Technologies for Seismic Retrofitting and Strengthening of Earthen and Masonry Structures: Assessment and Application

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Introduction

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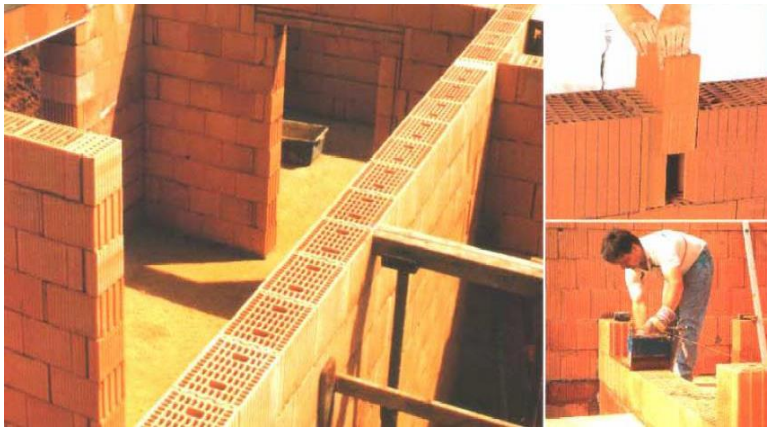
What is masonry?



A material with visible internal structure and low tensile strength:

Rubble masonry is not much different from unreinforced concrete or earth

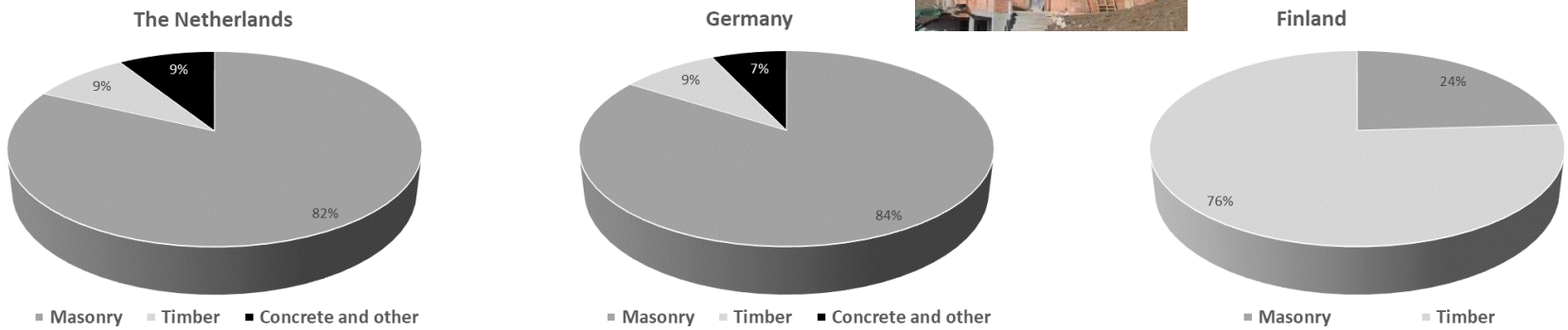
Existing built heritage

Global Building Inventory of twenty-two moderate to high seismicity, developed and developing, countries indicates, in which unreinforced masonry (URM) accounts for **more than half of the built heritage** (Jaiswal and Wald 2008)

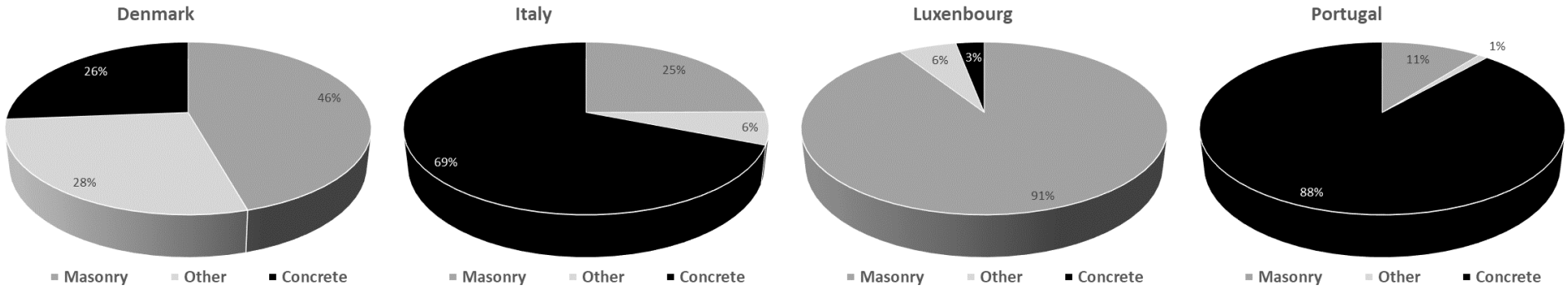
Country	Year	URM as % of inventory
Australia	2000	52.9
El Salvador	1990	48.0
Indonesia	2001	60.0
Iran	2005	56.7
Italy	2006	62.2
Mexico	2000	75.7
New Zealand	1998	7.0
Pakistan	1998	93.0
Peru	2007	73.2
Philippines	2000	30.8
Turkey	2002	47.1
United States	2002	15.0

(Frankie, Gencturk, and Elnashai 2013)

Modern buildings



Residential market (Pompeu Santos 2007)



Building structures (Sousa and Carvalho 2007)

Cusco, 1950

Ancash, 1970

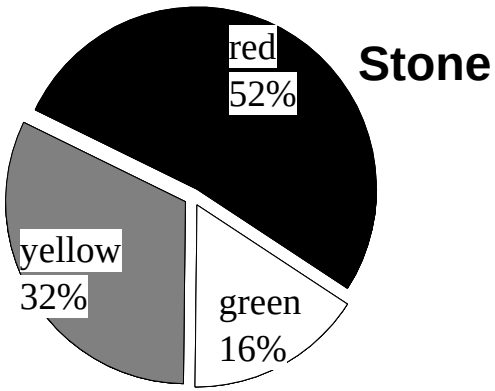
Pisco, 2007

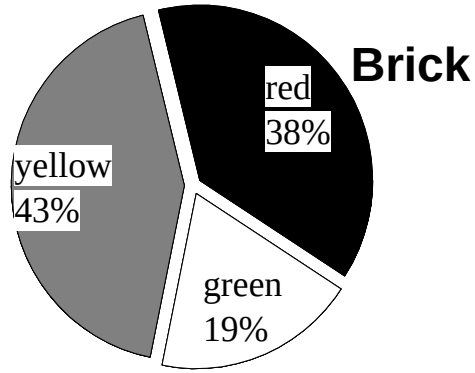
Misca, 2014

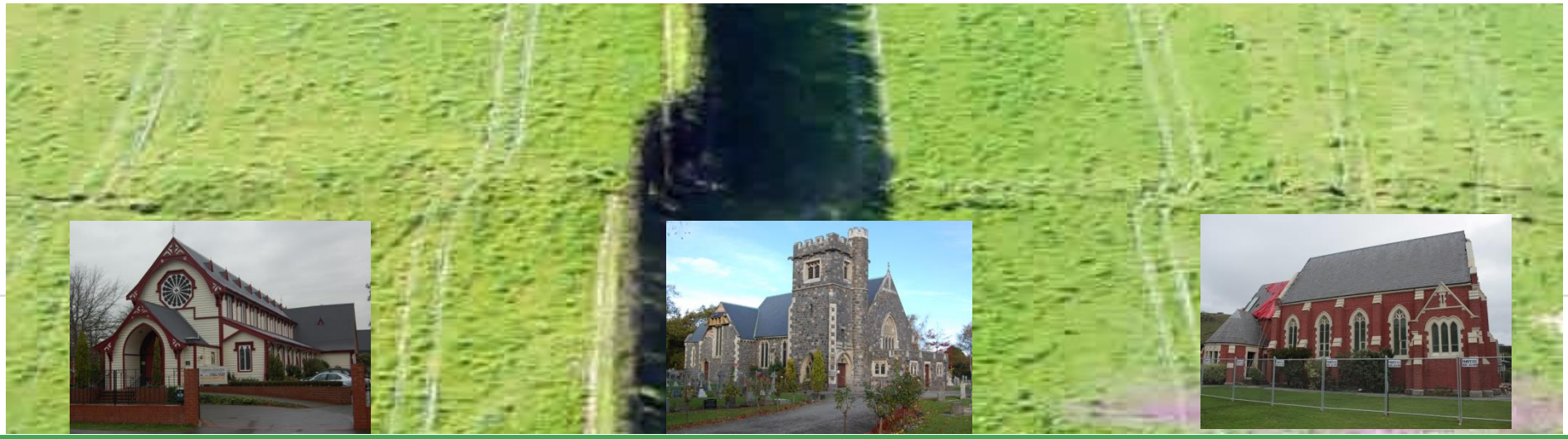
Arequipa, Peru

Example of churches in New Zealand (Earthquakes 2010-11)

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

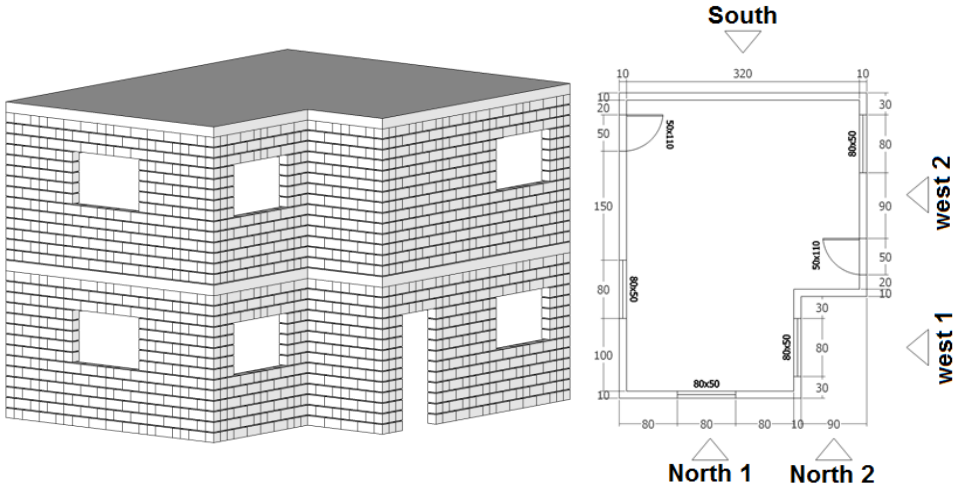






Modern masonry as good as other building technology

- Worst case scenario in masonry: embedded ring beam + unfilled vertical joints
- Light damage up to the design earthquake in Lisbon (rock)
- Ductile damage for 2.5x the design earthquake in Lisbon (rock), q = 2.5



Blind test prediction

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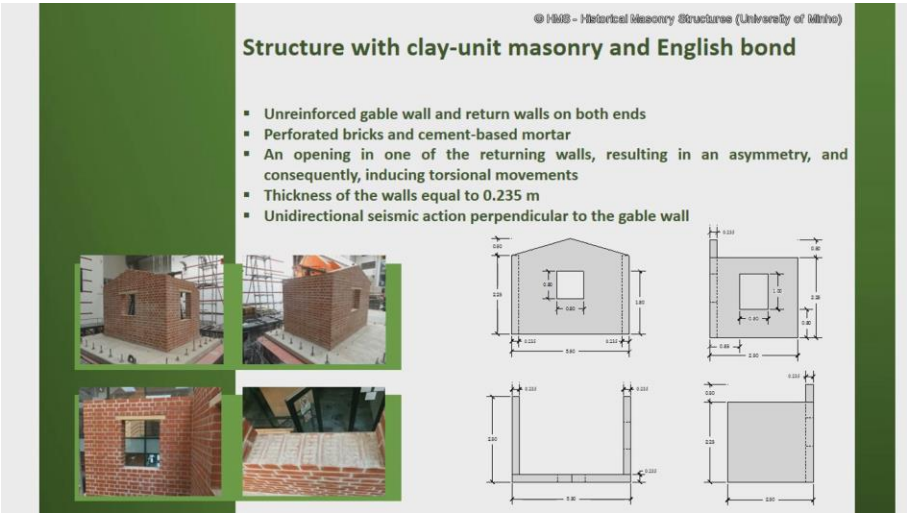
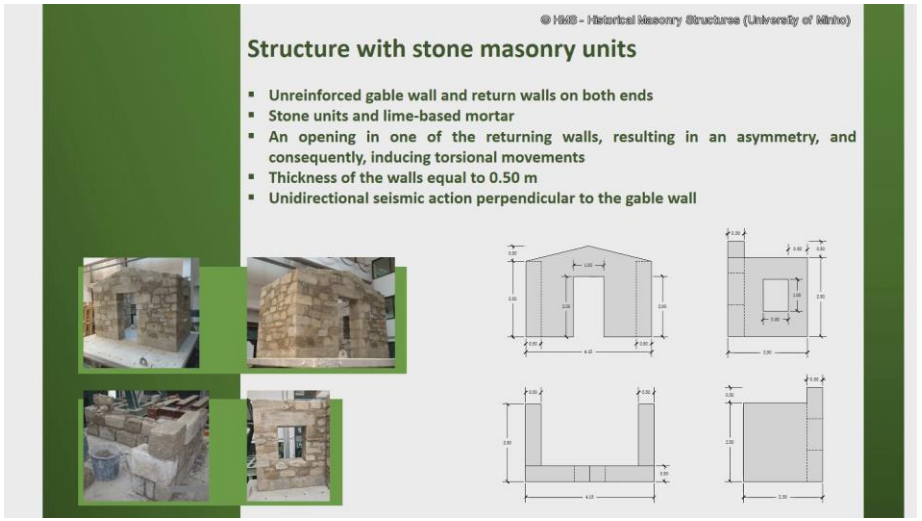
Existing Masonry Buildings: Without rigid diaphragm

- Recent benchmark test
- 25 international masonry experts
- 18 blind predictions
- 2 masonry types





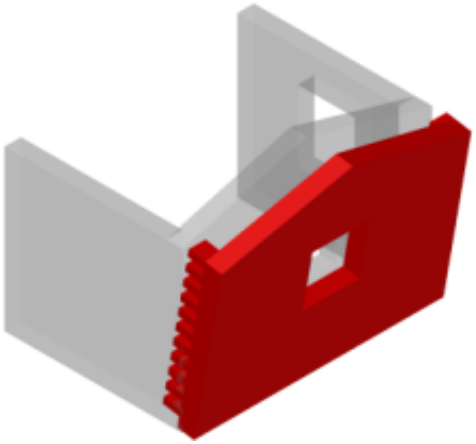
Data given & approaches adopted

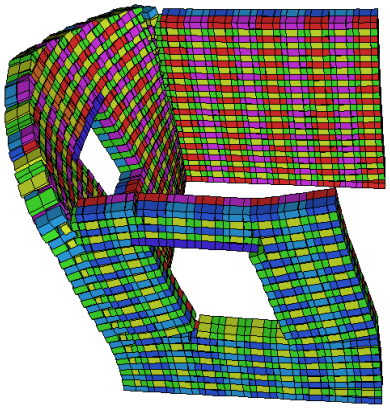
- Geometry
- Material properties (specific mass, Young´s modulus, tensile and compressive strength)
- Normalized accelerogram envelopes of the seismic action applied at the base, and the corresponding response spectra

