International Workshop:
"Role of research infrastructures in seismic rehabilita
Istanbul, February 8-9, 2012

Veronika SHENDOVA, Zoran RAKICEVIC, Mihail GAREVSKI, Roberta APOSTOLSKA, Zivko BOZINOVSKI

IMPLEMENTATION OF EXPERIMENTALY DEVELOPED METHODOLOGY FOR SEISMIC STRENGTHENING IN HISTORIC MONUMENTS

University Ss. Cyril and Methodius in Skopje
Institute of Earthquake Engineering and Engineering Seismology (UKIM-IZIIS) - Skopje

Dr. Veronika SHENDOVA

HEAD OF DEPARTMENT:
BUILDING STRUCTURES AND MATRIALS: DESIGN, ANALYSIS AND TESTING

Cultural Heritage

IMPORTANCE:

- key element for the history and the identity of the society, contributing to its economic and other well-being
- only remnant of human existence, creation and achievements in the past
- deserve special attention due to their individual historic, architectonic, documentary, economic, social and even political or spiritual value

PROTECTION:

- multidisciplinary approach: team of experts from different profiles
- one of the main tasks and problems: how far we should go as to the level of safety and the extent of the intervention
- a moral and legal obligation and the duty of present civilization

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Cultural Heritage

EARTHQUAKE PROTECTION:

- **Materials:**

✓ **reversible interventions - only a few limitations**

✓ **irreversible interventions - additional compatibility of new with old materials and their durability.**

- **Methods: detail analysis of existing structure**

✓ **sufficient bearing and deformability capacity - only repair**

✓ **not sufficient bearing and deformability capacity - strengthening (increase of** strength or/and deformability**)**

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Cultural Heritage

~~"Code for Historical Buildings and Monuments"~~

"Guide", "Recommendations", "Resolutions", "Charters"

and

Scientifically based methodology for earthquake protection of historic monuments and buildings in the process of their protection

Needs for in-situ, laboratory and experimental testing

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Needs for Experimental Testing

In General:

- significant progress in earthquake engineering
- moving towards Performance Based approach
- deficiencies in understanding of earthquake induced phenomena
- new structural concepts and their specific failure mechanisms
- refining the numerical models

In the case of Historic Buildings and Monuments:

- assessment of safety and seismic stability of existing structure
- investigation and verification of different protection techniques
- investigation of effectiveness, limitation of irreversible materials and their interaction with the existing masonry

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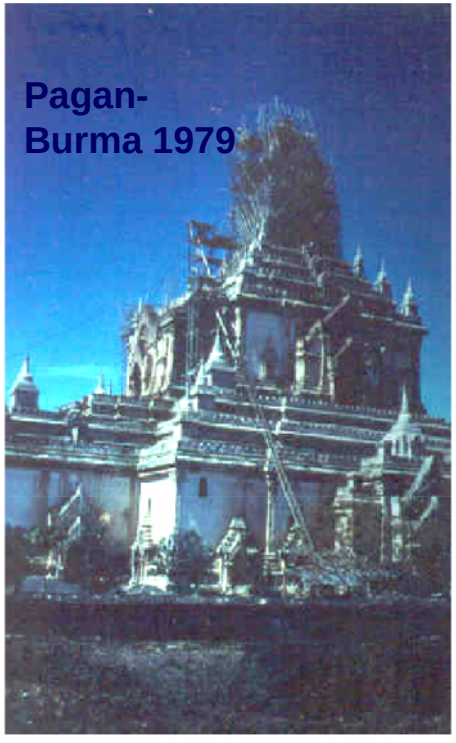
IZIIS' experience in the field

Skopje, 1963

Budva, 1979



Pagan-Burma 1979

Dubrovnik, 1986

Angkor-Cambodia, 1990

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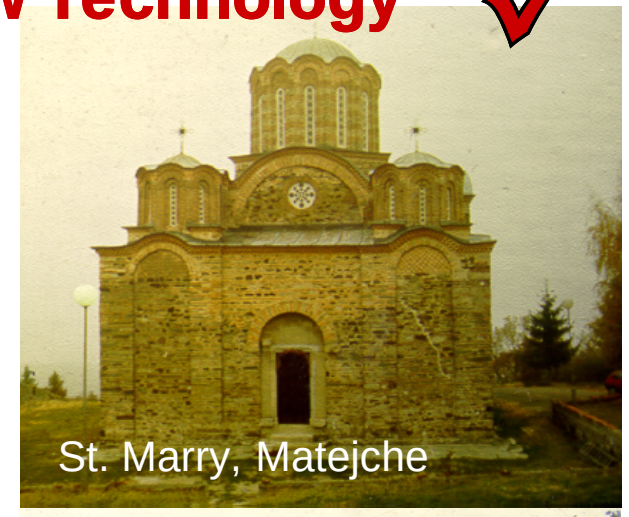
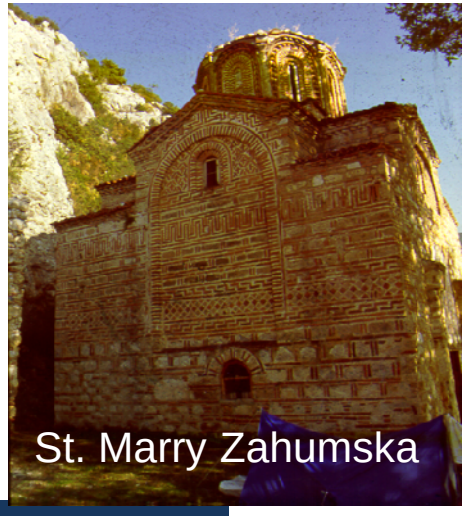
Methodology for Seismic Strengthening of Byzantine Churches

Traditional Technology vs. New Technology

- Typology
- Existing state
- Interventions
- Authenticity


St. Marry, Matejche


St. Nikita, Banjani


St. Marry Zahumska


St. Nicolas, Psacha

scientific-research projects: GCI, LA, EU Phare, IZIIS

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Investigation of prototype church – St. Nikita

- **Experimental and Laboratory Tests:**

  Mechanical and chemical characteristics of stone, brick and mortar

- **Seismic Hazard Parameters:**

  Maximum expected accelerations:

  0.15g, 0.20g, 0.34g **for return periods of *100, 200 , 1000* years**

- **Dynamic characteristics:**

  $f^{N-S} = 4.8$ Hz, $f^{E-W} = 6.0$ Hz

- **Existing Seismic Stability**

	$Ks = S_{ui} / G$	El Centro	Petrovac
occurrence of first cracks	0.17	0.14	0.12
ultimate state	0.21	0.20	0.20

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Experimental Investigations of the Model

- **OBJECTIVES** → **Investigation of seismic resistance and verification of the proposed strengthening concept**
- **Selection of the geometrical scale** → **Lr = 1:2.75**
- **Investigation of the model materials**

- **Experimental testing of wall elements**

- **Design of the church model**

scientific-research projects: GCI, LA, EU Phare, IZIIS

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Construction of the model

scientific-research projects

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Concept for Repair and Strengthening - traditional

***Design Criteria*:**

- ***Level I:*** **without damage, tp = 100 years**
- ***Level II*: linear behaviour, limited nonline**

years

- ***Level III*: deep nonlinearity- not disturb**

years

Selected method for strengthening:

- ***incorporation of horizontal steel ties***
- ***systematic injection of elements***
- ***incorporation of vertical steel ties***

