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A Case Study for the NOSA-ITACA Project: The "Voltone" in Livorno

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UNIVERSITÀ DEGLI STUDI FIRENZE

DICEA Dipartimento di Ingegneria Civile e Ambientale

Regione Toscana

FAS Fondo Aree Sottoutilizzate 2007-2013

Istituto di Scienza e Tecnologie dell'Informazione Consiglio Nazionale delle Ricerche

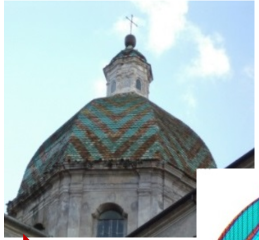
Finite Element Code **NOSA** [1]

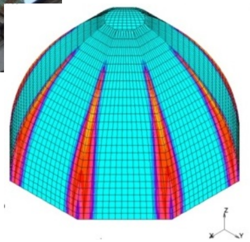
- **NOSA** is a code for studying the static and dynamic behaviour of masonry constructions (implemented by ISTI-CNR of Pisa) ;
- **Masonry** is described as a nonlinear elastic material with zero tensile strength and bounded compressive strength ;
- **NOSA** models the structural behaviour of masonry buildings by providing important information, such as the stress field and distribution of cracked regions, together with indications on their possible evolution ;
- In many cases, **NOSA** has provided important information on a structure's seismic vulnerability, which can be assessed with reference to current Italian and European regulations. Moreover, the effectiveness of various strengthening interventions, such as the application of chains, rods and retaining structures, can be evaluated.

[1] M. Lucchesi, C. Padovani, G. Pasquinelli, N. Zani, "Masonry constructions: mechanical models and numerical applications", Series: Lecture Notes in Applied and Computational Mechanics, Vol. 39, Berlin Heidelberg, Springer-Verlag, 2008

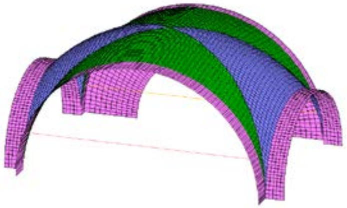
Finite Element Code **NOSA** : some applications

- 1995 Battistero del Duomo, Volterra
- 1996 Arsenale Mediceo, Pisa
- 1998 Teatro Goldoni, Livorno
- 1998 Chiesa Madre di S. Nicolò, Noto
- 2004 Chiesa di Santa Maria Maddalena, Morano Calabro (CS)

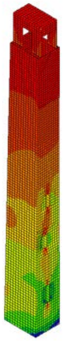




- 2005 Chiesa di San Ponziano, Lucca



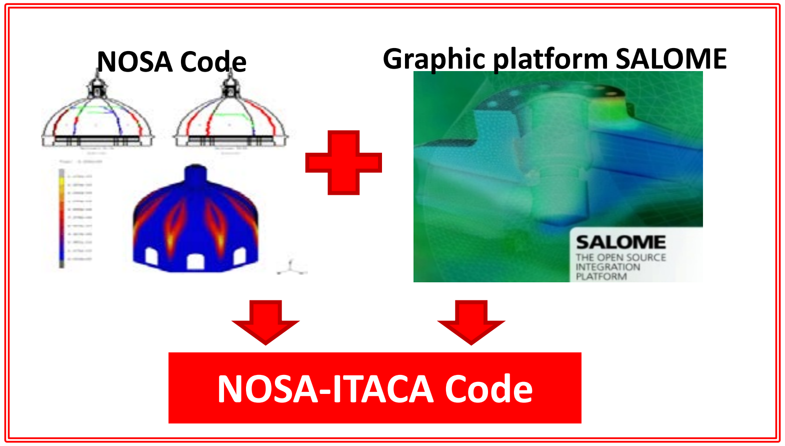
- 2008 Chiesa Abbaziale di Santa Maria della Roccella, Scolacium
- 2008 Torre “Rognosa” , San Gimignano
- 2010 Torre “delle Ore”, Lucca
- 2012 Chiesa di San Francesco, Lucca



NOSA-ITACA Project [2]

The project , funded by the Region of Tuscany (2011-2013), is divided into two parts:

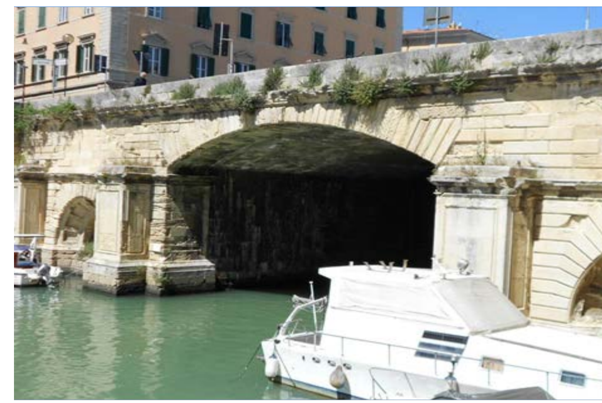
- Study of mathematical models for analyzing the static and dynamic behaviour of masonry constructions and procedures for assessing their static safety and seismic vulnerability;
- Development of the NOSA-ITACA code, resulting from integration of the NOSA code and the open source graphic platform SALOME (aim of the project: improving the performance of the NOSA code and equipping it with an interactive graphic tool for pre- and post-processing).



[2] Website ***http://www.nosaitaca.it/en/***

Case study : The 'Voltone' in Livorno, Italy

The **“Voltone”** (i.e., the great vault) is a 220-meter long, tunnel-like masonry structure located beneath Piazza della Repubblica in Livorno. It is constituted by a segmental vault, through which the “Fosso Reale” canal flows. The vault is set on two lateral walls and reinforced by buttresses placed at intervals of about 5.8 meters one from the other.



Research steps :

1. Characterization of the geometry and materials;
2. Preliminary numerical analysis: plane model;
3. Numerical analysis: three-dimensional model;
4. Evaluation of results: first investigations of the structure’s safety.

Step 1 : Characterization of the geometry and materials

<u>Aim</u> : measuring the thickness of the masonries and determining the stratigraphy and mechanical properties of their constituent materials.

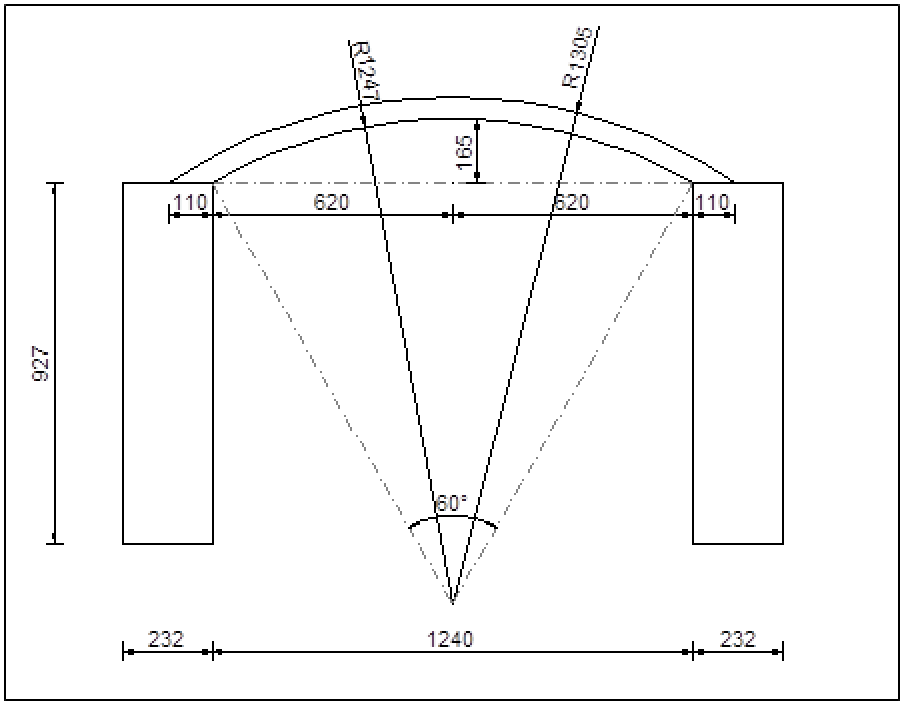
- Carrying out of a series of non-destructive tests (laser scan digital acquisition and georadar scan of the surface of the overlying square) ;
- Extracting four vertical core samples (two from the wall and surrounding soil, and two from the vault at the crown and haunch) ;
- Extracting of two horizontal core samples from the lateral walls;
- Historical and archaeological reports
- Laboratory tests