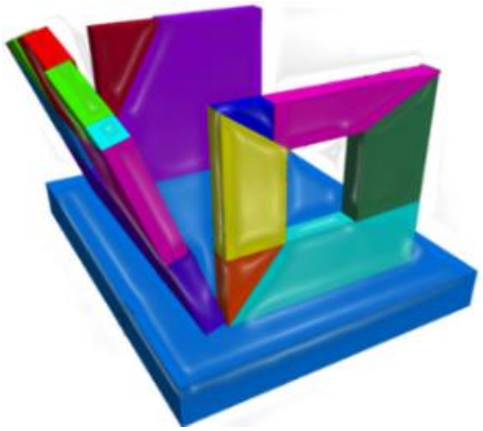
- Modelling approaches adopted:
  - rigid macro-blocks (23 models)
  - finite element modeling (7 macro-models, 3 micro-models)
  - discrete element method (3 meso-models)

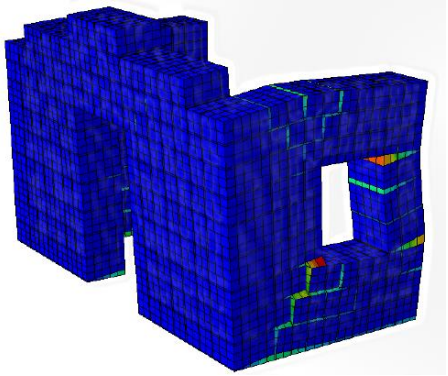
- Type of structural analysis:
  - Limit analysis based on the kinematic approach;
  - Static non-linear analysis (pushover), usually mass (a few first mode) proportional
  - Non-linear dynamic analysis with time integration, with artificial accelerograms applied at the base of structures generated by the experts

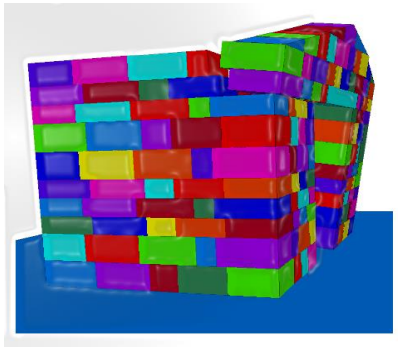
Examples of models adopted by experts







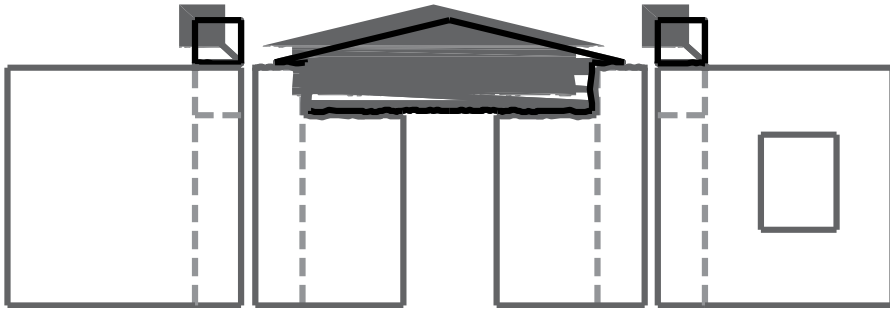




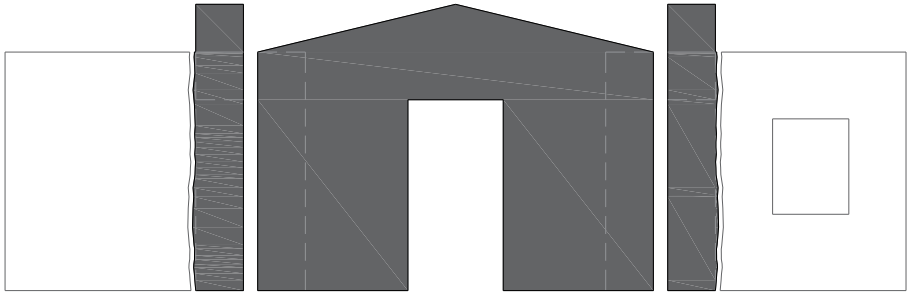
Macro-blocks FEM DEM

Stone building: 13 idealized collapse mechanism proposed

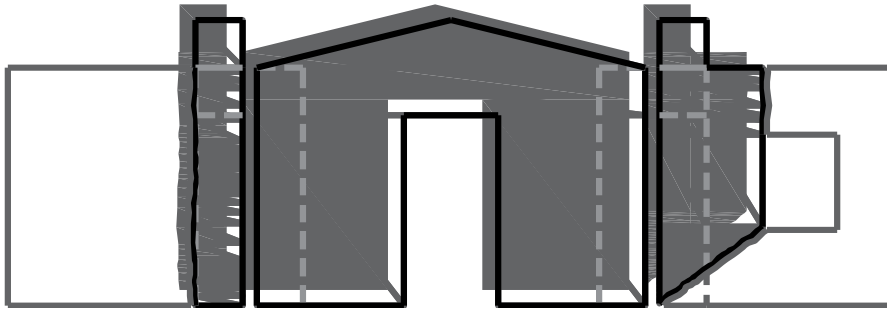
- Estimated PGA at collapse ranged from 0.22-2.50 g (COV=63%)
- Average estimated PGA of 0.91 g (Experimental equal to 1.07 g)
- Large variance due to incorrect prediction of collapse mechanism. For mechanisms similar to test, prediction range was 0.53-1.42 g (COV= 31%)



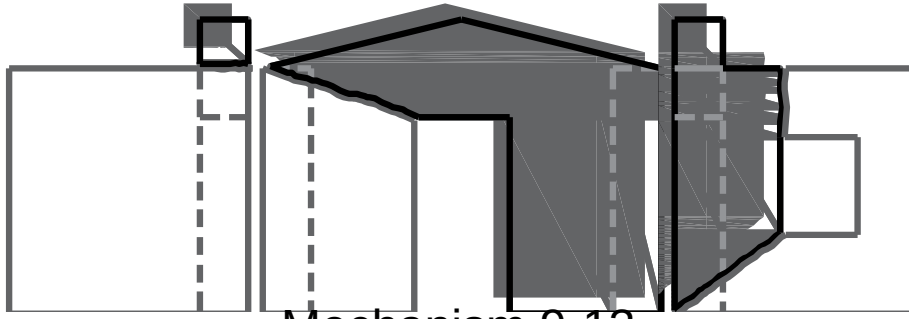
Mechanisms 1-4



Mechanism 5



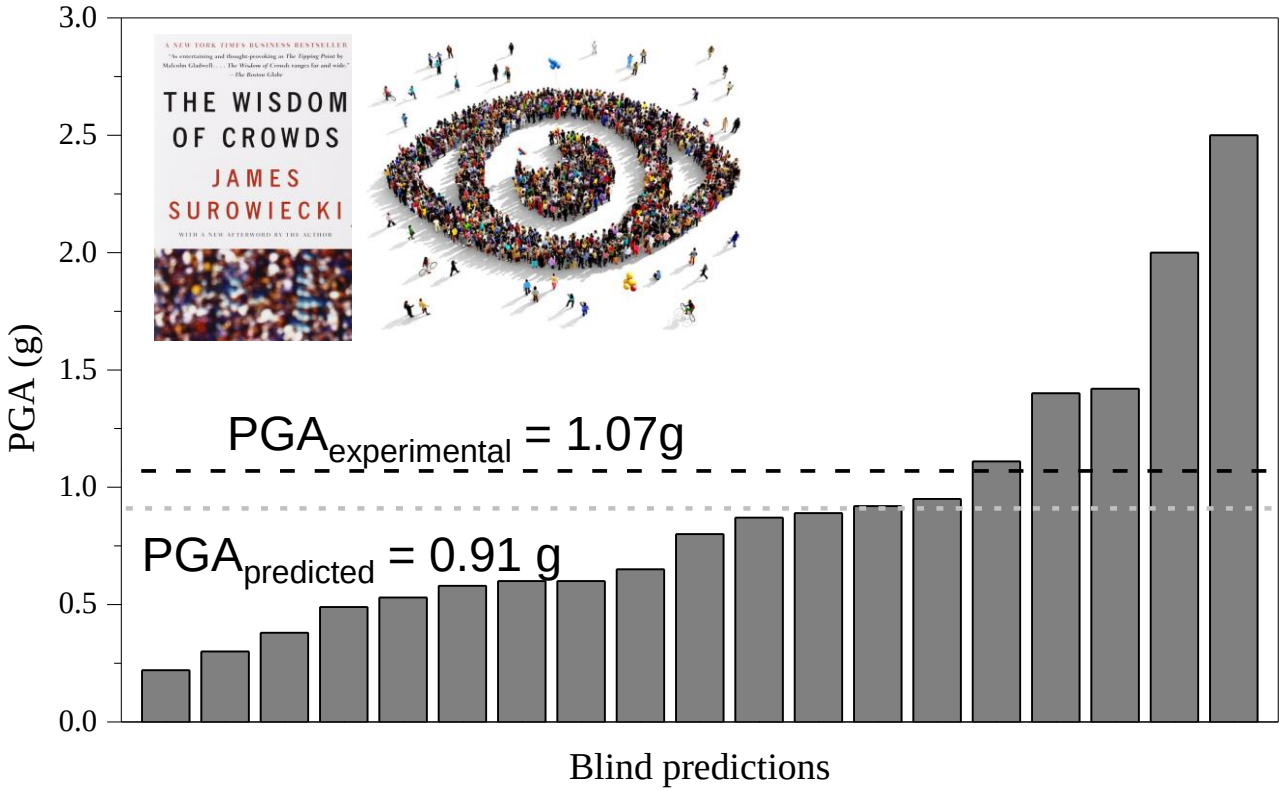
Mechanism 6-7



Mechanism 9-13

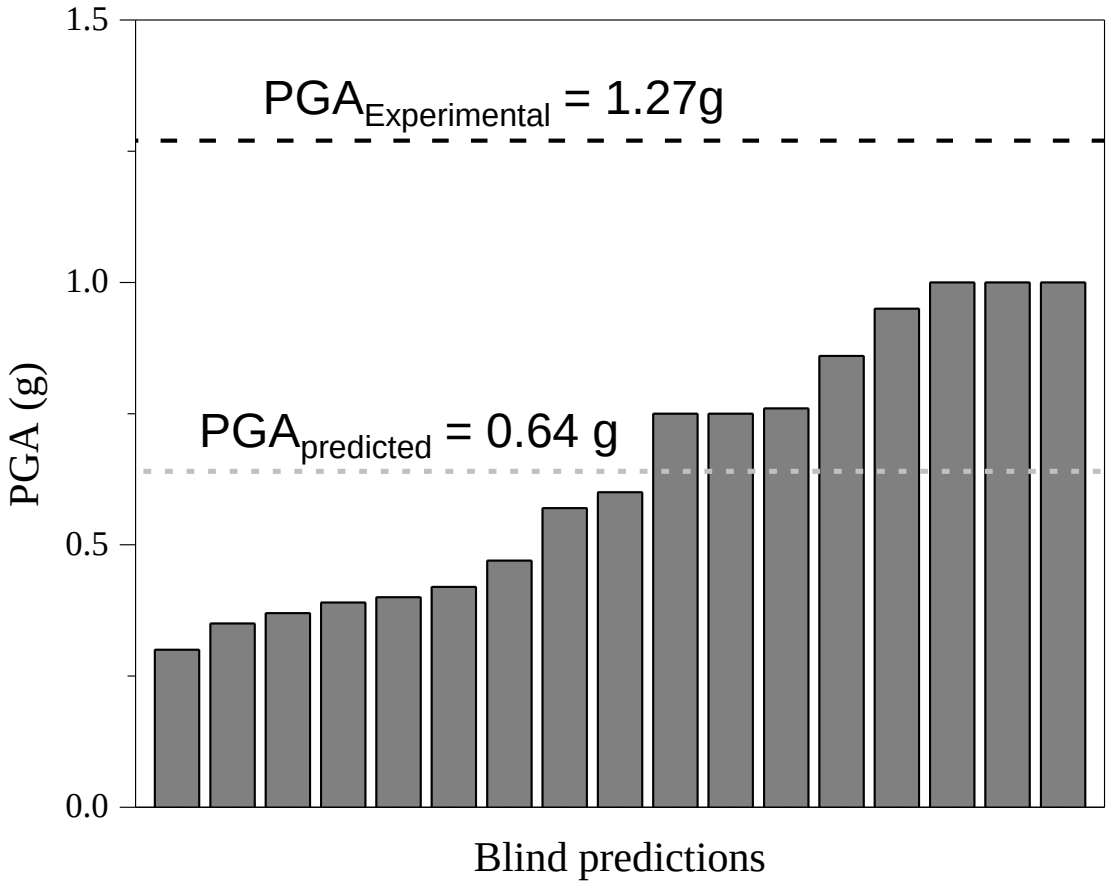
Stone building: 13 idealized collapse mechanism proposed (II)

- Average error between test and predicted PGA for good mech. was 28%
- 80% presented a predicted PGA lower than or equal to test
- Within good mech., two results presented collapse displacement at top (0.16 and 0.25 m).Test provided 0.22 m (about half of the wall thickness).



Brick building

- 17 predictions. Estimated PGA at collapse: 0.30-1.00 g (COV=39%)
- Experimental result (1.27 g). Average PGA of predictions: 0.64 g. All predictions lower than experimental results
- Problems: slenderness of the structure, torsional effects, material properties?



