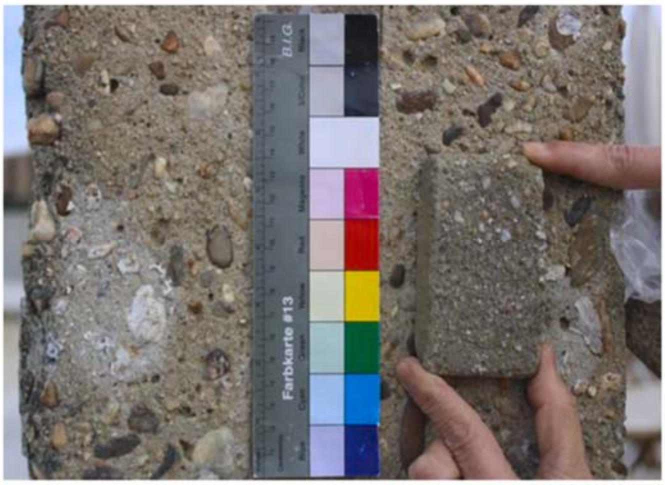
Repair #2 (i)

Repair #2 (ii)





Repair #2 (iii)

Repair #2 (iv)


(a)

(b)

(c)


Repair #2 (v)


(a)


(b)


(c)

Repair #2 (vi)

School in Braga, Portugal

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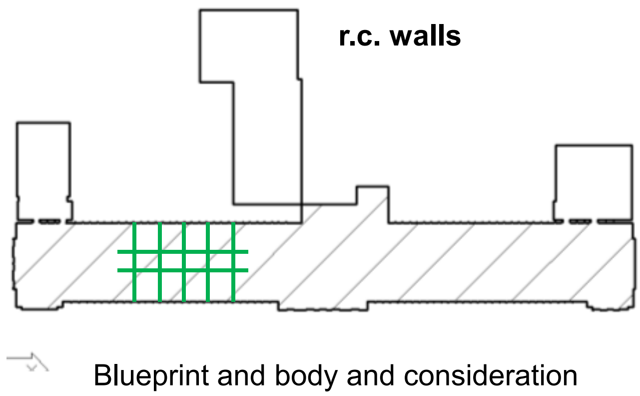
Universidade do Minho

Description

- Large size building with in plan dimensions (main body 110 x15 m^2) and 5 storeys (floor level + 4 storeys)

Cross section



Blueprint and body and consideration

- RC slabs and inner walls and ashlar granite masonry in exterior walls
- One of the first RC buildings in Braga (1930's)
- 5th floor with concrete floor with no use of attic
- 3rd and 4th floors originally for students dorms. Slabs supported in transverse beams, supported in external walls. Infill walls in RC (storey 2 / 5)

Description (I)


Main façade


Back Façade


Typical corridor (Level 2, 3 and 4)


Non-aligned walls and beams

Description (II)

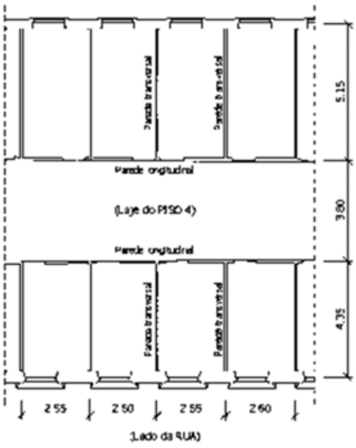


Hall at level 0 (span of 13 m)

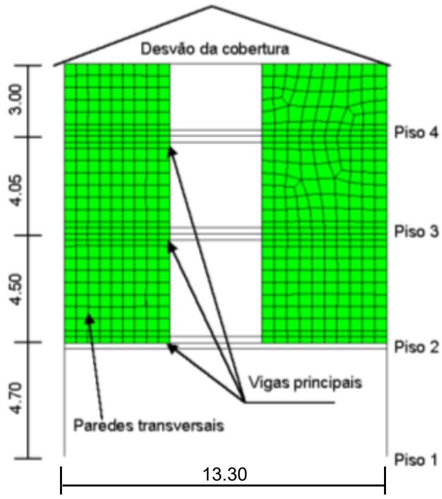

Attic


Irregularities

Geometrical Survey



Plan

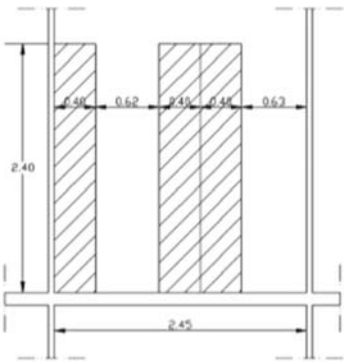


Cross Section

- Level 1 (Hall) is a free span space
- Transversal walls with spacing 2.60 m
- Non-symmetric transverse walls
- External masonry walls with variable thickness in height: 0.30-0.60 m.
- Main beams with 0.25 x 0.50 m^2 (levels 3 and 4) and 0.30 x 0.60 m^2 (level 2)

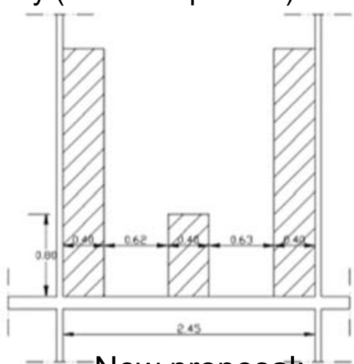
Safety Assessment of Slabs

- New use: Upper levels (3 and 4) to be used as archive, while lower levels (1 and 2) to remain as school. Very high loads planned (11 to 15 kN/m^2)
- Slabs with be OK for previous use. Strengthening needed for new use (half of the required reinforcement). A set of HEB 100 placed transversely to the cell, supported in a L 80x80 and a new timber board would be necessary (700 euro per cell).



Original proposal:
3 closet with 2.40 m

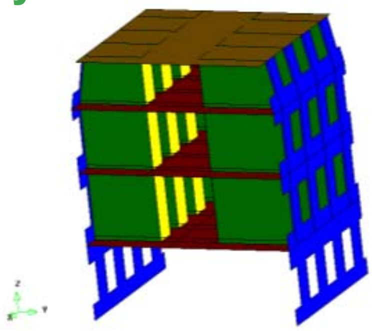
New floor with supports near walls



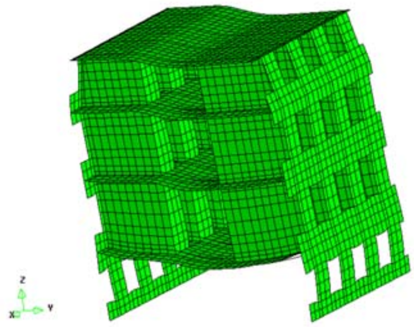
New proposal:
2.80 m + 0.80 m + 2.80 m (level 4)
3.60 m + 0.80 m + 3.60 m (level 3)
4.00 m + 0.80 m + 4.00 m (level 2)

No intervention

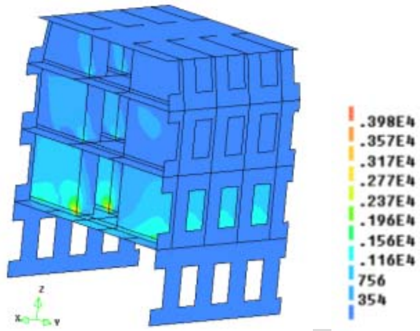
Safety Assessment of Full Building (I)