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Experimental verification of methodology

lower damage level even under higher level of input excitation

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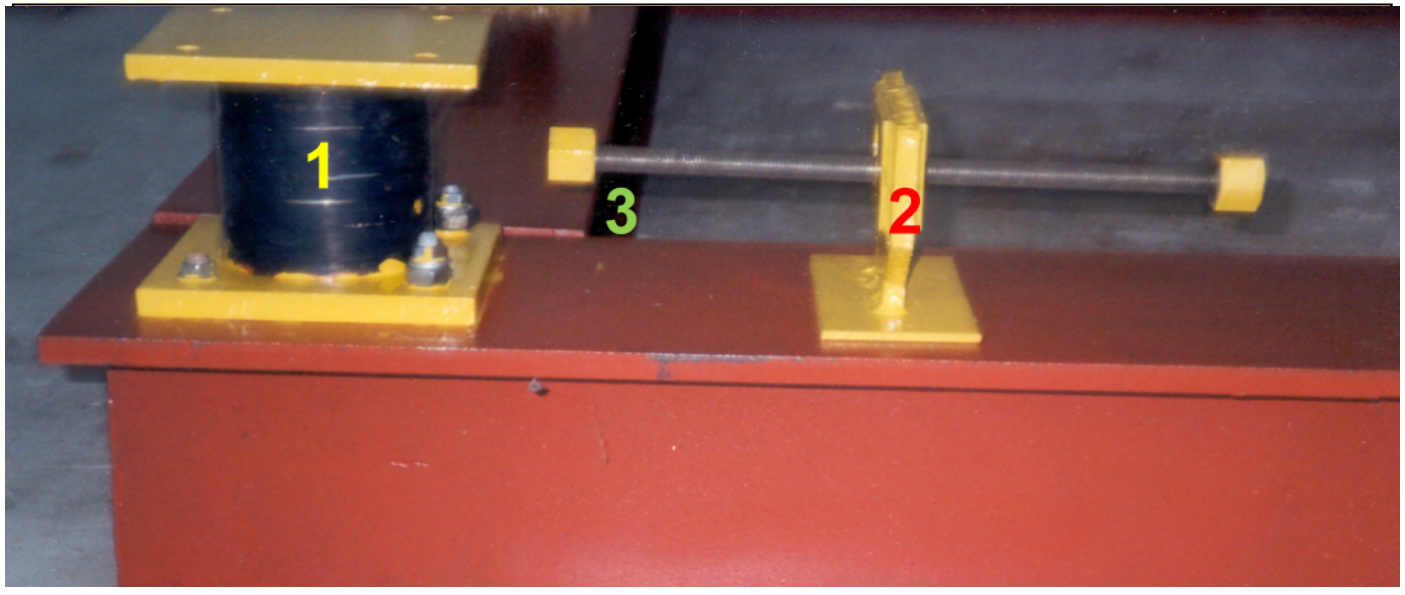
Earthquake Protection using Seismic Isolation - new



element 1: **Laminated rubber bearing element**

element 2: **Steel plate damper (hysteretic behavior)**

element 3: **Stopper element (limited displacement)**

scientific-research projects

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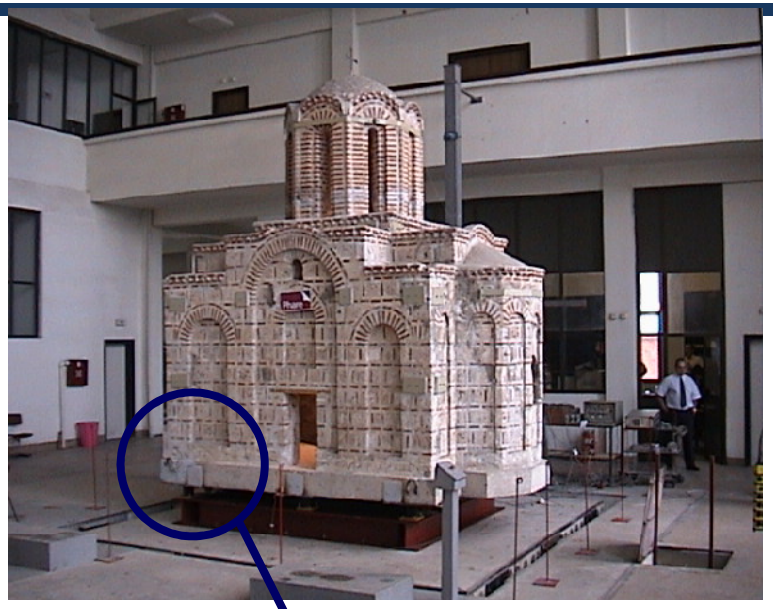
Shaking table testing of base-isolated model

scientific-research projects

Steel structure and Isolators



Isolator in action

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Traditional Technology vs. New Technology ✓

Test No: *10*

Input Excitation:

El Centro Earthquake, acc=0.54g

return period t_p =1000 years

P.Gavrilovic, G.N.Cvetanovska, R. Apostolska

Implementation..... In reconstruction

Consolidation and Reconstruction of the Structure of the St.Pantelymon Church in Plaoshnik, Ohrid

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Concept for Consolidation and Rebuilding

- ✓ Definition of design criteria (3 levels)
- ✓ Injection of the walls:
  - Walls below the floor level with cement emulsion
  - Walls over the floor by use of lime-based emulsions
- ✓ Contact between the existing and the rebuilt walls
- ✓ Strengthening and the consolidation of the existing foundation walls up to level 0.00
- ✓ Reinforced concrete floor slab with a thickness of 20 cm
- ✓ Construction of the church as massive stone and brick masonry in lime mortar with incorporated horizontal and vertical steel ties

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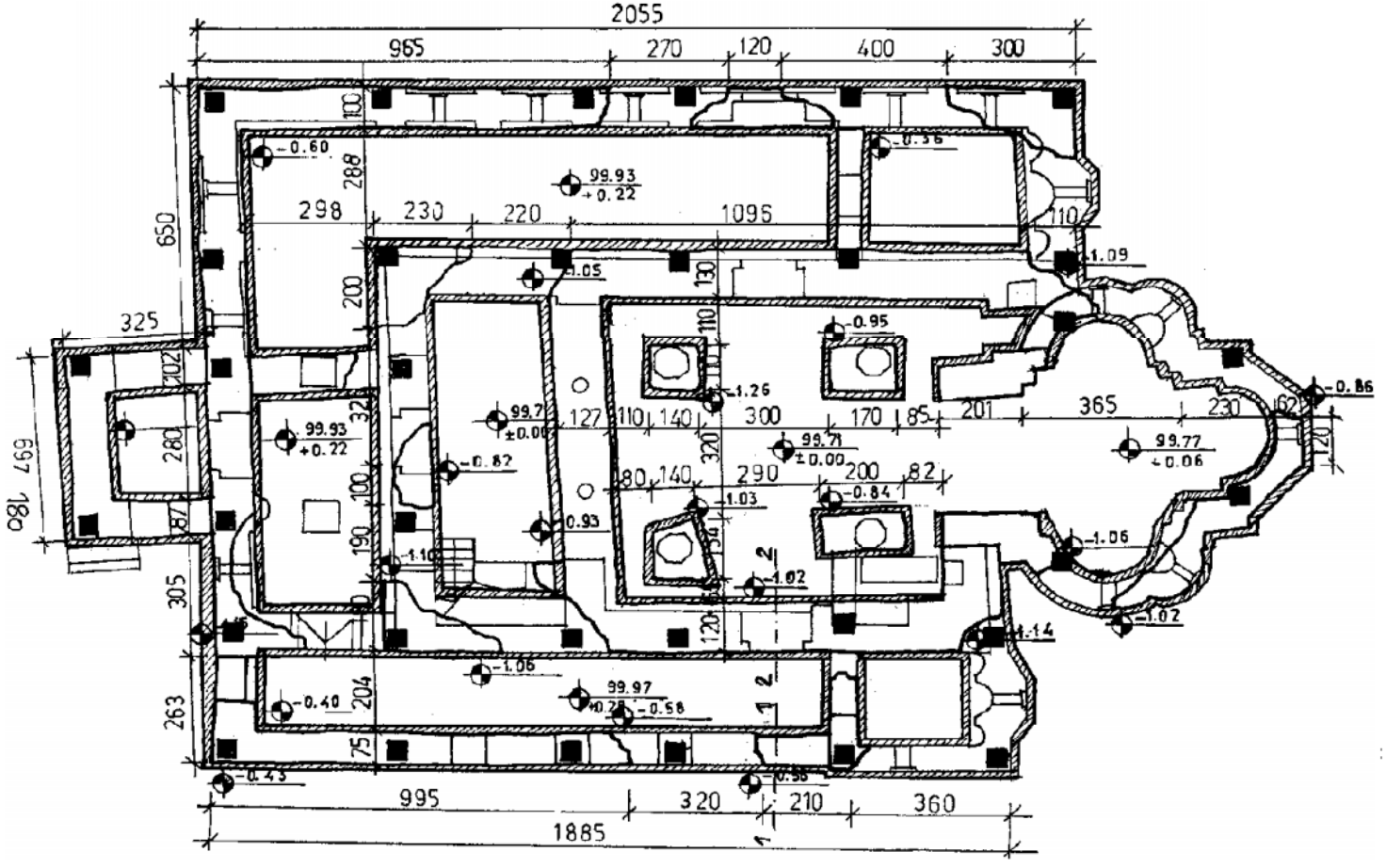
St.Pantelymon Church in Plaoshnik, Ohrid