It seems that…

- We can make assessments on the safe side
- Too much scatter in predictions is found
- Masonry out-of-plane failure assessment remains a research challenge

Engineering applications to earthen structures

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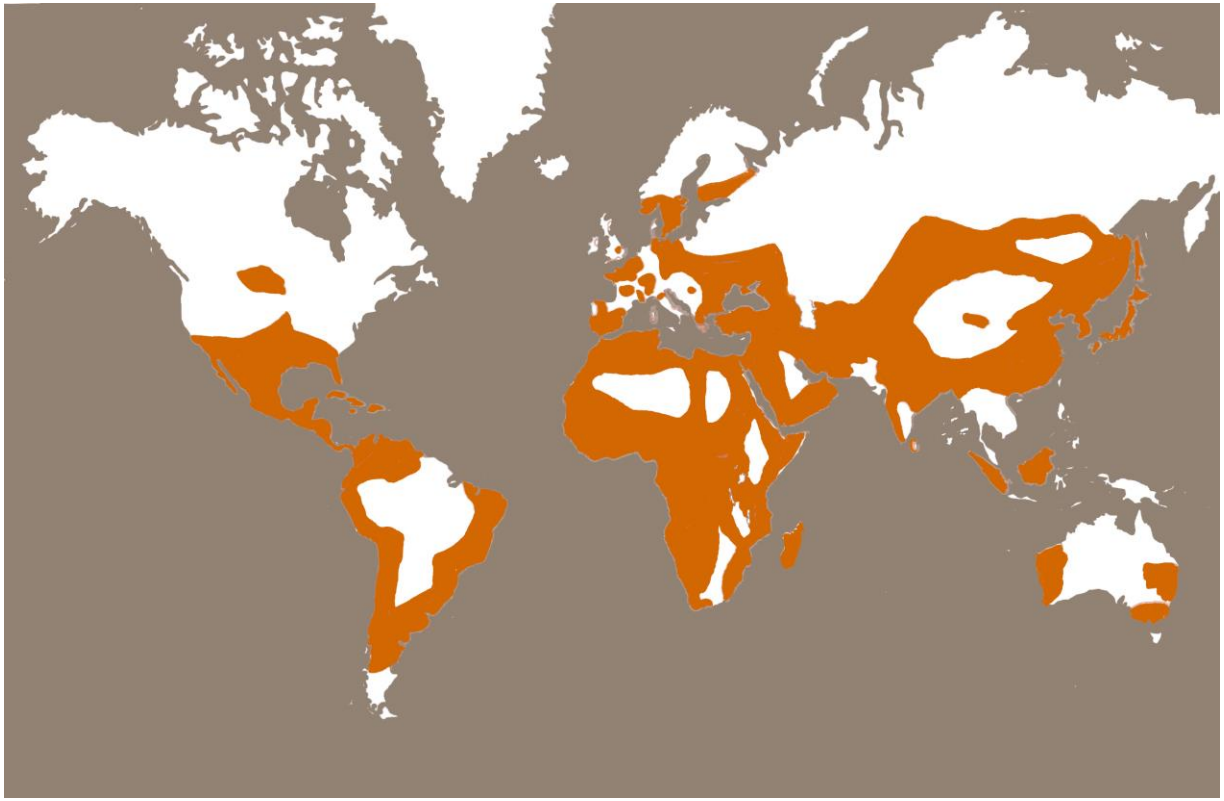
Earthen structures

- About 2 billion people (almost 50% of the population in developing countries)



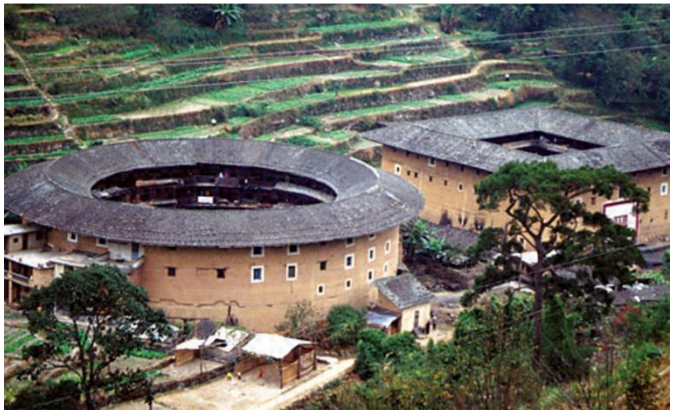
Historic earthen structures

- Significant portion of the built heritage worldwide

Houses of Tiébélé (Burkina Faso)

Arg-e-Bam (Iran)

Mosque of Djenné (Mali)



Hakka dwellings (China)

Kasbah Taourirt (Marocco)

Historic earthen structures

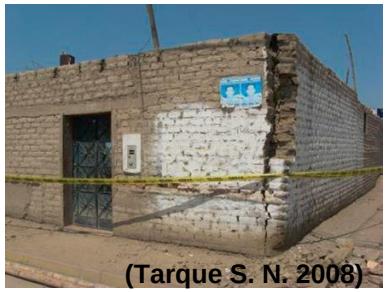
- Building techniques with intangible historical value, wide material availability and low-cost construction


Photo: Antonio Romanazzi


Photo: Getty Conservation Institute

Seismic vulnerability

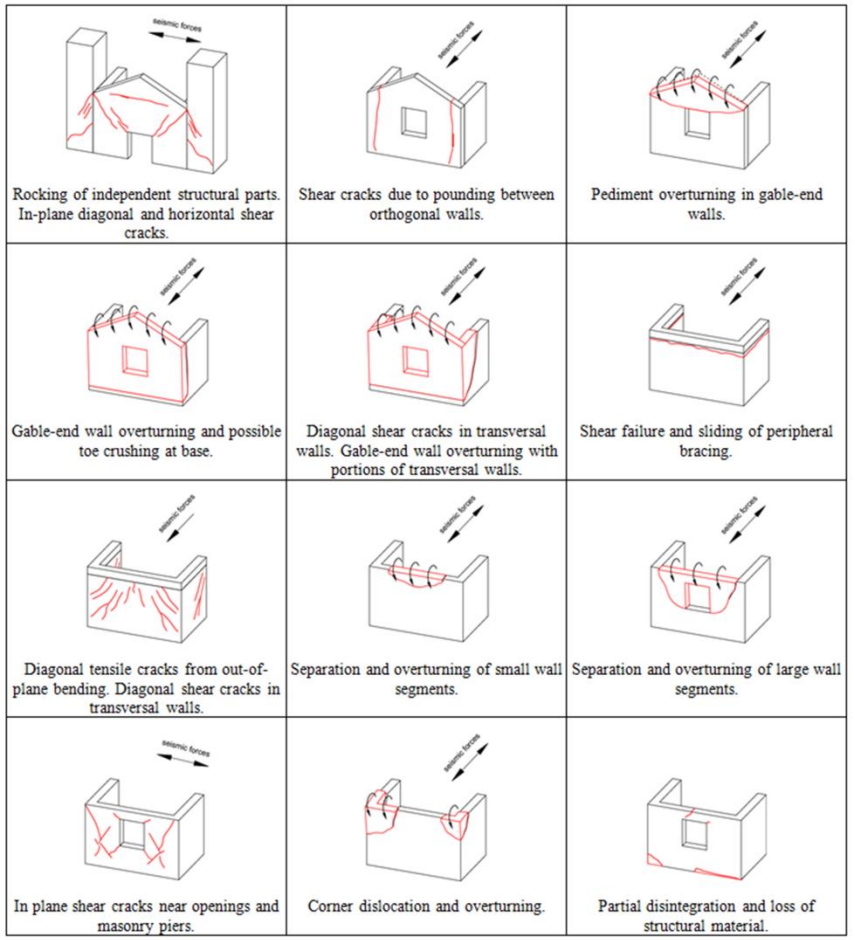
- Poor mechanical properties
- Lack of lateral confinement
- Lack of maintenance


(Tarque S. N. 2008)


Church at Cusco region, Peru


(Tarque S. N. 2008)


(Cancino C. et al 2009)



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

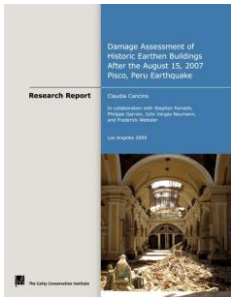
WORKSHOPS

TECHNICAL GUIDELINES	MANUALS FOR IMPLEMENTATION

PHASE IV: IMPLEMENTATION

MODEL CONSERVATION PROJECT





Getty Conservation Institute, Los Angeles

Prototype buildings

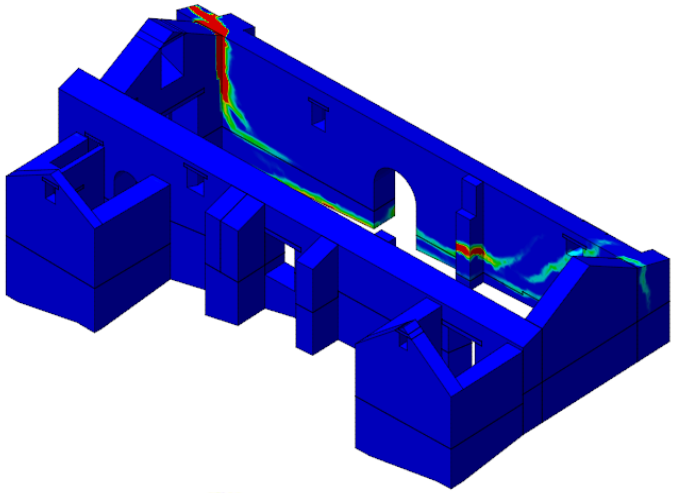
Church of Kuño Tambo

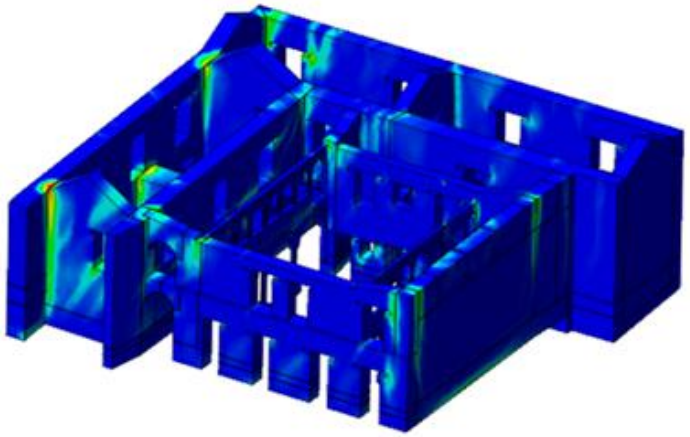
Casa Arones

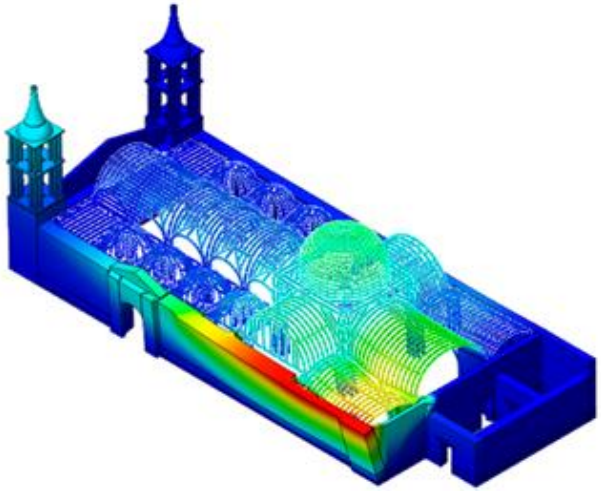
Ica Cathedral

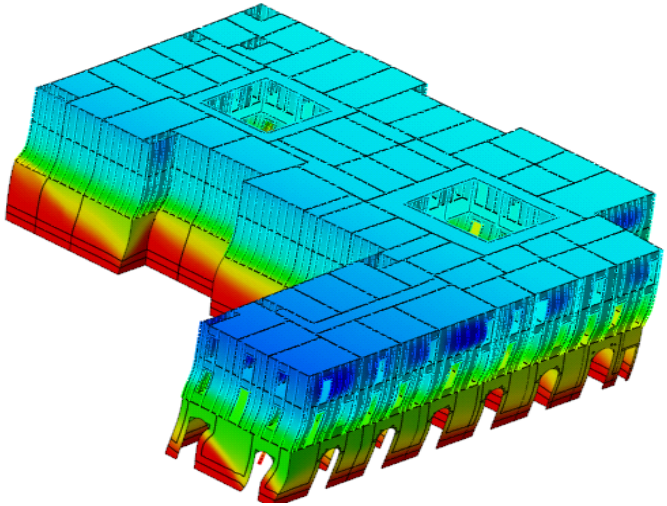
Hotel El Comercio

Our Role

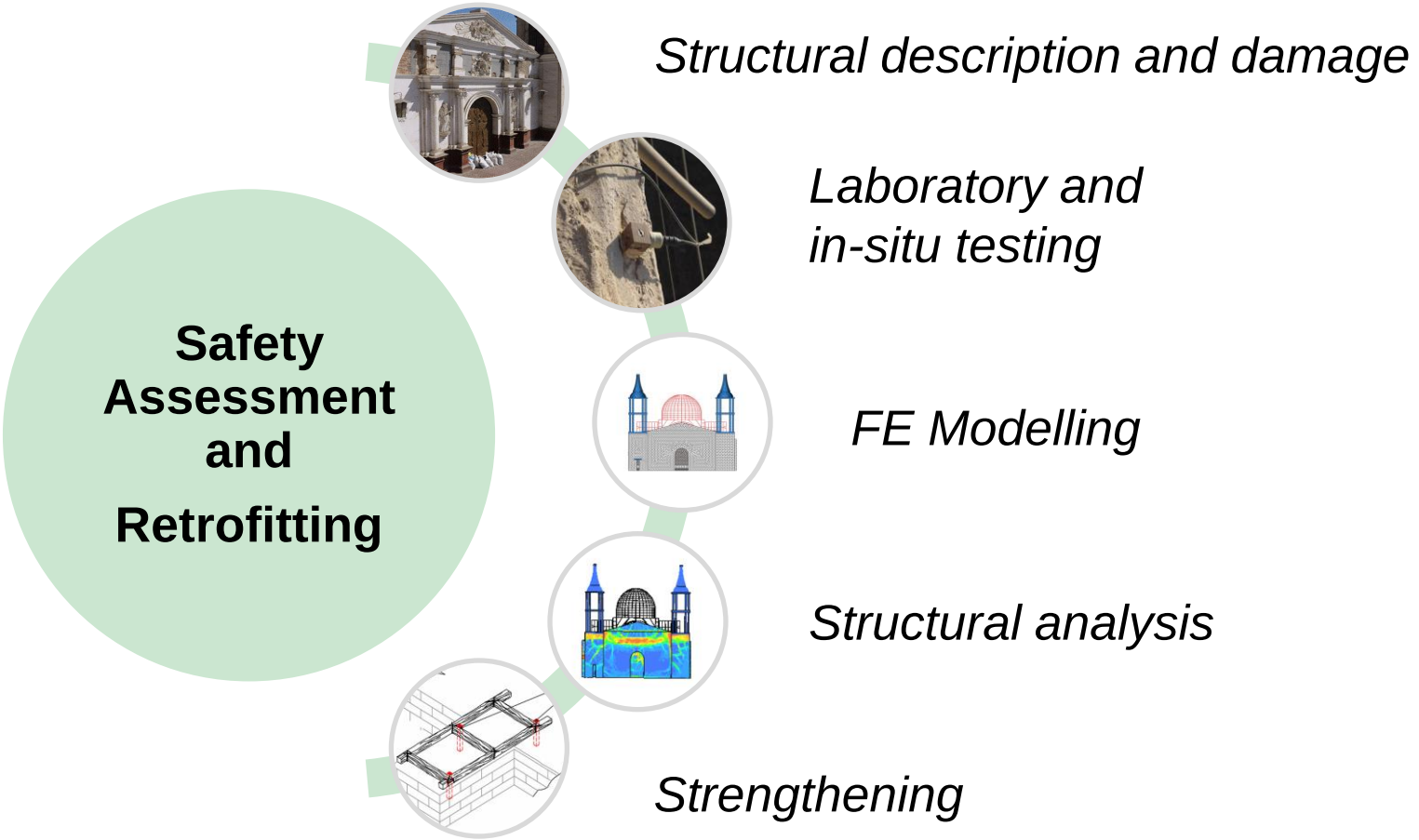








Methodology



Structural description and damage

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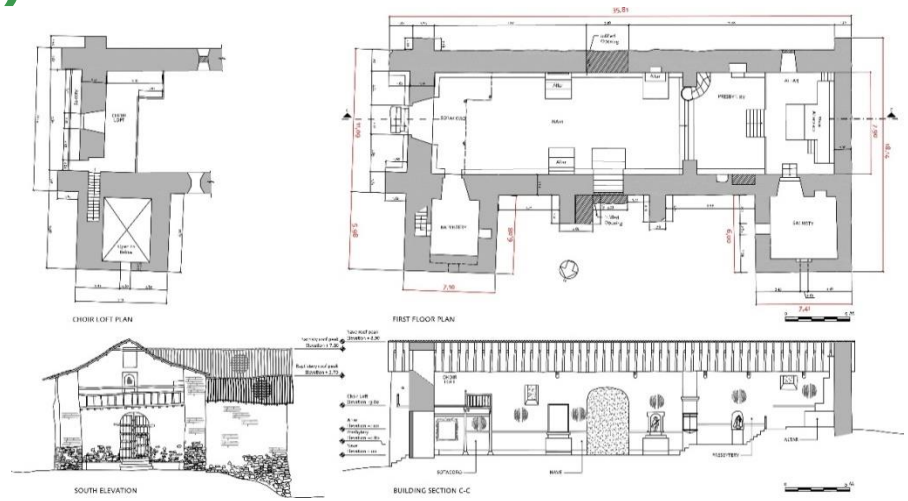
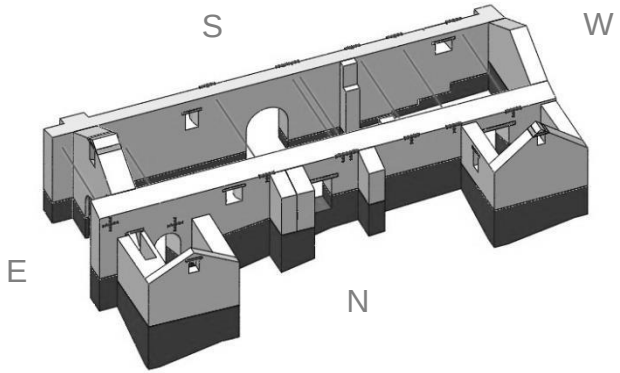
Church of Kuño Tambo (KT)