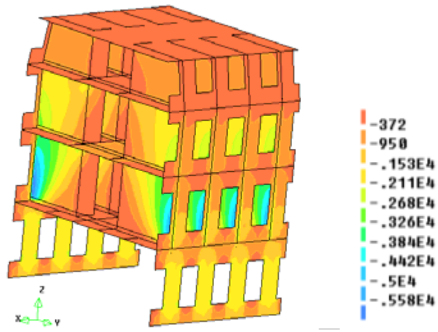
Three-dimensional model



Deformed mesh for G+Q

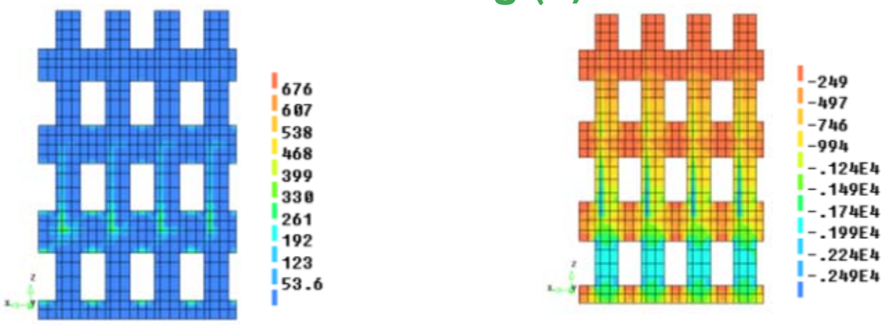


Principal tensile stresses

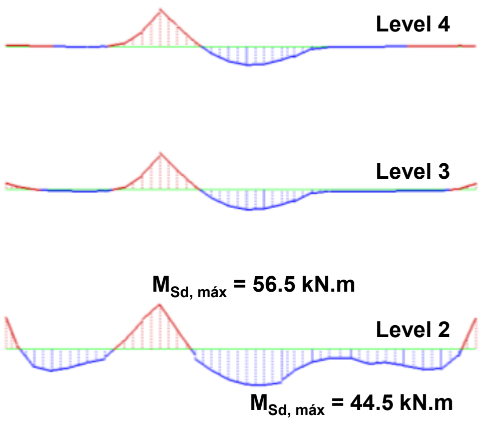


Principal compressive stresses

Safety Assessment of Full Building (II)

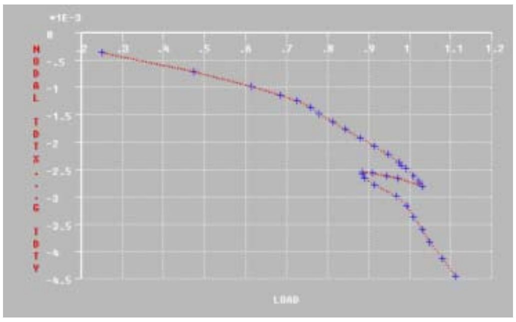


Principal stresses in external walls: tension and compression

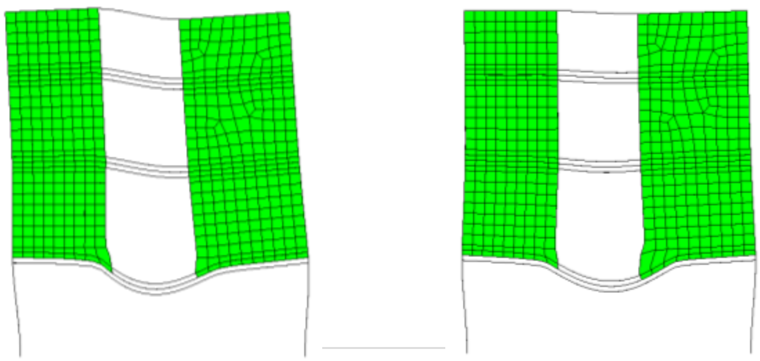


Bending moments

Safety Assessment of Full Building (IV)

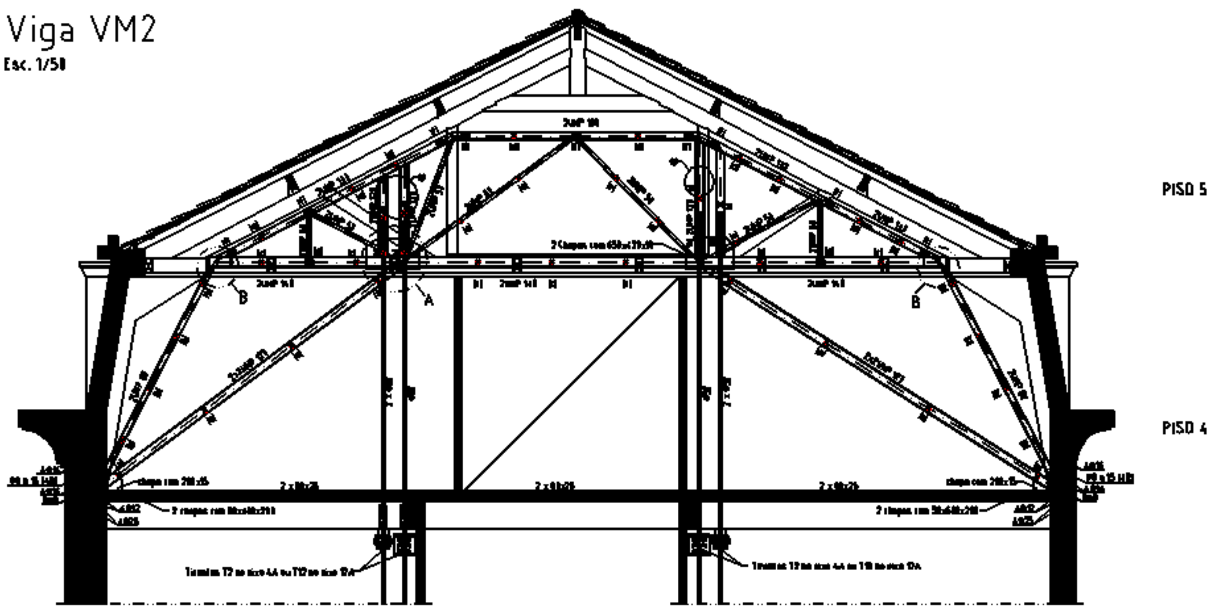


Load combination 1.35G+1.35Q and displacement at mid span (Level 2)

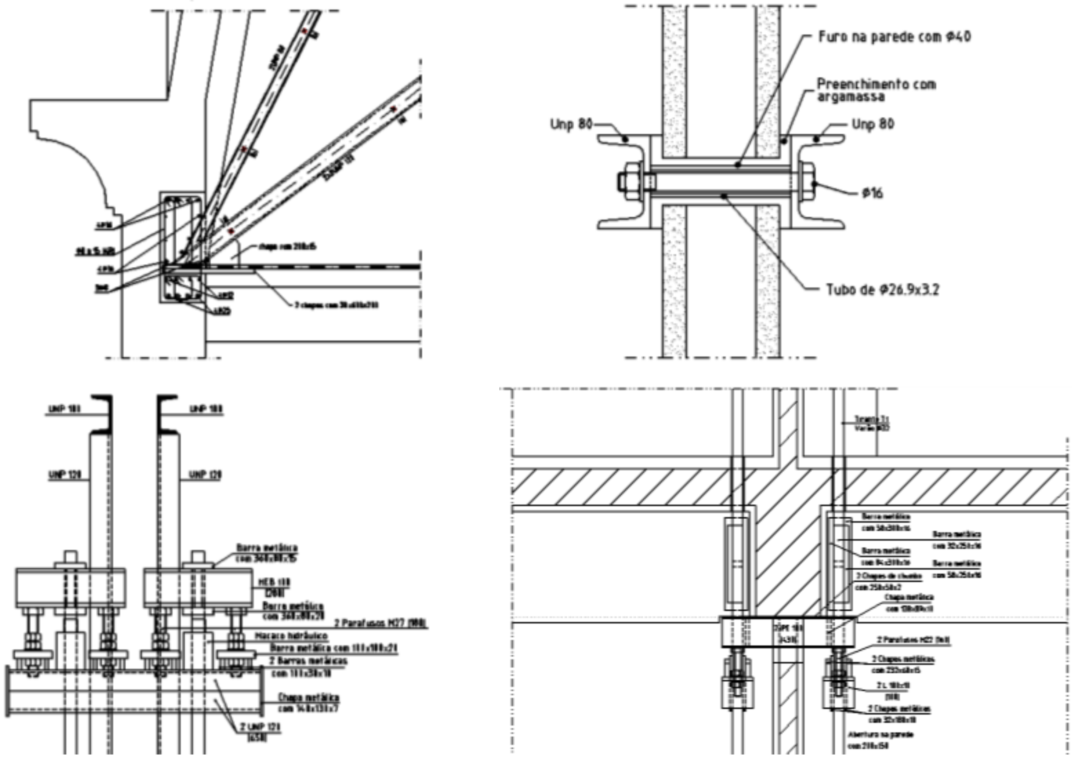


Progressive separation between Level 2 beams and walls

Strengthening (I)



