CONSIGLIO NAZIONALE
DEGLI INGEGNERI

ASSOCIAZIONE ITALIANA DI STORIA DELL'INGEGNERIA
AISI

Società
Italiana di
Scienza delle
Costruzioni

L'utilizzo della dinamica sperimentale per la diagnostica e il monitoraggio delle strutture

WEBINAR - 5 dicembre 2022

IDENTIFICAZIONE DINAMICA PER IL MONITORAGGIO DEL DANNO IN STRUTTURE IN MURATURA

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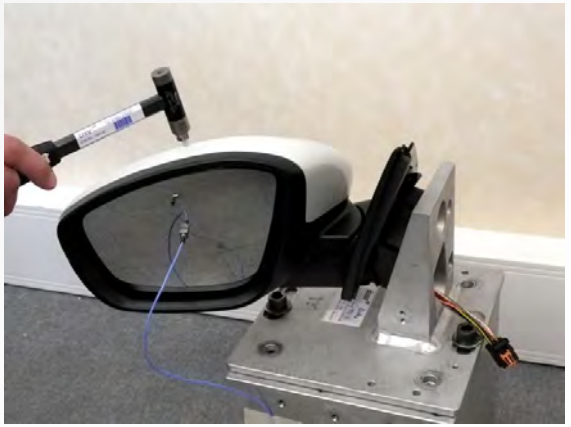
Università degli Studi di Enna Kore

THE NEED FOR LARGE SCALE RESEARCH INFRASTRUCTURES

- In all **engineering fields**, from the design phase to the production, experimental tests are of common use to increase the product reliability.

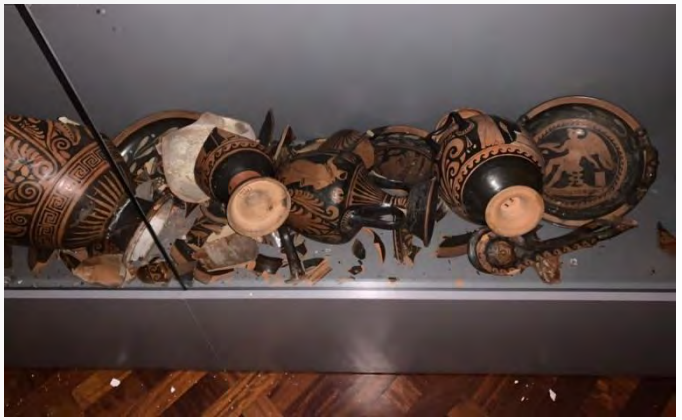


Characterization Tests	to calibrate analytical models
Qualification Tests	in presence of extreme load conditions
Manufacturing Tests	to bring out failures generated by the production process
Operational Tests	to verify the degradation status in operating conditions

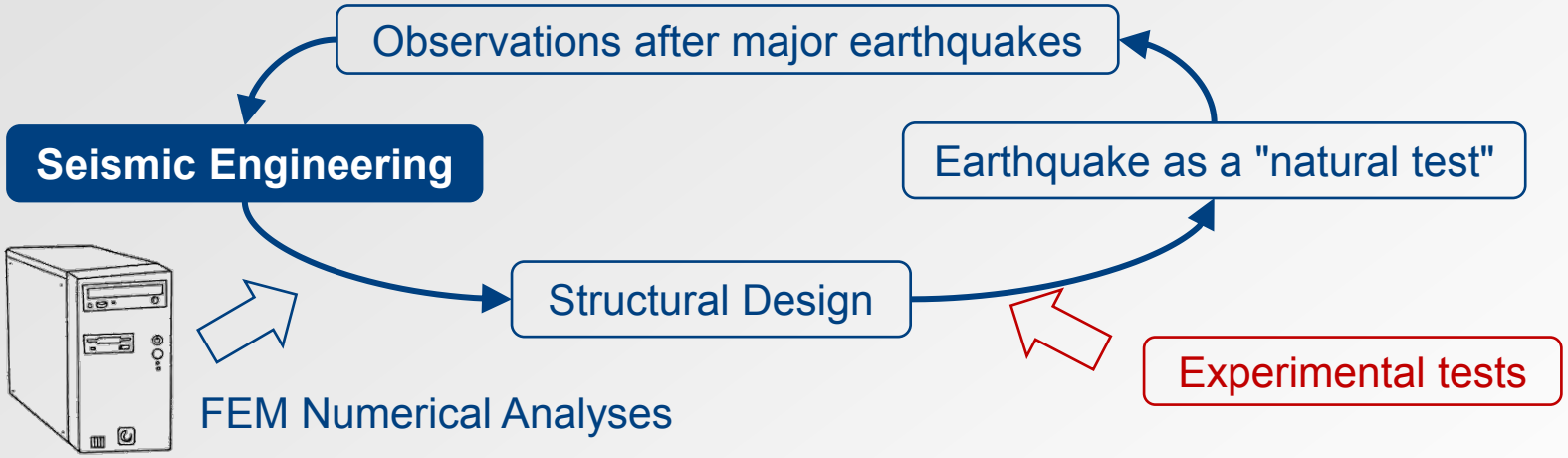
THE NEED FOR LARGE SCALE RESEARCH INFRASTRUCTURES

- The **civil engineering** sector is deeply atypical. Its products are unique in terms of geometric characteristics, standardization is very difficult and the methods of production and installation can often still be classified as artisanal.

- Recent earthquakes proved that countries in the Mediterranean area suffered greater casualties and overall economic losses with respect to Japan and USA, which are often subjected to stronger earthquakes



THE NEED FOR LARGE SCALE RESEARCH INFRASTRUCTURES



- Need for experimental tests:
  - they are absolutely **necessary** for the **development of new products**, **materials and solutions** for the seismic risk mitigation.
  - they are **complementary to numerical analyses** in order to predict the behavior of existing structures and to increase the reliability of the models themselves.
  - they constitute an **essential support** for the writing and validation of the **new seismic design codes** of the new structures.

THE NEED FOR LARGE SCALE RESEARCH INFRASTRUCTURES

- Civil structures subjected to earthquakes cannot be tested by only qualifying typical components, due to their extreme diversity.

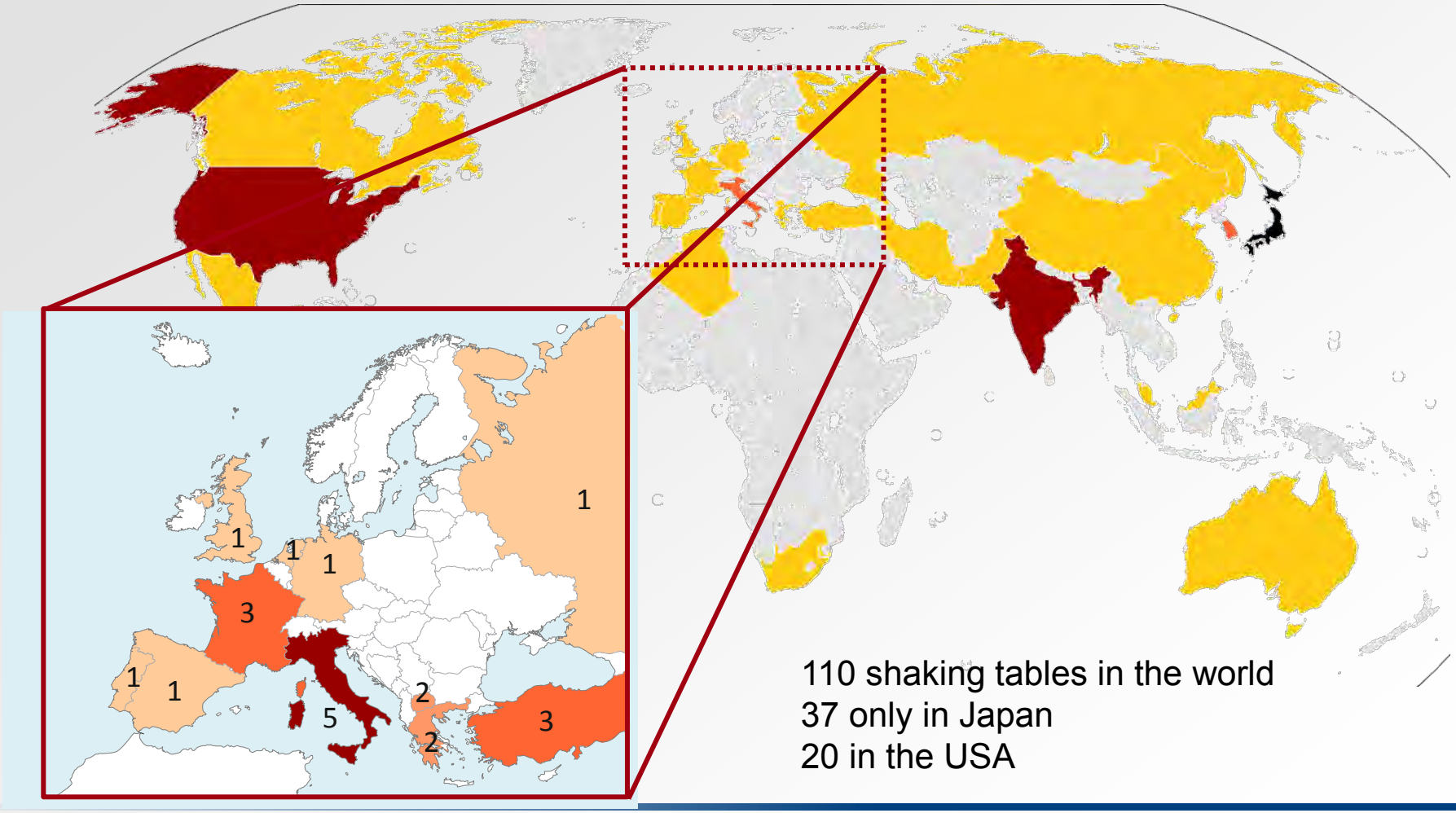
- The response under strong earthquakes cannot be tested in field nor in an ordinary laboratory, but large scale tests in expensive research infrastructures are required.