Implementation..... In reconstruction

plan of the structure at the level of -0.22m



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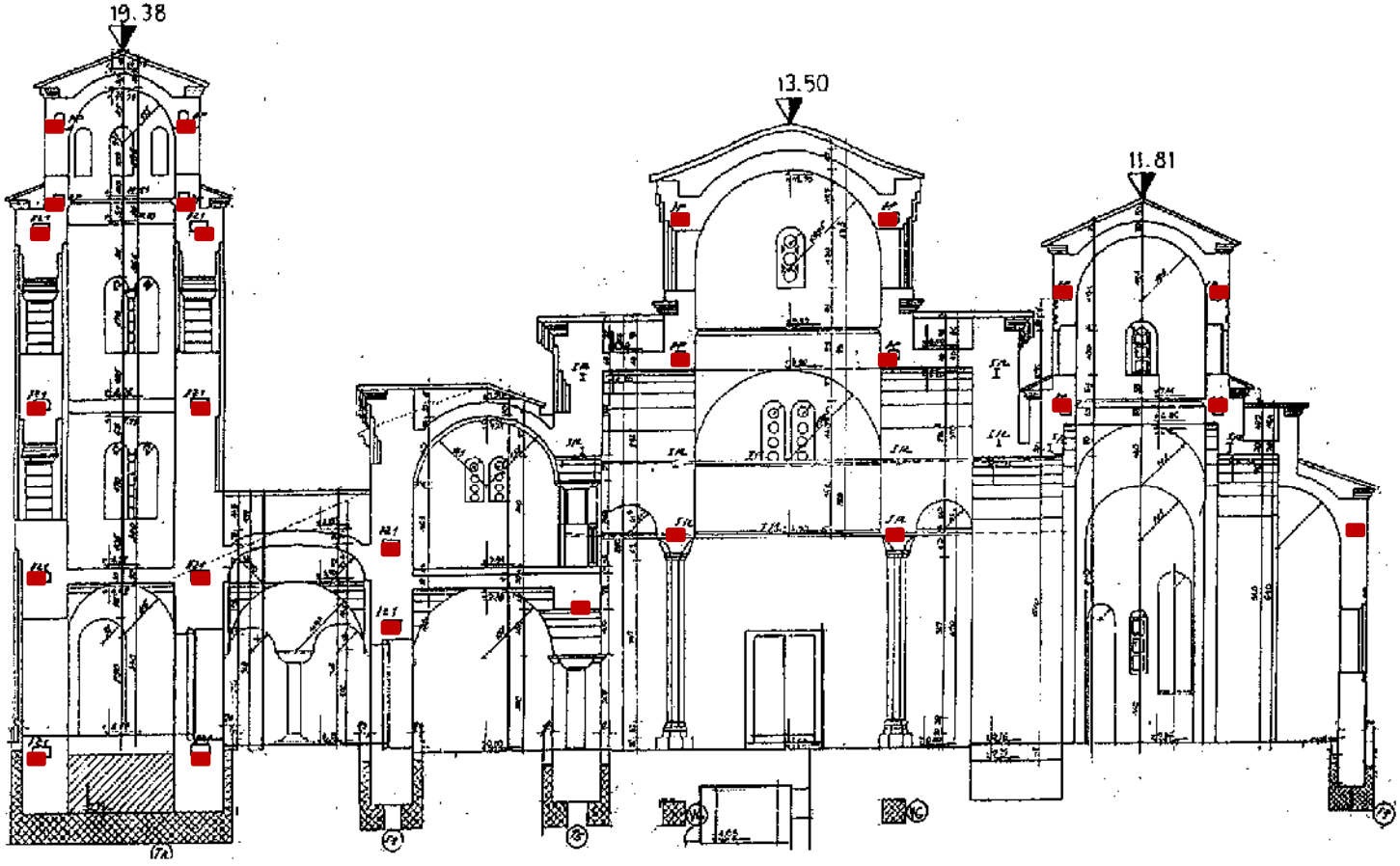
St.Pantelymon Church in Plaoshnik, Ohrid

Implementation..... In reconstruction



cross section of the structure

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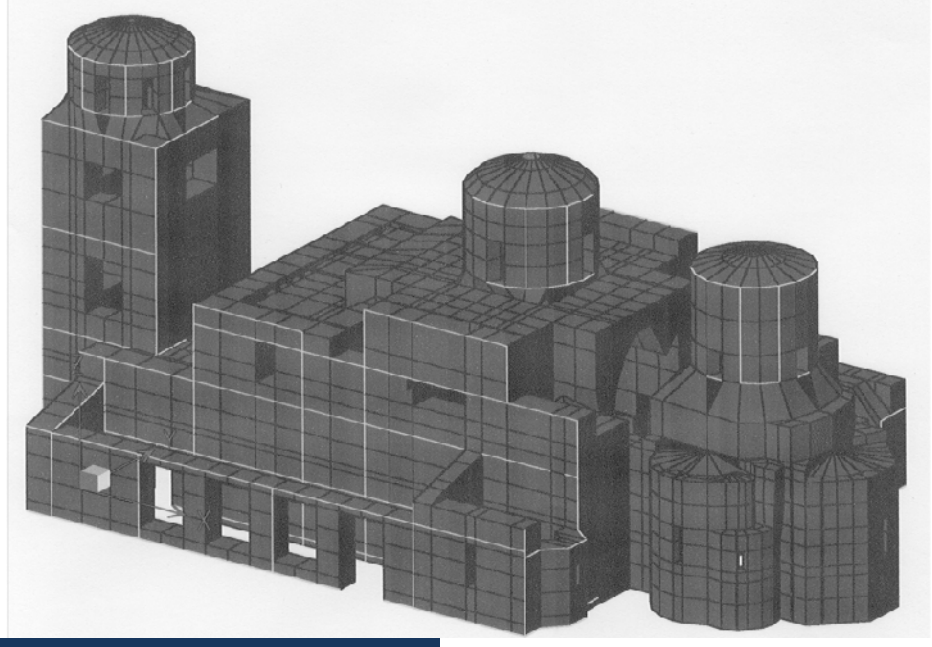
St.Pantelymon Church in Plaoshnik, Ohrid

Implementation..... In reconstruction

- ✓ **Analysis of the bearing and deformability capacity**
- ✓ **Nonlinear dynamic analysis for maximum expected actual earthquake effects (a_{max}=0.36g for tp=1000 years)**
- ✓ **Static and equivalent seismic 3D – FE analysis (SAP 2000)**



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St.Pantelymon Church in Plaoshnik, Ohrid

Realization 2001 - 2002

1

St.Pantelymon Church in Plaoshnik, Ohrid

V, Shendova, B. Stojanoski, P.Gavrilovic, (2004)

Implementation..... In reconstruction

Reconstruction, Seismic Strengthening and Repair of the St. Athanasius Church in Leshok

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Implementation..... In reconstruction

Concept for Repair, Strengthening and Reconstruction

1. **Definition of design criteria (3 levels)**
2. **Repair and structural strengthening up to the design level of seismic safety for the *damaged existing part***
3. **Complete reconstruction by maximum possible use of selected material in lime mortar plus structural strengthening elements for the design level of seiemic safety for the *demolished part***
4. **Dilatation (not less than 3 cm) between the structural units**

