SPECIAL MOBILITY STRAND

STRUCTURAL ASSESSMENT OF HISTORICAL CONSTRUCTIONS AND SELECTED RETROFITTING TECHNIQUES

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Introduction

- Masonry →one of the oldest materials used in construction of civil structures
- Masonry structures were built in the past based on the master's knowledge and experience.
  - neither scientific research, nor design standards
- Many buildings' current structural conditions do not satisfy the present guidelines.
- Natural disasters, aggressive environment and human intervention have caused extensive damage to these structures, many of which have been built with no considerations of these factors.

stone masonry

brick masonry

adobe

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"OLD" is a relative term

- In practice →defines a structure 50-100 years old.
- For ancient constructions → a building is considered to be historic if a ***few centuries*** have passed since the time it was built.

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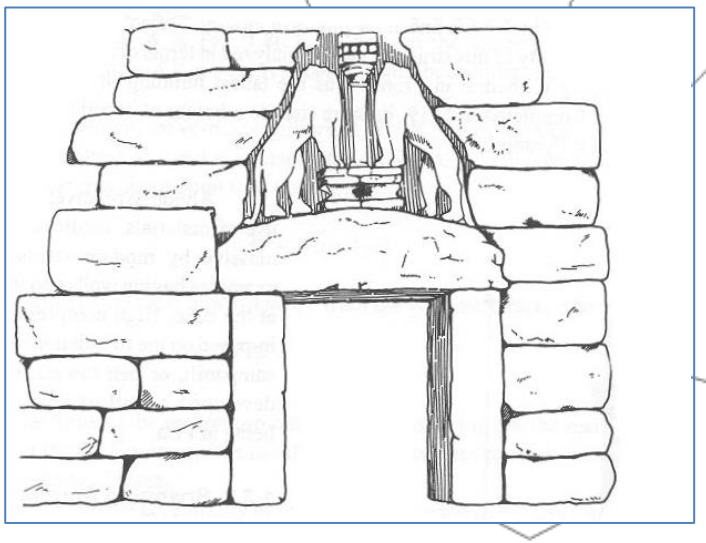
Some examples of historic constructions:

Egyptian pyramids (2800-2000 B.C.)



Lion Gate at Mycenae (13th century B.C.)

Parthenon of Athens (5th century B.C.)

Colosseum, Rome (1st century A.D.)

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Pont Du Gard (1st century A.D.)

Hagia Sophia, Istanbul (6th century A.D.)

Notre Dame de Paris, (14th century A.D.)

Florence Cathedral, (13 century A.D.)

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Advantages

- low material costs,
- good sound and heat insulation,
- locally availability,
- aesthetics and
- simplicity of construction.

- The construction technique which consists of assembling bricks, stone or block units on top of each other, laid dry or bonded with mortar, is essentially the same as thousands of years ago.

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Related problems

- Historical structures have suffered extensive damage due to:
  - Natural disasters,
  - aggressive environment and
  - human intervention

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Reasons for strengthening

- To eliminate structural problems or distresses due to:
  - unusual loading and exposure conditions,
  - inadequate design or
  - poor construction practices.
    - Caused by: overload, fire, flood, foundation settlement, deterioration, possible earthquakes, etc.
- To correct design or construction errors,
- To resist exceptional or accidental loadings,
- To increase tensile, shear, flexural or compressive strength of structural members.

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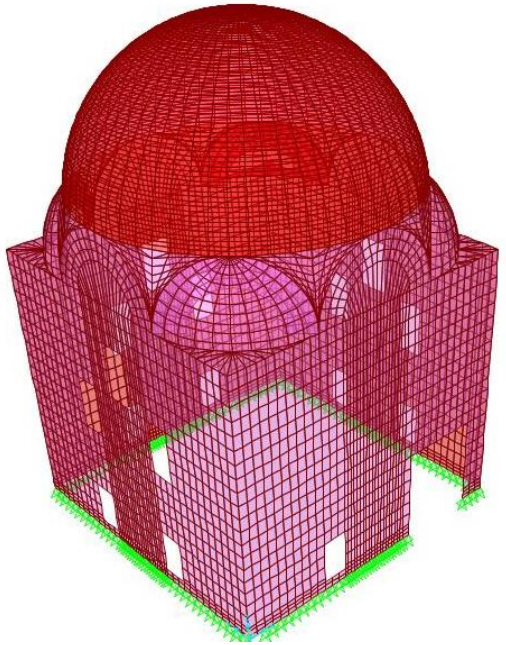
Analysis of historical constructions

- a very **challenging task** due to several uncertainties regarding mechanical properties and geometrical characteristics of the structure.

- Each masonry building is unique →should be treated with special care.



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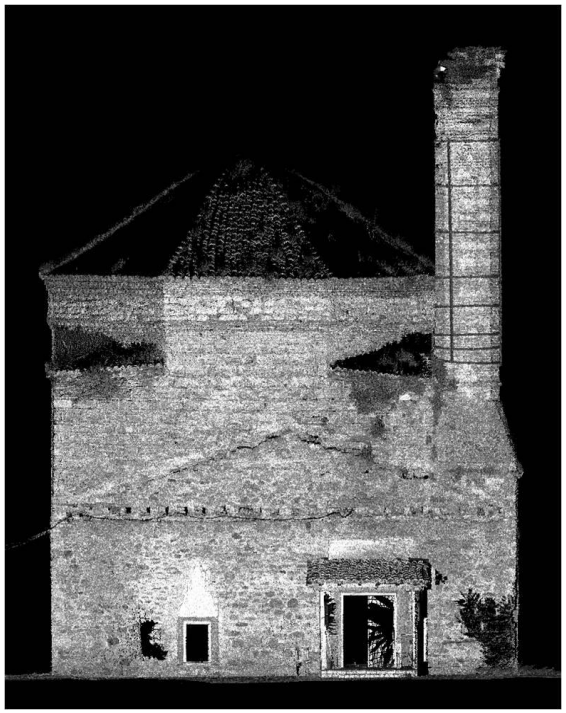
Analysis of historical constructions

- A correct structural analysis of the building requires:
  - a deep knowledge of building history and evolution,
  - geometry,
  - structural details,
  - material properties,
  - cracking pattern and
  - masonry construction techniques.



Point cloud after laser scanning

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Methodology

- Assessment of current structural conditions based on:
  - visual “symptoms”
  - Finite Element Model (FEM) analysis

- Objective:
  - to improve the existing capacity for static and possible earthquake loads,
  - possible causes of problems.

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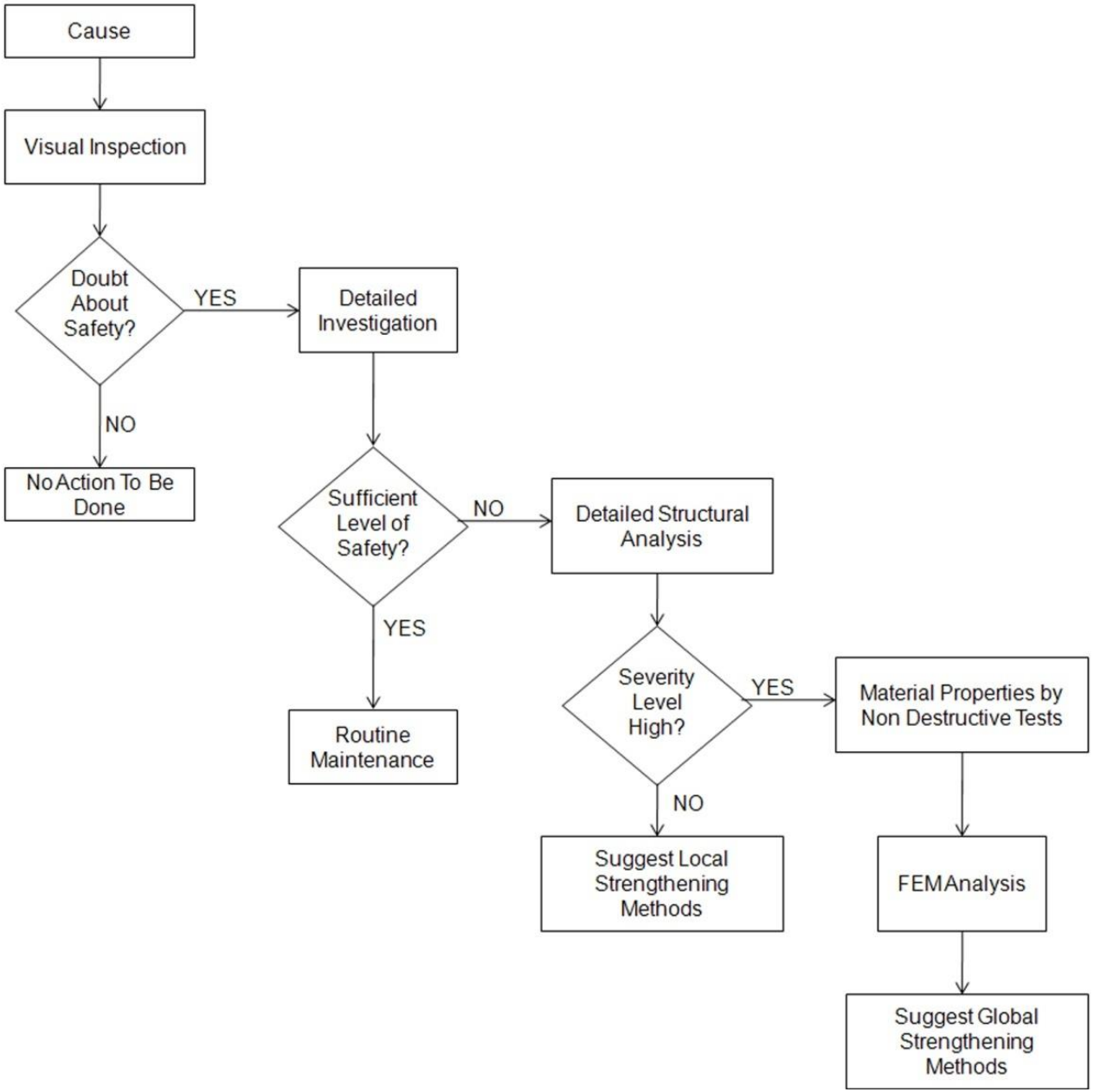

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ICOMOS[1] Recommendations

- No action should be taken without a proper evaluation of benefits and harm that can be done to the structure.
- Diagnosis should be based on qualitative and quantitative analysis.
- Remedial measures should address root causes rather than symptoms.
- Each intervention should be kept at minimum.

