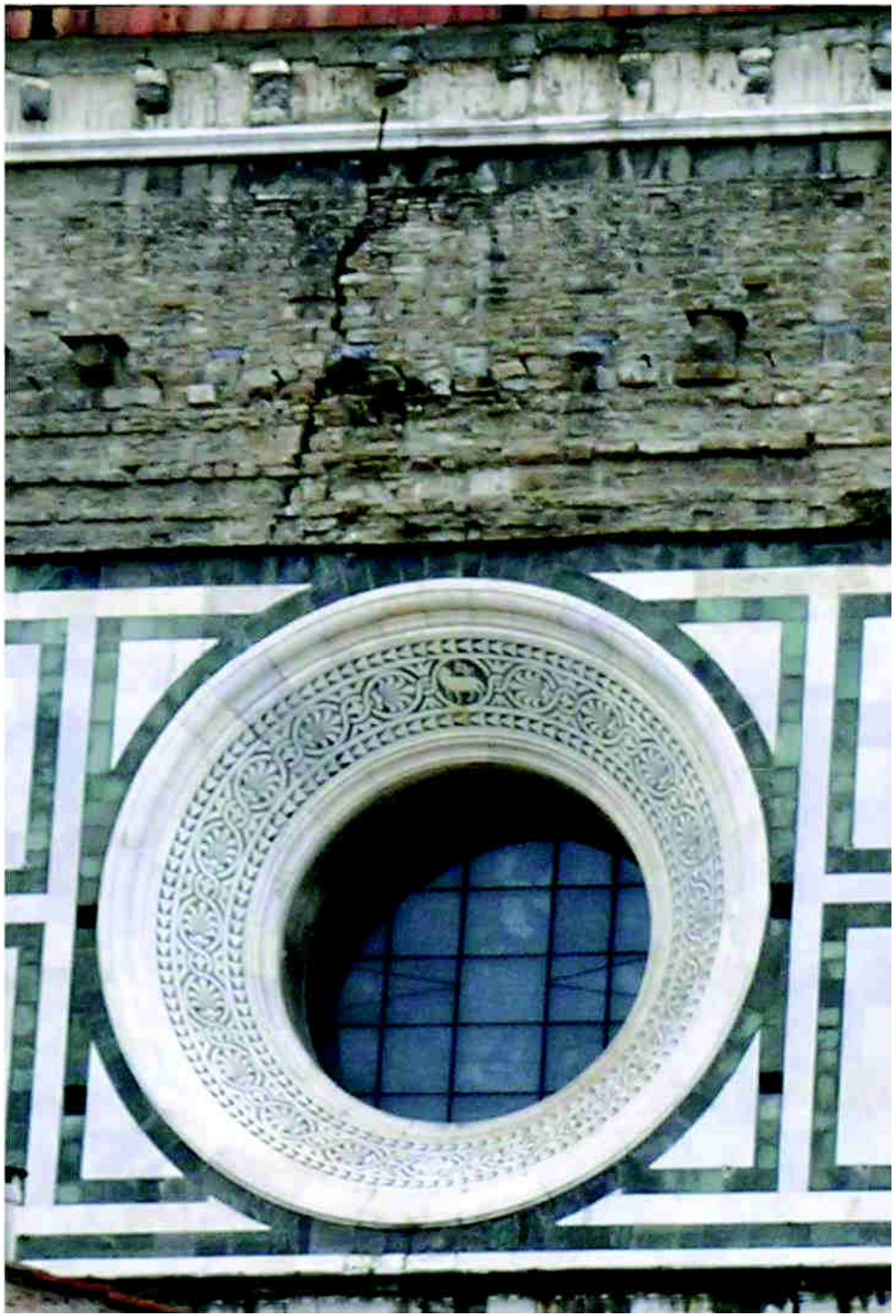
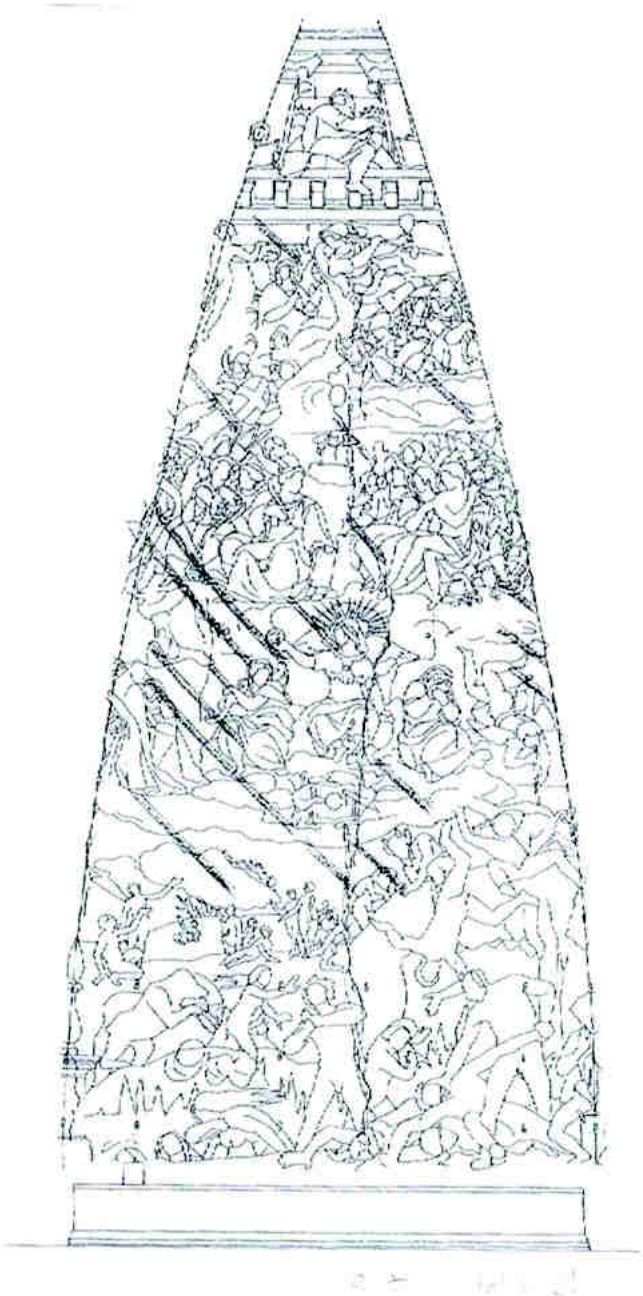
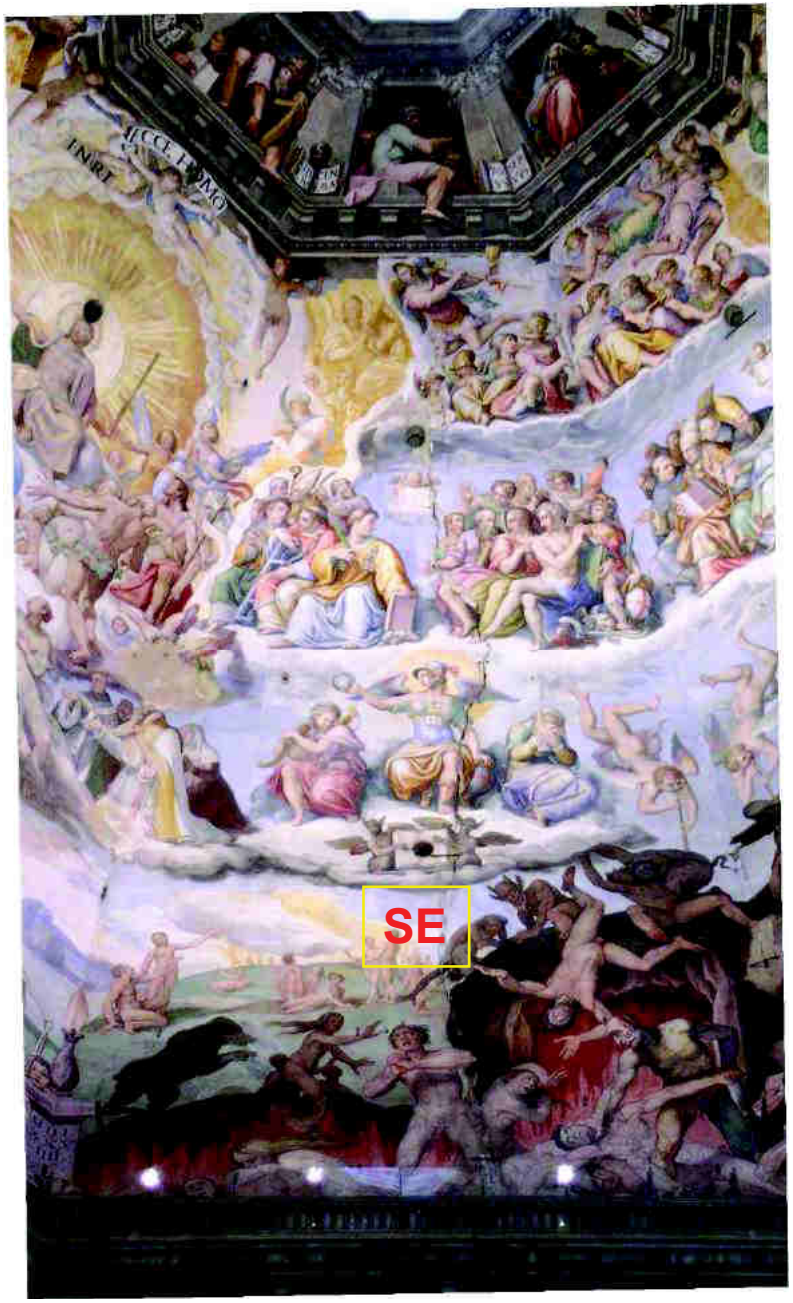
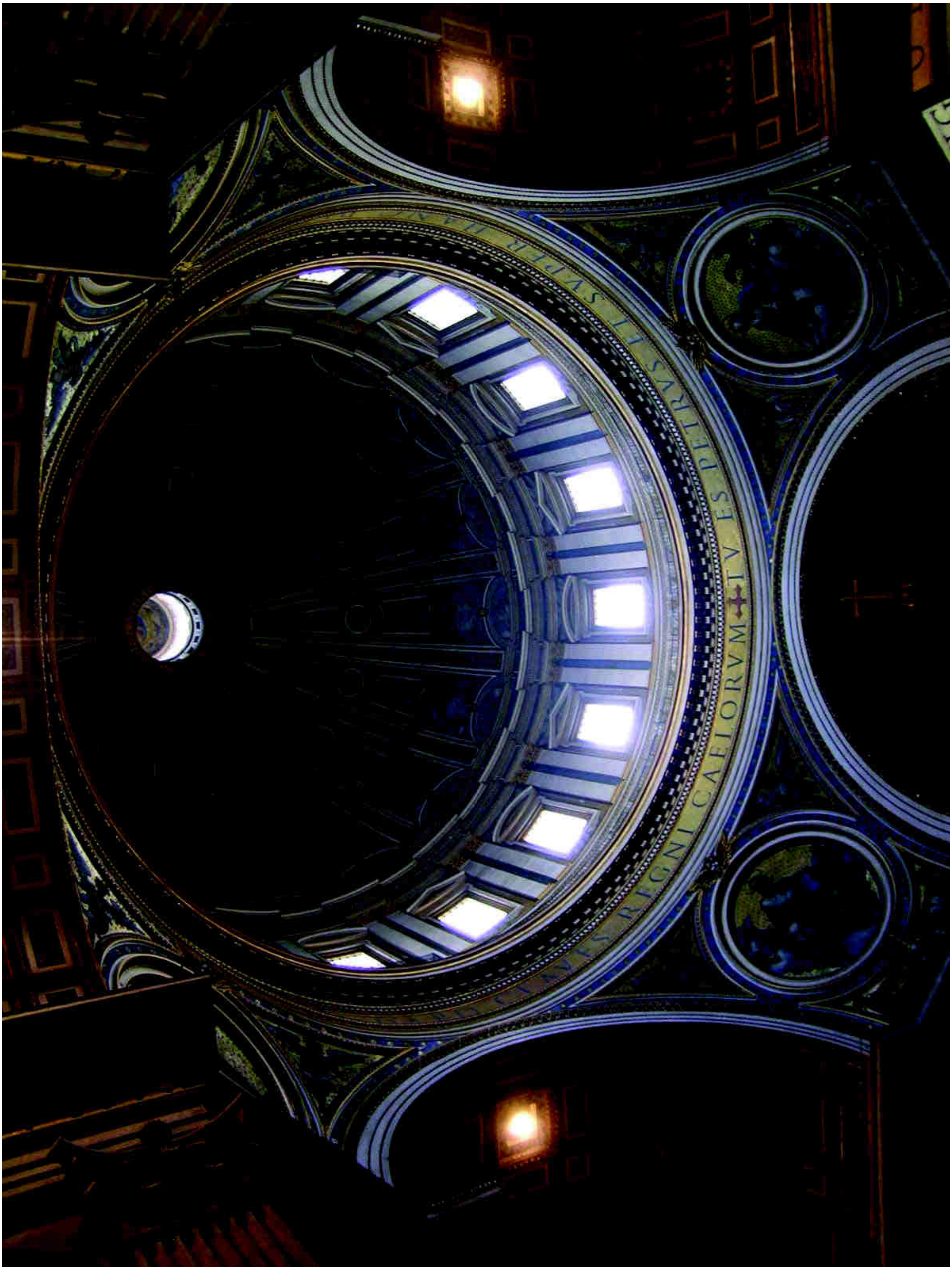


NE main meridional crack
External view




SE


San Pietro
J. Della Porta 1590
Φ_i 42.84 m


CLAVES REGNI CAELORVM TV ES PETRVS ET SVPER


TIBI DABO CLAVES REGNI CAELORVM

St. Peter dome in Rome (built 1590)
Development of cracks (1742)

PARERE
DI TRE
MATTEMATICI
Sopra i danni, che si sono trovati
NELLA CUPOLA
DI S. PIETRO
Sul fine dell'Anno MDCCXLII.
DATO PER ORDINE
DI NOSTRO SIGNORE
PAPA BENEDETTO XIV.

(Boscovich, Le Soeur e Jacquier, 1742)

TAVOLA. XV.

32. La gran ſpaccatura ſopra il pilone della Veronica ſul cornicioncino dell' Attico in [illegible] è di quattro once, e vene ſono due vicinissime, in cui essa diramasi di un'oncia e mezza fra tutte due. Quella in faccia ſopra il Longino è di due once e mezza: Ivi le ſpaccature in giro ſono in numero 27., e tanto groſſe, che meſſe insieme si trovano di 22. once, e poco piu sù di 24.
Quando sieno cominciati questi danni non si sà con certezza.

