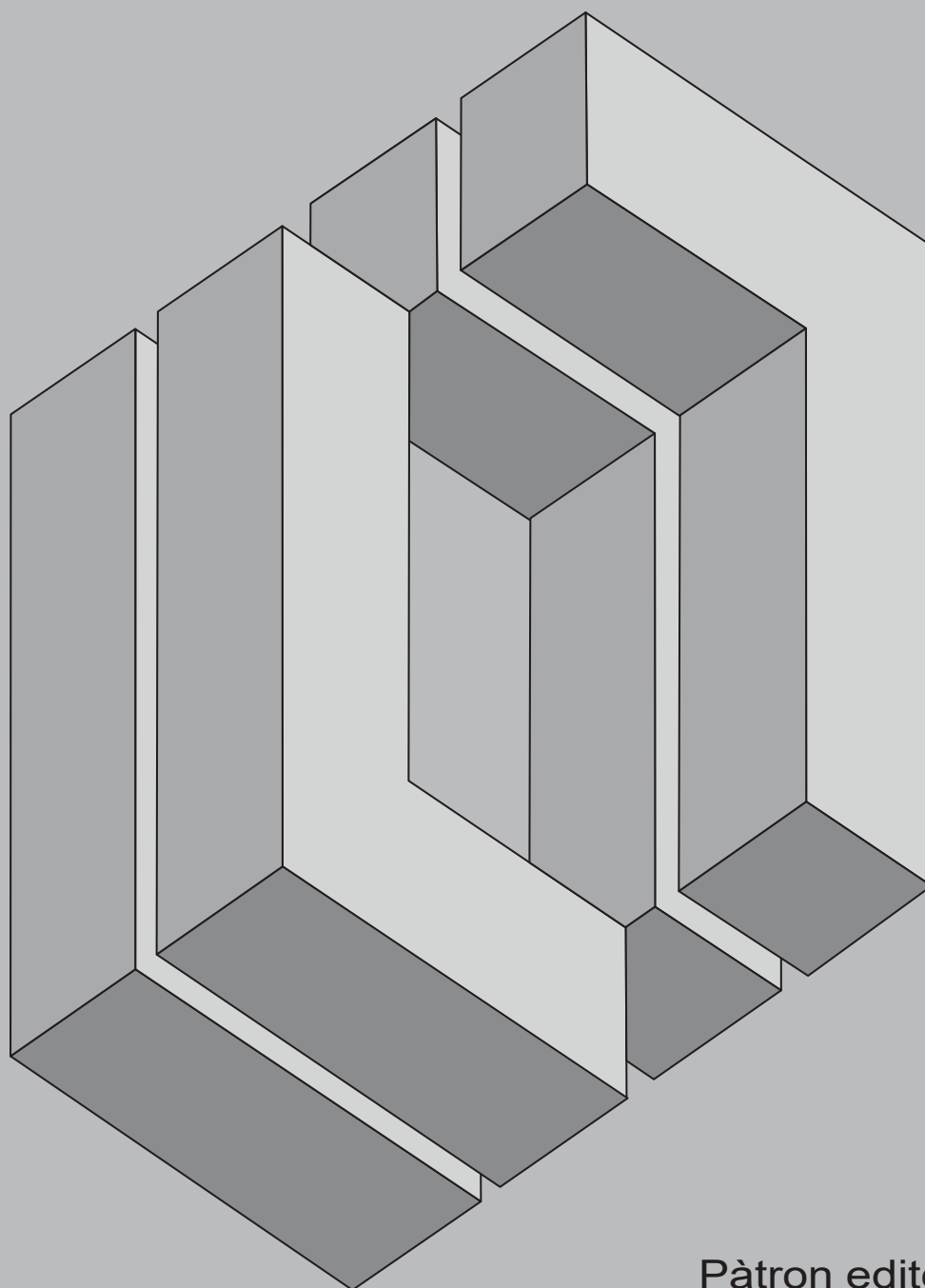
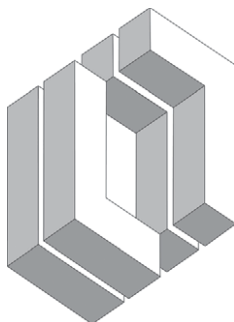


# ingegneria sismica

International Journal of Earthquake Engineering  
Trimestrale tecnico-scientifico

[www.ingegneriasismica.org](http://www.ingegneriasismica.org)





**Founder / Fondatore**

Duilio Benedetti – Politecnico di Milano

**Editor-in-Chief / Coordinatore editoriale**

Gianmario Benzoni – University of California San Diego – [benzoni@ucsd.edu](mailto:benzoni@ucsd.edu)

**Associate Editors / Coordinatori associati**

Fernando Fraternali – Università di Salerno, Italy  
Rosario Montuori – Università di Salerno, Italy  
Maria Adelaide Parisi – Politecnico di Milano, Italy

**Scientific Board / Comitato scientifico**

Raimondo Betti – Columbia University, USA  
Alfredo Campos Costa – LNEC Lisbon, Portugal  
Panayotis Caridys – National Technical University Athens, Greece  
Dina D'Ayala – University College London, UK  
Giacomo Di Pasquale – Dipartimento della Protezione Civile, Italy  
Johann Facciorusso – Università degli Studi di Firenze, Italy  
Giancarlo Gioda – Politecnico di Milano, Italy  
James M. Kelly – University of California Berkeley, USA  
Sergio Lagomarsino – Università di Genova, Italy  
Giuseppe Lomiento – Bianchi-Lomiento, Italy  
Claudia Madaï – Università degli Studi di Firenze, Italy  
Alessandro Martelli – ENEA Bologna, Italy  
Fabio Mazza – Università della Calabria, Italy  
Mauro Mezzina – Politecnico di Bari, Italy  
Maria Ofelia Moroni – Universidad de Chile, Santiago, Chile  
Elide Nistri – Università di Salerno, Italy  
Stefano Pampanin – University of Canterbury, New Zealand  
Floriana Pergalani – Politecnico di Milano, Italy  
Yuri Ribakov – Ariel University, Israel  
Paolo Rugarli – Castalia S.r.l., Milano, Italy  
Gaetano Russo – Università di Udine, Italy  
Milutin Srbulov – Mott MacDonald, U.K.  
Miha Tomasevic – Slovenian Civil Engineering Institute, Slovenia  
Mihailo Trifunac – University of Southern California, USA  
Keh-Chyuan Tsai – National Taiwan University, Taipei, Taiwan  
Thomas Wenk – Swiss Society for Earthquake Eng., Switzerland  
Aspasia Zerva – Drexel University, USA  
Paolo Castaldo – Politecnico di Torino, Italy

**Director / Direttore responsabile**

Fausto Giovannardi – Giovannardi e Rontini, Borgo San Lorenzo (FI), Italy

**Redazione, amministrazione, abbonamenti e pubblicità**

Patron Editore  
Via Badini 12, Quarto Inferiore  
40057 Granarolo dell'Emilia, Bologna  
Tel. (051) 767003 – Fax (051) 768252  
e-mail: [info@patroneditore.com](mailto:info@patroneditore.com)  
Sito: [www.patroneditore.com](http://www.patroneditore.com)

**Stampa:** Rabbi S.r.l. Bologna per conto della Patron editore  
Bologna, febbraio 2014

**Subscriptions see URL:**  
[www.ingegneriasismica.org](http://www.ingegneriasismica.org)

Sul sito [www.ingegneriasismica.org](http://www.ingegneriasismica.org) nella sessione archivi sono presenti tutti gli indici delle annate pubblicate.

Ingegneria Sismica  
Registrazione Tribunale di Bologna n. 5139 del 20.2.84

Realizzazione grafica della copertina: Arturo Galletti



# ingegneria sismica

International Journal of Earthquake Engineering

Anno XXXIV N.4 – Dicembre 2017

## Sommario/Contents

### FOUNDATION MATERIAL NONLINEARITY IN

#### DAM-RESERVOIR-MASSSED FOUNDATION COUPLED PROBLEMS

*La non linearità del materiale della fondazione di dighe a gravità tenendo in conto dell'interazione tra le sollecitazioni*

*Seyyed Meisam Aghajanzadeh, Hasan Mirzabozorg, Mohsen Ghaemian*

Pag-3

### THE INFLUENCE OF RECORD SELECTION IN ASSESSING UNCERTAINTY OF FAILURE RATES

*L'influenza della selezione degli accelerogrammi sulla stima dell'incertezza del tasso di fallimento*

*Mariano Angelo Zanini, Lorenzo Hofer, Flora Faleschini, Carlo Pellegrino*

Pag. 30

### PREDICTION OF SEISMIC RESPONSE OF MOMENT RESISTANT STEEL FRAMES USING DIFFERENT HYSTERETIC MODELS FOR DISSIPATIVE ZONES

*Previsione della risposta sismica di telai in acciaio mediante l'uso di diversi modelli isteretici per le zone dissipative*

*Valerio Giordano, Corrado Chisari, Gianvittorio Rizzano, Massimo Latour*

Pag. 42

### INFLUENCE OF INFILLED FRAMES ON SEISMIC VULNERABILITY ASSESSMENT OF RECURRENT BUILDING TYPOLOGIES

*Influenza delle tamponature nelle valutazioni di vulnerabilità sismica su tipologie costruttive ricorrenti*

*Maria Antonietta Aiello, Pier Luigi Ciampoli, Andrea Fiore, Daniele Perrone, Giuseppina Uva*

Pag. 58

### A CRITICAL REVIEW OF PLASTIC DESIGN APPROACHES FOR FAILURE MODE CONTROL OF STEEL MOMENT RESISTING FRAMES

*Revisione critica delle procedure per il controllo del meccanismo di collasso per i telai in acciaio*

*Giuseppe Dell'Aglio, Rosario Montuori, Elide Nistri, Vincenzo Piluso*

Pag. 82

### A NUMERICAL APPROACH TO THE MECHANICAL MODELING OF MASONRY VAULTS UNDER SEISMIC LOADING

*Un approccio numerico alla modellazione meccanica di volte murarie sotto azioni sismiche*

*Mariella De Piano, Mariano Modano, Gianmario Benzoni, Valentino Paolo Berardi, Fernando Fraternali*

Pag 104

### SEISMIC COLLAPSE MECHANISMS ANALYSES AND MASONRY STRUCTURES TYPOLOGIES: A POSSIBLE CORRELATION

*Analisi dei meccanismi di collasso e tipologie di strutture in muratura: una possibile correlazione*

*Giulio Zuccaro, Filomena Dato, Francesco Cacace, Daniela De Gregorio, Salvatore Sessa*

Pag. 121

## TO READERS AND AUTHORS

We are pleased to announce that *Ingegneria Sismica* is covered by SCOPUS, one of Elsevier products. Compendex will index papers and possibly extract data from the full text. Coverage increases dissemination of authors' work: the benefits are high visibility to a global audience. Since 1970,

## AI LETTORI ED AGLI AUTORI

Siamo lieti di comunicare che *Ingegneria Sismica* fa parte del database di SCOPUS, uno dei prodotti di Elsevier. Questo comporta l'indicizzazione degli articoli pubblicati e la eventuale citazione di dati estratti dal testo. Verrà così fortemente accresciuta la visibilità internazionale degli autori e degli argomenti trattati.