Laser scan digital

Georadar scan

Vertical coring

Step 1 : Characterization of the geometry and materials



Cross- section (cm)

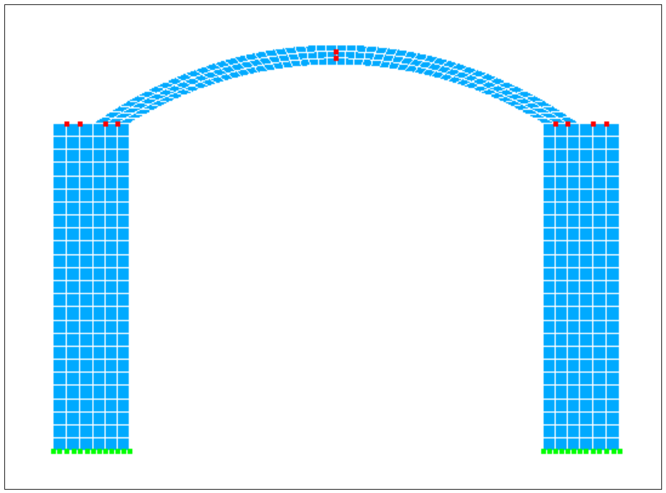
Geometrical characteristics

- Vault thickness is about 0.41÷0.43 m (constant along the section and length of the vault) except for the ends (in correspondence to roadways), where the thickness is about 0.7 m ;
- Lateral walls have variable height and their thickness is 2.32 m [3] ;
- The vault is greatly lowered ;
- Buttresses are placed at intervals of about 5.8 m one from the other [3].

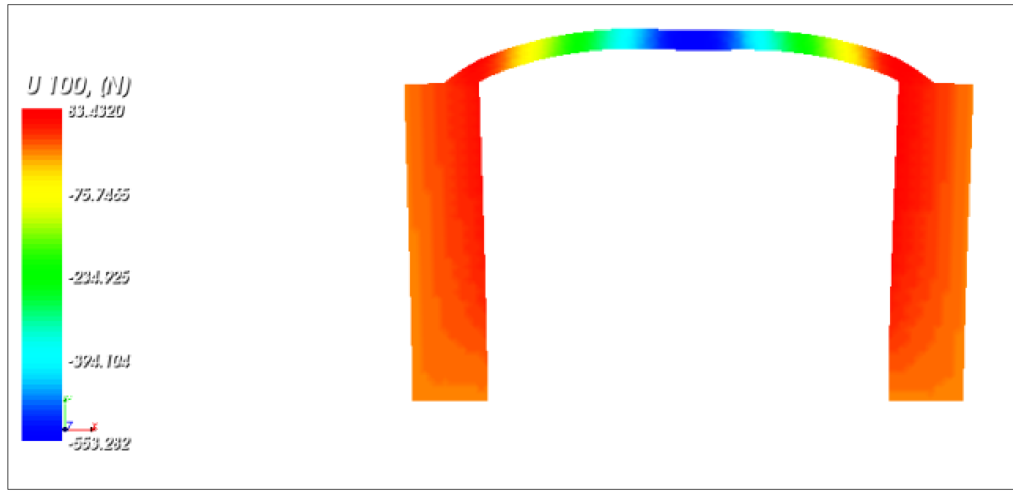
[3] C. Errico, M. Montanelli, "Il progetto del Voltone". Private communication, 2012

Step 2 : Preliminary numerical analysis - plane model

The **goal** of this preliminary analysis is investigating whether the buttresses are necessary for the structure's static equilibrium