Dynamic tests

Pseudo-dynamic or Hybrid tests

THE NEED FOR LARGE SCALE RESEARCH INFRASTRUCTURES

- Major shaking tables around the world:



110 shaking tables in the world
37 only in Japan
20 in the USA

THE L.E.D.A. "Laboratory of Earthquake engineering and Dynamic Analysis"

- L.E.D.A. Project was funded in 2011 Italian Ministry of Education, University and Research (MIUR);
- It hosts two large testing facilities: a strong wall-strong floor reaction system and two 6DOF shaking tables.

THE L.E.D.A. "Laboratory of Earthquake engineering and Dynamic Analysis"

- Two identical 6DOF shaking tables, which can operate independently or simultaneously

Feature	Single table	Dual table system
Dimensions	4 x 4 m	10 x 4 m
Payload	60 ton	100 ton
Operative frequency range	0.01 ÷ 60 Hz	0.01 ÷ 60 Hz
Stroke (horizontal axes)	±400 mm	±400 mm
Stroke (vertical axis)	±250 mm	±250 mm
Velocity (horizontal axes)	± 2.2 m/s	± 1.1 m/s
Velocity (vertical axis)	± 1.5 m/s	± 0.75 m/s
Acceleration (horizontal axes)	± 1.5 g	± 1.05 g
Acceleration (vertical axes)	± 1.0 g	± 0.7 g
Overturning moment	60 ton·m (triaxial test) 100 ton·m (uniaxial test)	100 ton·m (triaxial test) 100 ton·m (uniaxial test)
Control system	Trio Sistemi RT3-S – displacement, velocity and acceleration control loop @ 2 kHz clock	

THE L.E.D.A. "Laboratory of Earthquake engineering and Dynamic Analysis"

- For large of heavy specimens the shaking tables can be connected to realize a large platform

The 4 m × 10 m configuration represents **the largest 6DOF Shaking Table** actually operating in Europe!

Feature	Single table	Dual table system
Dimensions	4 x 4 m	10 x 4 m
Payload	60 ton	100 ton
Operative frequency range	0.01 ÷ 60 Hz	0.01 ÷ 60 Hz
Stroke (horizontal axes)	±400 mm	±400 mm
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Control system	Trio Sistemi RT3-S – displacement, velocity and acceleration control loop @ 2 kHz clock	

THE L.E.D.A. "Laboratory of Earthquake engineering and Dynamic Analysis"

- Seismic qualification of high-voltage grids equipment

THE L.E.D.A. "Laboratory of Earthquake engineering and Dynamic Analysis"

- Dynamic characterization of seismic protection devices

Mechanical inerter device
(in collaboration with UniRC)

Innovative seismic base-isolation device for museum contents
(PON e-WAS project)

THE L.E.D.A. "Laboratory of Earthquake engineering and Dynamic Analysis"

- Seismic test of innovative building technologies and materials

Confined Stone Wall system
(in collaboration with A&D and ENSA Paris Malaquais)

Barrel vaults strengthening with hemp fibres

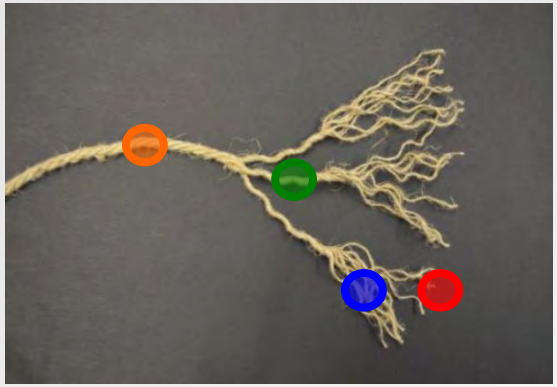
Programma di Sviluppo Rurale per l'Umbria 2014-2020 Misura 16 - Sottomisura 16.2

Nuove filiere della canapa in Umbria per l'innovazione dell'imprenditoria agricola nello sviluppo di sistemi antisismici eco-compatibili

step 1	step 2	step 3

Rope
Wire
Strand
Fiber

a)



b)

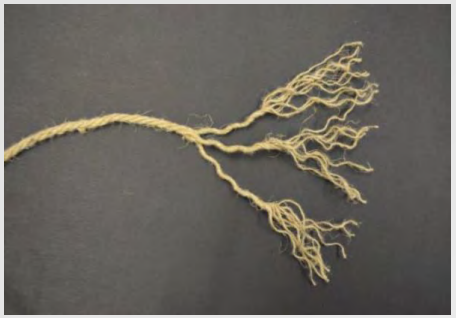
strengthening material mechanical characterization	static tests on reinforced masonry arches	dynamic tests on reinforced masonry vaults

step 1

strengthening material mechanical characterization

hemp rope

a)



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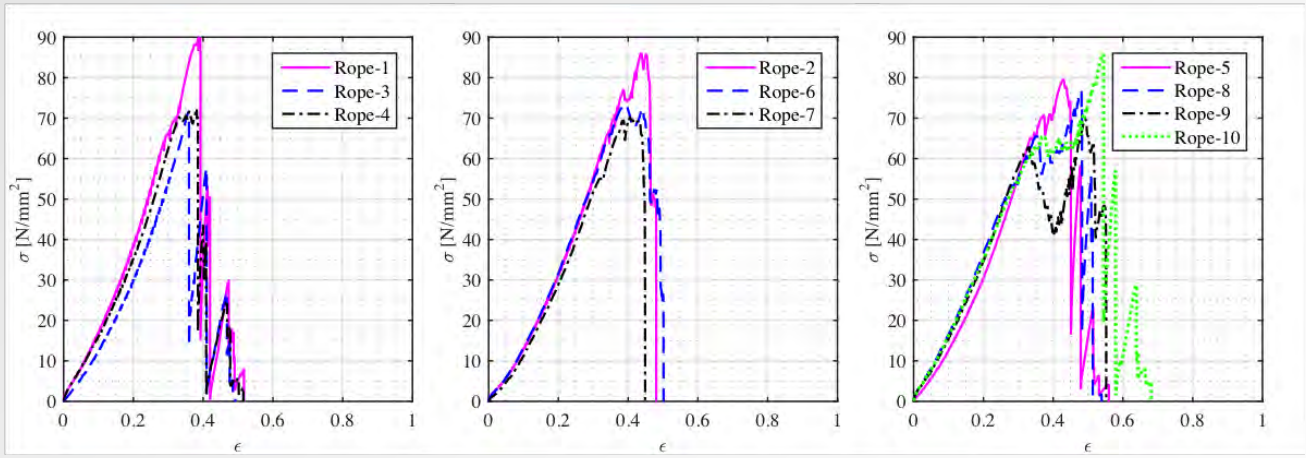
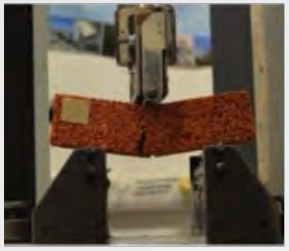
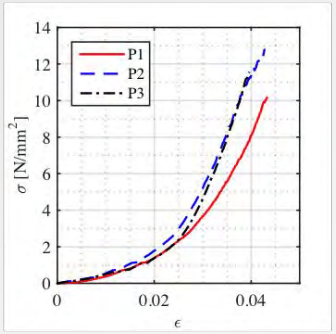
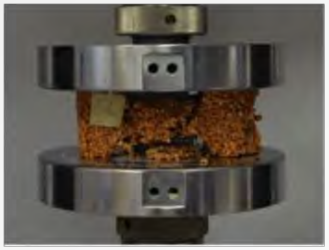


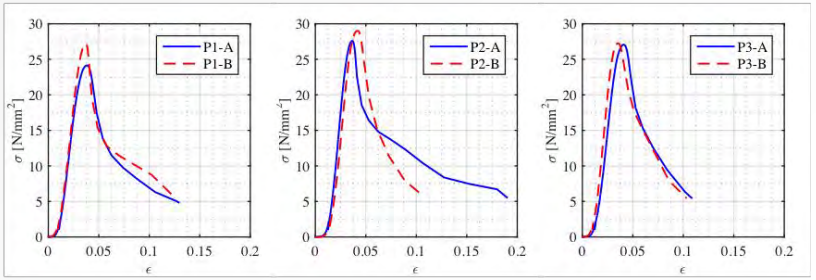
cocciopesto matrix





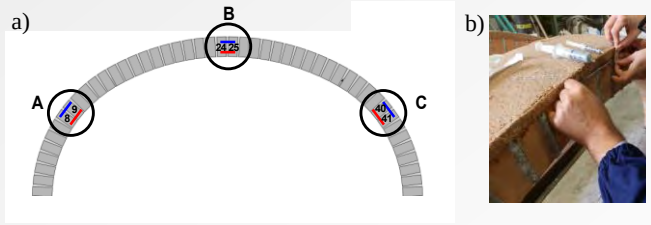
ground clay bricks + *organic binder*



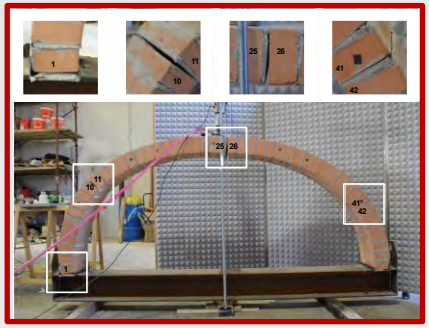


step 2

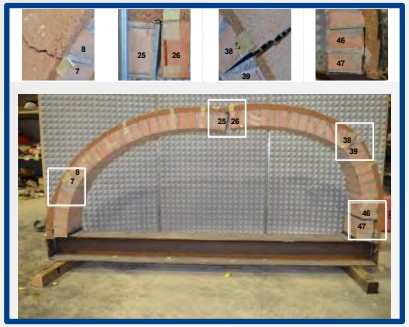
static tests on reinforced masonry arches