[1]**The International Scientific Committee for Analysis and Restoration of Structures of Architectural Heritage** presented a package of guidelines for conservation and restoration of historic structures. These guidelines were approved during Second International Congress of Architects and Technicians of Historic Monuments, in Venice, Italy, in 25-31 May 1964.

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Inspection and Assessment Procedure

- Adaptation of a suitable inspection form.
  - General details about the structure
    - (address, rough area, number of storey, total height)
  - Type of roof
  - Construction materials
  - Condition of load bearing walls

The severity level ranges from ***none*** (contains no structural damage), ***light***, ***moderate***, ***severe*** to ***near collapse*** (a heavy damage element or structure)

Based on the current state, recommendation is given whether to:
retrofit, demolish or conduct a further more detailed analysis

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FORM FILLED IN BY / DATE	
BUILDING ADDRESS/ GPS LOCATION **ROUGH AGE OF BUILDING [YEARS]**	
STRUCTURAL SYMMETRY	EXISTS IN PLAN / EXISTS IN ELEVATION / NO SYMMETRY
ROUGH AREA COVERED BY BUILDING **STRUCTURE [SQ. METERS]**	
NO. OF STORIES	( ) / NOT APPLICABLE
TOTAL HEIGHT OF BUILDING [M]	
WALL CONSTRUCTION	BRICK / STONE / MUD / OTHER
WALLS ARE LOAD BEARING	YES / NO / EXPLAIN
STRUCTURAL QUALITY OF WALLS	POOR / ADEQUATE / GOOD / OTHER
TYPICAL WALL THICKNESS [M]	
LATERAL LOAD RESISTING ELEMENTS **[BUTTRESSES / RING BEAMS / LINTELS /** **ETC.]**	DOME / VAULT / BRICK / OTHER / WALL
CONNECTIONS [WALLS TO ROOF ETC.]	POOR / ADEQUATE / GOOD / OTHER
ROOF	DOME / VAULT / BRICK / OTHER
MINARETS OR OTHER STRUCTURAL APPENDAGES	YES / NO / EXPLAIN
MORTAR / CEMENTING MATERIAL	LIME / CEMENT / MUD / OTHER / KHORASAN MORTAR
DAMAGE LEVEL : WALLS	NONE / LIGHT / MODERATE / SEVERE / NEAR COLLAPSE
DAMAGE LEVEL : ROOF	NONE / LIGHT / MODERATE / SEVERE / NEAR COLLAPSE
DAMAGE LEVEL : OTHER ELEMENTS	NONE / LIGHT / MODERATE / SEVERE / NEAR COLLAPSE
EARTHQUAKE HAZARD LEVEL	VERY LOW / LOW / MODERATE / HIGH / VERY HIGH
RECOMMENDATION	RETROFITTING / FURTHER ANALYSIS / DEMOLITION /OTHER

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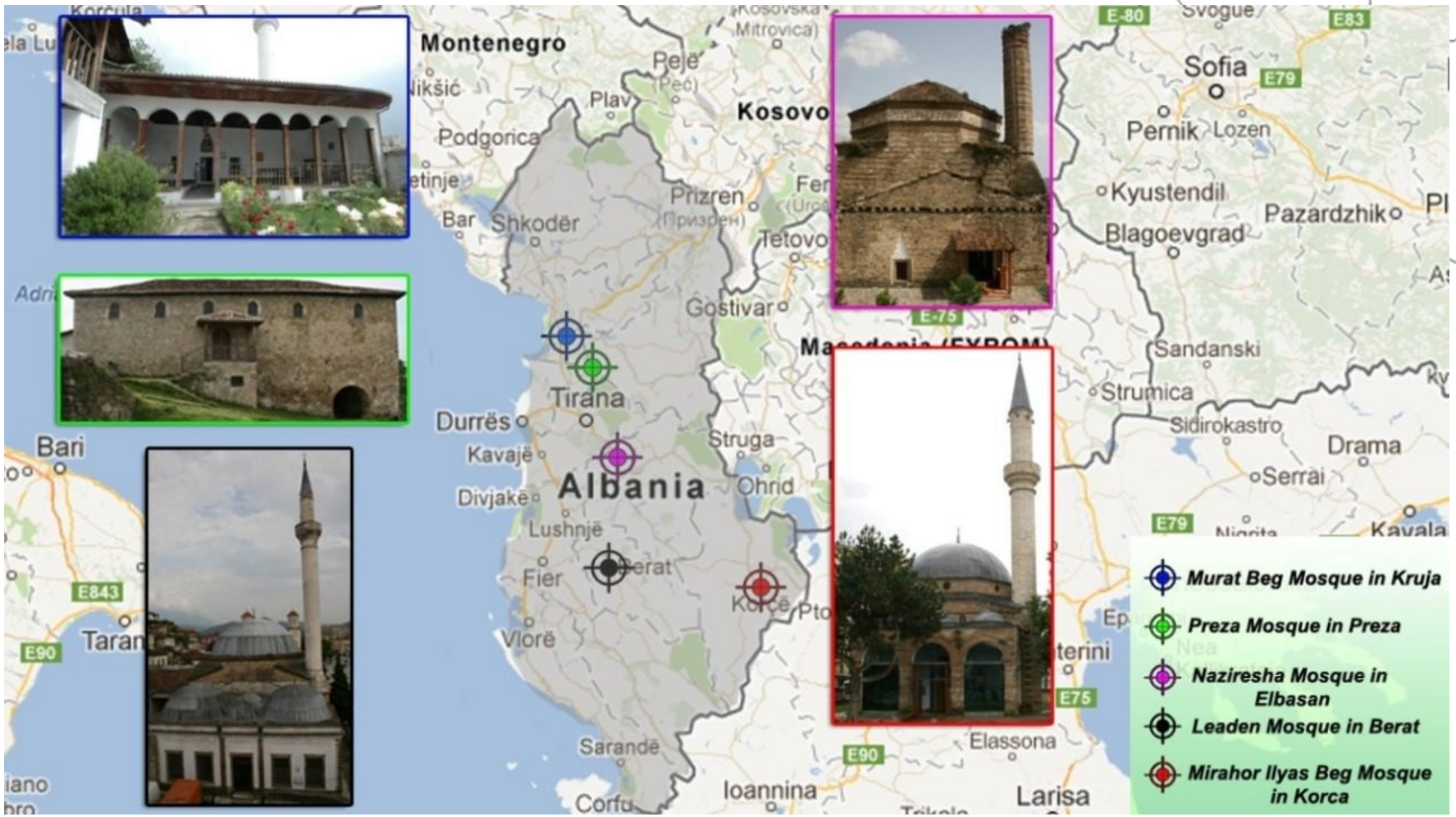
Case Studies



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Surveying equipment

- Calibrated high-resolution digital camera (Nikon D90)
- Optech ILRIS (3D Intelligent Laser Ranging and Imaging System)
- Topcon GPT 3007 Total Station