60 70 80 90

Ampiezza complessiva fessure sul perimetro 445 mm

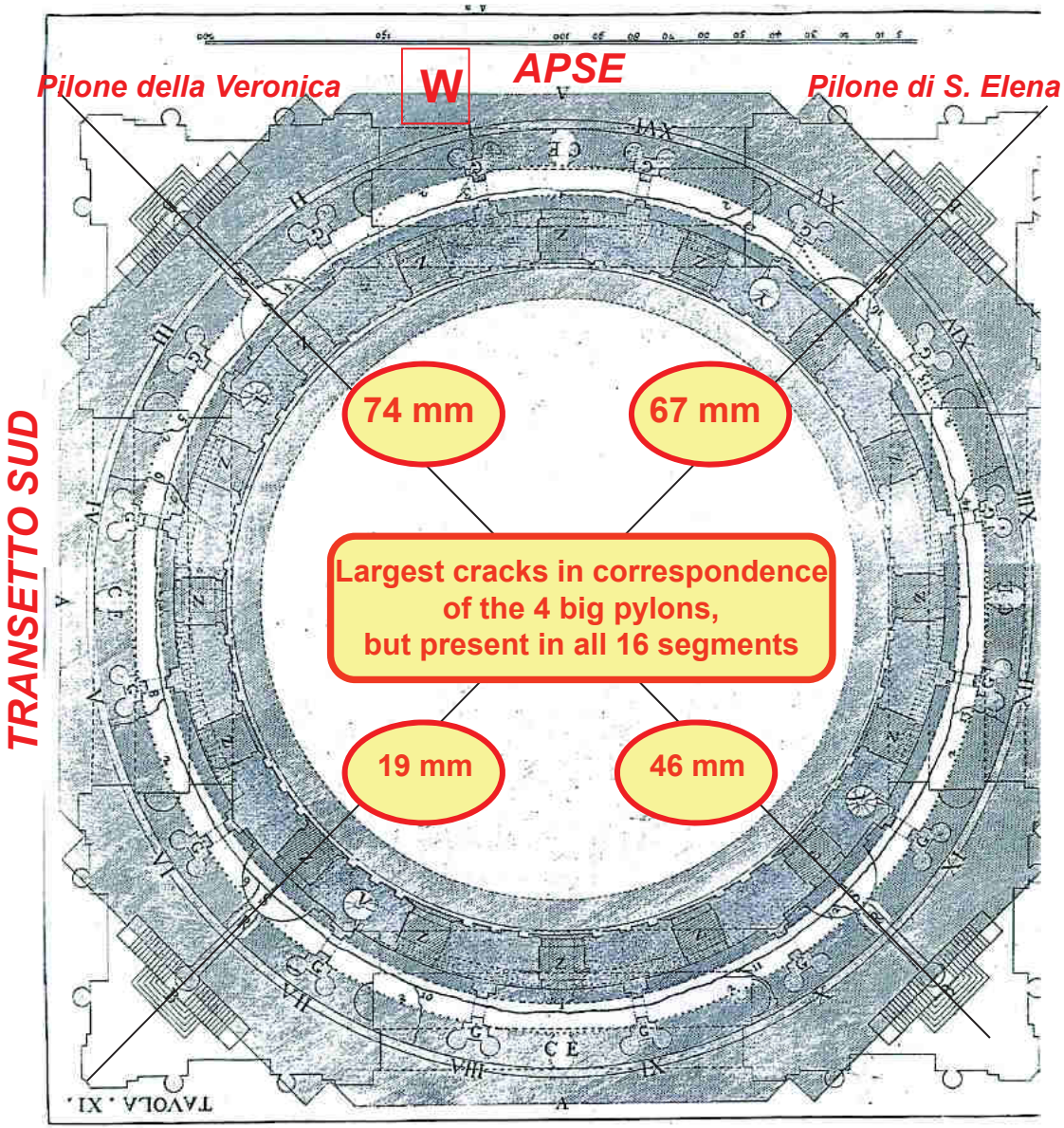
150 200

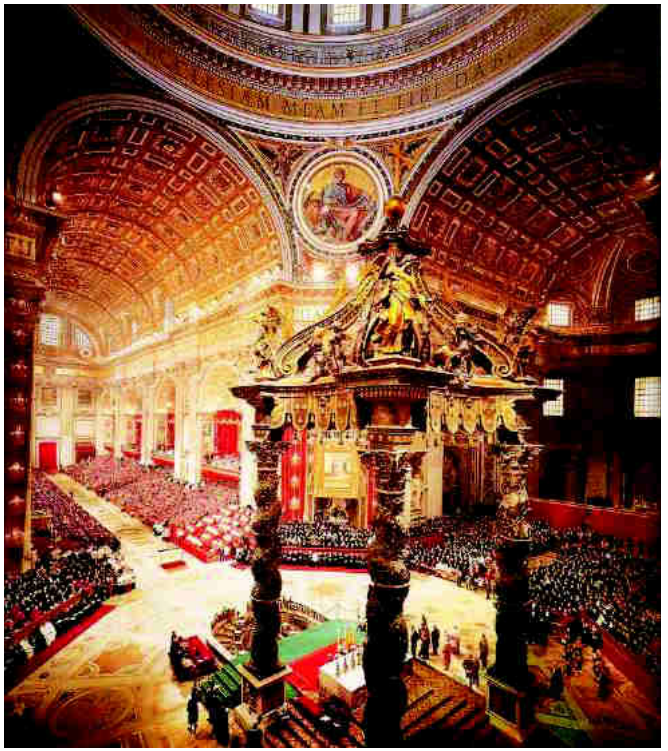
74 mm
19 mm nel 1680

Insufficienza dei contrafforti
Rotture per taglio con fessure inclinate

1 palmo = 12 once = 22.3 cm
1 oncia = 5 minuti = 1.86 cm
1 minuto = 0.371 cm

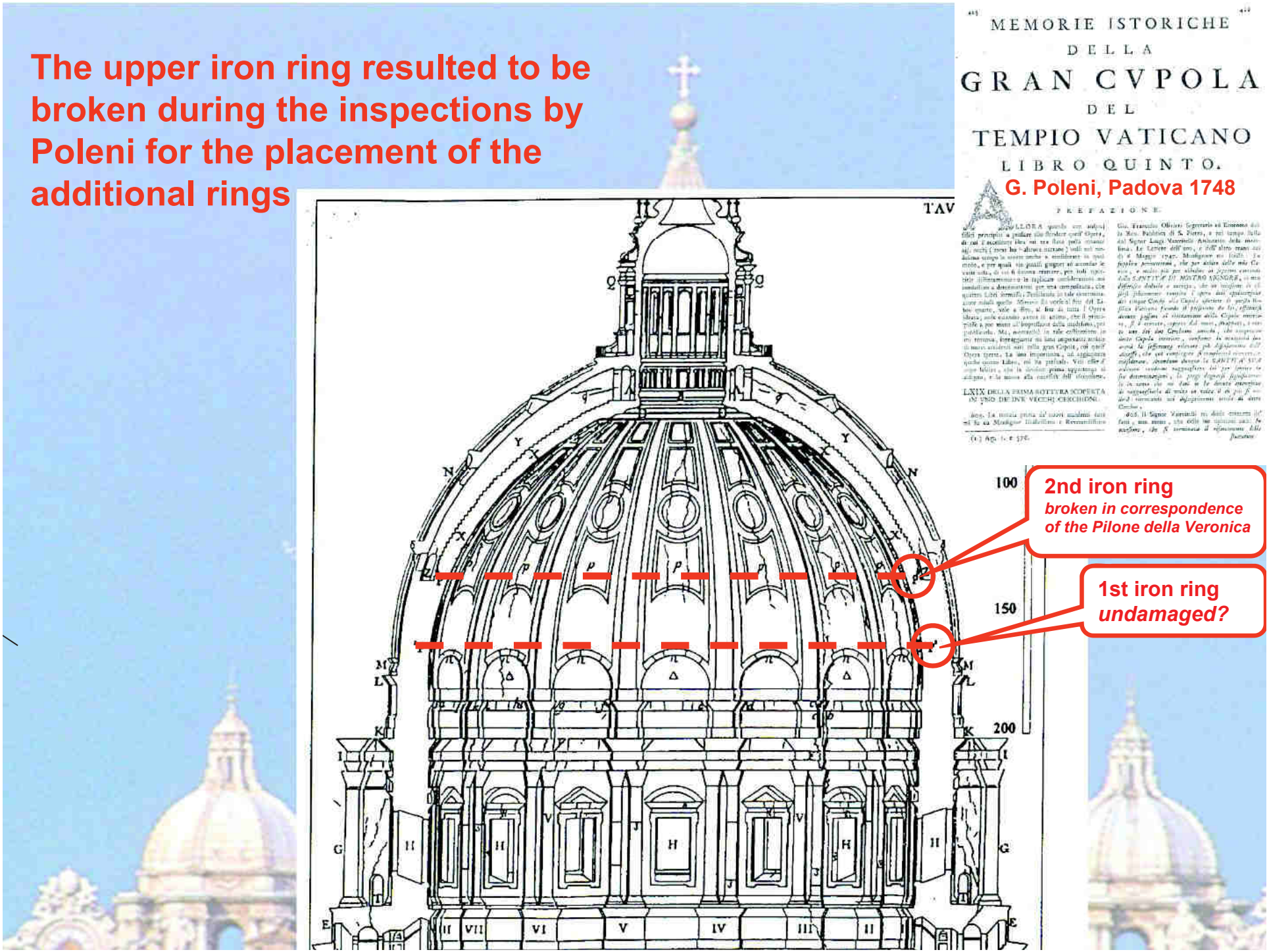
Beltrami 1929


Pilone della Veronica
W
APSE
Pilone di S. Elena
TRANSETTO SUD
TRANSETTO NORD
74 mm
67 mm
Largest cracks in correspondence
of the 4 big pylons,
but present in all 16 segments
19 mm
46 mm
Pilone di S. Andrea
Pilone di S. Longino
E
NAVE




Fessurazione in
chiave agli arconi
principali

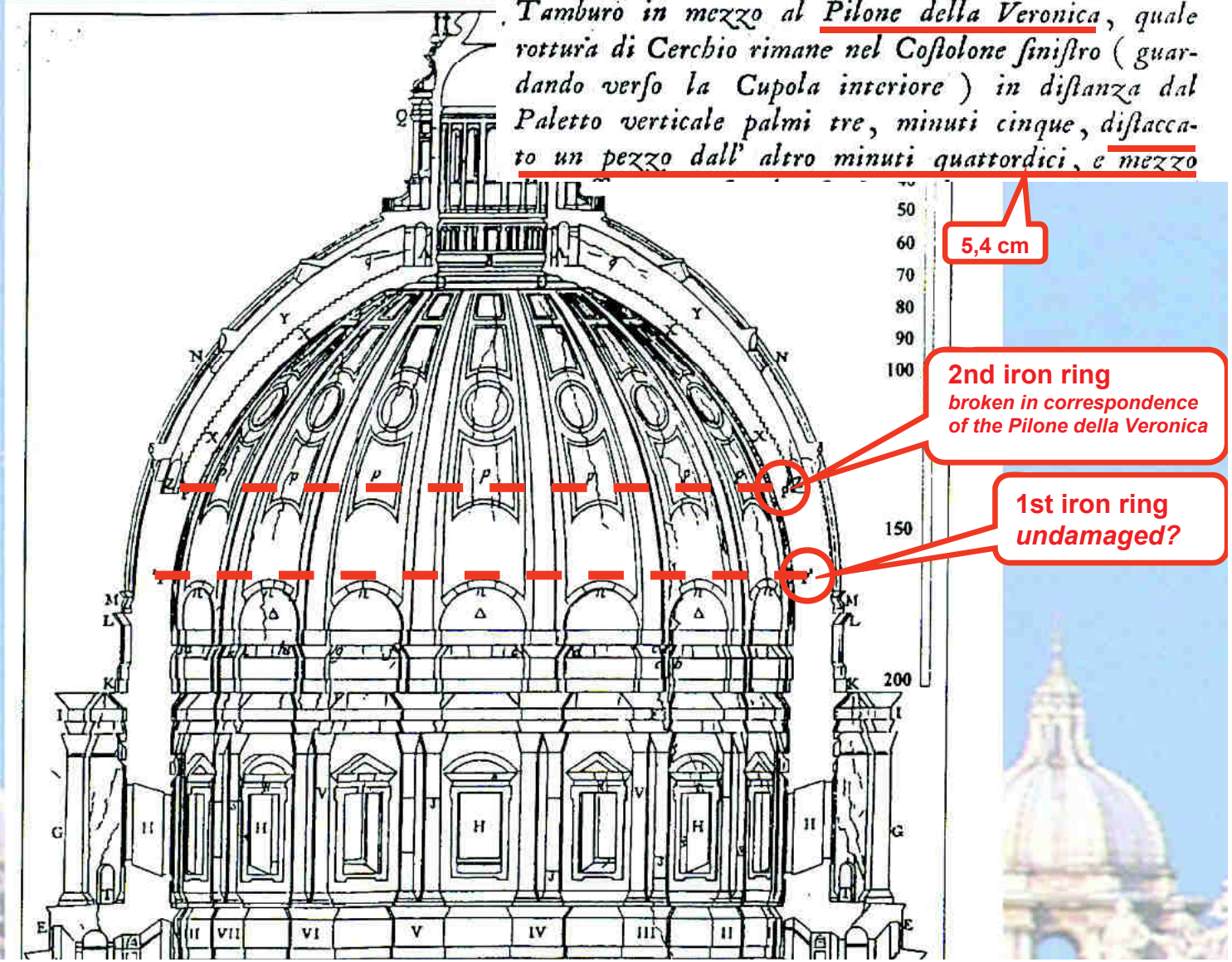
The upper iron ring resulted to be broken during the inspections by Poleni for the placement of the additional rings



The upper iron ring resulted to be broken during the inspections by Poleni for the placement of the additional rings

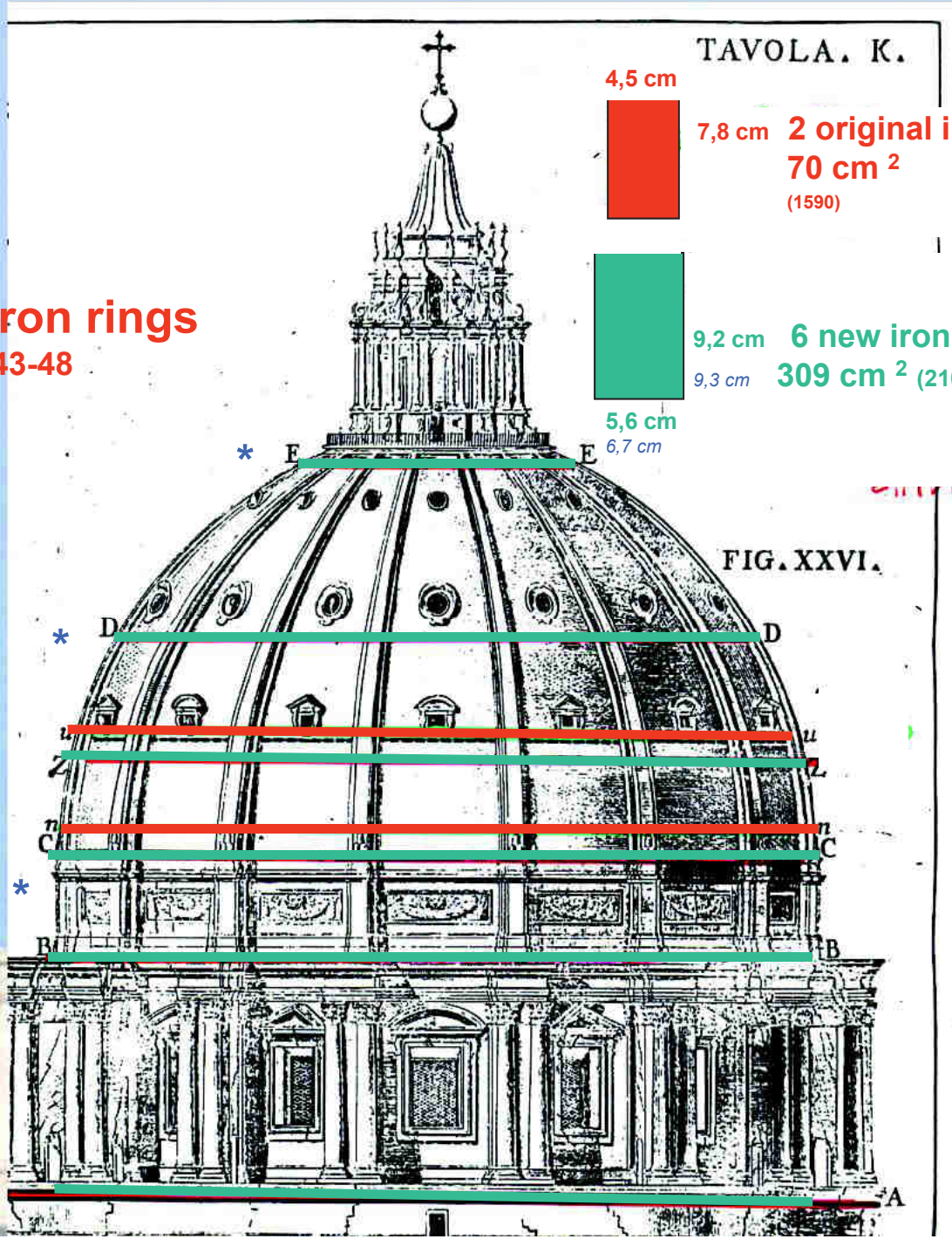
Nel medemo Cerchione ſi è ritrovata altra ſeconda rottura nel ſito corriſpondente ſulla Feneſtra del Tamburo in mezzo al Pilone della Veronica, quale rottura di Cerchio rimane nel Coſtolone ſiniſtro (guardando verſo la Cupola interiore) in diſtanza dal Paletto verticale palmi tre, minuti cinque, diſtaccato un pezzo dall' altro minuti quattordici, e mezzo

5,4 cm



Insertions of new iron rings

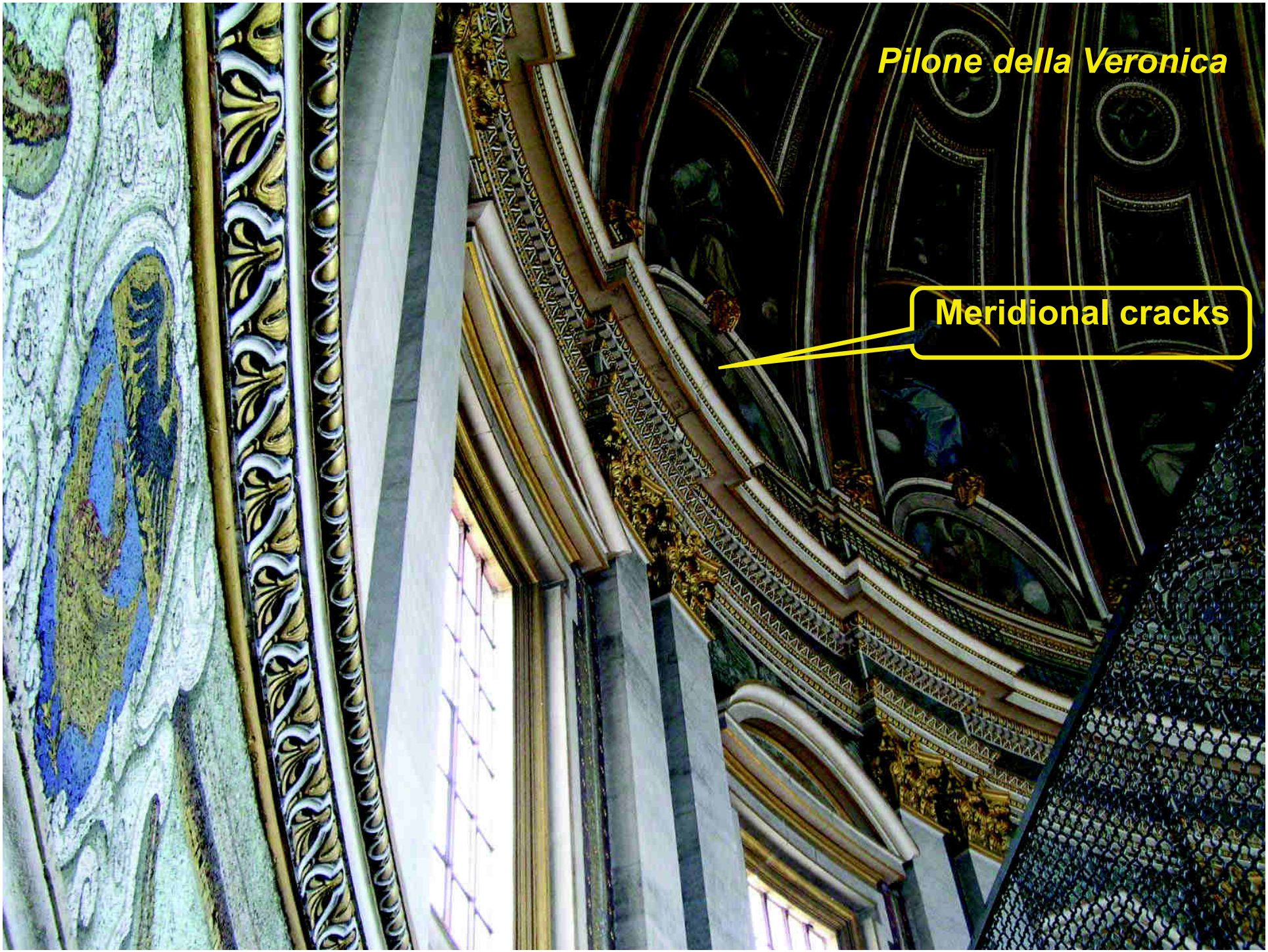
G. Poleni e L. Vanvitelli 1743-48

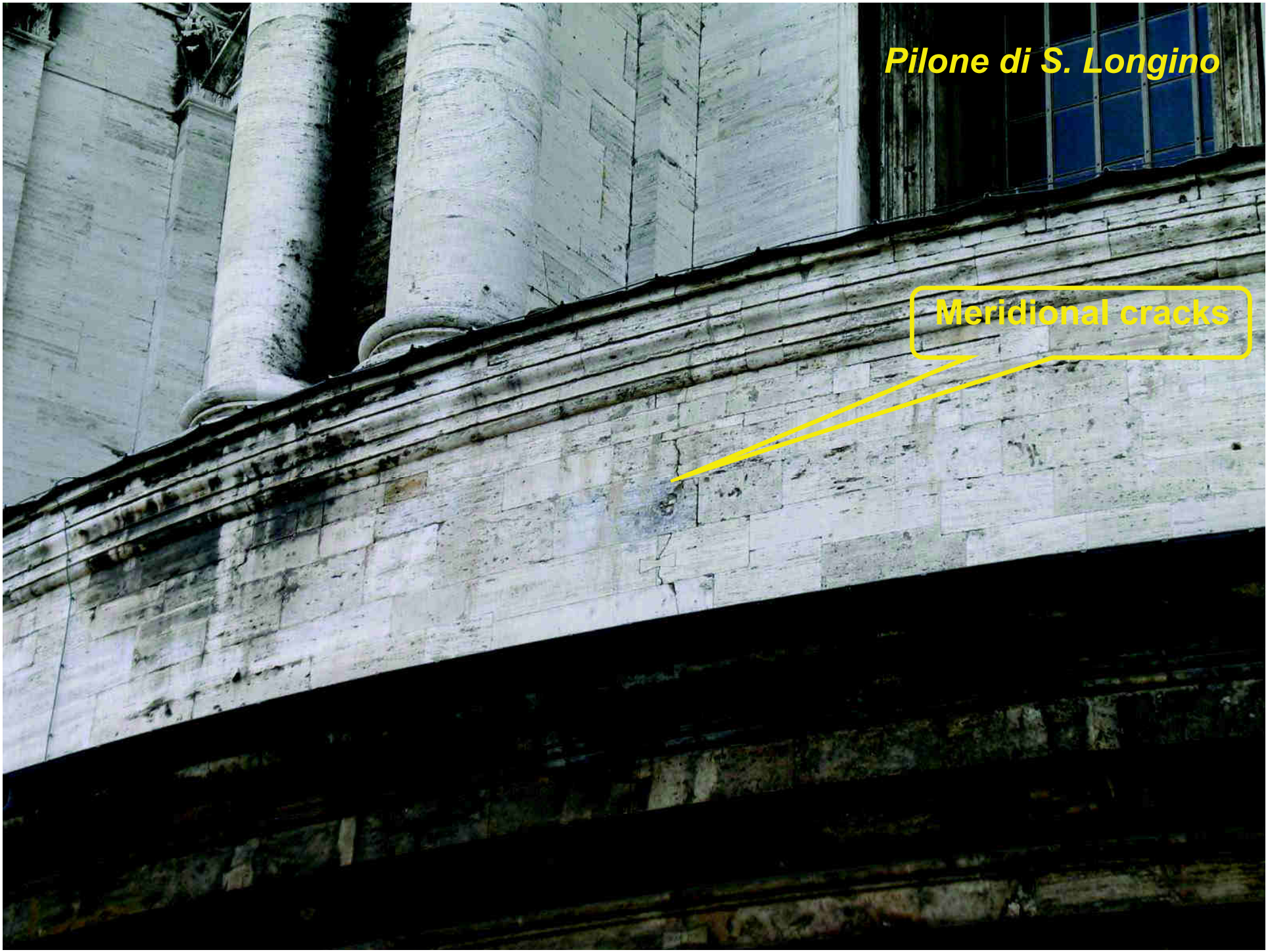


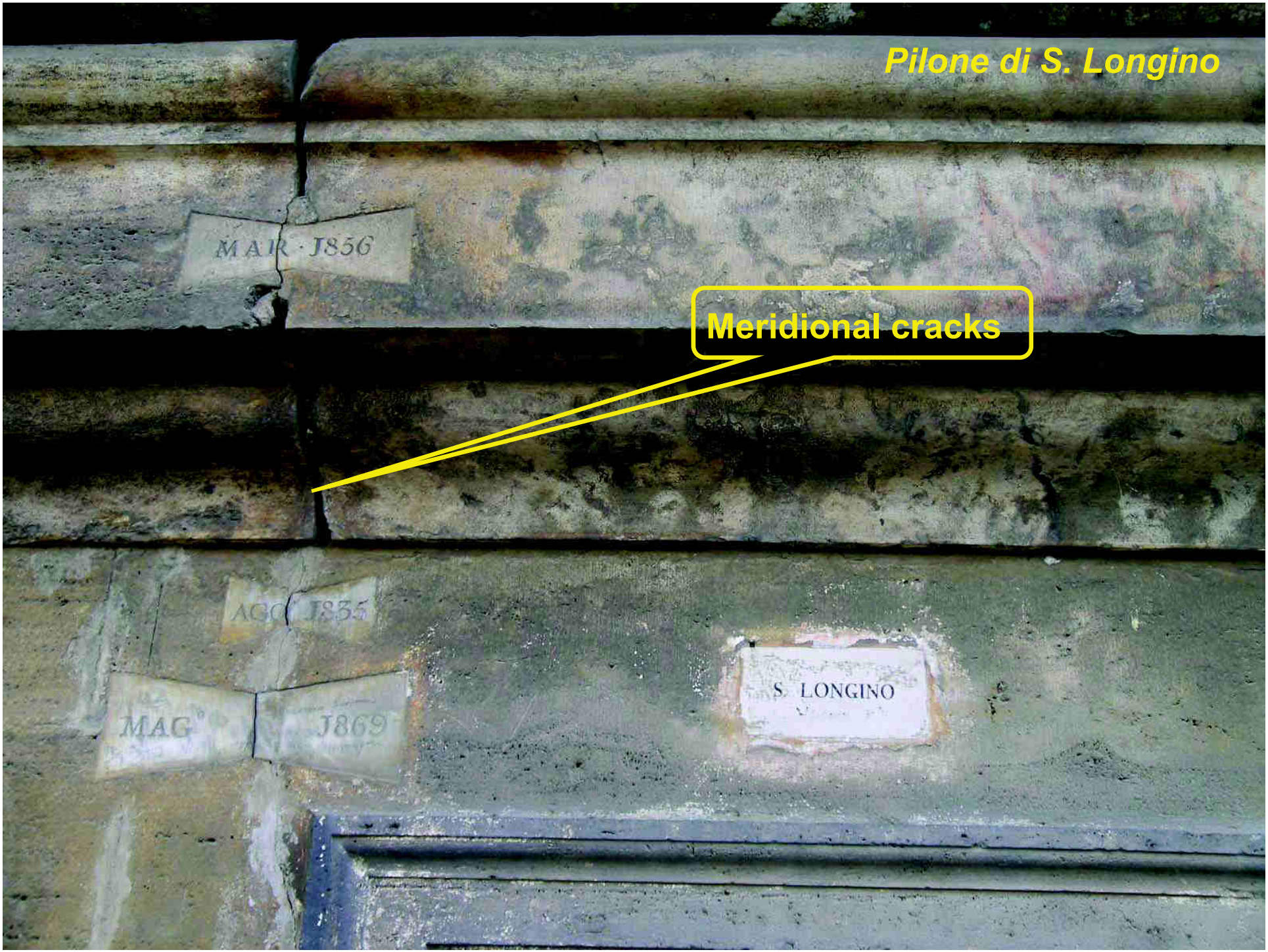
Posizione delle cerchiature proposta dai Tre Mattematici

