GRAN SASSO SCIENCE INSTITUTE
UNIVERSITY OF L'AQUILA
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GRAN SASSO SCIENCE INSTITUTE
CENTER FOR ADVANCED STUDIES
Istituto Nazionale di Fisica Nucleare

Long-term structural monitoring: two case study experienced after the 2009 L'Aquila Earthquake

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Outline

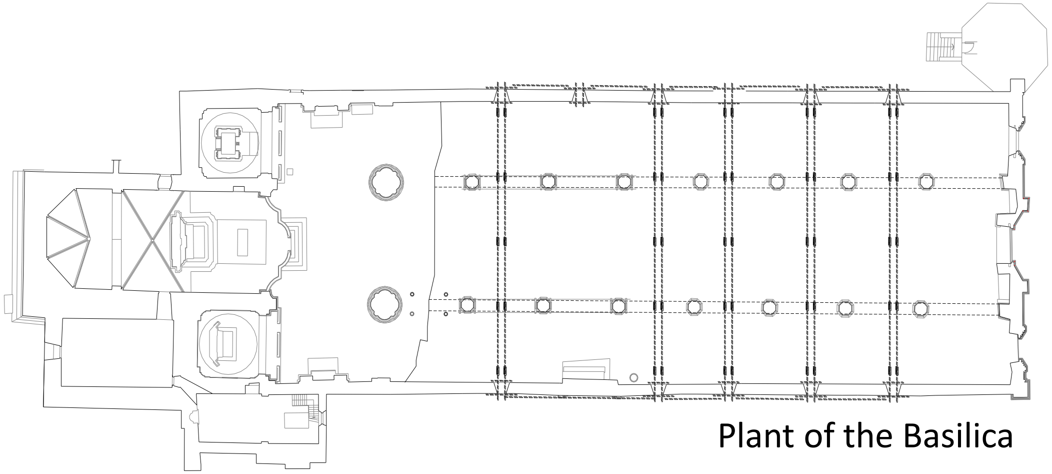
- **Long-term structural monitoring of the Basilica S. Maria di Collemaggio**

- **Seismic retrofitting and structural health monitoring of a masonry vault by using Glass Fiber Reinforced Polymer (GFRP) grids with embedded Fiber Bragg Grating (FBG) sensors**

Long-term seismic monitoring of the Basilica S. Maris di Collemaggio

The basilica S. Maria di Collemaggio is the most important church in the city of L'Aquila, Italy

Location



Plant of the Basilica

Main Facade

- The church has a central nave (61 *m* in length and 11.3 *m* in width) and two side aisles (7.8 *m* and 8.0 *m* in width).
- Naves and side aisles are separated by two series of seven columns (height of 5.3 *m*, central section of about 1 *m* in diameter).
- The two external and longitudinal walls, with a masonry thickness varying from 0.95 *m* to 1.05 *m* are connected on two sides with the church façade and transept area.

The basilica S. Maria di Collemaggio and L'Aquila Earthquake

Before the earthquake (6 April 2009)

After the earthquake

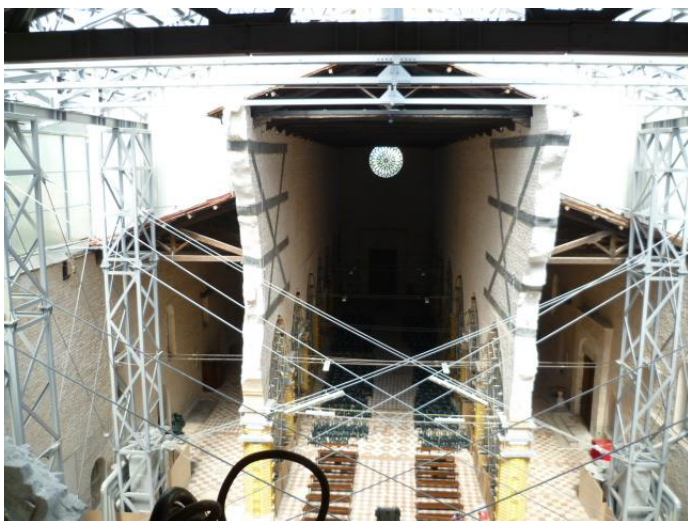
Partial collapse of the structure

Scaffolding system to preserve further collapse

Tendonds inserted between the external walls

Scaffolding inserted under the arches

View from above



Temporary composite tape wrapped around the columns for confinement

Long-term post-earthquake structural health monitoring project

The main goals of a long-term post-earthquarke SHM are:

(i) to investigate the possible causes of the collapse;

(ii) to monitor the performance of the scaffolding structures and other installed reinforcements (tendons between the walls and temporary composite tape wrapped around the columns for confinement);

(iii) to avoid the progression of damage;

(iv) to explore possible advantages arising from the use of innovative technologies

(v) to make a long-term analysis of the structure dynamic response and its modification after final retrofitting and reconstruction.

Milestones

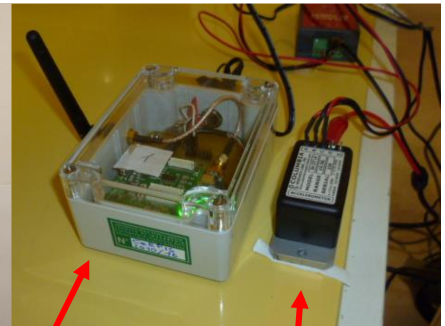
Phase 1: MEMSIC Imote2 based WSN for vibrational monitoring by means of acceleration measurements: calibration laboratory testing of wireless sensors nodes.

Phase 2: Numerical analysis to support the structural monitoring design.

Phase 3: Installation of the monitoring system: implementation of continuous vibrational monitoring.

Phase 4: Modal identification through measurements of the dynamic response due to different loading condition

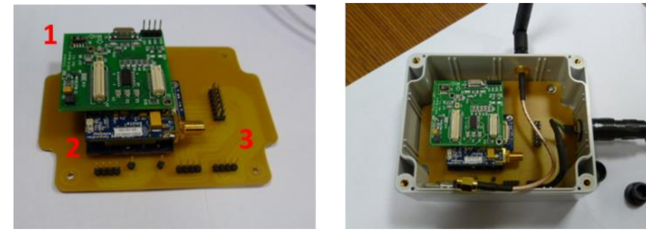
Experimental Tests Wireless vs Wired



Wireless Sensor Node

Wired accelerometer Columbia Model SA-107LN

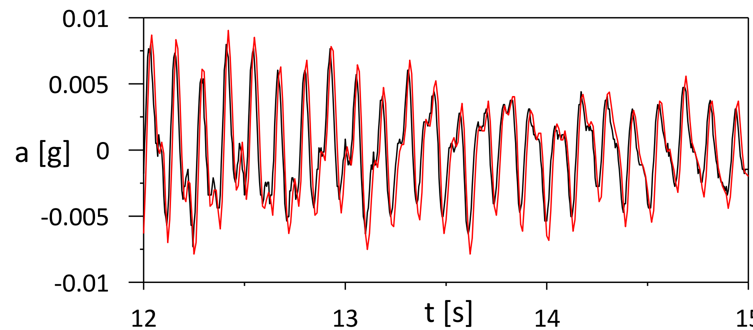
Experimental apparatus for wireless sensors characterization
Modular structural steel frame (1:3 scaling, 3m total height)

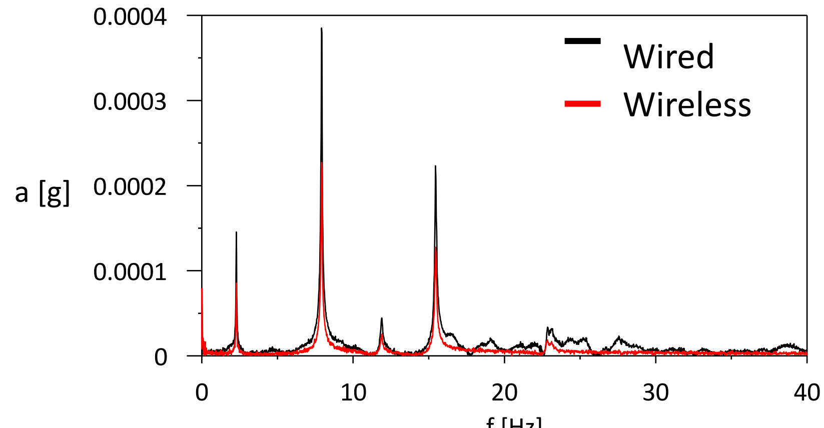


1) Sensor Board (MEMSIC SHM-A) with a MEMS accelerometer (ST microelectronics LIS344ALH)

2) MEMSIC IMOTE 2 platform for wireless communication with ISHMP toolsuite (University of Illinois)

3) Custom supply system and packaging



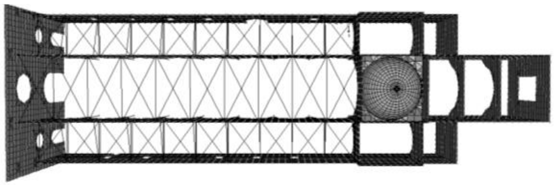


MEMS characteristics

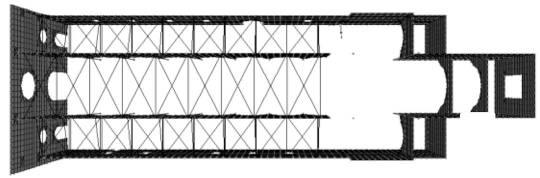
Parameter	Value
Axes	3
Measurement range	± 2g
Resolution	0.66 V/g
Power supply	2.4 V to 3.6 V
Noise density, x and y axes	22 - 28 mg/Hz
Noise density, z axis	30 - 60 mg/Hz
Temperature range	-40 to 85 °C
Supply current	0.85 mA