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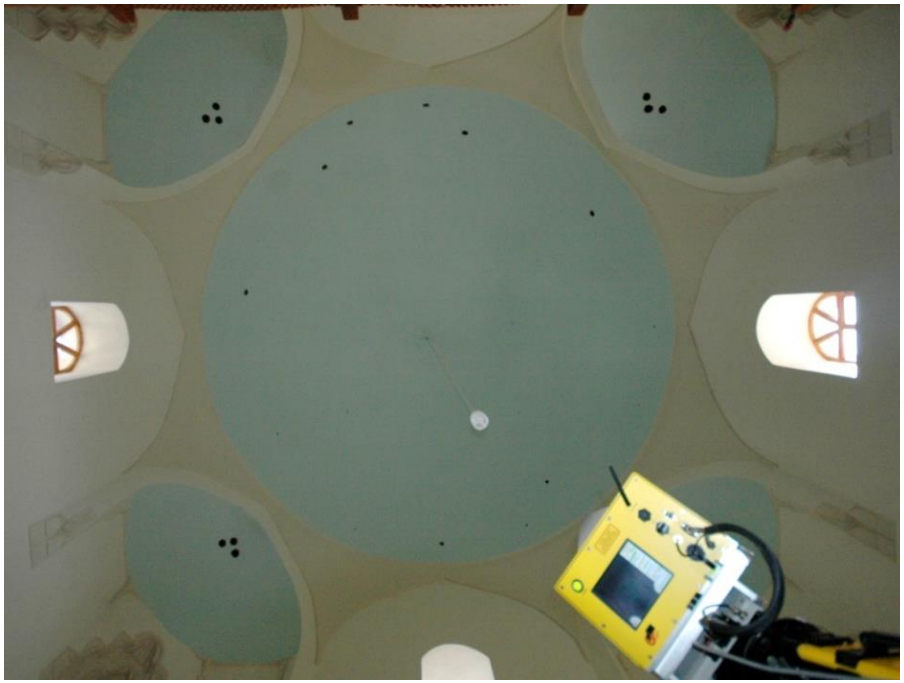
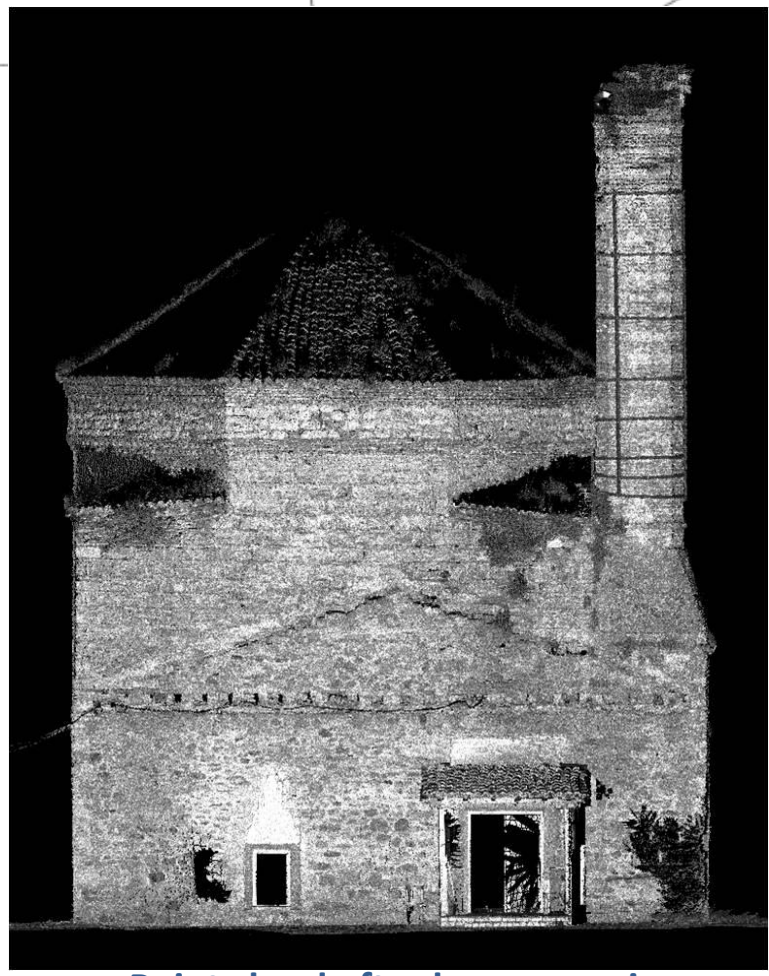
Laser scanning



Interior of the dome



Point cloud after laser scanning

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Laser scanning – Naziresha's Moque

Scan view of the structure from different scan stations.

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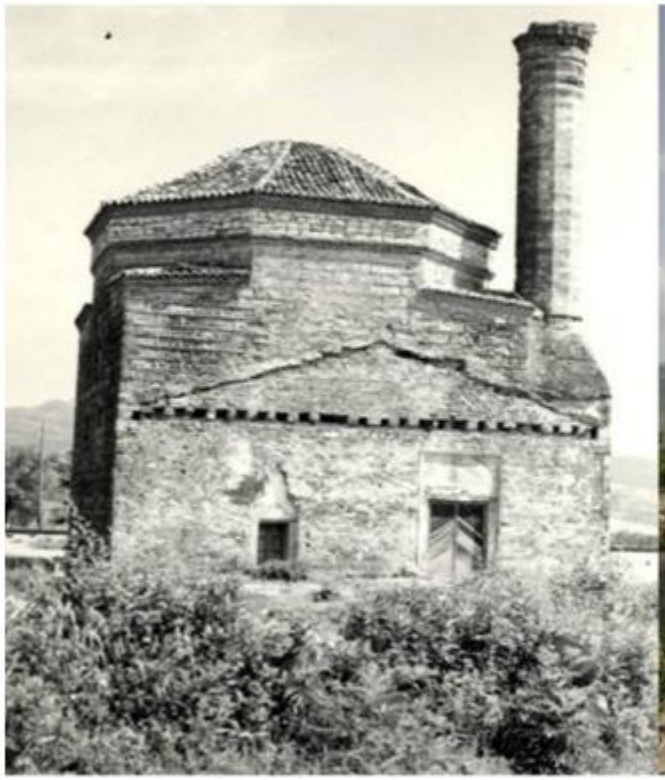

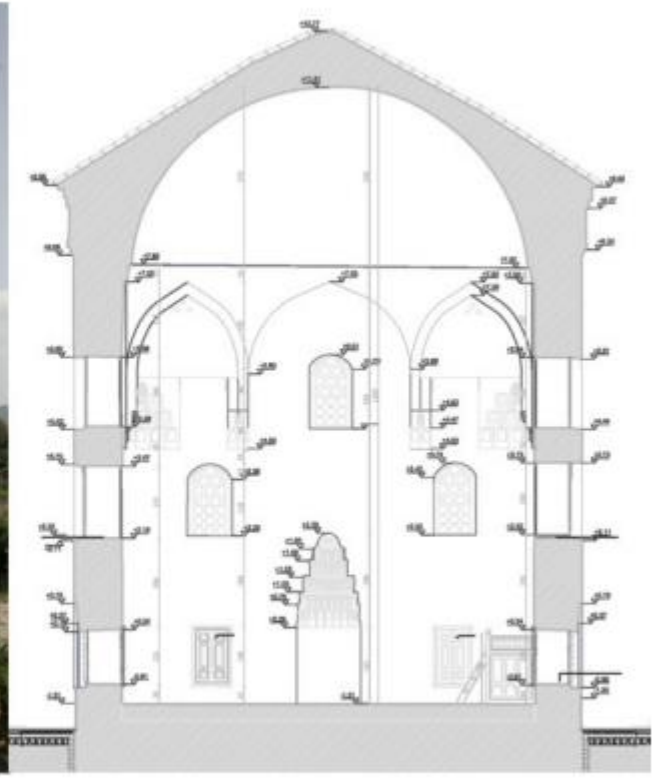

Main façade (old and present day) and the cross-section detail of the mosque.

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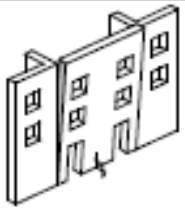
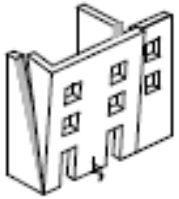
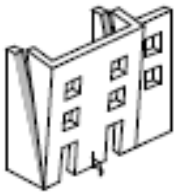
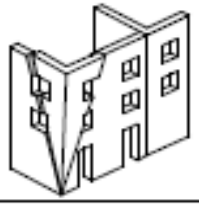
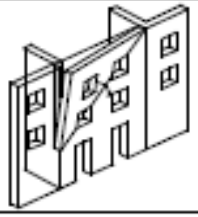
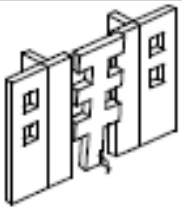
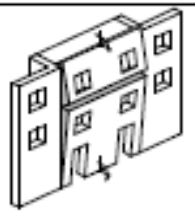
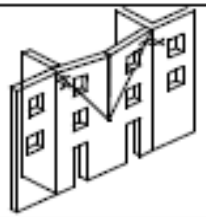
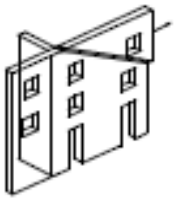
Failure Mechanism

A	B1	B2	C	D	E	F
VERTICAL OVERTURNING	OVERTURNING WITH 1 SIDE WING	OVERTURNING WITH 2 SIDE WINGS	CORNER FAILURE	PARTIAL OVERTURNING	VERTICAL STRIP OVERTURNING	VERTICAL ARCH
						

		FURTHER PARTIAL FAILURES		ASSOCIATED FAILURES	
G	H	I	L		
HORIZONTAL ARCH	IN PLANE FAILURE	VERTICAL ADDITION	GABLE OVERTURNING	ROOF/FLOORS COLLAPSE	MASONRY FAILURE
					 Insufficient cohesion in the fabric