Cerchi esterni

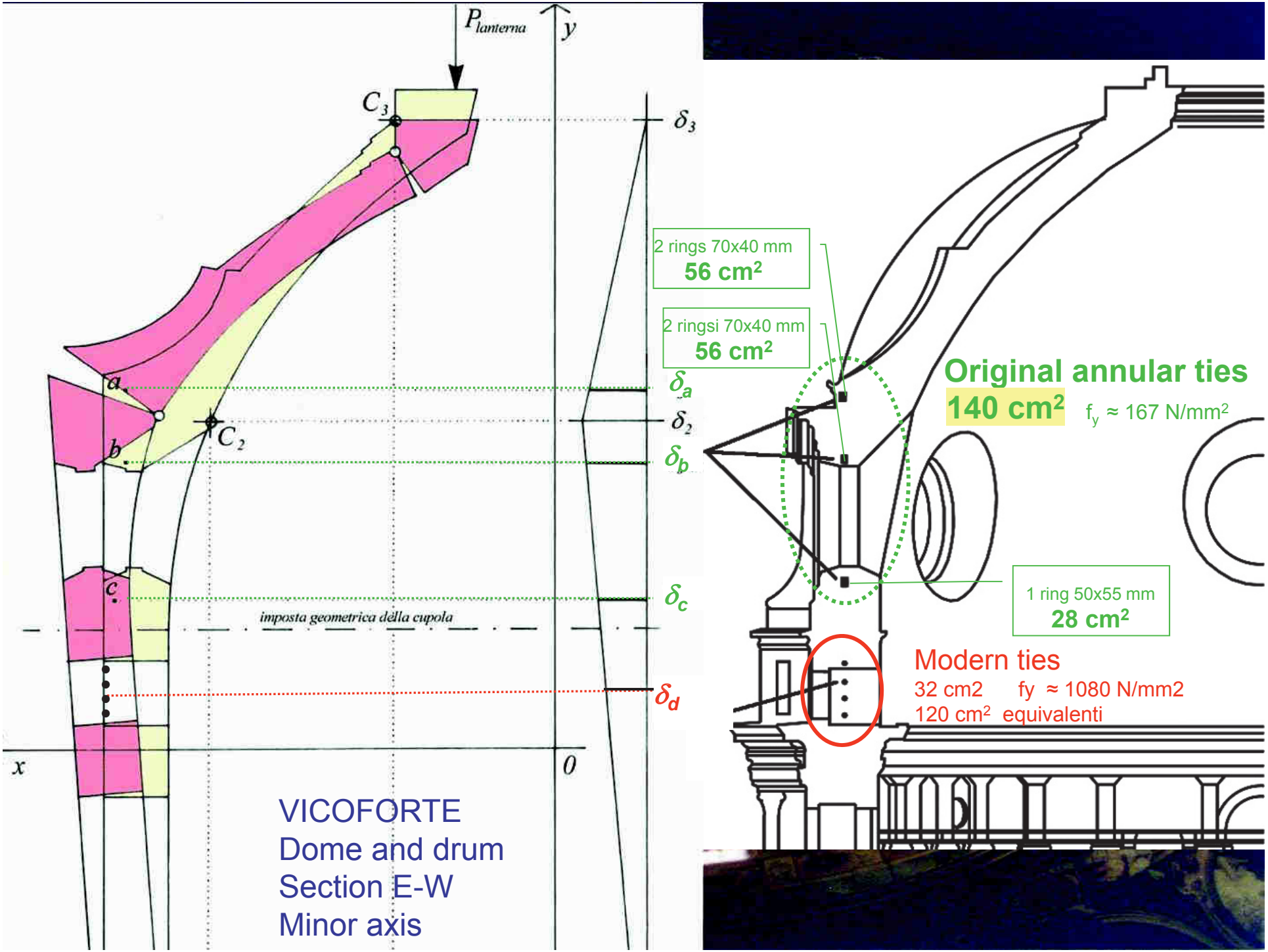
Cerchio interno


Pilone della Veronica
Meridional cracks


Pilone di S. Longino
Meridional cracks


Pilone di S. Longino
MAR · 1856
Meridional cracks
AGO 1835
MAG° 1869
S. LONGINO

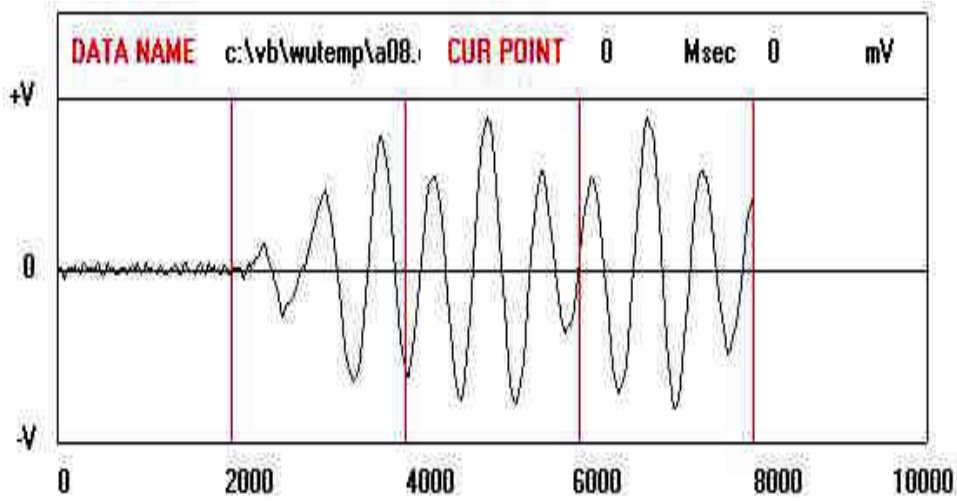

VICOFORTE
Original iron rings

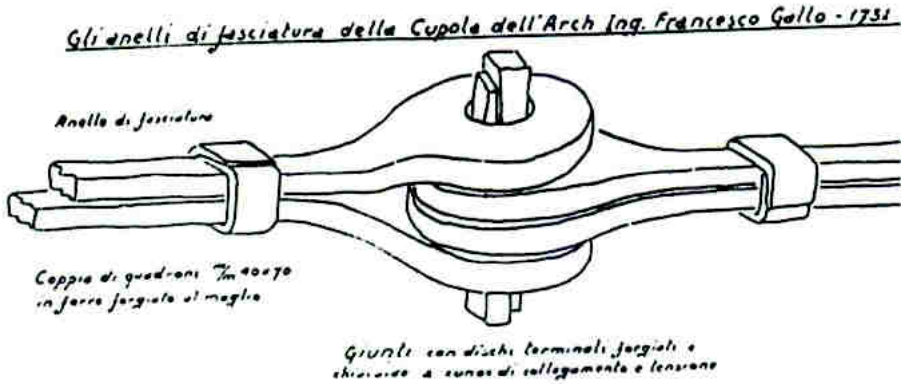

$P_{lanterna}$
y
C_3
δ_3
2 rings 70x40 mm
56 cm²
2 ringsi 70x40 mm
56 cm²
a
C_2
δ_a
δ_2
b
δ_b
Original annular ties
140 cm²
$f_y \approx 167$ N/mm²
c
δ_c
imposta geometrica della cupola
1 ring 50x55 mm
28 cm²
Modern ties
32 cm2 fy ≈ 1080 N/mm2
120 cm² equivalenti
δ_d
x
0
VICOFORTE
Dome and drum
Section E-W
Minor axis

Original iron rings (Gallo 1731)

Details

Continuity cheks by sonic testing

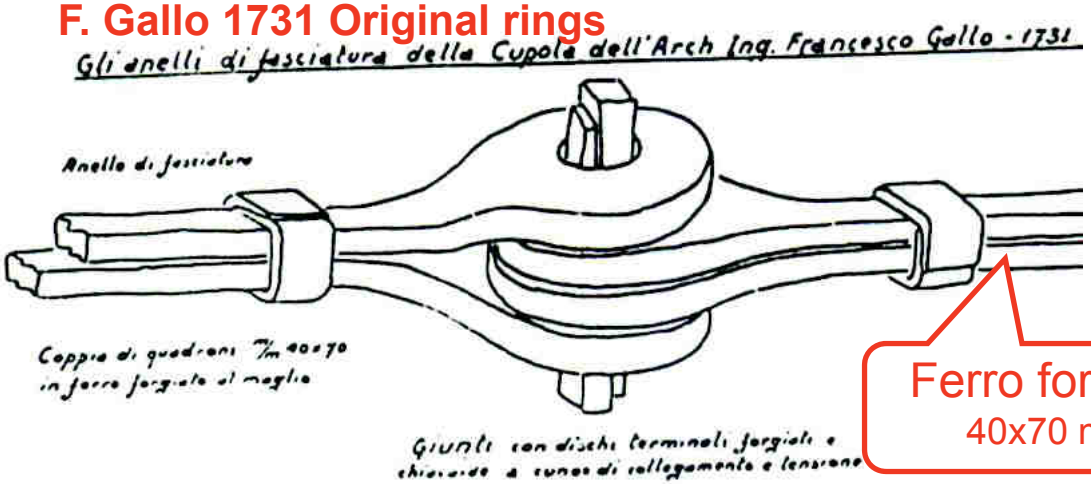




Fastening of circular rings

Vicoforte

F. Gallo 1731 Original rings



Ferro forgiato
40x70 mm

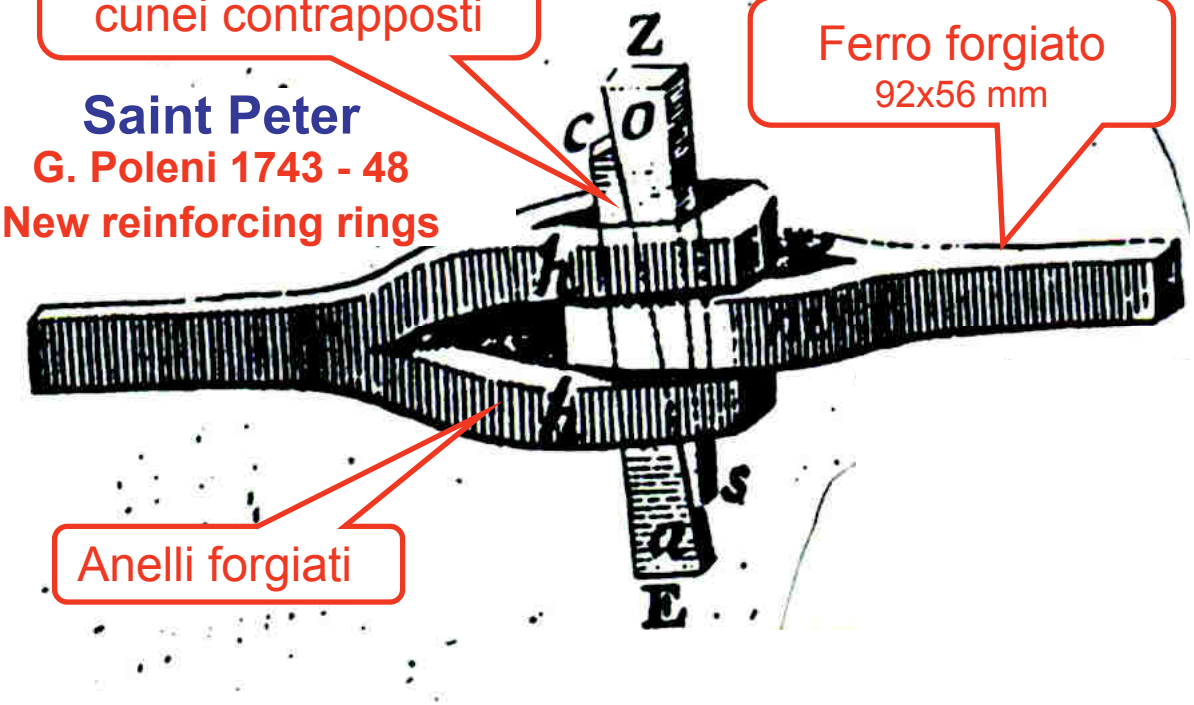
Chiavardatura a
cunei contrapposti

Ferro forgiato
92x56 mm

Saint Peter

G. Poleni 1743 - 48

New reinforcing rings

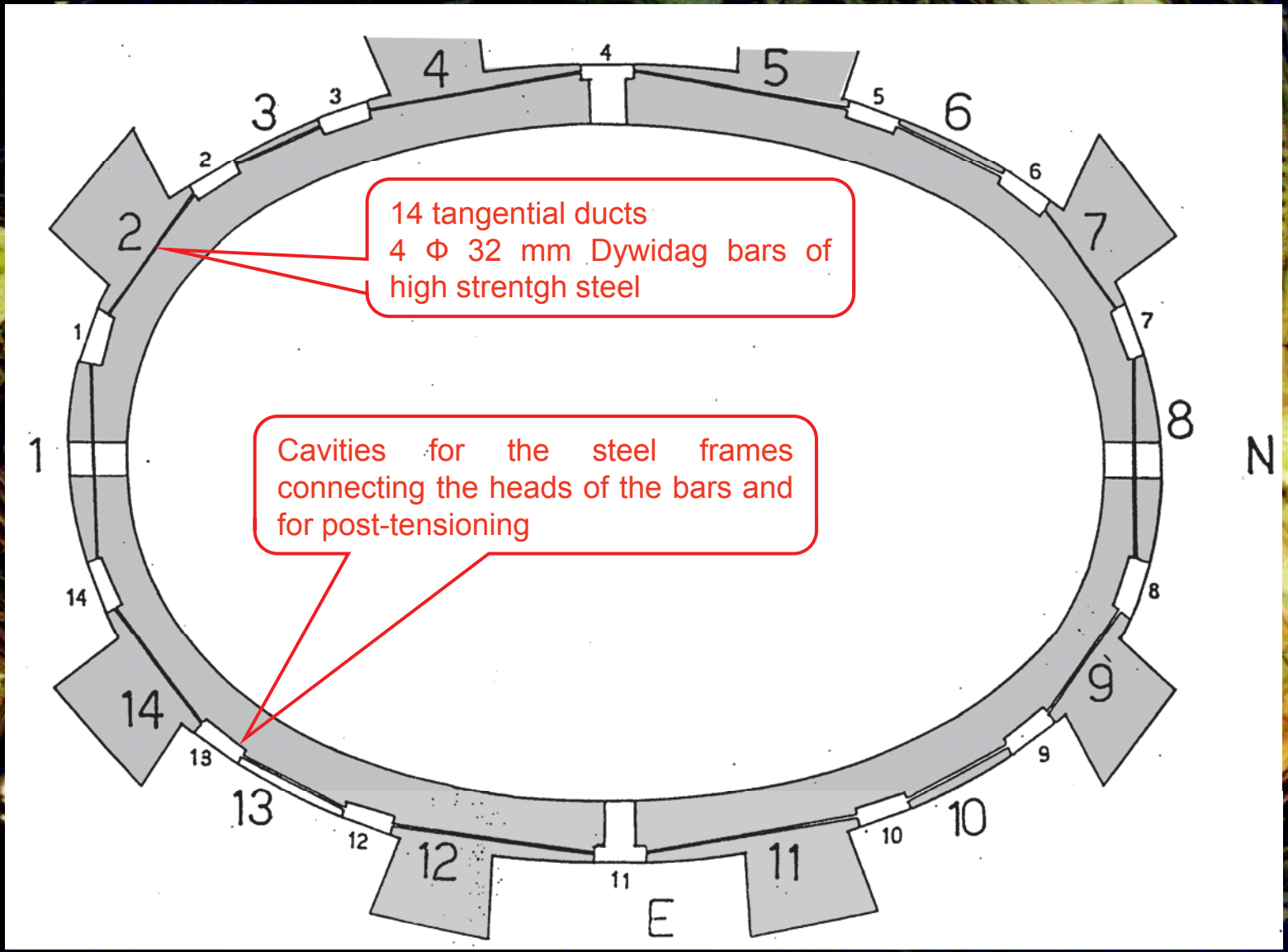


Anelli forgiati


VICOFORTE
DESCRIPTION OF 1985
STRENGTHENING WORKS

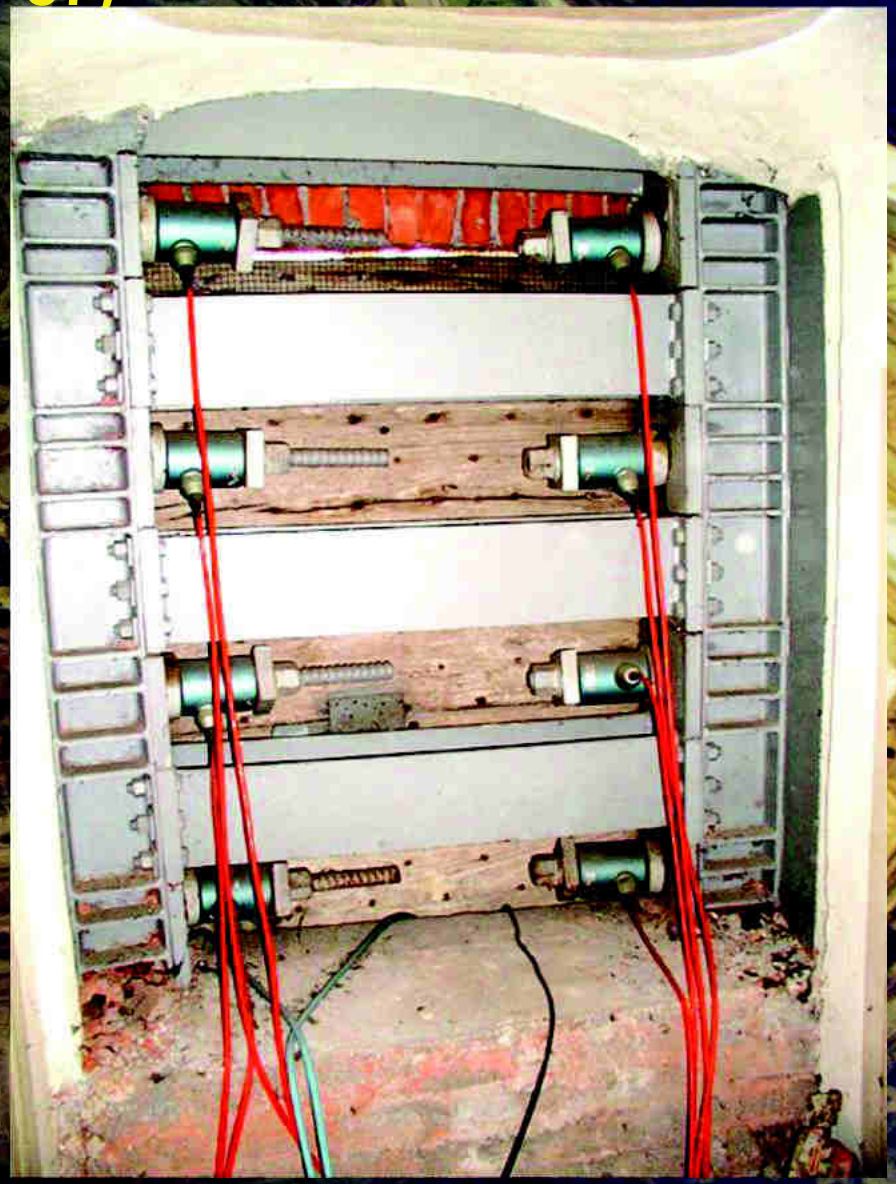
Post-tensioning ring at the base of the dome