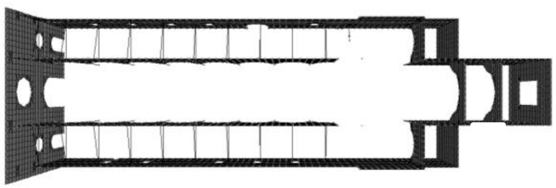
Numerical Analysis

A

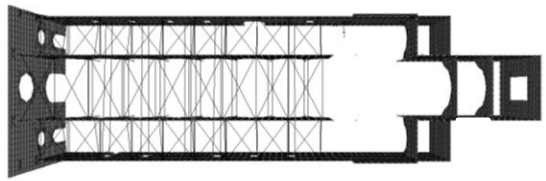


B





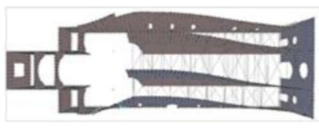
C



D

CONSTRUCTING A MODEL FOR THE CONFIGURATION AFTER THE 2009 L'AQUILA EARTHQUAKE

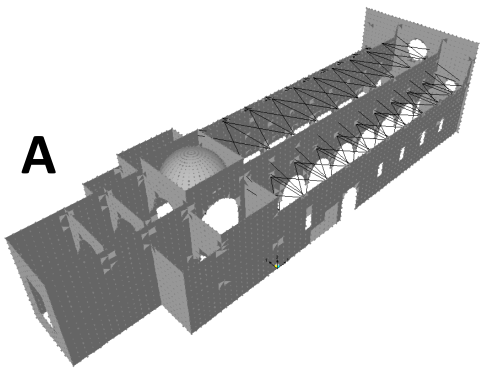
Mode 1 (D)



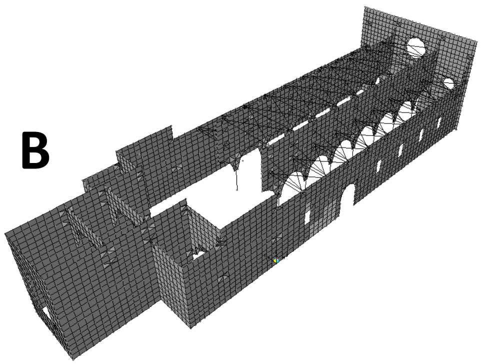
Mode 2 (D)

Model	Representativeness
A	Before the Earthquake
B	After the Earthquake with bracing
C	After the Earthquake without bracing
D	After the Earthquake with bracing and others interventios

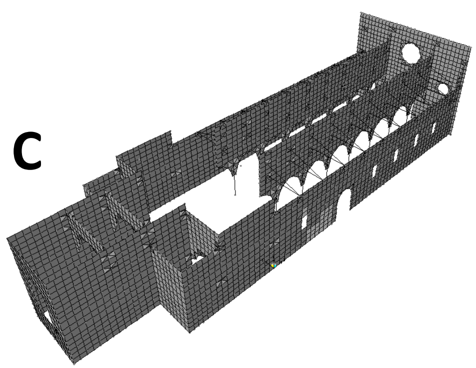
A



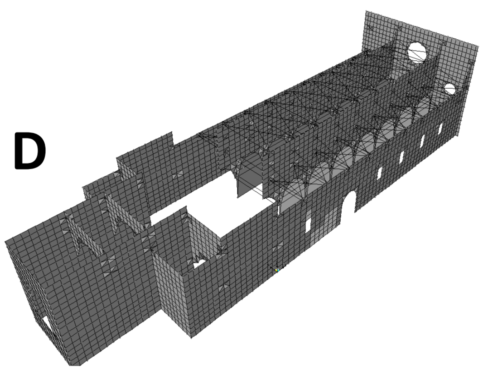
B



C



D



Installation of the monitoring system

June 2011

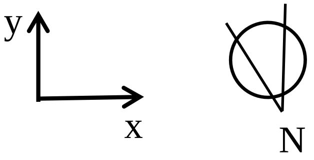




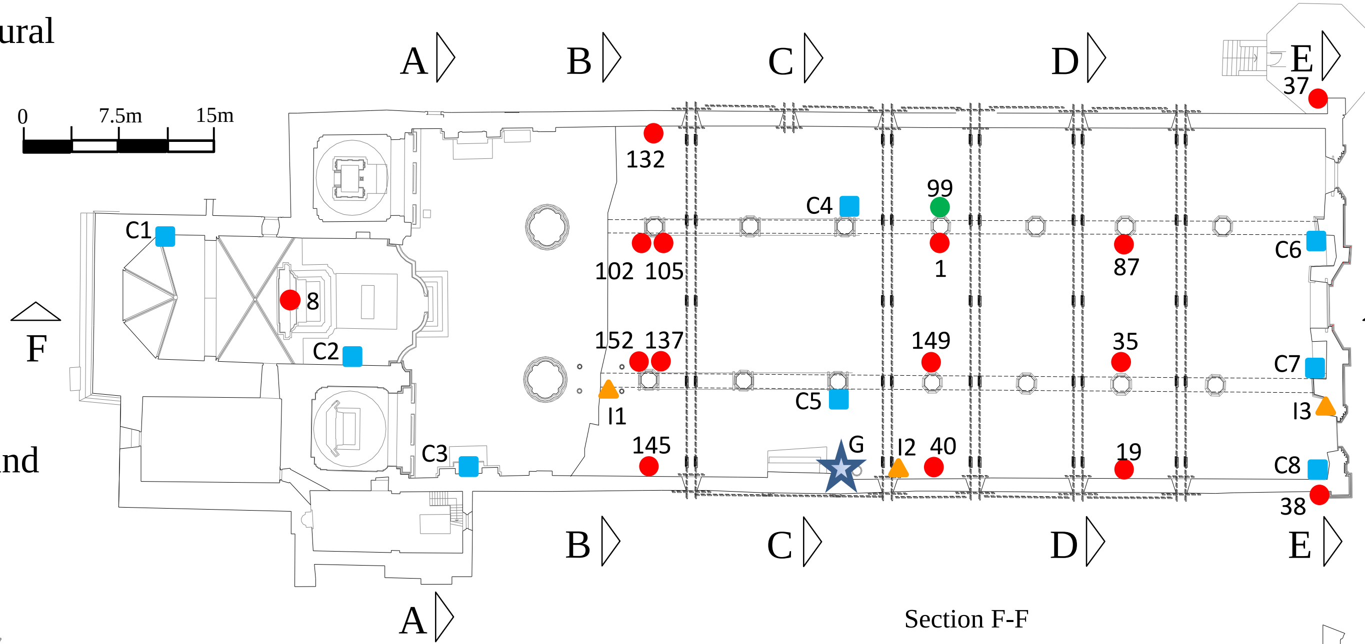


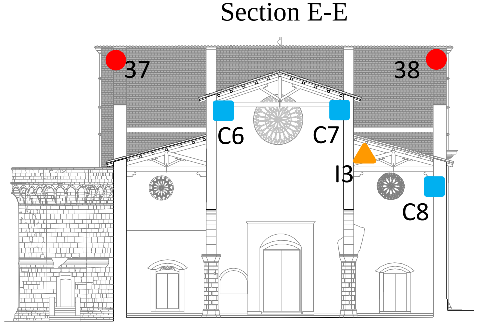
Multifunction wireless sensor positioning

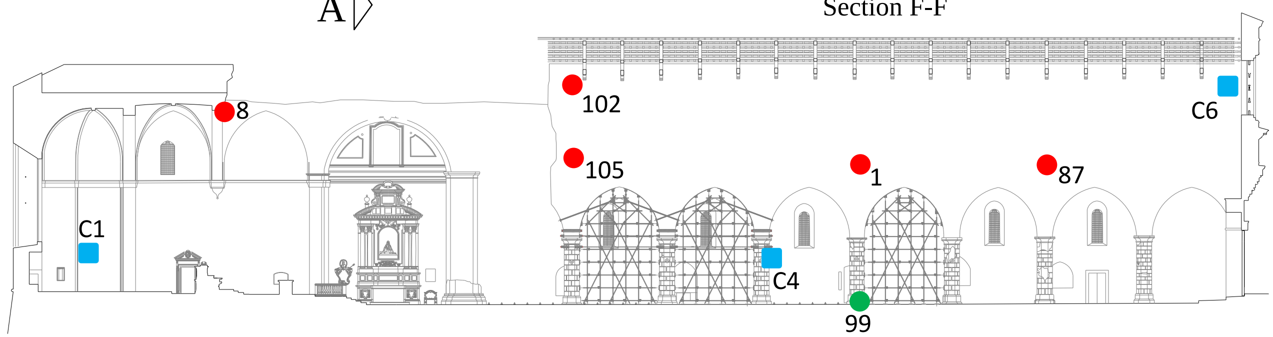
Layout of the complete structural health monitoring system

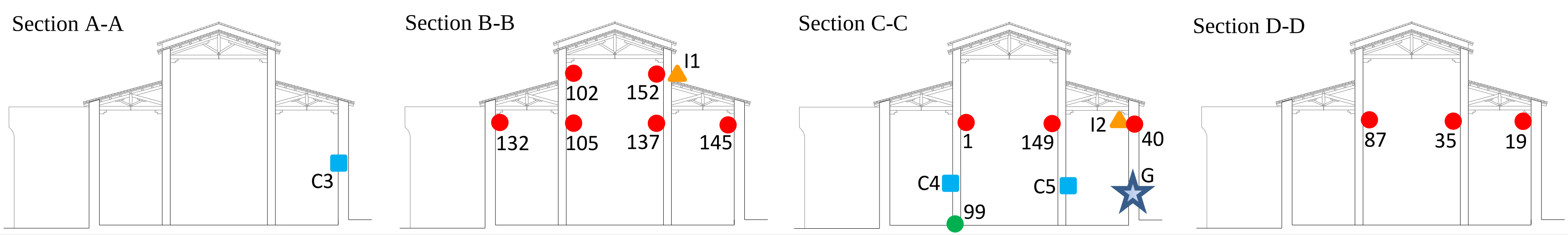


- accelerometer
- extensometer
- inclinometer
- accelerometer on the ground
- node gateway