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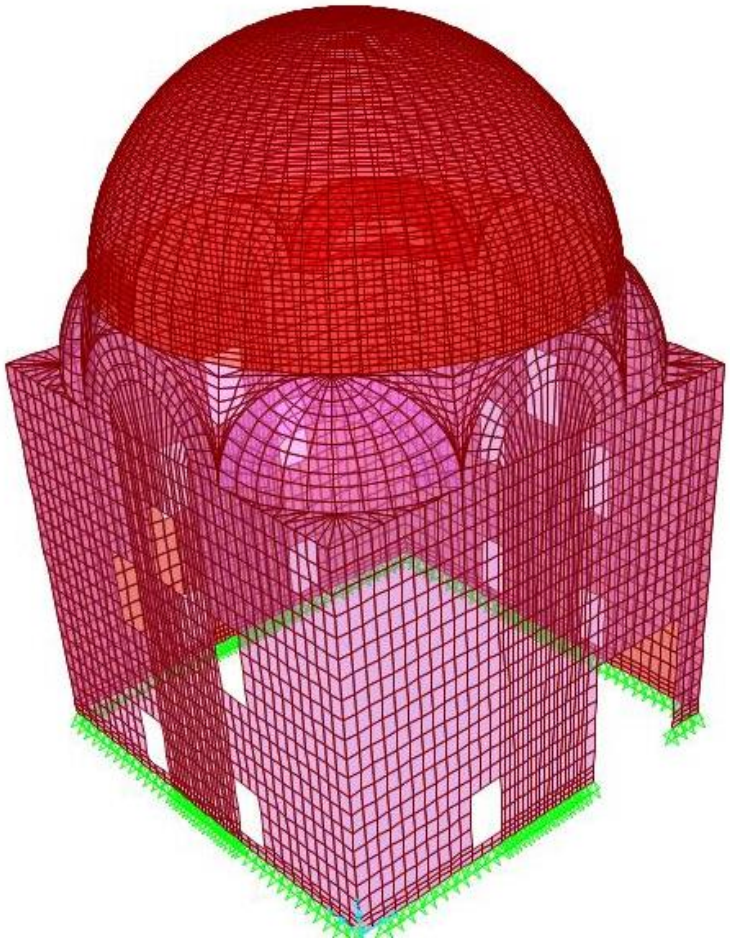
Finite Element Modeling

- 9604 joints and 9563 shell elements
- Brick + stone
- Macro modeling (Masonry units and mortar layers - continuum)
- Homogeneous linear elastic behavior of the structure is assumed.

Assumed material properties

	Brick	Stone
Unit weight, γ (kN/m³)	17	21
Modulus of elasticity, E (MPa)	2100	1740
Void ratio, υ	0.2	0.2
Tensile strength (MPa)	0.564	1.42
Compressive Strength (MPa)	1.03	4.06



Finite Element Model in Sap2000

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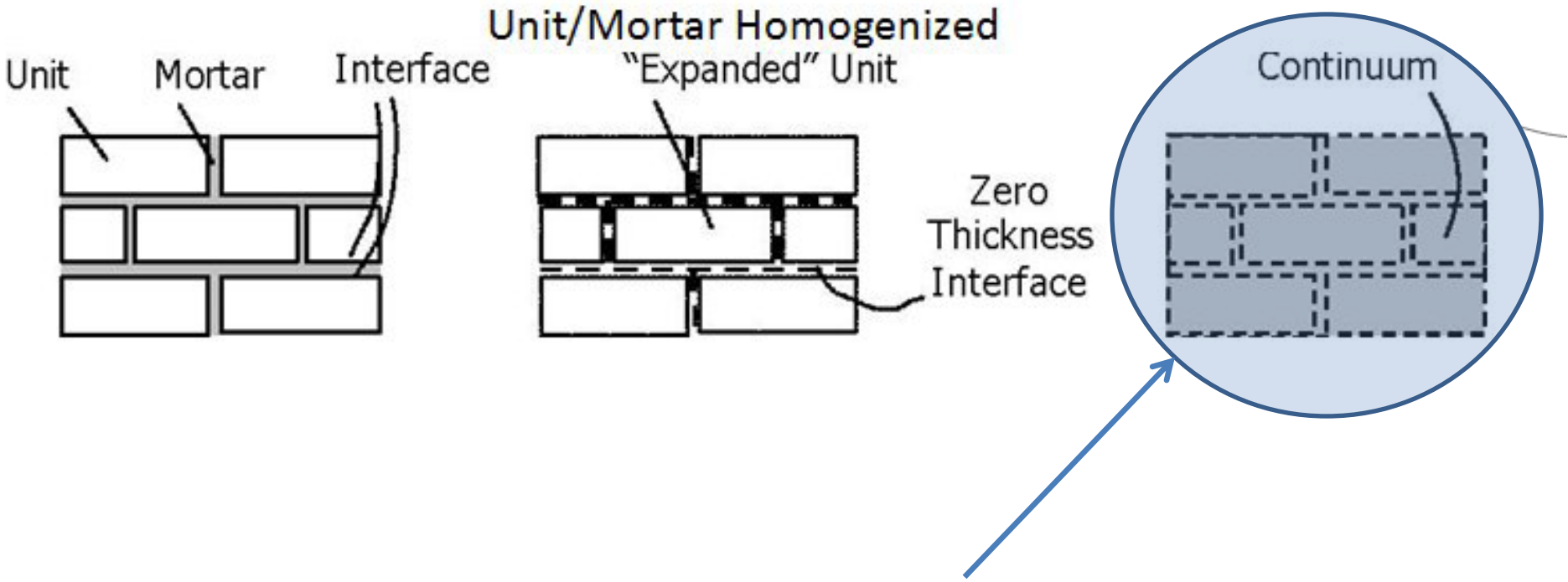
Idealization of the geometry



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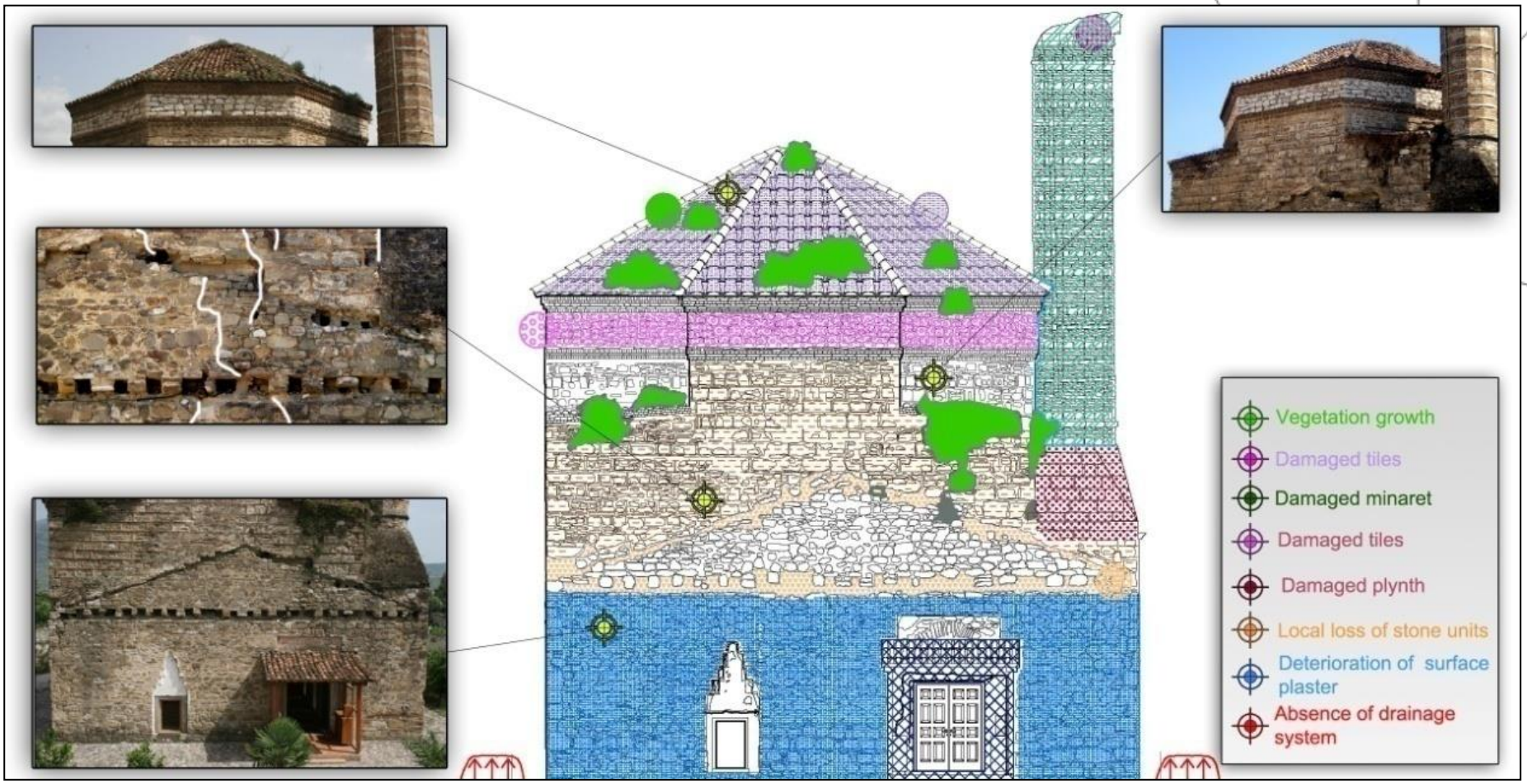
Condition Assessment Result – Naziresha's Mosque



Summary of the assessment results

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Condition Assessment Results – Murat Beg's Mosque

