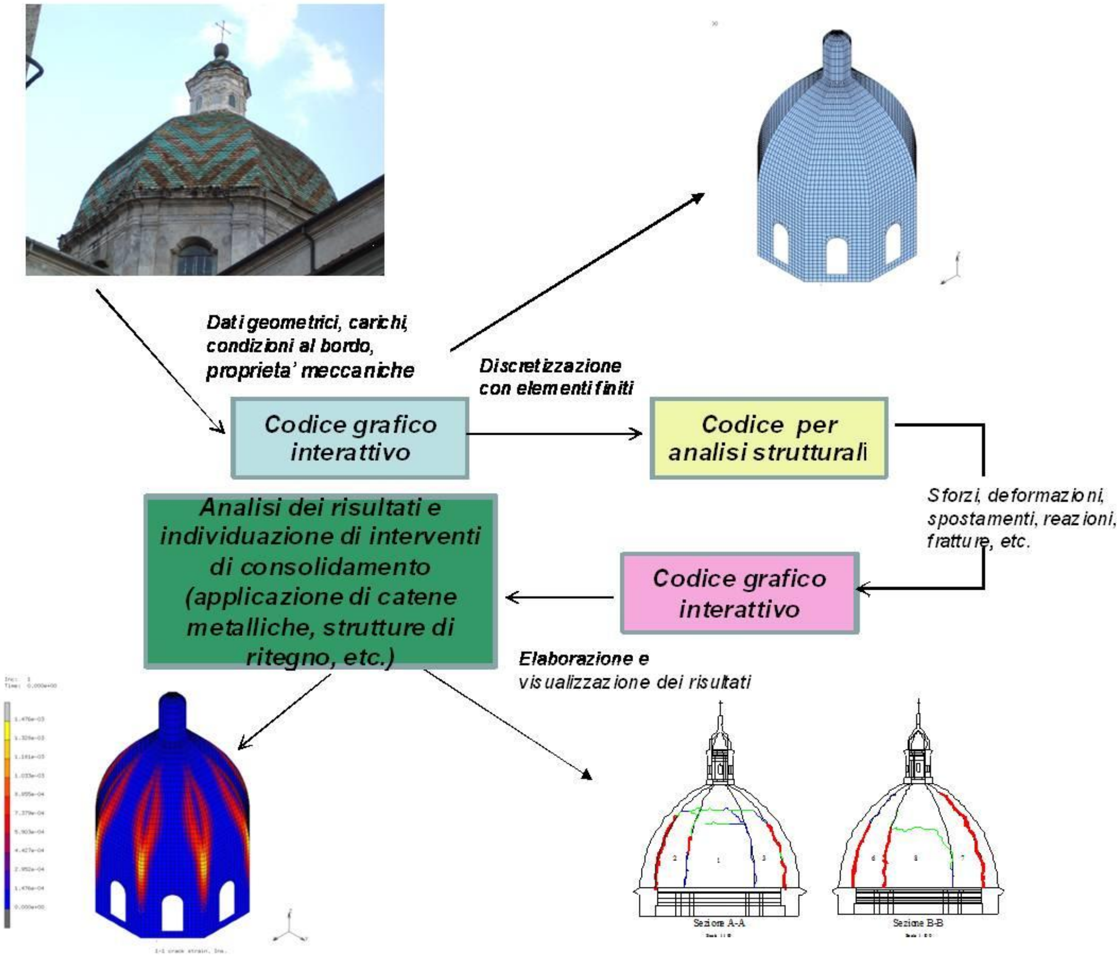
# *The NOSA-ITACA code for modelling and assessing the structural behaviour of ancient constructions*

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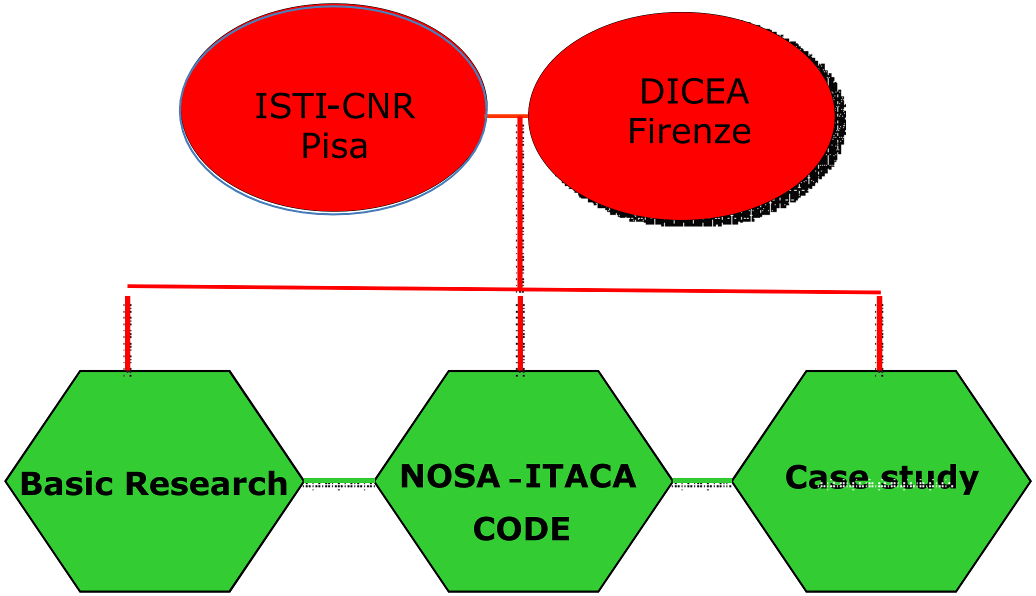
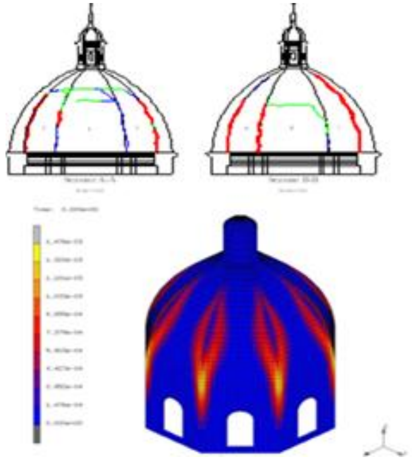
# The NOSA-ITACA project
# 2011-2013

## funded by the Region of Tuscany (PAR-FAS 2007-2013)

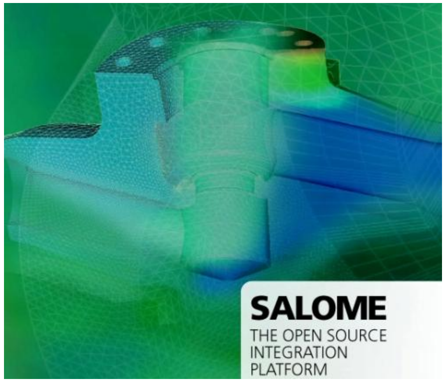


# The NOSA-ITACA project

**NOSA CODE: f.e.m. nonlinear solver**



**SALOME: pre-post processor**




**Case study: "Voltone", Livorno**

**NOSA-ITACA code**

Municipalities

Monuments and Fine Arts Offices

Professional offices

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•The NOSA-ITACA code is a finite element software for nonlinear analyses.