## A NUMERICAL APPROACH TO THE MECHANICAL MODELING OF MASONRY VAULTS UNDER SEISMIC LOADING

Mariella De Piano<sup>1</sup>, Mariano Modano<sup>2</sup>, Gianmario Benzoni<sup>3</sup>, Valentino Paolo Berardi<sup>1</sup>,  
Fernando Fraternali<sup>1</sup>

<sup>1</sup>Department of Civil Engineering, University of Salerno, Fisciano (SA), Italy

<sup>2</sup>Department of Structures for Engineering and Architecture, University of Naples Federico II,  
Italy

<sup>3</sup>Department of Structural Engineering, University of California San Diego, CA, USA

**SUMMARY:** *The seismic vulnerability assessment of existing and historical masonry structures is an important priority to preserve them over time. Several mechanical models available in literature are based on the limit analysis and may require a relevant computational burden. In this paper, an adaptive numerical method to analyse the seismic response of masonry vaults is presented. The approach is developed within Heyman's safe theorem and extends the funicular curve concept to the 3D case, by searching a 'safe' thrust surface within a design domain. The thrust surface is obtained by means of a Genetic Algorithm applied to a refinement adaptive finite element model. This approach can be easily implemented in existing FEM codes and gives a useful tool to assess seismic vulnerability of curved masonry structures and to design selective reinforcements. It is validated against a case study of a vault available in literature. Some numerical results dealing with a cloister vault subject to static and dynamic loads are given.*

**KEYWORDS:** *Masonry structures, Vaults, Genetic algorithm, Adaptive finite element model, Strengthening.*

### 1 Introduction

Seismic events show the high vulnerability of historical buildings to horizontal actions. In particular, masonry curved structures such as dome, vaults or simple arches, are one of the most diffused typologies in the international historical heritage. Several structural reinforcement techniques and studies have been used for the restoration and conservation of these constructions against seismic actions [Cattari *et al.*, 2012, Pugi and Galassi, 2013, Saisi *et al.*, 2014]. The crisis of masonry vaults may typically occur under both horizontal and vertical settlements or static and seismic loads [Fortunato *et al.*, 2014].

The retrofitting and strengthening of masonry structures is frequently performed through plating and/or wrapping strengthening techniques that employ traditional materials or fibre-reinforced composites [Fraternali and Reddy, 1993, Fraternali and Bilotti, 1997, Ascione *et al.*, 2013, Fraternali *et al.*, 2015, Ascione *et al.*, 2015].

Alternatively, it is possible to reduce the seismic excitation by recourse to conventional seismic isolation devices [Skinner *et al.*, 1993, Kelly, 1993, Benzoni and Casarotti 2009], or innovative seismic shielding techniques based on mechanical metamaterials [Daraio *et al.*,

2010, Ngo *et al.*, 2012, Leonard *et al.*, 2013, Yan *et al.*, 2014, Fabbrocino *et al.*, 2016, Palermo *et al.*, 2016, Mancusi *et al.*, 2017].

Several mechanical models available in literature are based on the limit analysis approach [Heyman 1995]. With reference to arches, the safe theorem of Heyman states that the structure is safe if a line of thrust (funicular curve) in equilibrium with the external loads and entirely contained within the volume of the structure can be found [De Jong, 2007, Block and Lachauer, 2014]. This theorem has been extended to double curved structures via either continuous or discontinuous approaches [Fraternali, 2010, 2011, Fabbrocino *et al.*, 2016, Carpentieri *et al.*, 2016, 2017]. The theoretical approach and the computational burden of such models makes their implementation in FEM code inappropriate.

In the recent years, structural optimization problems have been examined by means of genetic/evolutionary algorithms (GA), inspired by Darwin's evolution theory [Golberg *et al.*, 1986, Jenkins, 1992, Chapman *et al.*, 1994, Mitchell and Forrest 1994]. Differently from classical algorithms, GA can be applied to a wide variety of optimization problems, i.e. when the function is discontinuous, not derivable or strongly nonlinear [De Jong, 2007].

An advanced numerical model procedure that allow us to search a 'safe' thrust surface of masonry vaults is presented in this paper. The model is developed by means of a Breeder Genetic Algorithm (BGA) and applied to an adaptive FEM code [Fabbrocino *et al.*, 2015]. The BGA allows us to find a safe thrust surface by moving the FEM nodes of a vault within a design domain and minimizing a suitable "fitness function" here proposed.

The adaptive numerical method is validated by comparing its prediction for a cloister masonry vault under static load to the structural response evaluated in [D'Ayala and Tomasoni, 2008].

Numerical results are given for the case study of a cloister vault subject to static and dynamic load combinations. The presented approach offers a useful tool for the verification of existing masonry structures and the design of strengthening interventions with composite materials under static loads and seismic action.

## 2 Numerical model

The proposed numerical procedure is formulated within Heyman's safe theorem, by modeling the structural response of a masonry vault through a compressive membrane state across a material surface  $S$  (thrust surface), contained within the vault's volume. This surface is searched, by iterative procedure, with an adaptive Finite Element approach based on a genetic algorithm (BGA) that allows the shift of the locations of the membrane's nodes in order to minimize the tensile stresses. The F.E. model of the vault was developed within the linear elasticity via shell elements with dominant membrane behavior (Fig. 1). Model hypotheses include:

- no tensile strength of masonry;
- infinite compressive strength of masonry;
- sliding failure does not occur.

The last assumption requires values of friction between blocks of the order of 0.5–0.6.

Let denote the  $i$ -th coordinate of the  $j$ -th node,  $x_{i,j}$ ; the lower bound of  $x_{i,j}$  (corresponding to the intrados of the vault for unreinforced masonry),  $x_{i,jmin}$ ; the upper bound of  $x_{i,j}$  (corresponding to the extrados of the vault for unreinforced masonry),  $x_{i,jmax}$ ; control variables ranging in the interval  $[0,1]$ ,  $\xi_{i,j}$ .

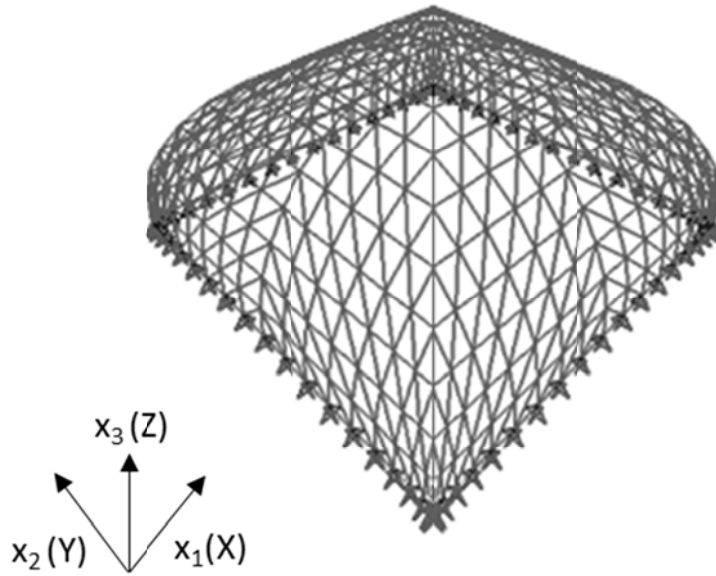


Figure 1 - FEM modelling of vaults

We research a safe thrust surface of vaults by moving FEM nodes within a design domain, expressed as follows:

$$x_{i,j} = x_{i,j}^{min} + \xi_{i,j}(x_{i,j}^{max} - x_{i,j}^{min})$$

The search of the safe thrust surface is performed through the BGA presented in [De Falco *et al.*, 1996, Fraternali *et al.*, 2011, Fabbrocino *et al.*, 2015], by minimizing a proper fitness function here proposed.

Such a fitness function evaluates the average value of the principal tensile stresses calculated at mesh nodes of unreinforced masonry and allows to obtain a faster minimization of tensile stresses respect to that given by the fitness function presented in [Fabbrocino F. *et al.*, 2015]. More specifically, if we assume  $n$  and  $N$  ( $=3n$  if all the 3 nodal coordinates govern the r-adaptation strategy) are the total number of the mesh nodes and control variables  $\xi_{i,j}$ , respectively, we can introduce the  $m$ -th “individual” corresponding to the  $t$ -th generation:

$$x_m^t = (x_{1,1}, \dots, x_{3,n})_m$$

The recombination of the  $\mu$  best individuals is performed by using the Extended Intermediate Recombination (EIR) [Mühlenbein *et al.*, 1999].

The BGA finds the safe thrust surface by performing the flow chart of Figure 2.