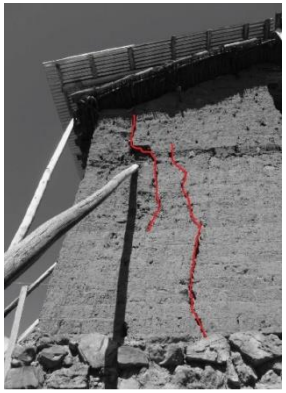
- Built in **17th century**
- **Structure**
  - Single nave with a sacristy and a baptistery
  - Adobe walls with rubble stone base course
  - Buttresses
  - Single gable timber roof
  - Timber ties and wall plates





Church of Kuño Tambo (KT)

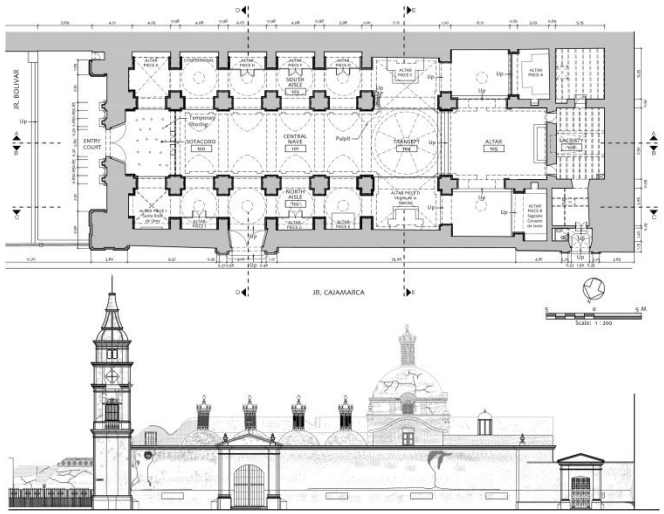
- **Damage**
  - Vertical cracks
  - Loss of material
  - Deterioration
- **Diagnosis**
  - Earthquakes
  - Settlements
  - Lack of maintenance

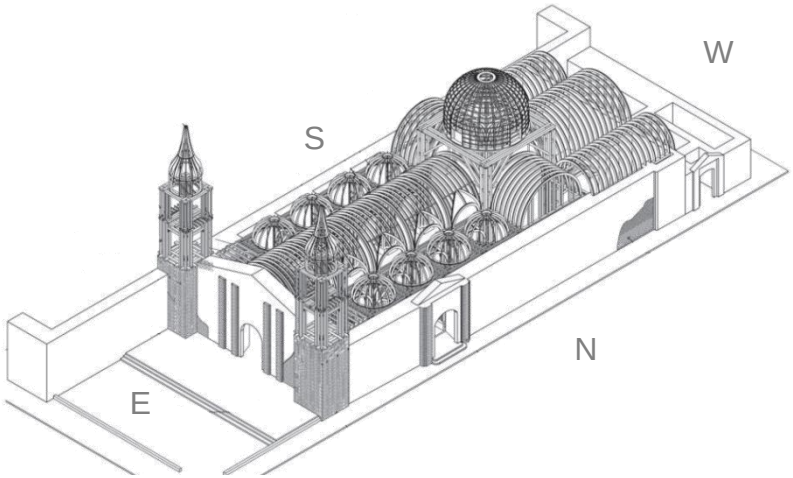


Ica Cathedral (IC)

- Built in **18th century**, national monument since 1982

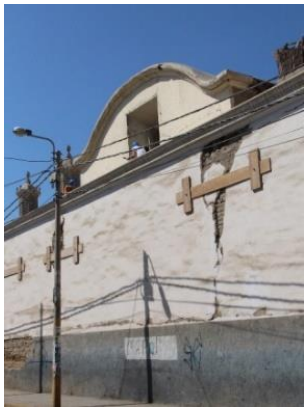
- **Structure**
  - External masonry envelope (rubble stone, fired brick, rubble stone)
  - Internal timber frame (*quincha* technique)





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

Laboratory and in-situ testing

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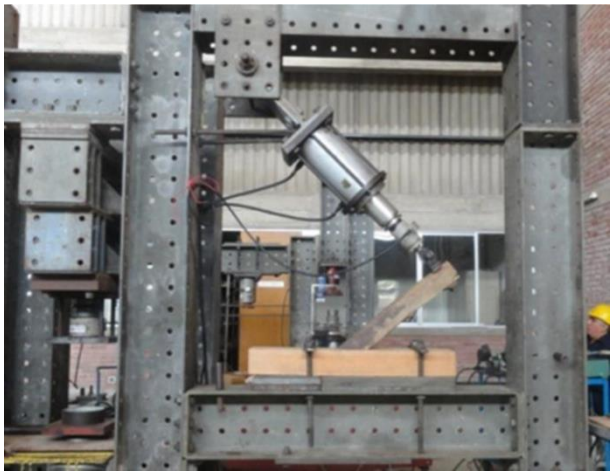
Laboratory testing

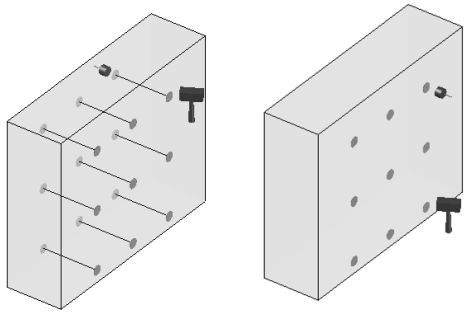
- **Material properties**
- **Behaviour of traditional structural systems**
- **Tests**
  - Adobe, brick, timber and lime mortar
  - Adobe and brick masonry
  - *Quincha* panels and timber connections
  - Traditional strengthening techniques



Laboratory tests performed by PUCP

Sonic tests

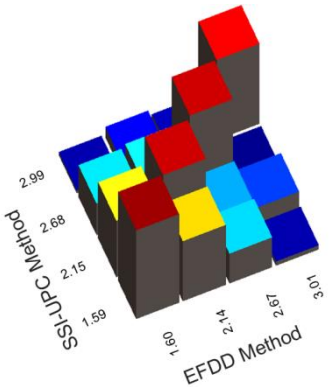
- Morphology
- Mechanical properties
- Tests
  - Direct tests
  - Indirect tests

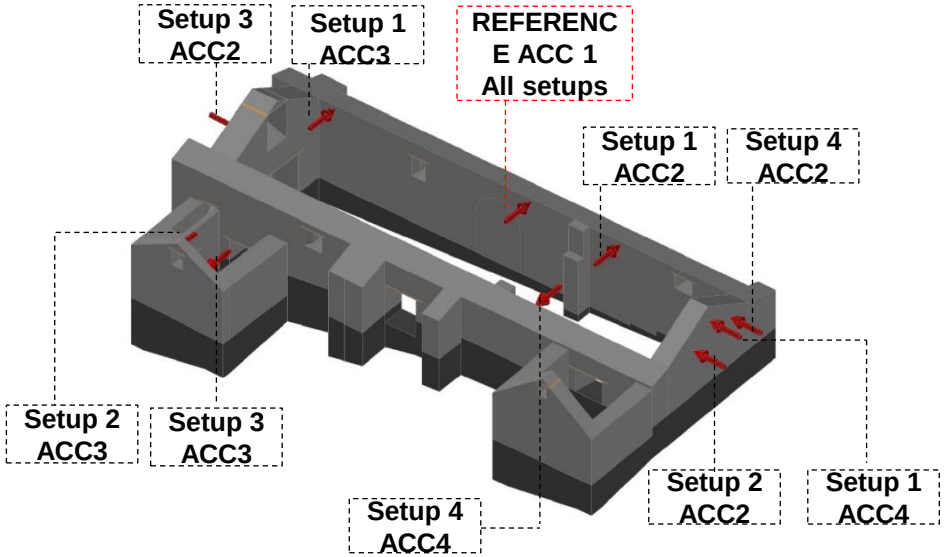


Sonic tests performed by UMinho

Dynamic identification tests

- Dynamic characteristics
- Calibration of the numerical models
- Test
  - Output-only (or ambient vibration) technique during service conditions



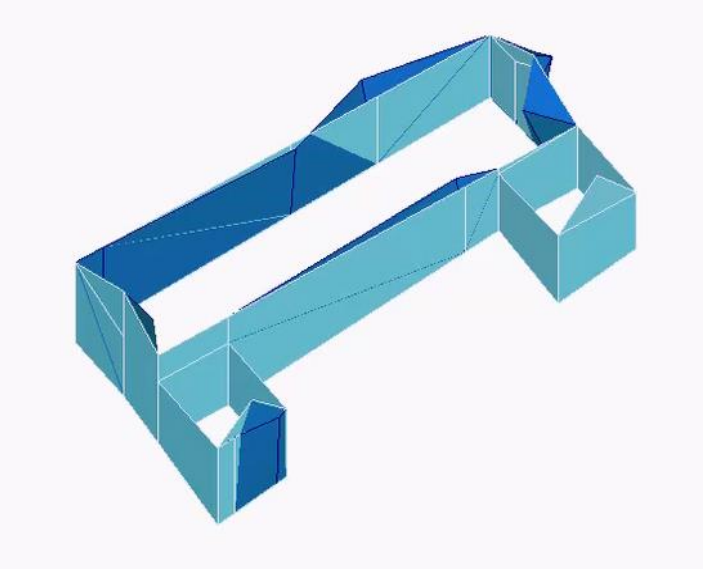


Dynamic identification tests performed by UMinho

Dynamic identification tests

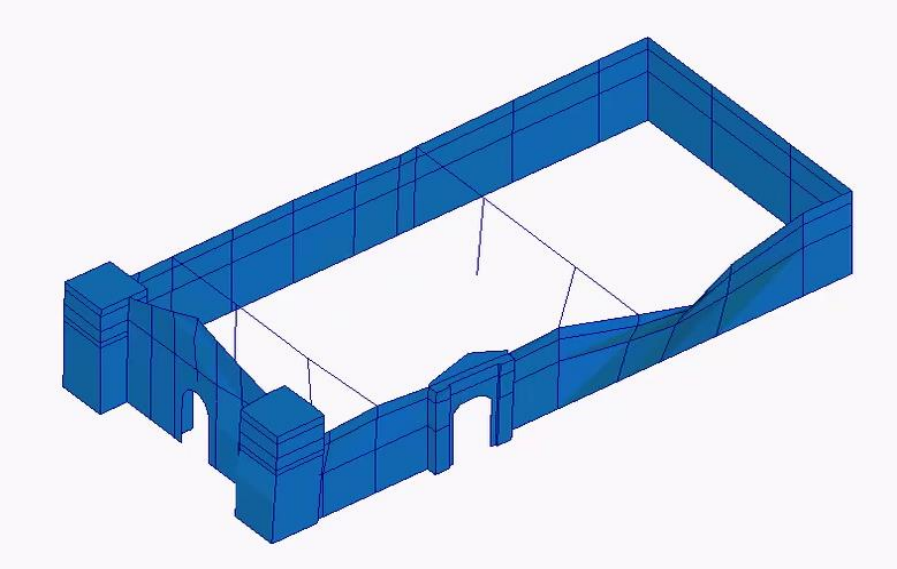
❑ Church of Kuño Tambo

- Poor connection at the corners
- Ineffectiveness of the existing tie beams



❑ Ica Cathedral

- Poor connection between the masonry and timber substructures



Finite element modelling and structural analysis

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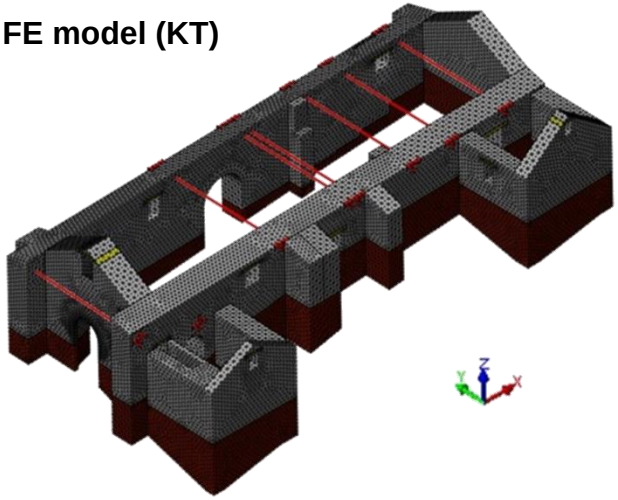
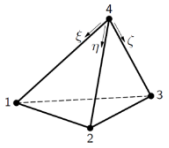
Finite Element (FE) modelling

- 3D macro-modeling FE approach
- Partial and global models
- Models created in Midas FX+ for DIANA software

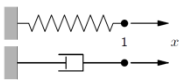
FE model (KT)



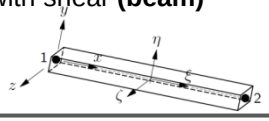
LE12L: Tetrahedron, 3sides, 4nodes **(solid)**



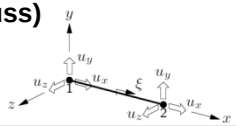
SP1TR: Translation, 1node **(spring)**



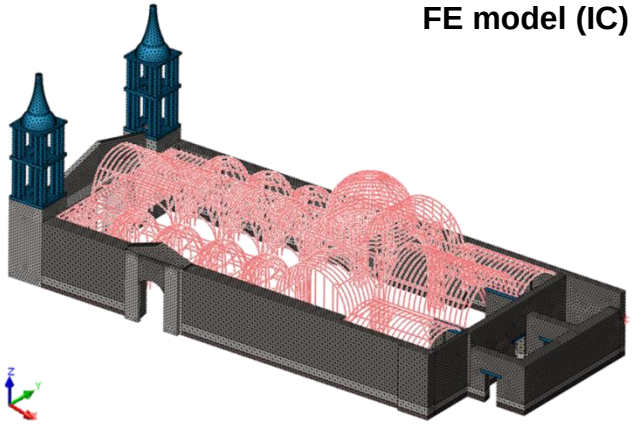
L13BE: Straight, 2nodes, with shear **(beam)**