Typical steel struss at roof level



(a) support of steel truss; (b) diagonals embracing the transverse walls; (c) jacks for the load transfer to the new system; (d) supports of new floor steel beams

Social Housing, Porto, Portugal

Description

- Municipality of Porto is the largest landlord in Portugal (43 neighborhoods, 40.000 tenants)
- 21 neighborhoods have been built around 1960’s with reinforced concrete / structural masonry systems. Original design projects, if any, cannot be found. They include 4500 balconies
- The usual configuration includes three types of balconies: in open staircases; inside flats; open long galleries

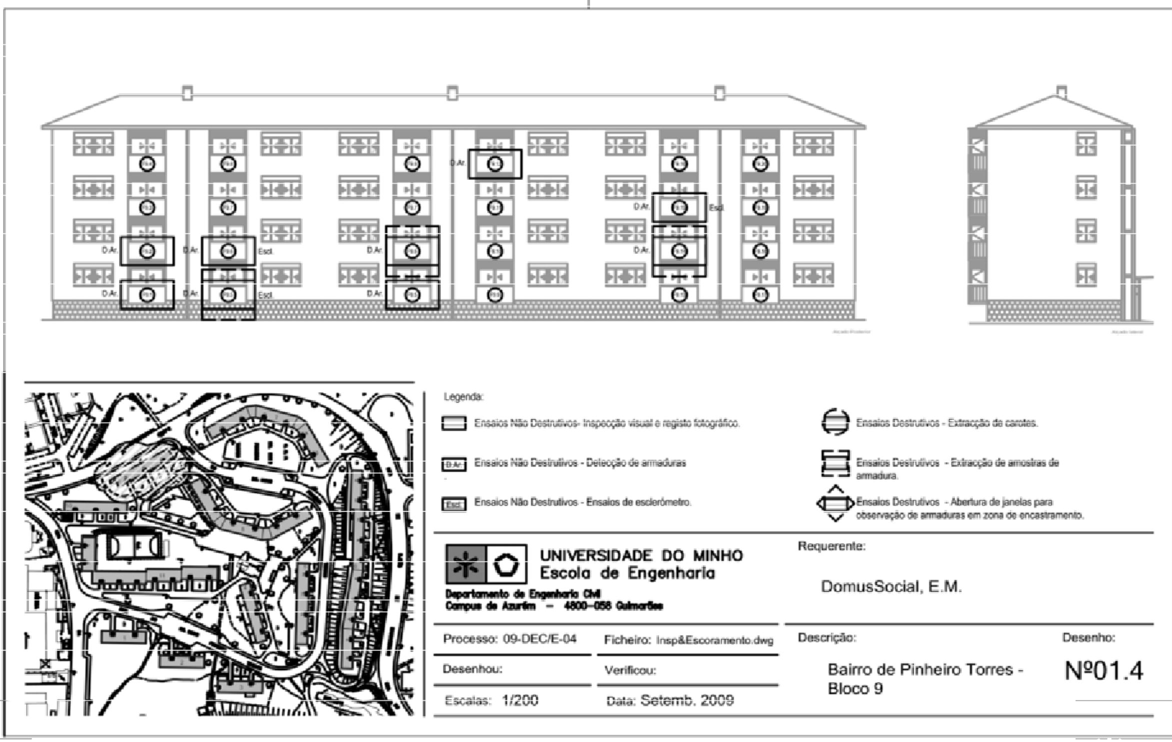

Accident

- An accident occurred: collapse of one balcony with 3 injured

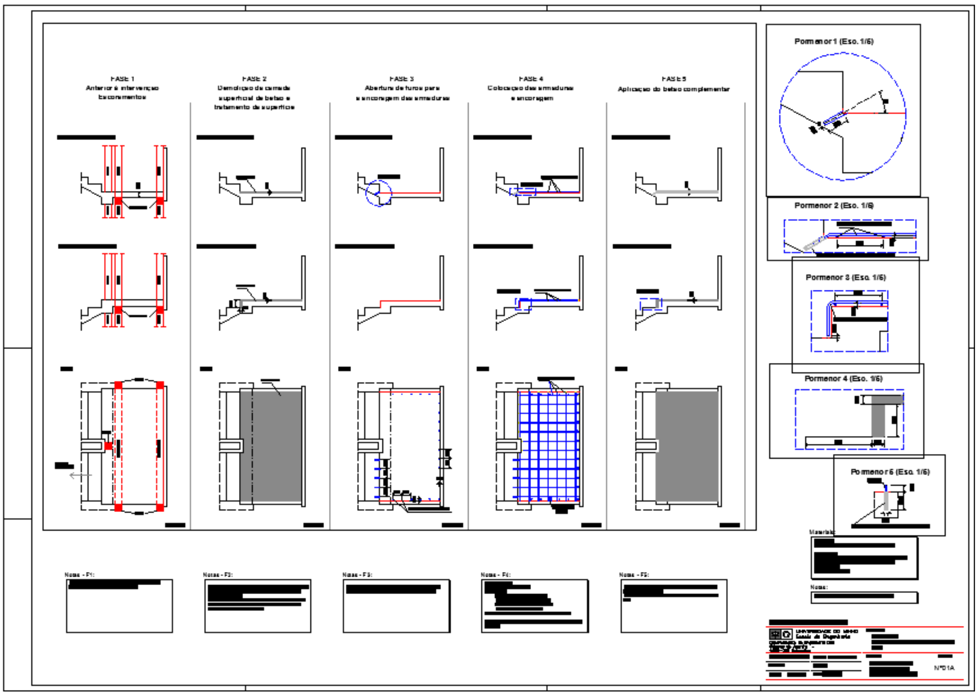


Phase I - Inspection

Phase II – Survey and Inspection: Testing Plan

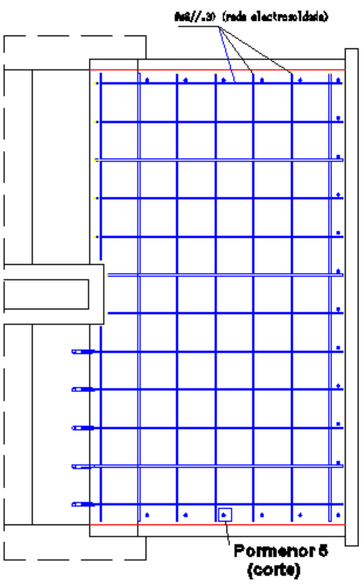


Phase II – Strengthening Case 1



Phase II – Strengthening Case 1 – Details

Planta



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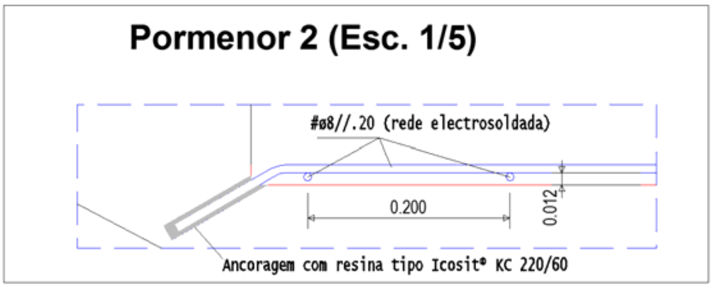
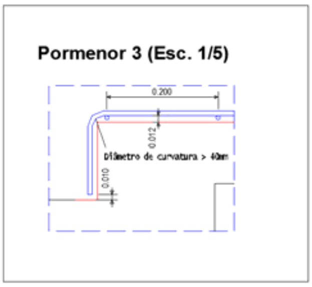
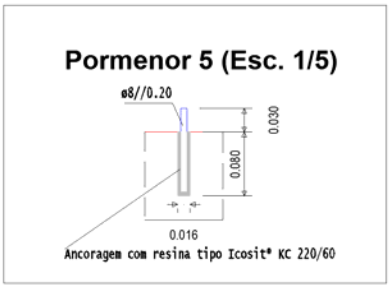






