PROJECT COORDINATOR: UNIVERSITÀ DEGLI STUDI DI PADOVA

ANALYTICAL AND LABORATORY MODELS AND CONNECTIONS BETWEEN WALLS

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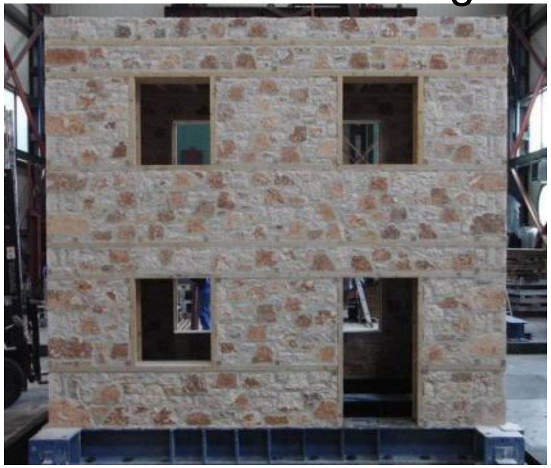
Research Rationale and Impact

Experimental campaigns carried out within Work Package 6 aim to:

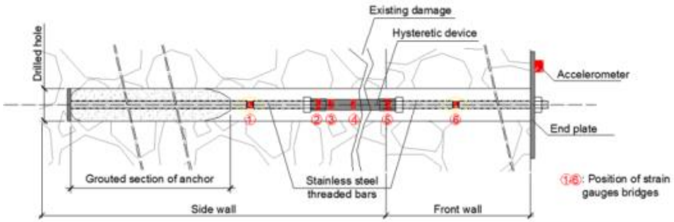
- Address the lack of standardised procedures for the experimental validation of unreinforced and strengthened connections;
- Provide end users with clear indications of how to design connection strengthening and where to source parameters required in the process;
- Assess a set of innovative techniques relying on ductility and energy dissipation;
- Tackle the lack of information regarding:

Less studied historic materials, such as earthen materials

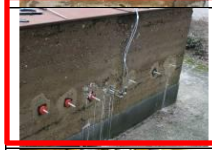
Traditional reinforcement systems, such as timber lacing



Possible use of innovative systems for joint strengthening, monitoring and early warning



Testing Programme

Type of specimen	Specimen	Materials – Description of the structure	Partner	Testing	
				Type of tests	Strengthening
Connection interface = 1 structural element + strengthening		English-bond brickwork masonry	UBATH/ CINTEC	Monotonic pull-out	Metallic grouted anchors w/o *dissipative anchoring devices*
		Earth block masonry/ rammed earth/ cob wall panels	BAM	Monotonic pull-out	GFRP/metallic grouted anchors
		Rubble stone masonry panels	UMINHO/ MONUMENTA	Monotonic pull-out	Grouted metallic anchors
Whole connection = 2 structural elements + strengthening		T-shaped double-bond brickwork masonry	UBATH/ CINTEC	Pseudo-static cyclic	Metallic grouted anchors w/o *dissipative anchoring devices*
		Timber carpentry joint	ITAM	Dynamic cyclic	Various (e.g. carbon plates, nails, *high-friction plates*, oak plates, pin)
		Rubble stone masonry panels and timber beams	UMINHO/ MONUMENTA	Monotonic pull-out	Metallic L profile bolted to beam and anchored to wall + *ductile anchor*
Whole structure		Three-leaf stone masonry walls with horizontal timber structures	NTUA	Recorded signals on shaking table	Timber-lacing

Test Results: Examples

ANCHOR PINS IN EARTHEN MATERIALS

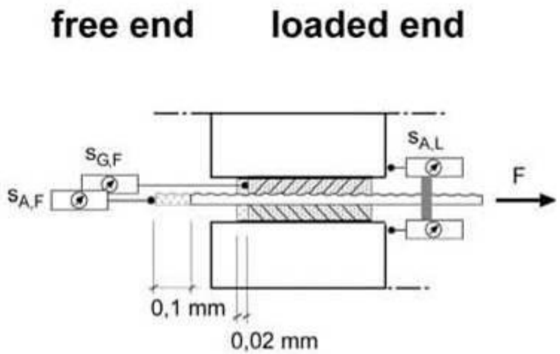
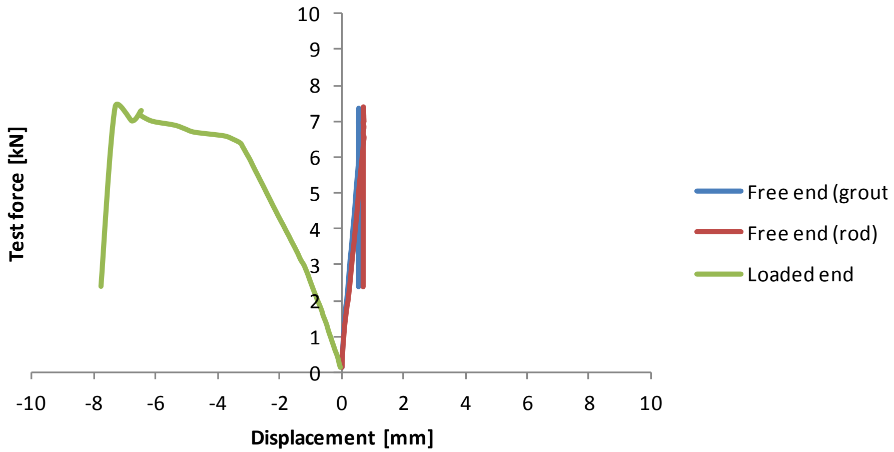


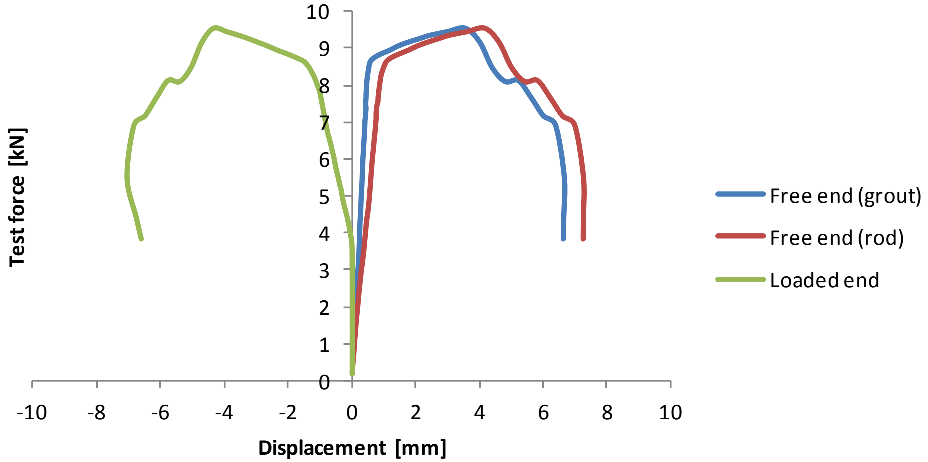
Diagram of tie rod and test configuration (Gigla, 2010)

Failure modes and bond strength values are identified by tests.

The use of nuts placed along the anchor rod improves the performance of anchors.



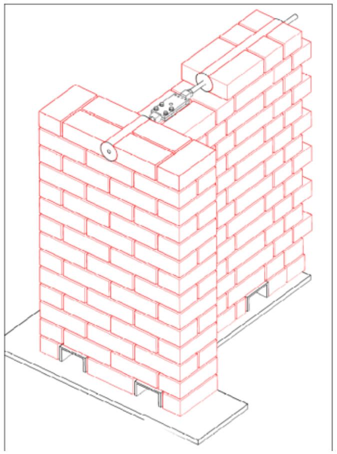
Cob samples with GFRP rods without nuts: failure at the intersection between injected grout plug and rod.