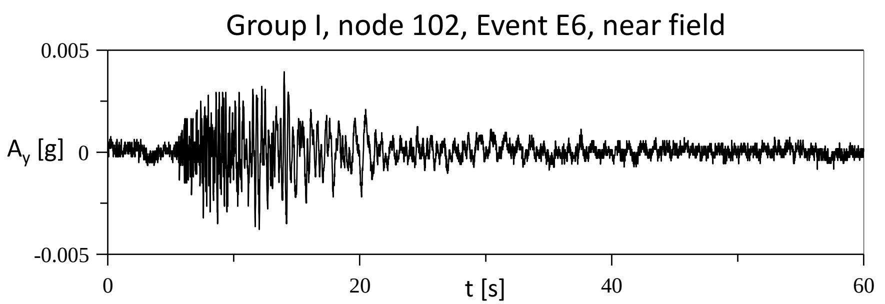


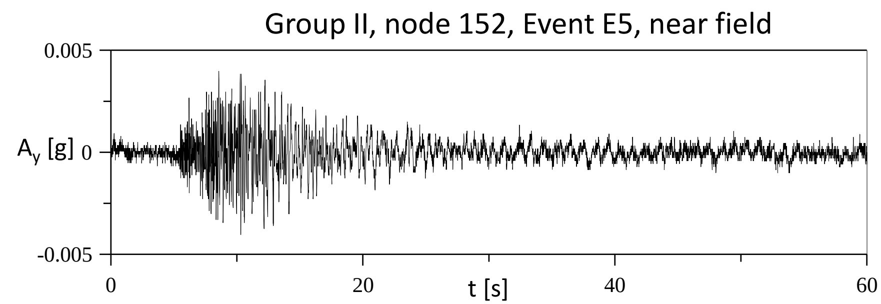


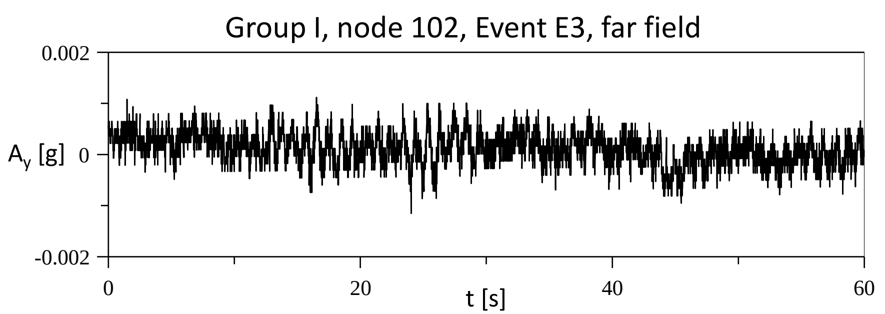
Main seismic events recorded by the WSN to the Basilica S. Maria di Collemaggio

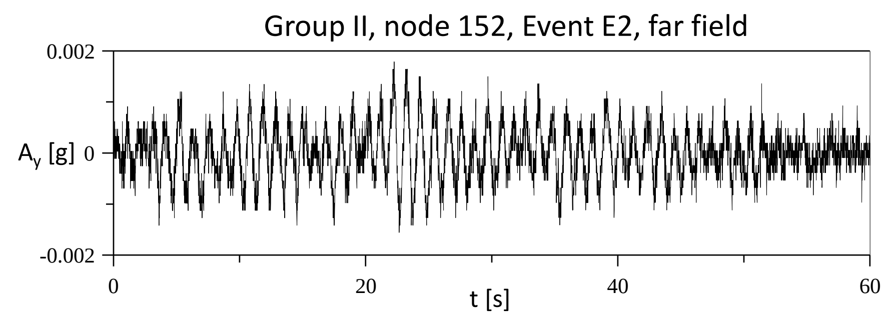
Event	Earthquake/epicenter	D	Date	Time (UTC)	M	PRA [mm/s^2]	Group
E1	Main Emilia/Finale Emilia	F	20/05/2012	2:03 AM	5.9	70.4	I
E2	After Emilia/Vigarano	F	20/05/2012	1:18 PM	5.1	17.9	II
E3	After Emila/Cervia-Ravenna	F	06/06/2012	6:08 AM	4.5	10.9	I
E4	L'Aquila/Scoppito	N	14/10/2012	4:32 PM	2.8	71.7	II
E5	L'Aquila/Pizzoli-Scoppito	N	30/10/2012	2:52 AM	3.6	72.7	II
E6	L'Aquila/Pizzoli	N	16/11/2012	3:37 AM	3.2	83.2	I
E7	L'Aquila/Val di Sangro	N	14/02/2014	8:51 PM	2.9	26.2 (60.4)	I
E8	L'Aquila/Valle dell'Aterno	N	04/09/2014	3:55 PM	2.1	18.8	I

D: distance of the epicenter (F=far; N=near); M: magnitude. () relative to the node 37 in global X-direction. PRA: Peak Registration Acceleration