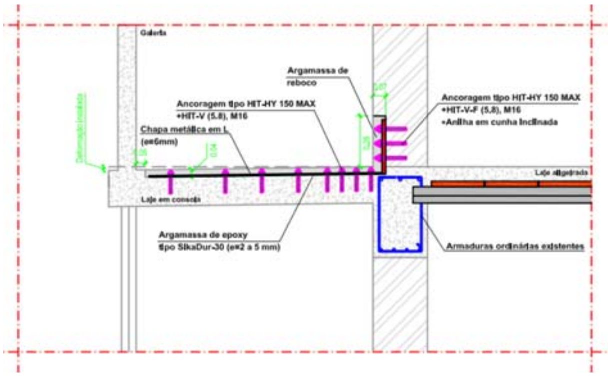
Phase II – Strengthening Case 1 – Execution

Staircase (go down)

Staircase (go up): Upper view

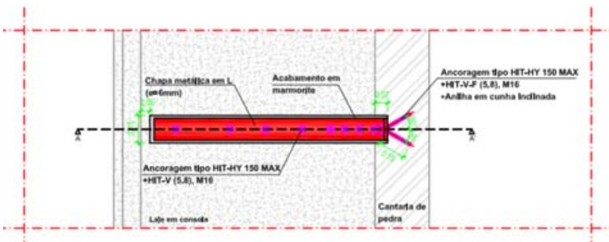
Lower view

Phase III – Balcony with Steel Plates



Studied solutions:

- External steel solution
- Steel profiles placed in the lower part of the slab

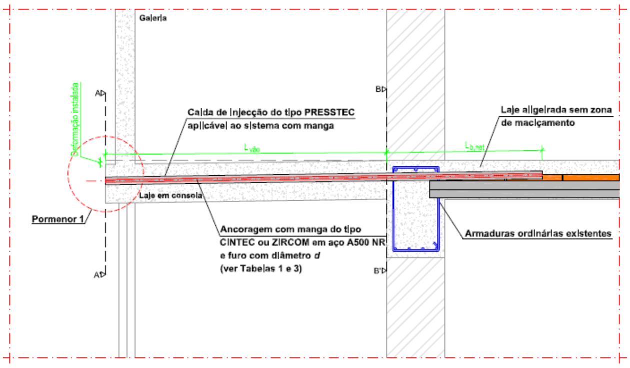


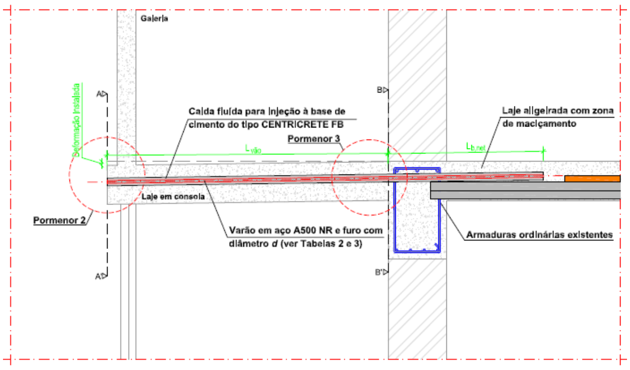
Notes:

- Steel protection
- Welding control (before EN1090)

Phase III – Balcony with Steel Plates – Execution

Phase III – Running balcony

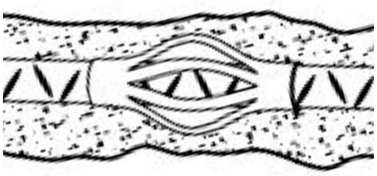




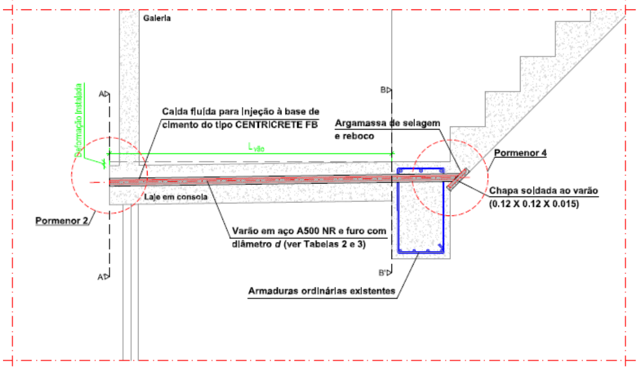
Nailing with and without socket

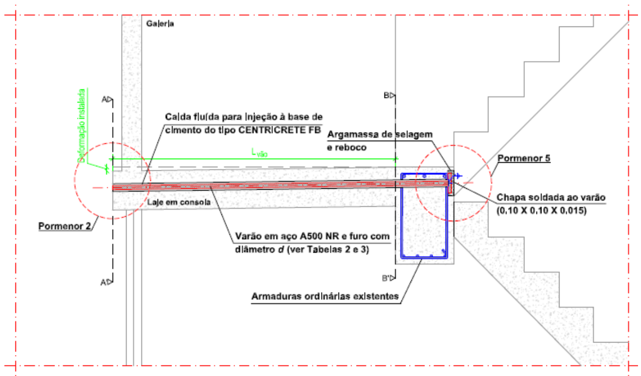
Notes:

- **Spacers**
- **Injection inlet / outlet**



Phase III – Vertical staircase

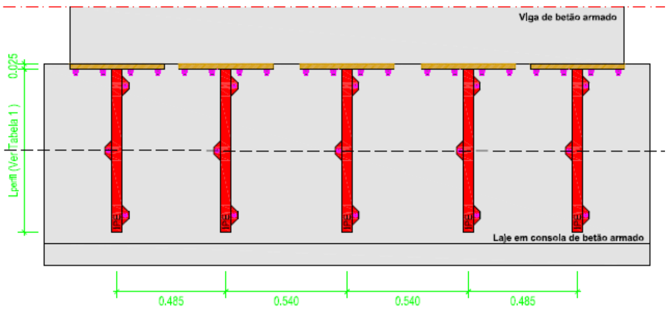


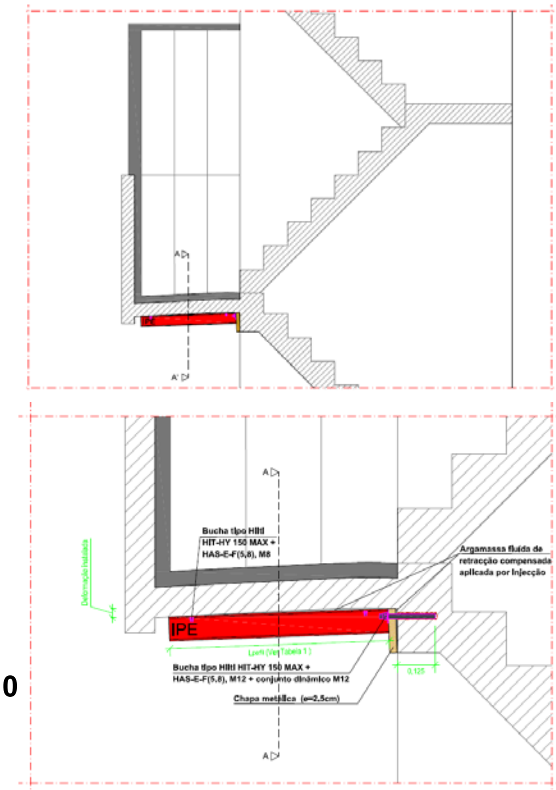


Staircase ramps (ascending / descending)