Summary of the assessment results

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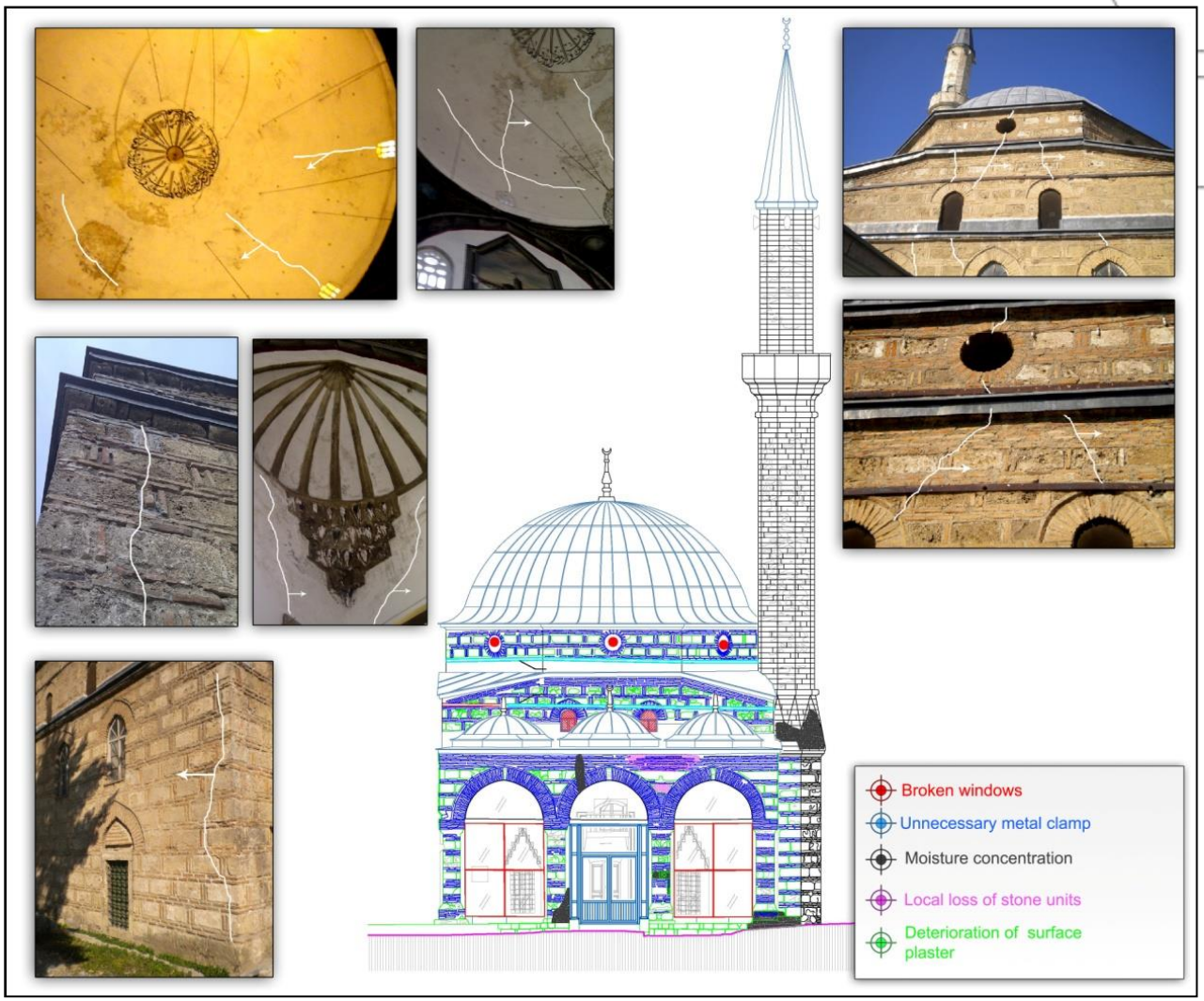
Assessment Results - Mirahor I. Beg's Mosque



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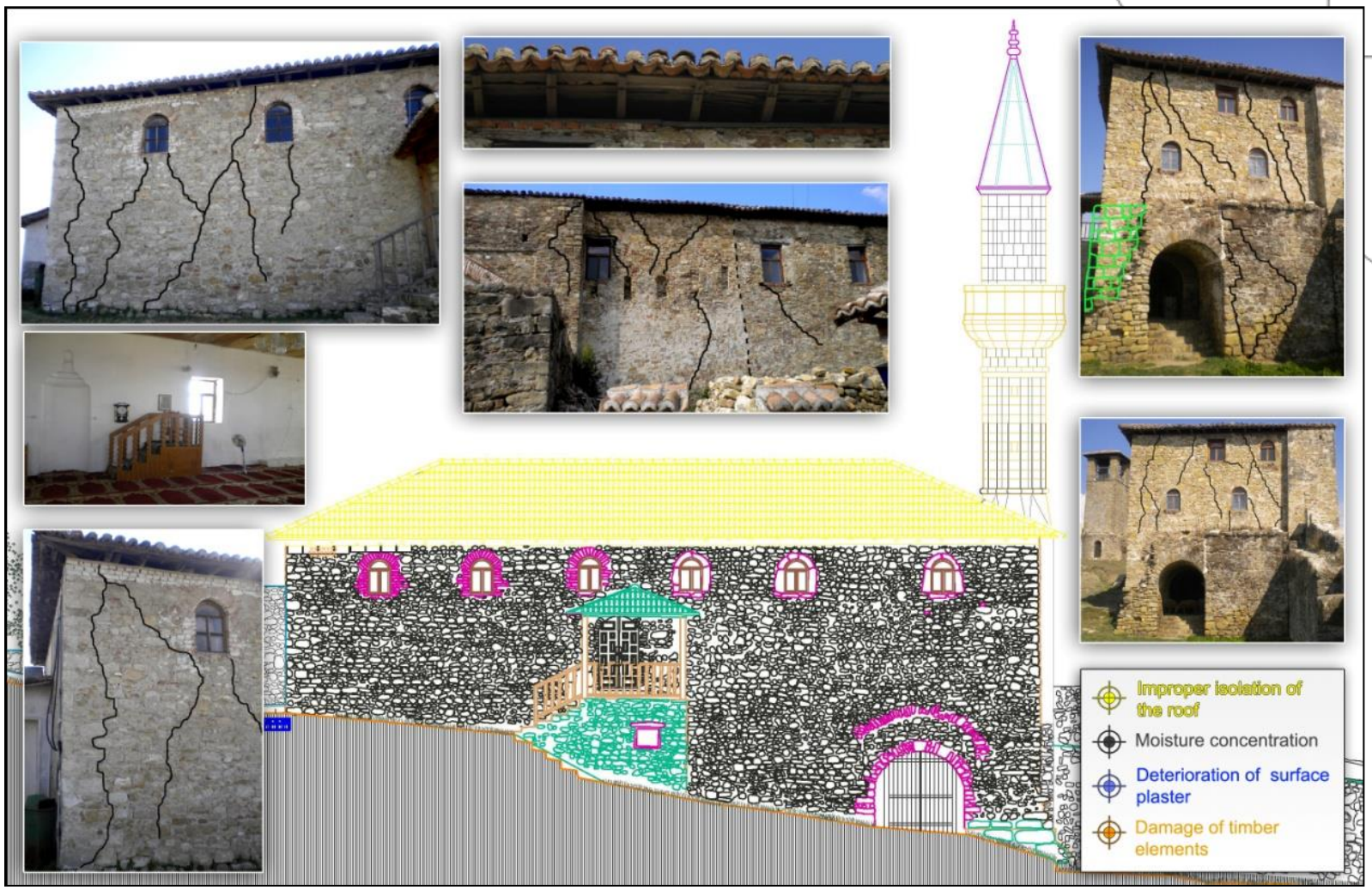
Assessment Results – Mosque of Preza