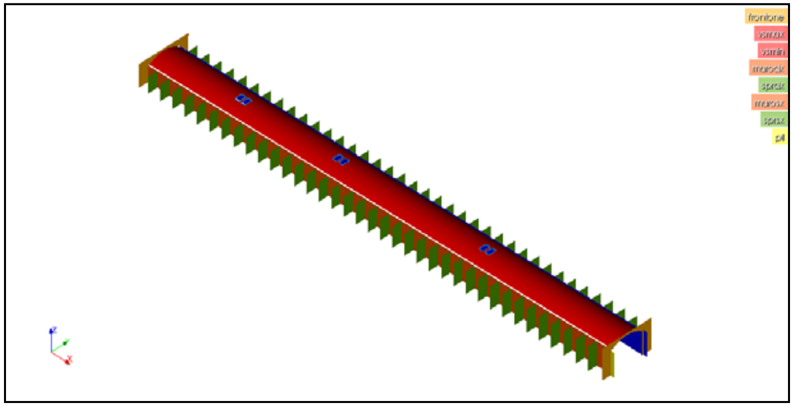
F.E.M. plane model



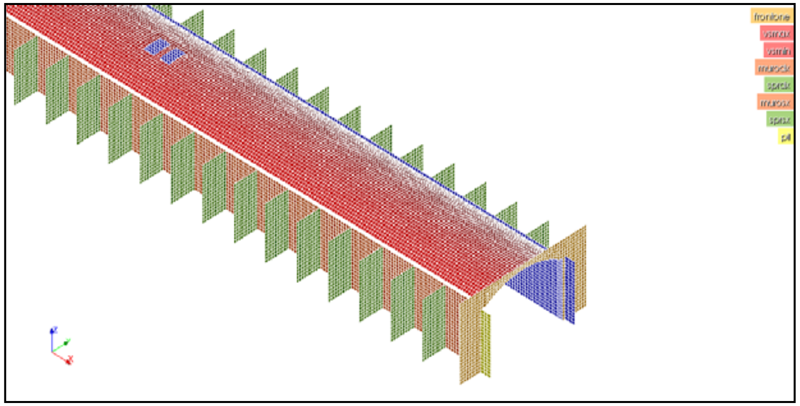
Displacements [m]

The vault model without buttresses **<u>is unable</u>** to reach convergence even for the permanent loads alone. This is a three-dimensional problem and the buttresses are necessary for equilibrium

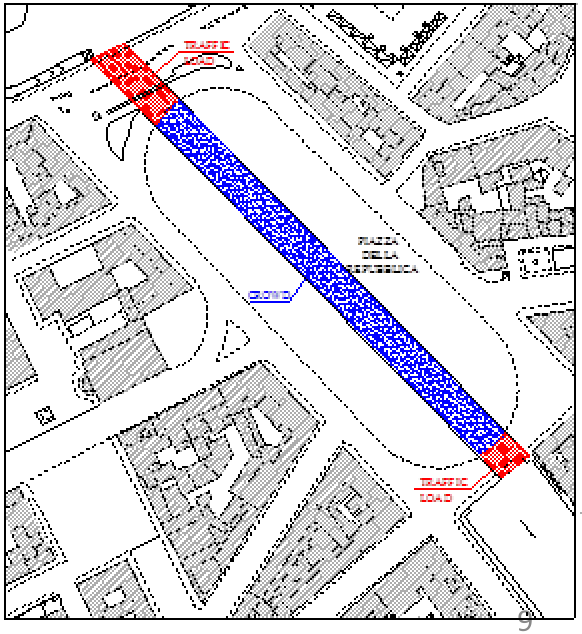
Step 3 : Numerical analysis - three-dimensional model