### 3 Validation

The procedure is validated by considering the masonry vault studied by D’Ayala and Tomasoni (2009) with span of 6 m, rise of 3 m and thickness of 0.12 m, subject only to self-weight. The mechanical properties of the material are indicated in Table 1 ( $\gamma_1$  = specific weight of masonry,  $E_m$  = Young modulus of masonry).

The comparison between the mechanical response obtained by the proposed procedure and the predictive behaviour of D’Ayala and Tomasoni (2009) is performed in terms of thrust surface and natural arches formation.

Table 1 – *Main mechanical properties of the materials*

$\gamma_1$ (kN/m <sup>3</sup> )	$E_m$ (MPa)
18.14	5000.00

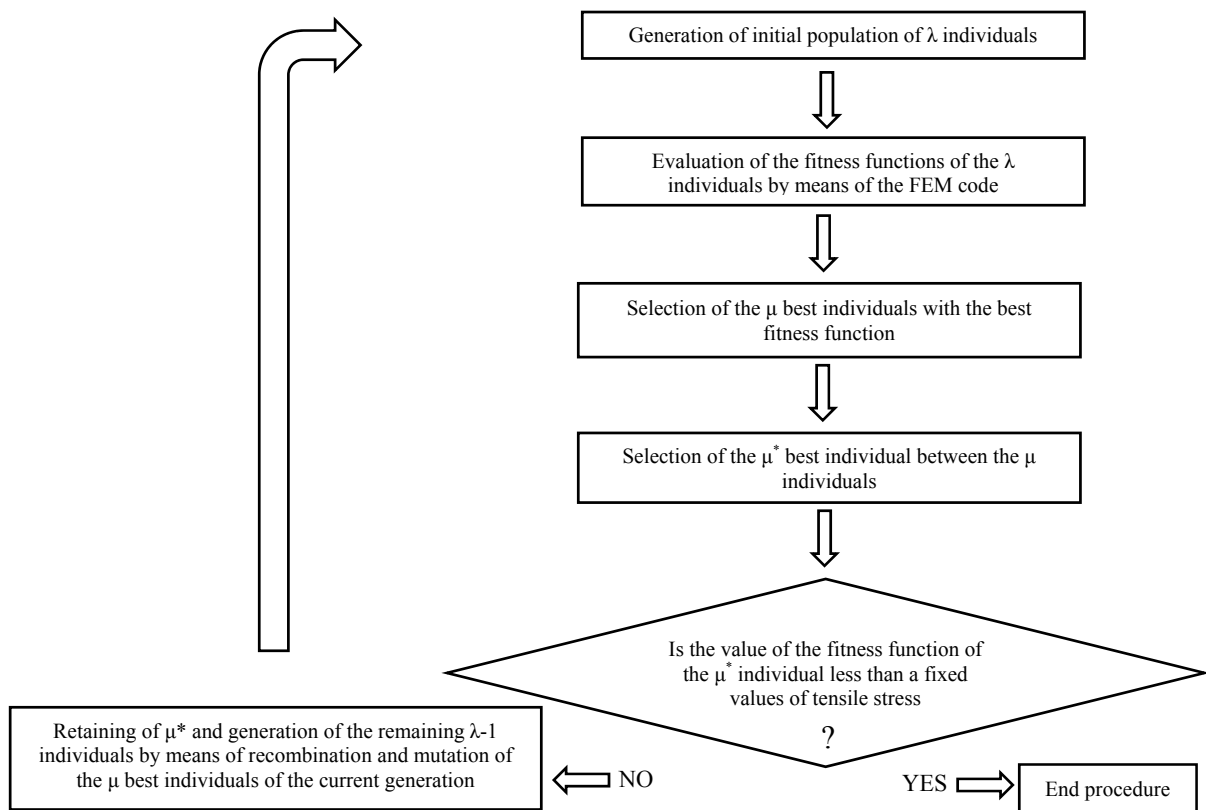


Figure 2 – BGA's flow chart

Let consider an eighth of the vault, by taking into account the symmetry of the vault geometry and the loads, and let divide it in four slices (Figure 3, a).

D'Ayala and Tomasoni (2009) shown that the pavilion vault is characterised by the formation of two plastic hinges at the 3<sup>rd</sup> and 4<sup>th</sup> slices of the vault: the first one located at the vault intrados for an angle of 70° with respect to the vertical direction; the second one located at the vault extrados for an angle of 30° with respect to the vertical direction. The authors also highlighted the natural arches configuration of the vault in the limit analysis solution (Figure 3, b).

The thrust surface obtained by the proposed procedure allows to predict the hinges formation above mentioned (Figures 4 and 5).

The procedure is also capable to describe the natural arches mechanism, taking into account the distribution of the minimum principal internal forces (Figure 6).

We denote 'RTS' the Reference Thrust Surface corresponding to the midsurface of the cloister vault and 'MTTS' the Minimum Tension Thrust Surface obtained via the proposed numerical procedure.

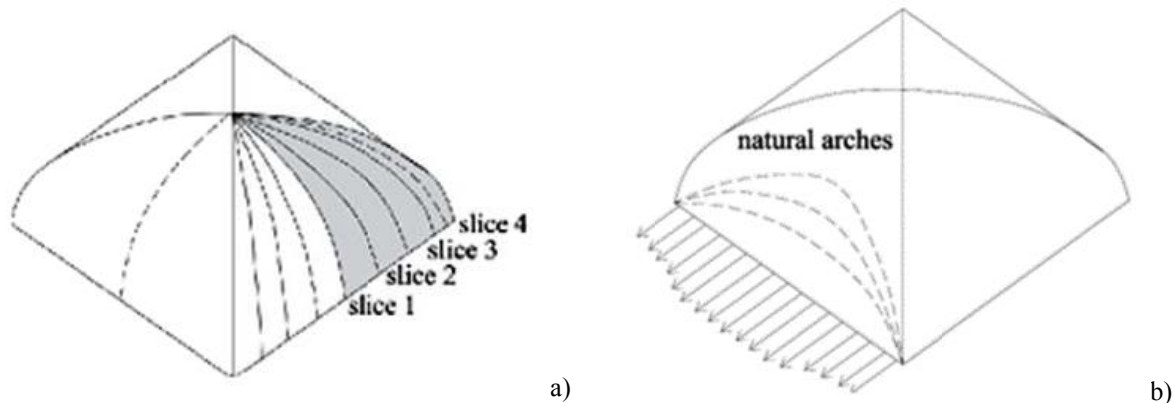


Figure 3 – (a) Slices definition and (b) natural arches in the limit analysis solution [D’Ayala and Tomasoni, 2009].

The maximum and minimum principal stresses associated to RTS are:  $\sigma_{\max} = 4.29 \times 10^{-1}$  MPa,  $\sigma_{\min} = -4.12 \times 10^{-2}$  MPa, respectively, and the average value of tensile principal stresses are equal to:  $\sigma_{\text{ave}} = 3.76 \times 10^{-8}$  MPa.

The MTTs gives the maximum principal stress ( $\sigma_{\max} = 9.00 \times 10^{-2}$  MPa) and the average value of the tensile principal stresses ( $\sigma_{\text{ave}} = 1.14 \times 10^{-8}$  MPa) considerably smaller than that obtained by the RTS. On the contrary, the minimum principal compressive stress of the MTTs ( $\sigma_{\min} = -3.73 \times 10^{-2}$  MPa) exhibits a negligible variation if compared to that given by the RTS (Figure 6).