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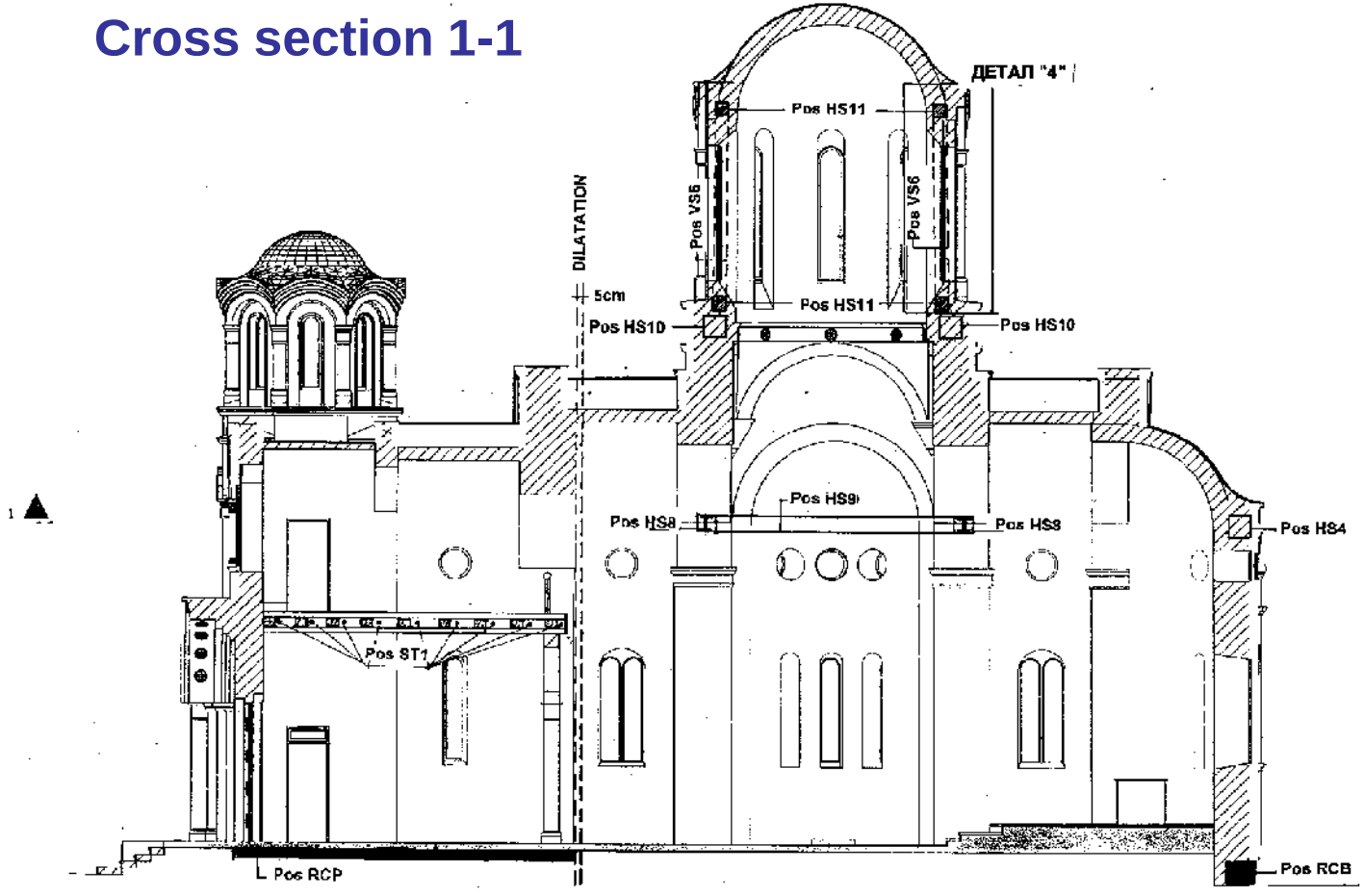
St. Athanasius Church in Leshok, (2004)

Implementation..... In reconstruction

Cross section 1-1



Level +1.90 m

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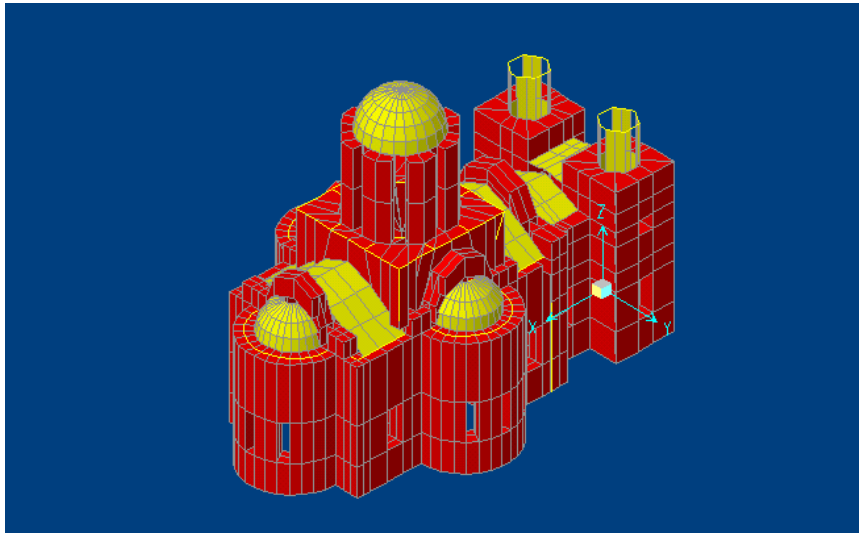
St. Athanasius Church in Leshok, (2004)

Implementation…… In reconstruction

- **Providing architectural documentation**
- **Cleaning up and identification**
- **Urgent preventive measures**
- **Archeological investigations**
- **Chemical analysis**
- **Other investigations**

St. Athanasius Church in Leshok, (2004)

- ✓ **Analysis of the bearing and deformability capacity**
- ✓ **Nonlinear dynamic analysis for maximum expected actual earthquake effects (amax=0.24g for tp=1000 years)**
- ✓ **Static and equivalent seismic 3D – FE analysis (SAP 2000)**



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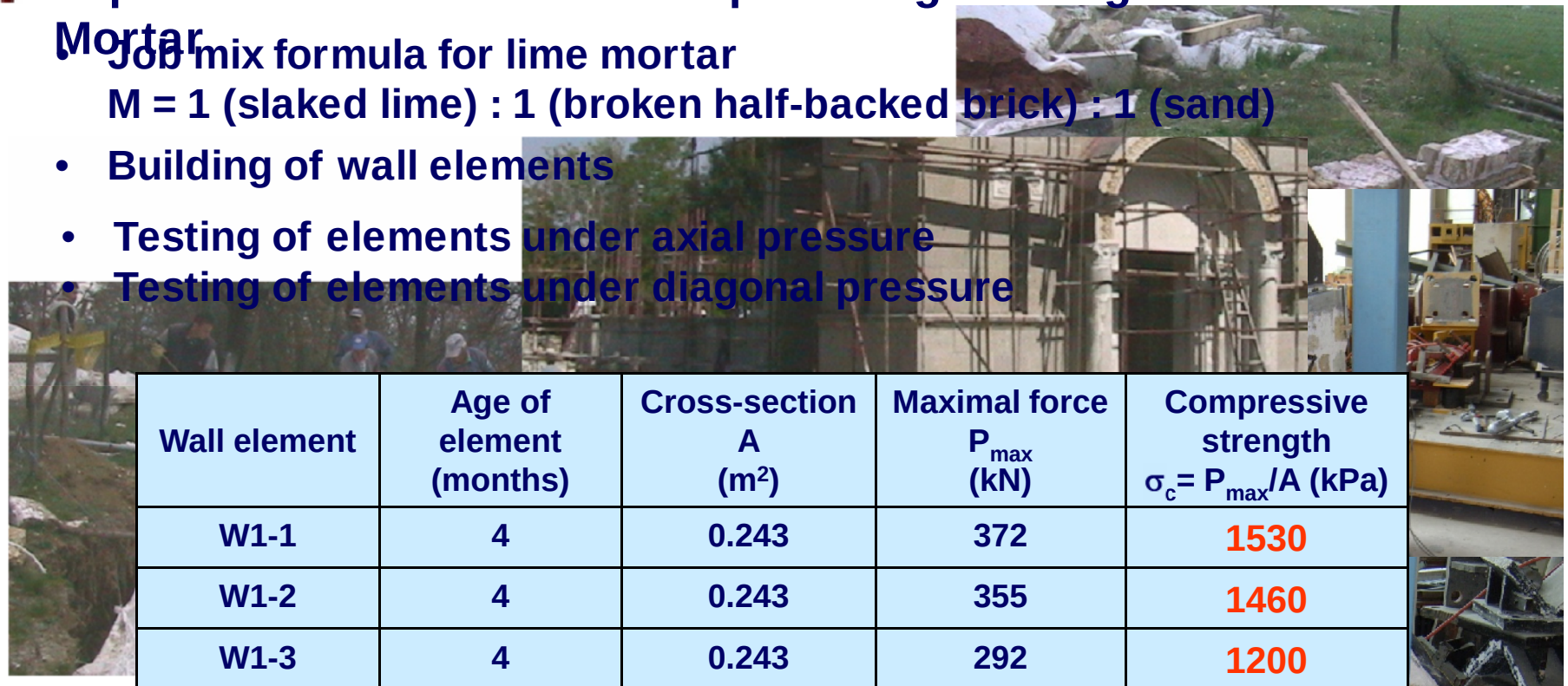
St. Athanasius Church in Leshok, (2004)