L6TRU: Straight, 2nodes **(truss)**

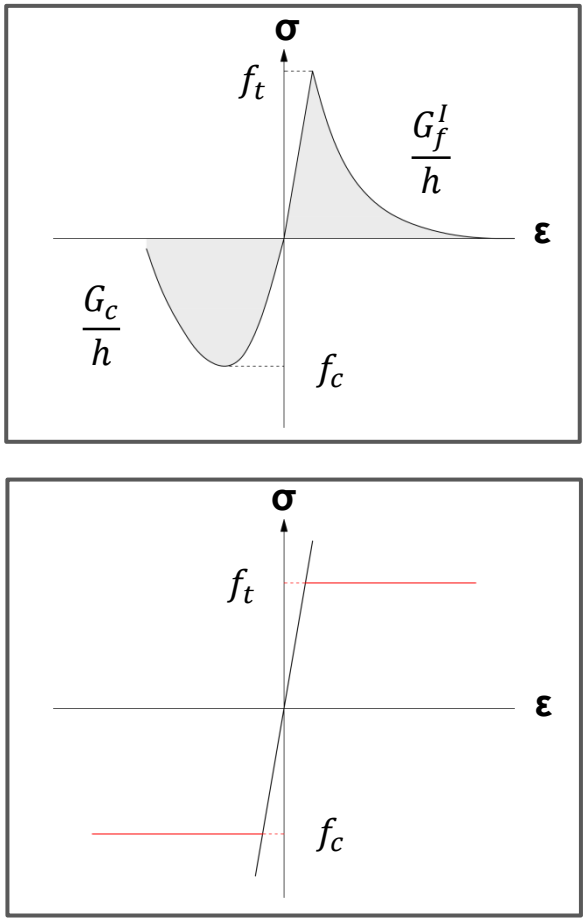


FE model (IC)



Material properties and mechanical characterization

- Use of **building standards codes** (e.g. EC6, NTC 2008, RNE 2006) and results from **tests**
- **Masonry**
  - Nonlinear behaviour (Total Strain Rotating Crack Model)
- **Timber**
  - Isotropic homogeneous and linear elastic behaviour
  - Von Mises criterion

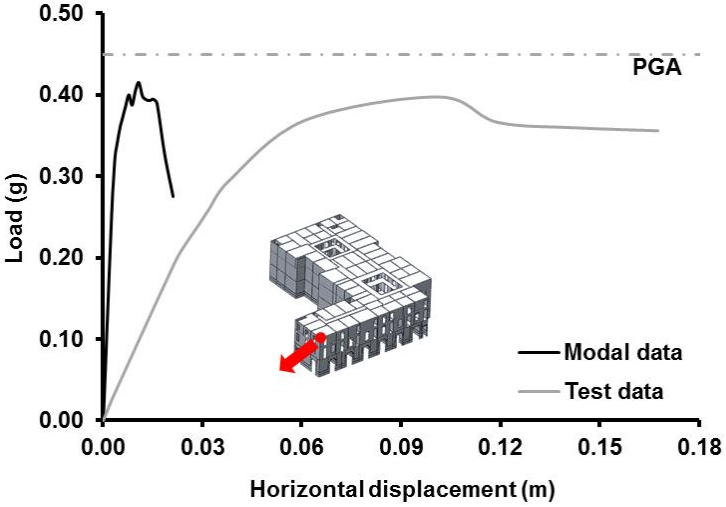


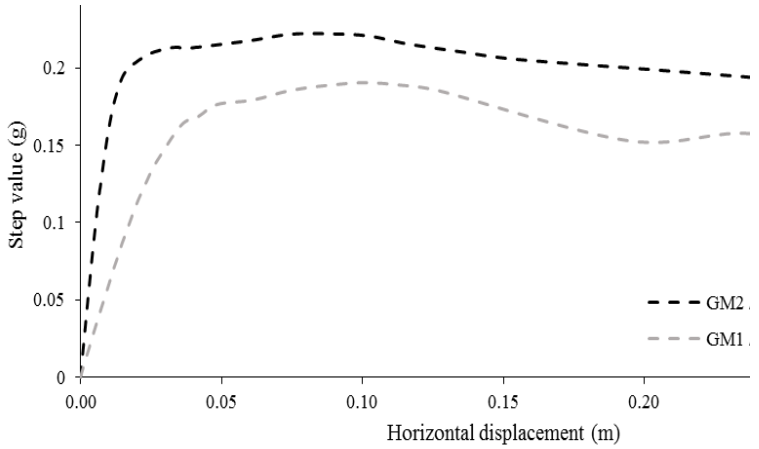
Short note on material properties (I)

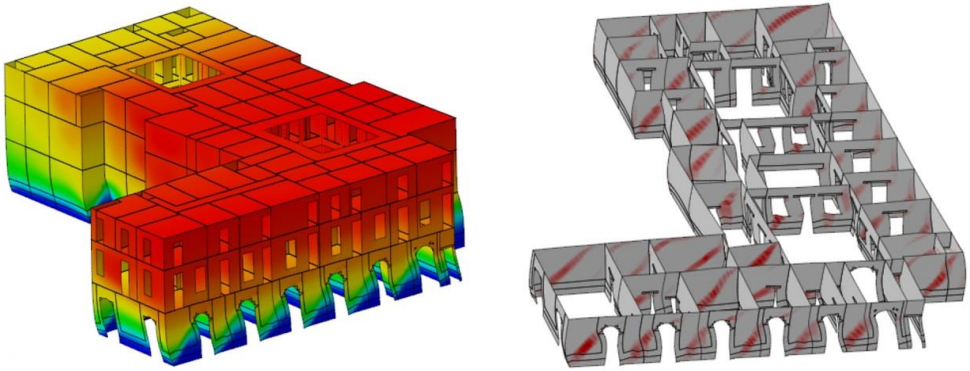
- The safety structures of historical masonry structures is usually geometry controlled, meaning that material properties tend to have a moderated influence on force based assessment

- Elastic properties were surprisingly complex to estimate and this affects to a great extent deformation response
  - Adobe masonry:
    - Tests in literature. E = 30 to 200 MPa
    - Tests with actual materials. E = 70 to 100 MPa
    - Sonic testing & dynamic identification. E = 250 to 300 MPa
  - Quincha walls:
    - Tests with actual materials. E = 50 MPa (no plaster)
    - Dynamic identification. E = 3000-4000 MPa (different levels)

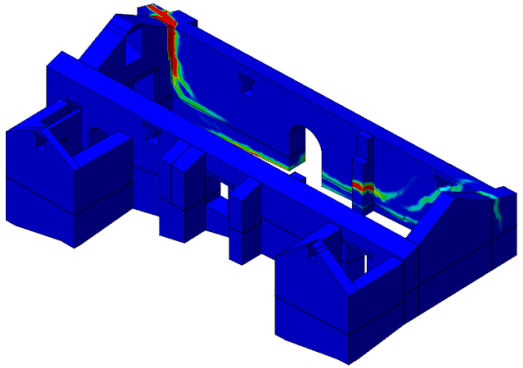
Short note on material properties (II)







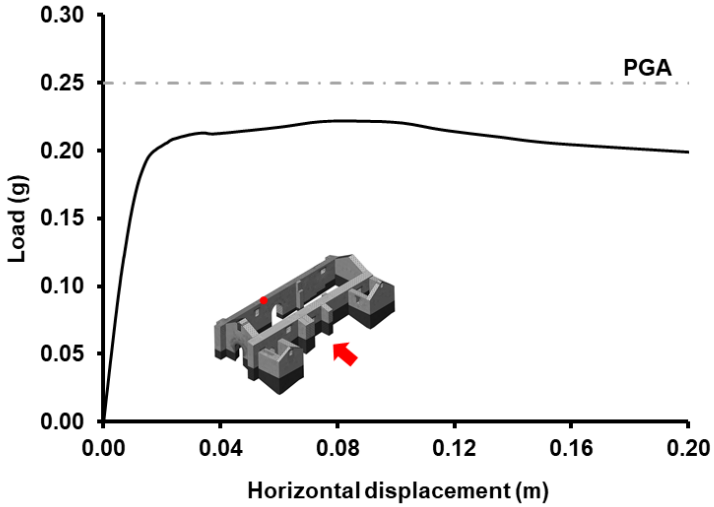
Hotel El Comercio (5% difference)

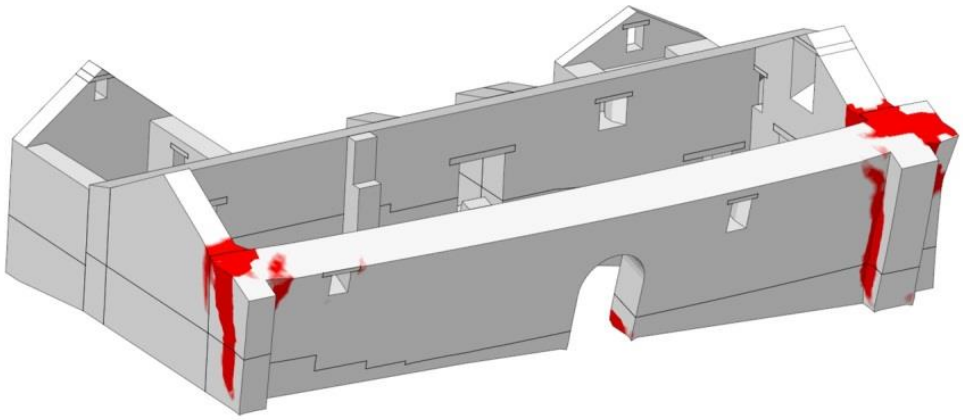


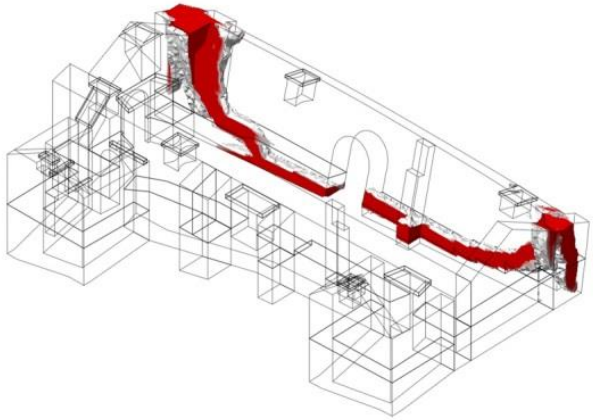
Church Kuño Tambo (15% difference)

Pushover analysis (KT)

- Minimum seismic capacity of **0.20g**, lower than the design PGA (0.25g)
- Out-of-plane overturning of the **southern lateral wall**

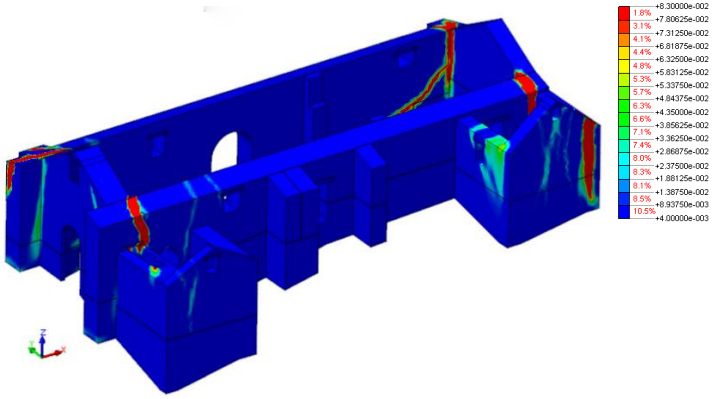




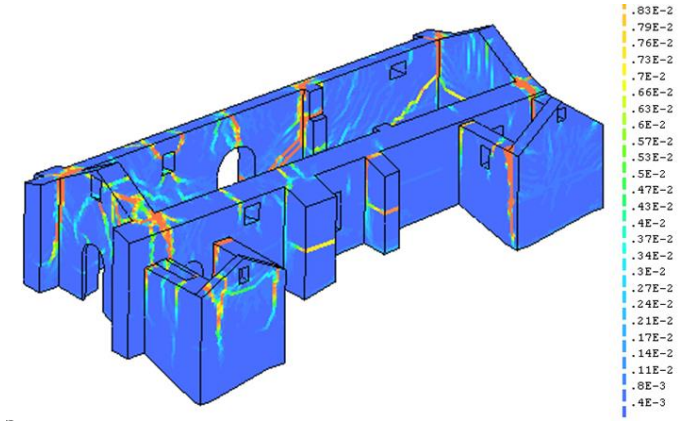


Validation of the numerical model (KT)

Existing damage



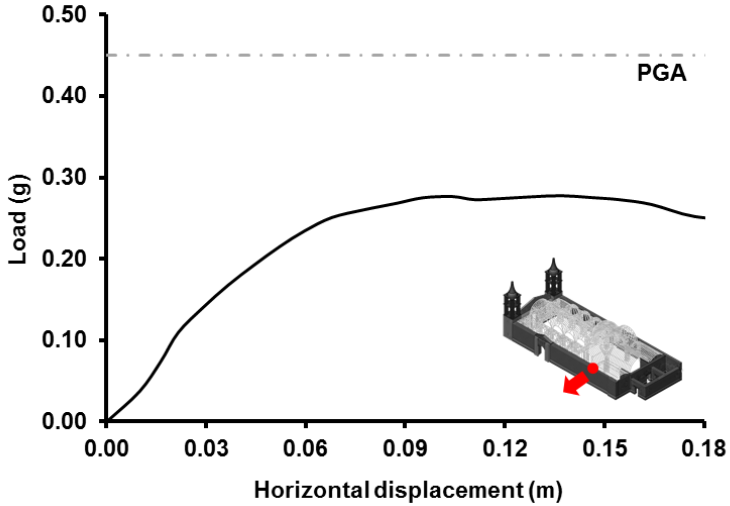
Pushover analysis - Max principal strains superposition

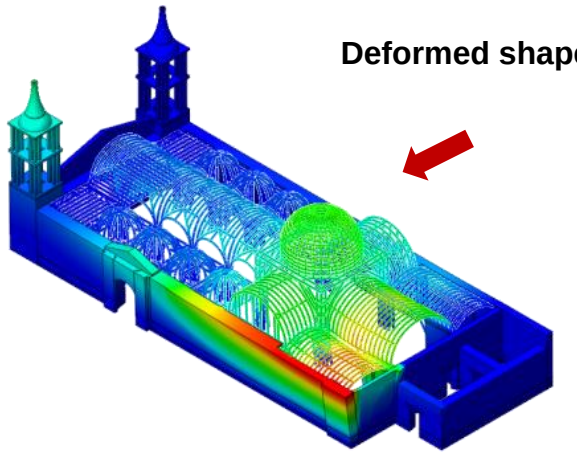


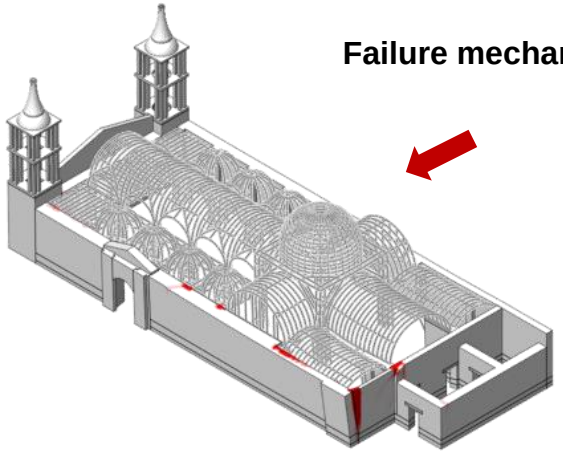
Time History analysis - Max principal strains