•Masonry is modelled by a nonlinear isotropic elastic material with zero tensile strength and limited compressive strength (masonry-like or no-tension material). [G. Del Piero, *Meccanica* 1989; S. Di Pasquale, *Meccanica* 1992; M. Lucchesi, C. Padovani et al., *Masonry Constructions and Numerical Applications,* Springer 2008].

- Static analyses
- Dynamic analyses
- Thermo-mechanical analyses
- Modal analyses

→

- Stress fields
- Collapse loads
- Elastic, fracture and crushing strain fields
- Displacement fields
- Time- histories
- Eigenvalues and eigenvectors

- NOSA-ITACA library: beam, truss, shell, 2D, 3D elements (35 elements)

The NOSA-ITACA version will be freely downloadable by
http://www.nosaitaca.it/it/software/

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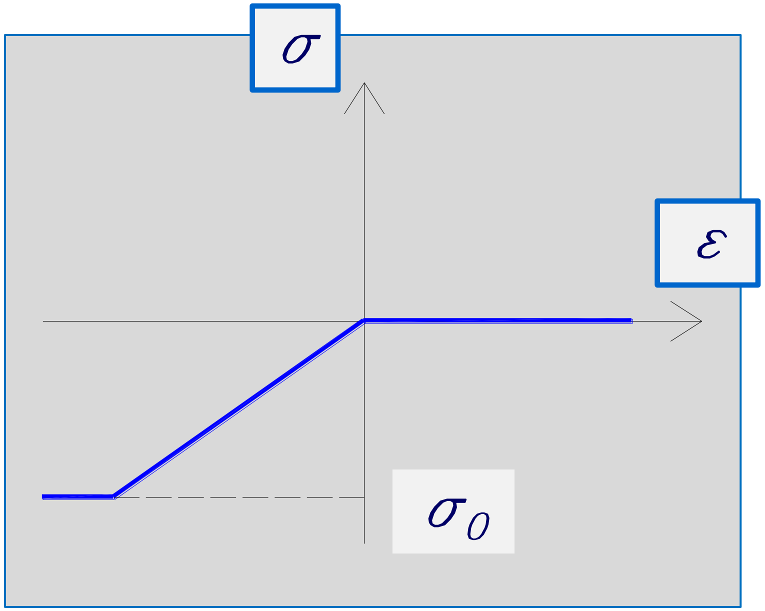
A previous version of the code (COMES-NOSA) is already downloadable.

| | |
|---|---|
| $\boldsymbol{E}$ | the infinitesimal strain tensor, |
| $\boldsymbol{T}$ | the Cauchy stress tensor, |
| $\boldsymbol{E}^e$ | the elastic part of the strain, |
| $\boldsymbol{E}^f$ | the fracture strain, |
| $\boldsymbol{E}^c$ | the crushing strain, |
| $\mathrm{E}, \nu$ | the modulus of elasticity and the Poisson's ratio, |
| $\sigma_0 < 0$ | the masonry maximum compressive stress. |




**Given $\boldsymbol{E}$, find $\boldsymbol{E}^f$, $\boldsymbol{E}^c$, $\boldsymbol{T}$ such that**

$$\boldsymbol{E} = \boldsymbol{E}^e + \boldsymbol{E}^f + \boldsymbol{E}^c,$$

$$\boldsymbol{E}^f \cdot \boldsymbol{E}^c = 0,$$

$$\boldsymbol{T} = \frac{\mathrm{E}}{1+\nu}\left[\boldsymbol{E}^e + \frac{\nu}{1-2\nu}\, tr(\boldsymbol{E}^e)\boldsymbol{I}\right],$$

$$\boldsymbol{T} \cdot \boldsymbol{E}^f = \left(\boldsymbol{T} - \sigma_0 \boldsymbol{I}\right) \cdot \boldsymbol{E}^c = 0,$$

$$\boldsymbol{T}, \boldsymbol{E}^c \le 0, \quad \boldsymbol{T} - \sigma_0 \boldsymbol{I} \ge 0, \quad \boldsymbol{E}^f \ge 0$$

$$\Rightarrow \quad \boldsymbol{T} = \hat{\boldsymbol{T}}(\boldsymbol{E}), \quad \mathrm{D}_{\boldsymbol{E}}\hat{\boldsymbol{T}}(\boldsymbol{E})$$

## Some example 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
- 2005 Chiesa di San Ponziano, Lucca
- 2008 Chiesa Abbaziale di Santa Maria della Roccella, Roccella Ionica
- 2008 Torre "Rognosa" , San Gimignano
- 2010 Torre "delle Ore", Lucca
- 2013 "Voltone" di Piazza della Repubblica, Livorno
- 2013 Chiesa Di San Francesco, Lucca

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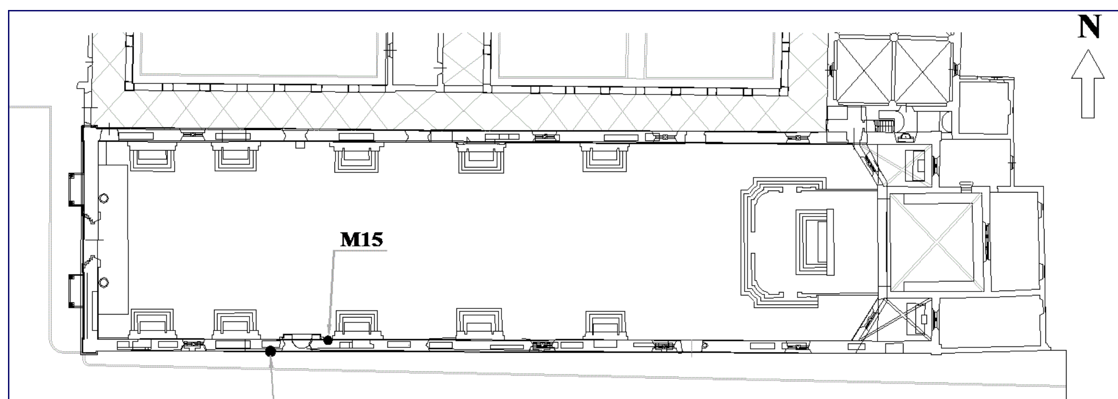
Fondazione Cassa di Risparmio di Lucca