- **Experimental verification of Input Design Strength of Lime Mortar**
  - **Job mix formula for lime mortar**
    M = 1 (slaked lime) : 1 (broken half-backed brick) : 1 (sand)
  - **Building of wall elements**
  - **Testing of elements under axial pressure**
  - **Testing of elements under diagonal pressure**



Wall element	Age of element (months)	Cross-section A (m^2)	Maximal force P_{max} (kN)	Compressive strength $\sigma_c = P_{max}/A$ (kPa)
W1-1	4	0.243	372	1530
W1-2	4	0.243	355	1460
W1-3	4	0.243	292	1200

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St. Athanasius Church in Leshok, (2004)

Implementation..... In reconstruction

Reconstruction and Seismic Strengthening of the Blown Up Church of the Holy Trinity in Mostar

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Implementation..... In reconstruction

Concept for Strengthening and Reconstruction

1. **Definition of design criteria**
2. **Full reconstruction with maximum possible use of the existing preserved material and minimum additional intervention**
3. **Three general states have been analyzed:**

(1) structural system of plain stone masonry (PS);

(2) strengthened structure by horizontal steel element (HS)

(3) strengthened structure by horizontal & vertical steel strengthening elements -confined masonry (HVS)

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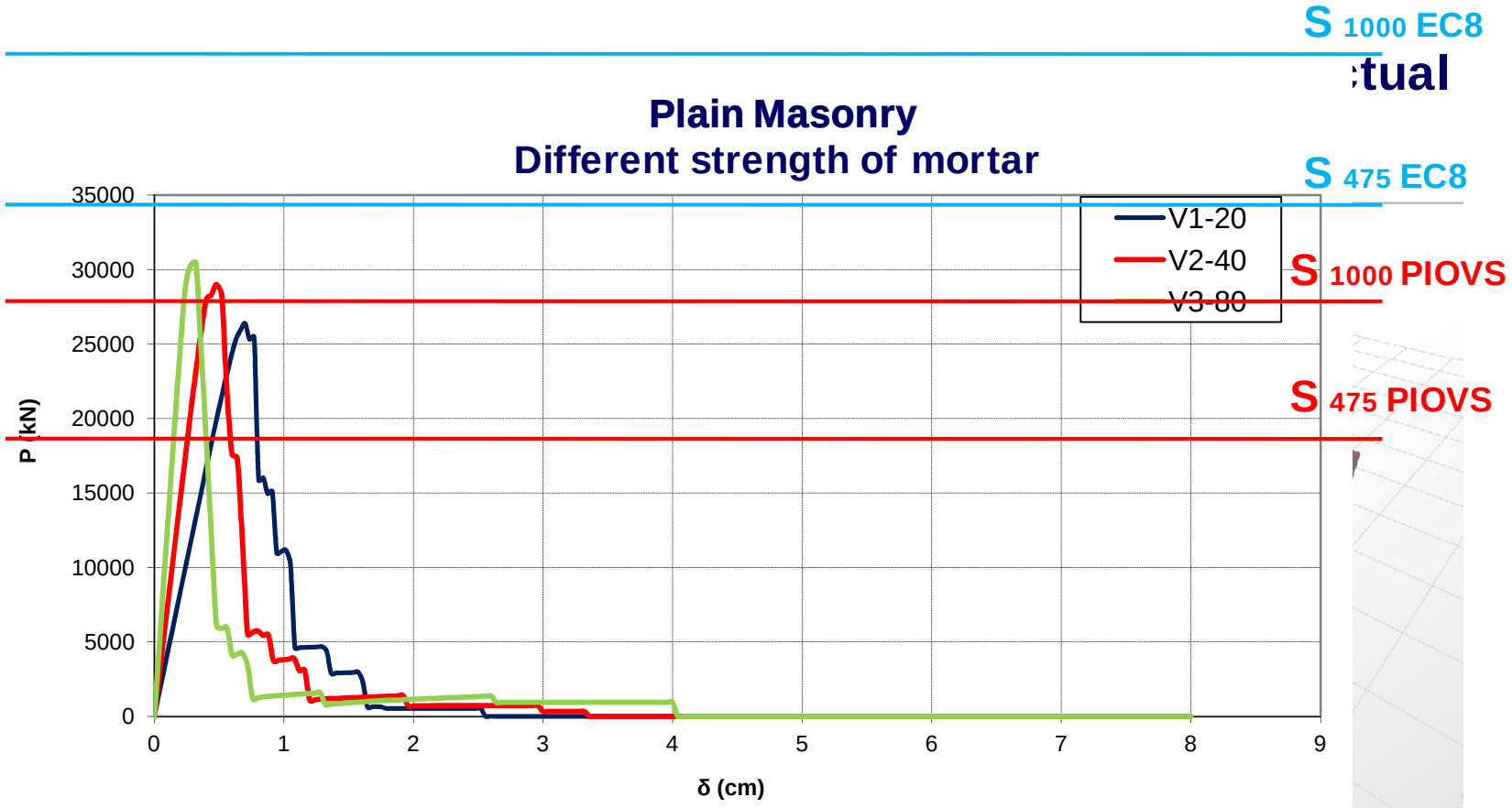
Church of the Holy Trinity in Mostar, (2011)

✓ Analysis of the bearing and deformability capacity



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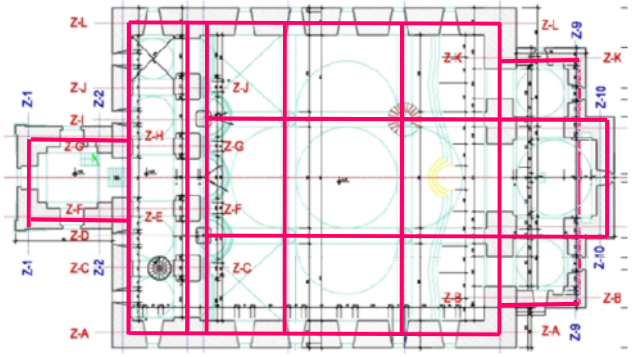
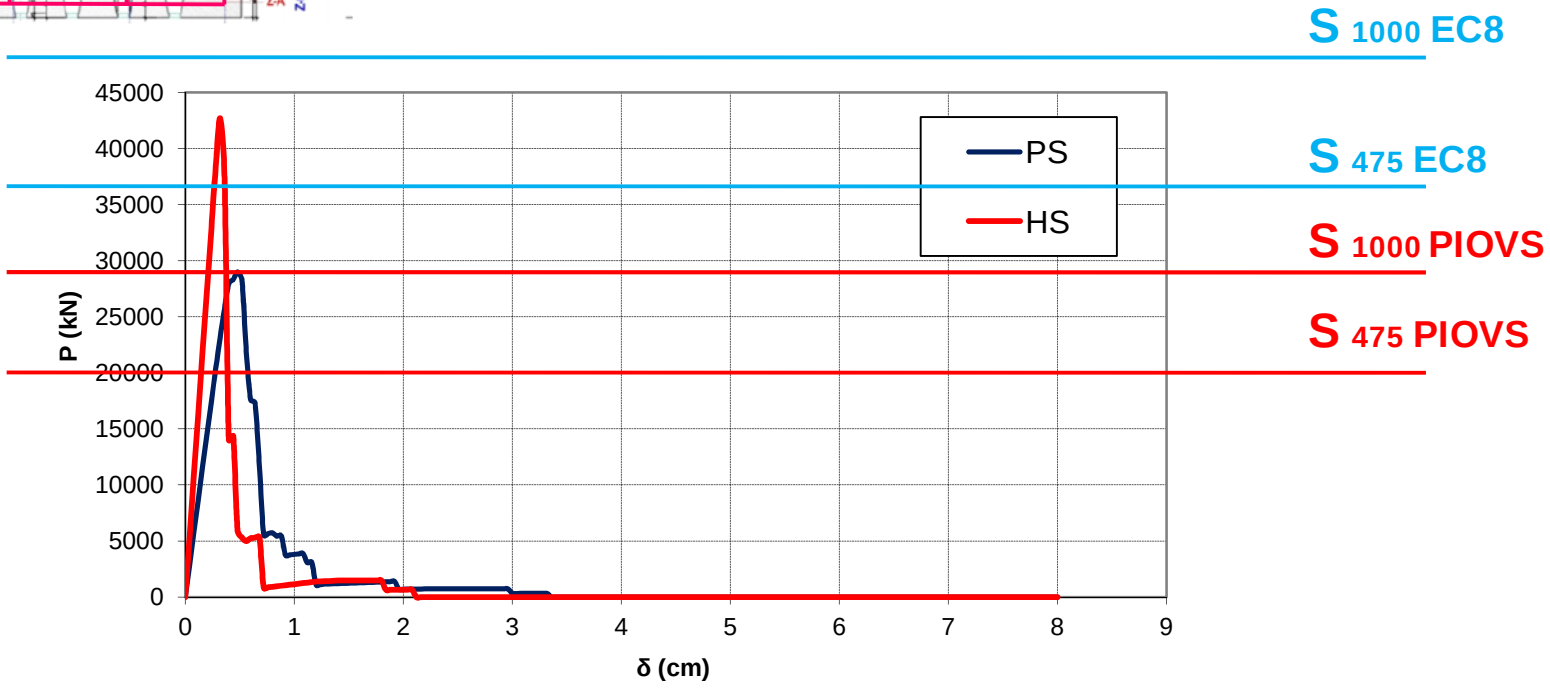
Church of the Holy Trinity in Mostar, (2011)