(1985-87)



Post-tensioning ring at the base of the dome (1985-87)

- 14 groups of tangential ties
- 4 superimposed Dywidag 32 mm bars (32 cm^2 in total) of high-strength steel
- each bar is located in ducts drilled in the masonry
- the 14 groups of bars are interconnected by steel trusses




VICOFORTE
RELIABILITY
ASSESMENTS

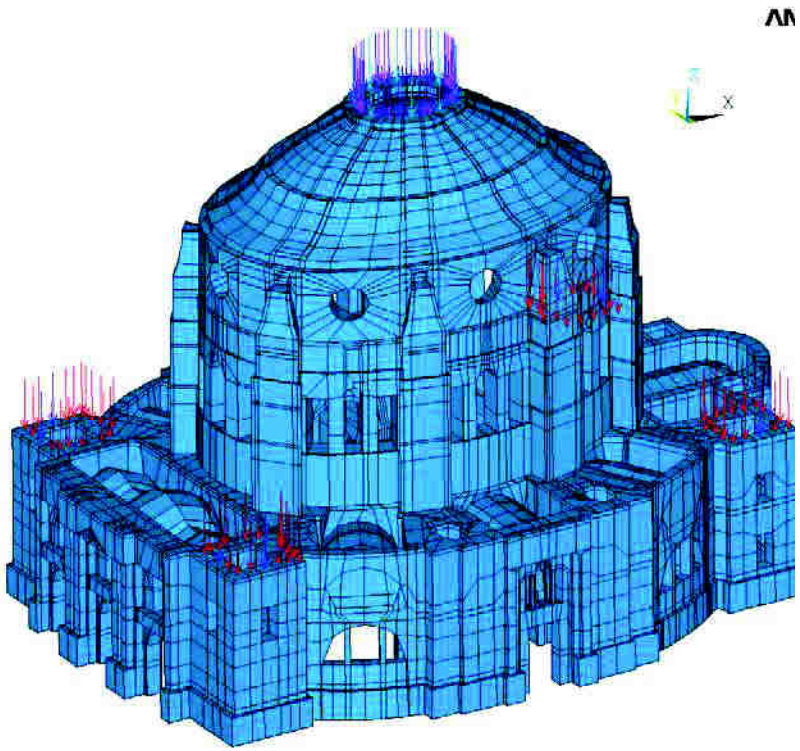

1. Reliability assesments
under gravity loads

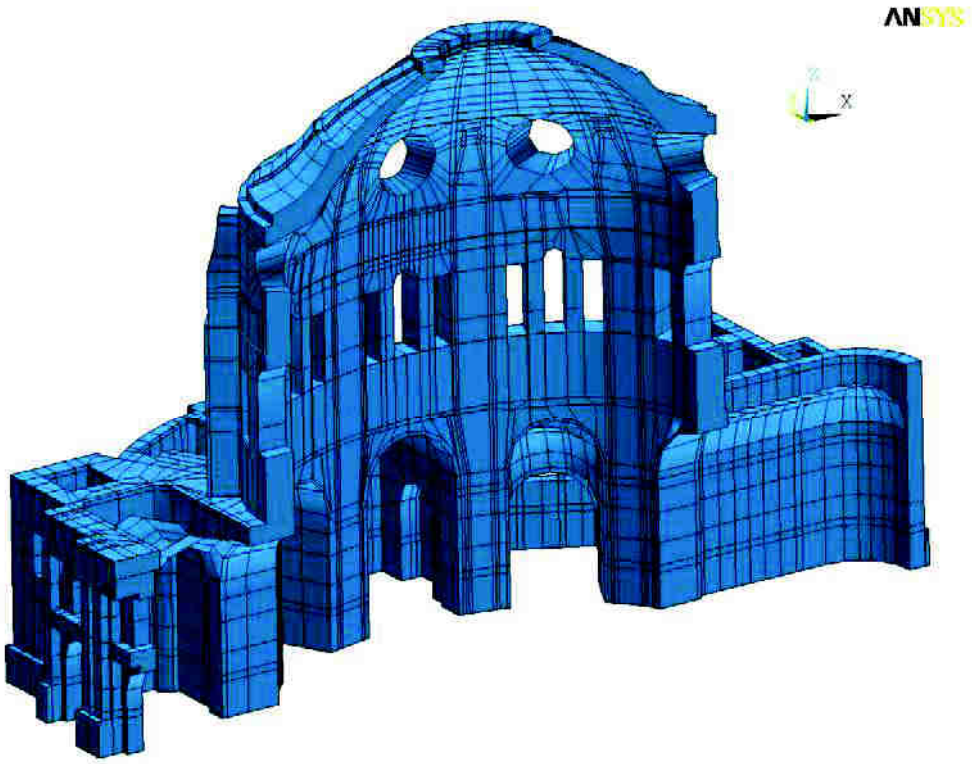
Modeling strategies

- Different analyses using various material and structural models, with different levels of sophistication, focusing on different aspects of the structural response:

1. Linear-elastic FEM analysis of the entire undamaged building
2. Linear-elastic FEM analysis of the damaged dome-drum system
3. Damage FEM analysis of the dome-drum system
4. Limit state analysis of the dome-drum system

1. Linear-elastic FEM analysis of the entire undamaged building

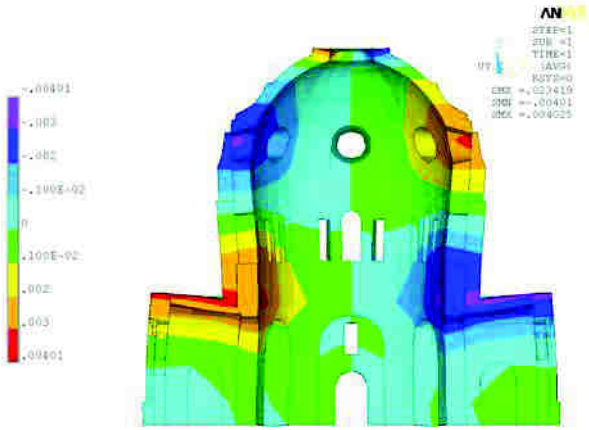




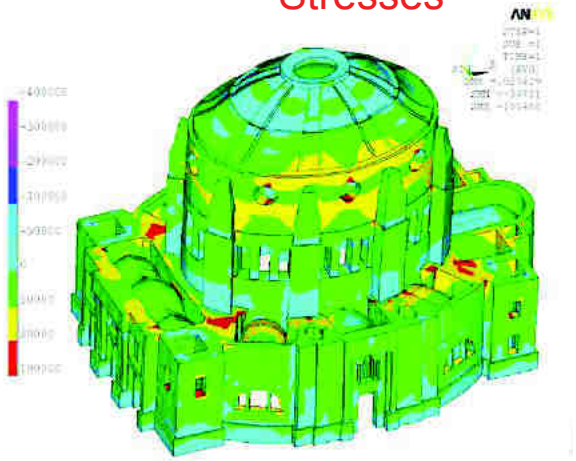
Alberto Spadafora, Politecnico di Torino
Global FE linear elastic model

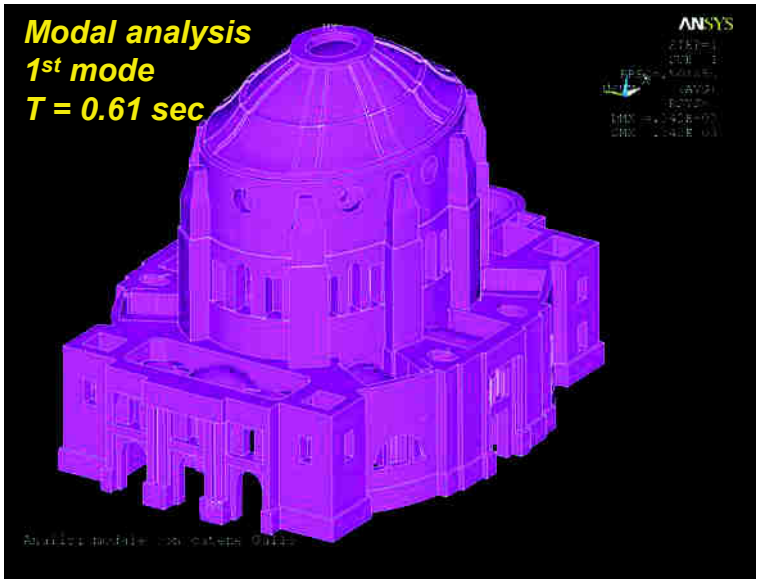
1. Linear-elastic FEM analysis of the entire undamaged building

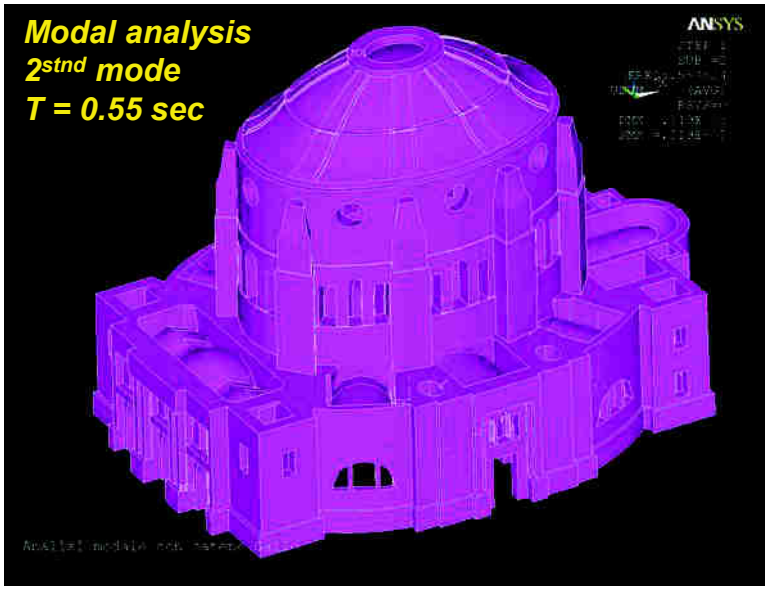
Deformations



Stresses

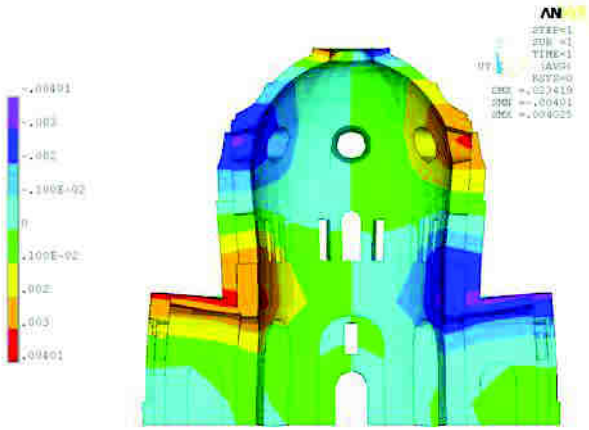




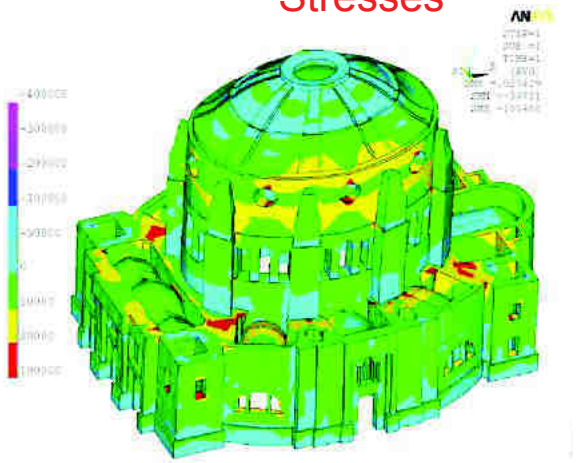


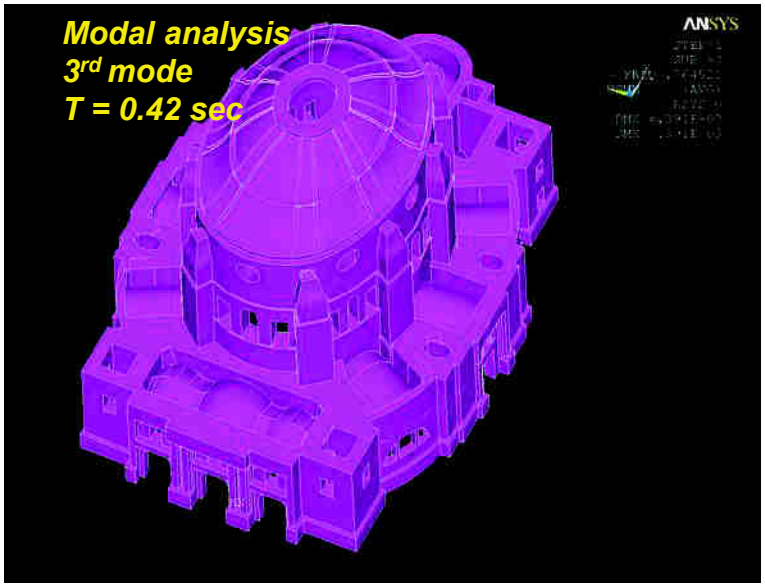
1. Linear-elastic FEM analysis of the entire undamaged building

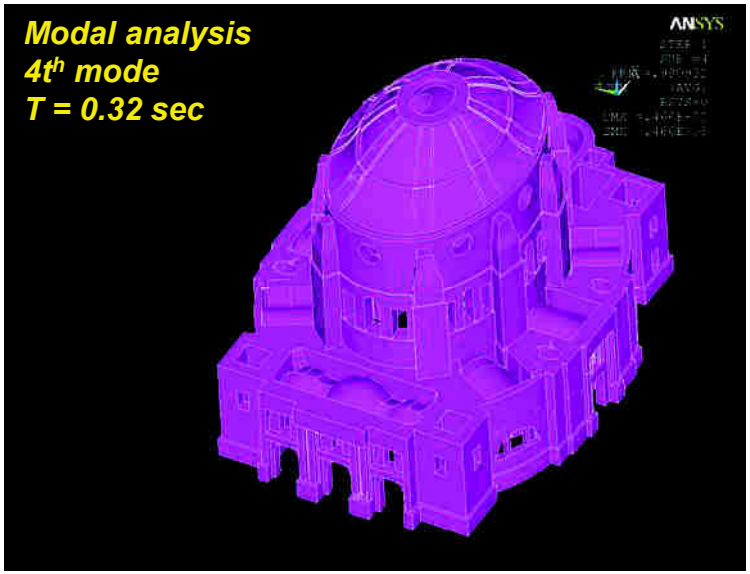
Deformations



Stresses





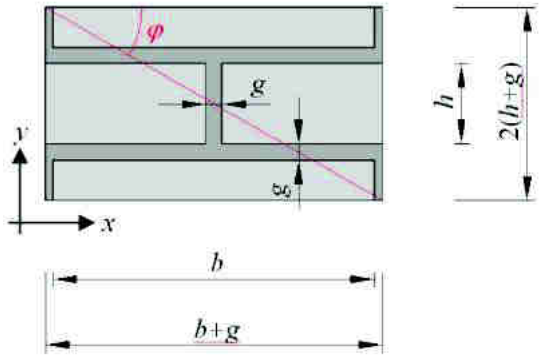


3. Damage FEM analysis of the dome-drum system

THE CONSTITUTIVE MODEL

HIPOTHESES AND GENERAL FEATURES

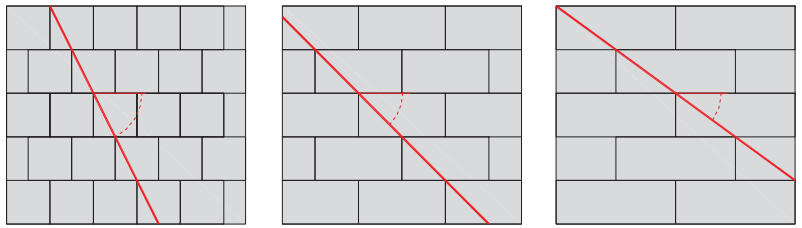
REFERENCE VOLUME:



HYPOTHESES:

- **PLANE STRESS**
- **MORTAR JOINTS AS INTERFACES**
- **UNIFORM STRESSES AT INTERFACES**
- **MORTAR HEAD JOINTS AS GEOMETRICAL DISCONTINUITIES**

ANGLE OF INTERLOCKING



φ = 63.43° φ = 45° φ = 33.69°

$$\varphi = tg^{-1}\left(2\frac{h+g}{b+g}\right)$$

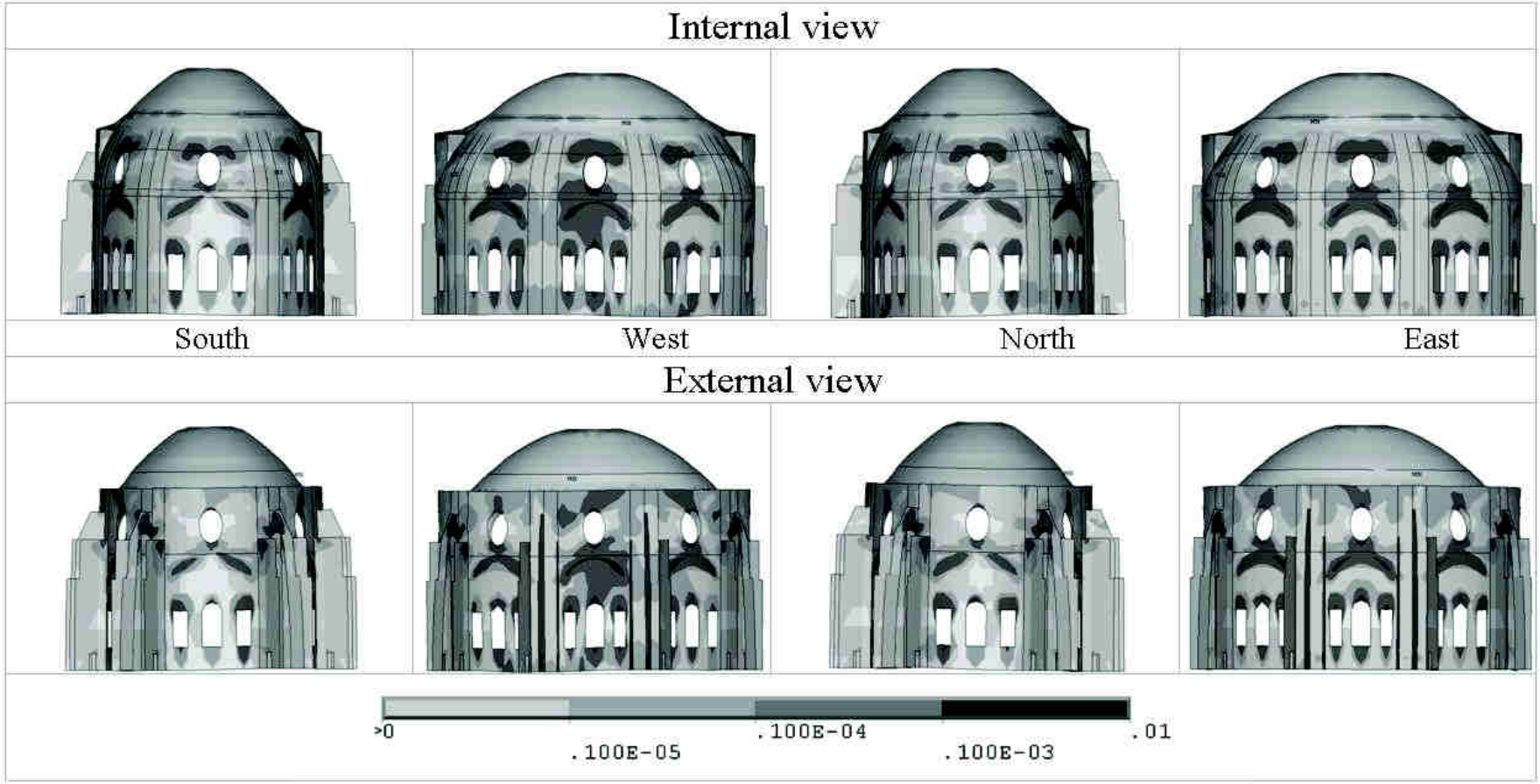
DAMAGE + FRICTION IN MORTAR JOINTS

DAMAGE IN BLOCKS

DAMAGE IN COMPRESSION

→ **NON LINEAR BEHAVIOUR**

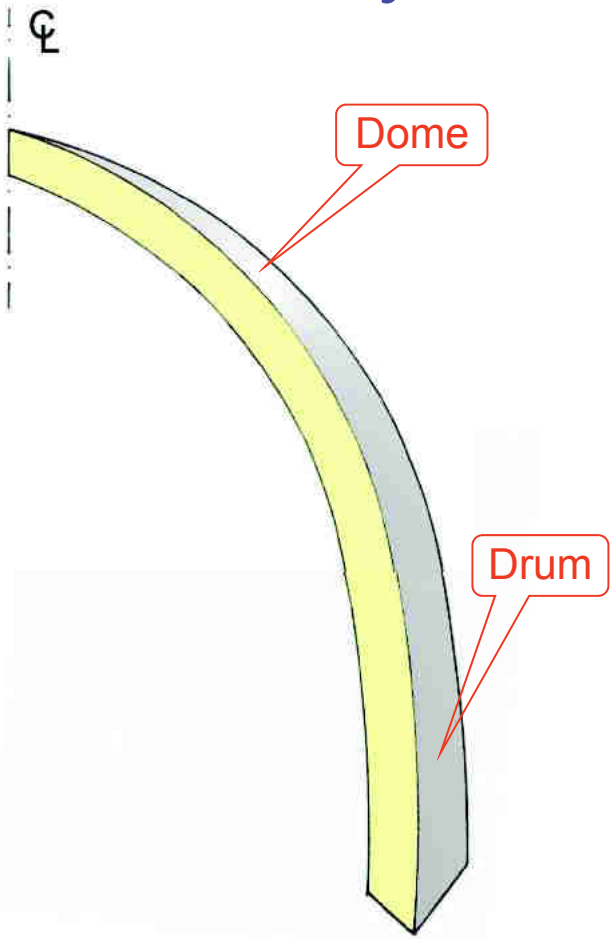
3. Damage FEM analysis of the dome-drum system