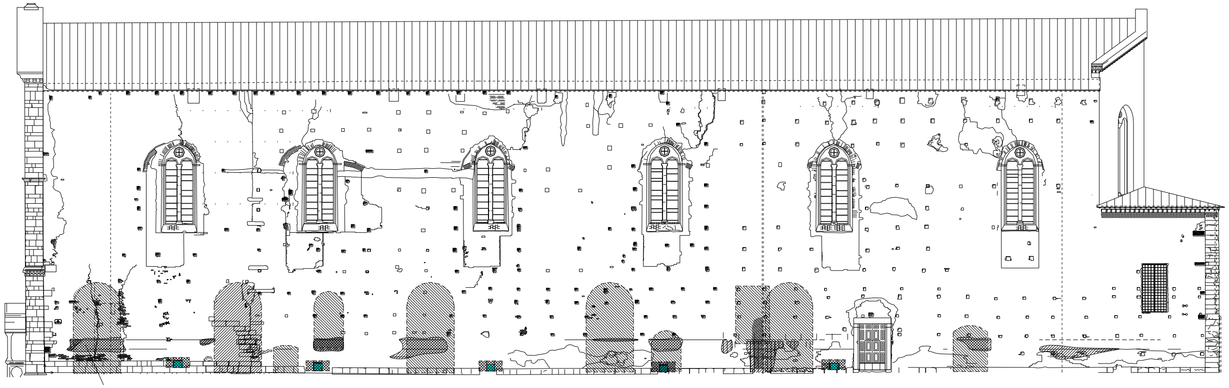
# The Church of San Francesco



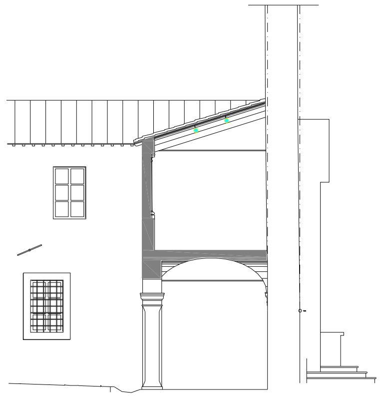
# The Church of San Francesco: reinforcement operations

Fondazione Cassa di Risparmio di Lucca

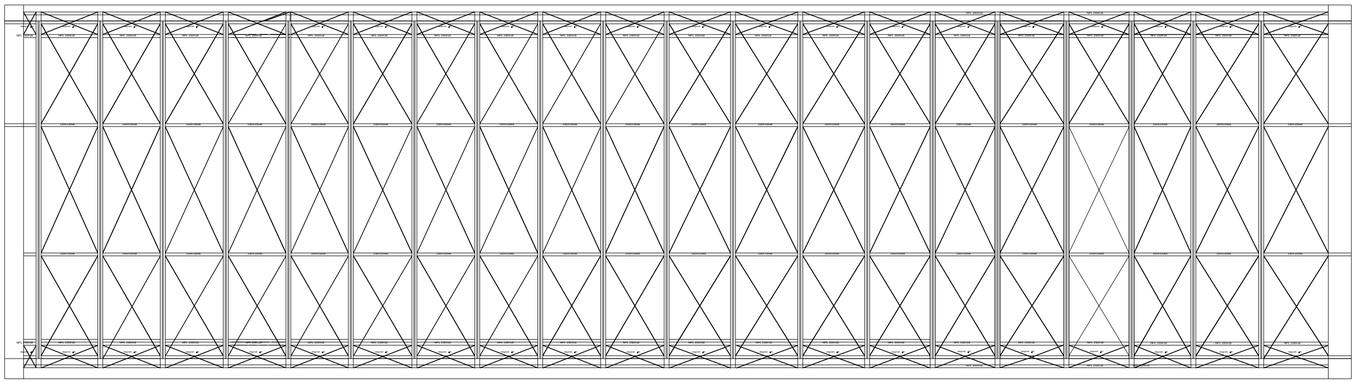
## On masonry



## On the cloister



## On the roof



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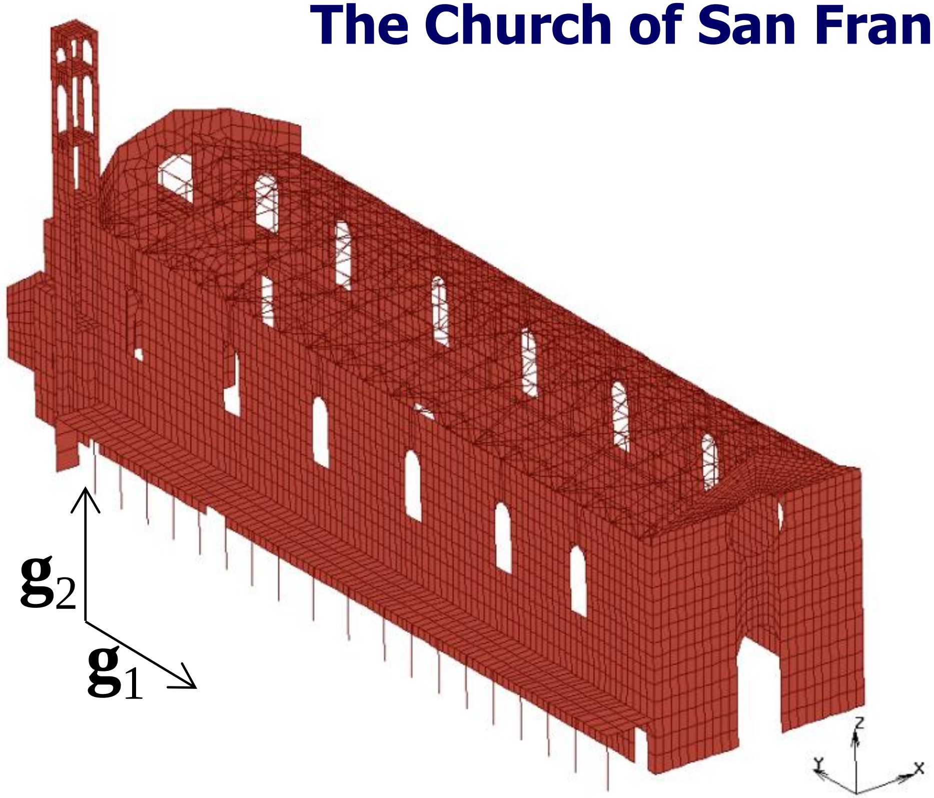
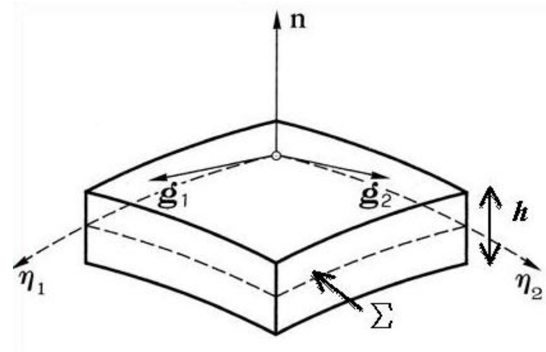
# The Church of San Francesco: The finite element mesh