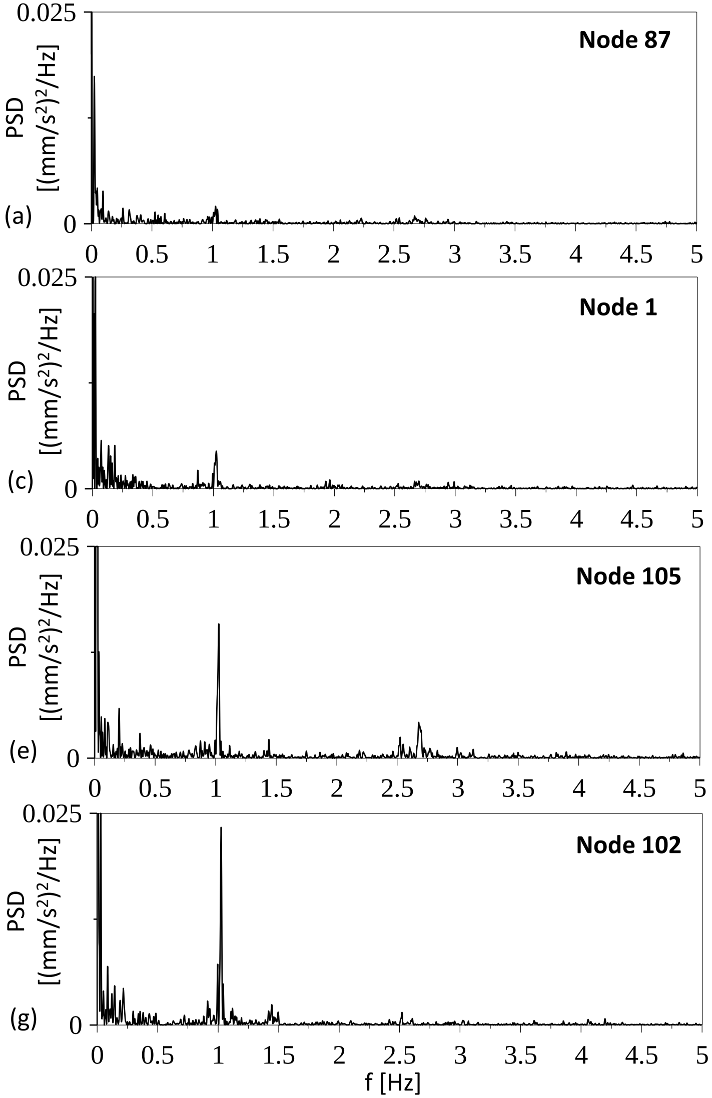




Group I

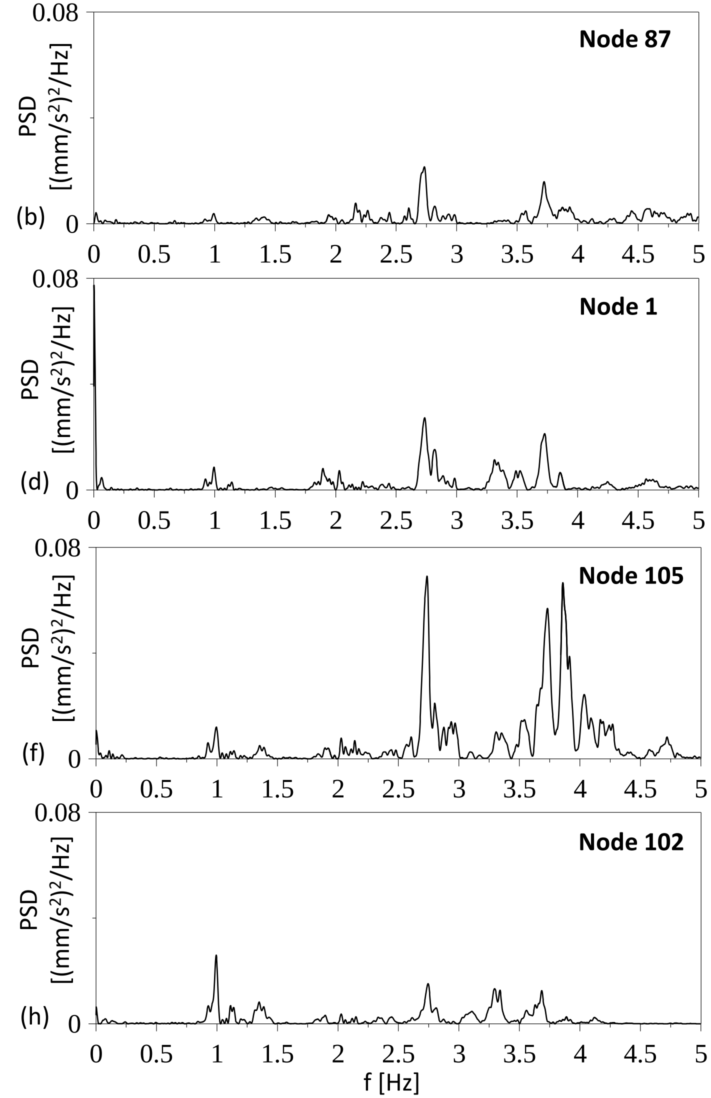
Far field

06 June 2012



Near field

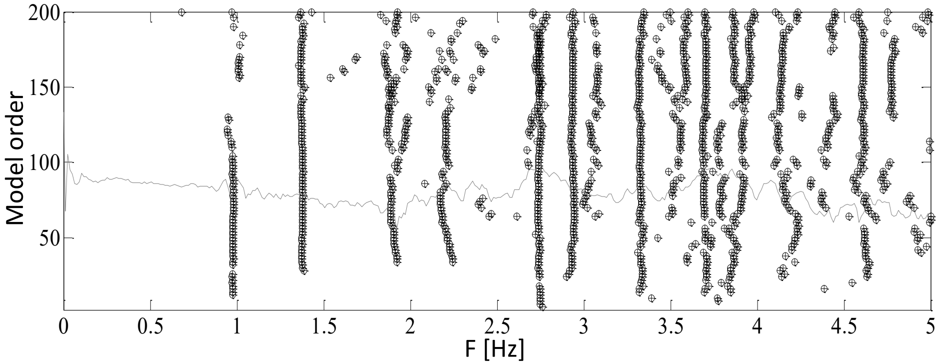
16 November 2012



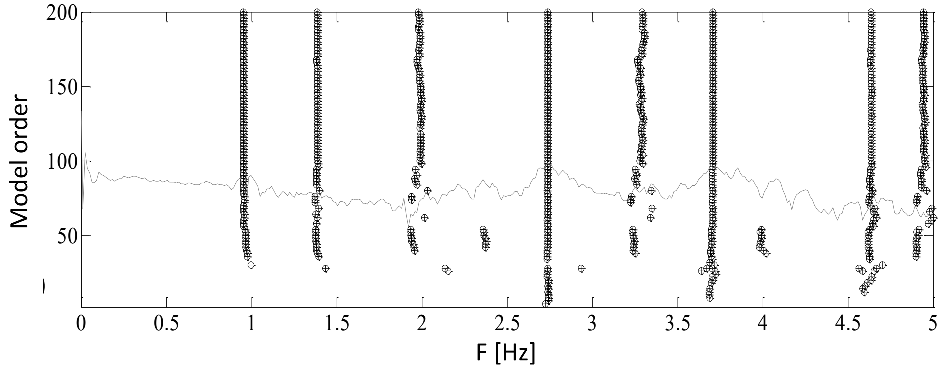
Stochastic Subspace Identification: Group I and Group II

Event E6, 16 November, 2012 – Measurements belonging to the Group I

all output (nodes 102, 105, 1, 87)

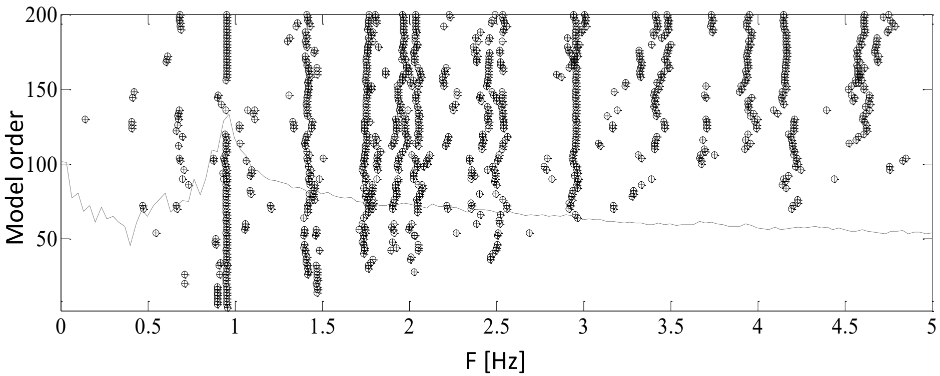


Node 87 as reference

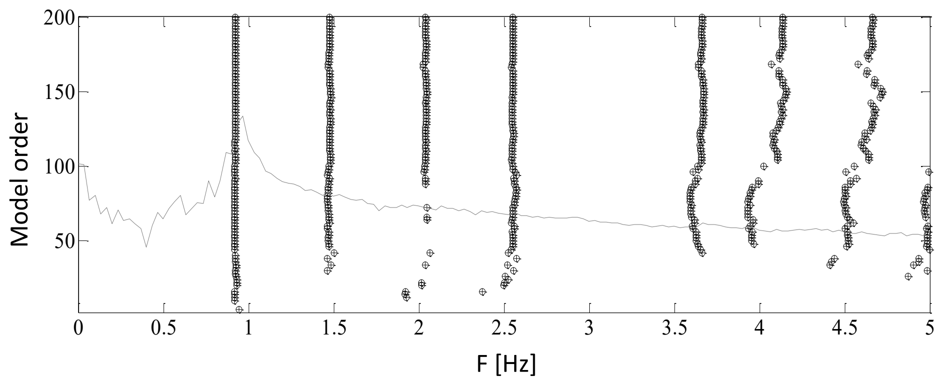


Event E2, 20 May, 2012 – Measurements belonging to the Group II

all output (nodes 137, 152, 145, 149, 40, 35, 19)

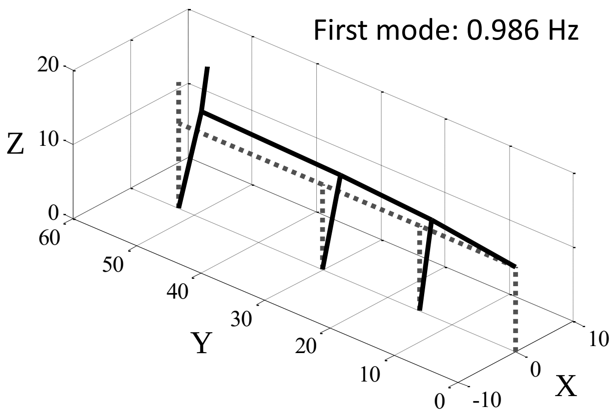


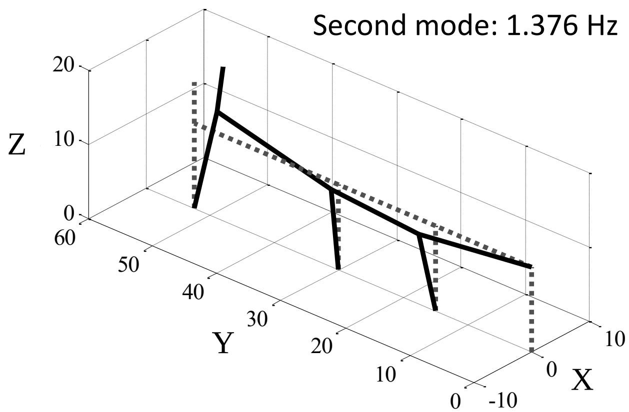
Node 152 as reference

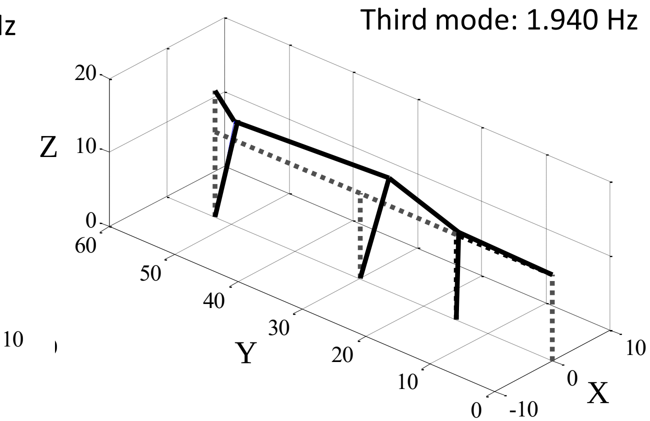


Modal identification

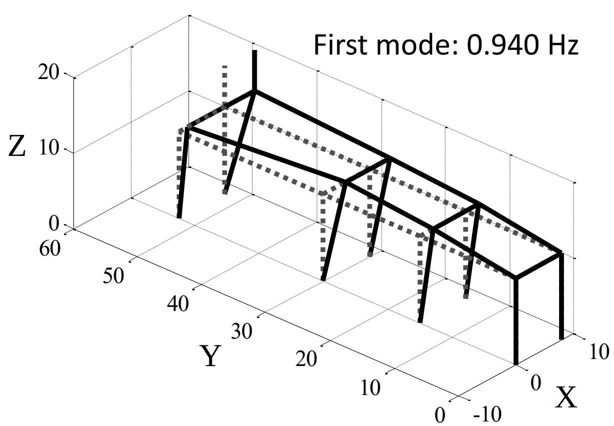
Modes identified thruoght the measurements coming from the nodes belonging to the Group I