Implementation..... In reconstruction



Strengthening with horizontal strengthening elements



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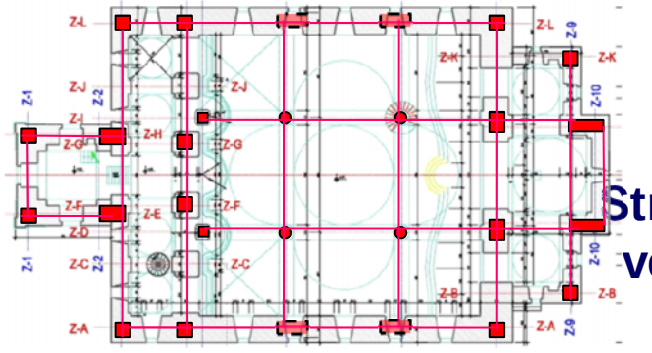
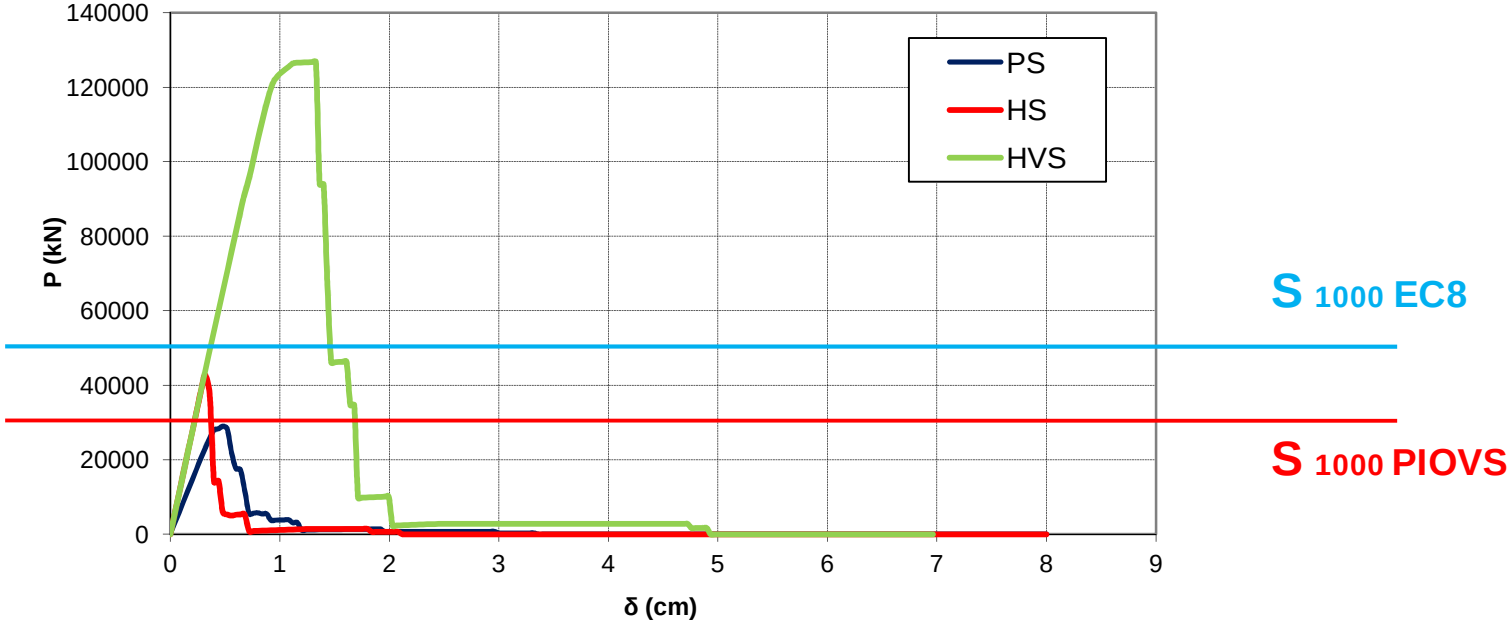
Church of the Holy Trinity in Mostar, (2011)

Implementation..... In reconstruction



Strengthening with horizontal and vertical strengthening elements



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Church of the Holy Trinity in Mostar, (2011)

Implementation…… In reconstruction

Realization 2011

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Seismic Strengthening of Mustafa Pasha Mosque, Skopje

- One of the biggest and best preserved Ottoman monuments in Skopje and Balkan
- Damaged by Skopje earthquake in 1963 (domes, east facade, minaret)
- Today - cultural historic monument of extraordinary importance

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Mustafa Pasha Mosque, Skopje(2010)

Architectural Conservation project (2006):

Ministry of Culture and Tourism & University of Gazi, Turkey and

Ministry of Culture & National Conservation Center, Macedonia decided:

- to remove all the cement covering of central dome and domes of the porch
- to consolidate all the domes by injection with lame based mixtures
- to isolate the RC belt course
- to remove cement mortar from all the facade joints
- to provide investigation form structural and geotechnical point of view

Repair and Seismic Upgrading (2007-2010)

- ✓ investigation of the main dynamic characteristics,
- ✓ investigations of the characteristics of the built-in materials,
- ✓ shaking table testing of the mosque model;
- ✓ investigations of the soil conditions;
- ✓ detailed geophysical surveys for definition of geotechnical/geodynamic models.

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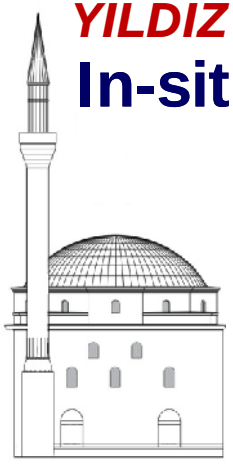
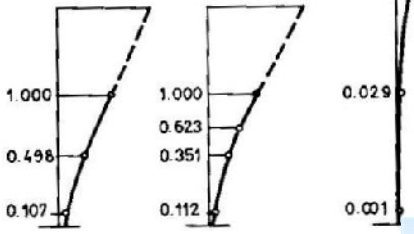
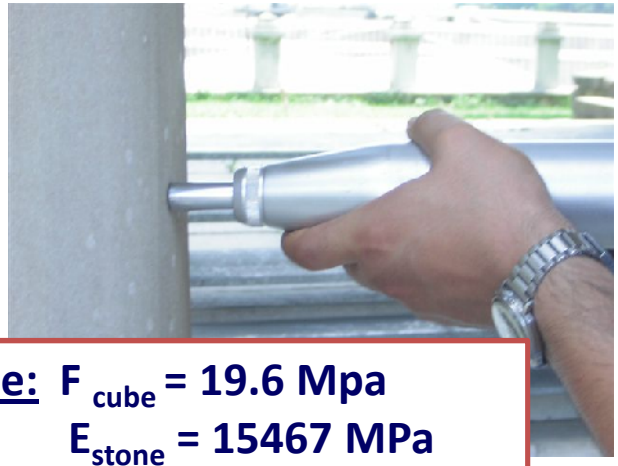
YILDIZ Technical University & IZIIS

In-situ investigation





$f_{1\text{-}1}$=3.0Hz $f_{2\text{-}2}$=3.2Hz f_m=



stone: F_{cube} = 19.6 Mpa

E_{stone} = 15467 MPa

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Implementation…… In Strengthening