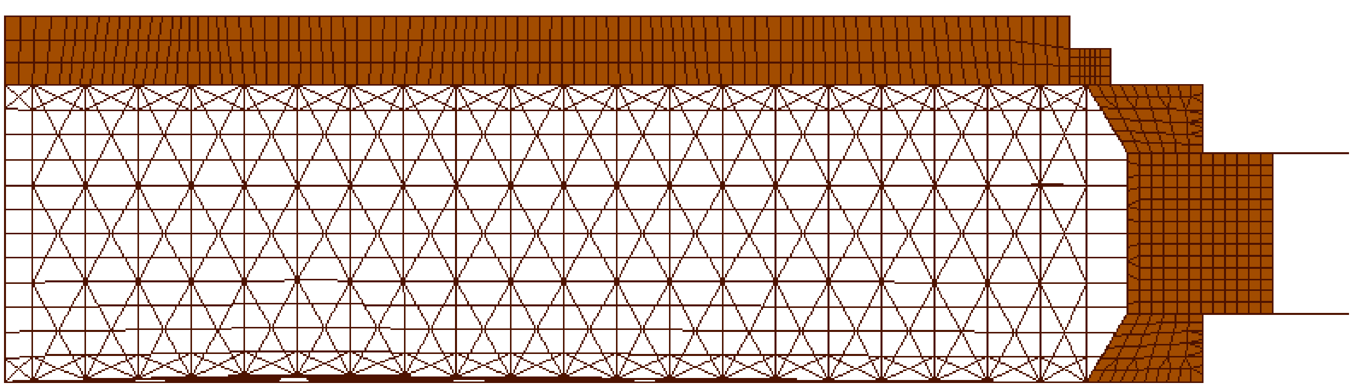

$$\Sigma_\zeta = \{\mathbf{p}' \mid \mathbf{p}' = \mathbf{p} + \zeta\mathbf{n},\ \mathbf{p} \in \Sigma,\ \mathbf{n} = \mathbf{n}(\mathbf{p})\},$$

$$\zeta \in [-h/2, h/2].$$

Stresses $$T_{11} = \mathbf{g}_1 \cdot \mathbf{T}\mathbf{g}_1, \qquad T_{22} = \mathbf{g}_2 \cdot \mathbf{T}\mathbf{g}_2,$$

Normal forces $$N_{11} = \int_{-h/2}^{h/2} T_{11}\, d\zeta, \qquad N_{22} = \int_{-h/2}^{h/2} T_{22}\, d\zeta$$

Bending moments $$M_{11} = \int_{-h/2}^{h/2} T_{11}\zeta\, d\zeta, \quad M_{22} = \int_{-h/2}^{h/2} T_{22}\zeta\, d\zeta.$$



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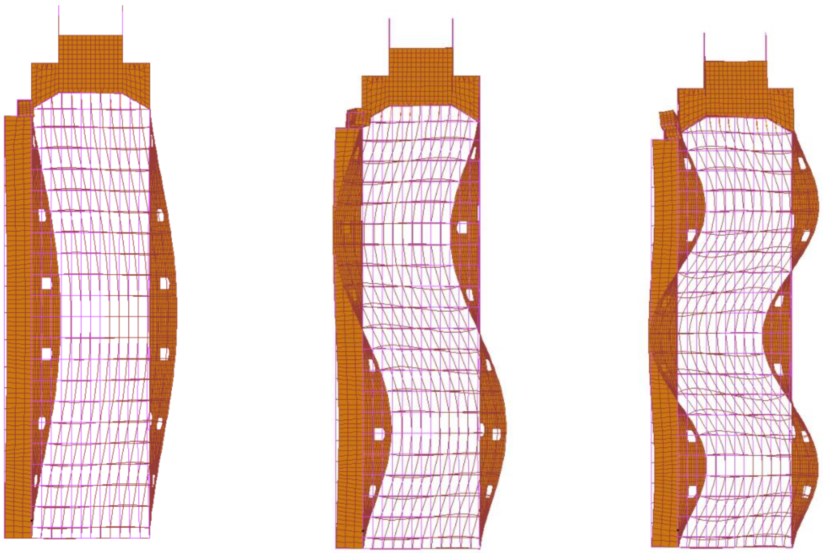
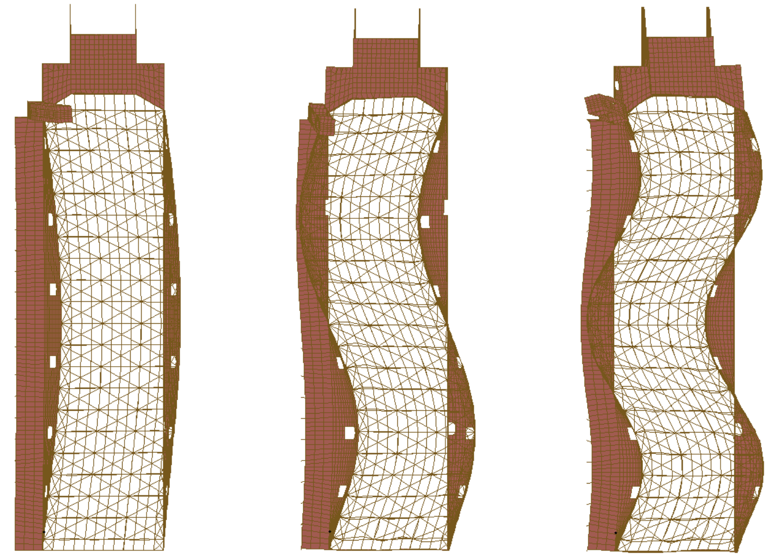
# The Church of San Francesco: modal analyses