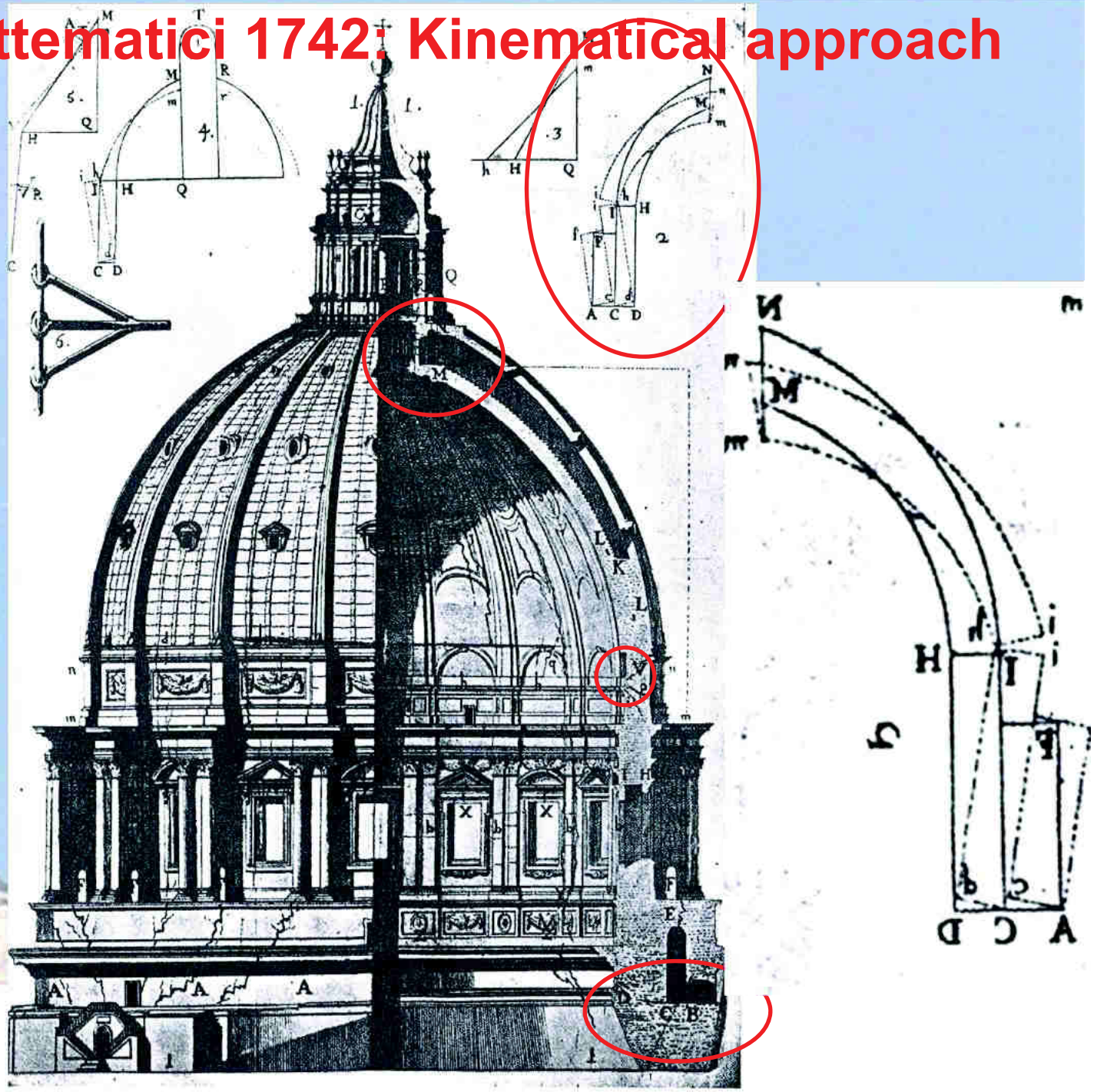
Principal inelastic strains considering foundations settlements

4. Limit state analysis of the dome-drum system

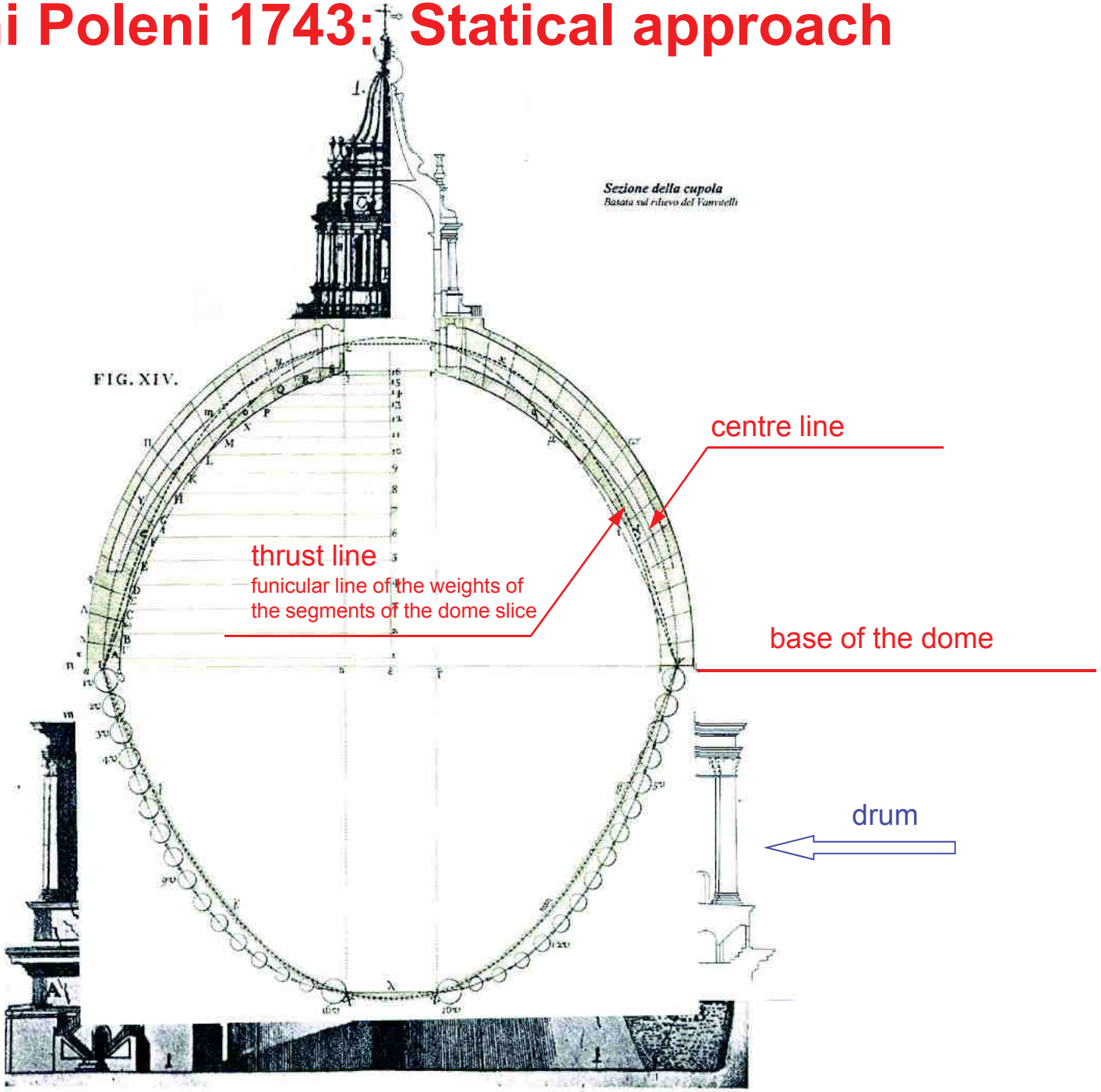
- Assessment of the stability of a thin slice of the dome-drum system under the conservative assumption of separation by fully developed meridional cracks
- Assumptions for the masonry:
  - *No tensile strength*
  - *Unlimited compressive strength*
  - *No sliding* *(Kooharian 1953, Heyman 1966)*
- Application of the statical or kinematical theorem



✓ I Tre Mattematici 1742: Kinematical approach

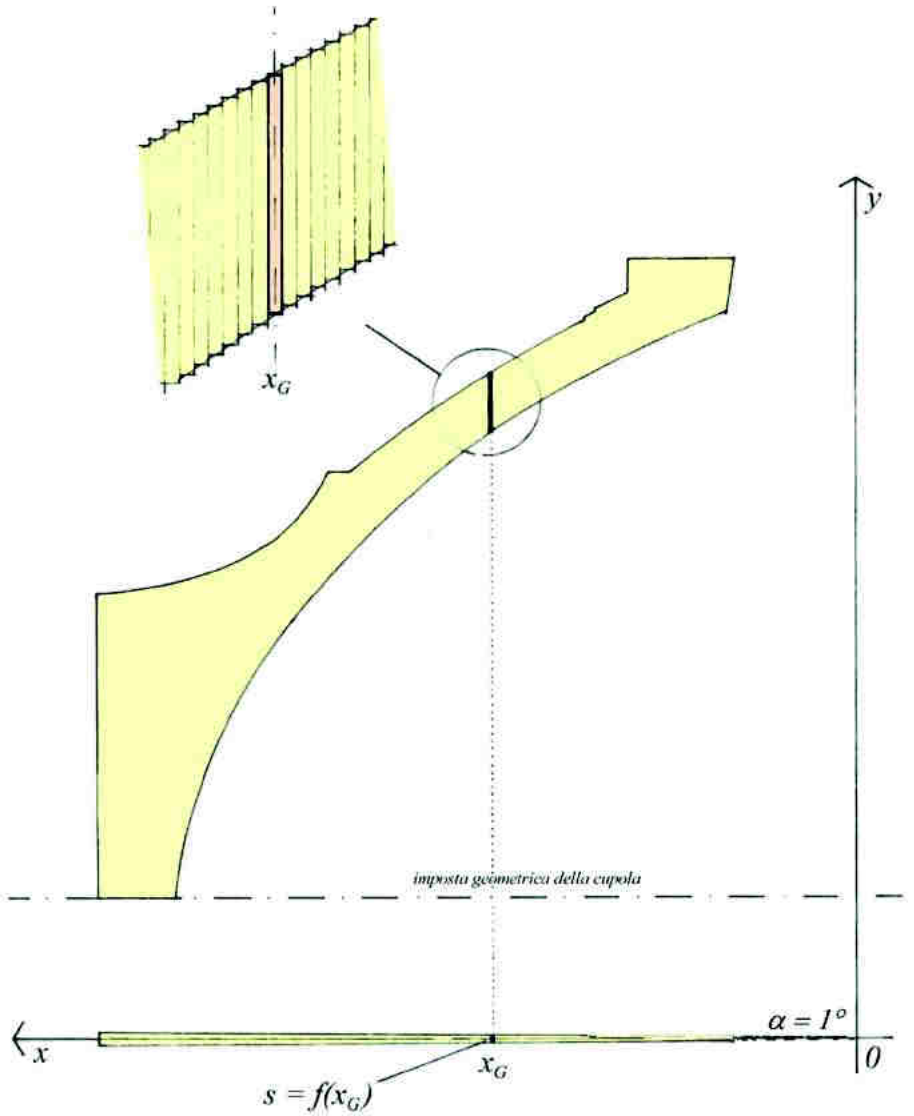


✓ Giovanni Poleni 1743: Statical approach



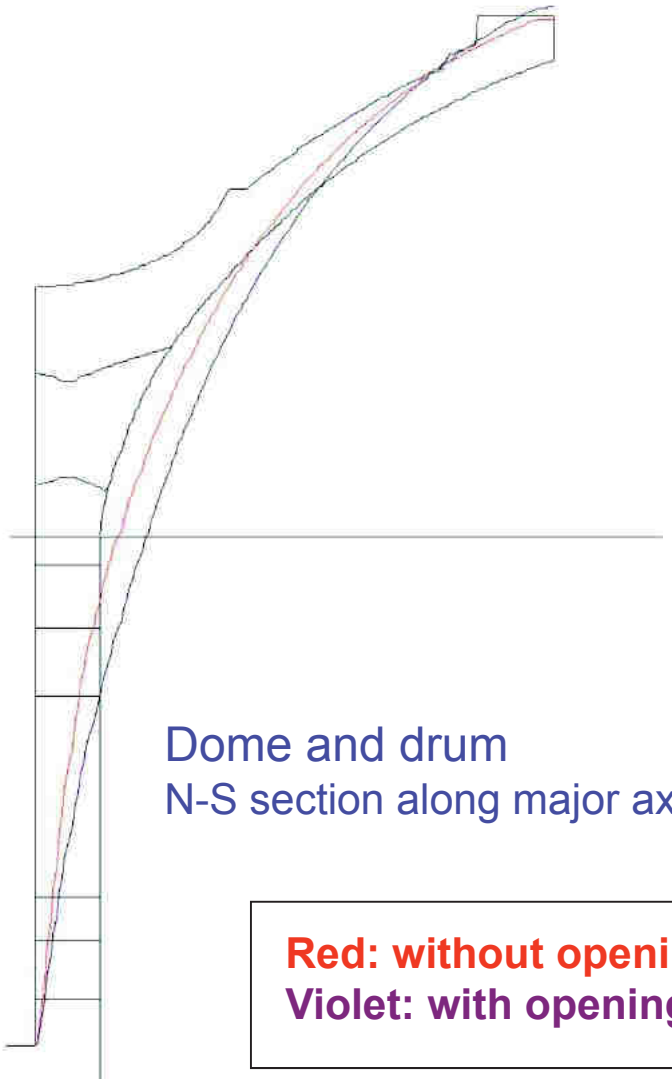
Operational model

- Lunes of the dome and drum of 1° of amplitude are considered
- The structural section is divided in vertical elements of finite small dimension (0.10 m)



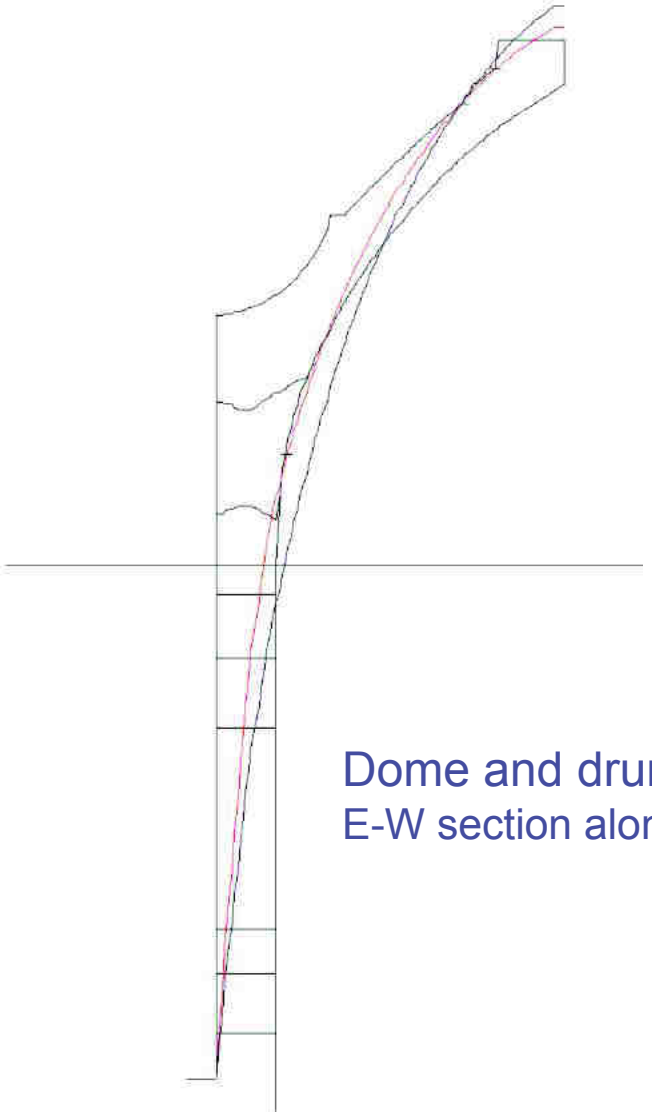
Statical approach

The contribution of the original iron rings is ignored



Dome and drum
N-S section along major axis

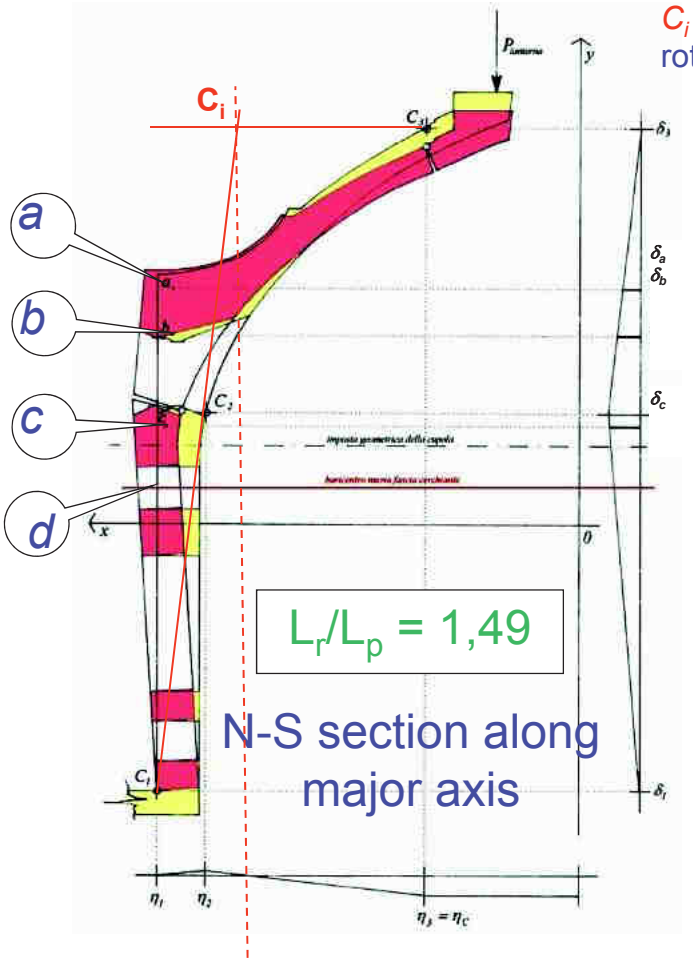
Red: without openings
Violet: with openings