Three-dimensional F.E.M. model



Detail of the model

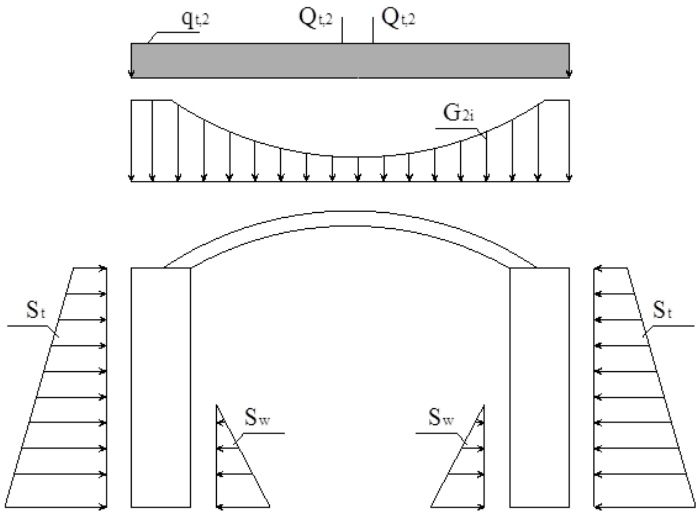


Mesh characteristics : 45379 nodes ; 43084 thick-shell elements.

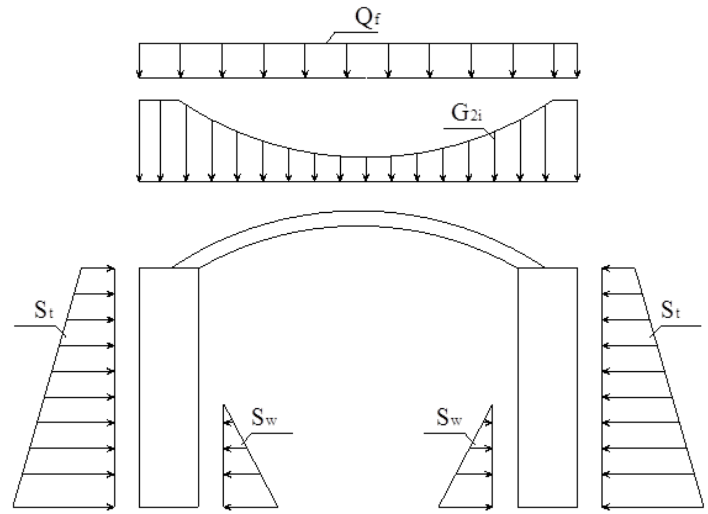
Loads acting on the structure :

- Permanent loads (i.e. the weight of the structure “G_1” and filling material “G_2”);
- Soil pressure “S_t” and water pressure “S_w” on the lateral walls;
- Accidental loads (dense crowd “Q_f” in the central area of the square, and a traffic load “$Q_{k,i}$” for category II bridges on the square’s ends, where roadways are located).

Step 3 : Numerical analysis - three-dimensional model



Loads scheme on the square's ends



Loads scheme in the central square

The loads, shown in the picture, are applied to the structure in accordance with the load combinations for ultimate limit states prescribed by Italian regulations and expressed by the following relation :

$$\gamma_{G1} \cdot G_1 + \gamma_{G2} \cdot G_2 + \gamma_{Q1} \cdot Q_{k1} + \gamma_{Q2} \cdot \psi_{02} \cdot Q_{k2} + \gamma_{Q3} \cdot \psi_{03} \cdot Q_{k3} + \ldots$$

The analyses were conducted modelling **masonry** as a non-linear elastic material with zero tensile strength and bounded compressive strength.

Step 4 : Evaluation of results - first investigations of the structure's safety

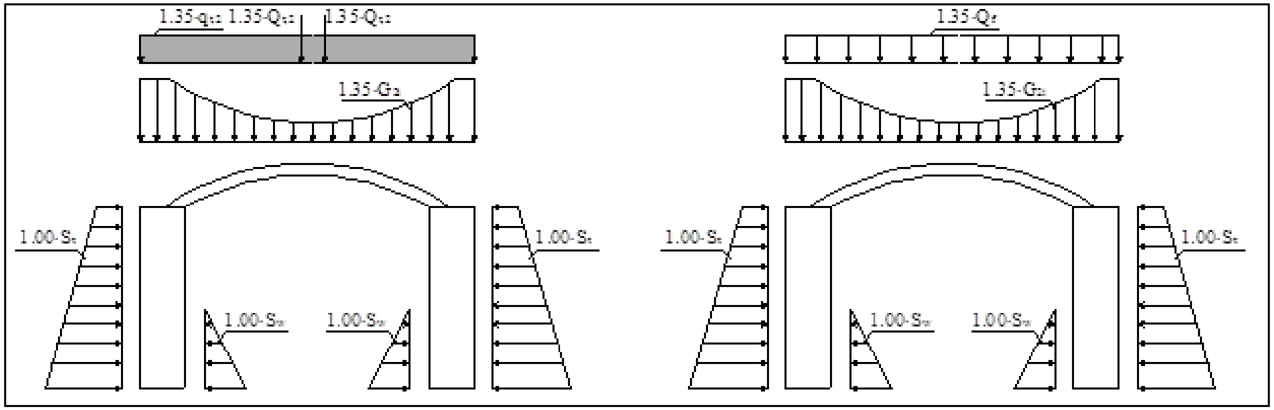
The analyses have enabled calculating the stress field the structure and then assessing itssafety; checks are being carried out in light of current Italian regulations.