EU FP6 – PROHITECH Project (2004 – 2007)

Shaking table testing of the mosque model (2006-2007)

original state

strengthened by CFRP bars & wrap

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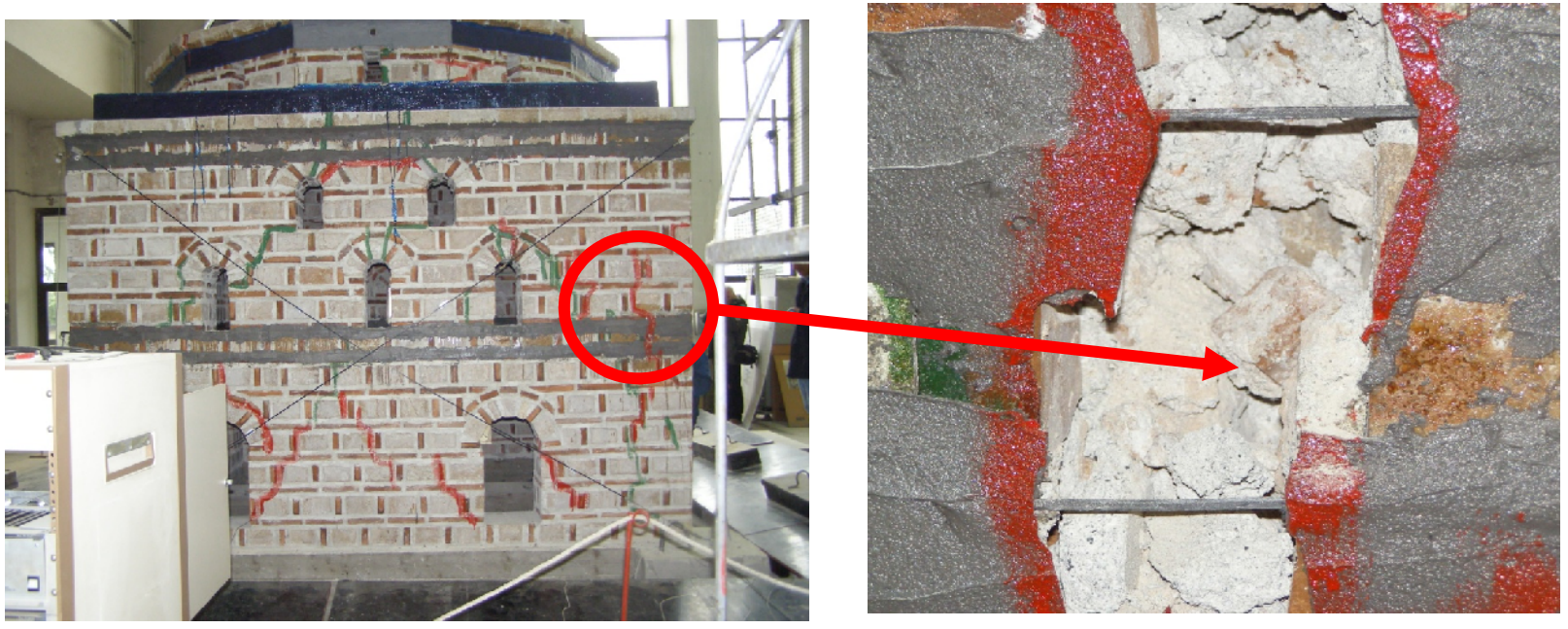

The applied strengthening was very efficient even for higher input excitation

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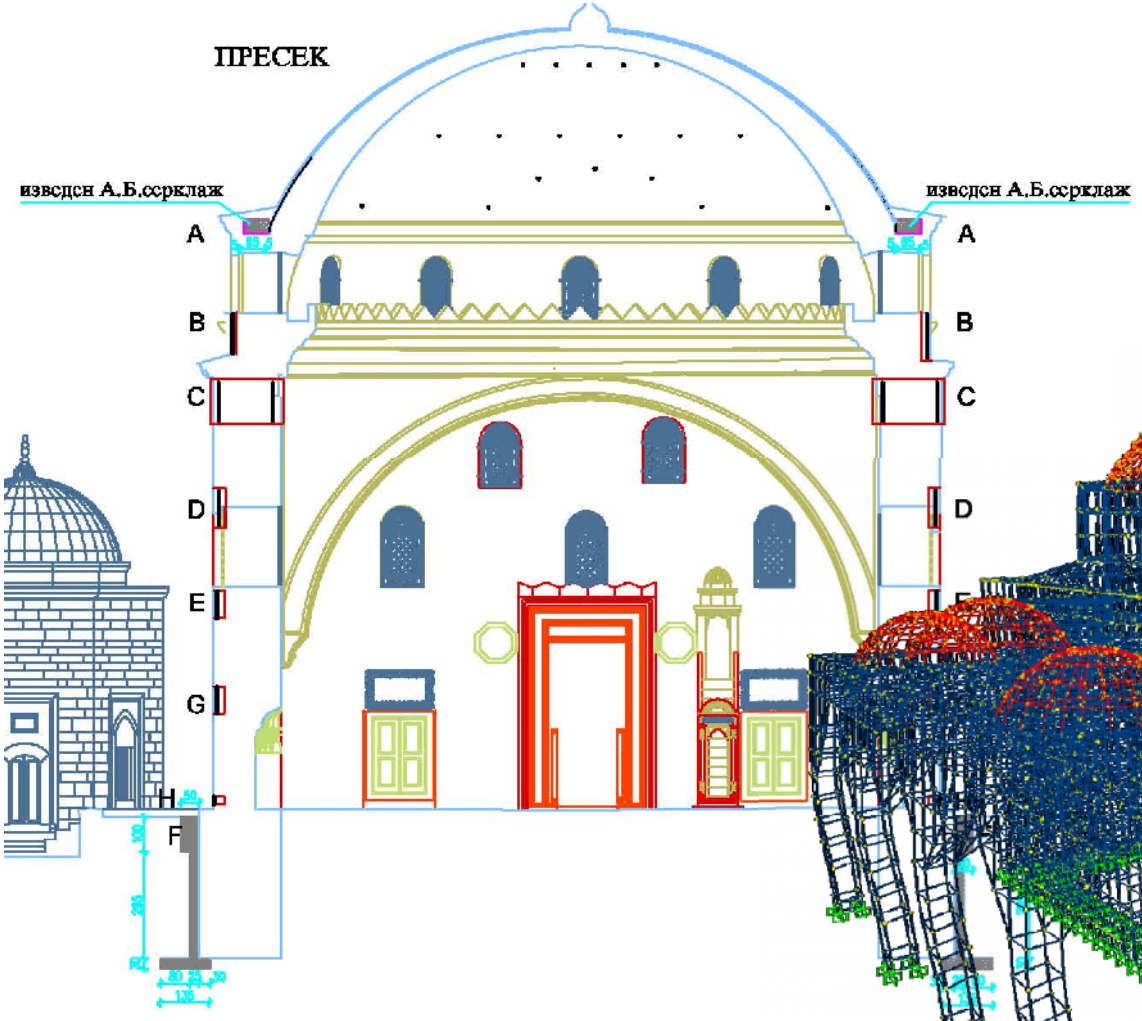
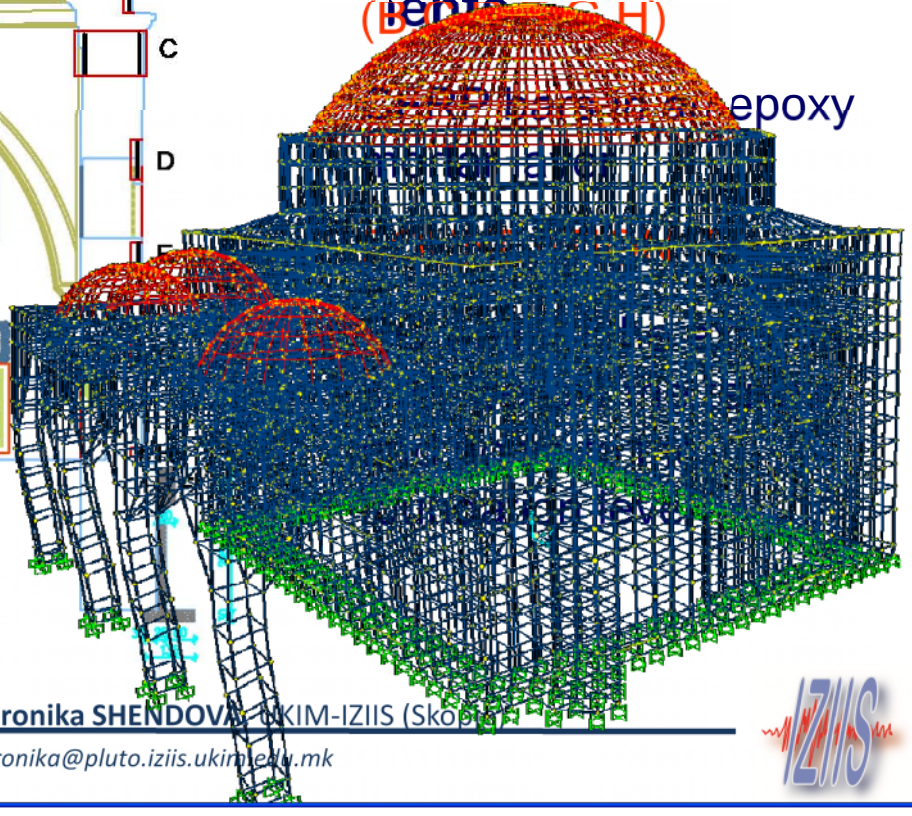
Implementation…… In Strengthening