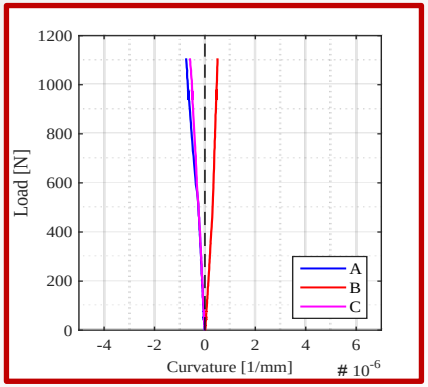


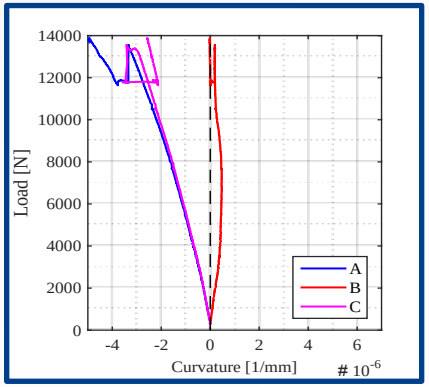
unreinforced



reinforced







Gioffrè, M., et al. "*A novel hemp-fiber bio-composite material for strengthening of arched structures: Experimental investigation*." Construction and Building Materials 308 (2021)

step 3	dynamic tests on reinforced masonry vaults

- develop **bio-reinforcement** design solutions to mitigate the seismic vulnerability
- **improve the knowledge** on the dynamic behavior of masonry vaulted structures excited by ground motions
- investigate on **damage detection** by dynamic experimental tests

ASSESS THE EFFECTIVENESS OF THE PROPOSED BIO-COMPOSITE MATERIAL TO IMPROVE THE SEISMIC PERFORMANCE OF MASONRY VAULTED STRUCTURES

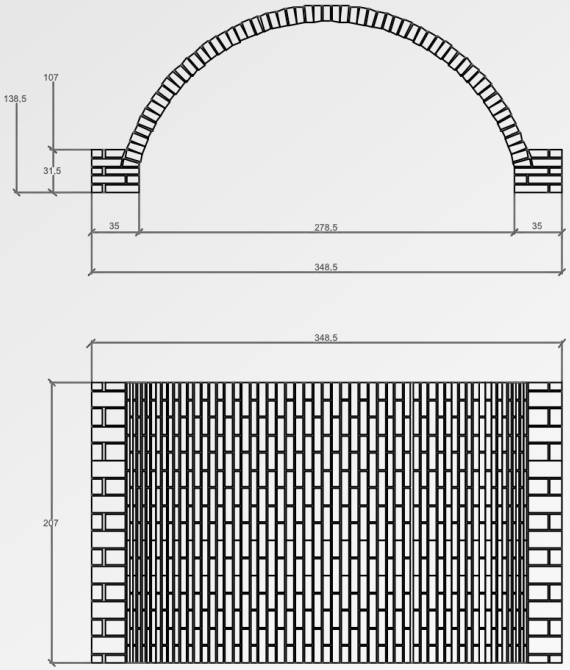
- **SHAKING TABLE** experimental tests on URM and RM vaults
- **DYNAMIC BEHAVIOR** comparison of the two vaults

Step 3

vaults geometric characteristics

unreinforced masonry vault

reinforced masonry vault



geometric characteristics

- plan: 3.50 m x 2,10 m
- height: 1,5 m

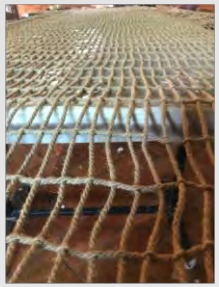
solid clay bricks

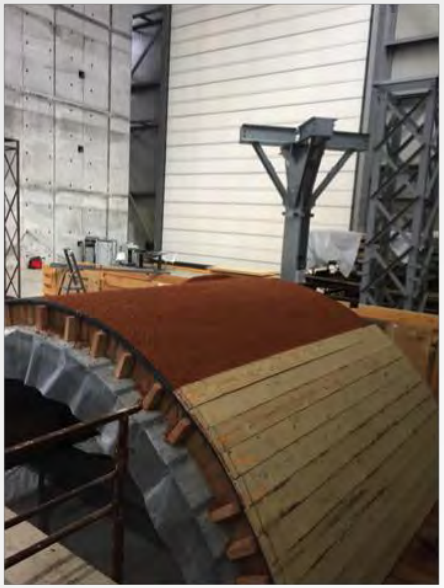
- dimensions
  55 x 120 x 250 mm^3
- weight for unit volume
  1697 Kg/m^3
- compressive strength
  40.8 N/mm^2

M15 mortar

Step 3

reinforcement features



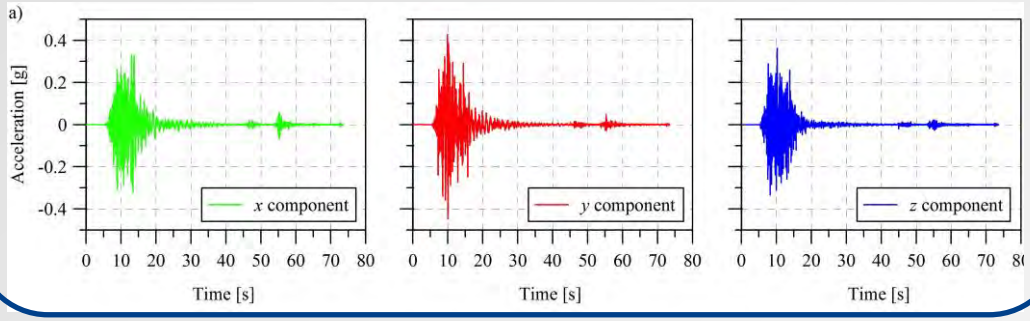




- bidirectional rope net
- 7 cm x 2 cm spacing
- 30 mm thick layer of cocciopesto matrix

shaking table tests

reference accelerogram
Norcia earthquake, October 30th 2016



- scaled seismic input sequence
- damage accumulation → changes in vibration features
- AVT after each seismic input

DAMAGE effect on the main dynamic features

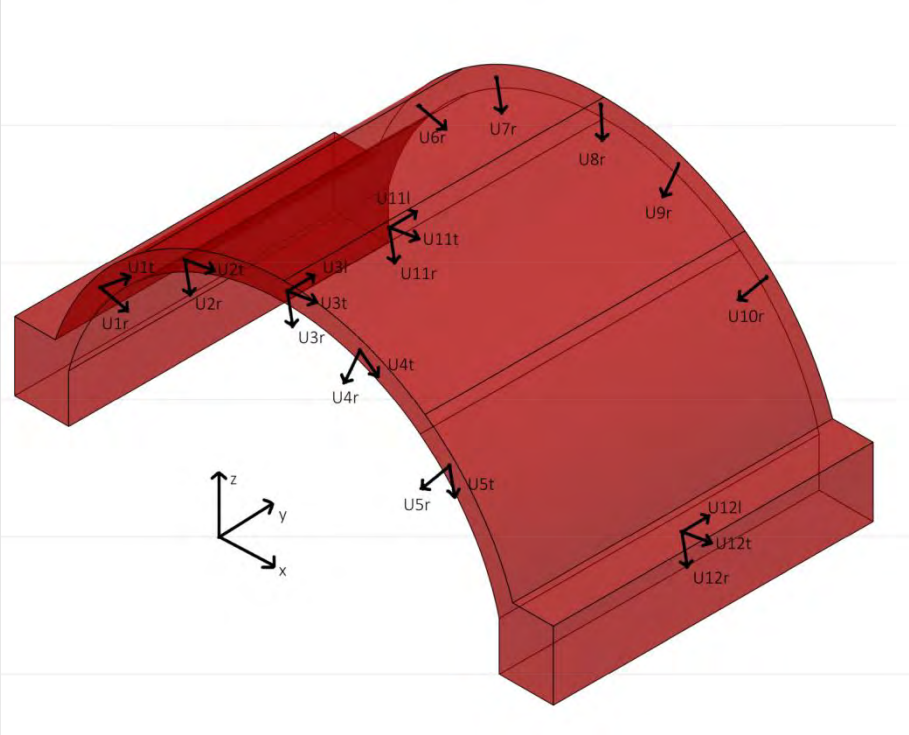
unreinforced masonry vault

Test	Code	Description
1	AVT0 - URM	Ambient Vibration Loading
2	E1-URM	Seismic input 0.20 N
3	AVT1 - URM	Ambient Vibration Loading
4	E2-URM	Seismic input 0.40 N
5	AVT2 - URM	Ambient Vibration Loading

reinforced masonry vault

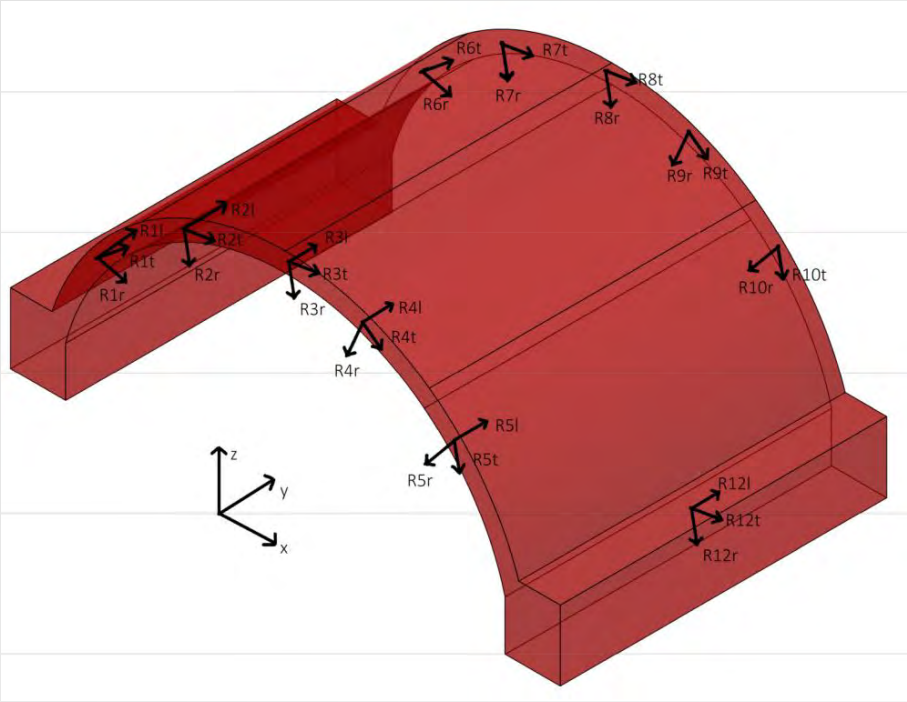
Test	Code	Description
1	AVT0 - RM	Ambient Vibration Loading
2	E1-RM	Seismic input 0.20 N
3	AVT1 - RM	Ambient Vibration Loading
4	E2-RM	Seismic input 0.40 N
5	AVT2 - RM	Ambient Vibration Loading
6	E3 - RM	Seismic input 1.00 N
7	AVT3 - RM	Ambient Vibration Loading
8	E4 - RM	Seismic input 2.20 N
9	AVT4 - RM	Ambient Vibration Loading
10	E5 - RM	Seismic input 2.30 N
11	AVT5 - RM	Ambient Vibration Loading