Pushover analysis (IC)

- Minimum seismic capacity of **0.28g**, much lower that the design PGA (0.45g)
- Out-of-plane mechanism of the **northern lateral wall**

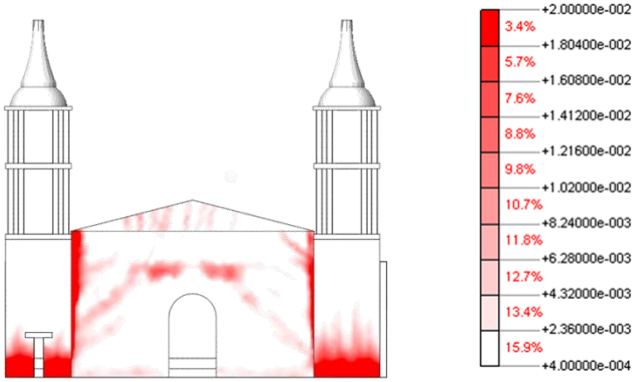




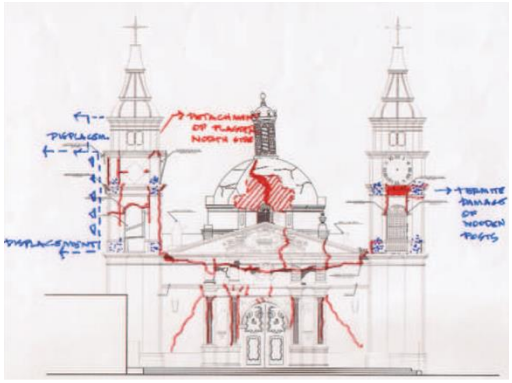


Validation of the numerical model (IC)

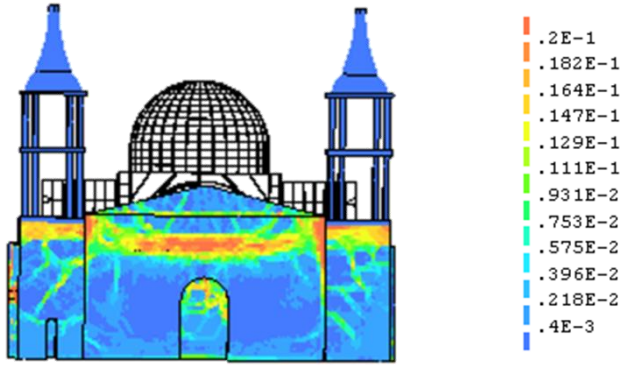
Existing Damage



Pushover Analysis - Max Principal Strains



In-situ damage survey (Cancino et al, 2015)



Time History Analysis - Max Principal Strains

Strengthening

Universidade do Minho

Philosophy and guidelines

- **Conservation principles** (ICOMOS, 2003)
  - Minimal intervention, safety, authenticity, reversibility, durability, material compatibility
  - **Guidelines** and **recommendations** in seismic building codes and standards for new earthen buildings

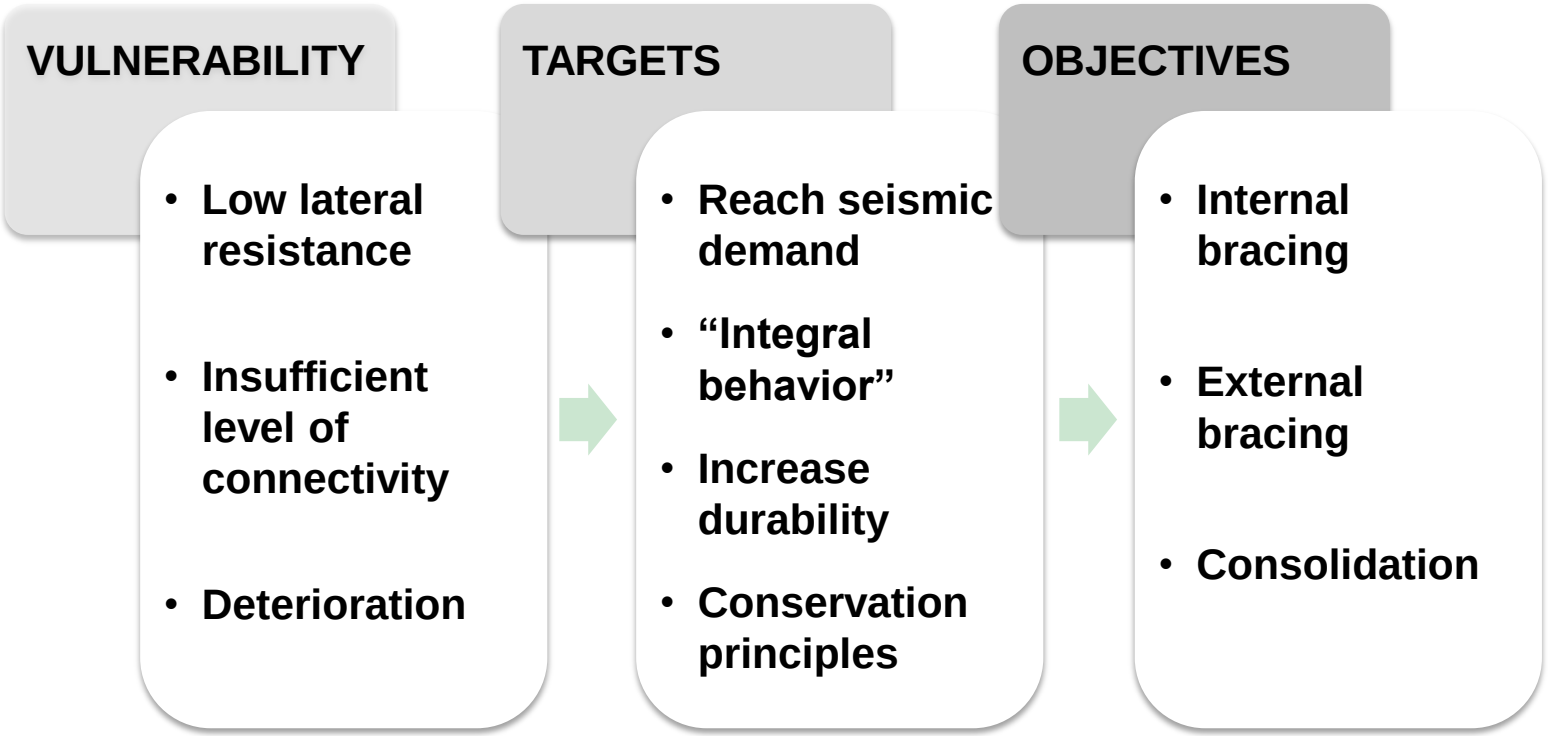
	Technical Norm	Description
PERU	Norma E.030 (2016)	Design of earthquake resistance of buildings
	RNE E.10 (2006)	Design of timber elements for structural use
	Junta del Acuerdo de Cartagena PADT- REPORT (2000)	Design manual for timber of the Andean group
	Norma E.080 (2017)	Guidelines for design of reinforced adobe structures
NEPAL	NBC 204 (1994)	Guidelines for earthquake resistant building construction in earthen buildings
INDIA	IS.13827 (1993)	Guidelines for improving earthquake resistance of earthen buildings
NEW ZEALAND	NZS 4297:1998	Engineering design of earth buildings
	NZS 4298:1998	Materials and workmanship for earth buildings

Philosophy and guidelines

Ica Cathedral		Engineering principles			
		Safety (470)	Durability (430)	Feasibility (410)	Economy (400)
Conservation principles	Min. intervention (150)	30 / 70	30 / 70	40 / 60	50 / 50
	Reversibility (160)	40 / 60	40 / 60	40 / 60	40 / 60
	Authenticity (260)	50 / 50	70 / 30	70 / 30	70 / 30
	Arch. Config. (260)	50 / 50	70 / 30	70 / 30	70 / 30
	Orig. material (130)	30 / 70	30 / 70	30 / 70	40 / 60
	Trad. Techniques (160)	40 / 60	40 / 60	40 / 60	40 / 60
	New/Orig. (170)	40 / 60	40 / 60	50 / 50	40 / 60
	Compatibility (200)	50 / 50	50 / 50	50 / 50	50 / 50

Church of Kuño Tambo		Engineering principles			
		Safety (430)	Durability (340)	Feasibility (240)	Economy (290)
Conservation principles	Min. intervention (220)	40 / 60	40 / 60	70 / 30	70 / 30
	Reversibility (220)	40 / 60	50 / 50	70 / 30	60 / 40
	Authenticity (260)	50 / 50	70 / 30	70 / 30	70 / 30
	Arch. Config. (260)	50 / 50	70 / 30	70 / 30	70 / 30
	Orig. material (280)	70 / 30	70 / 30	70 / 30	70 / 30
	Trad. Techniques (200)	30 / 70	50 / 50	70 / 30	50 / 50
	New/Orig. (210)	40 / 60	50 / 50	70 / 30	50 / 50
	Compatibility (250)	50 / 50	60 / 40	40 / 60	70 / 30

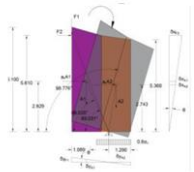
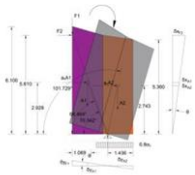
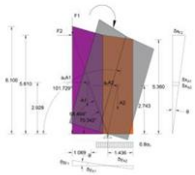
Methodology

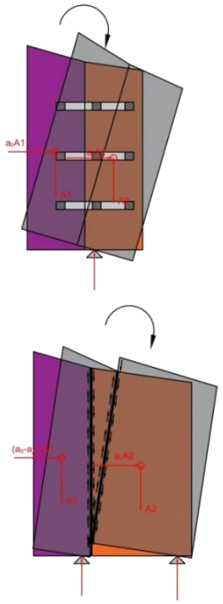


Strengthening techniques

❑ Buttresses

- To address out-of-plane mechanisms of **large span walls**
- Design with **simple analysis tools** (Limit Analysis)
- **Proper connection** between the existing earthen walls

Design proposal	Kinematic mechanism	DLS	ULS	Displacement control	a_o^*
2 Buttresses		✓	✓	✓	0.28g
3 Buttresses		✓	✓	✓	0.32g
4 Buttresses in full height		✓	✓	✓	0.37g



Design of buttresses (KT)

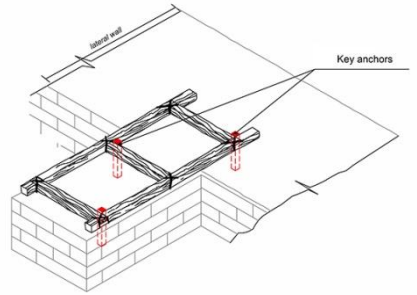
Strengthening techniques

- **Bracing elements** (*corner keys, horizontal keys, bond beams and anchored tie beams*)
  - To improve the connection between **walls, wall-to-floor** and **wall-to-roof connections**
  - Located at **various levels,** involving mostly the upper parts
  - **Confinement in masonry** and **friction** or **shear action**

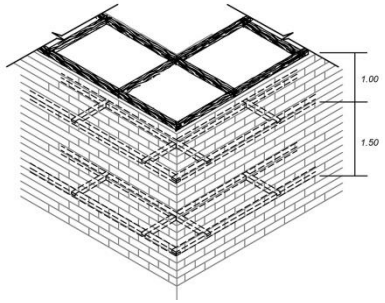
Experimental results on pull-out tests from PUCP

Strengthening techniques

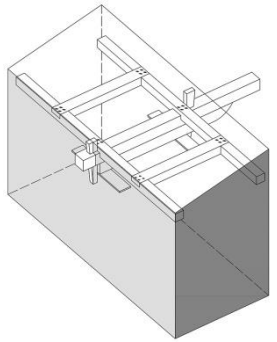
❑ Bracing elements (KT)



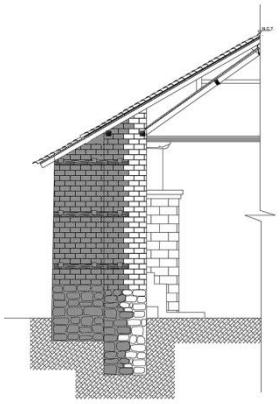
Horizontal timber key between buttress and adjoining wall. Vertical key anchors to enhance connectivity



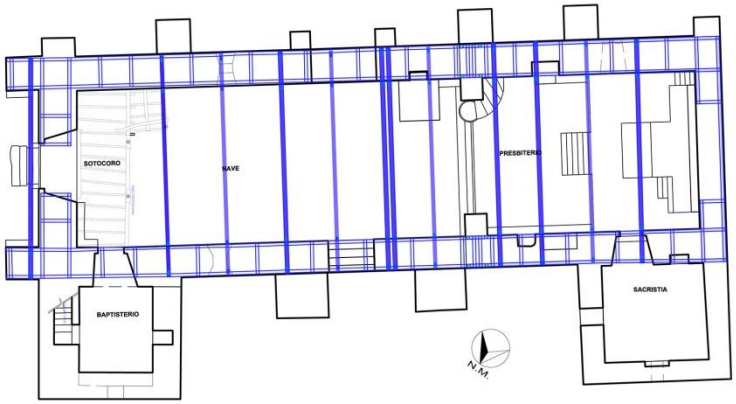
Timber embedded corner keys in elevation. Continuous bond beam at top