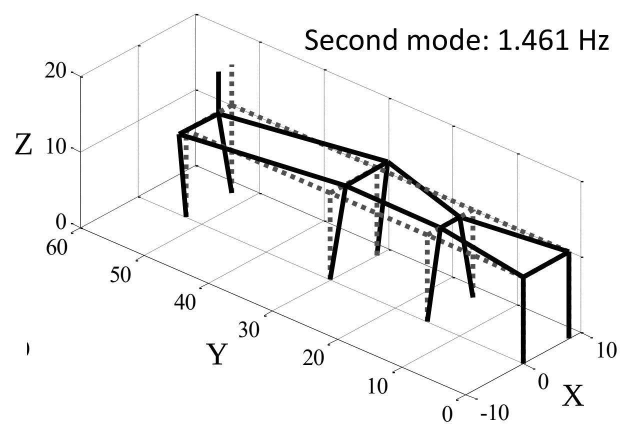


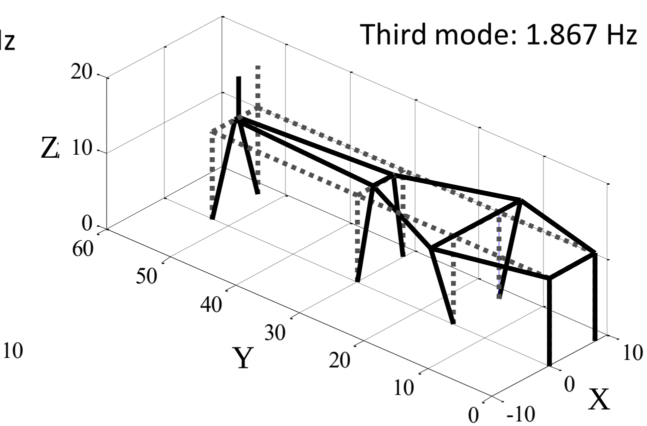




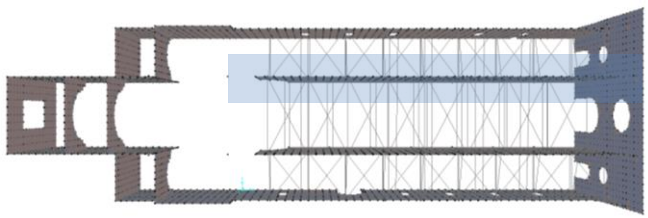
Modes identified thruoght the measurements coming from the nodes belonging to the Group II

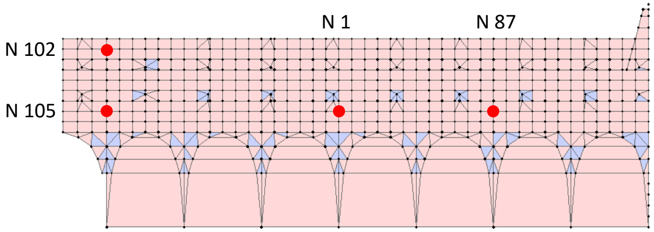






Finite modal updating





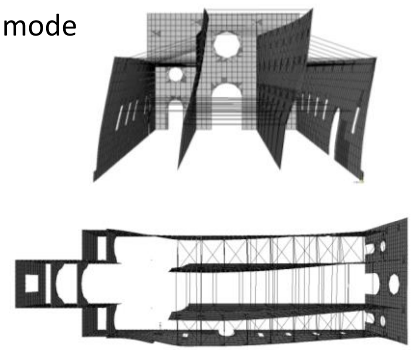
	Frequencies		
Modes	Identified	Numerical	Δ %
1	0.9780	0.9500	2.95
2	1.3970	1.5600	-10.45
3	1.9100	2.0100	-4.98

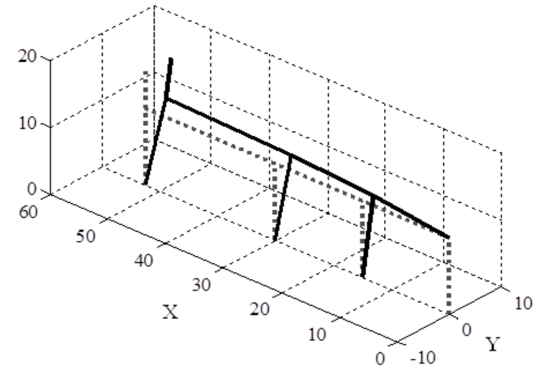
	MAC		
Modes	Reduced		
1	0.9885	0.2081	0.5100
2	0.4118	0.9727	0.0555
3	0.1327	0.0940	0.7840

	MAC		
Modes	Expanded		
1	0.9929	0.0078	0.0010
2	0.0079	0.9706	0.0209
3	0.0343	0.0240	0.9447

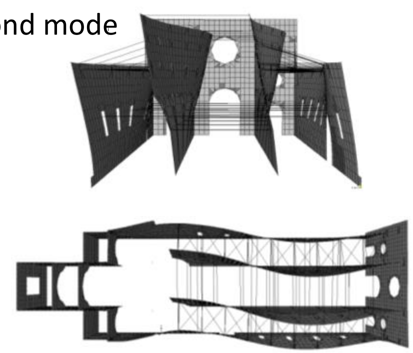
Numerical | **Identified**

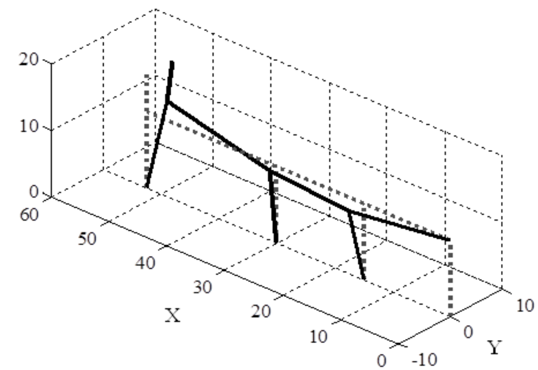
First mode



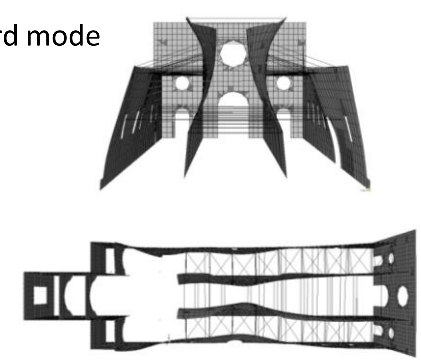


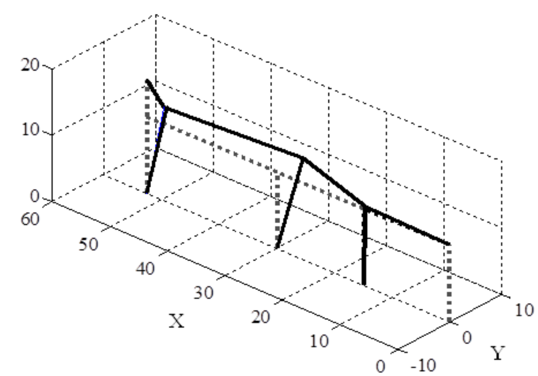
Second mode





Third mode





Conclusions

The work described the design, deployment, management and performance of a WSN used for the vibration-based seismic monitoring of a monumental structure, the Basilica S. Maria di Collemaggio in L'Aquila after the partial transept collapse caused by the catastrophic 2009 earthquake.

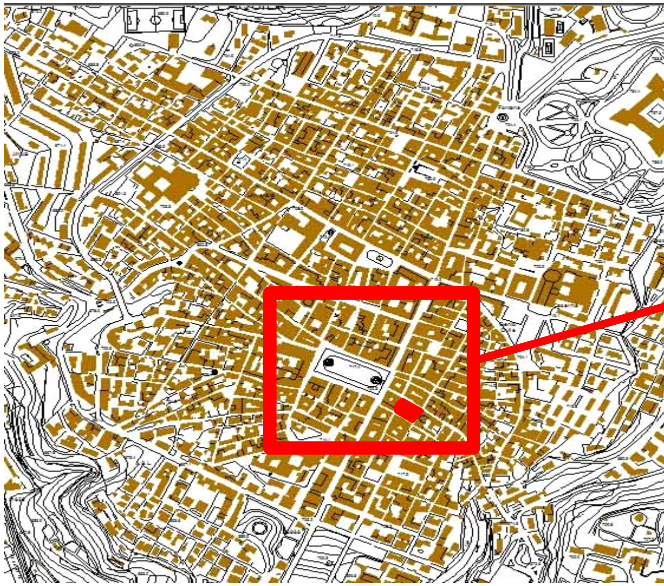
The data acquired during some low-energy seismic events have been analyzed to extrapolate the principal modal characteristics (frequencies, modal shapes and damping). Procedure working in frequency domain, time domain and time-frequency domain have been applied providing stable results also for different seismic events (far and near field).

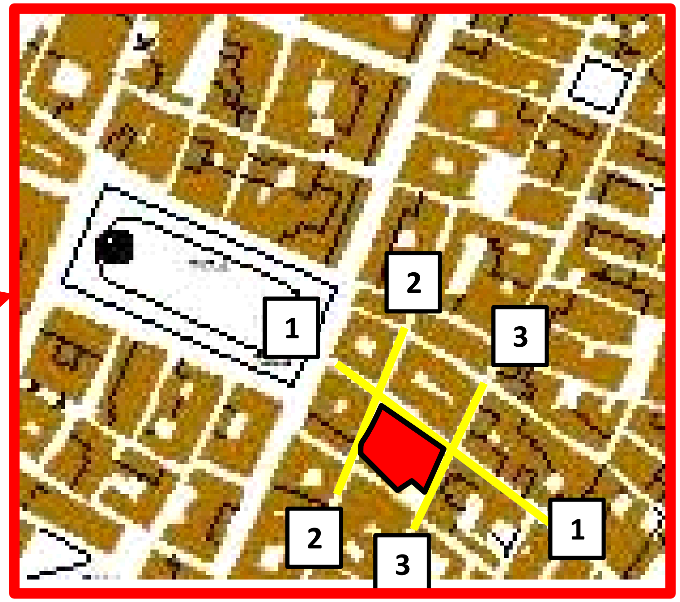
The difficulty in the interpretation of the structural behaviour due to the its interaction with safety system has to be highlighted. Future development will be addressed by the improvements of the finite element models representative of the actual behaviour.