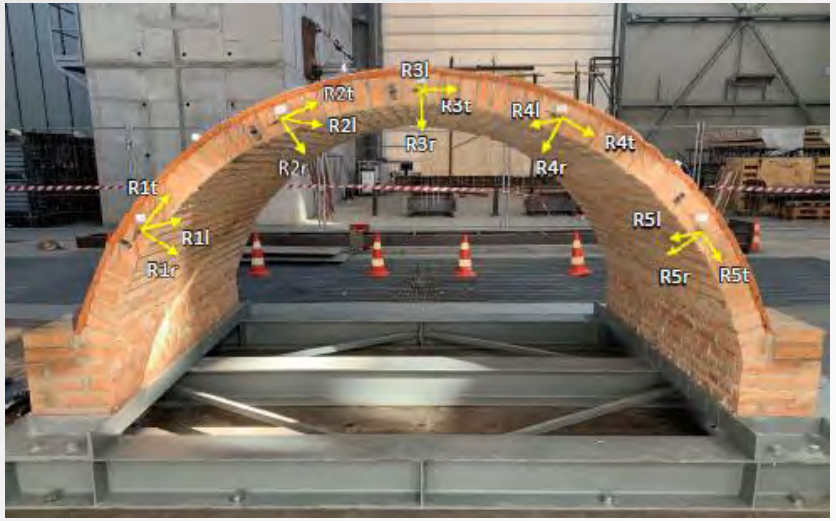
setup #1

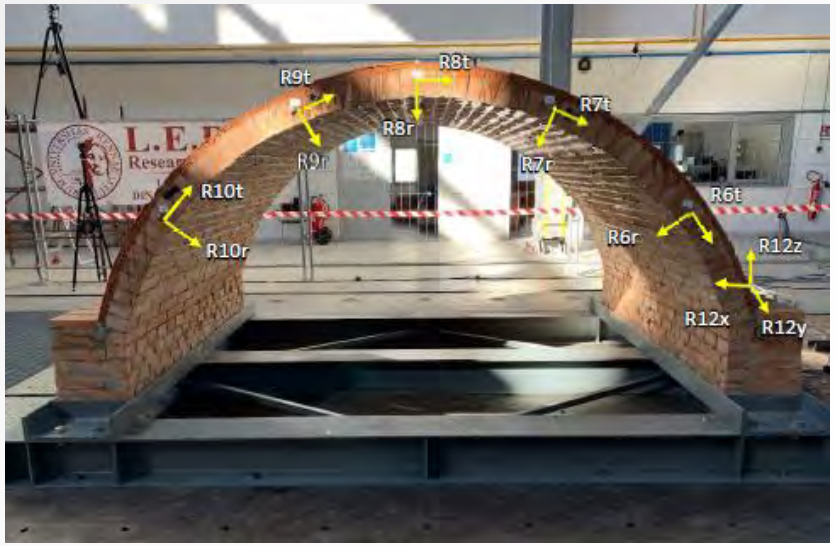


- 22 accelerometers (triaxial, biaxial,uniaxial)

setup #2







- 28 accelerometers (triaxial, biaxial,uniaxial)

damage indicators

vibration frequency

$$d_i^f = 1 - \frac{f_{i,d}}{f_{i,u}}, \qquad i = 1, \ldots, m$$

- $f_{i,d,}$ i-th vibration frequency identified in the **DAMAGED** conditions
- $f_{i,u,}$ i-th vibration frequency identified in the **UNDAMAGED** conditions

vibration shape

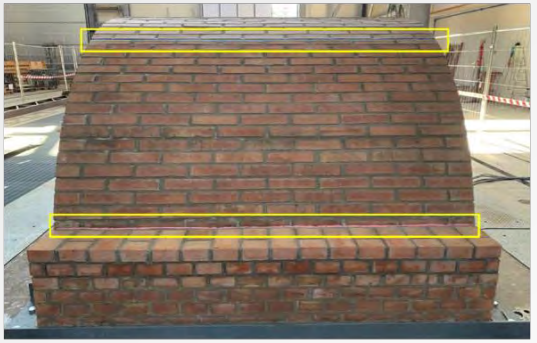
$$MAC_{u,d}(\phi_i^u, \phi_i^d) = \frac{|\phi_i^{u*} \phi_i^d|^2}{||\phi_i^u|| ||\phi_i^d||}$$

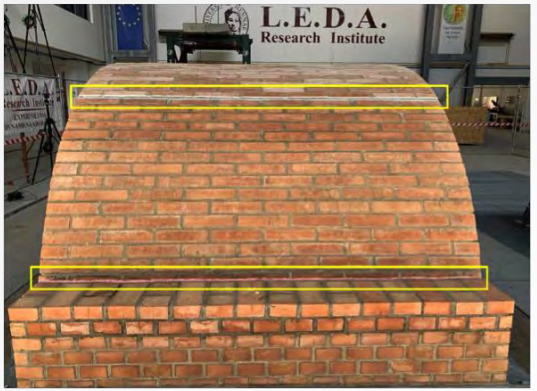
$$d_i^{MS} = 1 - MAC_{u,d}^i, \qquad i = 1, \ldots, m$$

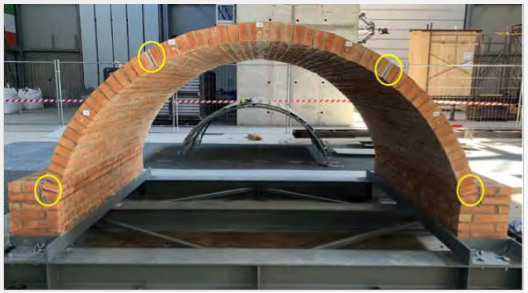
- ***MAC = 1*** for perfect correlation
- MAC can be used to quantify vibration **shapes variations** induced by damage

damage patterns – URM vault

Test	Code	Description
1	AVT0 - URM	Ambient Vibration Loading
2	E1-URM	Seismic input 0.20 N
3	AVT1 - URM	Ambient Vibration Loading
4	E2-URM	Seismic input 0.40 N
5	AVT2 - URM	Ambient Vibration Loading







- **TEST E1-URM (0.20 N)**
  - large displacements and rotations
- **TEST E2-URM (0.40 N)**
  - increasing present damage *(4 alternate cylindrical hinges)*

damage patterns – URM vault

Test	Code	Description
1	AVT0 - URM	Ambient Vibration Loading
2	E1-URM	Seismic input 0.20 N
3	AVT1 - URM	Ambient Vibration Loading
4	E2-URM	Seismic input 0.40 N
5	AVT2 - URM	Ambient Vibration Loading