## Without reinforcing

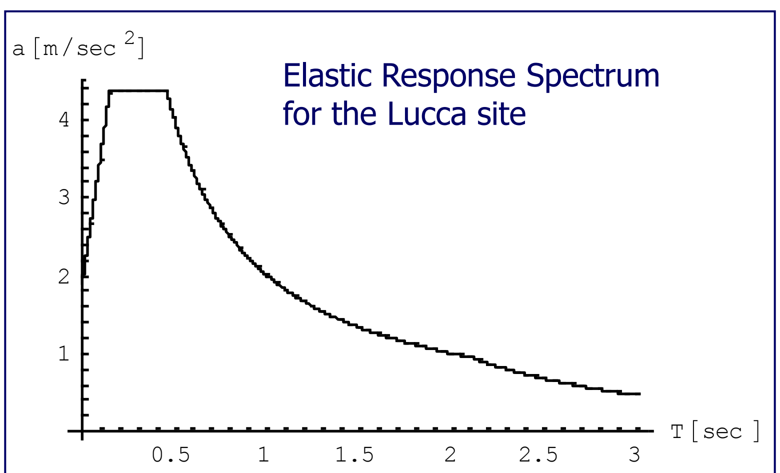


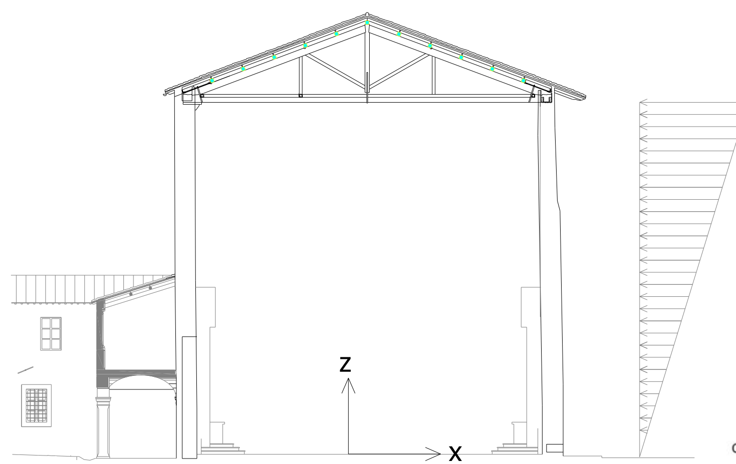
T1=1,26 s

## With reinforcing



T1r=1,04 s

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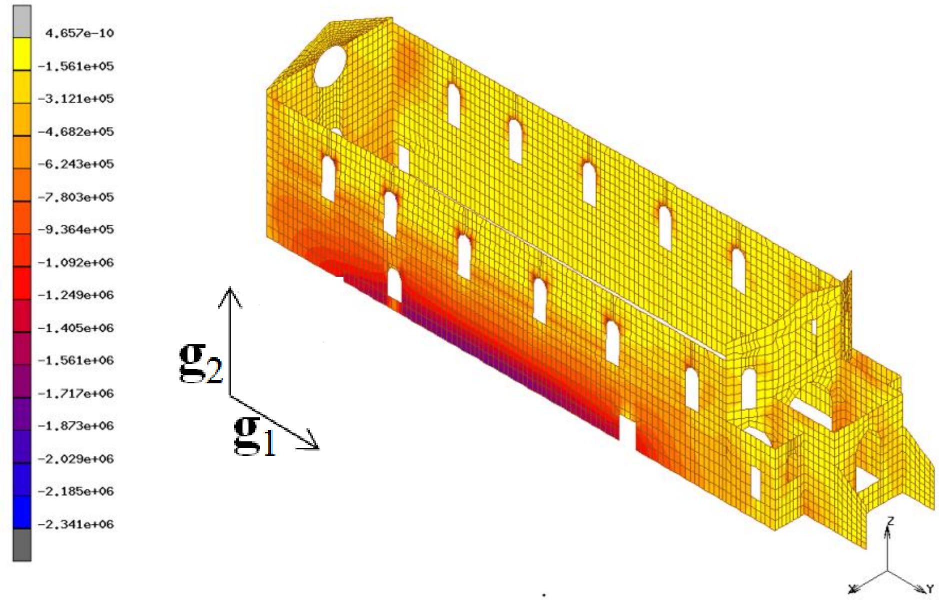
## The Church of San Francesco: evaluation of the seismic vulnerability