Safety checks aimed at studying the structure's behaviour at its ultimate limit states are being implemented and tested in the NOSA-ITACA code. They are based on the partial safety factors method expressed by the inequality

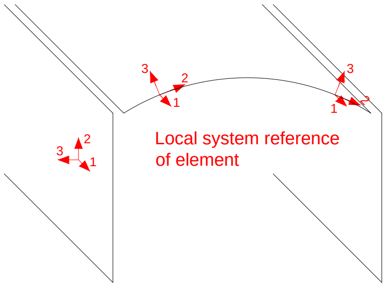
$$\frac{E_d}{R_d} \leq 1$$

where E_d is the bending moment calculated by applying the design loads on the model (design effect), while R_d is the limit moment (design strength), i.e. the maximum value of the bending moment that can be attained in the section evaluated according to the materials' mechanical characteristics, the section's geometry and appropriate safety coefficients and depending on the normal force acting in the section.

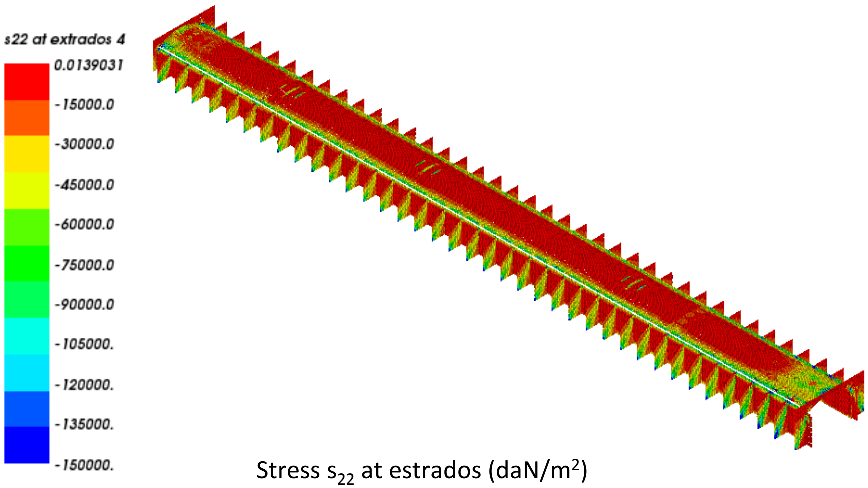
Step 4 : Evaluation of results - first investigations of the structure's safety



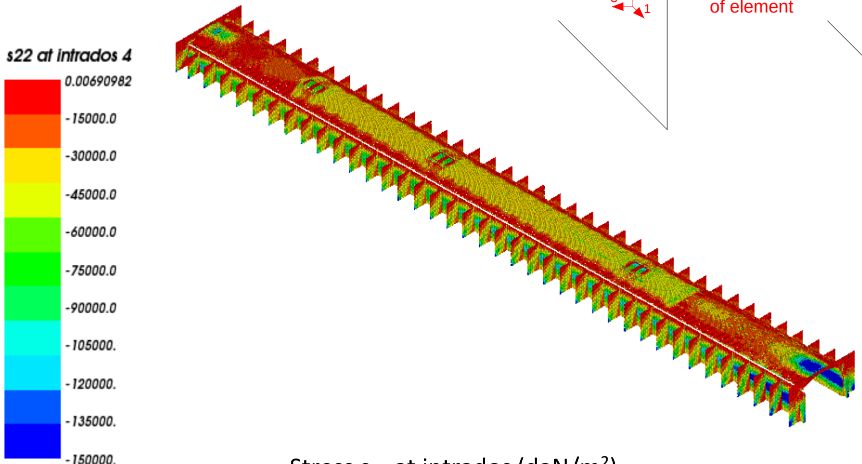
Example of loads combination



Results achieved by **Nosa-Itaca** :