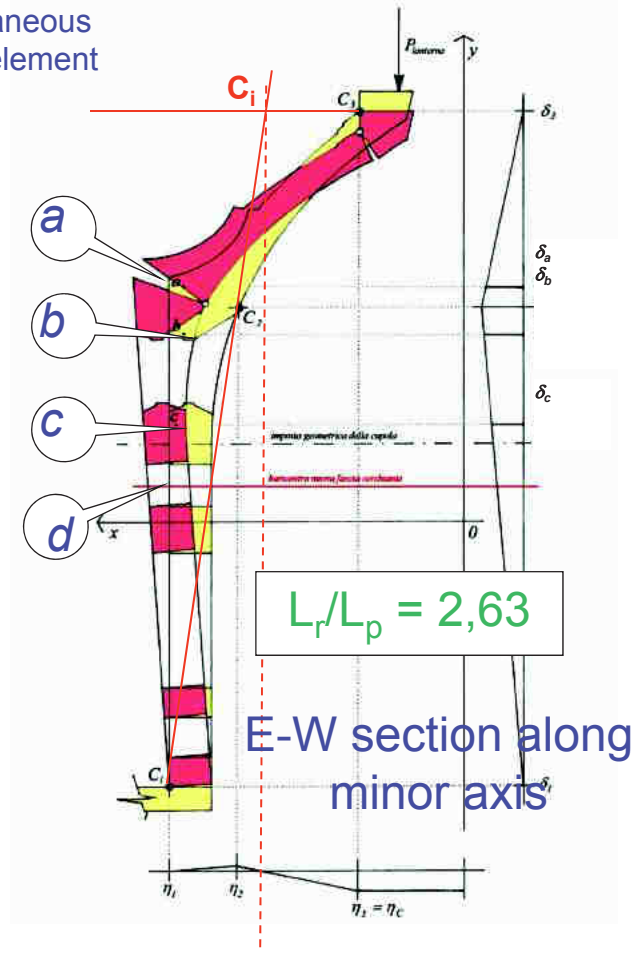


Dome and drum
E-W section along minor axis

Kinematical approach

C_i : centers of instantaneous rotation of the dome element

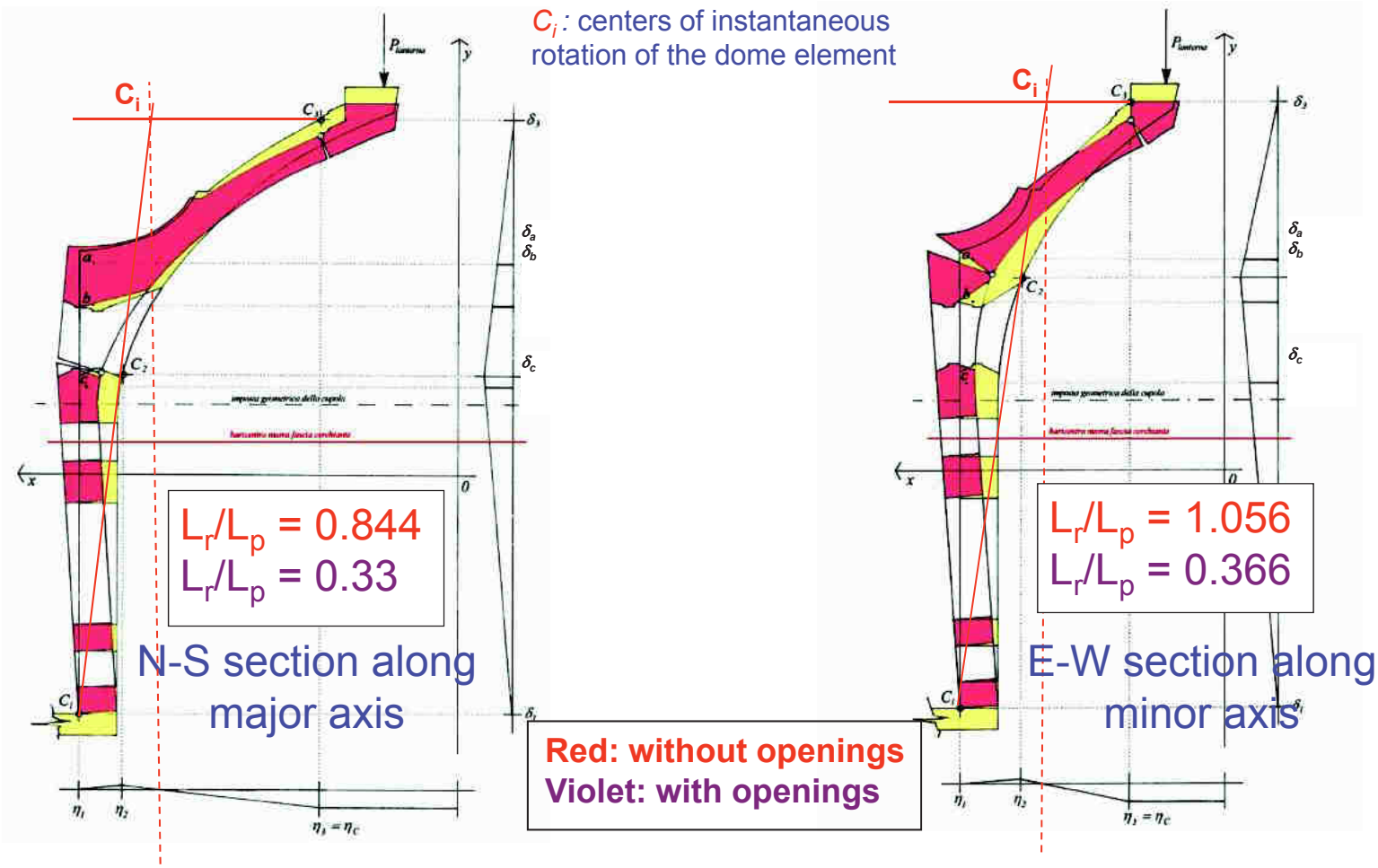




Determination of the minimum ratio L_r/L_p between resisting and pushing virtual works taking into account the contribution of the original iron rings and the presence of window openings.

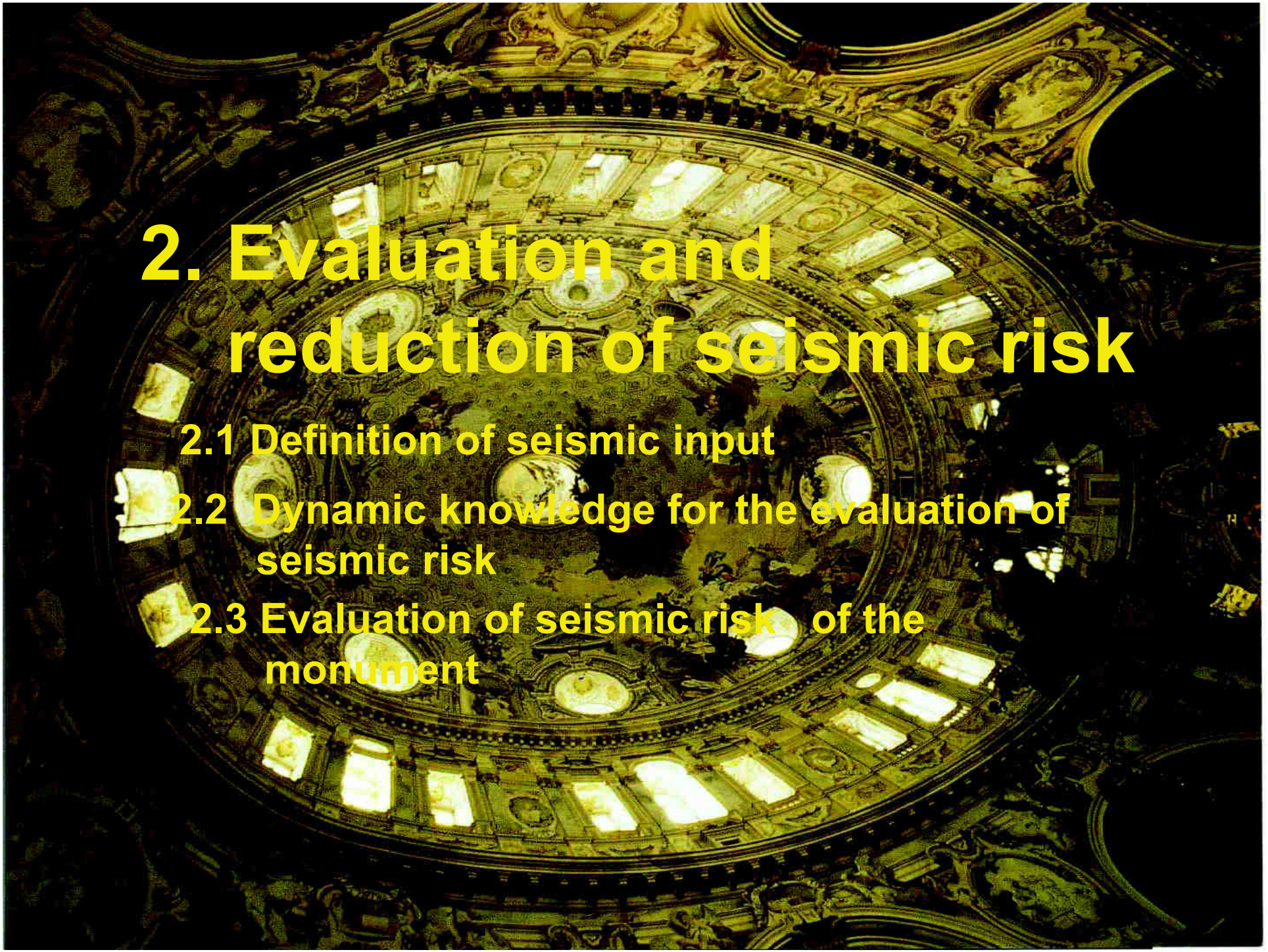
Alessandro Reffo, Politecnico di Torino

Kinematical approach



Determination of the minimum ratio L_r/L_p between resisting and pushing virtual works ignoring the contribution of the original iron rings.

Alessandro Reffo, Politecnico di Torino



2. Evaluation and reduction of seismic risk

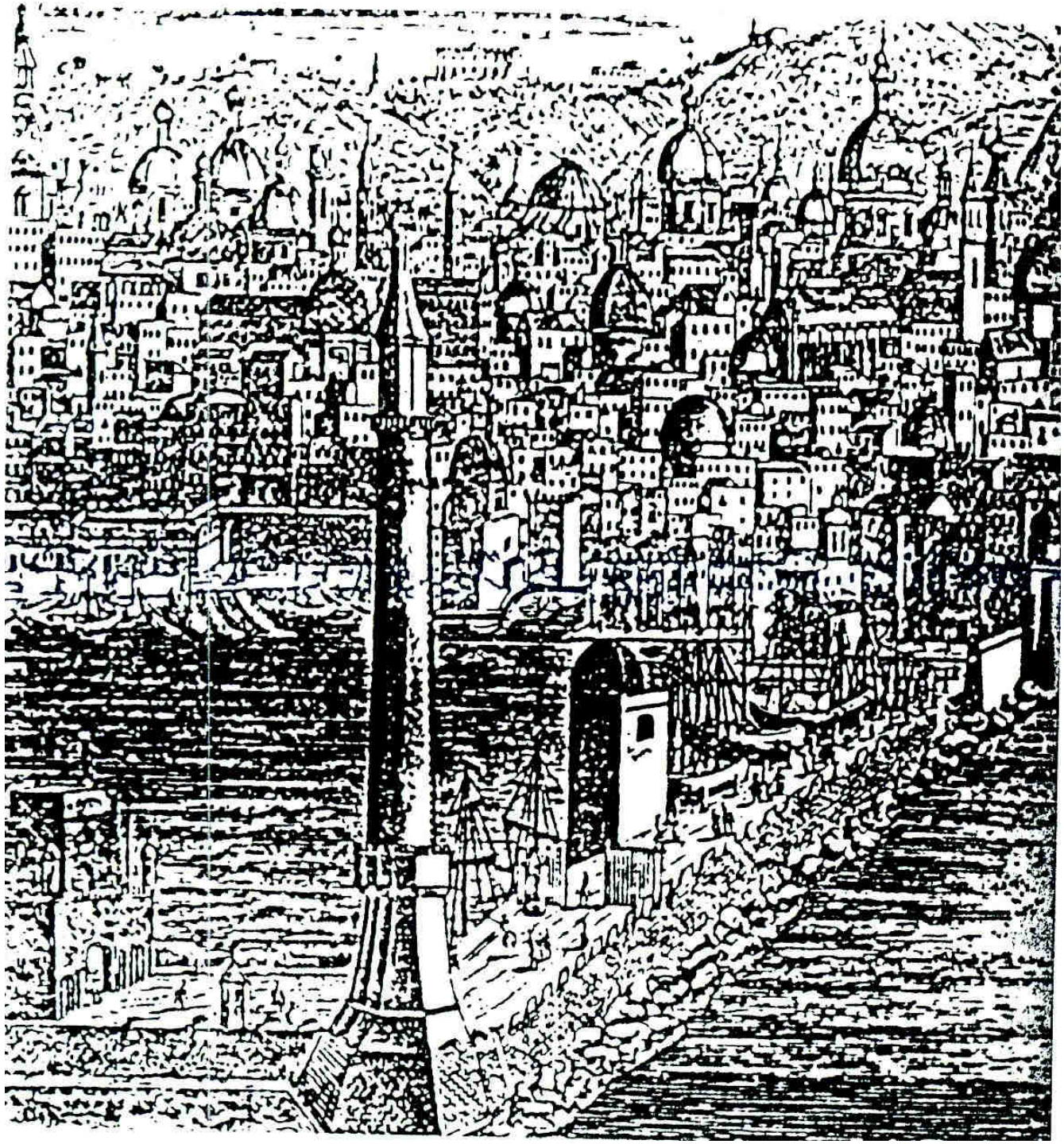
2.1 Definition of seismic input

2.2 Dynamic knowledge for the evaluation of seismic risk

2.3 Evaluation of seismic risk of the monument

Vulnerabilty of dome-drum systems under gravity and seismic loads

Just a few of these domes survive today



Wernot

View of Naples around 1700

Seismic vulnerabilty of dome-drum systems in the recent l'Aquila-Abruzzi earthquake

(april 2009)


S.Maria Paganica


Santa Maria del Suffragio


PALAZZO DEL
S.Agostino


S.Agostino

2. Evaluation and reduction of seismic risk
Introductory comment

- In Italy seismic classification has progressively been extended from about 15-20% of the country after the big earthquakes at the beginning of past century (Messina 1908, southern Italy 1915) to about 60-70 % of the nation in the ’80s, and to the **whole geographical area since 2003** (after the 2002 Puglie earthquake).
- Italy, like India, is recognized as one the most important “container” of cultural and architectural heritage the world over
- Consequently, the problem of safeguarding for future generations this heritage in a seismic active zone arises
- In 2006, as a result of joint work between the Ministry of Cultural Heritage, the Seismic Protection Department of the central government and the Universities, ***Italian Guidelines for the evaluation and reduction of seismic risk of cultural heritage*** have been edited (revised 2008, 2011, see Part 1) .
- The joint project of Evaluation and reduction of seismic risk for Vicoforte, coordinated by the Politecnico di Torino, in cooperation with the Universities of Pavia (IUSS Eucentre and ROSE School) and of Genoa, intends to be an advanced model project, to be proposed as a model format for other important monuments

2. Evaluation and reduction of seismic risk
Introductory comment

- In Italy seismic classification has progressively been extended from about 15-20% of the country after the big earthquakes at the beginning of past century (Messina 1908, southern Italy 1915) to about 60-70 % of the nation in the '80s, and to the **whole geographical area since 2003** (after the 2002 Puglie earthquake).
- Italy, like India, is recognized as one the most important "container" of cultural and architectural heritage the world over
- Consequently, the problem of safeguarding for future generations this heritage in a seismic active zone arises
- In 2006, as a result of joint work between the Ministry of Cultural Heritage, the Seismic Protection Department of the central government and the Universities, ***Italian Guidelines for the evaluation and reduction of seismic risk of cultural heritage*** have been edited (revised 2008, 2011, see Part 1) .
- This need was well evidenced by the severe losses of architectural masterpieces in earthquakes that in recent years hit Assisi (1997) and Abruzzo region (2009). In the second event, the **high vulnerability of dome-drum systems** was demonstrated by the collapse or great damage of quite a few of them.
- The joint project of Evaluation and reduction of seismic risk for Vicoforte, coordinated by the Politecnico di Torino, in cooperation with the Universities of

Evaluation of seismic risk

A wider attention has been given in recent years to the **conservation of cultural heritage in seismic areas**. **Guidance documents** have been developed for countries characterized by an exceptional cultural heritage and by significant seismicity, like Italy (Directive PCM).

Directive PCM underscores the importance of an **assessment and mitigation of seismic risk based on good structural knowledge of cultural heritage**. This need was well evidenced by the severe losses of architectural masterpieces in earthquakes that in recent years hit Assisi (1997) and Abruzzo region (2009). In the second event, the **high vulnerability of dome-drum systems** was demonstrated by the collapse or great damage of quite a few of them.

The Basilica at Vicoforte has been chosen as a **case study for the evaluation of its seismic risk with reference to the guidance criteria of the Directive**, in the frame of an agreement with Italian Ministry for Cultural Heritage.

Earthquake in Abruzzo region


2.1 Definition of seismic input

Definition of the seismic input

The research was articulated in two phases:

1) Site-specific Probabilistic Seismic Hazard Analysis (PSHA) and Deterministic Seismic Hazard Analysis (DSHA)

The output of the PSHA consists of probabilistic uniform hazard acceleration spectra at the site, for different reference return periods.

A number of recorded spectrum-compatible accelerograms were selected as inputs for ground response analysis.

Horizontal PGA, for a return period of 475 years = 0.096 g

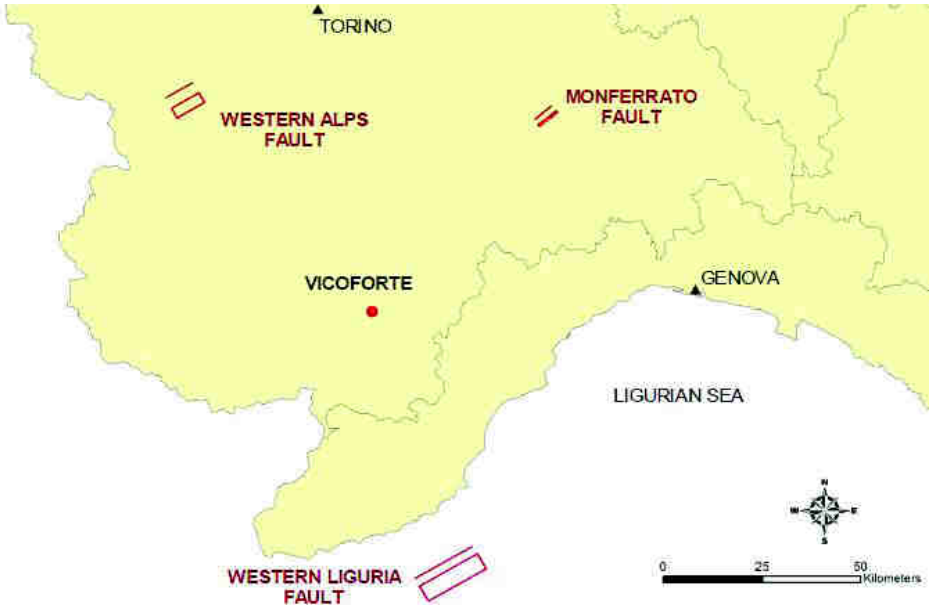
Horizontal PGA, for a return period of 2475 years = 0.160 g

Site of low seismicity with sources located distant from the site

The DSHA was adopted to define **the worst shaking** scenario which would occur in the future, compatibly with the **tectonic and seismic setting of the region**.

To this aim, the main seismic sources in the area of interest were identified on the bases of past earthquakes and a tectonic setting and finite faults numerical analyses were performed .

The probabilistic approach provides more severe ground shaking scenarios with respect to deterministic methods.



Map of the area of interest with the surface projections of fault planes considered for computation of ground shaking scenarios

2) Investigation of the seismic site response through 1D stochastic and 2D deterministic approaches, in order to evaluate possible amplification effects due to localized lithostratigrafic characteristics at the site

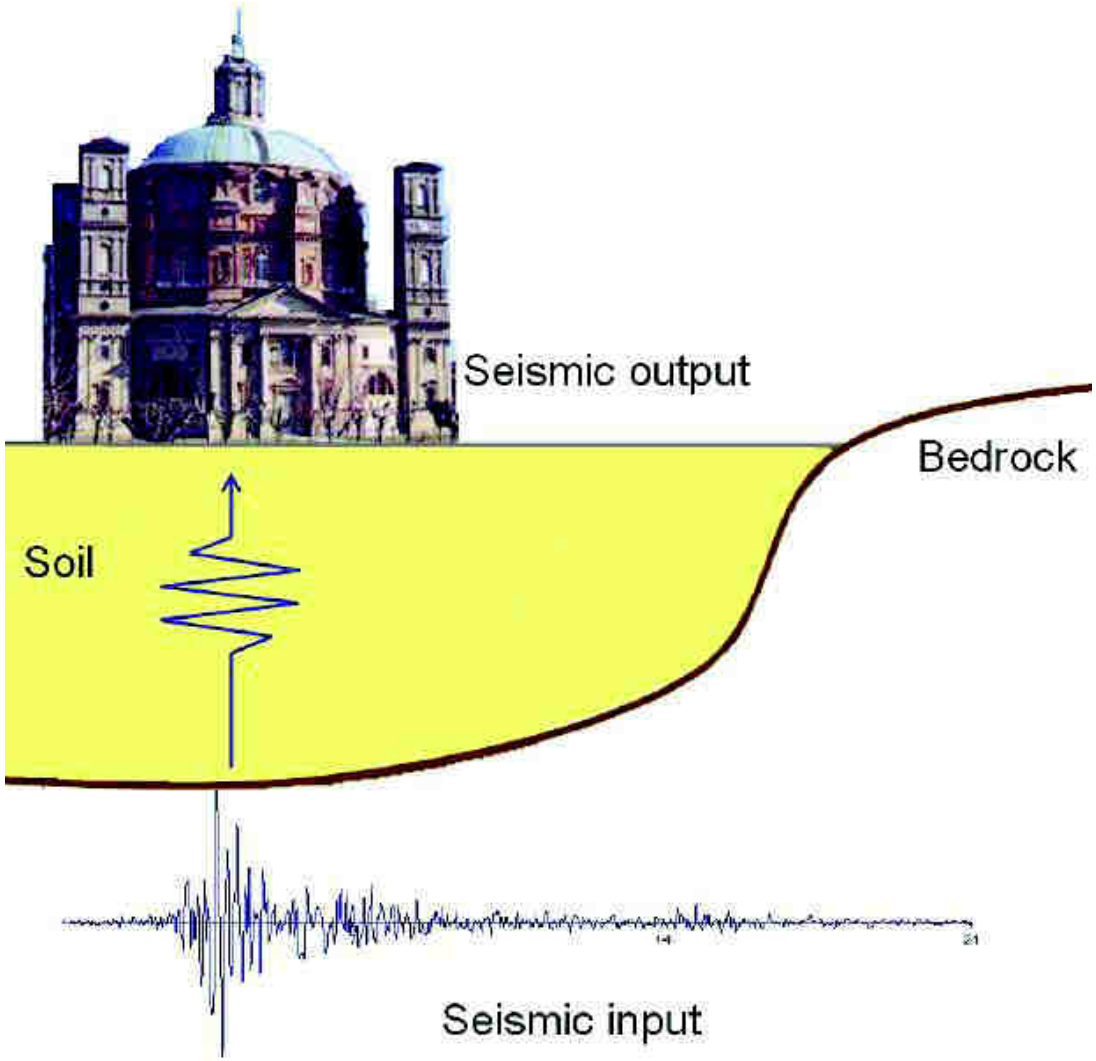
To this aim, a **3D subsoil model** was constructed, integrating the results of the different geotechnical investigation campaigns.