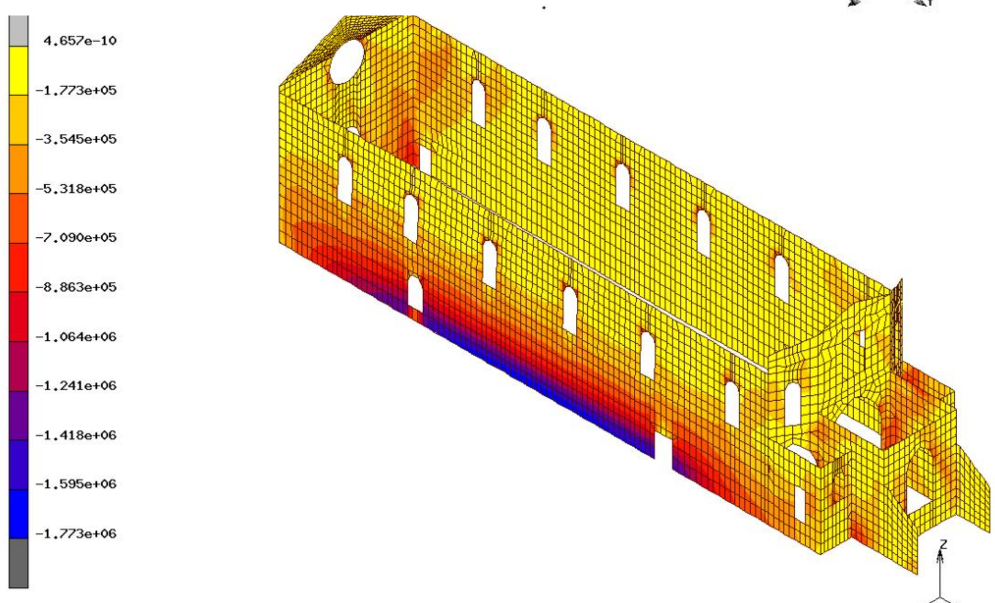
Without reinforcing

$H_U$=4,1% Weigth




Stresses $T_{22}$

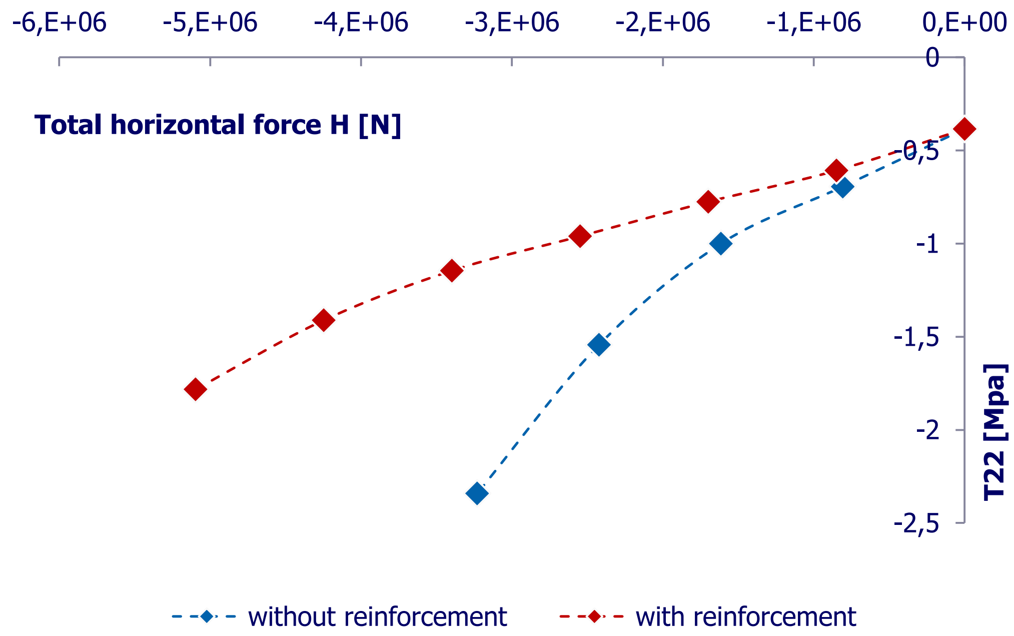
SLV




With reinforcing

$H_U$=6,5% Weigth

## The Church of San Francesco: evolution of the maximum values of normal stresses



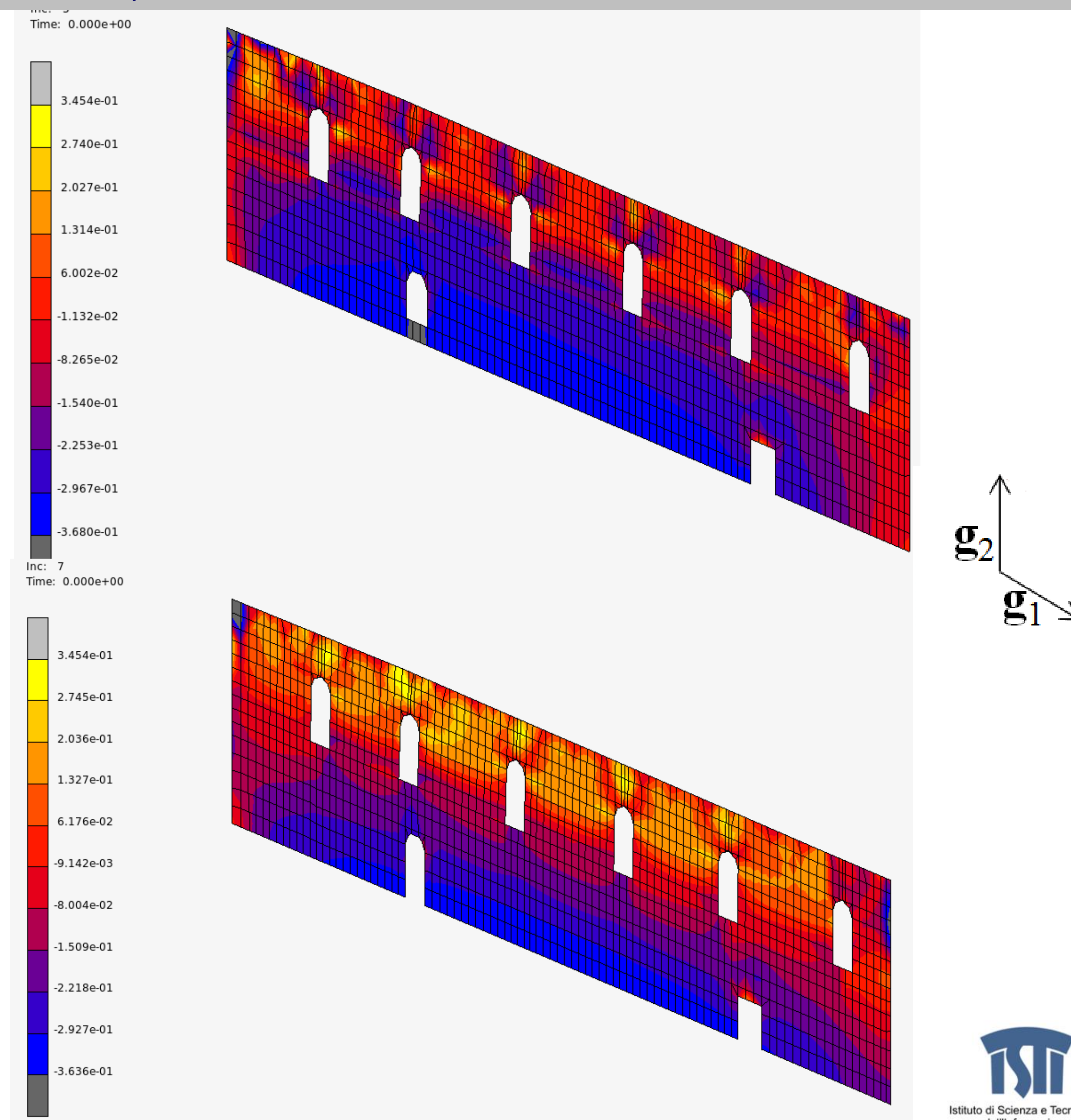
# Eccentricities $e_{22}$

# SLV

Without reinforcing

$e_{22} = M_{22}/N_{22}$

With reinforcing

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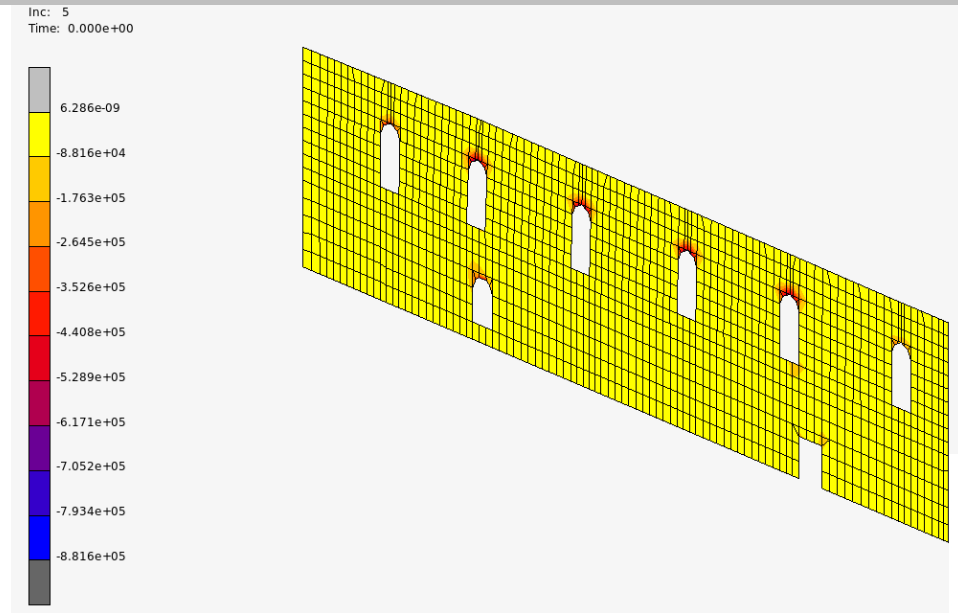
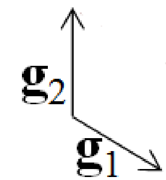
# Stresses $T_{11}$