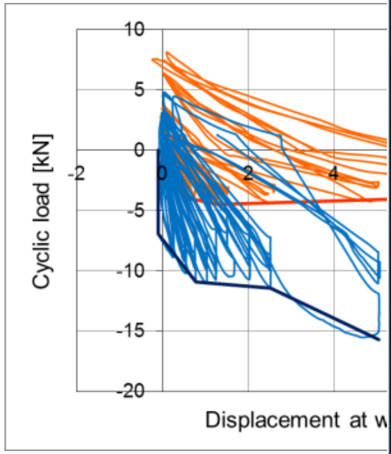


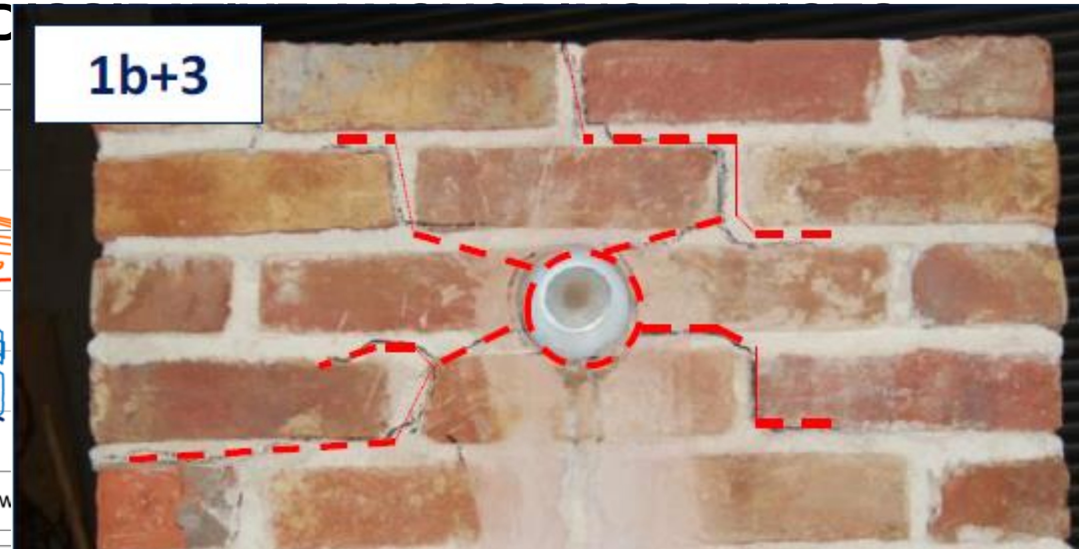
Cob samples with GFRP rods with nuts: combined failure of injected grout plug and of the intersection between injected grout plug and borehole surface.