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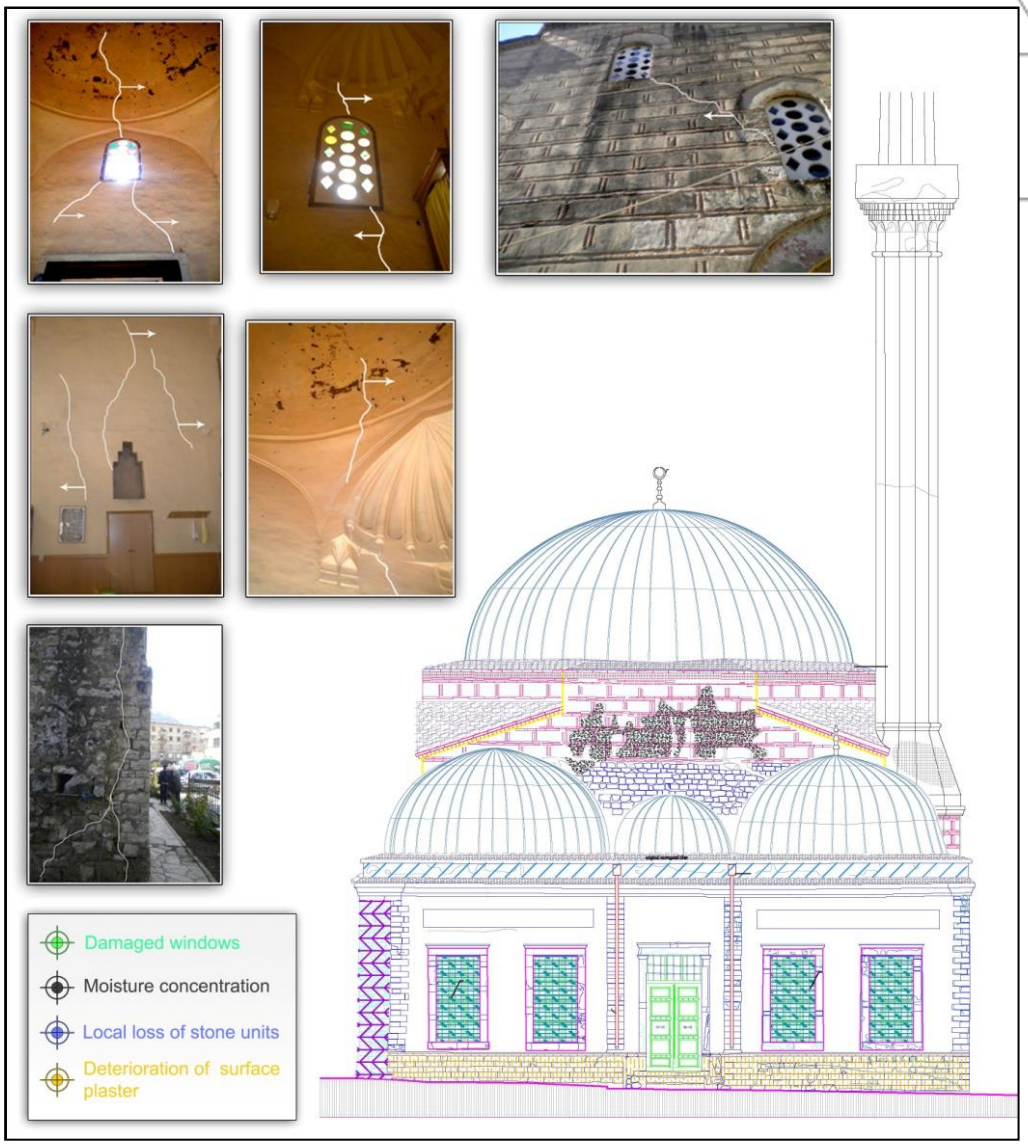
Assessment Results – Leaden Mosque



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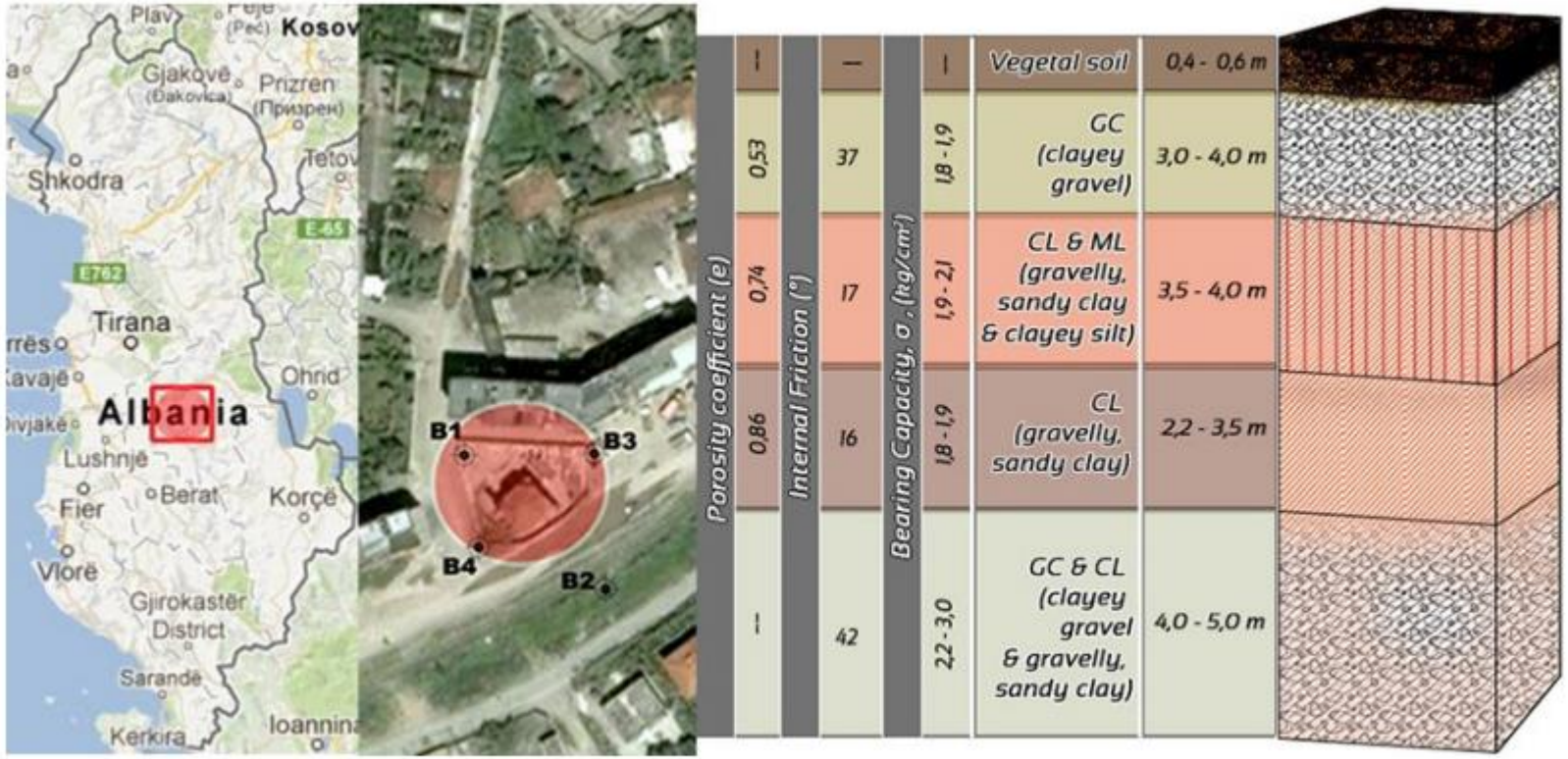
Investigation of Soil Profile



Soil profile and location of the mosque.

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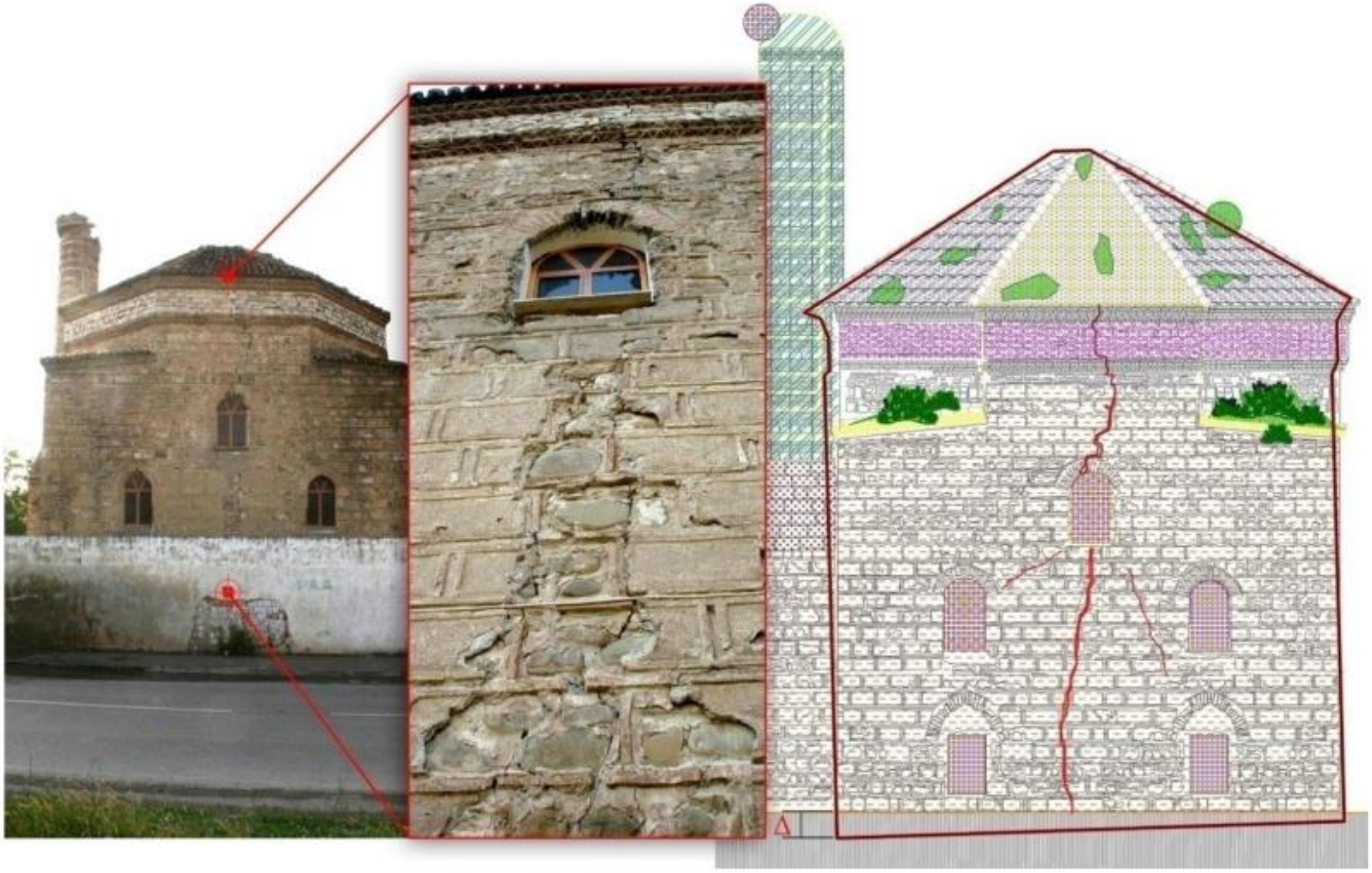

Cracks on the structure due to differential settlement.