DOME Structure (A)
CFRP wrap in a layer of epoxy glue within a width of 2.9m

BEARING WALLS
(B[illegible] G, H)

[illegible] epoxy



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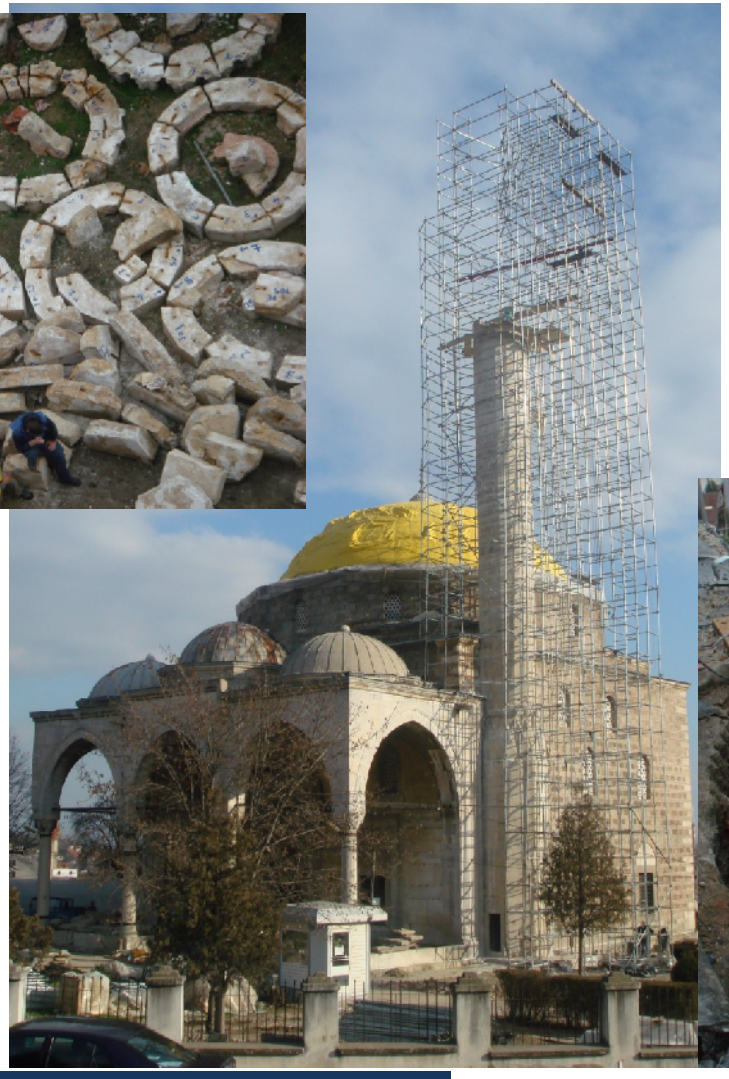
Realization, 2007-2010



Repair of minaret

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Mustafa Pasha Mosque, Skopje(2010)

Strengthening of foundation

- ✓ Injection of the cracks by lime mortar
- ✓ Incorporation of RC wall (25cm) along the perimeter of the foundation walls
- ✓ Separation of RC wall from the existing foundation by polyurethane coating
- ✓ Placement of chrome steel in previously formed openings filled with epoxy mortar

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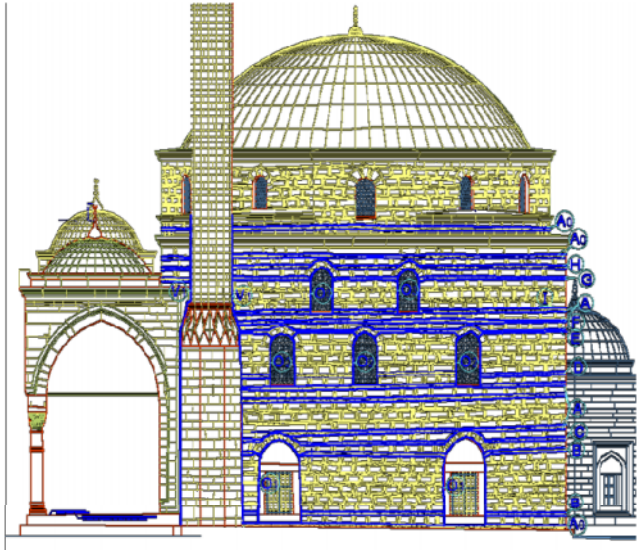
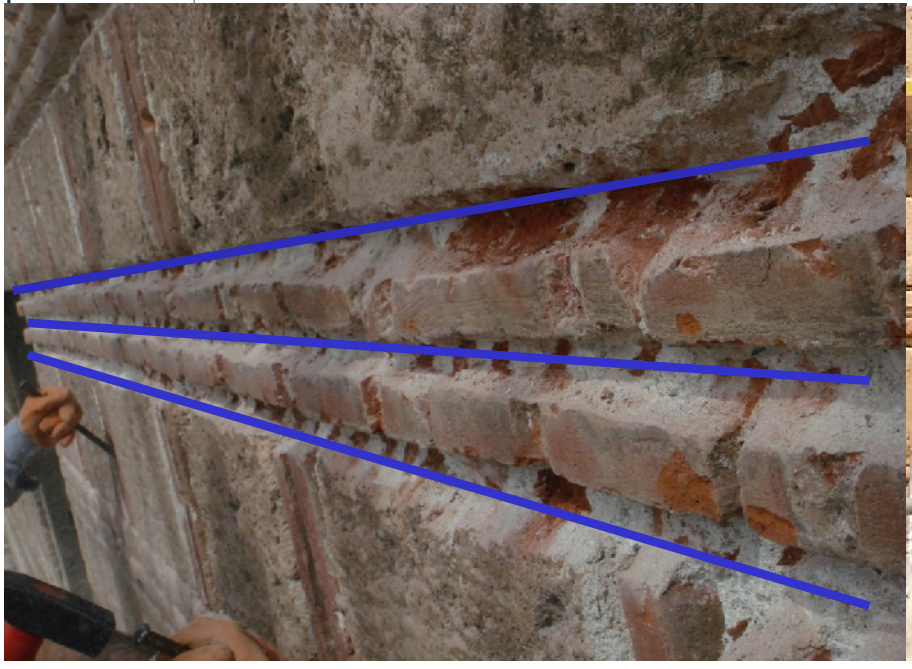


Strengthening of bearing walls

- ✓ **Cleaning of all joints on the outside with a depth of max 7-8 cm**
- ✓ **Placement of CFRP bars (d=1cm) in an epoxy mortar layer**
- ✓ **Filling of the joints with pointing lime**



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Strengthening of central dome

- ✓ Removal of the cement mortar layer
- ✓ Coating of existing rc ring with injection mixture based on lime mortar
- ✓ Placement of CFRP wrap in a layer of epoxy glue along the perimeter with the width of 3m
- ✓ Coating of entire dome with a protective layer of lime mortar

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Instead of Conclusion.....

Proving the effectiveness of the selected strengthening could be successfully overcome by using "design by testing" methodology.

It is very powerful tool, especially when the object of design is a complex structure, which is difficult and unsafe to analyze by using traditional methods.

THANK YOU!

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