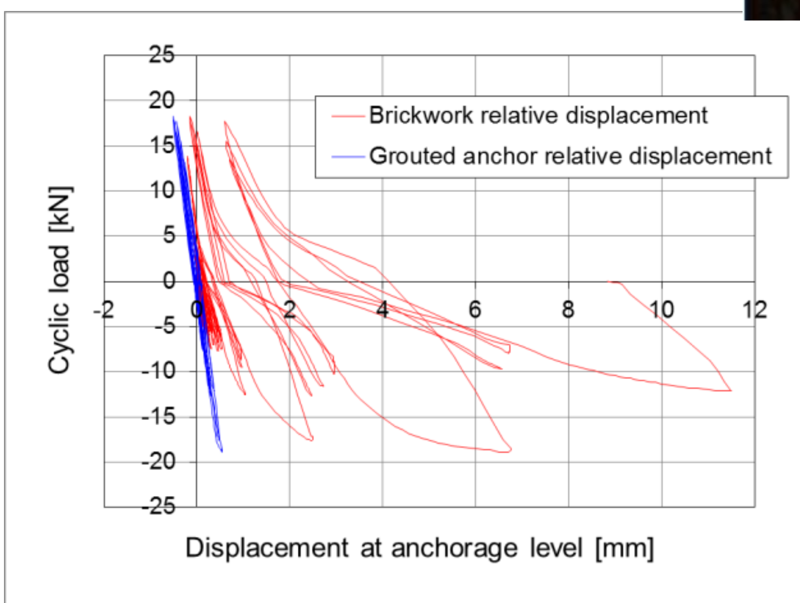
Test Results: Examples

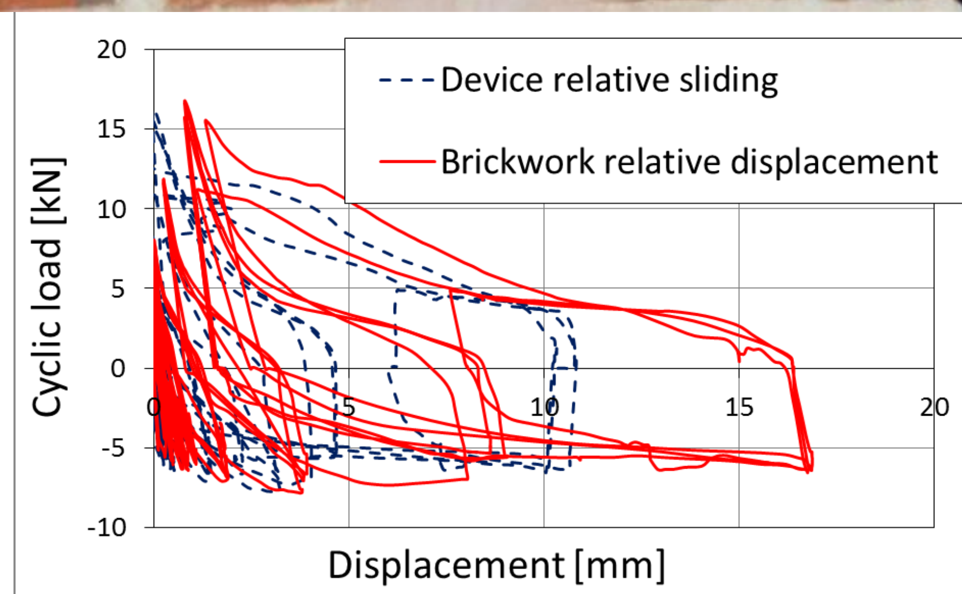
GROUTED ANCHORS AND D









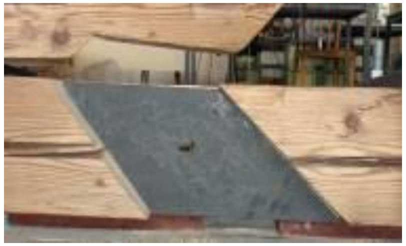


Test Results: Examples

STRENGTHENING OF ROOF HALVED DOVETAIL JOINTS

Unreinforced

Brake plates

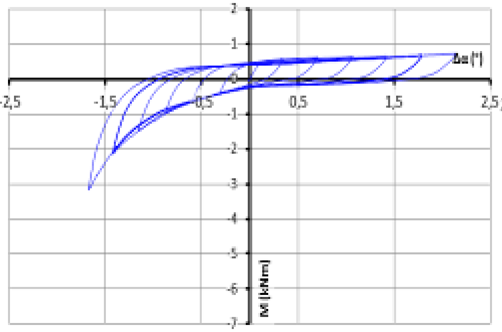


Steel screw bolts

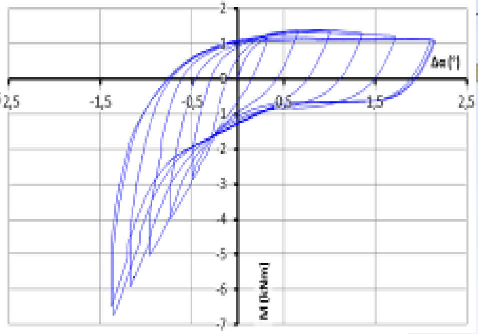
Steel nails

Sample reinforced by oak plates

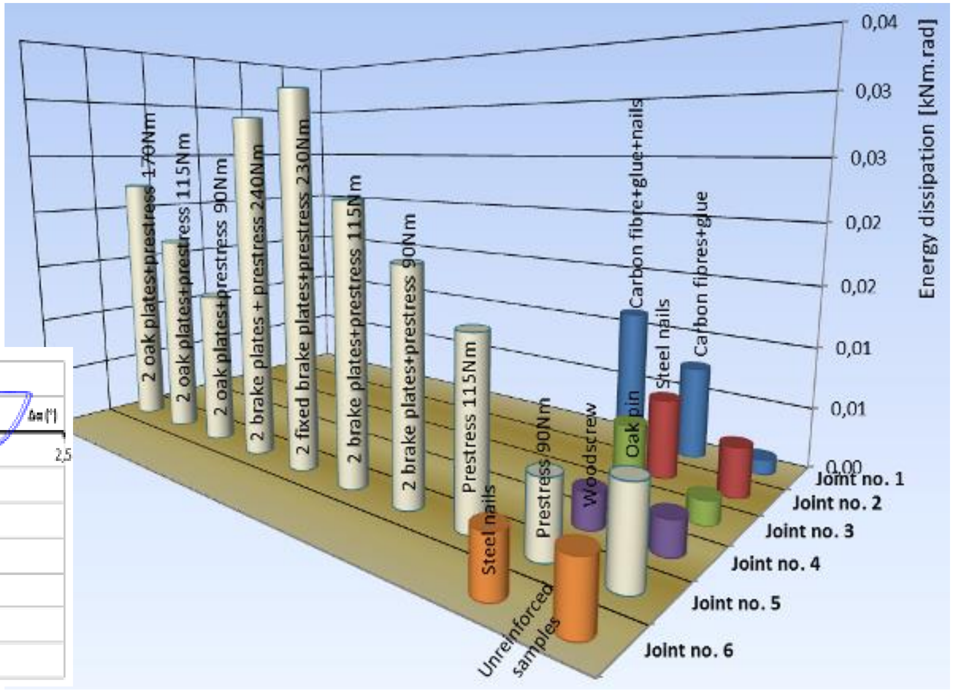
Prestress=90Nm



230Nm



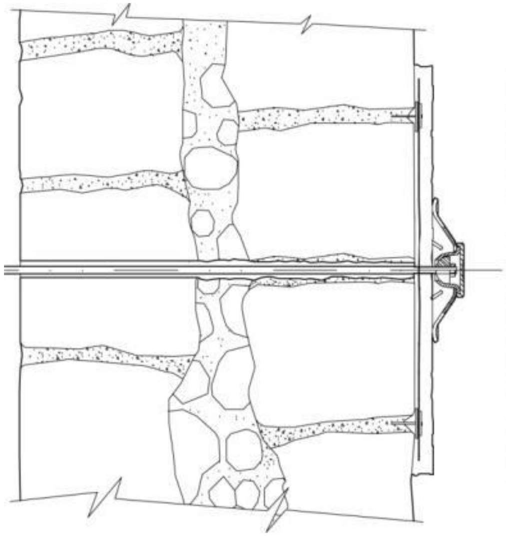
Several strengthening systems have been investigated. The most effective in terms of energy dissipation is brake plates inserted within the joint and controlled by a bolt that controls the friction developed by the assembly.

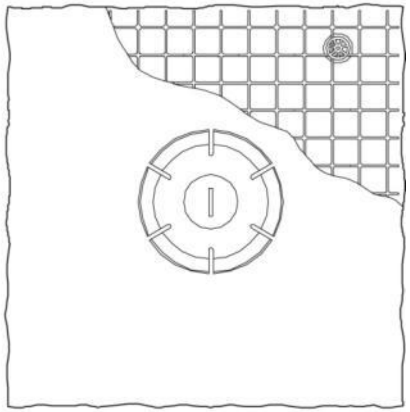


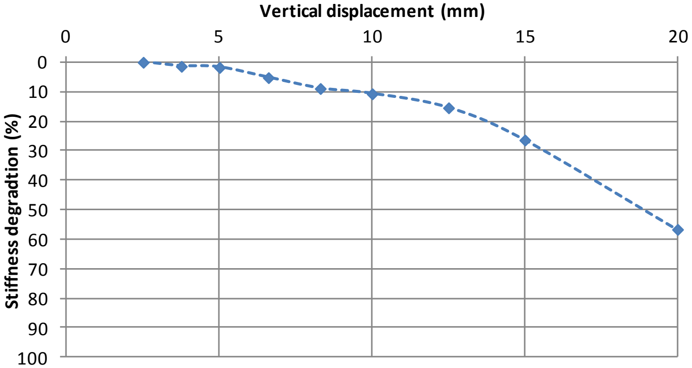
Test Results: Examples

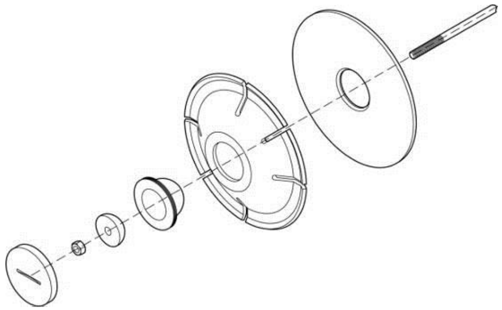
DUCTILE ANCHORS

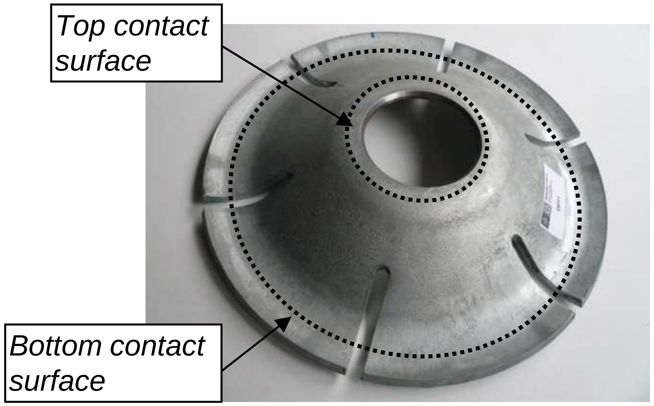
Specially designed plates provide extra ductility to the strengthening so that cracking in weak parent material can be avoided.

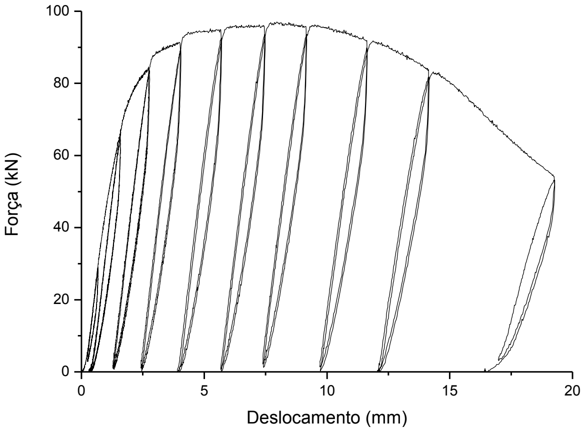












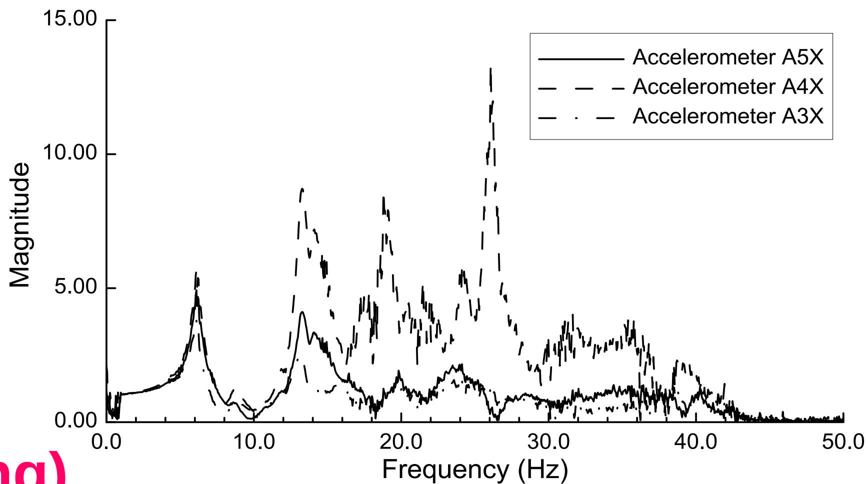
Test Results: Examples

TIMBER LACING OF DOUBLE-LEAF MASONRY STRUCTURE

Timber lacing improves the seismic response of masonry buildings by: reducing crack width, improving the box-like behaviour and reducing maximum displacement