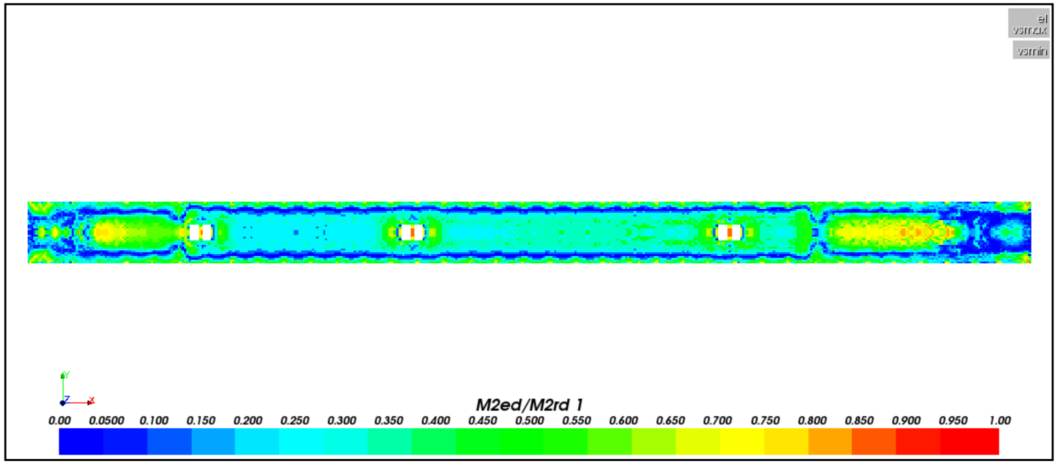


Stress s_{22} at estrados (daN/m^2)



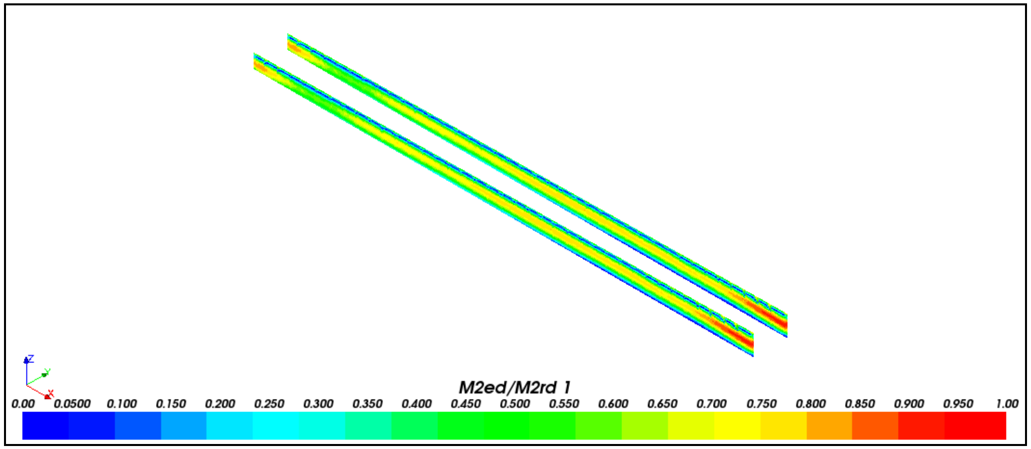
Stress s_{22} at intrados (daN/m^2)

Step 4 : Evaluation of results - first investigations of the structure's safety



The ratio between bending moment and limit moment in the vault

The ratio between bending moment and limit moment in the lateral walls



Limit Moment (per unit length) is calculated via the following expression:

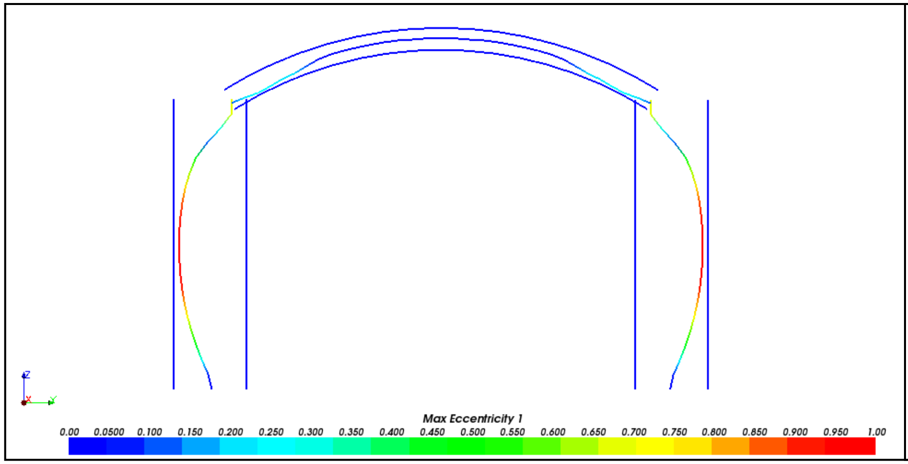
$$M = (t^2 \cdot \sigma_{Ed} / 2) \cdot (1 - \sigma_{Ed} / \sigma_0)$$

where :

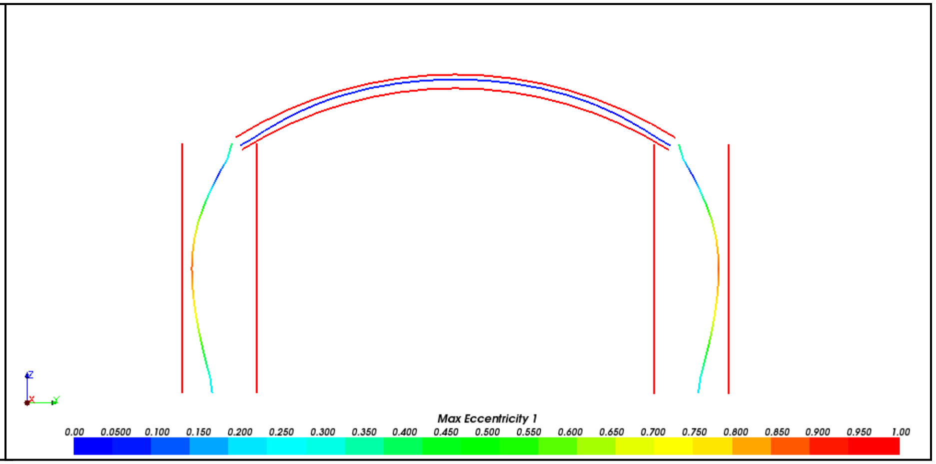
- t , thickness element
- σ_0 , masonry compressive strength
- σ_{Ed} , mean stress acting in the element equal to the ratio between axial force and thickness of the element

Step 4 : Evaluation of results - first investigations of the structure's safety

The results are also reported in terms of the *line of thrust,* a diagram which allows evaluating the static safety of a masonry vault graphically. A line of thrust that is wholly contained within an arch's ring is an index of static safety.



Line of thrust at the end of the square (eccentricity expressed in m)



Line of thrust in the central area of the square (eccentricity expressed in m)

Conclusions

- It is crucial to correctly model masonry materials, whose response to tension is different from that to compression.
- The constitutive equation, which is known as the masonry-like (or no-tension) model, has been implemented in the finite element code **NOSA**, successfully applied to the static analysis of several historical masonry buildings.
- The **NOSA-ITACA project** is being carried out with the aim of enhancing the NOSA code, integrating it with the open-source graphical user interface, SALOME, and disseminate it among both private and public bodies involved in the conservation of the national architectural heritage.
- **NOSA-ITACA** code has been used to study the "Voltone" a large vaulted masonry structure. This case study provides an opportunity to validate both the models proposed and the calculation tool developed.

Thanks you for your kind attention

Daniele Pellegrini