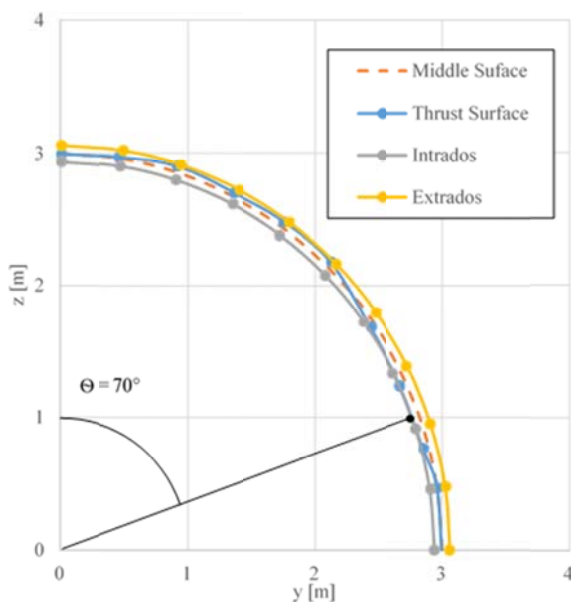


Figure 4 – Thrust surface section at centroid of the 3<sup>rd</sup> slice

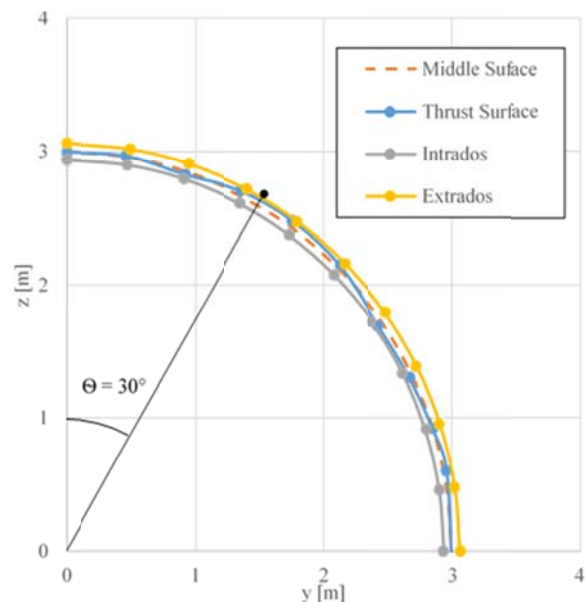


Figure 5 – Thrust surface section at centroid of the 4<sup>th</sup> slice

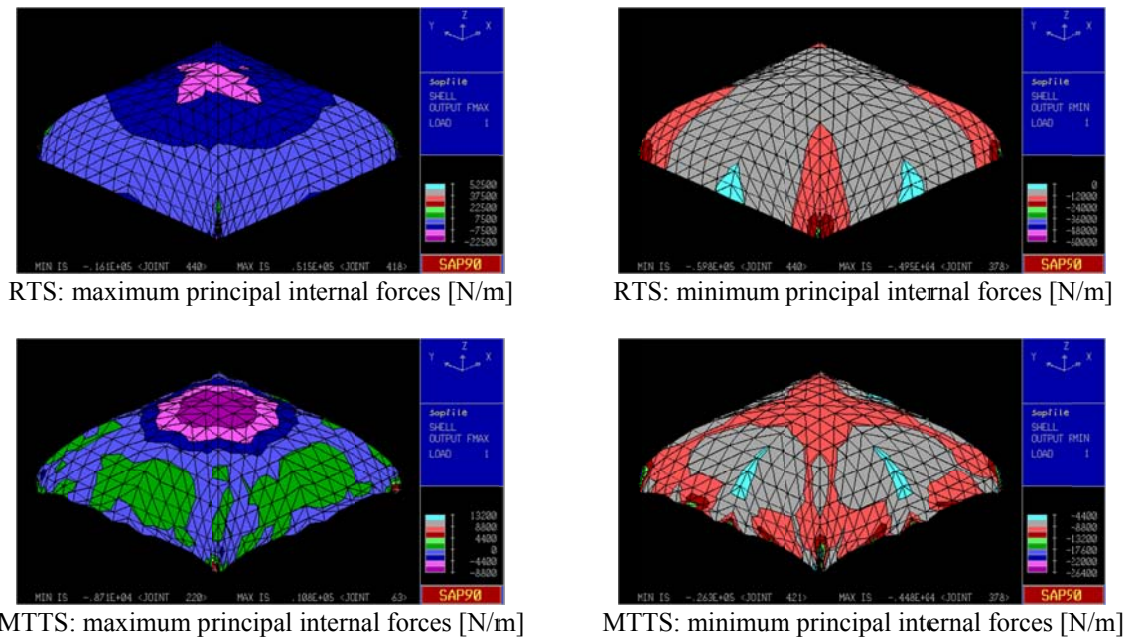


Figure 6 – Views of the unreinforced vault subject to its self-weight

#### 4 Case study

We analyze a tuff masonry cloister vault subject to static and dynamic loads.

The cloister vault, as well known, is generated by the intersection more barrel vaults set on opposite sides of a base polygon. The stress state in this kind of vault is more complex than that exhibited by groin and barrel vaults.

The examined vault is characterized by the constant thickness of 0.25 m and its geometry is depicted in Figure 7. The masonry framework is modelled, within the numerical procedure, by means of the SAP90 FEM code. The mesh consists of 441 nodes and 800 triangular shell elements with dominant membrane thickness (Figure 8).

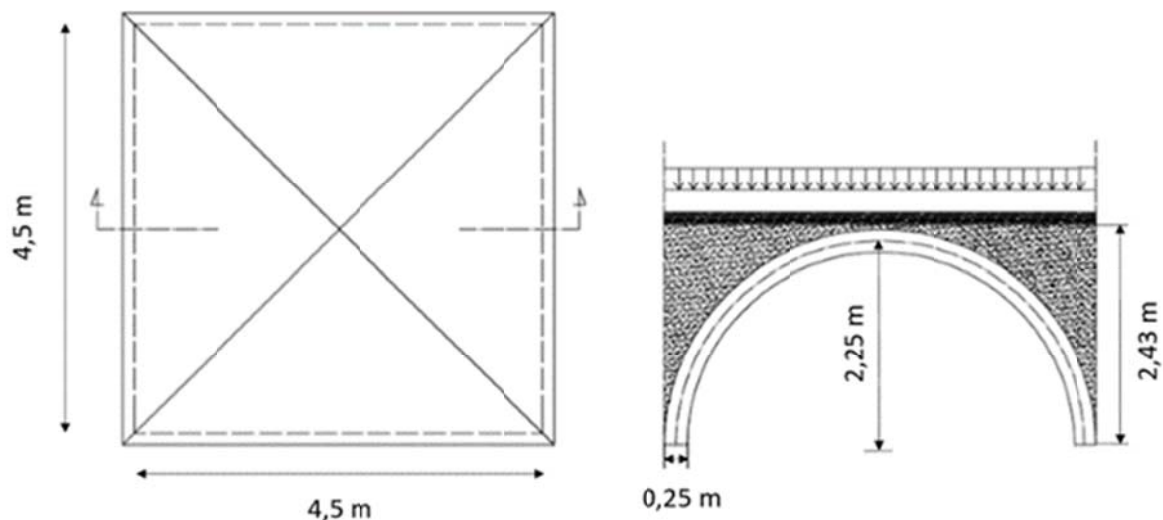


Figure 7 – Plan and section of the cloister vault

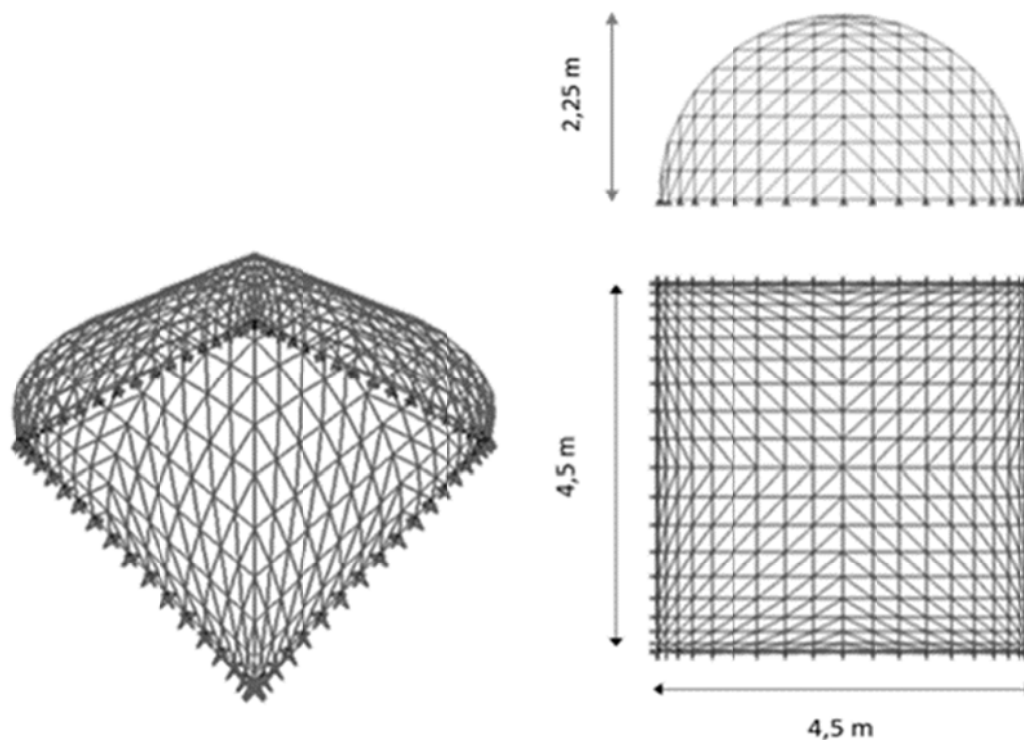


Figure 8 - 3D, front and top views of the finite element modelling

We assumed the physical and mechanical properties of the materials, reported in Table 2 ( $\gamma_2$  = specific weight of filling material). The basis of the cloister vaults is restrained by fixed hinge supports.

We consider three static case studies:

- cloister vault subject to its self-weight;
- cloister vault subject to the dead and live loads;
- cloister vault subject to the dead and half side live loads.

We also examine the vault under the load combination obtained by vertical and seismic loads. The seismic action is modelled according to static approach suggested in European Standard EN 1998-1 [Magenes, 2006]. In particular, horizontal forces in the  $X$  direction are set 0,50 of vertical forces (corresponding to the action of dead and live loads).

Finally, we propose a strengthening intervention with FRCM composites of the vault and we study the mechanical behaviour of the reinforced vault.

Within numerical simulations, the fitness function is applied to unreinforced masonry; the relocating of FEM nodes of the unstrengthened masonry is allowed along the  $Z$ -axis of the Cartesian frame within the vault volume; the relocating of FEM nodes of reinforced masonry is allowed along the  $Z$ -axis beyond the physical domain of the structure for the FRCM regions, on the opposite side of the reinforcements. Plots of maximum and minimum principal internal forces are given in the following, referred to the RTS and the MTTs.

Table 2 – Physical and mechanical properties of the materials

$\gamma_1$ (kN/m <sup>3</sup> )	$\gamma_2$ (kN/m <sup>3</sup> )	$E_m$ (MPa)
15.00	10.00	1500.00

### 4.1 Self-weight

Firstly, we apply the numerical model to the vault subject to its self-weight. Starting from the FEM analysis on the RTS and the MTTs (Figure 9), the maximum and minimum internal forces acting on midsurface of shell elements are obtained (Figure 10).

In terms of local stresses, the maximum and minimum principal stresses on the RTS are equal to  $\sigma_{\max} = 3.04 \times 10^{-2}$  MPa and  $\sigma_{\min} = -4.40 \times 10^{-2}$  MPa, respectively, and the average value of the tensile principal stresses is equal to  $\sigma_{\text{ave}} = 3.73 \times 10^{-9}$  MPa.