Bond beam, tie beam and vertical timber anchors

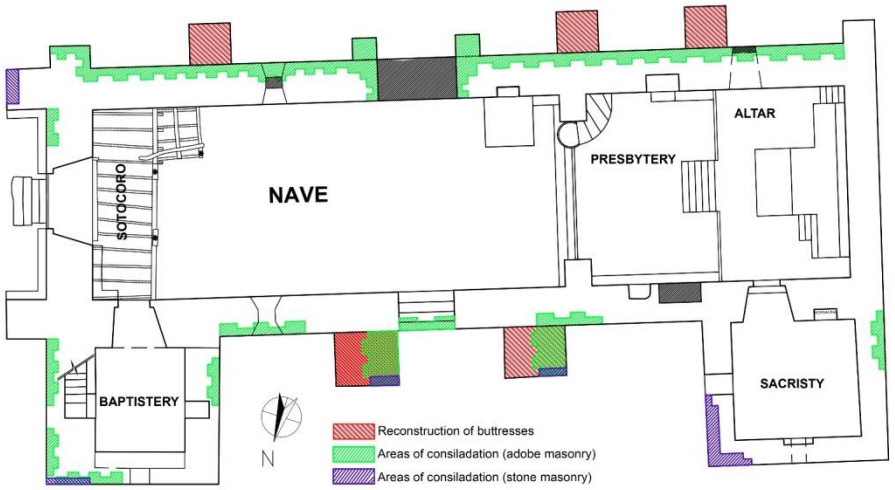


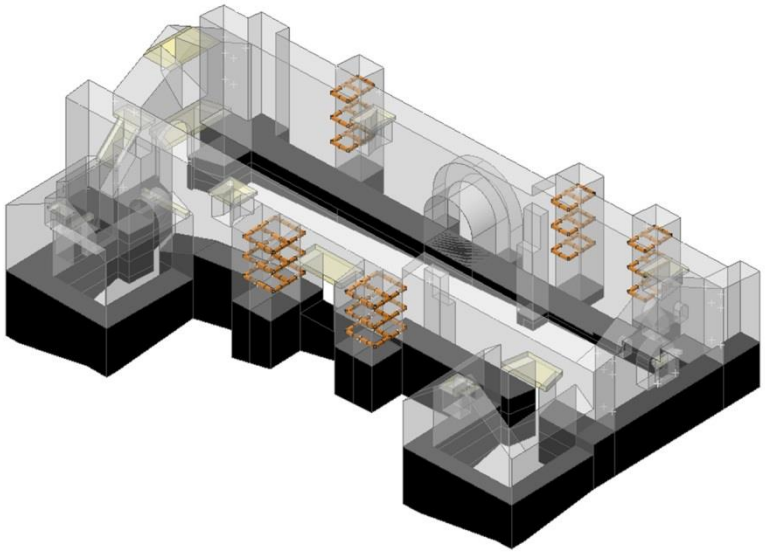
New buttress with horizontal timber keys and interlocking, and geo-mesh, lower part of stabilized adobe (replaced by brick masonry during execution)

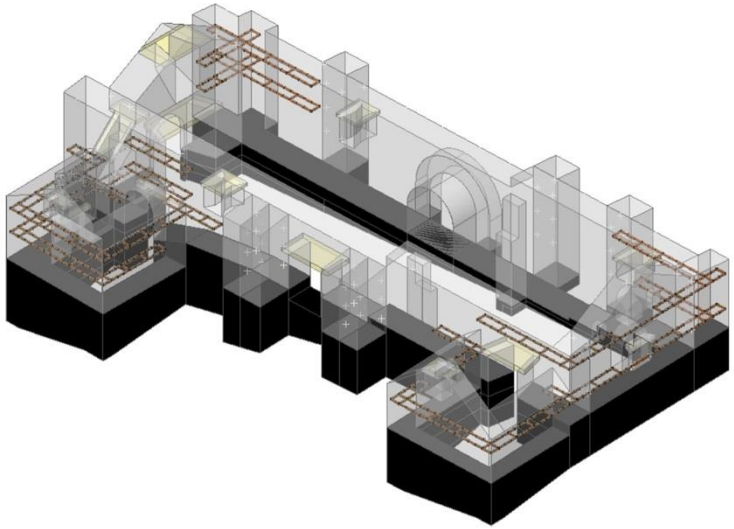


Bond-beam at top eaves. Configuration with two longitudinal timber beams and transversal timber blockers. Connection with tie beams

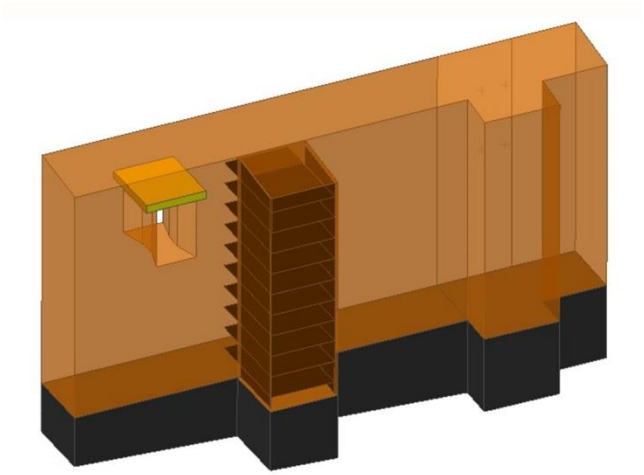
Kuño Tambo (I)

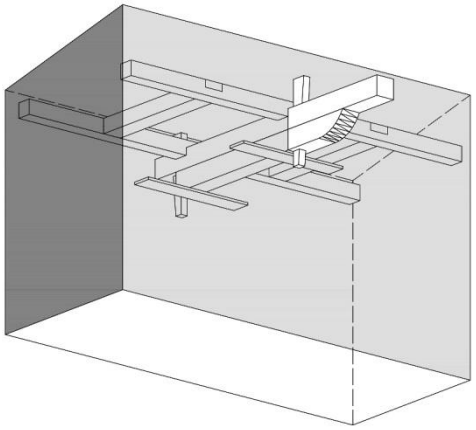

ALTAR
PRESBYTERY
NAVE
SOTOCORO
BAPTISTERY
SACRISTY
N
Reconstruction of buttresses
Areas of consiladation (adobe masonry)
Areas of consiladation (stone masonry)

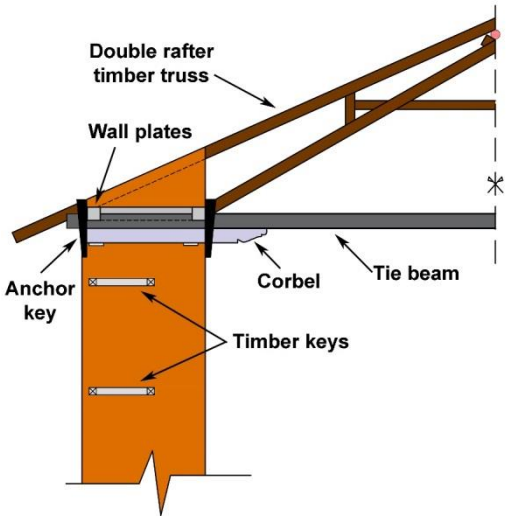




Kuño Tambo (II)

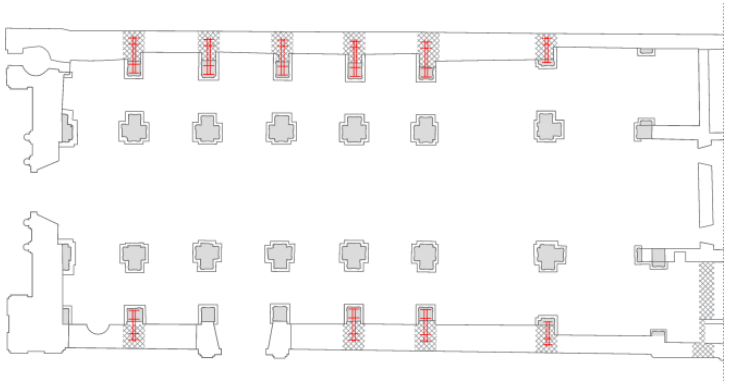




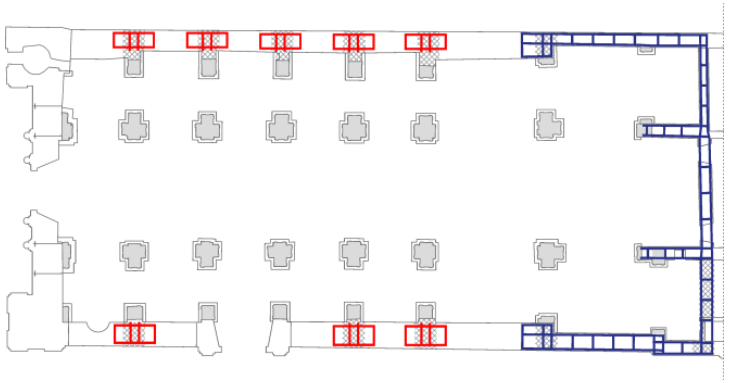


Strengthening techniques

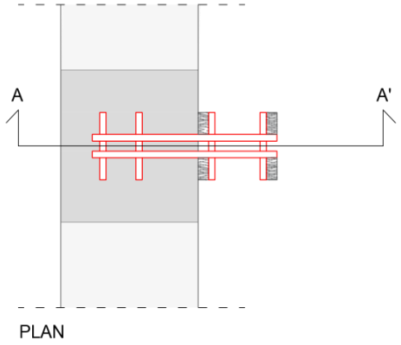
❑ Bracing elements (IC)

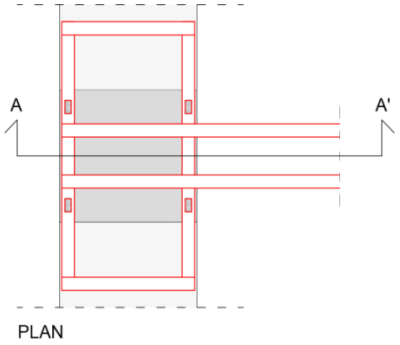


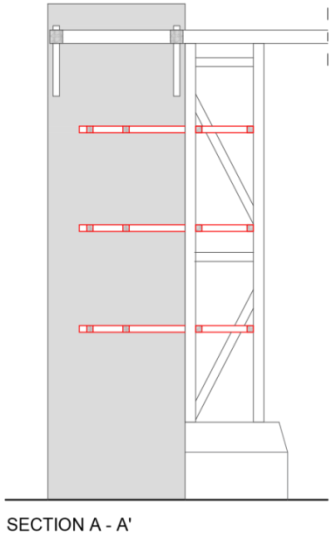
Timber anchoring system at the lower levels

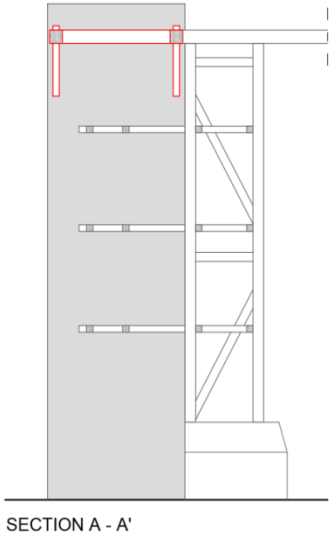


Timber anchoring system at the upper level



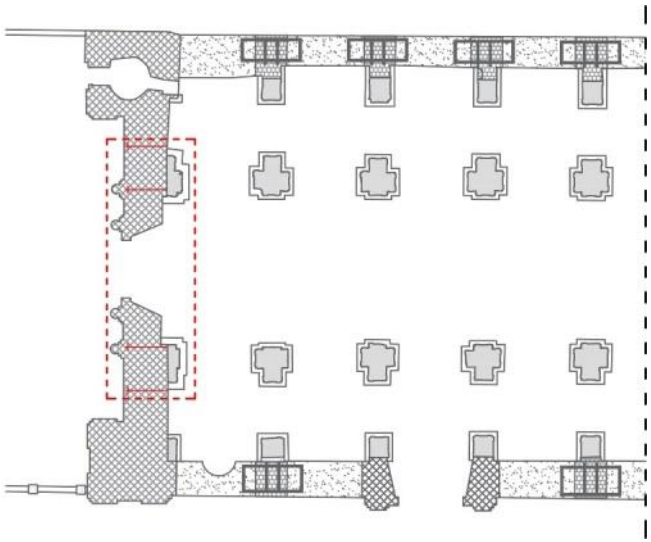


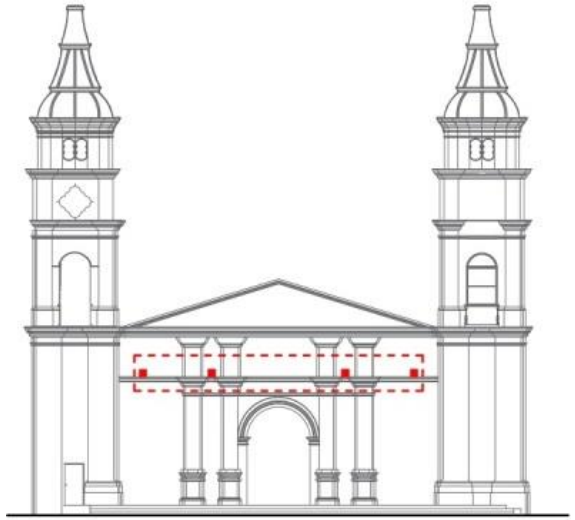




Strengthening techniques

❑ Bracing elements (IC)



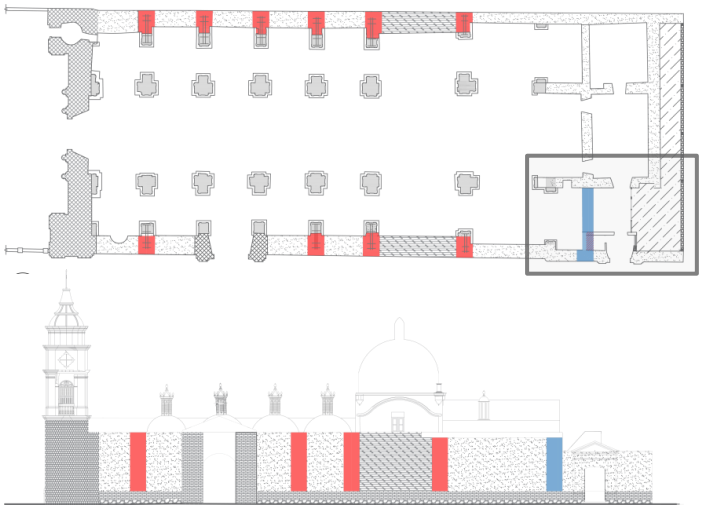


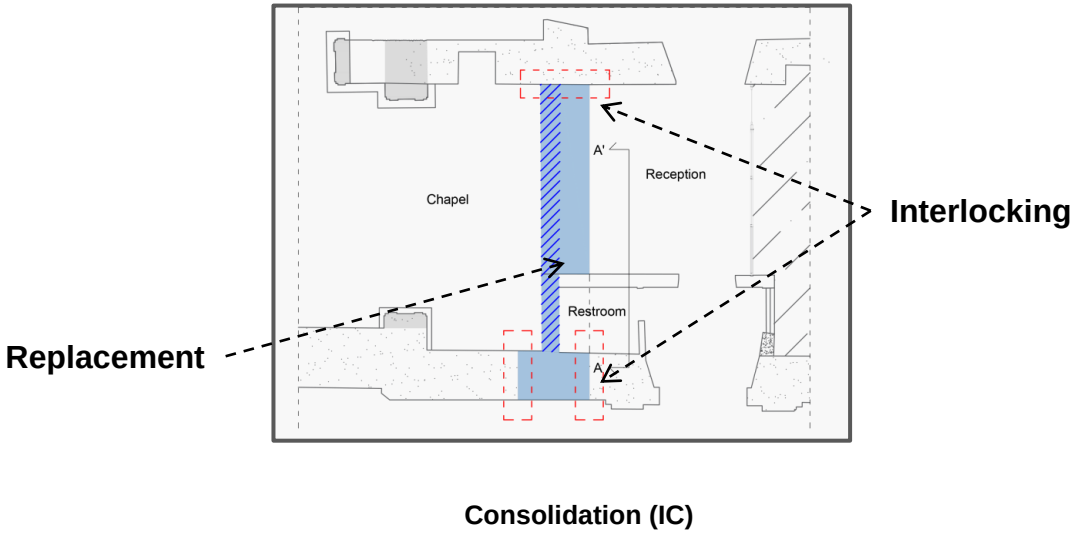
Steel anchoring system at the main façade