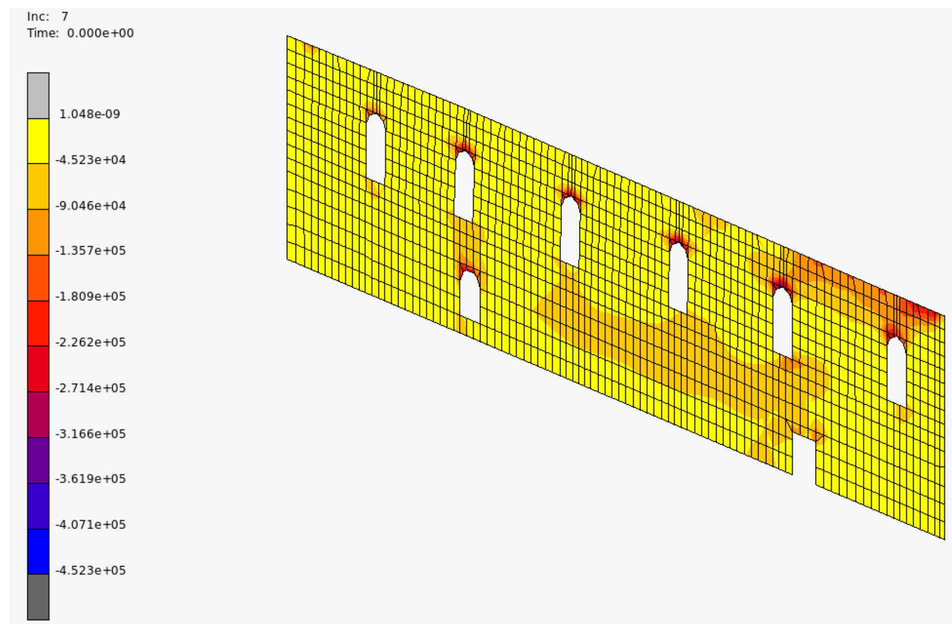
SLV

Without reinforcing




With reinforcing

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# The Church of San Francesco: evaluation of the seismic vulnerability