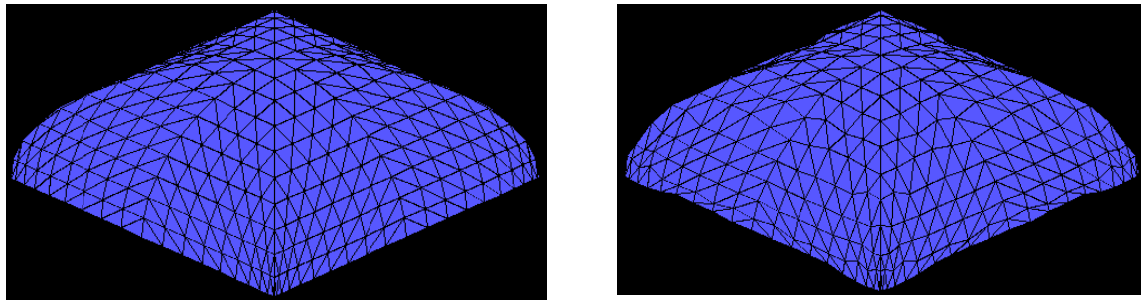


Figure 9 – Plan and section of the cloister vault

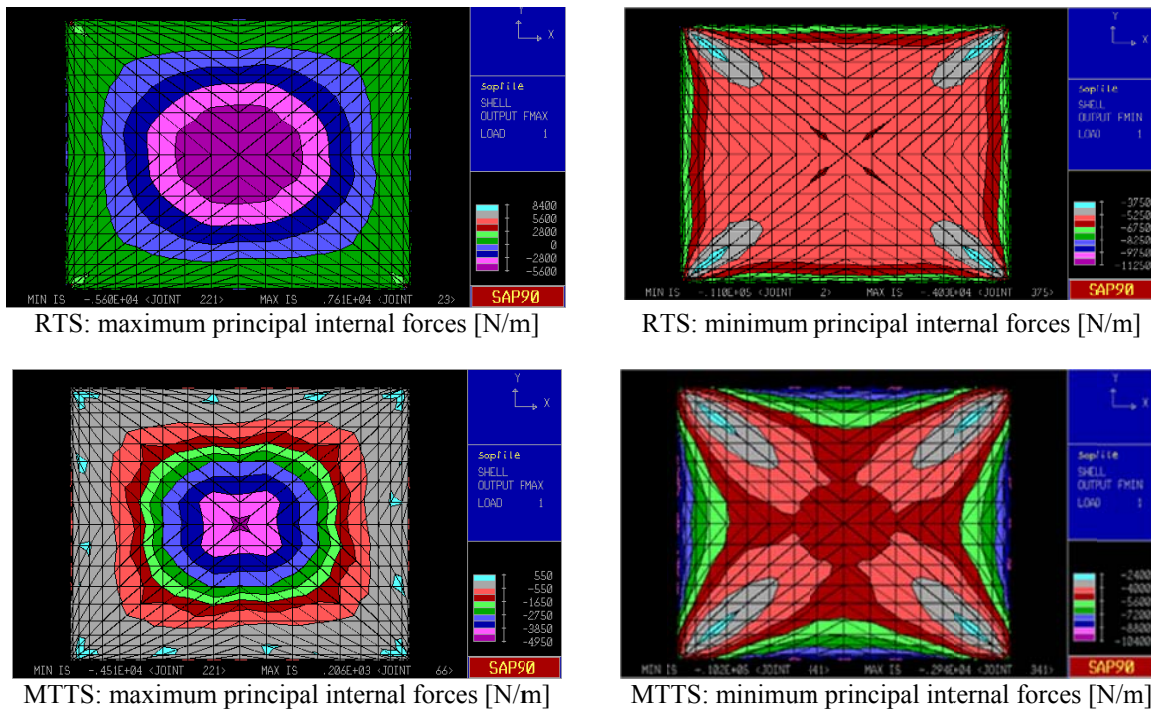


Figure 10 – Top views of the unreinforced vault subject to its self-weight

The results obtained by considering the MTTs highlight the maximum principal stress ( $\sigma_{\max} = 8.24 \times 10^{-4}$  MPa) and the average value of the tensile principal stresses ( $\sigma_{\text{ave}} = 5.35 \times 10^{-10}$  MPa) are significantly smaller than that obtained by the RTS, and the minimum principal compressive stress given by the MTTs ( $\sigma_{\min} = -4.08 \times 10^{-2}$  MPa) is almost unchanged compared to that given by the RTS.

### 4.2 Dead and live loading

Let us examine the vault subject to the following static design load combination,  $LC_{St}$ :

$$LC_{St} = G_1 + (G_{2,1} + G_{2,2}) + Q$$

where:

- $G_1$  is the dead load due to the self-weight of the vault;
- $G_{2,1}$  is the dead load due to the weight of the filling material;
- $G_{2,2}$  is the dead load due to the permanent overload and it is assumed equal to 3.00 kN/m<sup>2</sup>;
- $Q$  is the live load and it is fixed equal to 4.00 kN/m<sup>2</sup>.

The FEM analysis referred to the RTS and the MTTs of Figure 11 gives the maximum and minimum internal forces acting on midsurface of shell elements of Figure 12.

The corresponding maximum and minimum principal stresses on the RTS are equal to  $\sigma_{max} = 1.03 \times 10^{-1}$  MPa and  $\sigma_{min} = -1.40 \times 10^{-1}$  MPa, respectively, and the average value of the tensile principal stresses is equal to  $\sigma_{ave} = 1.26 \times 10^{-8}$  MPa.

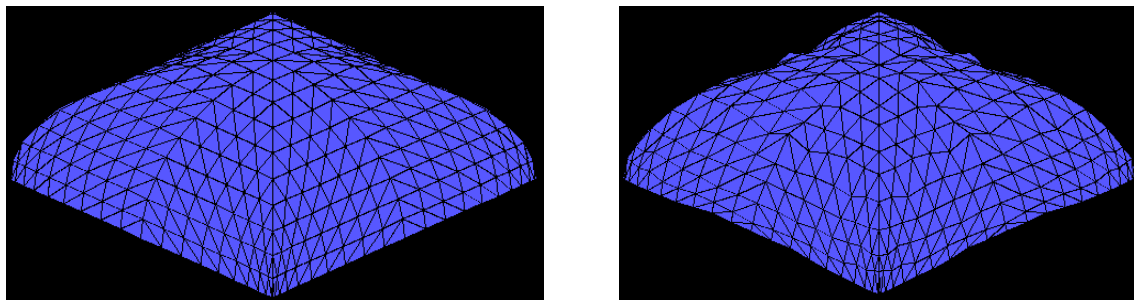


Figure 11 – RTS and MTTs configurations

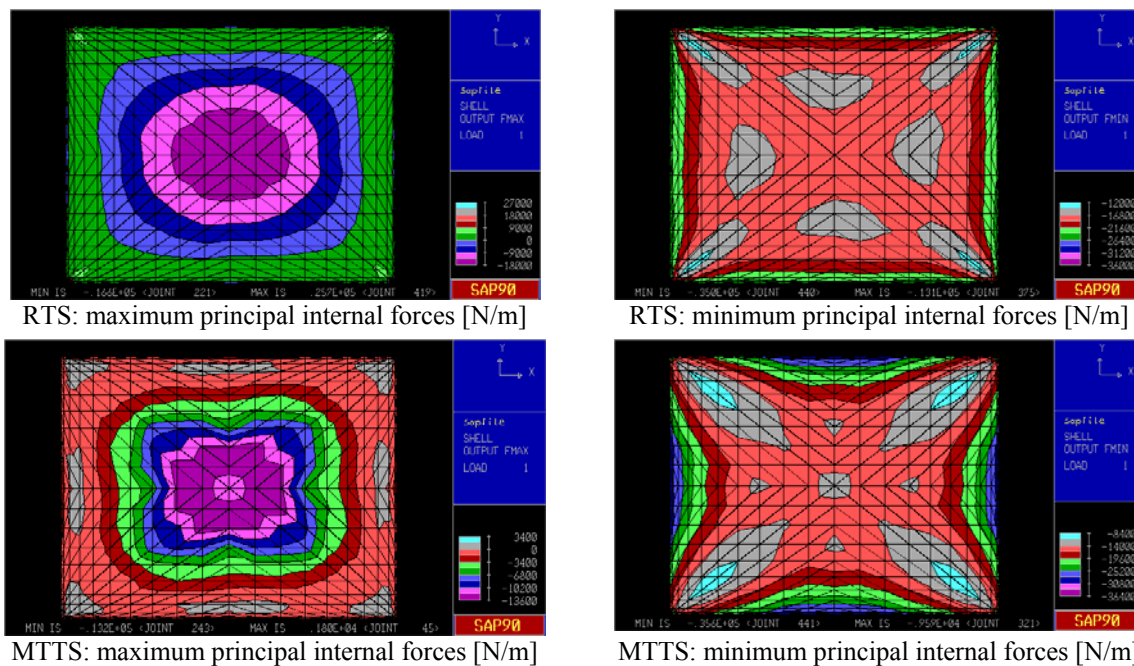


Figure 12 – Top views of the unreinforced vault subject to dead and half side live loads

The MTTs allows to point out the maximum principal stress ( $\sigma_{\max} = 7.20 \times 10^{-3}$  MPa) and the average value of the tensile principal stresses ( $\sigma_{\text{ave}} = 3.01 \times 10^{-9}$  MPa) are significantly smaller than that obtained by the RTS, and the minimum principal compressive stress given by the MTTs ( $\sigma_{\min} = -1.42 \times 10^{-1}$  MPa) remains almost unchanged in magnitude compared to that given by the RTS.

### 4.3 Dead and half side live loading

The vault is analysed under the LC<sub>St</sub> combination of the previous case, by assuming half side live loads (Figure 13).

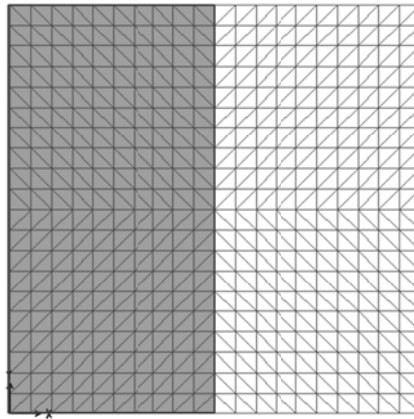


Figure 13 – Plan of the live loads (the live loads are applied on the grey surface).

The MTTs is obtained starting from the RTS (Figure 14) and the corresponding membrane stress maps are depicted in Figure 15.