Phase III – Vertical staircase – Execution

Phase III – Isolated Staircase





Notes:

- Bedding Mortar
- Hot-dip galvanized anchors (45 micron vs. 5-10
- Steel protection
- Welding control

Phase III – Isolated Staircase – Execution

Cathedral of Porto

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Selected Aspects of the Works (I)

Remedial measures in the roof structures included cleaning, application of biocide, application of preservation products, consolidation, strengthening and local replacement

Selected Aspects of the Works (II)

Replacement of the ceramic tiles including new anchors, traditional eaves, strengthening in the corners, introduction of under-roof sheating and walkways.

Selected Aspects of the Works (III)

Remedial measures for stone, including removal of biological activity, dry and low pressure water cleaning, localised consolidation…

…application of water repellents, reconstitution of voids, crack closure and injection, replacement of iron ties, and, exceptionally, replacement of stone pieces.




Repair of grilles and all iron elements included control of anchors and new anchors, and measures for proper rainwater flow, plus protection against further corrosion




Physical protection of the granite stone include sheeting in the external horizontal planes and installation of a electrical anti-pigeon system.

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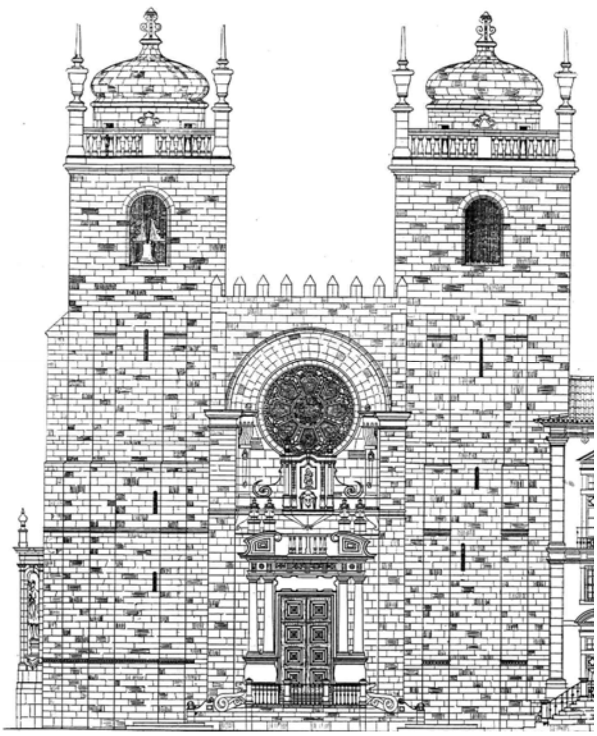
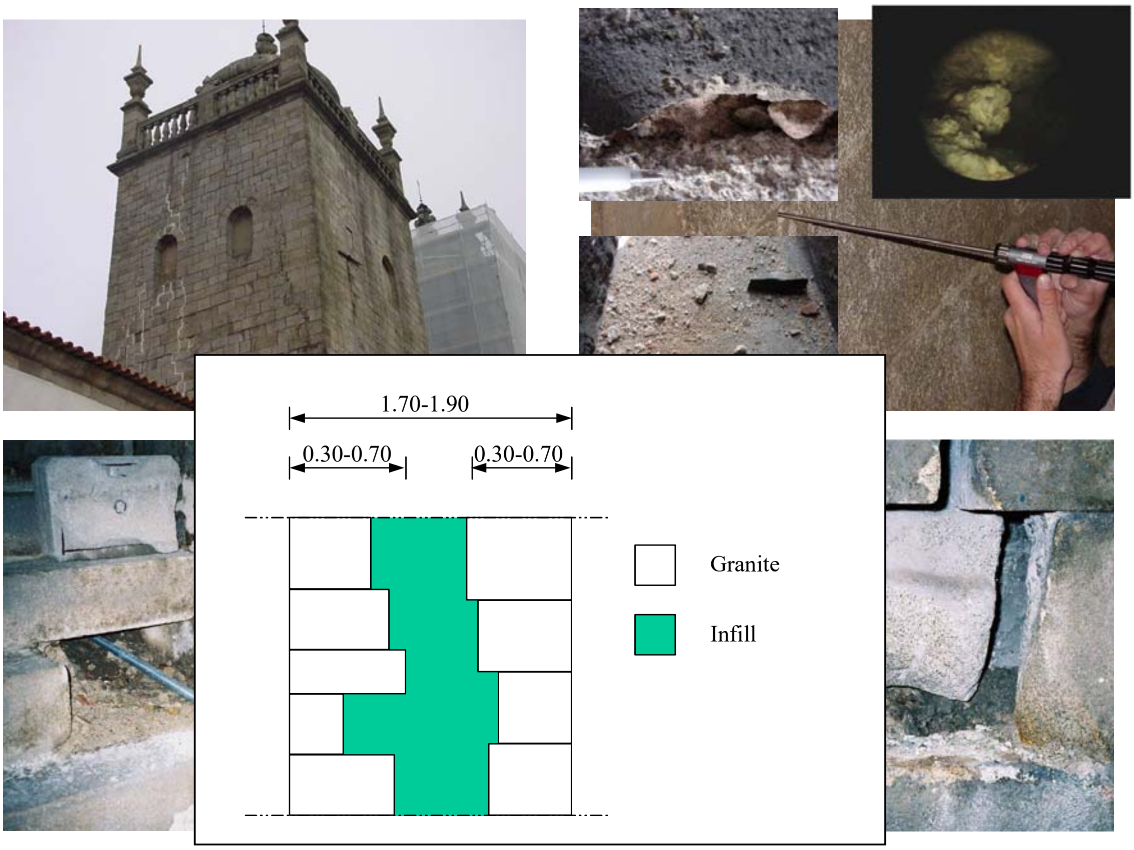
Selected structural Issues