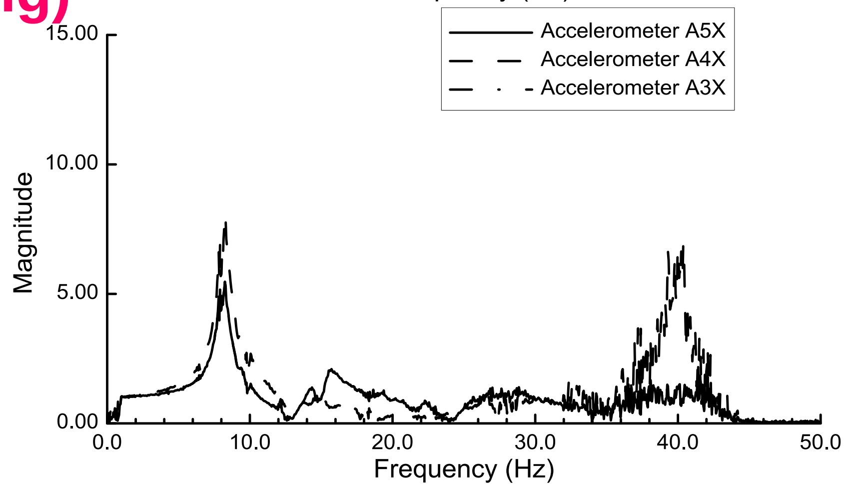
BM1 (unreinforced)

No. of test	Excitation	Direction of excitation	Base acceleration [g]	
			X	Y
1BS	Sine sweep	X	–	–
2BS	Sine sweep	Y	–	–
3BS	Kalamata	X & Y	0.04	0.037
8BS	**Kalamata**	**X & Y**	**0.29**	**0.24**



BM2 (reinforced by timber lacing)

No.of test	Excitation	Direction of excitation	Base acceleration [g]	
			X	Y
1BS	Sine sweep	X	–	–
2BS	Sine sweep	Y	–	–
3BS	Kalamata	X&Y	0.04	0.04
10BS	**Kalamata**	**X&Y**	**0.40**	**0.32**



PERFORMANCE PARAMETERS - E.G. ANCHORS

How should one dimension an anchor? What parameters does one need for the design? How are these parameters identified by tests? How do test compare with design codes and other references? How can be dissipative devices integrated in the design?

ULS:

$$F_{1U} = a_U M \leq \frac{\pi d^2}{4} f_y n = F_{2U}$$

$$F_{2U} =\leq \pi d_2 l f_b = F_3$$

$$F_{2U} \leq \sqrt{2} l \left(l + d_2 \right) \tau_k = F_3$$

DLS:

$$F_{1D} = a_D M \leq F_{2D}$$

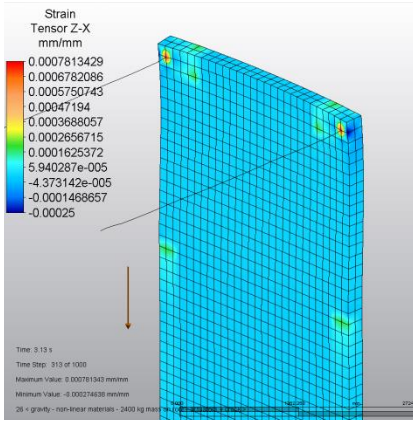
F_{2D}: device activation load (yielding of hysteretic element/sliding of friction element

Research Output and Impact

Typology of strengthening	Performance parameters	Range from experimental results	Range calculated by codes/tech. references
Grouted metallic anchors in brickwork substratum	Tensile capacity of the assembly depending on $\mathbf{f_{b\ b/p}}$: bond strength binder/parent material (N/mm^2) calculated on the cylindrical surface of the grouted socket	For tested weak brickwork masonry (f_c=3.1 MPa, f_w=0.5 MPa), calculated from tests as: $\mathbf{f_{b\ b/p}=f_b=F_{b/p\ bond}/A_{hole}}$ with $\mathbf{F_{b/p\ bond}}$ recorded load at failure and $\mathbf{A_{hole}}$ inner cylindrical surface of drilled hole: 0.26 MPa (CoV 34%)	Calculated as: $\mathbf{f_{b\ b/p}=f_{vk}=f_{vk,0}+0.4\sigma_d}$ (EN 1996-1-1: 2005) with $\mathbf{f_{vk,0}}$ initial shear strength and $\boldsymbol{\sigma_d}$ vertical load. For tested conditions it would be expected: 0.08 MPa
	Tensile capacity of assembly depending on $\mathbf{F_{yield}}$: yielding capacity of hysteretic dissipative device (kN)	33 kN (for hysteretic device size suitable to coupling with M16 threaded bar)	27.8 kN calculated as: $\mathbf{F_{yield}=f_{y,yield}A_{yield}}$ (EN 1993-1-1:2005) with $\mathbf{f_{y,yield}}$ yielding strength of steel of hysteretic element and $\mathbf{A_{yield}}$ net cross sectional area of hysteretic element
Strengthening of dovetail halved roof joint using combination of: 2 brake plates or 2 oak plates with bolt (prestressing element)	Energy dissipation calculated as area of hysteresis loops of joint (Nm·rad) and depending on: a) Coefficient of friction of plates (oak and brake plates: μ=0.4 [12, 13]) b) Bolt prestress level applied by torque (Nm) and limited by compressive strength of wood (spruce 2.0-2.5 MPa) [14]	Increase of energy dissipation in comparison with unstrengthened joint: a) Bolt with brake plates: - 180% (torque: 90 Nm) - 410% (torque 230 Nm) b) Bolt with oak plates: - 90% (torque: 90 Nm) - 240% (torque 170 Nm)	Minimum increase of energy dissipation in comparison with unstrengthened joint calculated as: $I_{min}=\mu_{plate}/\mu_{spruce}-1=100\%$ μ_{spruce} =0.2 Coefficient of friction of wood of joint (spruce; see (Leonardo da Vinci Pilot Project: *Design of Timber Structures according to EC5*)
Metallic ties with end plate at connection between rubble stone masonry and timber elements	Tensile capacity of the assembly depending on $\mathbf{f_{c/p}}$, strength of parent material to punching failure (N/mm^2)	Calculated from tests as: $\mathbf{f_{c/p}=F_{cp}/A_l}$ with $\mathbf{F_{cp}}$ pull-out force and $\mathbf{A_l}$ failure surface defined as trunked cone surface, with smallest base corresponding to anchor plate, apothem inclined at 45° and height equal to wall width. 0.13MPa	Calculated as: $\mathbf{f_{c/p}=f_{vk}=f_{vk,0}+0.4\sigma_d}$ (EN 1996-1-1: 2005) with $\mathbf{f_{vk,0}}$ initial shear strength and $\boldsymbol{\sigma_d}$ vertical load. For tested conditions **(**$f_{vk,0}$=0.1 MPa, σ_d=0.2 MPa) it would be expected: 0.18 MPa

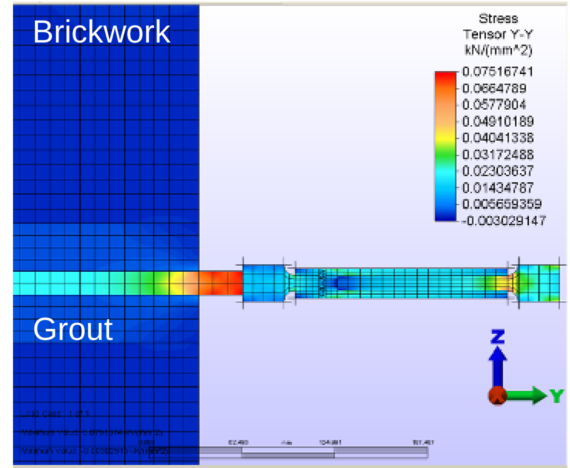
Further on-going work on dissipative devices

COMPUTATIONAL VALIDATION



E.g. Standard anchor in masonry substratum

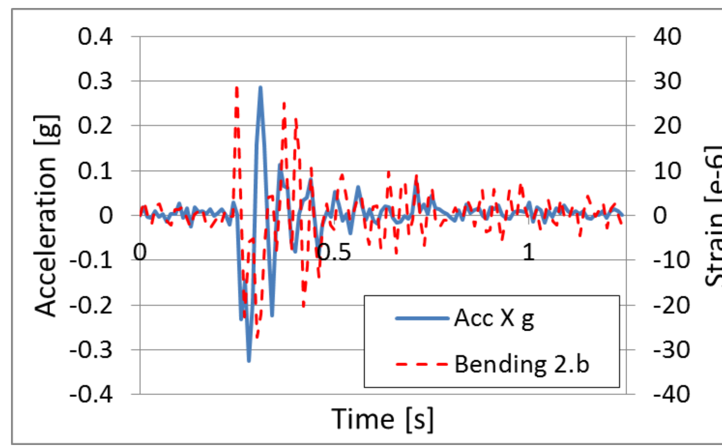
E.g. Friction anchor – stress at slip load



ON-SITE VALIDATION THROUGH MONITORING

S. Giuseppe dei Minimi, L'Aquila, Italy
Out-of-plane damage of façade as consequence of April 2009 earthquake

Position of instrumented yielding anchor



Microtremor recorded by bending gauge and accelerometer

Research Rationale and Impact

Experimental campaigns carried out within Work Package 7:

Investigation of global intervention strategies on the seismic behaviour of sub-structures, as well as scaled models of entire buildings.