The RTS gives the maximum and minimum principal stresses of  $8.08 \times 10^{-2}$  MPa and  $-1.18 \times 10^{-1}$  MPa, respectively. The corresponding average value of the tensile principal stresses of  $1.03 \times 10^{-8}$  MPa is also obtained.

The results show the maximum principal stress ( $\sigma_{\max} = 6.04 \times 10^{-3}$  MPa) and the average value of the tensile principal stresses ( $\sigma_{\text{ave}} = 2.75 \times 10^{-9}$  MPa) of MTTs, which are significantly smaller than that obtained by the RTS. The minimum principal compressive stress given by the MTTs ( $\sigma_{\min} = -1.18 \times 10^{-1}$  MPa) is almost unchanged compared to that given by the RTS.

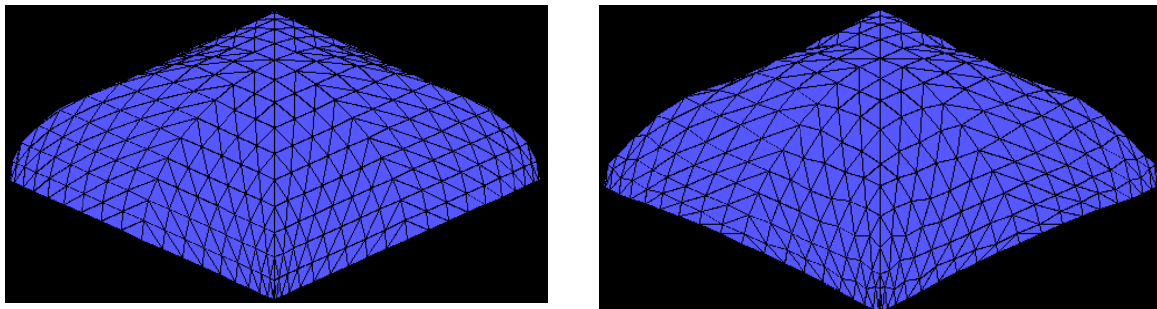


Figure 14 – RTS and MTTs configurations

### 4.4 Seismic loading and strengthening with FRCM strips

Let us examine the vault subject to the following dynamic design load combination,  $LC_{Dyn}$ :

$$LC_{Dyn} = E + G_1 + (G_{2,1} + G_{2,2}) + \psi_{2,1}Q$$

where:

- $E$  is a the load due to the seismic excitation along the X-axis of the Cartesian frame;
- $G_1$  is the dead load due to the self-weight of the vault;
- $G_{2,1}$  is the dead load due to the weight of the weight of filling material;
- $G_{2,2}$  is the dead load due to the permanent overload and it is assumed equal to 3,00 kN/m<sup>2</sup>;
- $\psi_{2,1}$  is the combination coefficient and it is assumed equal to 0,80;
- $Q$  is the live load ad it is fixed equal to 4,00 kN/m<sup>2</sup>.

The effects of the seismic excitations are modelled by means of horizontal forces according to a conventional static approach to seismic actions on the buildings (European Standard EN 1998-1) [Casapulla *et al.*, 2010, Casapulla *et al.*, 2017]. The seismic actions are set 50% of the vertical forces. The RTS and the obtained MTTs are reported in Figure 16 and the corresponding maps of the maximum and minimum internal forces are shown in Figure 17. The maximum principal stresses on the RTS and the MTTs are equal to  $\sigma_{max} = 3.50 \times 10^{-1}$  MPa and  $\sigma_{max} = 1.50 \times 10^{-1}$  MPa, respectively; the minimum principal stresses on the RTS and the MTTs are equal to  $\sigma_{min} = - 4.28 \times 10^{-1}$  MPa and  $\sigma_{min} = - 5.28 \times 10^{-1}$  MPa, respectively; and the average values of tensile principal stresses are equal to  $\sigma_{ave} = 4.00 \times 10^{-8}$  MPa and  $\sigma_{ave} = 2.65 \times 10^{-8}$  MPa, respectively. It is worth noting that, also in this simulation, a relevant reduction of the maximum tensile principal stresses (56 %) can be obtained by considering the MTTs as an alternative configuration to the RTS.

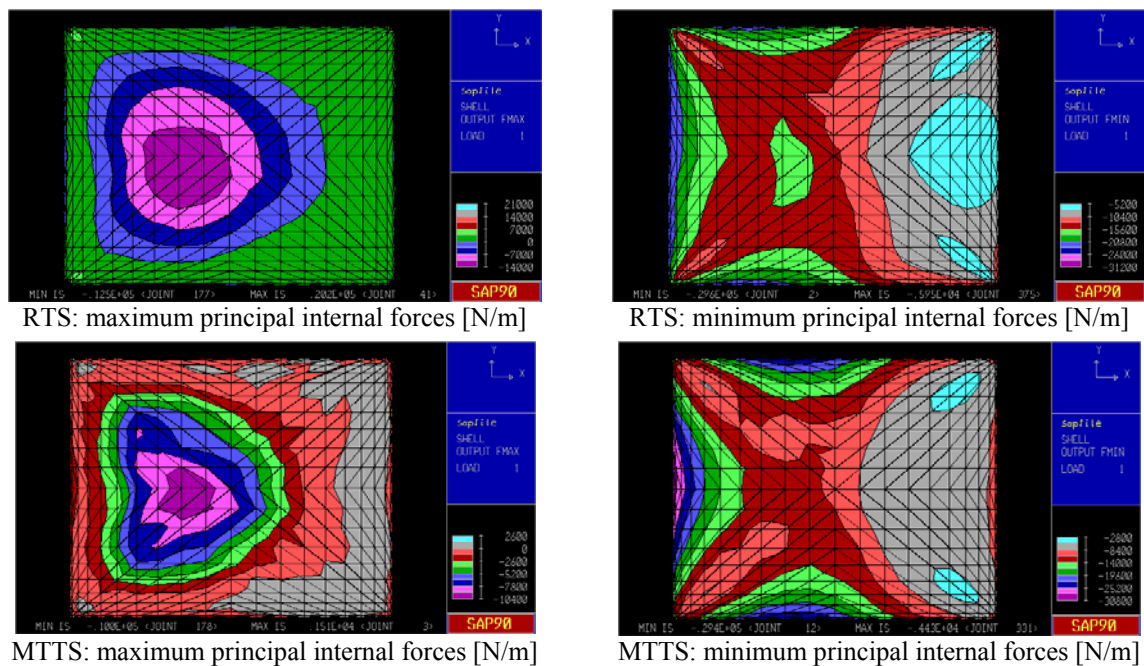


Figure 15– Top views of the unreinforced vault subject to dead and half side live loads.

The FEM analysis on the MTTs has highlight, close to the vault basis, the principal tensile stresses are comparable to the tensile strength of tuff masonry ( $1.00 \times 10^{-1}$  MPa) and the corresponding principal directions are roughly horizontal.

Therefore, a selective strengthening intervention with composite materials is proposed [Ascione and Berardi, 2011, D'Ambrisi *et al.*, 2014, Fraternali *et al.*, 2015, Fabbrocino *et al.*, 2016, Monaco *et al.*, 2017].

More specifically, commercial unidirectional FRCM strips is considered (Figure 18), whose mechanical properties are given in Table 3.

We assume to place the reinforcement at the extrados, close to the vault basis subject to principal tensile stresses comparable to the masonry tensile strength, and the fibre orientation parallel to the vault basis.

The FEM analysis on the MTTs of the reinforced vault (Figure 19) gives the maximum and minimum internal forces acting on midsurface of shell elements (Figure 20).

The corresponding maximum tensile stresses in unreinforced masonry are less than the tensile strength of tuff masonry.