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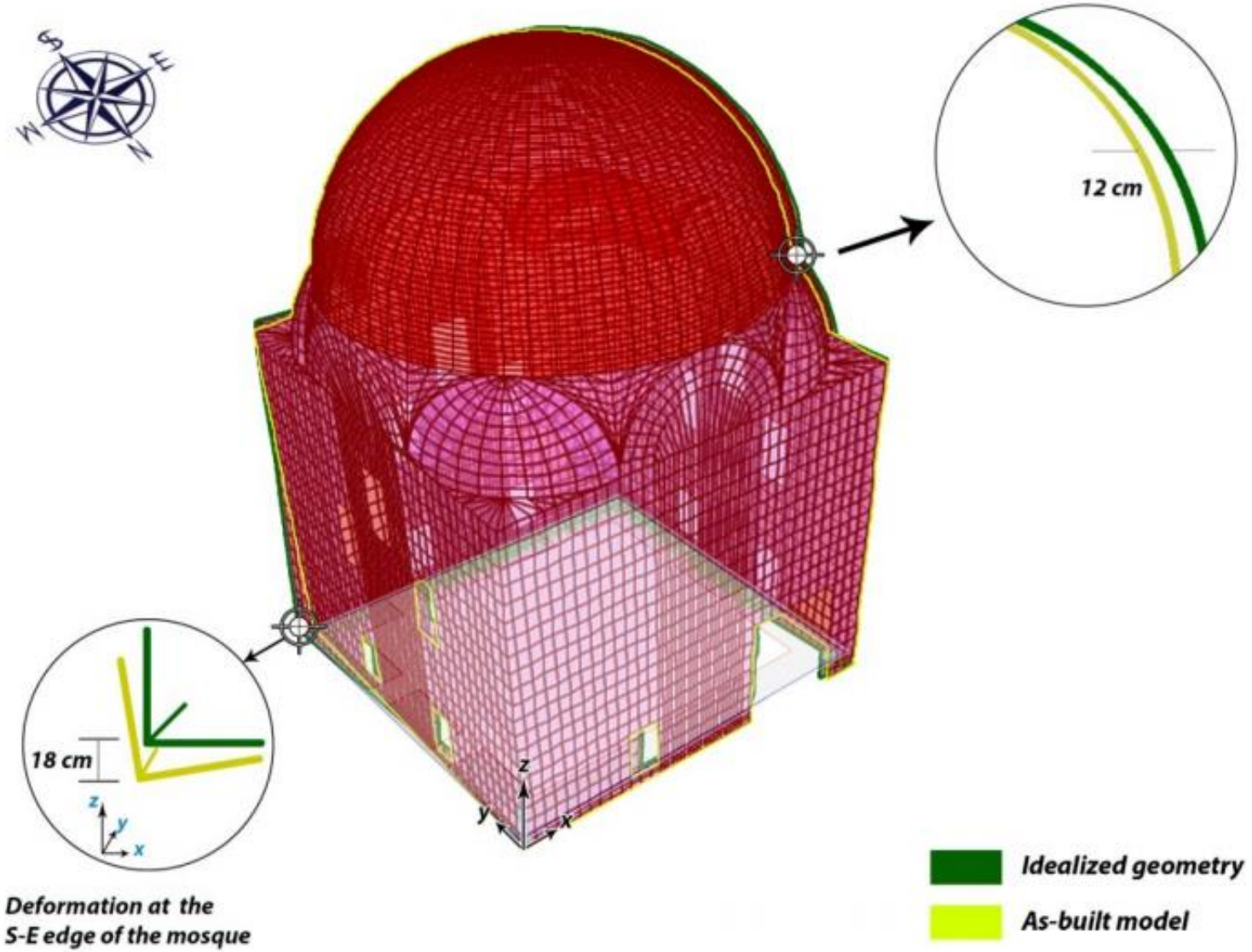

Deformation at the S-E edge of the mosque

Deformation of the structure at the S-E corner.

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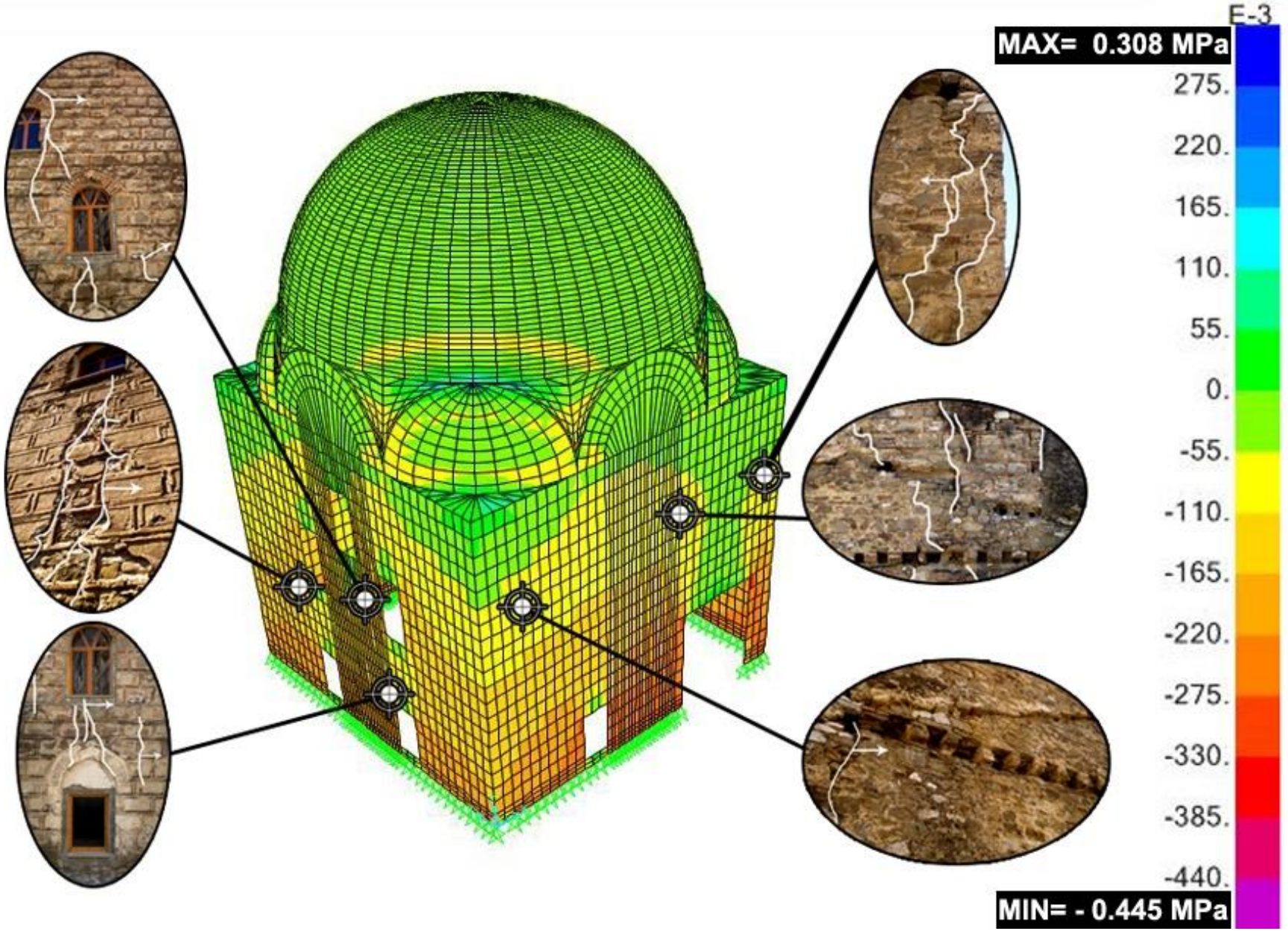

S22 stress distribution and actual cracks seen on the façade of Naziresha Mosque

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Basis of the intervention design: The Walls

- Additional tensile and shear resisting elements should be added where necessary and injection should be applied where voids are seen.

- In areas where non-structural cracks less than 10 mm wide are found, injection technique should be used.

- Structural shear and tensile cracks near the openings should be repaired with longitudinal FRP bars bonded with epoxy resin or mortar.