Seismic retrofitting and structural health monitoring of a masonry vault by using Glass Fiber Reinforced Polymer (GFRP) grids with embedded Fiber Bragg Grating (FBG) sensors

The polycentric pavillion vault

LOCATION: DownTown of L’ Aquila city

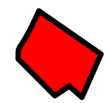




1 1 Cimino Street

2 2 Santa Giusta

3 3 Rosso Guelfaglione



”Two Courts” BLOCK

The polycentric pavillion vault

''FIRST'' DEFINING OF MECHANICAL PARAMETERS

For defining of the mechanical parameters of the vault was not possible use destructive testing.

Sheet-placed bricks
4 cm thickness

The ITALIAN BUILDING CODE furnishes a range of value for main mechanical parameters; furthermore, furnishes some correction factor depending on the quality of bricks and mortar, joints wodth and other properties.

E [MPa]	ν	f_m [MPa]	W (kN/m^3)
3375	0.15	5.4	18

The polycentric pavilion vault

THE INNOVATIVE STRENGTHENING SYSTEM

In order to overcome the durability and eco-compatibility issues of epoxy resins it is used hydraulic lime glue in conjuction with glass fiber grid.

APPLICATION STAGES

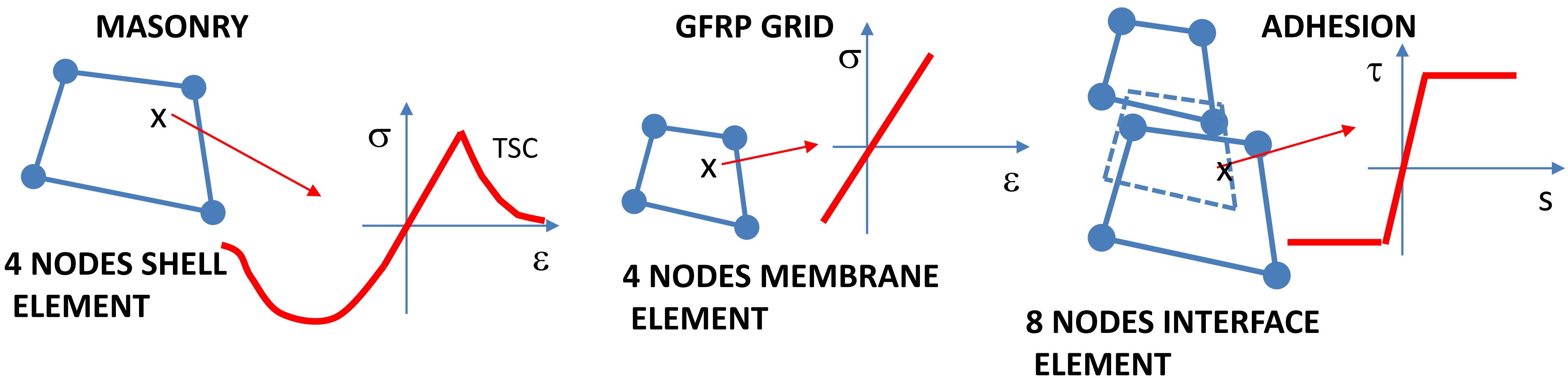
1. Cleaning and wetting of top surface,
2. Placement of First layer of hydraulic lime mortar,
3. Placement of GFRP grid,
4. Covering of reinforcement with second layer of hydraulic lime mortar.

Non Linear Finite Element Modeling

MIDAS CODE AS COMPUTATIONAL TOOL (MIDAS FEA)

MICROMECHANICAL APPROACH:

- Masonry vault is modelled by using four nodes Mindlin-Reissner shell elements with nonlinear constitutive law called Total Strain Crack model (TSC)
- GFRP grid is modelled by using four nodes membrane elements with linear elastic constitutive law
- Adhesion between the GFRP reinforcement and the masonry support is modelled by using eight node interface elements with a friction Coulomb model

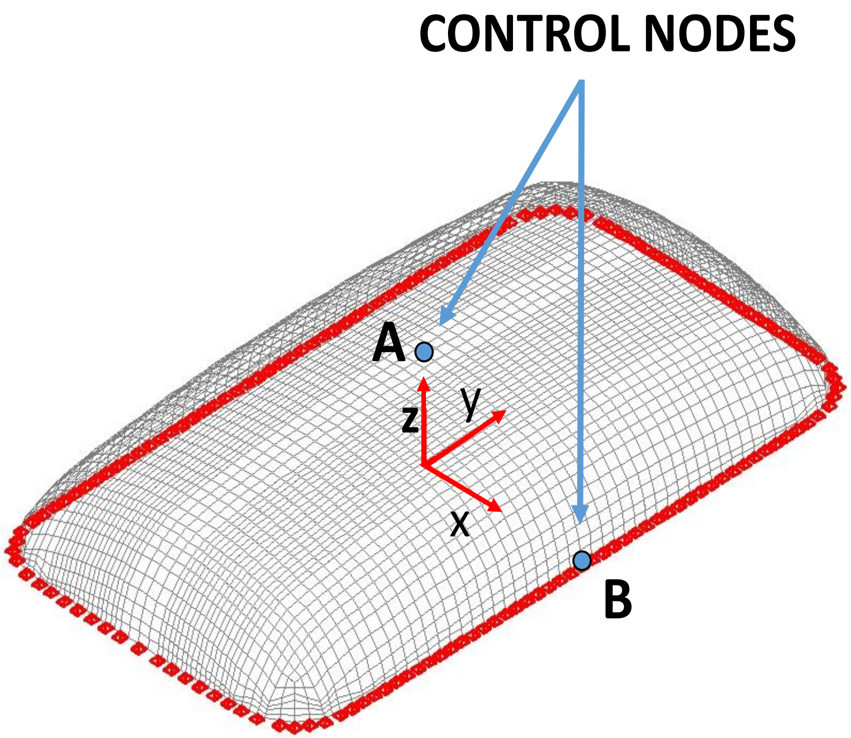


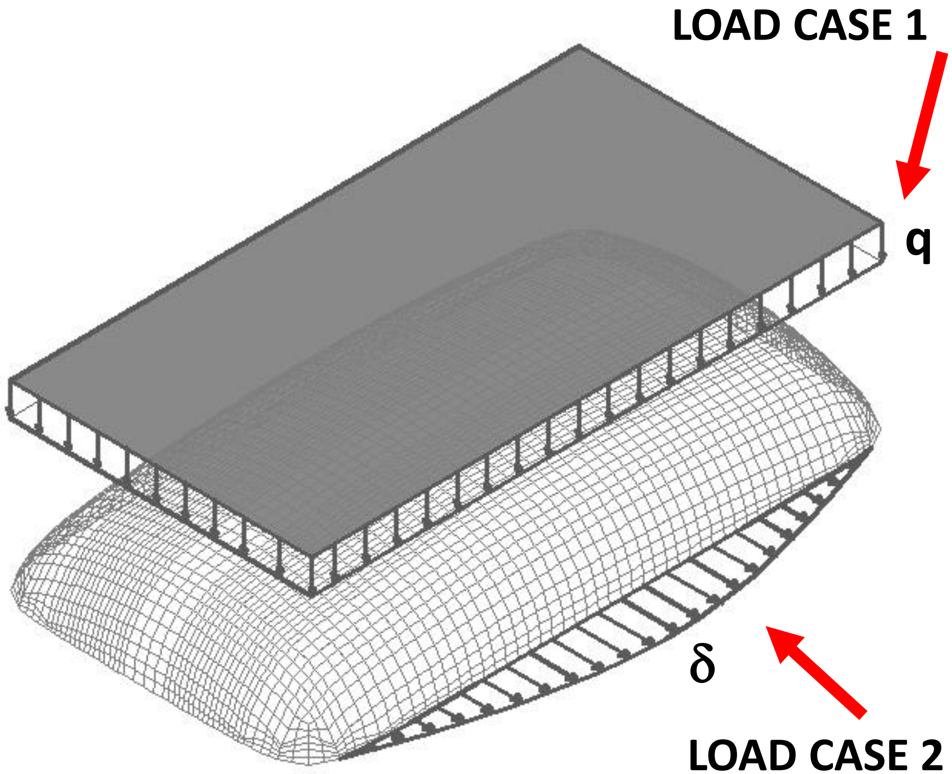
Non Linear Finite Element Modeling

DISCRETIZATIONS (3696 finite elements which assures the convergence of the numerical results)

BOUNDARY CONDITIONS (pinned at the basis)

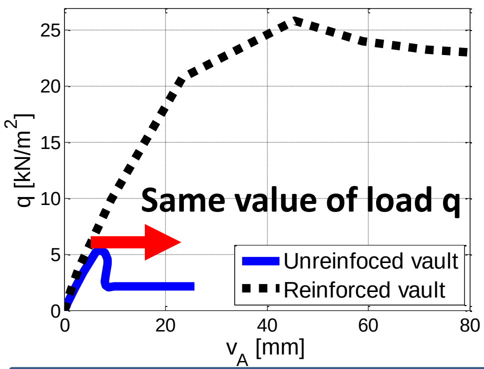
2 LOAD CASES (uniformly distributed vertical load and horizontal displacements with a parabolic distribution)