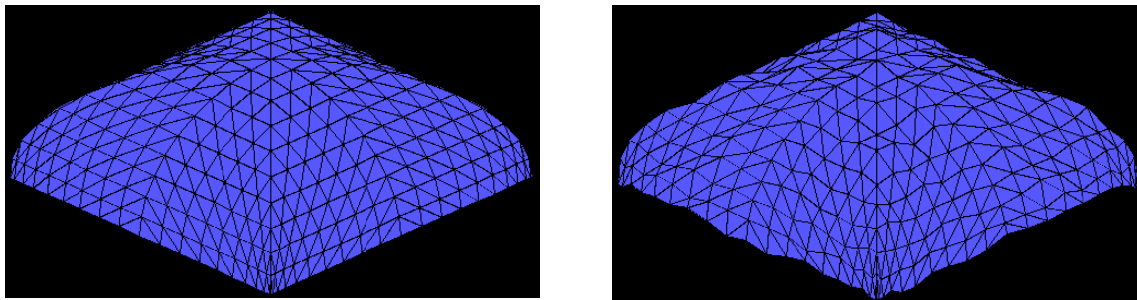


Figure 16 – RTS and MTTs configurations

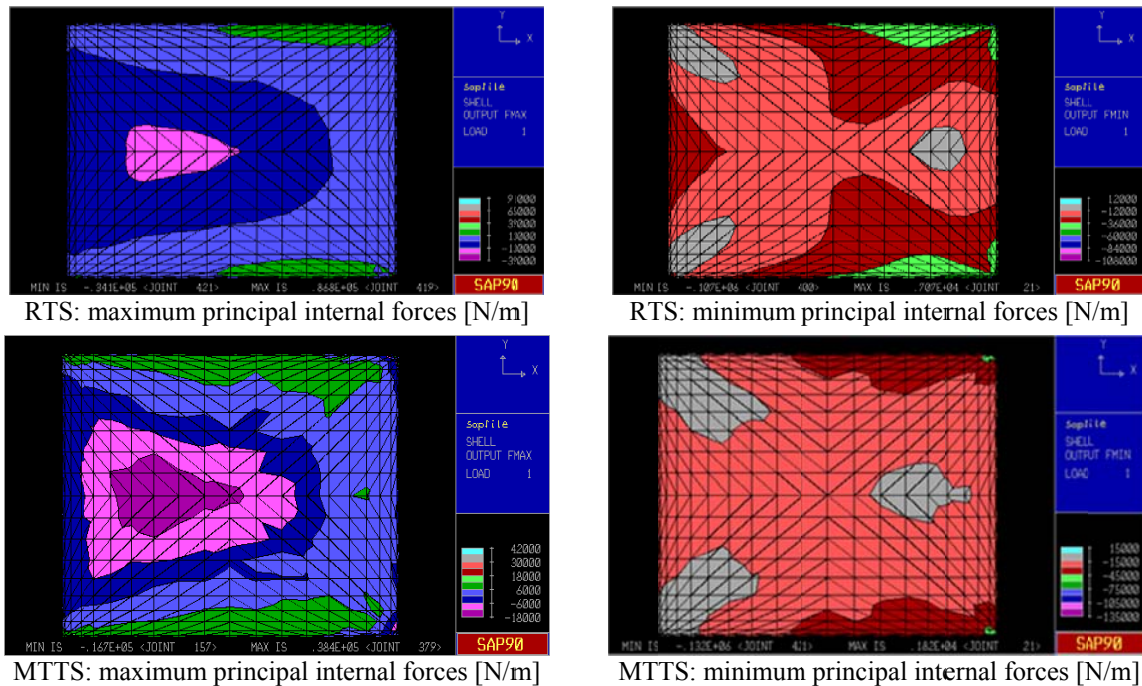


Figure 17 – Top views of the unreinforced vault subject to seismic loads

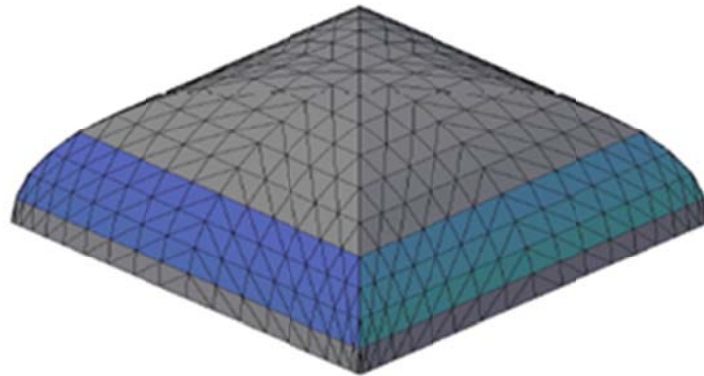


Figure 18 – 3D views of the reinforced vault (the FRCM strips are applied on the blue surface).

Table 3 - Mechanical properties of FRCM

Carbon fiber			
Tensile strength (MPa)	Young modulus (GPa)	Density (g/cm <sup>3</sup> )	Ultimate strain (%)
4800	240	1.82	13.30
Cementitious Matrix			
Compressive strength (MPa)	Flexural strength (MPa)	Young modulus (MPa)	
≥ 20.0 (after 28 d)	≥ 3.5 (after 28 d)	≥ 7000 (after 28 d)	

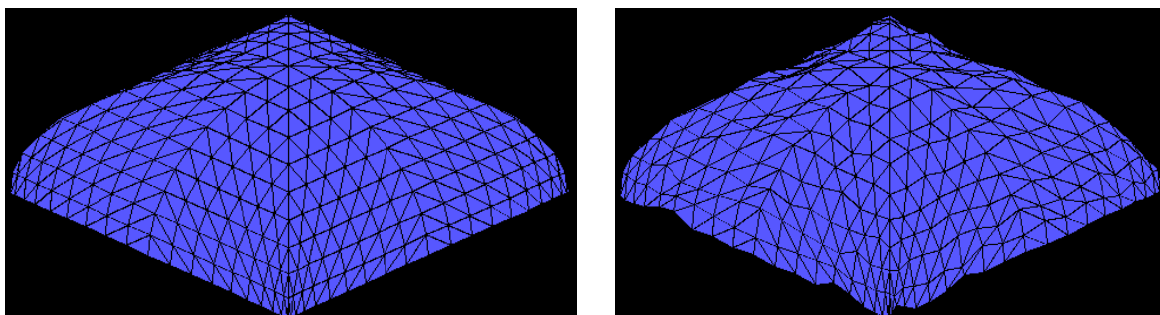
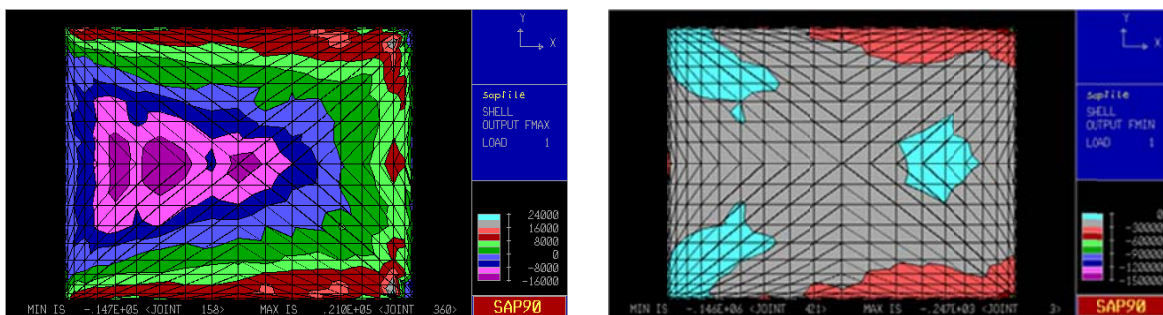


Figure 19– MTTs configuration.



MTTS: maximum principal internal forces [N/m]

MTTS: minimum principal internal forces [N/m]

Figure 20 - Top views of the reinforced vault subject to seismic loads of 'MTTS' configurations.

## 5 Concluding Remarks

An adaptive numerical method able to approach the equilibrium problem of unreinforced and reinforced masonry vaults has been shown. This procedure allows to approximate the no-tension membrane (thrust surface) behaviour of masonry through an elastic analysis of the masonry referred to a Minimum Tension Thrust Surface. Such a surface is obtained via a r-adaptive finite element featuring linearly elastic shell elements with dominant membrane behaviour. The moving of the FEM nodes is governed by a Breeder Genetic Algorithm within a design domain and minimizing the average value of the principal tensile stresses in unreinforced masonry. The advanced numerical model has been validated against a case study of a vault available in literature. A cloister vault subject to several load combinations, both static and dynamic, has been studied in depth. The proposed model applied on the Minimum Tension Thrust Surface has given tensile stresses significantly smaller than that obtained by means of the FEM analysis on the midsurface of the vault. The model has been also utilized to design and verify a FRCM reinforcement, required within the dynamic load combination. The proposed approach may represent a useful tool to evaluate the vulnerability of existing curved masonry structures and to design optimal reinforcement patterns [Fraternali *et al.*, 2015, Fabbrocino *et al.*, 2016, Berardi *et al.*, 2017 (1,2,3)]. We address generalizations of the proposed model accounting for a limit state analysis with finite friction [D'Ayala and Tomasoni, 2009], and the dynamic response of masonry vaults under seismic excitations to future work.

## References

- Ascione, L., and Berardi, V. P. (2011). Anchorage device for FRP laminates in the strengthening of concrete structures close to beam-column joints. *Composites Part B: Engineering* **42**, 1840-1850.
- Ascione, L., Berardi, V. P., Giordano, A., Spadea, S. (2013). Buckling failure modes of FRP thin-walled beams. *Composites Part B: Engineering* **47**, 357-364.
- Ascione, L., Berardi, V. P., Giordano, A., Spadea, S. (2015). Pre-buckling imperfection sensitivity of pultruded FRP profiles. *Composites Part B: Engineering* **72**, 206-212.
- Benzoni, G., and Casarotti, C., (2009). Effects of Vertical Load, strain rate and cycling on the response of lead-rubber seismic isolators. *Ingegneria Sismica – International Journal of Earthquake Engineering* XIII(3), 293-312.
- Berardi, V. P., Chiozzi, A., Fraternali, F., Grillanda, N., De Piano, M., Milani, G., Tralli, A. (2017). A numerical approach to the evaluation of collapse load multiplier of masonry curved structures, Proc. Aimeta 2017, XXIII Conference of the Italian Association of Theoretical and Applied Mechanics **3**,1515-1525, Salerno, 4-7 September 2107, Italy.
- Berardi, V. P., De Piano, M., Teodosio, G., Penna, R., Feo, L. (2017). Adaptive models of no-tension masonry vaults, Proc. Aimeta 2017, XXIII Conference of the Italian Association of Theoretical and Applied Mechanics **3**, 1402-1414 Salerno, 4-7 September 2107, Italy.
- Berardi, V. P., De Piano, M., Teodosio, G., Penna, R., Feo, L. (2017). Advanced numerical models for the analysis of unreinforced and strengthened masonry vaults, Proc. Compdyn 2017, 6th Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering **2**,5056-5069 ,Rhodes Island, June 15-17 2017, Greece.
- Block, P., and Lachauer, L. (2014). Three-dimensional funicular analysis of masonry vaults. *Mechanics Research Communications* **56**, 53-60.