WP7 constitutes the continuation of previous work packages (WP 3, WP4, WP5, WP6), which involve individual structural members and connections. Within WP7, shaking table tests are carried out on large scale subassemblies or building models.

"ELEMENT" SCALE (WP4, 5, 6) → GLOBAL SCALE (WP7)

AIM: Assess the seismic response of buildings under realistic dynamic conditions

Within WP7, the following points have been checked:

1. **Realistic input** (simulation of real earthquakes)
2. **Realistic output** (as parts of a building or as a building are subjected to seismic actions)
3. **Efficiency of interventions developed in previous WPs under dynamic conditions.**
4. **Calibration of the analytical models** (assisting the work within WP8, Guidelines for End-Users-WP10)

Testing Programme-Subassemblies

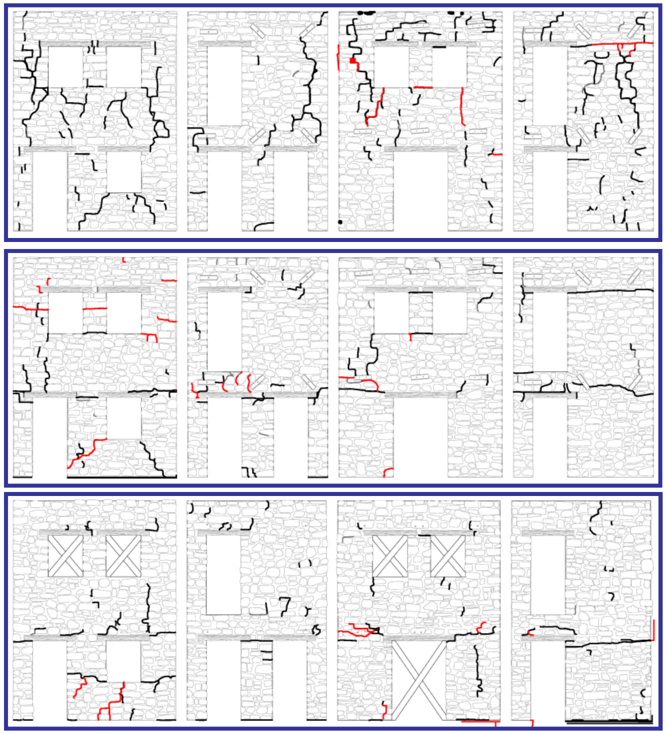
	Type of Specimen	Specimen	Materials – Description of the structure	Partner	Testing	
					Type of tests	Strengthening
1	Element		Three-leaf stone masonry	UNIPD	Shaking table tests. Out-of-plane input motion	(a) As built (b) Transverse steel ties (c) Grouting (d) Combined (b) and (c)
2	Element		Adobe	ITAM	Shaking table tests-uniaxial	Plain/reinforced walls Plain/reinforced columns
3	Subassembly		Adobe + light timber floor	BAM	Unidirectional sliding table tests	As-built
4	Subassembly		Adobe + heavy timber floor	BAM	Unidirectional sliding table tests	As-built
5	Subassembly		Adobe + light roof with stiff diaphragm	BAM, ITAM	Unidirectional sliding table tests	As-built
6	Subassembly		Three-leaf stone masonry piers + timber floor	NTUA	Shaking table tests- uniaxial	(a) As built (b) Grouting, enhancement of diaphragm action of floor
7	Subassembly		Three-leaf stone masonry piers + brick arches and cross vault	NTUA	Shaking table tests. Motion along two axes	(a) [As built] (b) Grouting, timber struts, steel ties, external vertical prestressing

Testing Programme-Building models

	Type of specimen	Specimen	Materials – Description of the structure	Partner	Testing	
					Type of tests	Strengthening
1	Model building		Three-leaf stone masonry + timber floors (double planking and steel ties)	UNIPD	Shaking table tests. Motion along two axes	(a) As-built (b) Grouting
2	Model building		Three-leaf stone masonry + timber floors (double planking and steel ties)	UNIPD	Shaking table tests. Motion along two axes	(a) Grouting
3	Model building		Three-leaf stone masonry + timber floors	NTUA	Shaking table tests. Motion along two axes	(a) As built (b) Grouting of masonry and enhancement of diaphragm action of floors
4	Model building		Three-leaf stone masonry + timber floors + timber laces	NTUA	Shaking table tests. Motion along two axes	(a) As built (b) Grouting (c) Enhancement of diaphragm action of top floor

Test Results: Examples

Effect of strengthening techniques on the seismic behaviour of models

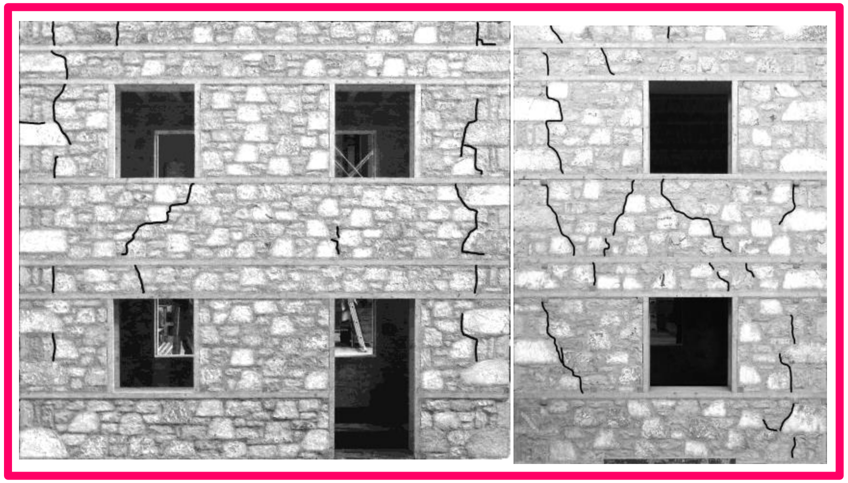


URM Model

RM Model

SM Model

BM2BS



BM2AS

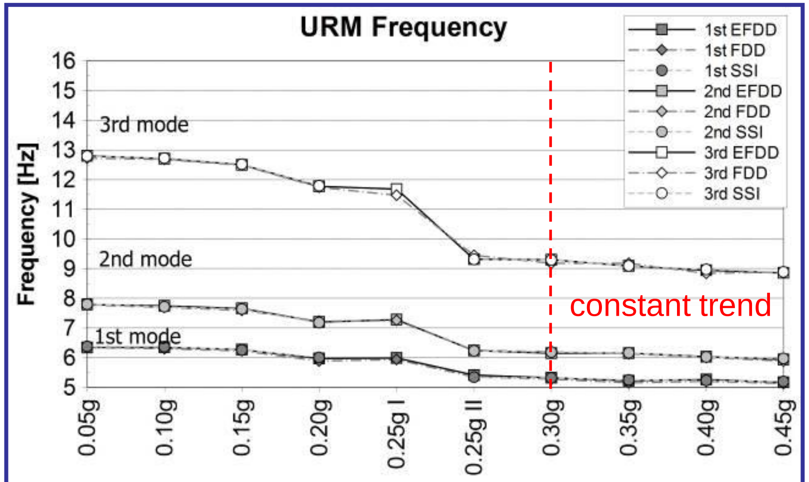
Grouting prevents the detachment of the leaves of 3-leaf masonry.