Non Linear Finite Element Modeling

NUMERICAL RESULTS FOR LOAD CASE 1 **2) Principal stresses**



Brittle → Plastic

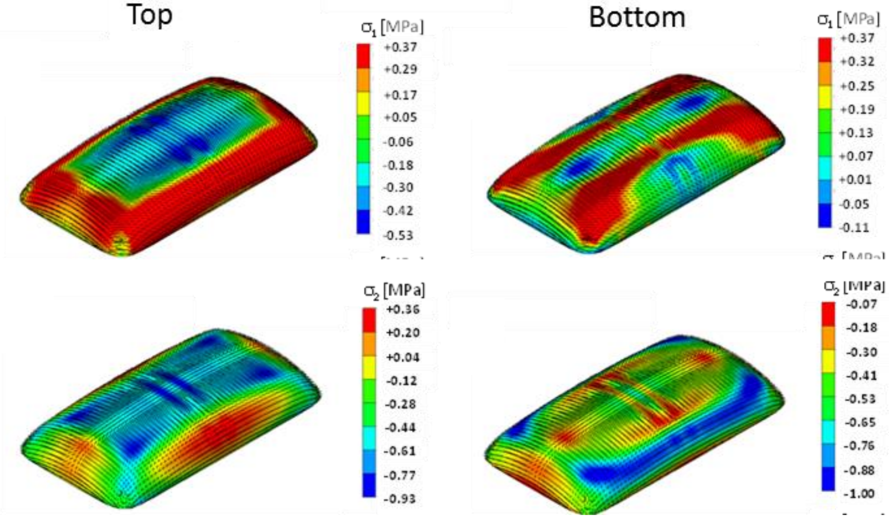
Strength x5 greater

NO SLIP between masonry and reinfor.

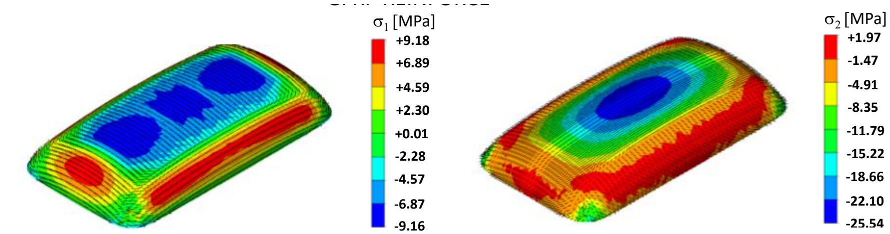
REINFORCED

Masonry

Top Bottom

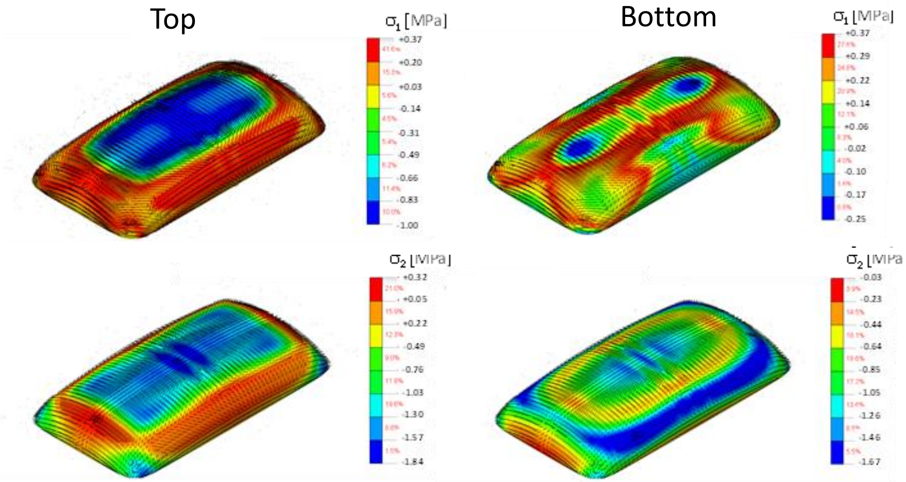


GFRP reinforcement



UNREINFORCED

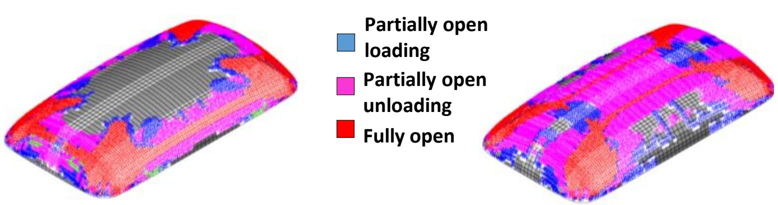
Top Bottom



3) Final cracking status

UNREINFORCED

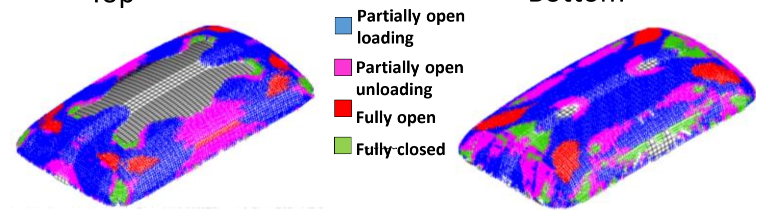
Top Bottom



- Partially open loading
- Partially open unloading
- Fully open

REINFORCED

Top Bottom



- Partially open loading
- Partially open unloading
- Fully open
- Fully closed

Integrating of Fiber Optic Sensors

WHICH MEASUREMENT

Definition of optic sensors is related to the type of measurement in the space. Sometimes is needed to measure alongside a line (strip reinforcements) and sometimes is needed a point measure.

Distributed measurement

BRILLOUIN SENSORS

MULTIPLEXED FABRY-PEROT SENSORS

MULTIPLEXED FIBER BRAGG GRATING SENSORS

Others …….

Point measurement

FABRY-PEROT SENSORS

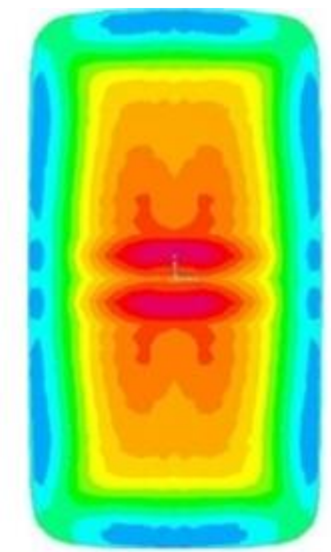
FIBER BRAGG GRATING SENSORS

Others …….

NETWORK CABLING AND SENSORS INSTALLATION

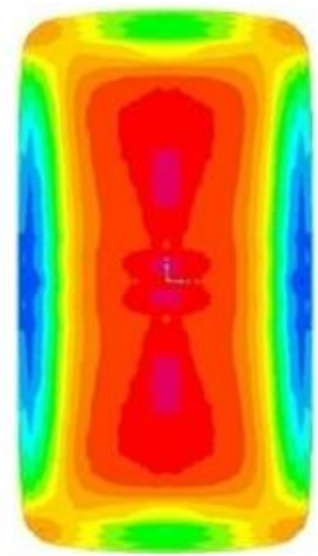
The definition of the sensors position is based on the results of linear and non-linear finite element analyses run.

Principal stresses of top surface are taken into account.