Mode	AVT0	AVT1	AVT2
M1	18.36	17.58	9.77
M2	25	24.70	17.87
M3	37.40	36.62	34.18
M4	40.91	41.40	39.16

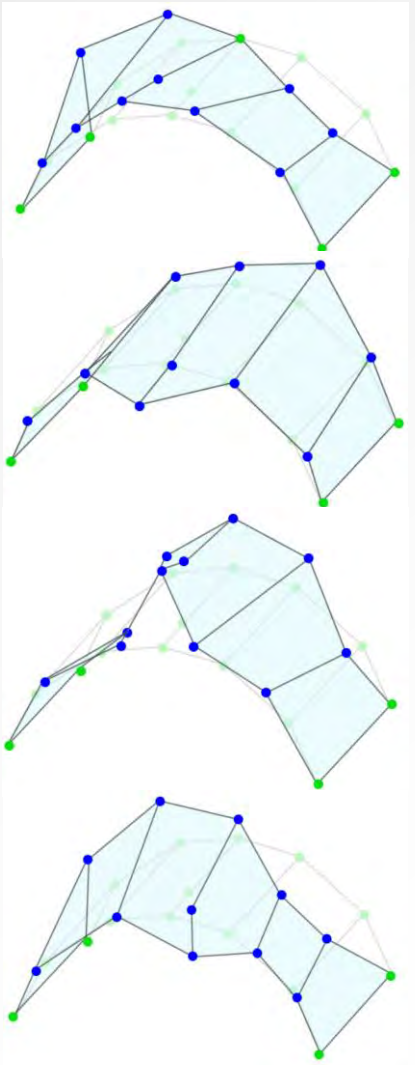
VIBRATION FREQUENCY DECREASE

M1 - URM

M2 - URM

M3 - URM

M4 - URM



damage patterns – URM vault

Test	Code	Description
1	AVT0 - URM	Ambient Vibration Loading
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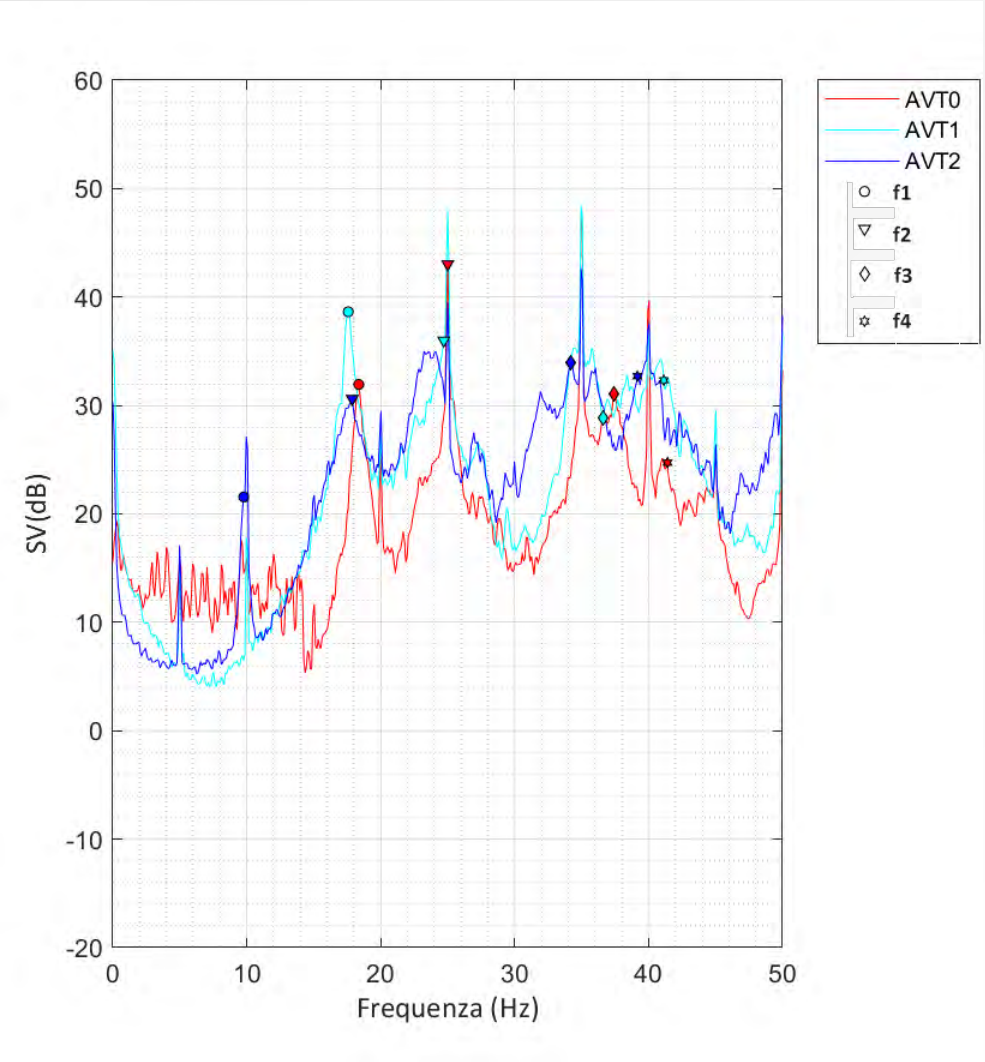
5	AVT2 - URM	Ambient Vibration Loading

Mode	AVT0	AVT1	AVT2
M1	18.36	17.58	9.77
M2	25	24.70	17.87
M3	37.40	36.62	34.18
M4	40.91	41.40	39.16

VIBRATION FREQUENCY DECREASE



damage patterns – RM vault

Test	Code	Description
1	AVT0 - RM	Ambient Vibration Loading
2	E1-RM	Seismic input 0.20 N
3	AVT1 - RM	Ambient Vibration Loading
4	E2-RM	Seismic input 0.40 N
5	AVT2 - RM	Ambient Vibration Loading
6	E3 - RM	Seismic input 1.00 N
7	AVT3 - RM	Ambient Vibration Loading
8	E4 - RM	Seismic input 2.20 N
9	AVT4 - RM	Ambient Vibration Loading
10	E5 - RM	Seismic input 2.30 N
11	AVT5 - RM	Ambient Vibration Loading

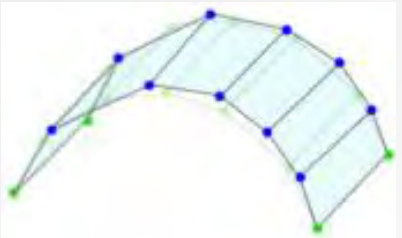
- **TEST E5-RM (2.30 N)**
  - global failure

damage patterns – RM vault

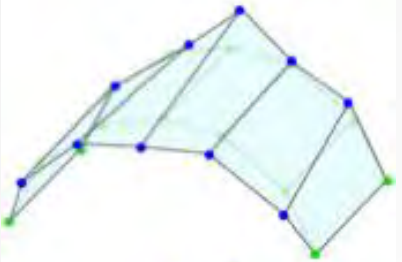
Test	Code	Description
1	AVT0 - RM	Ambient Vibration Loading
2	E1-RM	Seismic input 0.20 N
3	AVT1 - RM	Ambient Vibration Loading
4	E2-RM	Seismic input 0.40 N
5	AVT2 - RM	Ambient Vibration Loading
6	E3 - RM	Seismic input 1.00 N
7	AVT3 - RM	Ambient Vibration Loading
8	E4 - RM	Seismic input 2.20 N
9	AVT4 - RM	Ambient Vibration Loading
10	E5 - RM	Seismic input 2.30 N
11	AVT5 - RM	Ambient Vibration Loading

Mode	AVT0	AVT3	AVT4	AVT5
M1	19.14	16.69	11.72	6.64
M2	27.54	26.76	29.20	24.32
M3	37.79	33.49	22.27	12.32
M4	47.95	45.02	41.50	41.50