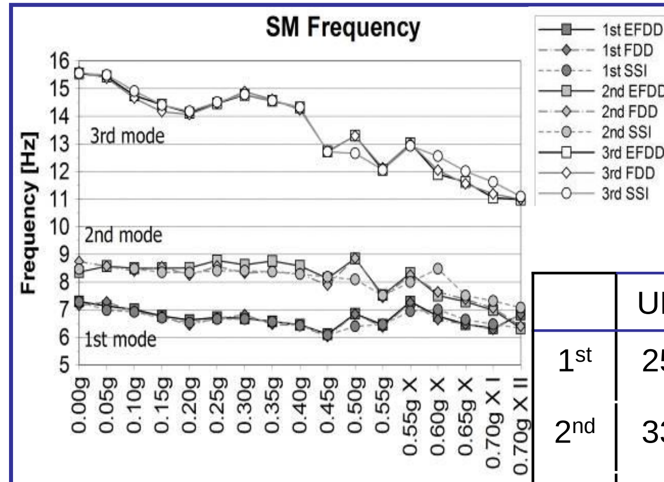
Intervention techniques limit/modify the failure mechanism (BS: out-of-plane bending, AS: shear, sliding & rocking)

Test Results: Examples

Effect of strengthening techniques on the seismic behaviour of models

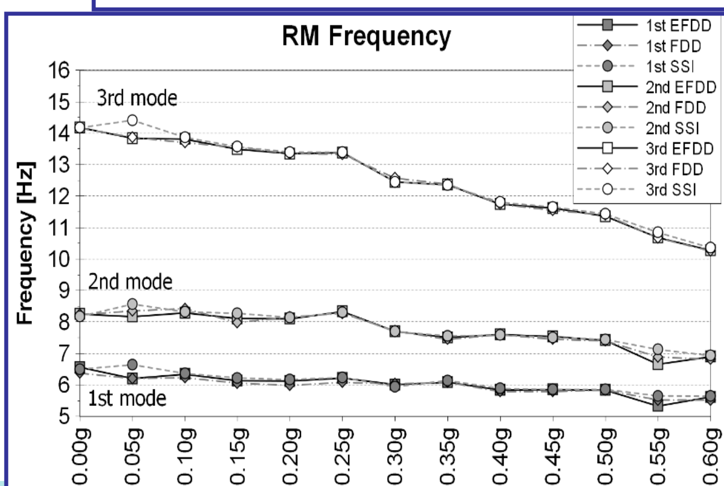
- The dynamic properties of the original structure (different structures) are modified, and thus, their seismic response.





Frequency decreasing

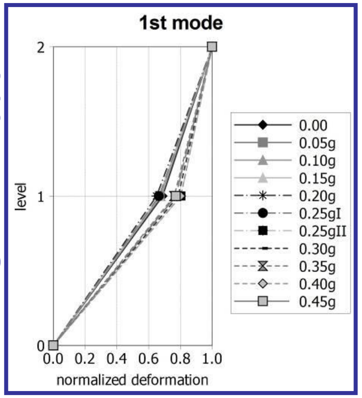
	URM	RM	SM
1st	25.5	15.5	14.4
2nd	33.8	20.8	24.3
3rd	47.4	38.0	39.2



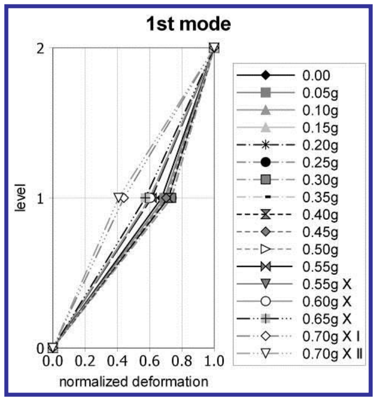
- **URM:** overall decreasing behaviour and sudden modification at 0.25g. Over this seismic input almost constant behaviour.
- **SM:** overall decreasing behaviour with a local increasing between 0.20g and 0.40g. Similar trend slope at initial and final stages.
- **RM:** overall decreasing behaviour without any local increasing. Sudden modifications on the frequency trend are avoided.

Test Results: Examples

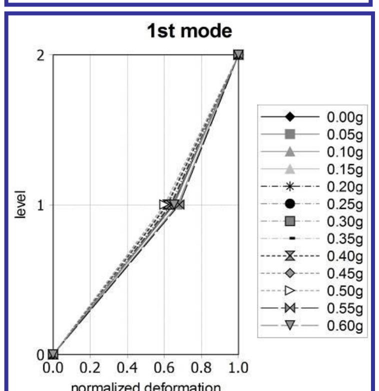
URM Model



SM Model



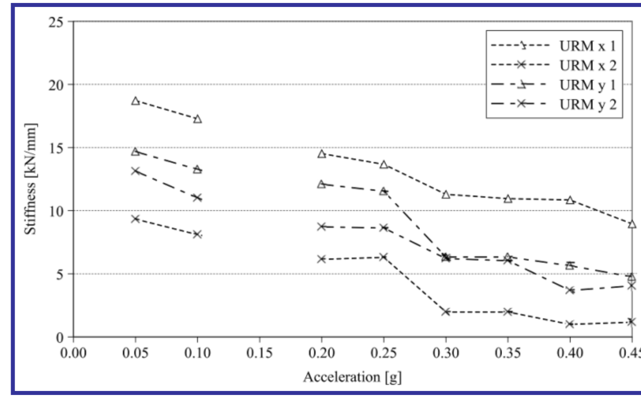
RM Model

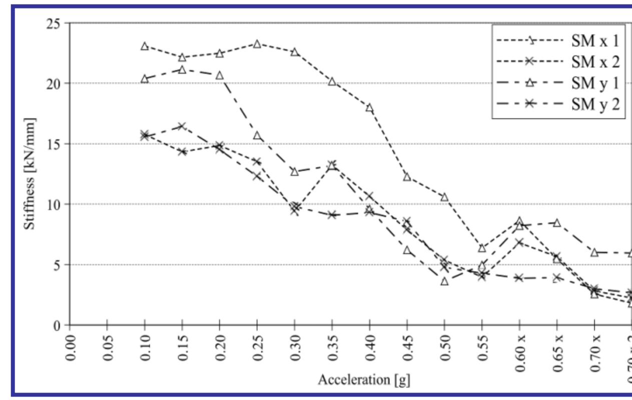


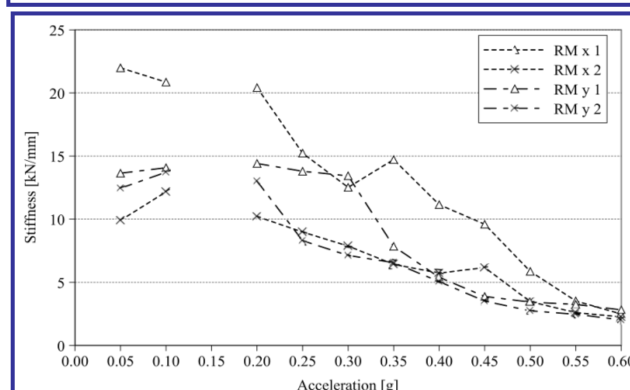
URM: Two identifiable ranges, with a sudden drop at 0.25g.

SM: Wide range of variation with a gradual modification of mode shapes. Overall behaviour denotes a large range of variation, and increasing of second floor deformation at increasing loads.

RM: Limited variation of modal deformations and more monolithic behaviour than URM model.