$\sigma_{11}^{max} = 0.096\ MPa$

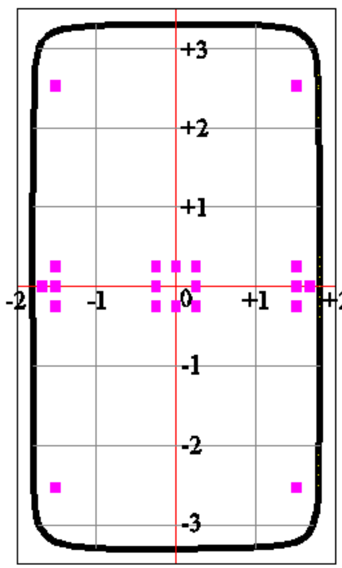
$\sigma_{11}^{min} = -0.21\ MPa$



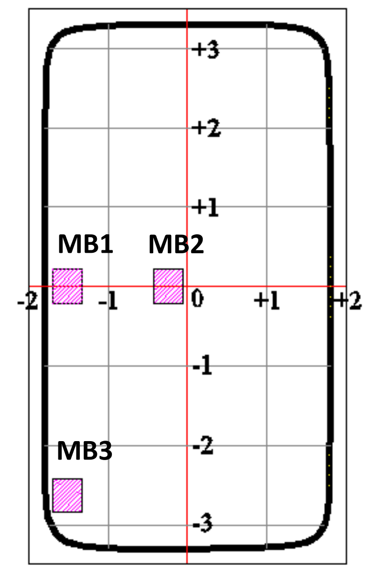
$\sigma_{22}^{max} = 0.15\ MPa$

$\sigma_{22}^{min} = -0.18\ MPa$

Maximum and minimum principal stresses



Optimal positioning



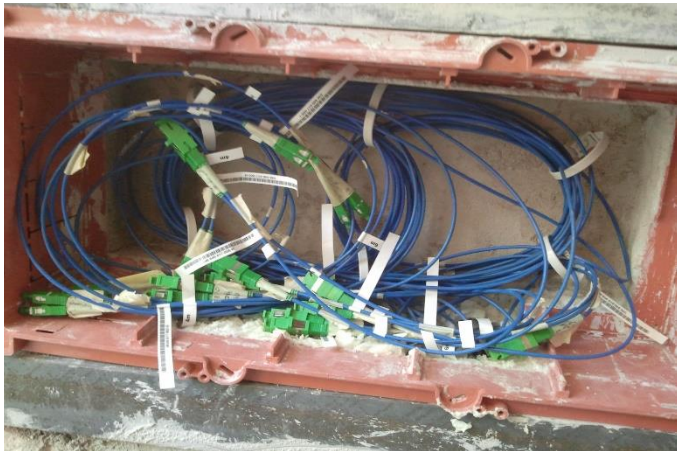
Choosen positions

Integrating of Fiber Optic Sensors

NETWORK CABLING AND SENSORS INSTALLATION: **PLACEMENT OF CABLE DUCTS AND OPTIC CABLES**

Placement on top vault surface of plastic ducts

Inserting (Cabling) of optic cables inside the plastic ducts

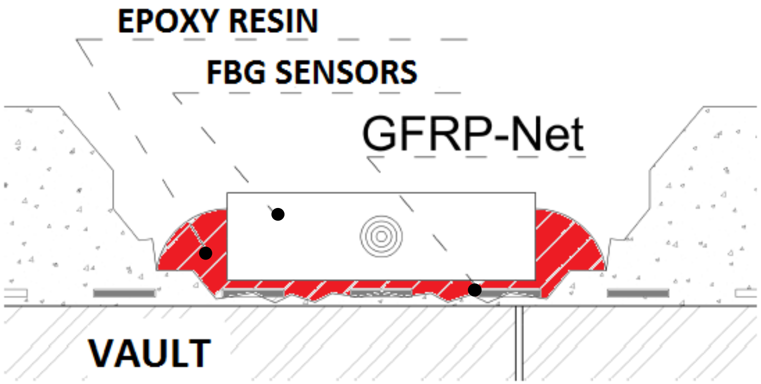


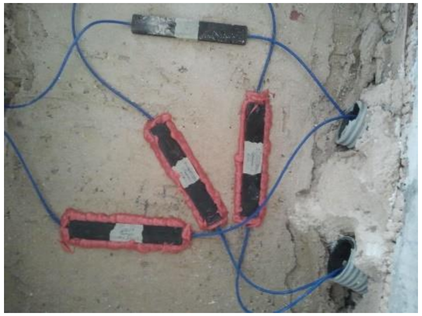
Integrating of Fiber Optic Sensors

NETWORK CABLING AND SENSORS INSTALLATION: **SUBSTRATE PREPARATION AND SENSORS GLUING**

Substrate preparation inside measurement boxes

Gluing of sensors





n. 3 strain sensors
n.1 temperature

NETWORK CABLING AND SENSORS INSTALLATION: **CABLES PROTECTION**

Placement of Protection ducts around to optic cables

Closing of Measurement Boxes

Long Term SHM

LONG TERM MONITORING TESTS

In-service condition (occupied house) the schedule of the research project includes measurements each two months and after earthquakes.

The monitoring system can be connected with the network of the city for real-time measurement.

1° LOADING TEST OF JULY 2015

To calibrate the monitoring system a static test has been performed. The load was increased from 0 to 2,5 kN (on square loading area of 0,50 m) at the center of the vault.

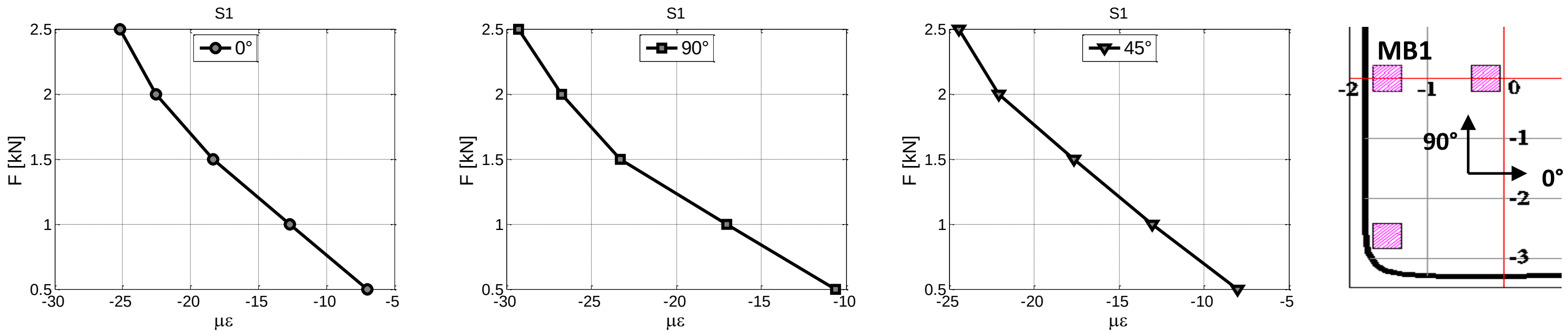
q= 0,5 kN

q= 1,0 kN

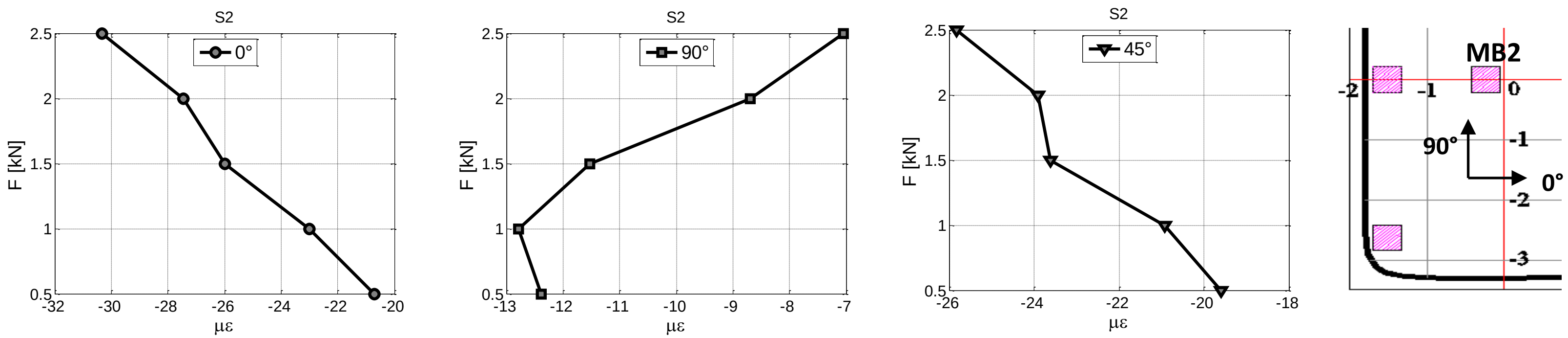
q= 2,0 kN

ANALYSIS OF EXPERIMENTAL STRAIN DATA

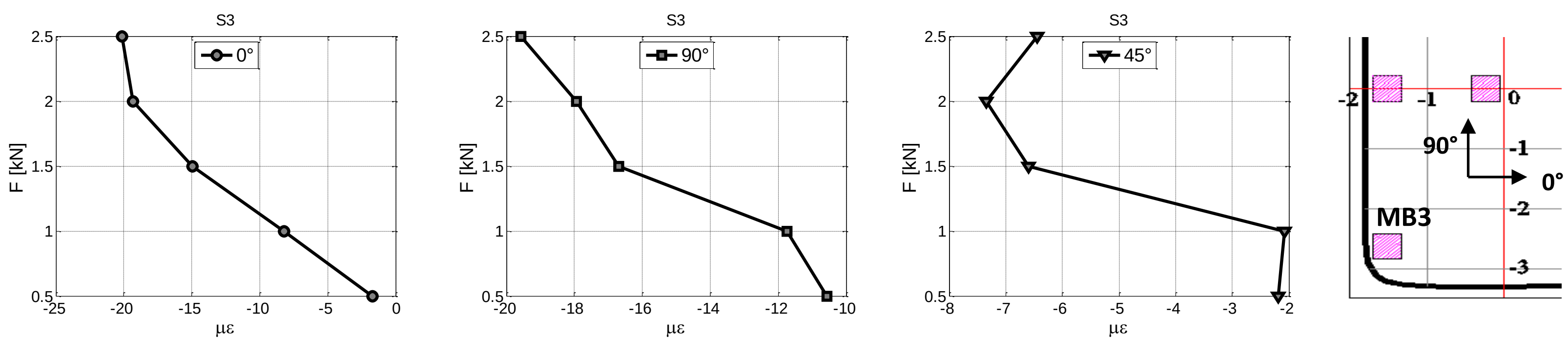
MBOX 1



MBOX 2



MBOX 3



Conclusions and Future Directions

Developed and tested on real structure of a SMART strengthening system for masonry (innovative materials with integrated sensors)

Performed of Linear and complex Non-linear Finite Element Analyses for defining proper placement of sensors and mechanical response of the vault

Comparisons of numerical outcomes with experimental data to assure good calibration of sensors

Potenza F., Federici F., Lepidi M., Gattulli V., Graziosi F., Colarieti A., “Long term structural monitoring of the damaged Basilica S. Maria di Collemaggio through a low-cost wireless sensor network”, *Journal of Civil Structural Health Monitoring*, vol 5, pp. 655-676, 2015, doi 10.1007/s13349-015-0146-3.

Gattulli V., Potenza F., Toti J., Valvona F., Marcari G., “Ecosmart Reinforcement for a Masonry Polycentric Pavilion Vault”, *The Open Construction and Building Technology Journal*, vol. 10 (Suppl 2: M7), pp. 259-273, 2016, doi: 10.2174/1874836801610010259.