- Local reconstruction “cucci scucci” technique is suggested to be used in the places sanding phenomenon is seen and where massive loss of building units is observed

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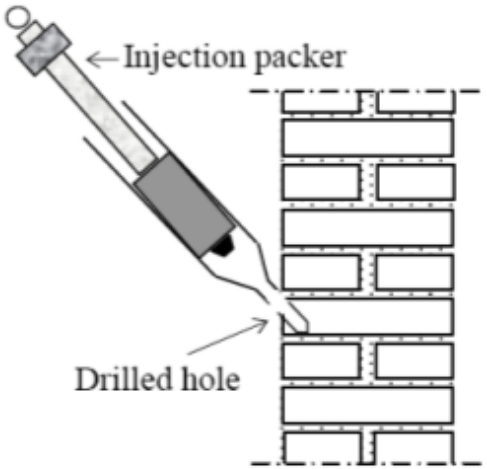
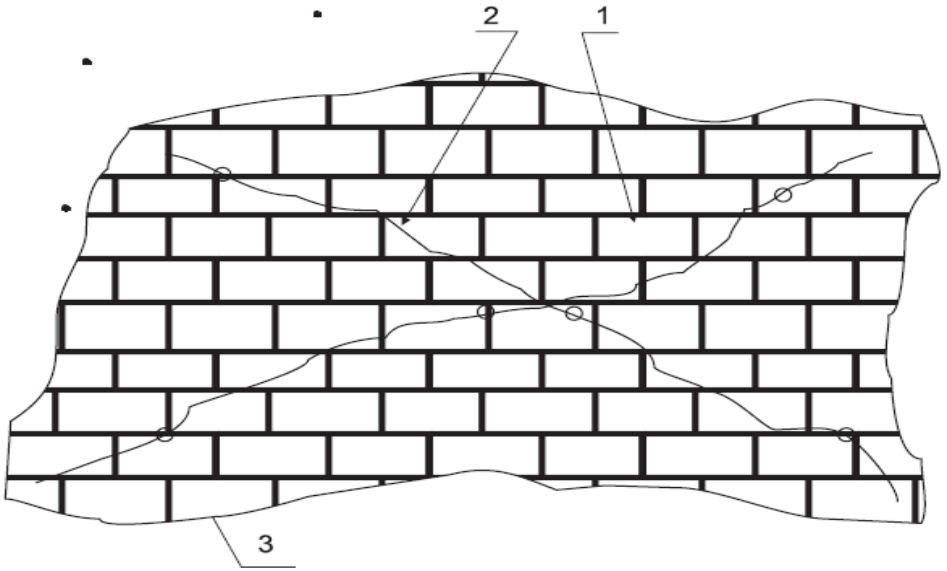
Injection

❖Injection into the voids a binder (epoxy resin, cement-base grout of hydraulic lime mortar) by producing better connection.



Injection system



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Injection

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Strengthening techniques for URM historical structures

- Local Reconstruction “Cucci Scucci”
- Injection
- Tying
- External and Internal Prestressing Ring
- FRP Materials

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Local Reconstruction “Cucci Scucci”

- Removing masonry parts and replacing with new ones having the same properties.

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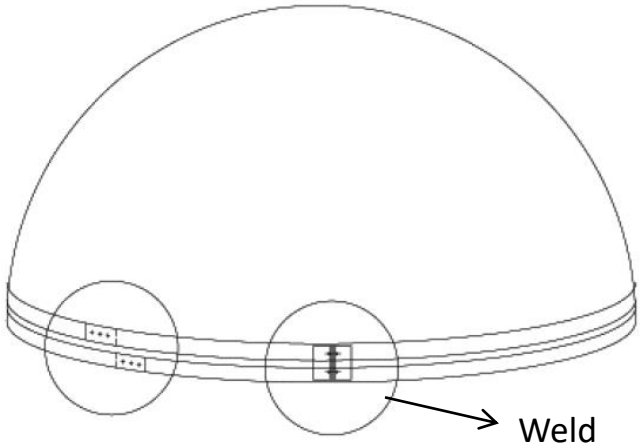
Internal and External Prestressing Rings

- Adding a circumferential stainless steel ring around the structural member that exhibits high concentration of tensile stresses.



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FRP Materials

- Fiber Reinforced Polymers
- Composite material made of:
  - Continuous polymer (Resin)
  - Reinforcing fibers

- Increase:
  - out-of-plane flexural strength,
  - in-plane shear strength,
  - stiffness at service loads

- Change the behavior of masonry from weak and brittle to strong and ductile

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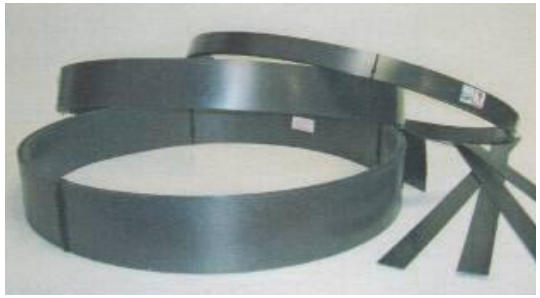
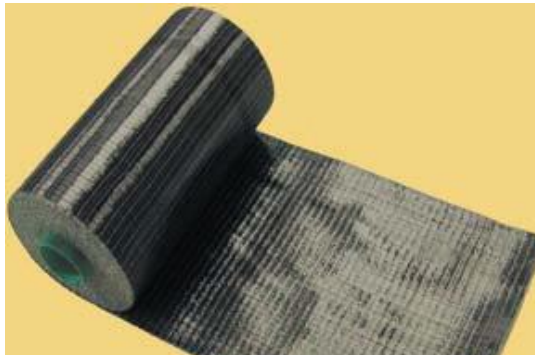
FRP laminate (a), sheet (b), bars (c)





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ACKNOWLEDGEMENTS

The text material was adopted from Author's contribution to the book:

- "Handbook of Research on Seismic Assessment and Rehabilitation of Historic Structures" Asteris&Plevris Eds., 2015 and

- "Assessment of Historical Structures, A case study of five Ottoman Mosques in Albania", by Mustafaraj, 2014.

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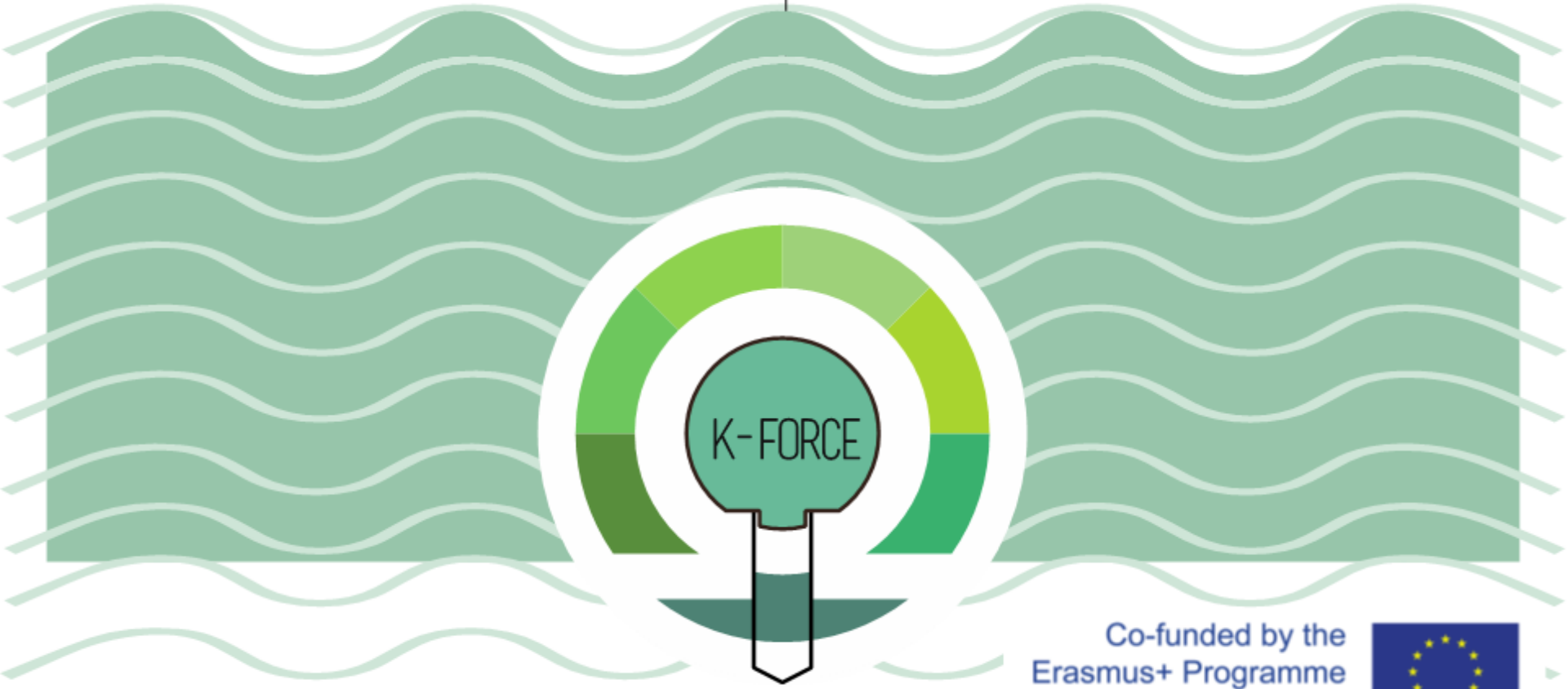

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Thank you
for your attention

ENEA MUSTAFARAJ

Knowledge **FO**r **R**esilient so**C**i**E**ty