From the **1D stochastic approach**, the mean PGA at the free surface for the 475 years return period results equal to 0.2 g.

Amplification of about 2 with respect to the PGA at the outcropping bedrock.

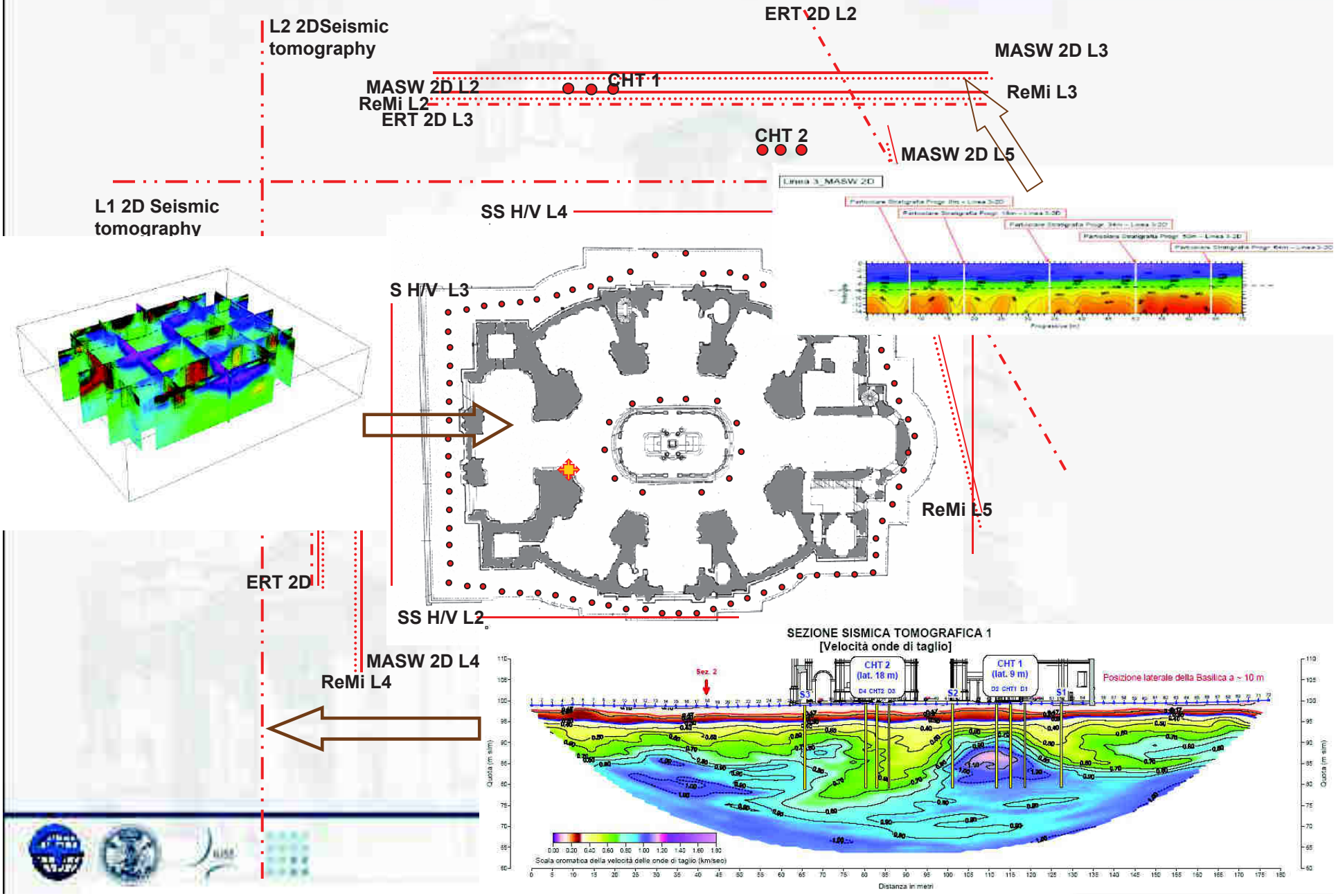
Some **amplification phenomena** are observed from the results of the **2D deterministic** ground response analysis also.

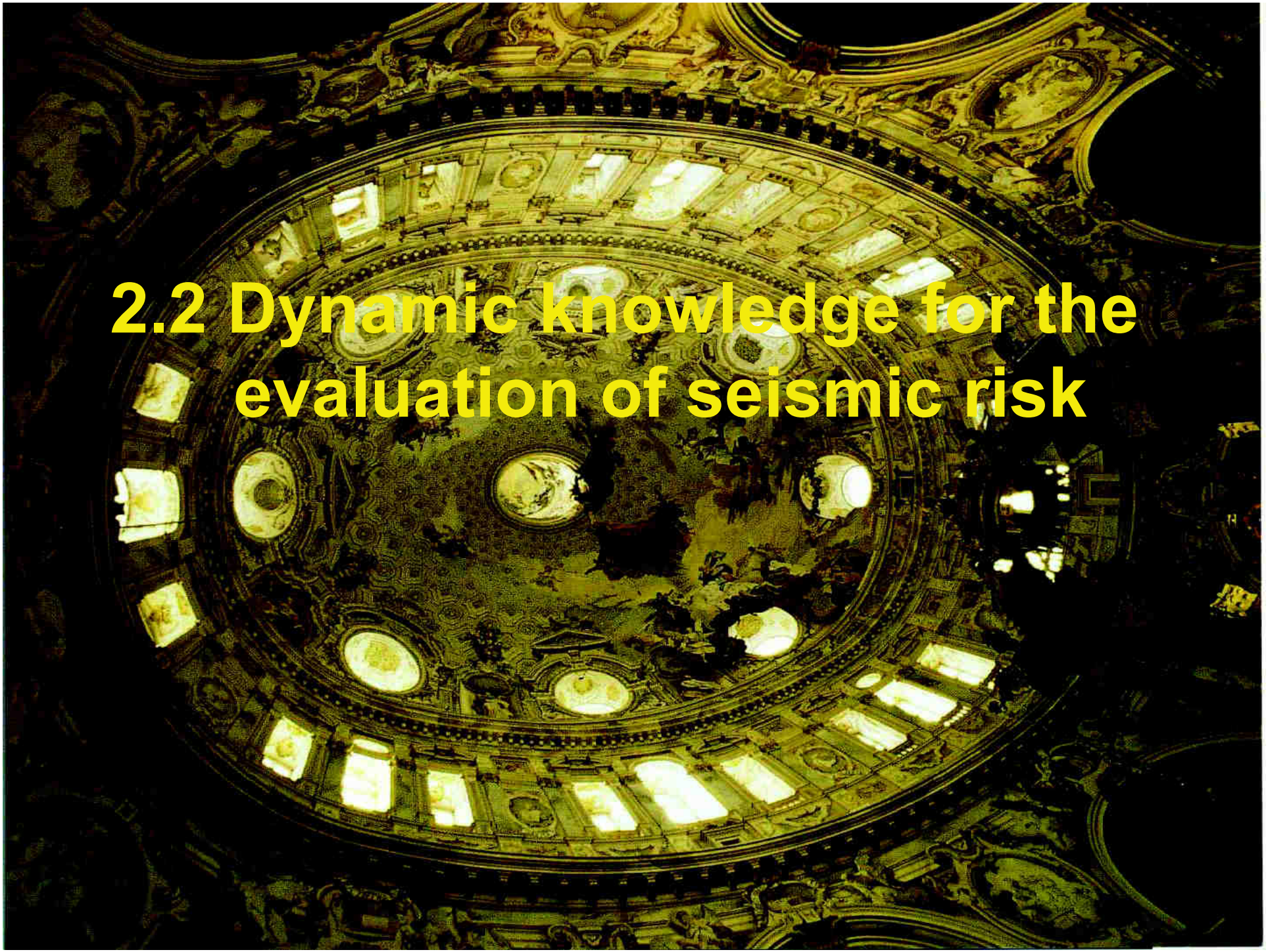
Finally, as an output of the study, **dynamic impedances** at the foundation of the Basilica were computed to be used in s**oil structure interaction analysis**.



Influence of site conditions on the seismic response

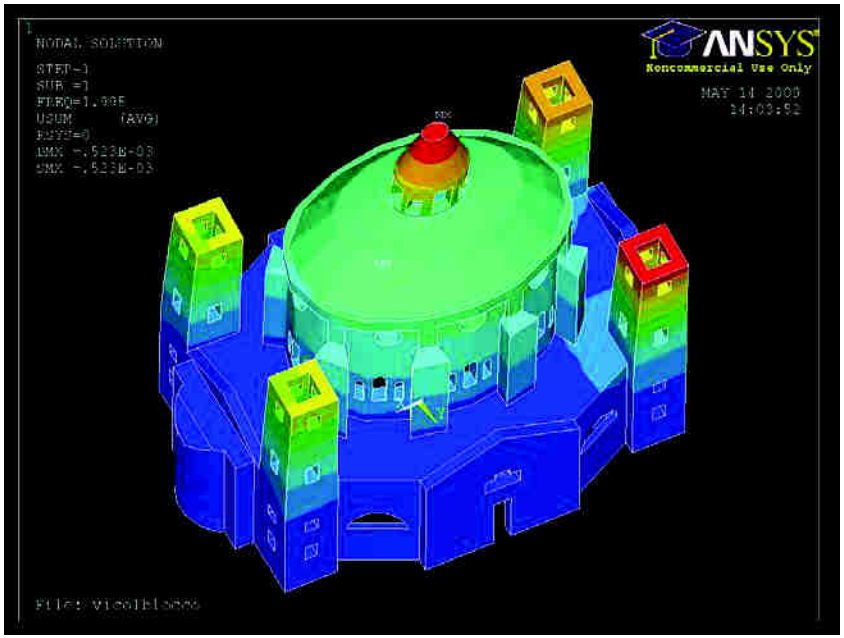
GEOTECHNICAL SITE CHARACTERIZATION





2.2 Dynamic knowledge for the evaluation of seismic risk

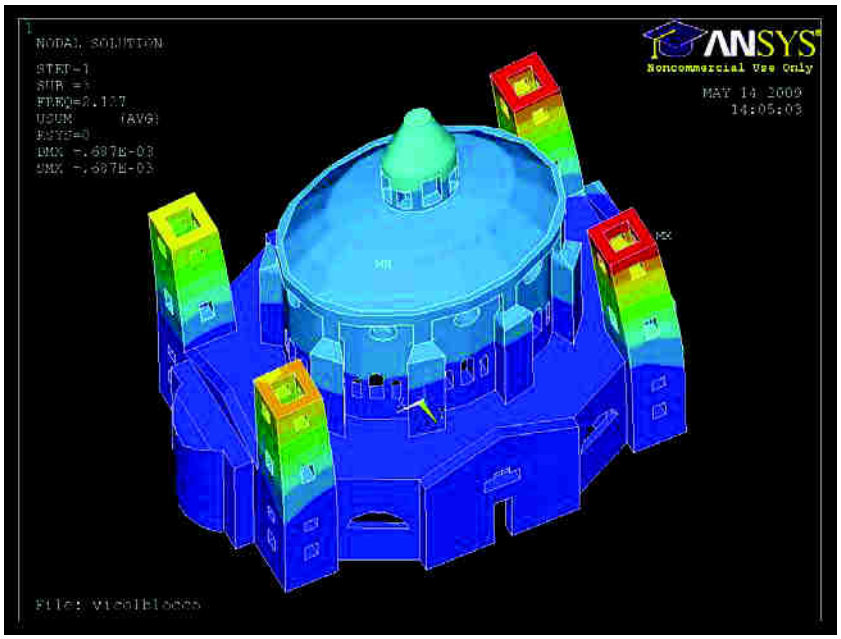
SAFELY ATTRIBUTED SHAPES: CALIBRATED MODEL



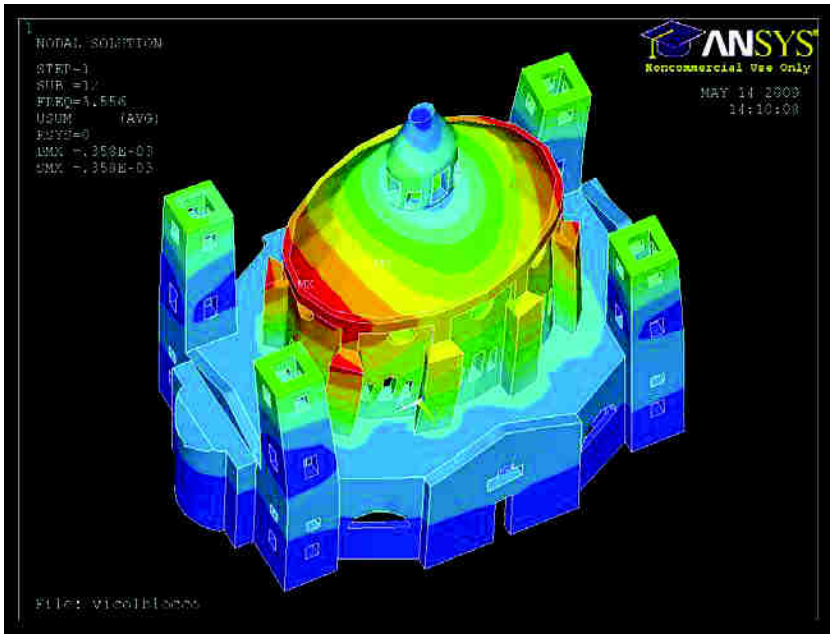
1° Bending along Y (MODE 1)

Legend: **contour plot** ANSYS :

- Mode 1 = Y dispacement
- Mode 3 = X displacement
- Mode 12 = Total displacement



1° Bending along X (MODE 3)

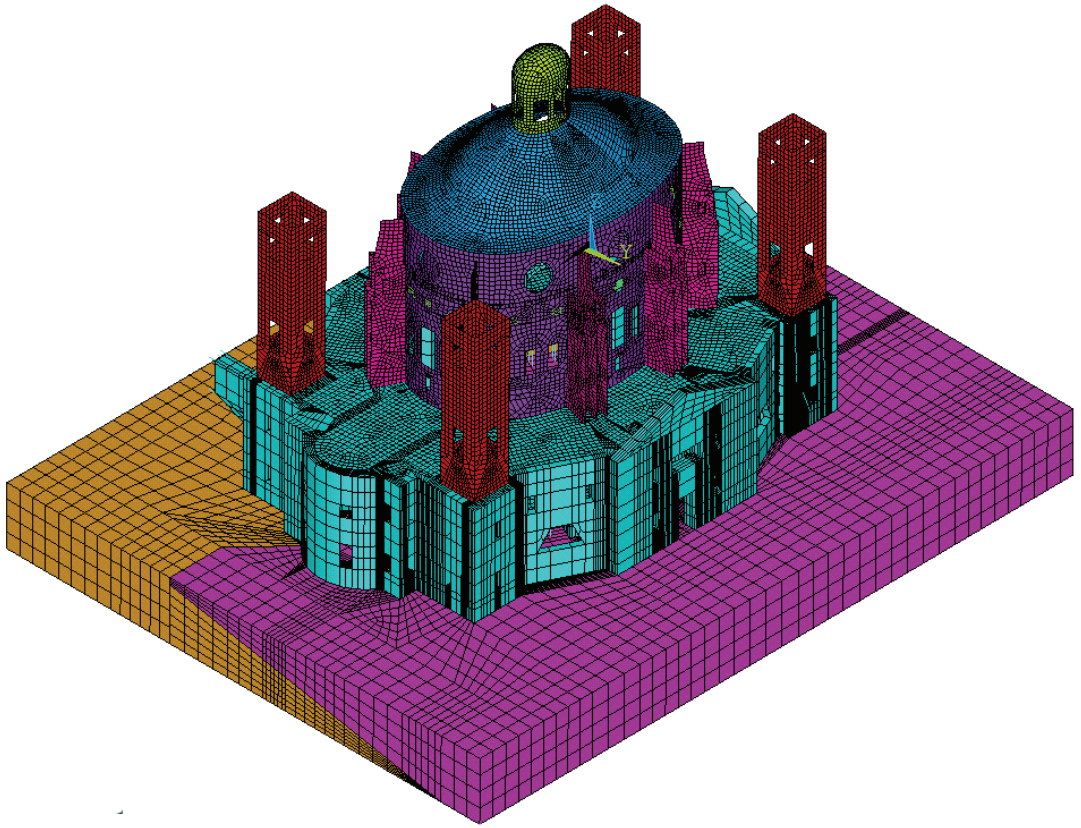


1° Torsion of the dome (MODE 12)

The Soil Structure Interaction SSI FE model

A total of 9 different materials

- Dome
- Drum
- Bell-towers
- Buttresses
- Lantern
- Basement
- Iron-ties
- Marlstone
- Clay



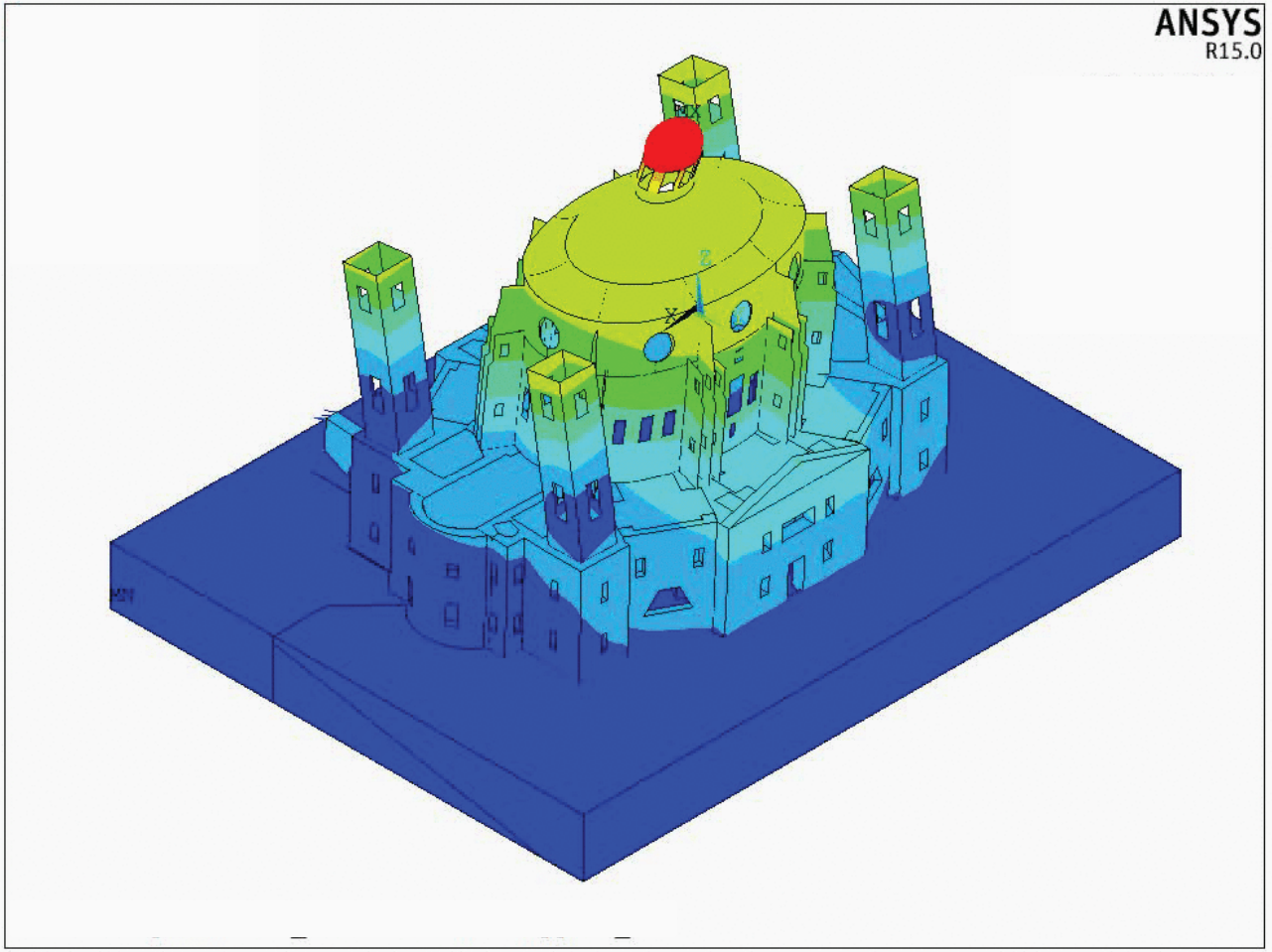
Elastic linear isotropic model:

- Solid elements for the soil and the basement
- Shell elements for the rest of the structure
- Link for the strengthening system

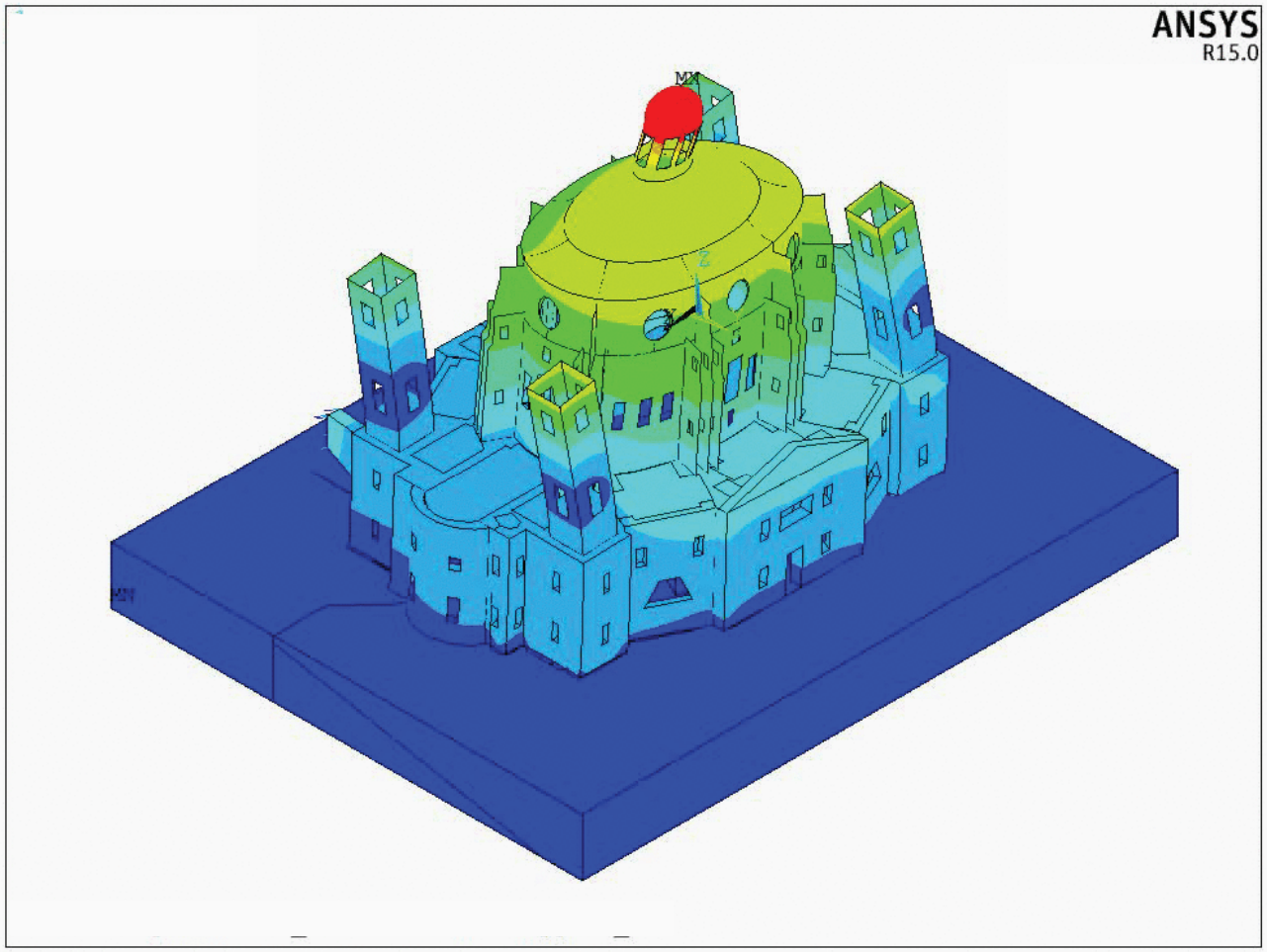
- **The introduction of the soil in the model (*Soil Structure Interaction SSI FE model*) allowed for a better calibration of the dynamic model.**

- **The new SSI dynamic model has been used for sensor placement of a *Structural Health Monitoring (SHM)* system and will be used to study the effect of the bar strengthening system in the hypothesis of a semi-active control technology system.**

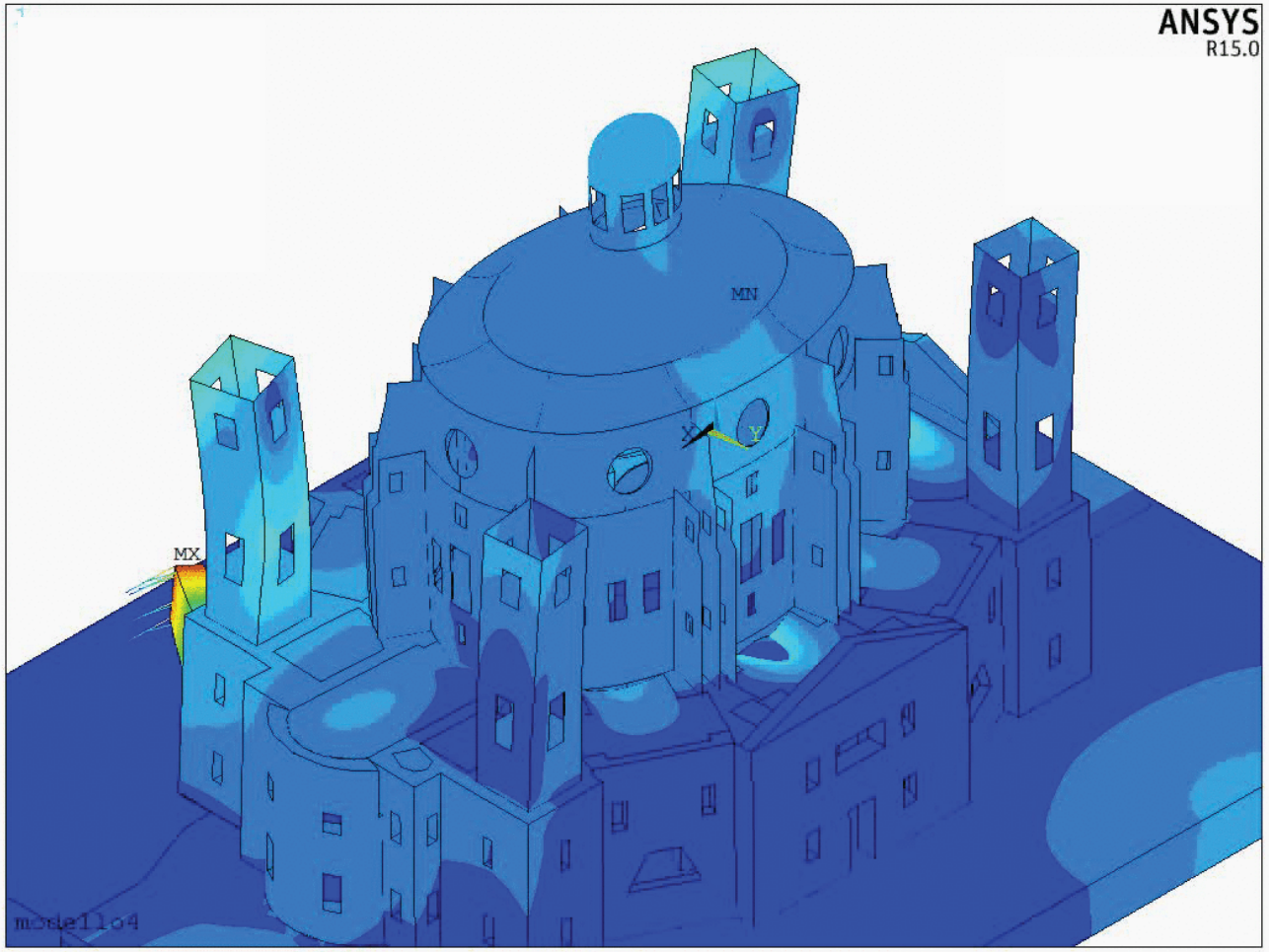
1st flexural mode (1.99 Hz)



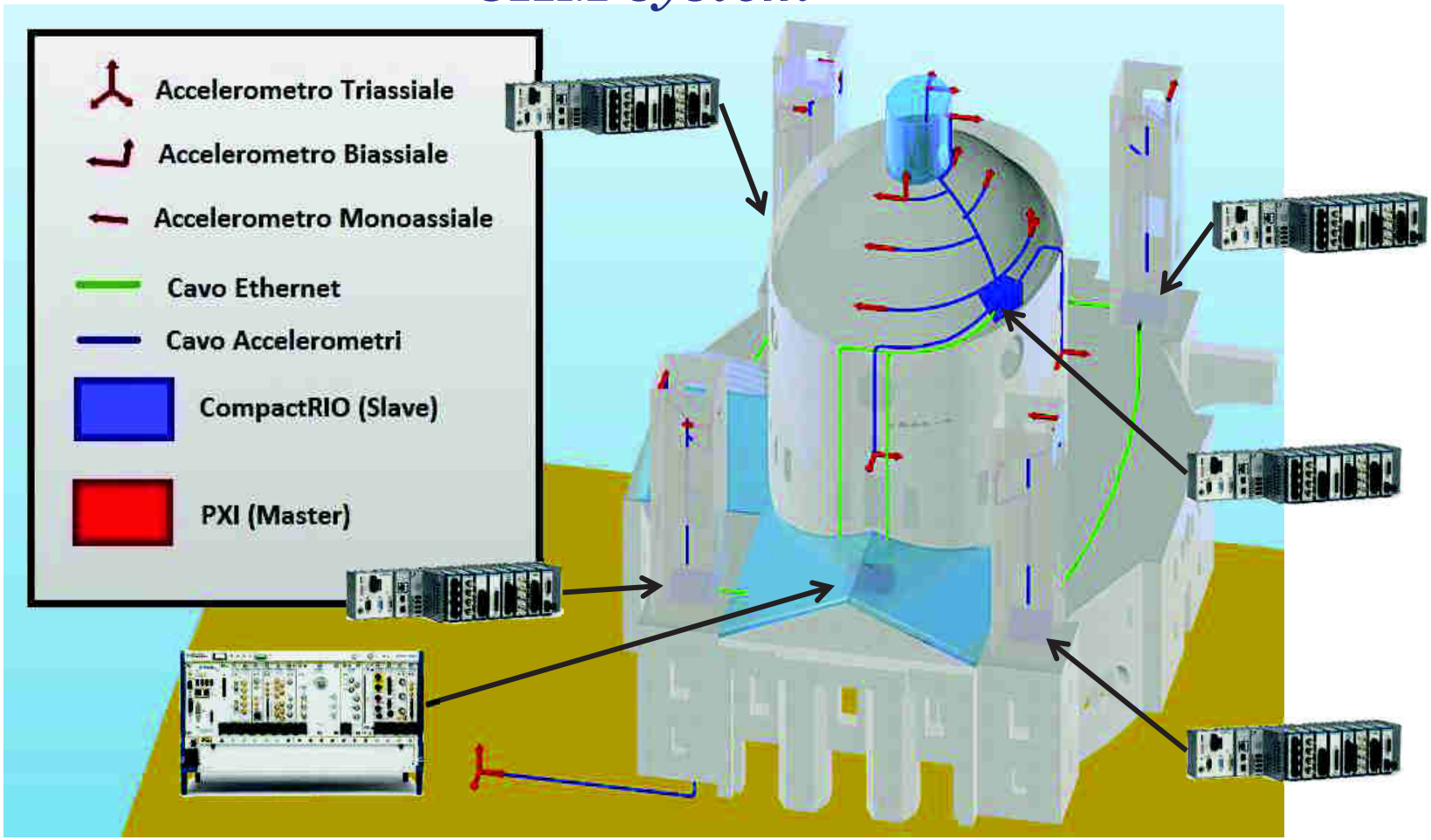
2nd flexural mode (2.08 Hz)



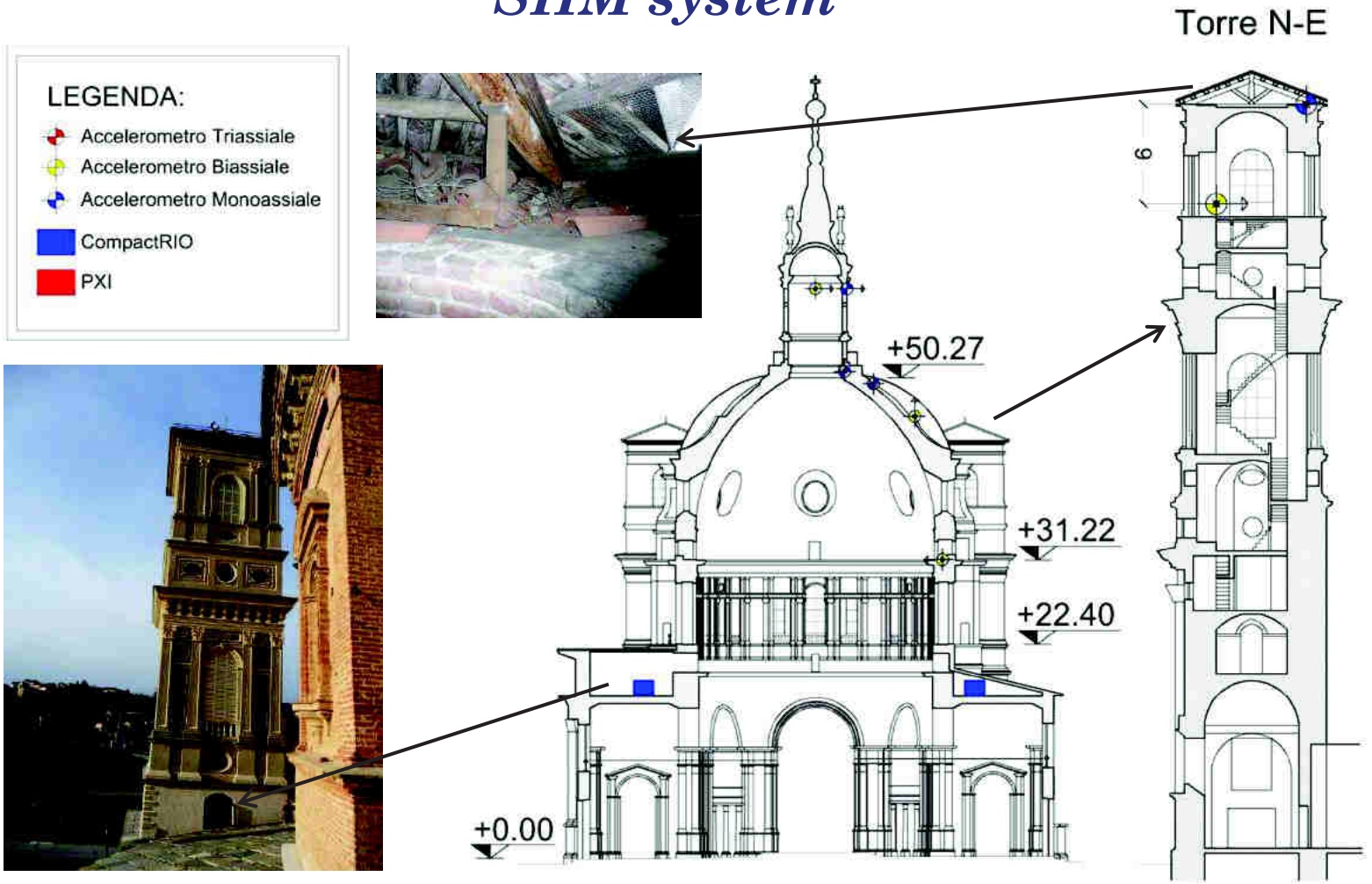
1st Vertical mode (6.02 Hz)



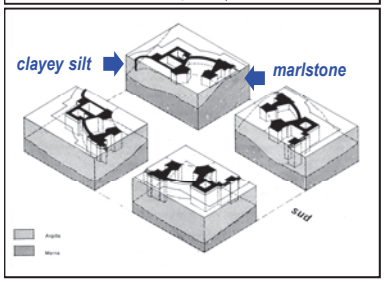
A new dynamic Structural Health Monitoring SHM system

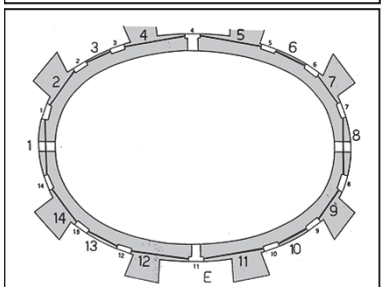


A new dynamic Structural Health Monitoring SHM system




2.3 Evevaluation of seismic risk of the monument
Work in progress....



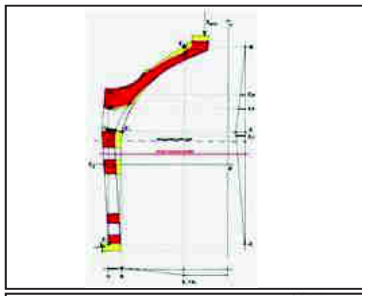


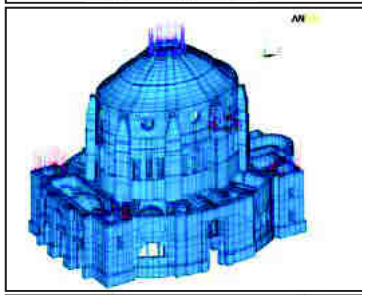
CONCLUSIONS

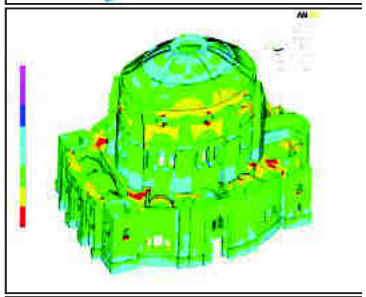
- The contribution of structural engineering and geotechnics to the conservation of historical monuments is significant

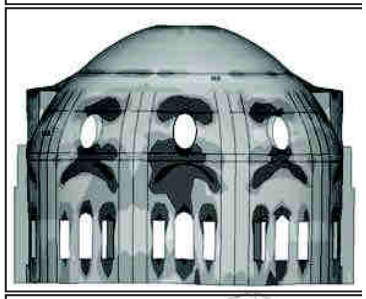
- In particular in ambients like the Italian ambient containing one of the most important cultural/architectural heritage, in the world in a region which is seismically active

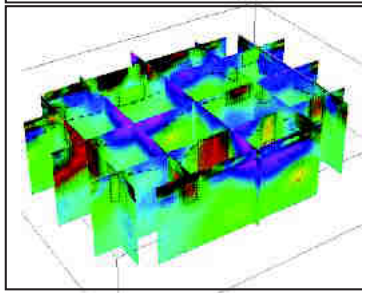
- The case case study of the survey and structural modeling for the reliability assessment of the world's largest elliptical masonry dome at Vicoforte, Italy, fits in this perspective, and is intended to be proposed as a scholastic case study of advanced approaches within international debate

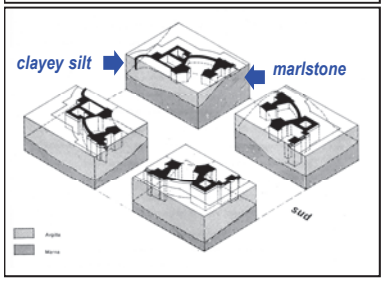


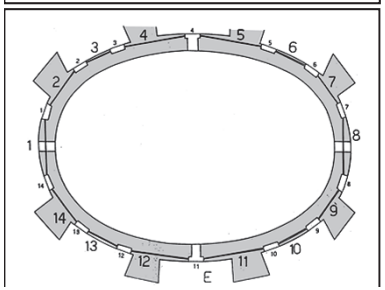












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THANK YOU