Universidade do Minho

Structural Issues. Towers

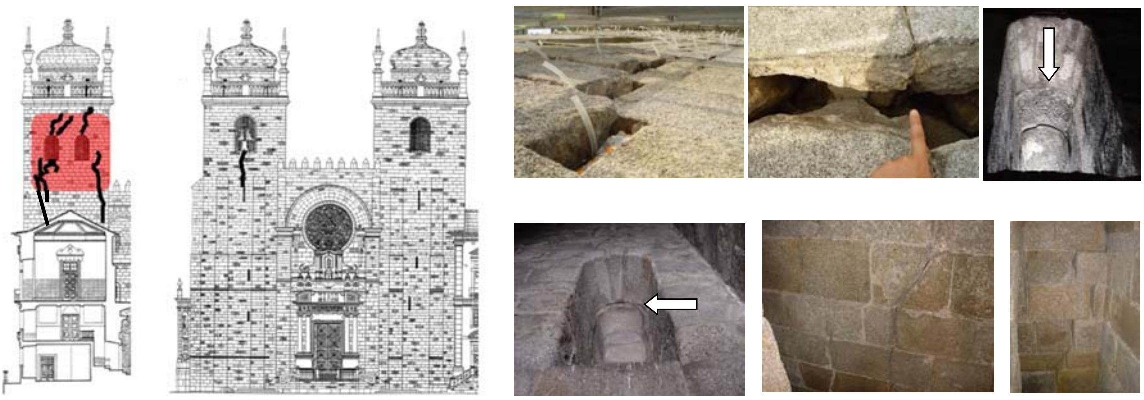


North Tower South Tower

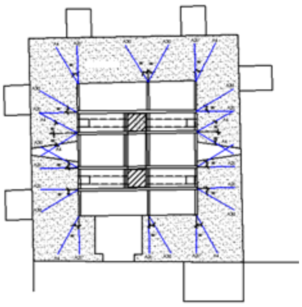


Visual inspection

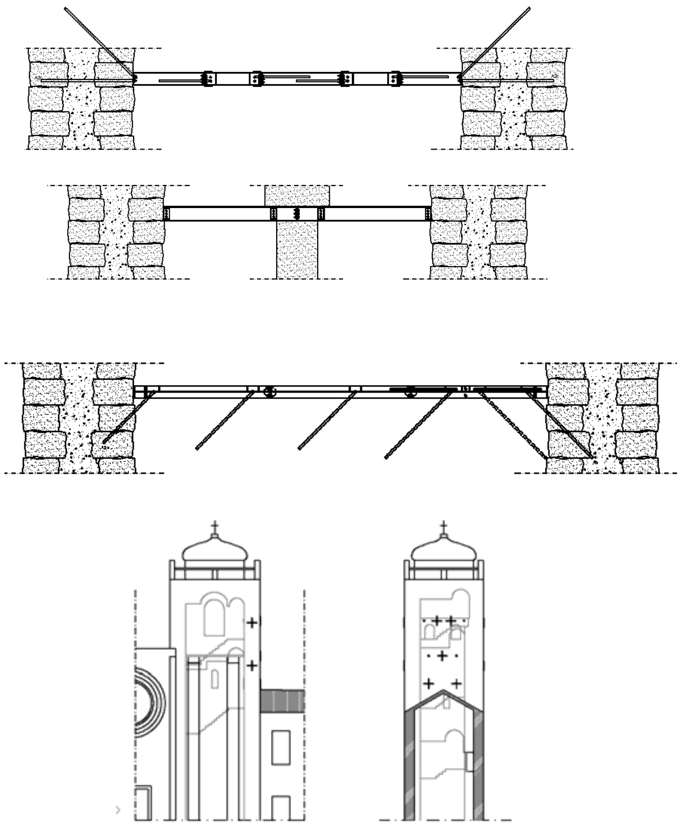
Ties heavily stressed, deformed and broken

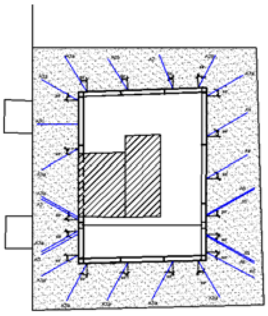


Severe cracking and bulging (lack of integrity and outer leaf loose)



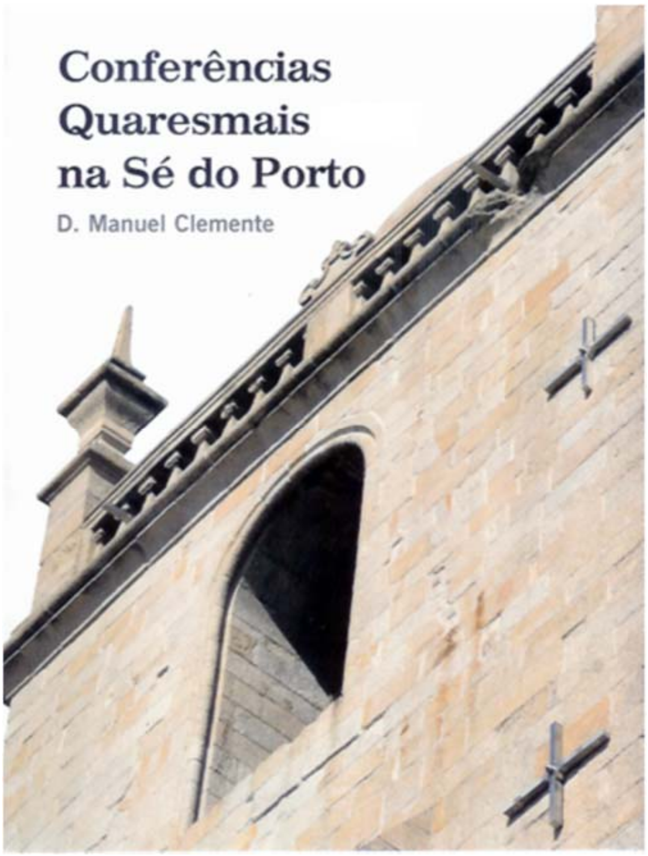
North Tower





South Tower


3ACL
10


Conferências
Quaresmais
na Sé do Porto
D. Manuel Clemente

Getty SRP

Universidade do Minho

Cusco, 1950

Ancash, 1970

Pisco, 2007

Misca, 2014

Seismic Retrofitting Project (SRP), after GSAP
Seismic Stabilization of Historic Structures (1990–96)

PHASE I: RESEARCH

FEASIBILITY | PROTOTYPES | PEER REVIEW GROUP

SURVEY AND GRAPHICS | NDT: THERMO-IMAGING | PROSPECTIONS

CONSTRUCTION ASSESSMENT

PHASE II: ANALYSIS, TESTING AND DESIGN

STATIC AND DYNAMIC TESTS | MODELING ANALYSIS

NUMERICAL MODELING PROTOTYPES STRUCTURAL BEHAVIOUR

TRADITIONAL RETROF.TECHNIQUES | RETROFITTING TECHNIQUES | HIGH-TECH RETROF.TECHNIQUES

NUMERICAL MODELING PROTOTYPES RETROFITTED

PHASE III: DISSEMINATION

WORKSHOPS

TECHNICAL GUIDELINES | MANUALS FOR IMPLEMENTATION

PHASE IV: IMPLEMENTATION

MODEL CONSERVATION PROJECT











Getty Conservation Institute, Los Angeles

Prototype buildings


Church of Kuño Tambo

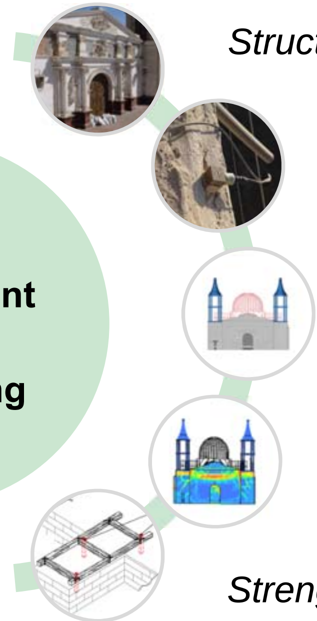

Casa Arones


Ica Cathedral


Hotel El Comercio

Methodology

Safety Assessment and Retrofitting



Structural description and damage

Laboratory and in-situ testing

FE Modelling

Structural analysis

Strengthening

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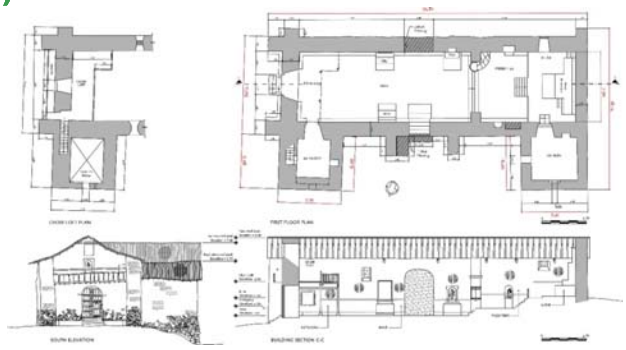
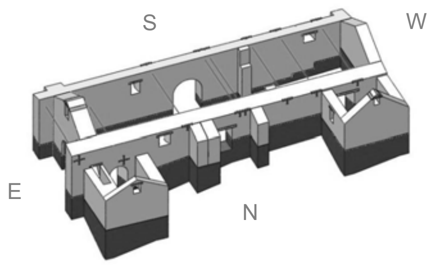
Structural description and damage