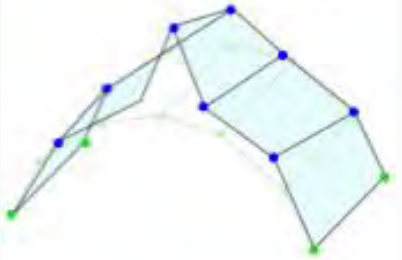
M1 - RM



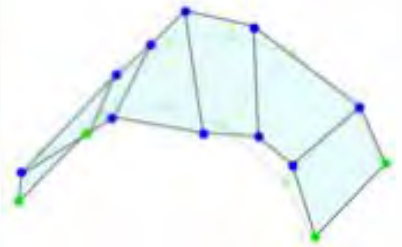
M2 - RM



M3 - RM



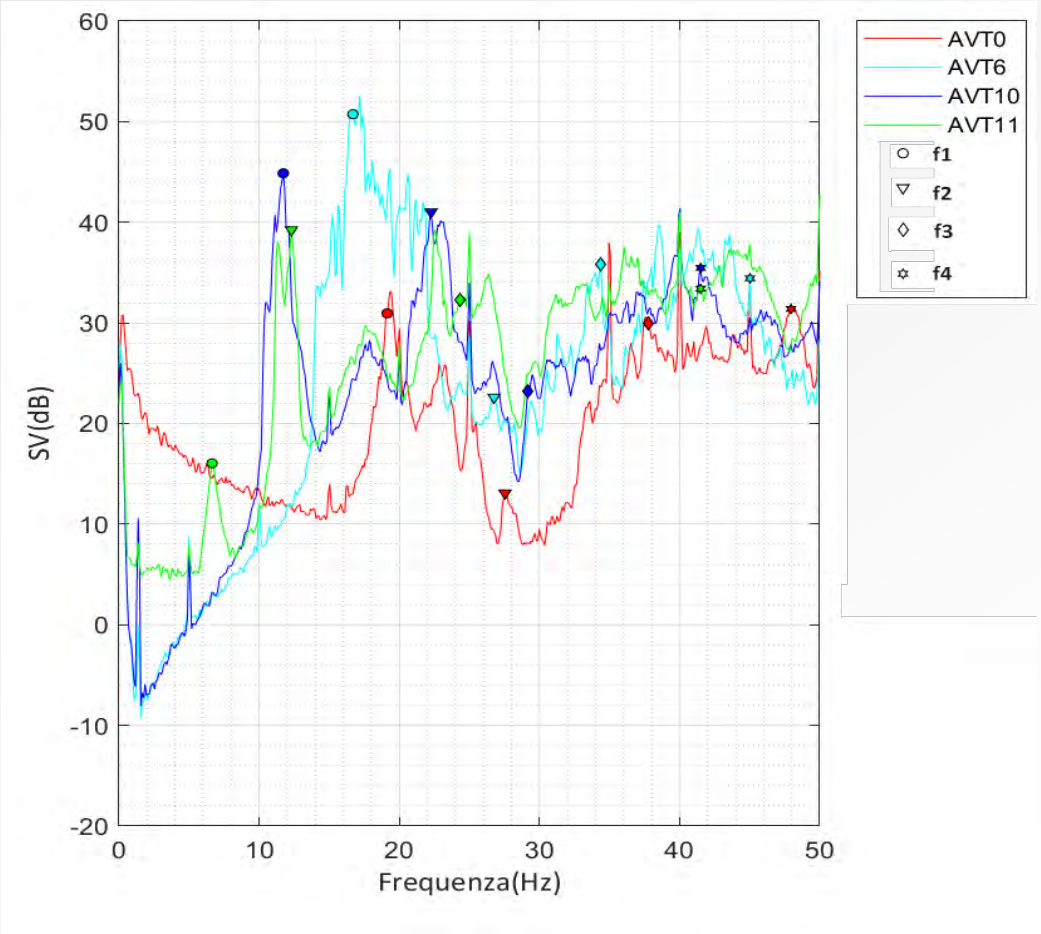
M4 - RM



damage patterns – RM vault

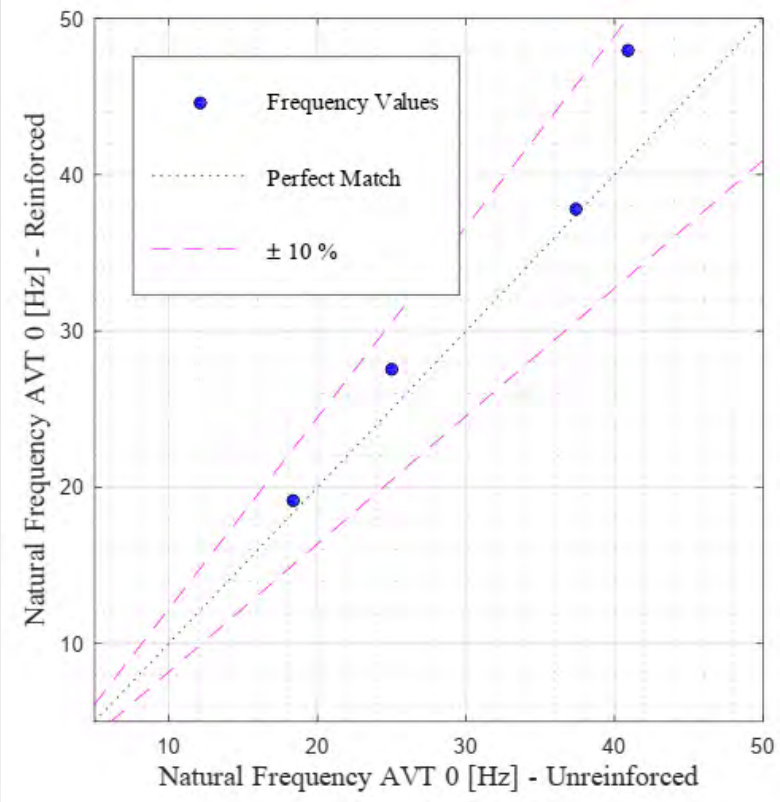
Test	Code	Description
1	AVT0 - RM	Ambient Vibration Loading
2	E1-RM	Seismic input 0.20 N
3	AVT1 - RM	Ambient Vibration Loading
4	E2-RM	Seismic input 0.40 N
5	AVT2 - RM	Ambient Vibration Loading
6	E3 - RM	Seismic input 1.00 N
7	AVT3 - RM	Ambient Vibration Loading
8	E4 - RM	Seismic input 2.20 N
9	AVT4 - RM	Ambient Vibration Loading
10	E5 - RM	Seismic input 2.30 N
11	AVT5 - RM	Ambient Vibration Loading

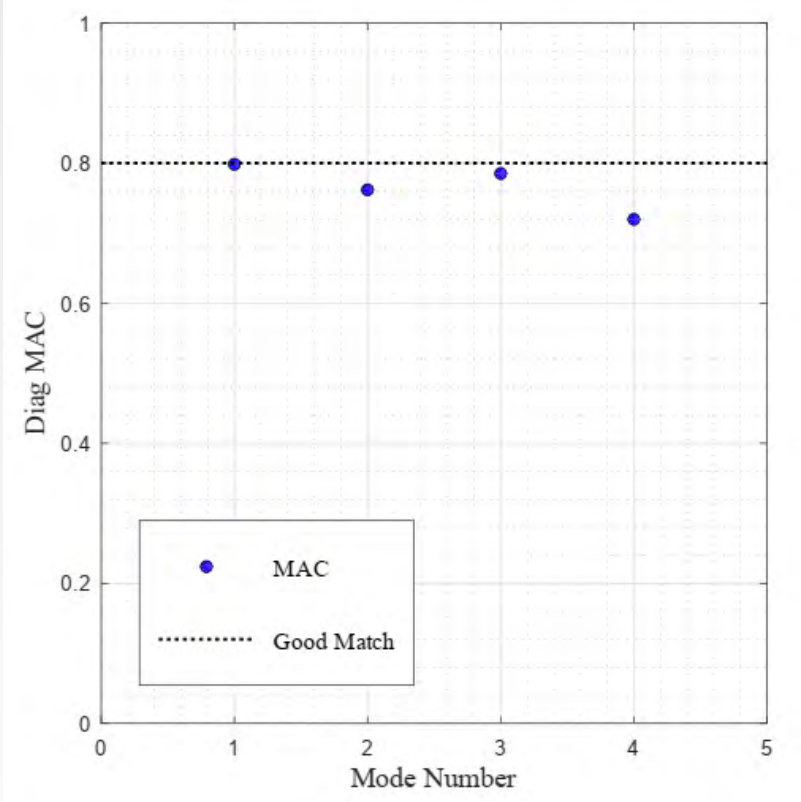
Mode	AVT0	AVT3	AVT4	AVT5
M1	19.14	16.69	11.72	6.64
M2	27.54	26.76	29.20	24.32
M3	37.79	33.49	22.27	12.32
M4	47.95	45.02	41.50	41.50



comparison

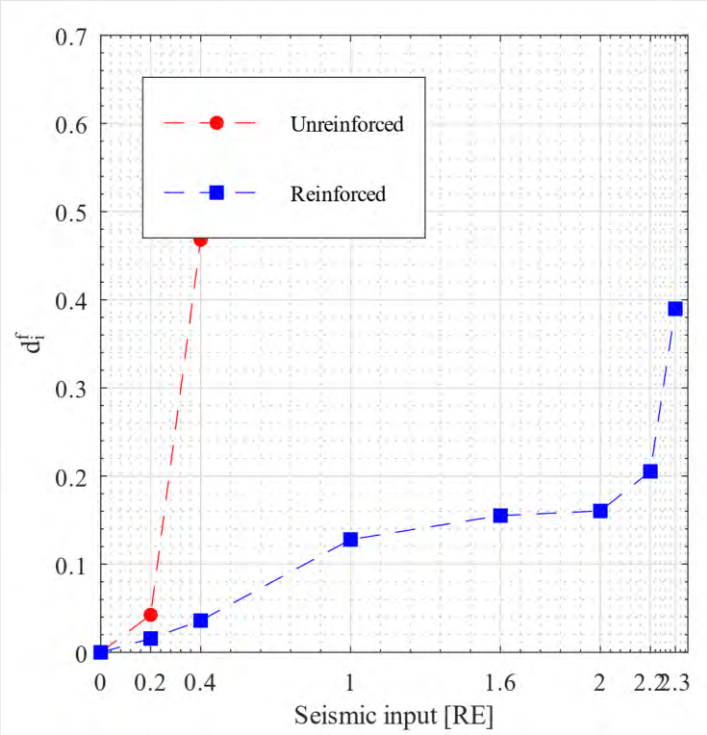
- Dynamic identification before seismic input sequence