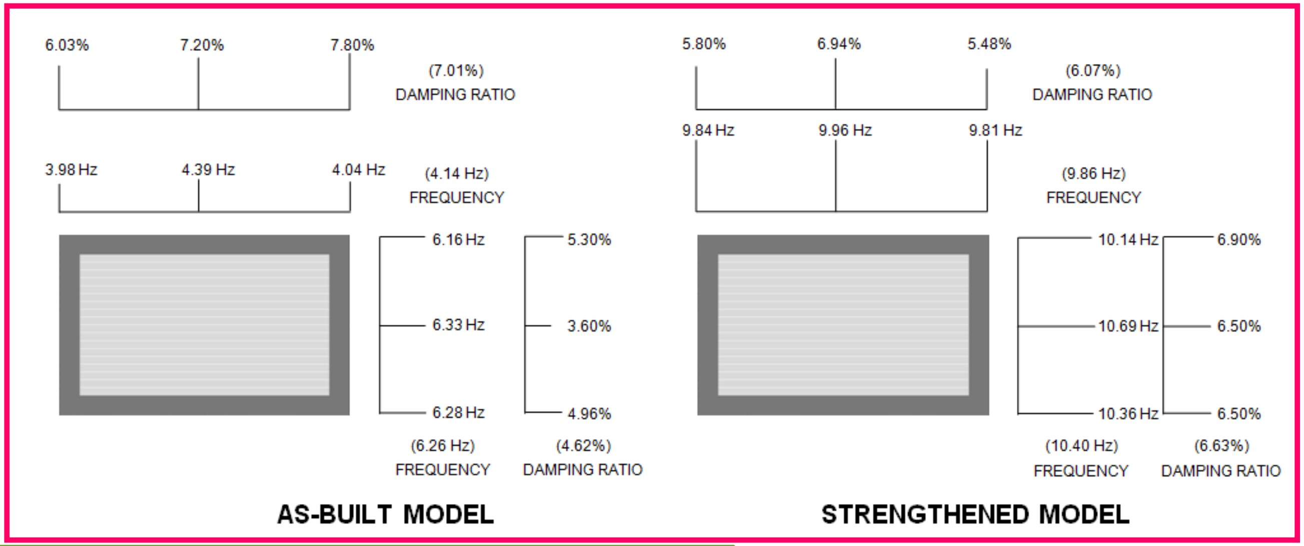


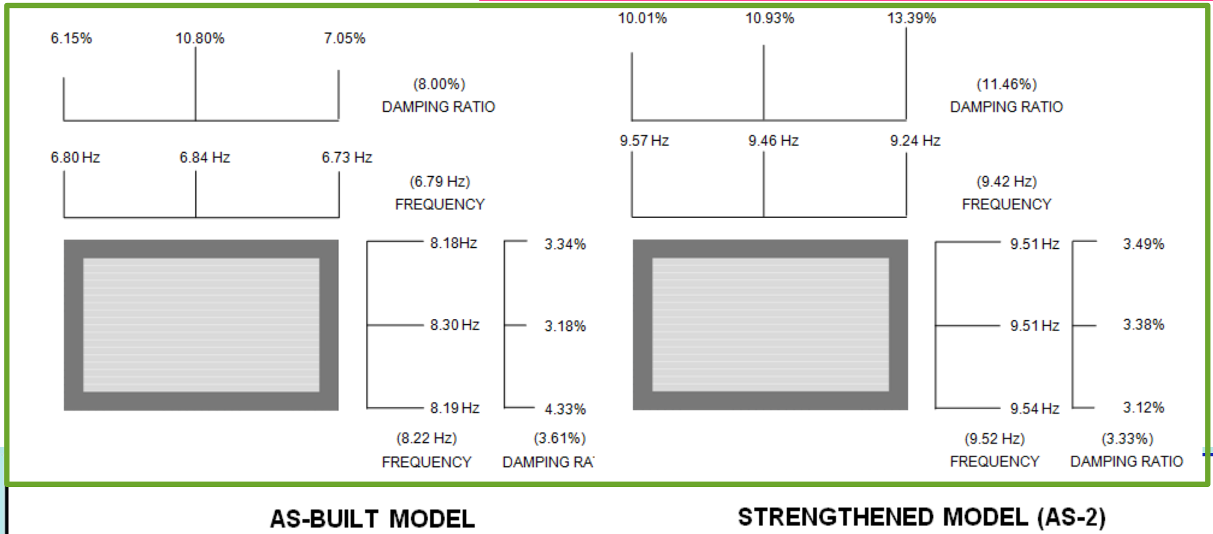
Test Results: Examples

Effect of strengthening techniques on the seismic behaviour of models

Grouting + Enhancement of the diaphragm action → The repaired/strengthened specimens become stiffer, whereas a more box type response of the specimens is ensured.