Strengthening techniques

❑ Consolidation

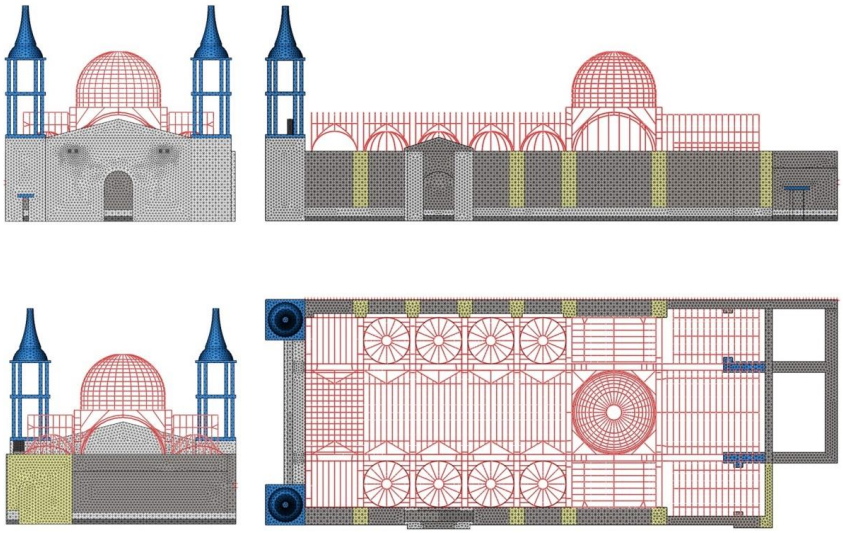
- To enhance **integrity** and to ensure **limited long-term deterioration**
- Replacement of selected parts, **as limited as possible**
- **Interlocking** between old and new masonry

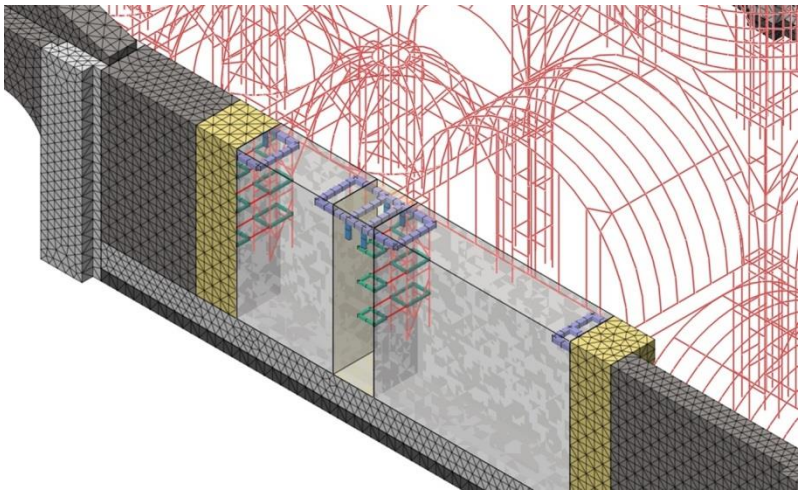


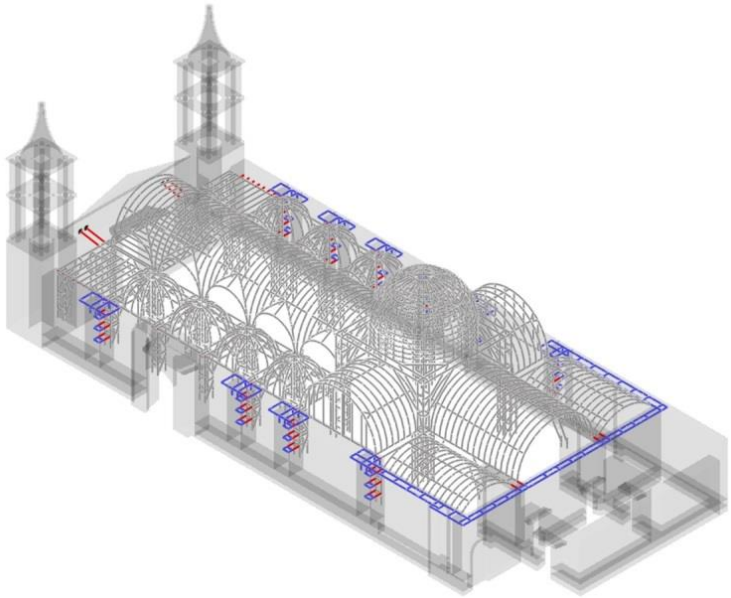


Consolidation (IC)

Ica Cathedral

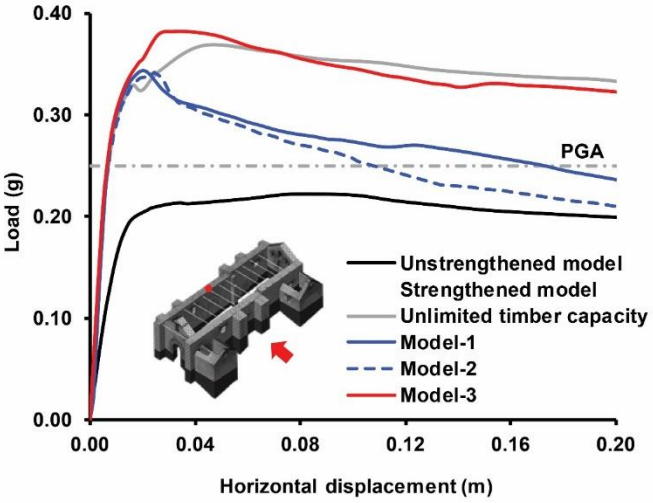


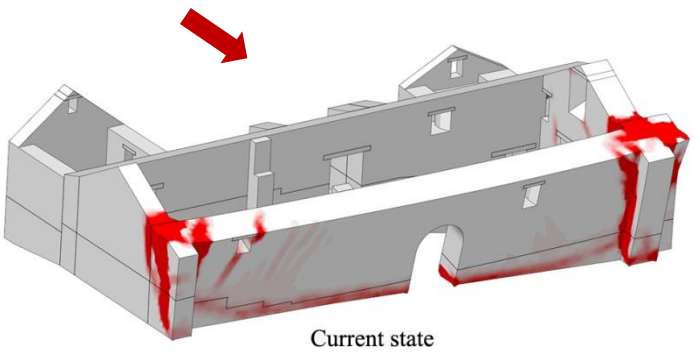


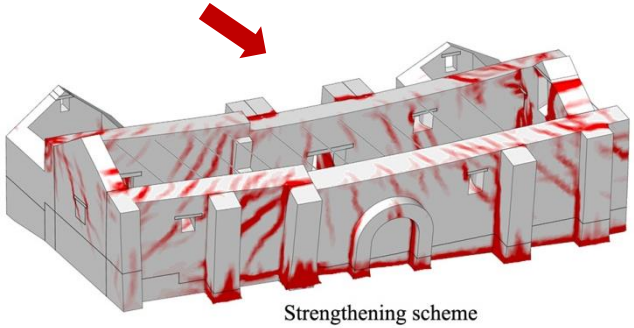


Pushover analysis (KT)

- 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



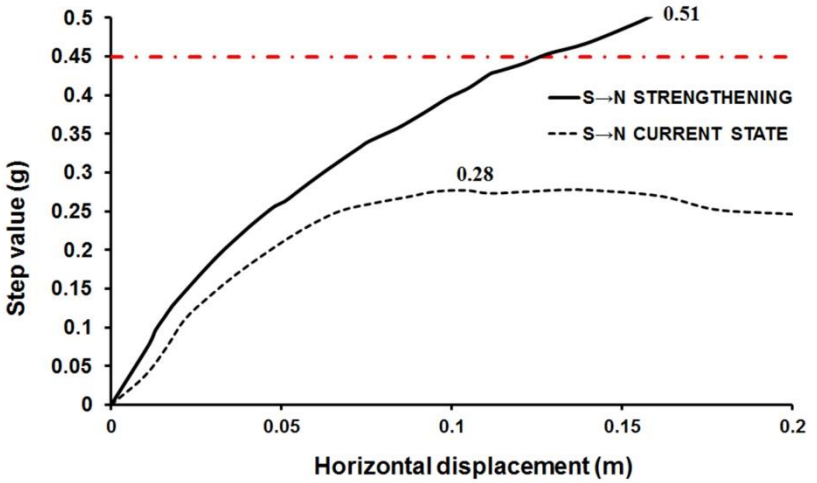


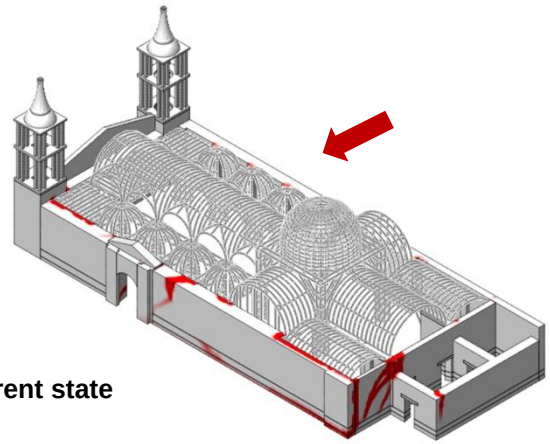


Failure mechanism in terms of tensile strains

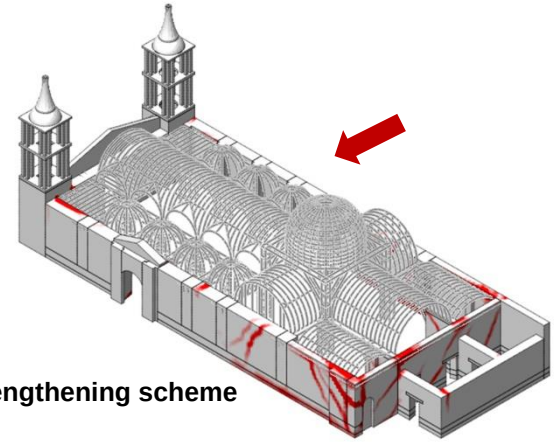
Pushover analysis (IC)

- 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





Current state

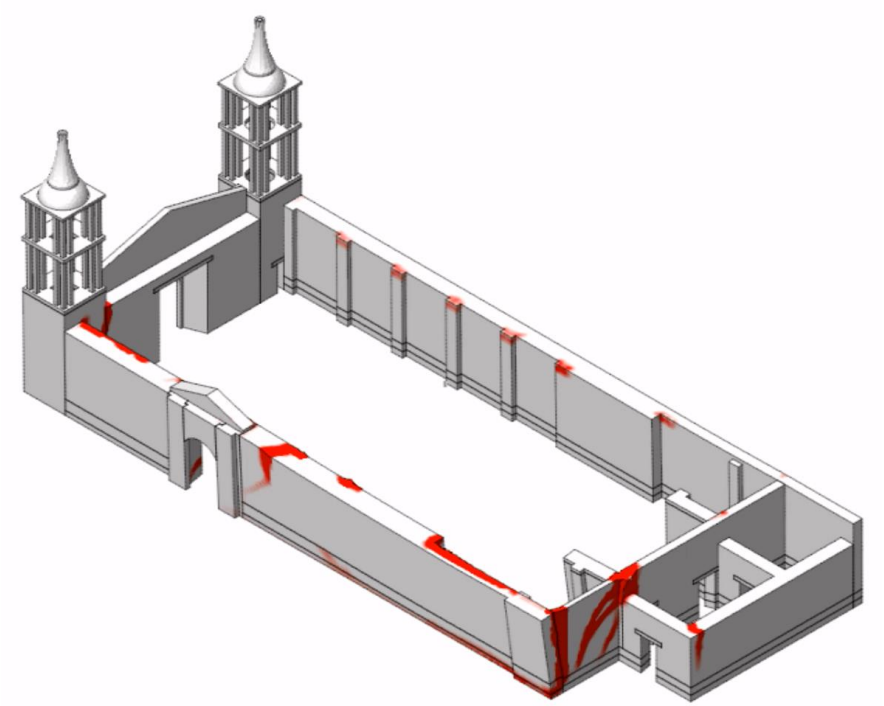


Strengthening scheme

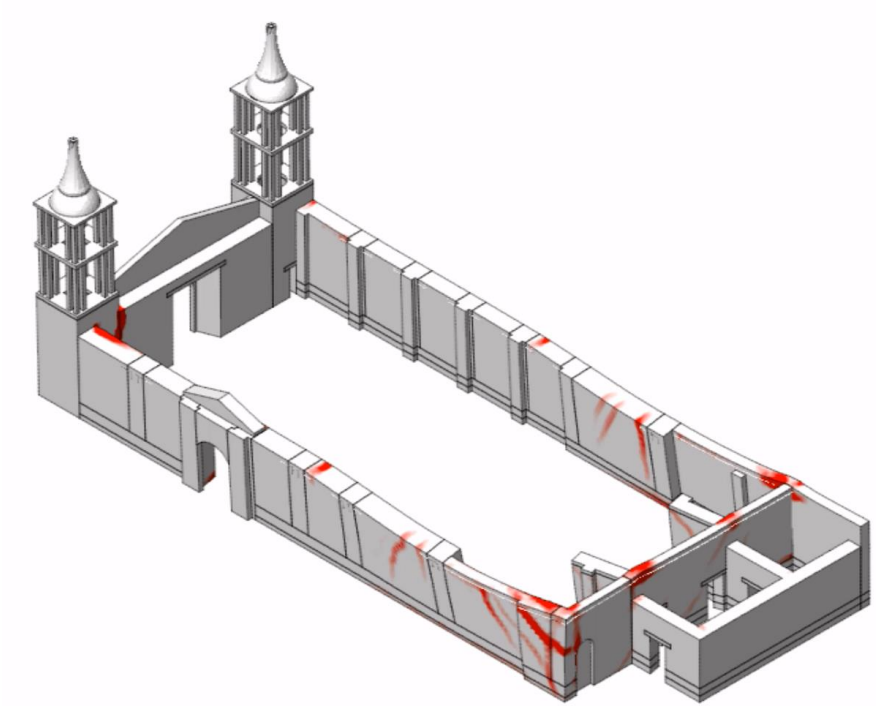
Failure mechanism in terms of tensile strains

Pushover analysis (IC)

Non-strengthened



Strengthened



Conclusions

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Conclusions

- Out-of-plane failure of masonry is a critical issue for historic structures. Remains a challenge under dynamics but our predictions seem conservative
- Adequate structural analysis methods are available for existing cultural heritage buildings, allowing reasonable predictions of safety and providing assistance in designing strengthening measures
- Based on recommendations from national building codes, conservation principles and local practices, innovative traditional strengthening techniques can improve the integrity of earthen and masonry structures
- The results obtained for KT and IC after strengthening show:
  - An improved global seismic behaviour of the structures
  - Compliance with seismic local demand

Conclusions

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Technologies for Seismic Retrofitting and Strengthening of Earthen and Masonry Structures: Assessment and Application

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