Church of Kuño Tambo (KT)

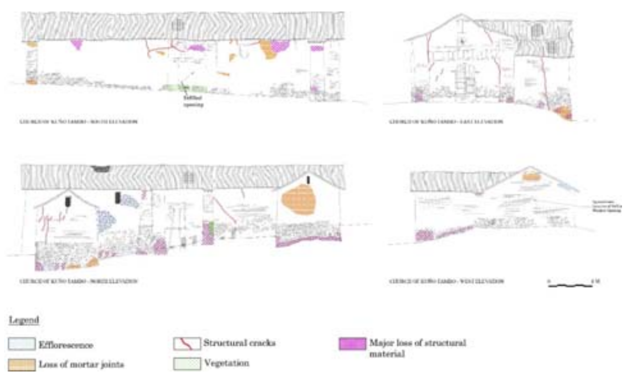
- ❑ Built in **17th century**
- ❑ **Valuable mural paintings**
- ❑ **Structure**
  - Single nave with a sacristy and a baptistery
  - Adobe walls with rubble stone base course
  - Buttresses
  - Single gable timber roof
  - Timber ties and wall plates





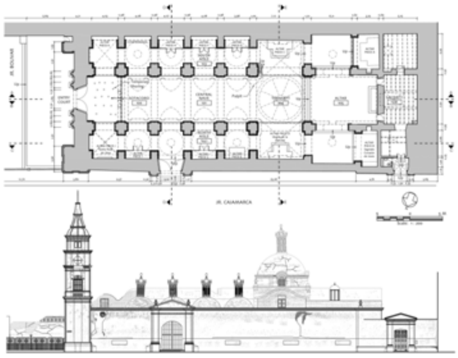
Church of Kuño Tambo (KT)

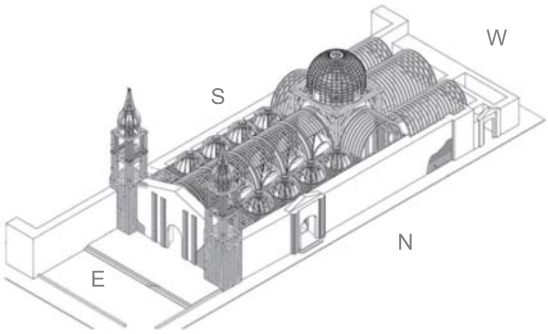
- ❑ **Damage**
  - Vertical cracks
  - Loss of material
  - Deterioration
- ❑ **Diagnosis**
  - Earthquakes
  - Settlements
  - Lack of maintenance



Ica Cathedral (IC)

- ❑ Built in **18th century**, national monument since 1982
- ❑ **Structure**
  - External masonry envelope (rubble stone, fired brick, rubble stone)
  - Internal timber frame (*quincha* technique)





Ica Cathedral (IC)

- ❑ **Damage**
  - Collapse of the roof system
  - Vertical cracks
  - Loss of material
  - Deterioration
- ❑ **Diagnosis**
  - Earthquakes in 2007 (MW 7.9-8.0) and in 2009 (MW 5.8)
  - Lack of maintenance

Strengthening

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Methodology

VULNERABILITY

- Low lateral resistance
- Insufficient level of connectivity
- Deterioration

TARGETS

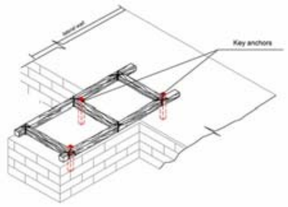
- Reach seismic demand
- "Integral behavior"
- Increase durability
- Conservation principles

OBJECTIVES

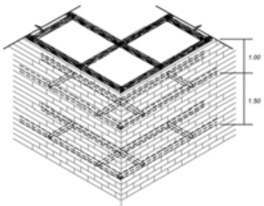
- Internal bracing
- External bracing
- Consolidation

Strengthening techniques

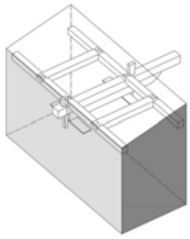
❑ Bracing elements (KT)



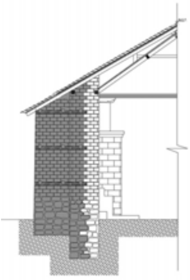
Horizontal timber key between buttress and adjoining wall. Vertical key anchors to enhance connectivity



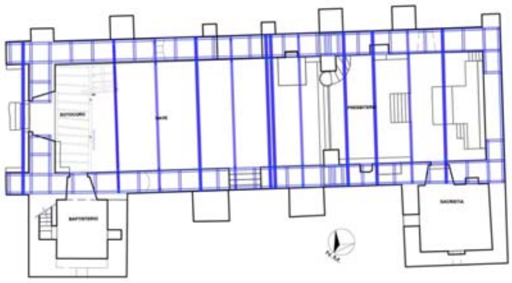
Timber embedded corner keys in elevation. Continuous bond beam at top



Bond beam, tie beam and vertical timber anchors

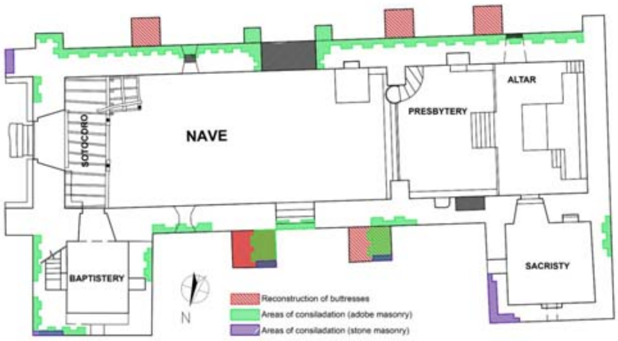


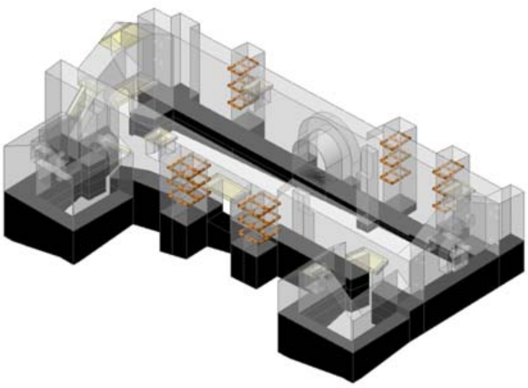
New buttress with horizontal timber keys and interlocking, and geo-mesh, lower part of stabilized adobe (replaced by brick masonry during execution)

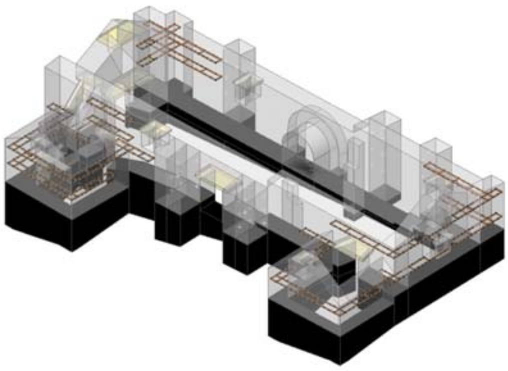


Bond-beam at top eaves. Configuration with two longitudinal timber beams and transversal timber blockers. Connection with tie beams