- Carpentieri, G., Fabbrocino, F., De Piano, M., Berardi, V. P., Feo, L., Fraternali, F. (2016). Minimal mass design of strengthening techniques for planar and curved masonry structures, Proc. Of the 7th European Congress on Computational Methods in Applied Sciences and Engineering **4654**, 1-10 Crete 5-10 June 2016, Greece.
- Carpentieri, G., Skelton, R. E. (2017). On the minimal mass design of composite membranes. Composites Part B: Engineering **115**, 244-256.
- Casapulla, C., Jossa, P., Maione, A. (2010). Rocking motion of a masonry rigid block under seismic actions: A new strategy based on the progressive correction of the resonance response | [Il moto sotto sisma del blocco murario: Analisi per progressiva correzione della risposta in risonanza]. Ingegneria Sismica - International Journal of Earthquake Engineering, XXVII(4):35-48.
- Casapulla, C., Maione, A., Argiento, L. U. (2017). Seismic analysis of an existing masonry building according to the multi-level approach of the Italian guidelines on cultural heritage. Ingegneria Sismica - International Journal of Earthquake Engineering, XXXIV(1):40-59.
- Cattari, S., Abbati, S.D., Ferretti, D., Lagomarsino, S., Ottonelli, D., Tralli, A. (2012). The seismic behaviour of ancient masonry buildings after the earthquake in Emilia (Italy) on May 20th and 29th, 2012 | [La risposta delle costruzioni in muratura a seguito delle scosse del 20 e 29 Maggio 2012 in Emilia]. Ingegneria Sismica - International Journal of Earthquake Engineering, XXIX(2-3):87-119.
- Chapman, C. D., Saitou, K., Jakiela, M. J. (1994). Genetic algorithms as an approach to configuration and topology design. Journal Mechanical Design **116**, 1005-1012.
- D'Ayala D., F., and Tomasoni E. (2008). The structural behaviour of masonry vaults: Limit analysis with finite friction. Proc. Of the 6th International Conference on Structural Analysis of Historic Construction, I: 47-61, 2-4 July 2008, Bath, United Kingdom.
- D'Ambrisi, A., Mezzi, M., Feo, L., & Berardi, V. P. (2014). Analysis of masonry structures strengthened with polymeric net reinforced cementitious matrix materials. Composite Structures, **113**(1), 264-271.
- Daraio, C., Ngo, D., Nesterenko, V. F., Fraternali, F. (2010). Highly Nonlinear Pulse Splitting and Recombination in a Two Dimensional Granular Network. Physical Review E **82**, 036603.
- De Falco, I., Del Balio, R., Della Cioppa, A., Tarantino, E. (1996). A comparative analysis of evolutionary algorithms for function optimisation, Proc. Of 2th Workshop on Evolutionary Computation, 29-26, Nagoya 11-22 March 1996, Japan.
- De Jong, K. (2007). Evolutionary computation: a unified approach, Proc. of the Genetic and Evolutionary Computation Conference, London 7-11 July, United Kingdom.
- Fabbrocino F., Farina I., V. P., Berardi, A. J. M., Ferreira, Fraternali, F. (2015). On the thrust surface of unreinforced and FRP-/FRCM-reinforced masonry domes. Composite. Part B Engineering **83**, 297-305.
- Fabbrocino, F., Amendola, A., Benzoni, G., Fraternali, F. (2016). Seismic application of pentamode lattices. Ingegneria Sismica-International Journal of Earthquake Engineering **1-2**, 62-71.
- Fortunato, A., Fraternali, F., Angelillo M. (2014). Structural capacity of masonry walls under horizontal loads. Ingegneria Sismica - International Journal of Earthquake Engineering XXXI(1):41-51.
- Fraternali, F. (2010). A thrust network approach to the equilibrium problem of unreinforced masonry vaults via polyhedral stress functions. Mechanics Research Communications **37**, 198-204.
- Fraternali, F. (2011). A mixed lumped stress-displacement approach to the elastic problem of masonry walls. Mechanics Research Communications **38**, 176-180.
- Fraternali, F., and Bilotti, G. (1997). Non-Linear Elastic Stress Analysis in Curved Composite Beams. Computers & Structures **62**, 837-869.

- Fraternali, F., and Reddy, J.N. (1993). A Penalty Model for the Analysis of Laminated Composite Shells. *International Journal of Solids and Structures* **30**, 3337-3355.
- Fraternali, F., Carpentieri, G., Modano, M., Fabbrocino, F., Skelton, R.E. (2015). A tensegrity approach to the optimal reinforcement of masonry domes and vaults through fiber-reinforced composite materials. *Composite Structures* **134**, 247-254.
- Fraternali, F., Marino, A., Elsayed, T., Della Cioppa, A. (2011). On the structural shape optimization via variational methods and evolutionary algorithms. *Mechanics of Advanced Materials And Structures* **18**, 225-243.
- Golberg, D. E., Samtani, M. P. (1986). Engineering optimization via genetic algorithm, Proc. Of the 9th Conference Electronic Computation, University of Alabama, Birmingham., February 23-26 1986, United States.
- Heyman, J. (1995). *The stone skeleton*. New York: Cambridge University Press.
- Jenkins W. M (1992). Plane frame optimum design environment based on genetic algorithm. *Journal of Structural Engineering*, ASCE 118.
- Kelly, J. M. (1993). *Earthquake-resistant design with rubber*. London: Springer-Verlag.
- Leonard, A., Fraternali, F., Daraio, C. (2013). Directional wave propagation in a highly nonlinear square packing of spheres. *Experimental Mechanics* **53**(3), 327-337.
- Magenes, G. (2006) Masonry building design in seismic areas: recent experiences and prospects from a European standpoint, Proc. Of the 1st European Conference on Earthquake Engineering and Seismology, Geneva, September 3-8 2006, Switzerland.
- Mancusi, G., Fabbrocino, F., Feo, L., Fraternali, F. (2017) Size effect and dynamic properties of 2D lattice materials. *Composites Part B: Engineering* **112**, 235-242.
- Mitchell, M., and Forrest S. (1944). Genetic algorithms and artificial life. *Artificial life Journal* **1**, 267-289.
- Monaco, A., Minafò, G., Cucchiara, C., D'Anna, J., La Mendola, L. (2017). Finite element analysis of the out-of-plane behavior of FRP strengthened masonry panels. *Composites Part B: Engineering* **115**, 188-202.
- Mühlenbein, H., Schomisch, M., Born, J. (1999). The parallel genetic algorithm as function optimizer. *Parallel Computing* **17**, 619-632.
- Ngo, D., Fraternali, F., Daraio, C. (2012). Highly Nonlinear Solitary Wave Propagation in Y-Shaped Granular Crystals with Variable Branch Angles. *Physical Review E* **85**, 036602-1-10.
- Palermo, A., Krödel, S., Marzani, A., Daraio, C. (2016). Engineered metabarrier as shield from seismic surface waves, *Scientific Reports* **6**.
- Pugi, F., and Galassi, S. (2013). Seismic analysis of masonry voussoir arches according to the Italian building code [Analisi sismica di archi a conci in muratura secondo la normativa Italiana]. *Ingegneria Sismica - International Journal of Earthquake Engineering*, XXX(3):33-55.
- Saisi, A., Gentile, C., Guidobaldi, M. (2014). Dynamic and seismic health monitoring of a historic masonry tower. *Ingegneria Sismica - International Journal of Earthquake Engineering*, XXXI(3).
- Skinner, R. I., Robinson, W. H., Mcverry, G. H. (1993). *An introduction to seismic isolation*. Wiley.
- Yan, Y., Laskar, A., Cheng, Z., Menq, F., Tang, Y., Mo Y. L., Shi, Z. (2014). Periodic Materials-Based 3-D Seismic Base Isolators for Nuclear Power Plants. Proc. Of ASME Pressure Vessels and Piping Conference. In: *Seismic Engineering* **8**:V008T08A00, Anaheim, July 20-24 2014, California.



## UN APPROCCIO NUMERICO ALLA MODELLAZIONE MECCANICA DI VOLTE MURARIE SOTTO AZIONI SISMICHE

Mariella De Piano<sup>1</sup>, Mariano Modano<sup>2</sup>, Gianmario Benzoni<sup>3</sup>, Valentino Paolo Berardi<sup>1</sup>,  
Fernando Fraternali<sup>1</sup>

<sup>1</sup>Department of Civil Engineering, University of Salerno, Fisciano (SA), Italy

<sup>2</sup>Department of Structures for Engineering and Architecture, University of Naples Federico II,  
Italy

<sup>3</sup>Department of Structural Engineering, University of California San Diego, CA, USA

**SUMMARY:** *Il patrimonio storico-artistico nazionale ed internazionale è costituito da un numero rilevante di edifici in muratura, che testimoniano l'evoluzione dell'arte del costruire nelle diverse epoche storiche. La tutela e la salvaguardia di detti manufatti costituisce una priorità improcrastinabile, in particolare nei confronti delle azioni sismiche.*

*La ricerca scientifica ha pertanto focalizzato la propria attenzione sulla formulazione di modelli meccanici affidabili per la verifica della vulnerabilità sismica delle membrature murarie. Numerosi studi disponibili in letteratura sono fondati sull'analisi limite "no-tension" alla Heyman (1995), che consente di pervenire alla determinazione di un moltiplicatore di collasso della struttura, a fronte, tuttavia, di un onere computazionale che talvolta può essere oneroso, in particolare per geometrie curve, e di una difficile interfaccia di tale metodo con i codici di calcolo agli elementi finiti attualmente disponibili in commercio.*

*In tale contesto si inquadra il presente lavoro, che intende illustrare un approccio numerico adattativo per l'analisi della risposta sismica di volte in muratura rinforzate e non.*

*Il metodo proposto fa uso del teorema statico dell'analisi alla Heyman, fornendo un'utile estensione del concetto di poligono funicolare degli archi al caso tridimensionale delle volte. Nel dettaglio, la superficie delle pressioni, intesa come superficie sulla quale sono mobilitati sforzi membranali di sola compressione che resistono ai carichi esterni, è ricercata, per via iterativa, mediante un codice agli elementi finiti di tipo adattativo, governato da un algoritmo genetico, che è in grado di variare le posizioni dei nodi della superficie membranale resistente nello spazio contenuto tra l'intradosso e l'estradosso della struttura.*

*L'approccio presentato può essere impiegato sia per la verifica della vulnerabilità sismica di volte esistenti, che per la progettazione di interventi di consolidamento strutturale, a fronte di tempi ridotti di analisi, consentendo un'agevole integrazione nei codici di calcolo agli elementi finiti di tipo commerciale. Esso è stato validato nei confronti di diversi esempi notevoli, prestando particolare attenzione a problemi strutturali di volte sollecitate da carichi verticali e forze sismiche equivalenti, in presenza o meno di rinforzi con malte cementizie fibrorinforzate, nello spirito delle norme tecniche vigenti.*

**KEYWORDS:** *Strutture murarie, Strutture voltate, Algoritmi genetici, Metodi agli elementi finiti adattativi, Consolidamento strutturale.*