BM1





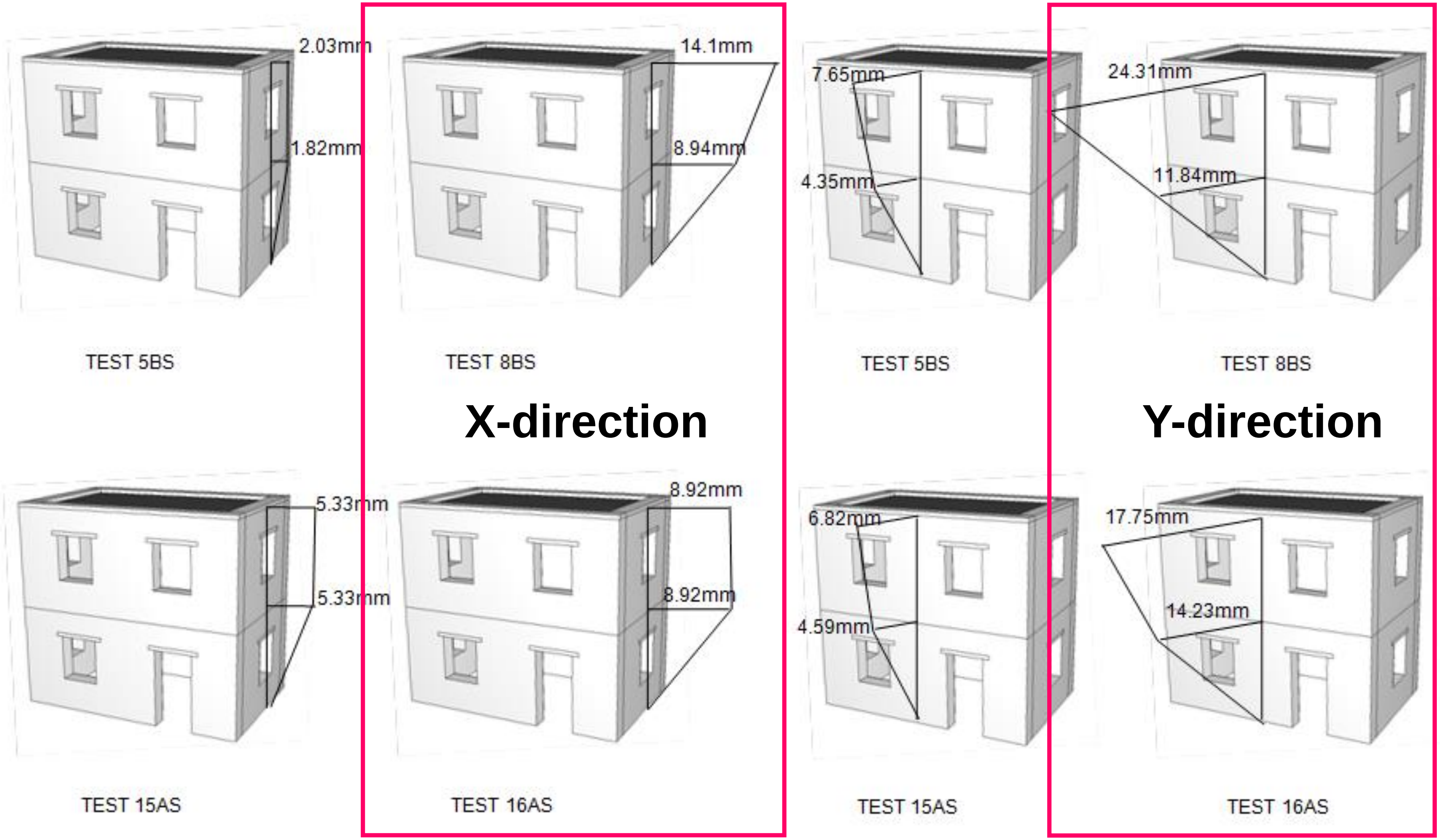
BM2

Test Results: Examples

BM1

AS-BUILT

STRENGTHENED



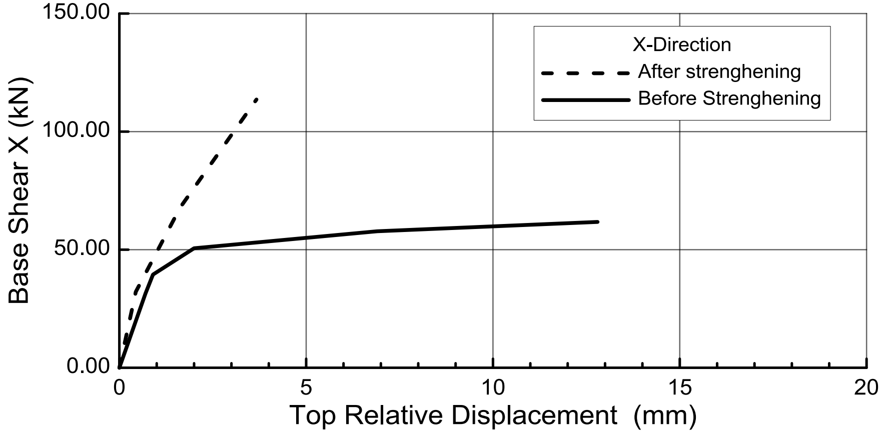
Test Results: Examples

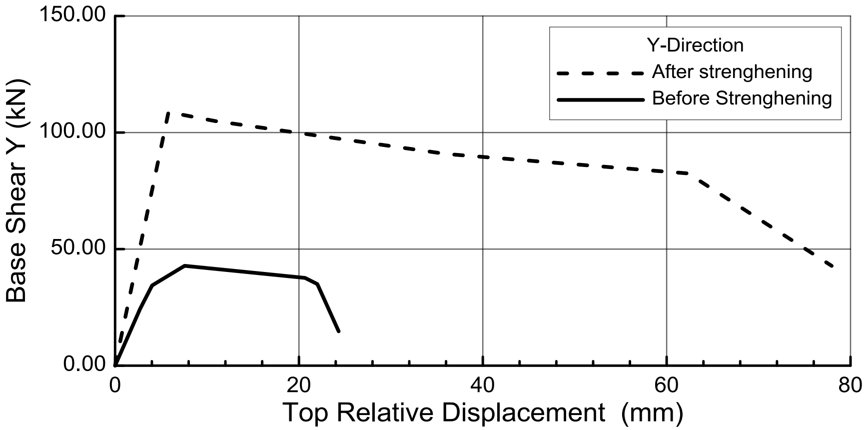
Effect of strengthening techniques on the seismic behaviour of models

The overall behaviour of the structure is improved and a more monolithic behaviour up to higher seismic input is ensured.

- After interventions the structures can sustain significantly higher seismic base accelerations
- The application of interventions reinstates and increases the initial stiffness of virgin models.
- The bearing (and deformability) capacity of the structure increases, although the weight of the structure due to grouting increases by 10%.

BM1



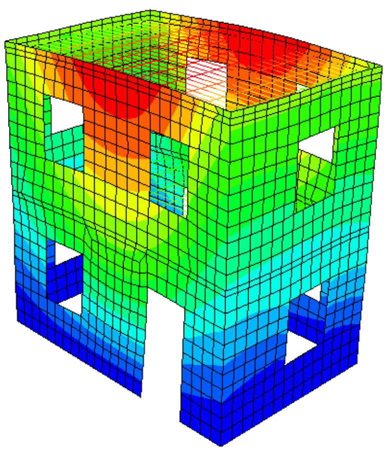


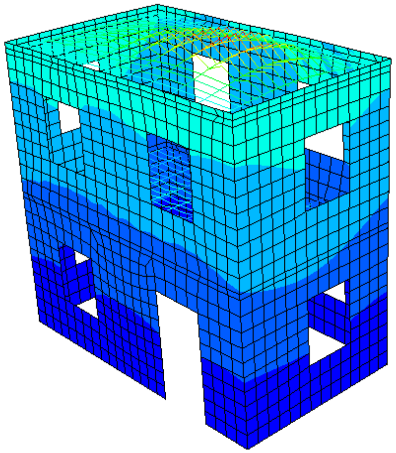
Numerical validation

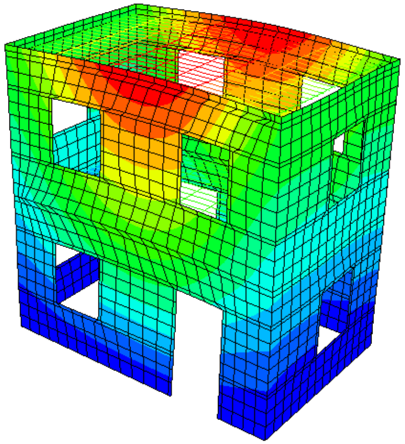
Comparison between experimental and numerical values of natural frequencies.

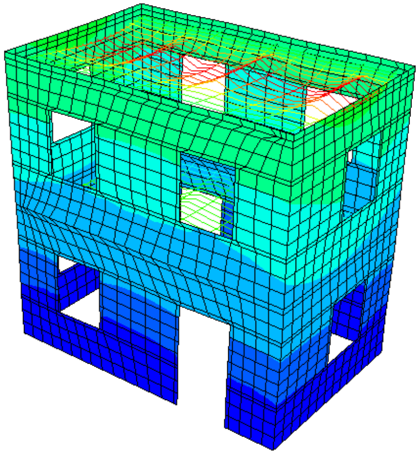
Plain masonry model

Timber-laced masonry model









f_y=4.87Hz (exp 4.20Hz)

f_x=6.58Hz (exp. 6.22Hz)

f_y=6.67Hz (exp 6.72Hz)

f_x=8.58Hz (exp. 8.18Hz)

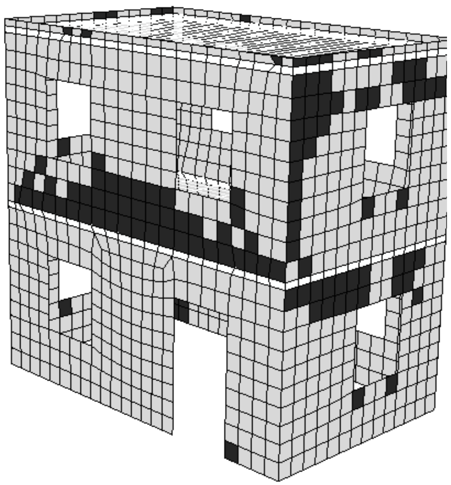
Nonlinear time history analysis

Numerical validation

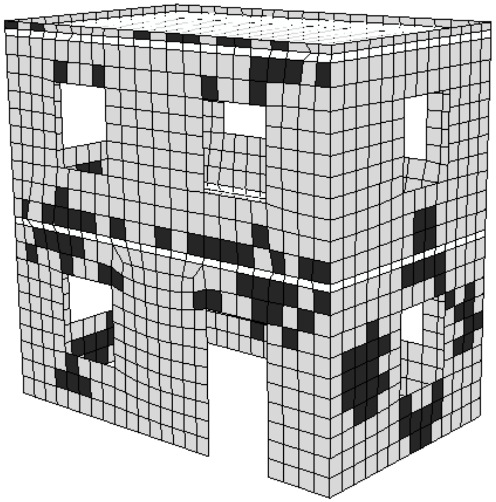
Plain masonry model

Comparison between experimental and numerical results

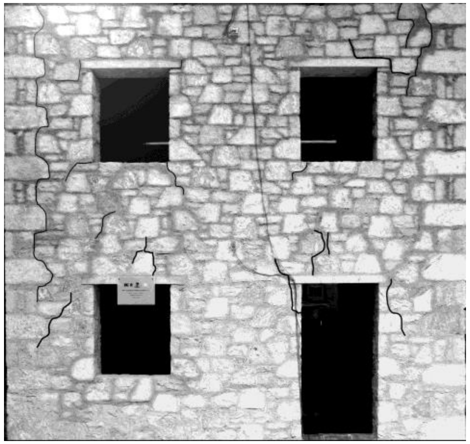
Damage index at the end of load history (damage areas in black color)

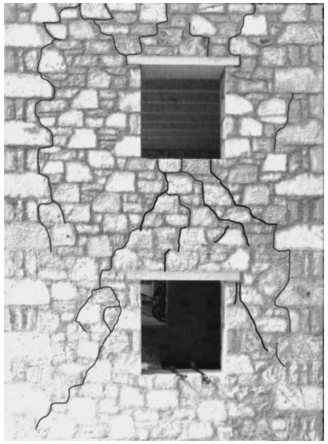


Tensile damage index



Shear damage index





Output

WP3-Catalogue (Out-of-plane and in-plane resistance, energy dissipation, equivalent viscous damping, variation of dynamic characteristics (frequencies, mode shapes, damping ratios), displacement capacity, stiffness variation, connections, bearing capacity, deformability, drift values**)**.

WP8-Calibration of analytical models, Modeling of intervention techniques (grouting, 2nd pavement, wall-to-floor connection)
-sensitivity analysis

WP10 –Guidelines for the design, the execution and the procedure of applying grouting and enhancement of the diaphragm action of the walls (WP5, floor to wall connection)

-Performance levels, response parameters for seismic assessment and design (in local and global level)

SEVENTH FRAMEWORK PROGRAMME

Thank you for your attention!

For further info, please visit: http://www.niker.eu/