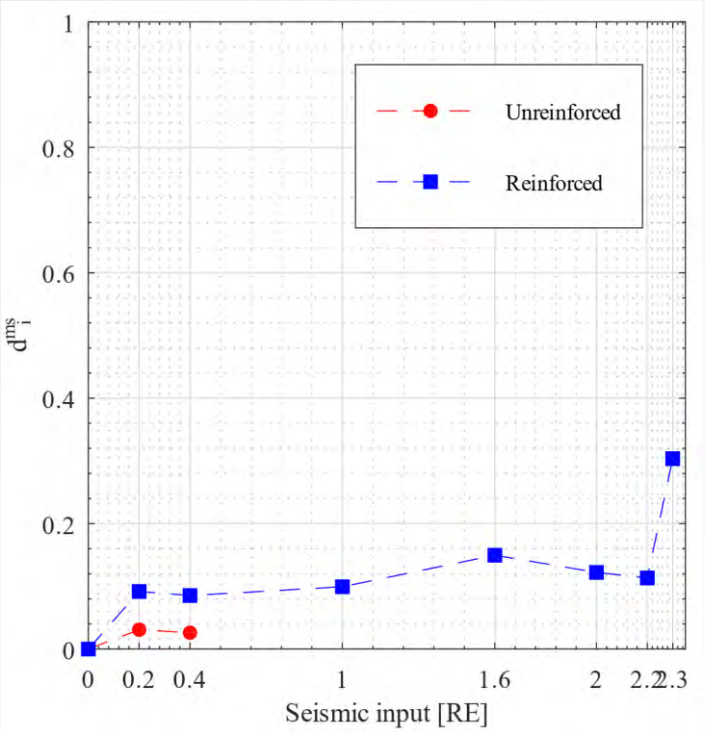


comparison – damage indicator

- vibration shape M1



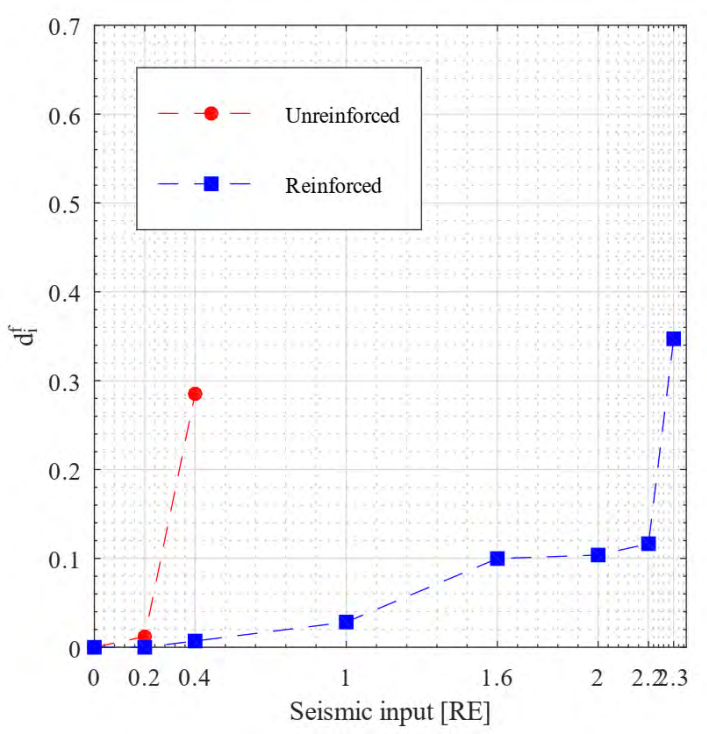
vibration frequency

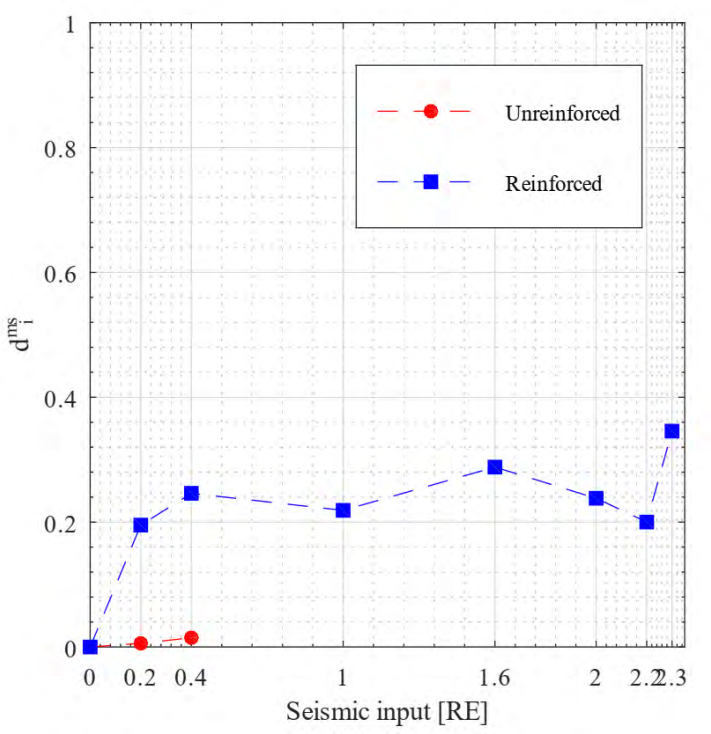


vibration shape

comparison – damage indicator

- vibration shape M2



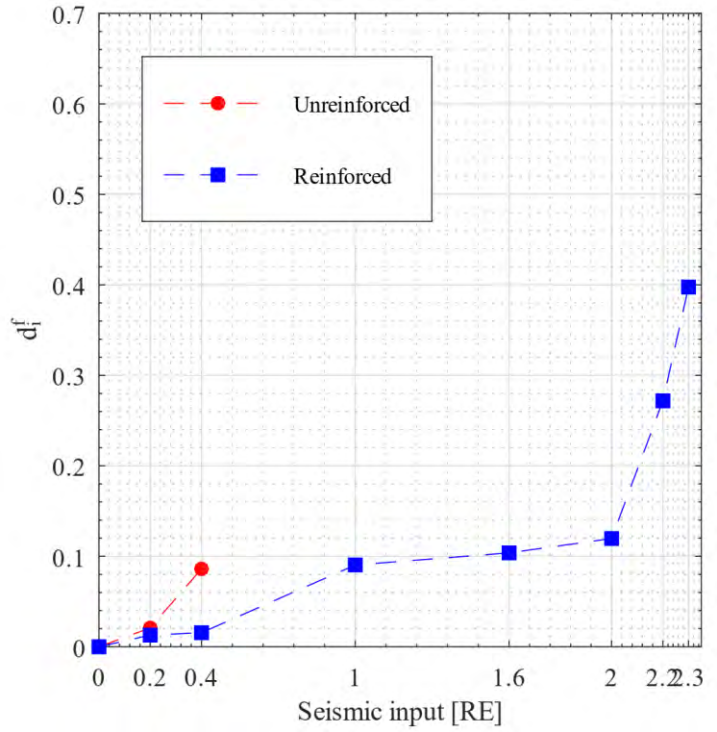


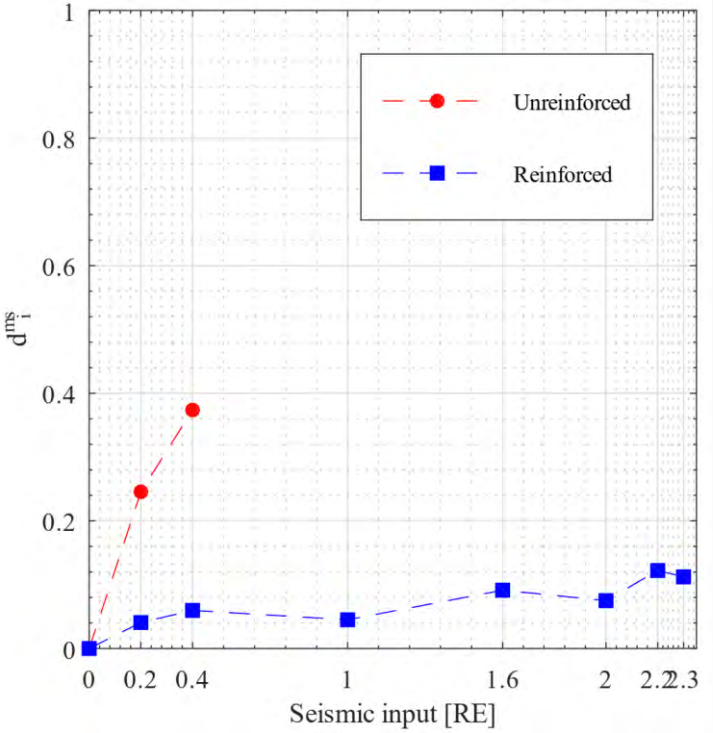
vibration frequency

vibration shape

comparison – damage indicator

- vibration shape M3



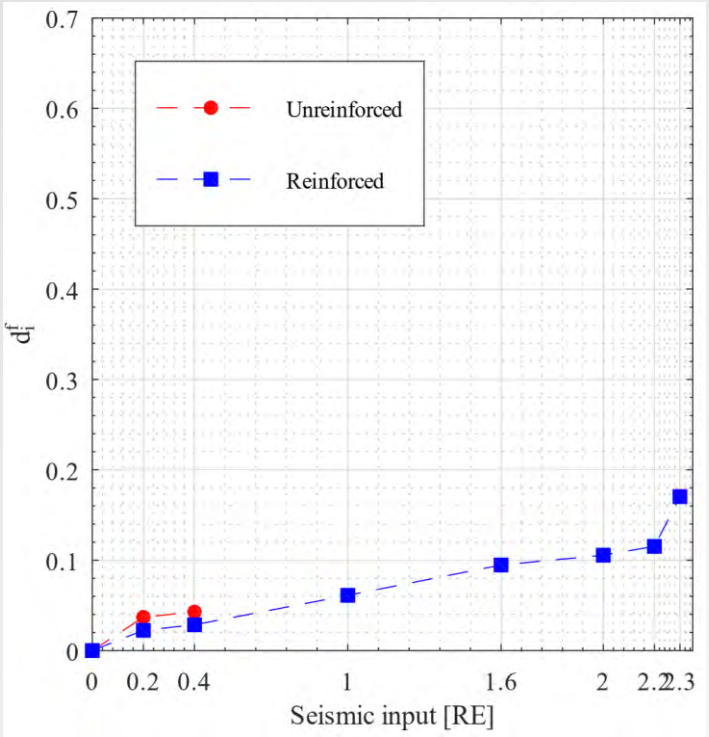


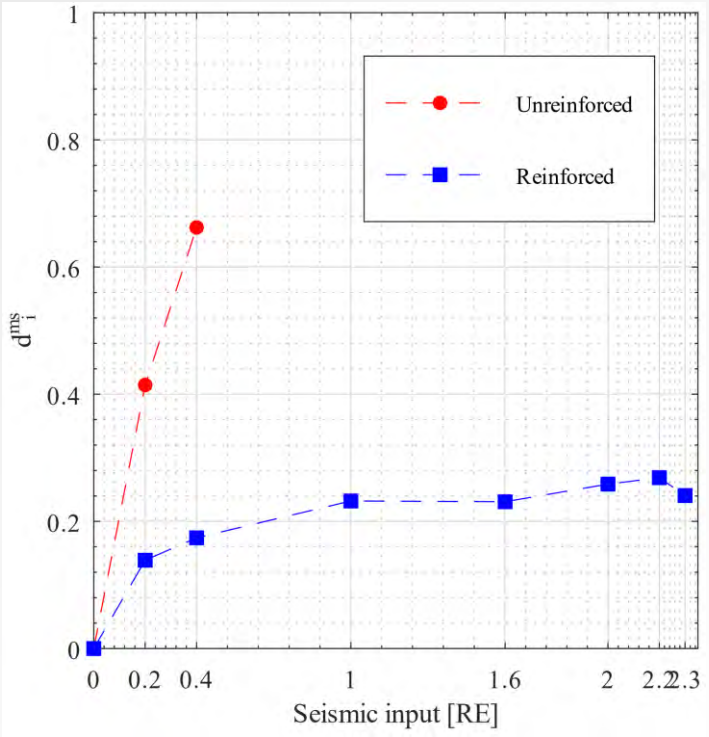
vibration frequency

vibration shape

comparison – damage indicator

- vibration shape M4





vibration frequency

vibration shape

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tecniche antisismiche innovative nella tradizione delle costruzioni