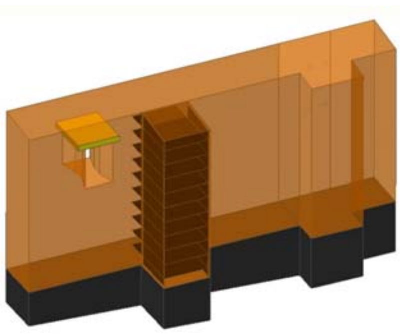
Kuño Tambo (I)

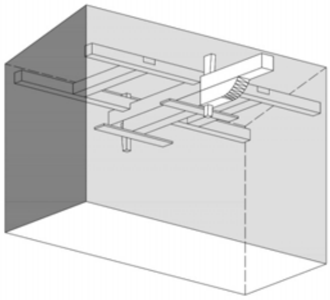


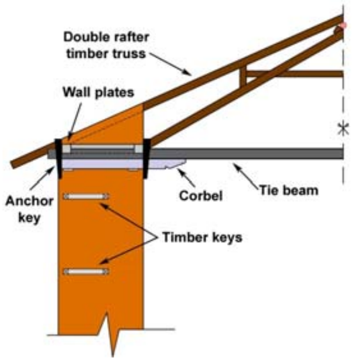




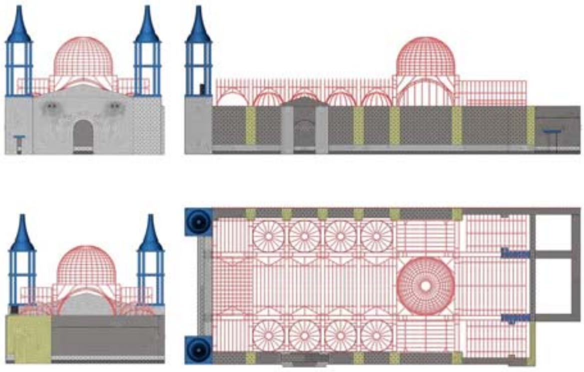
Kuño Tambo (II)

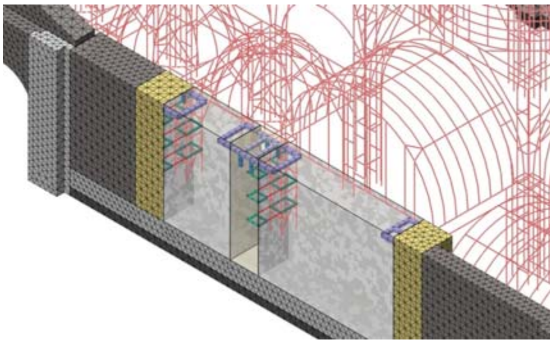


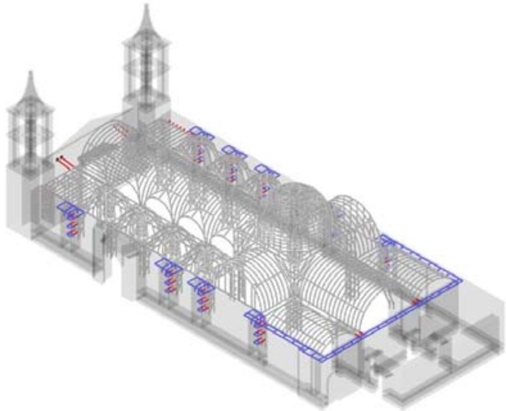




Ica Cathedral

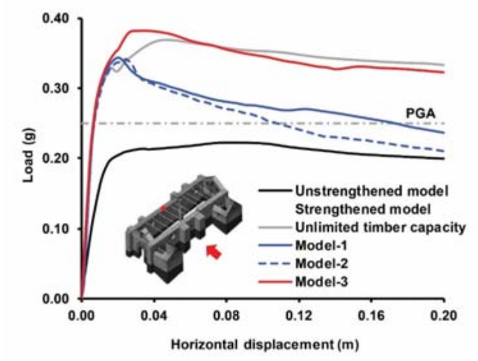


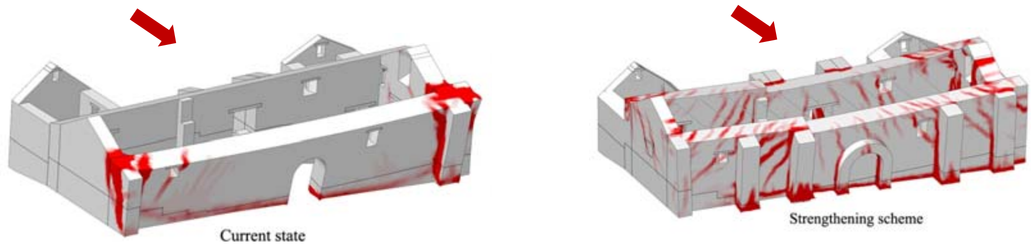




Pushover analysis (KT)

- Seismic capacity of **0.34g,** higher than the design PGA
- Out-of-plane bending mechanism, with more masonry involved
- Damage widely spread, with smaller crack width

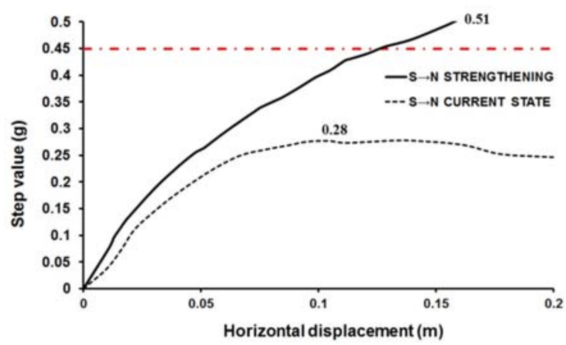


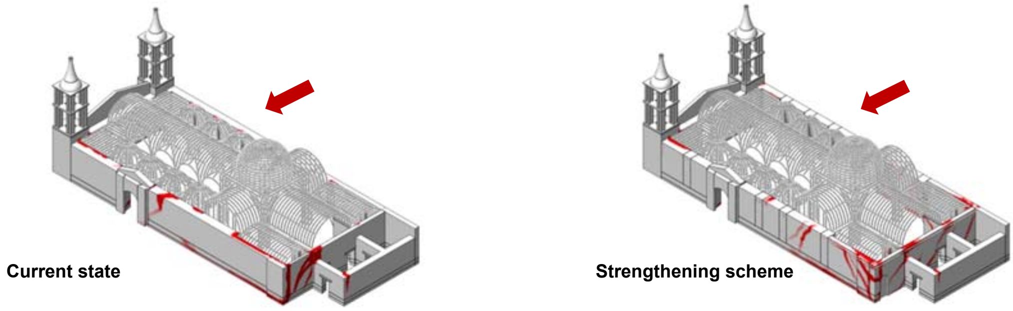


Failure mechanism in terms of tensile strains

Pushover analysis (IC)

- Seismic capacity higher than the design PGA **(0.45g)**
- Out-of-plane bending mechanism, activating both the longitudinal walls
- Damage more distributed in the north-west corner





Failure mechanism in terms of tensile strains isise

Important message ☺

Wrong doing…

Wrong doing…

Hopefully doing right…

Conclusion

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Conclusions & Prospects

- Conservation of the built heritage is the present of construction in Europe and will gain increasing relevance in the world context
- The safety assessment of heritage buildings poses a strong demand on structural engineering skills and adopted structural analysis techniques
- Structural conservation is an exciting topic, challenging engineers and architects to think out of the box and go beyond standard practices

Preservation of Historic Structures: Methodology, Safety Assessment and Practice

Paulo B. Lourenço

pbl@civil.uminho.pt

Universidade do Minho

https://www.youtube.com/user/isisehms