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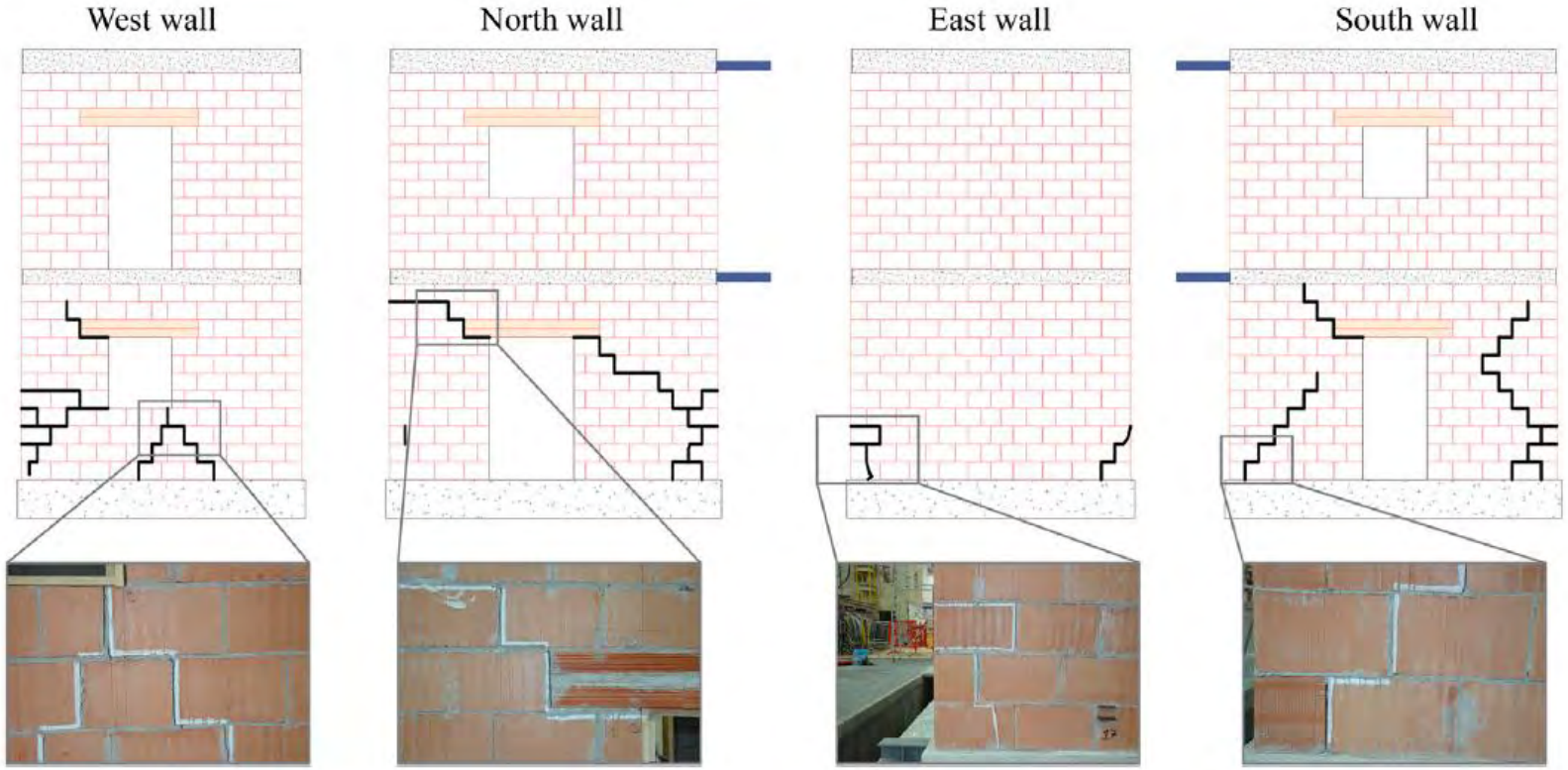
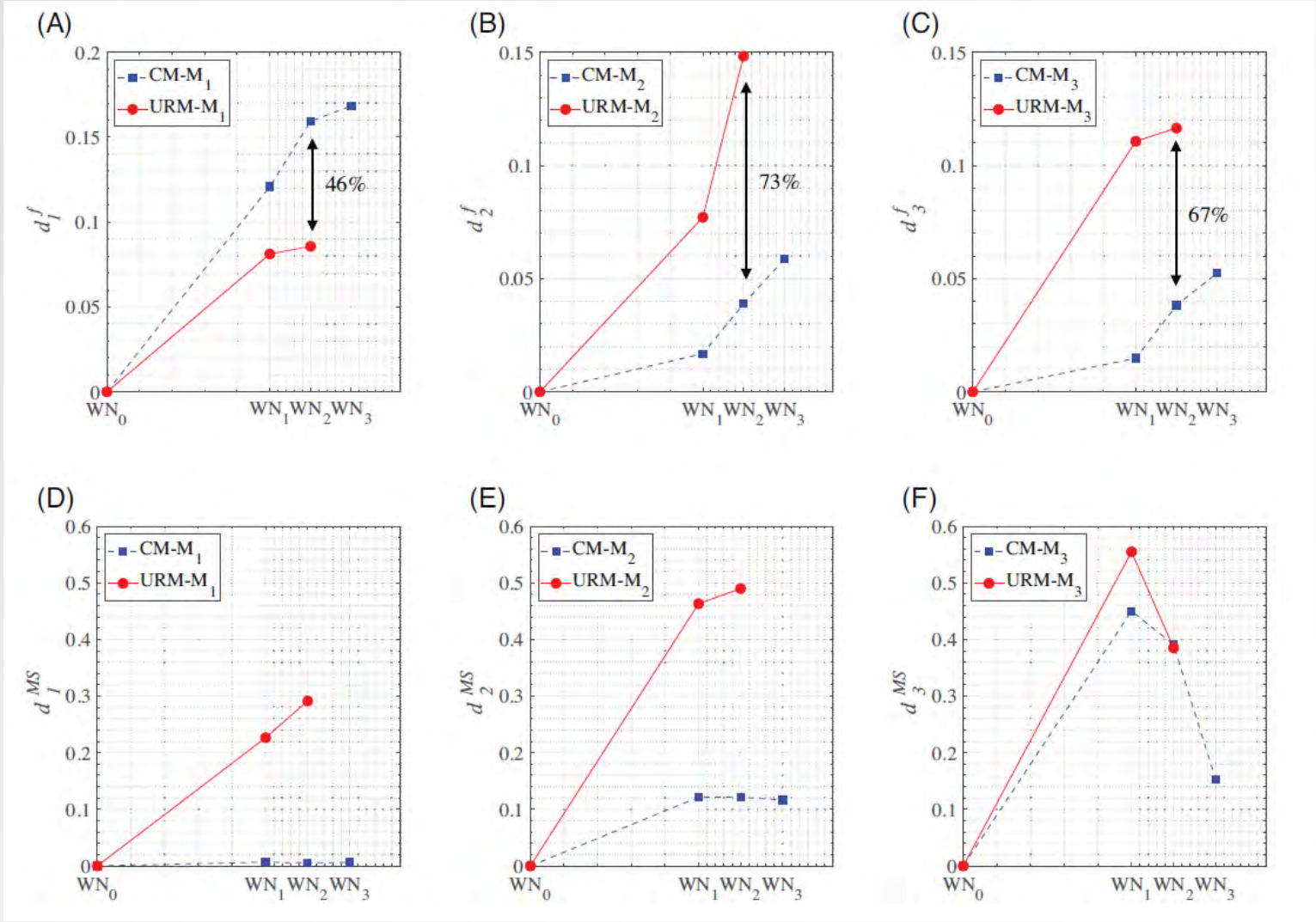


FIGURE 12 Damage survey on the URM building model after the E2-URM seismic level

Pepi, C., Cavalagli, N.,Gusella, V., Gioffrè, M.. (2021) "*Damage detection via modal analysis of masonry structures using shaking table tests*.", Earthquake Engineering and Structural Dynamics, Volume 50, Issue 8, 2077-2097


(A)
CM-M1
URM-M1
46%
(B)
CM-M2
URM-M2
73%
(C)
CM-M3
URM-M3
67%
(D)
CM-M1
URM-M1
(E)
CM-M2
URM-M2
(F)
CM-M3
URM-M3
WN0
WN1WN2WN3

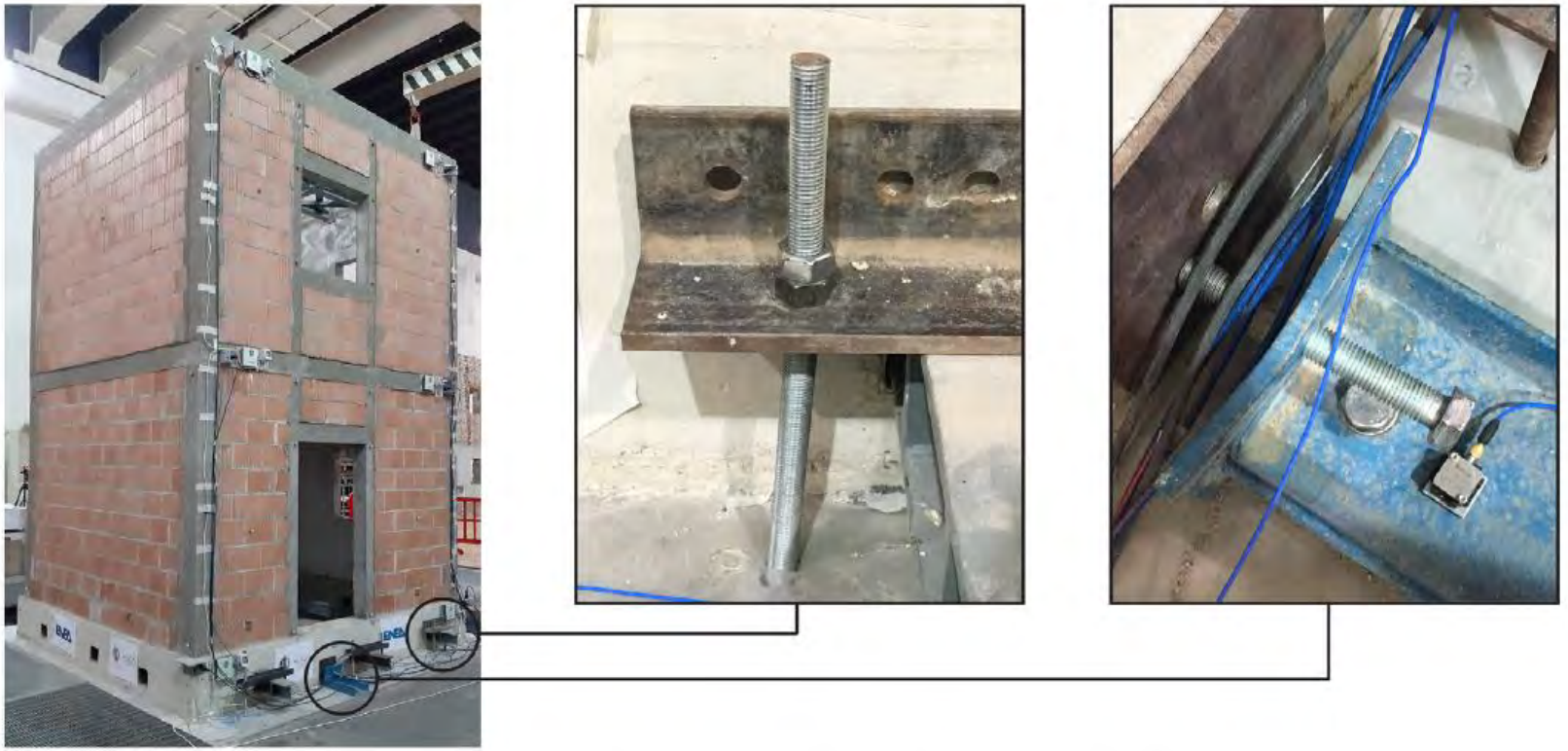


FIGURE 15 Localized damage at the CM building model support after the E3-CM seismic level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