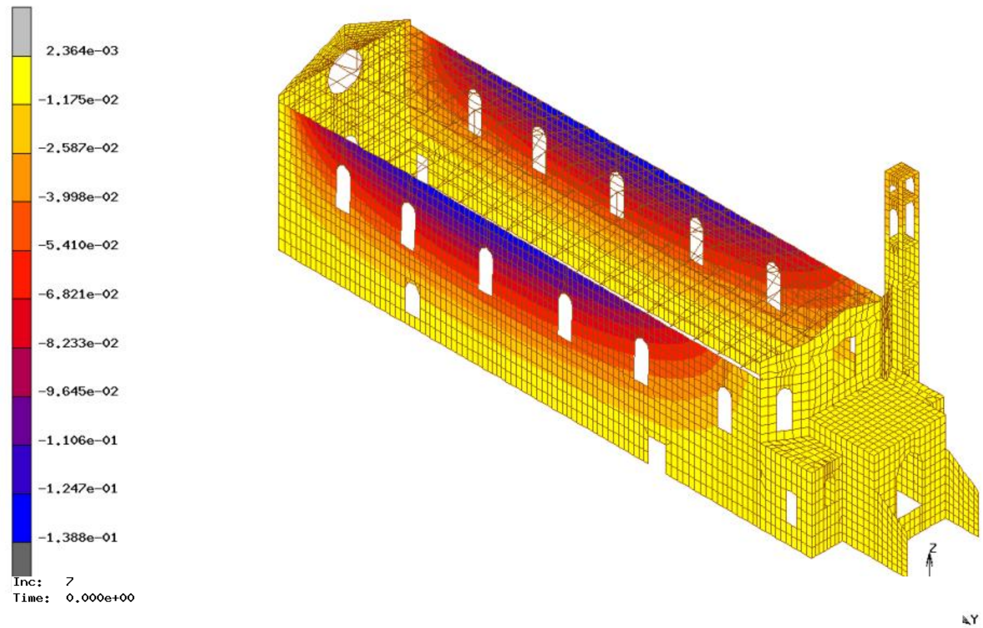
Displacements $u_x$

SLV

Without reinforcing

$H_U$=4,1% Weigth

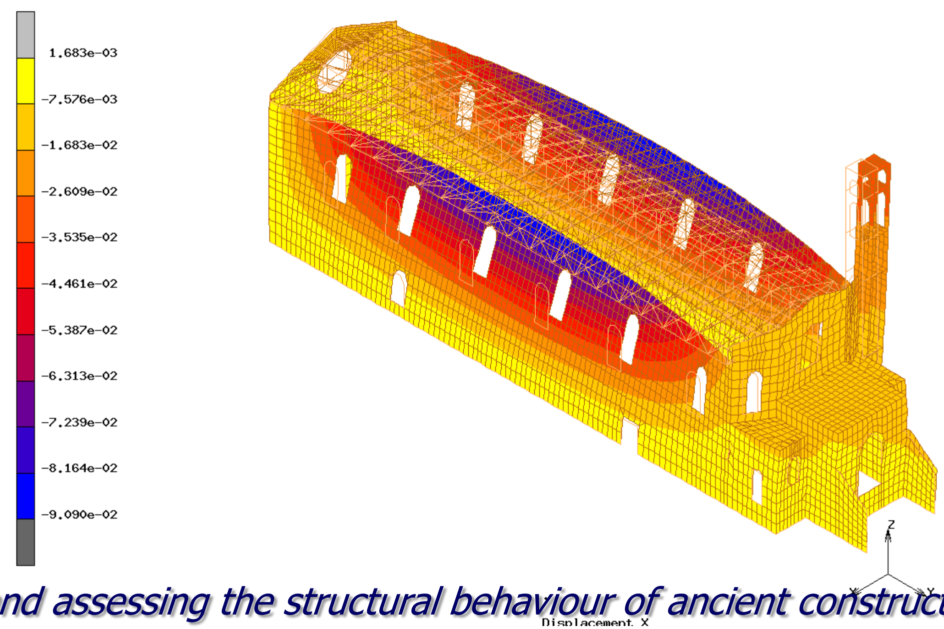
$U_{xmax}/h$= 0,0078




With reinforcing

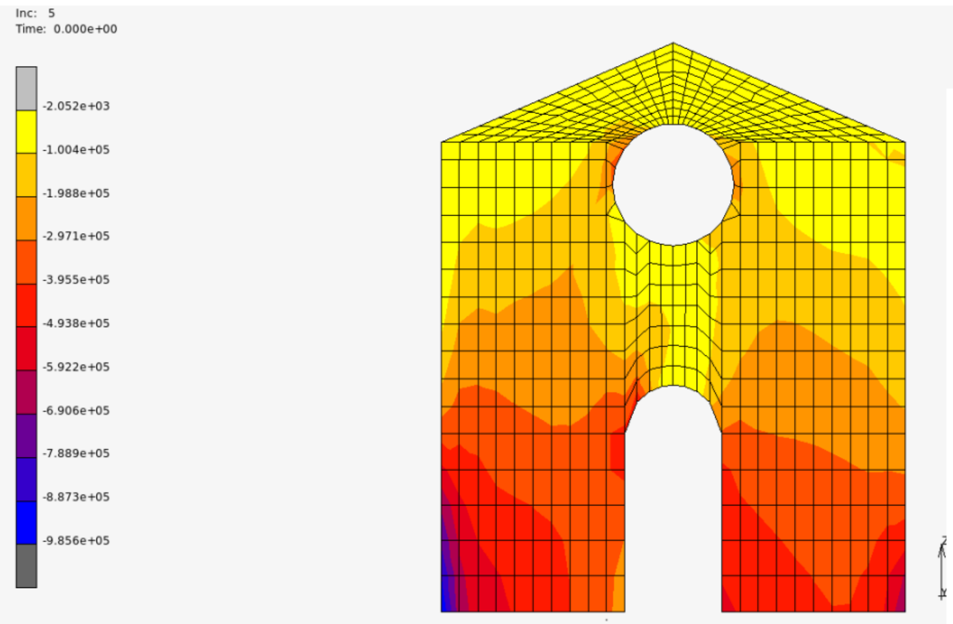
$H_U$=6,5% Weigth

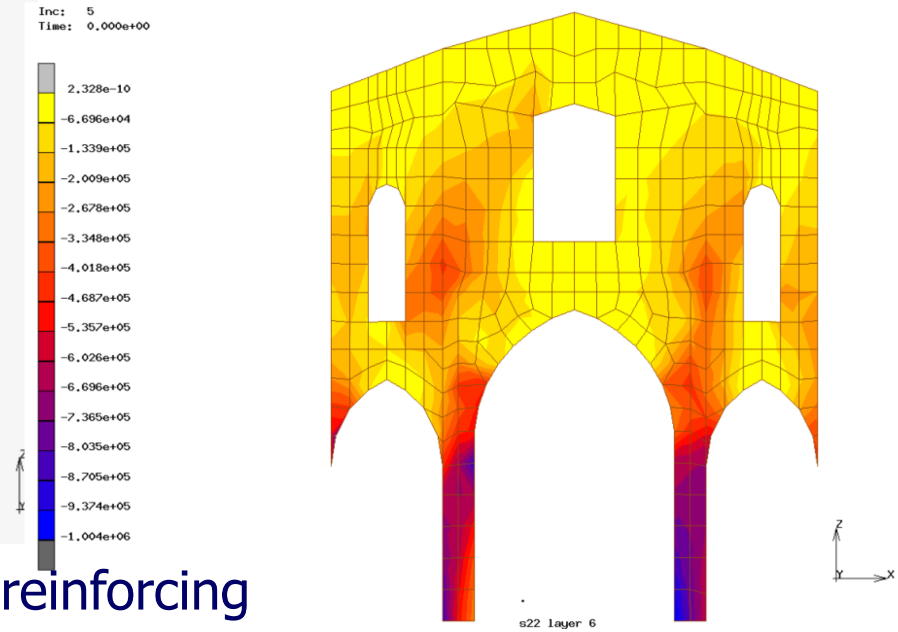
$U_{xmax}/h$= 0,005



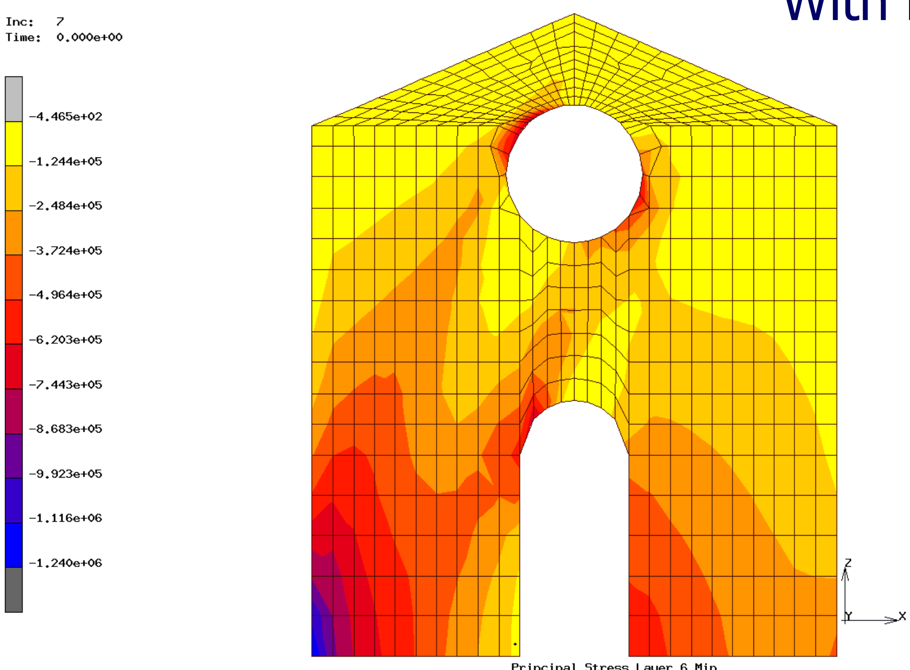
# Without reinforcing

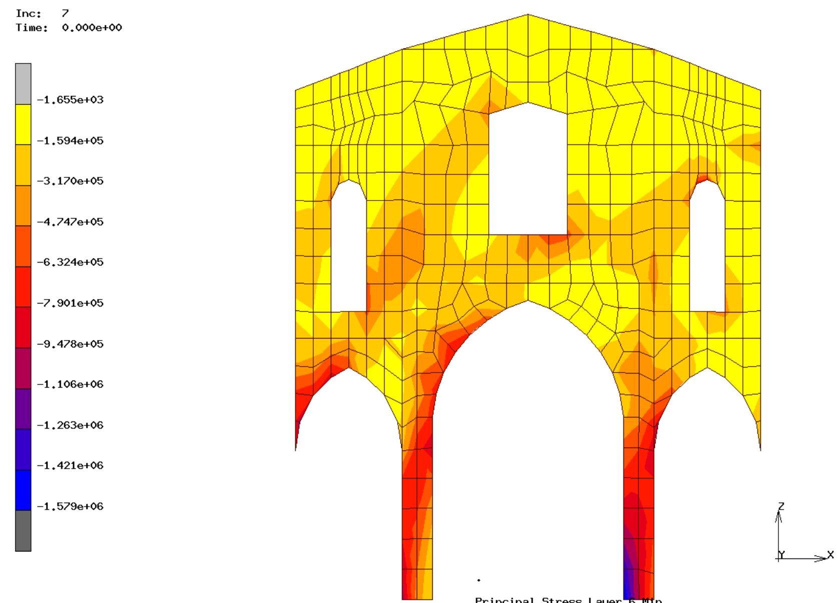
# Principal stresses




# With reinforcing

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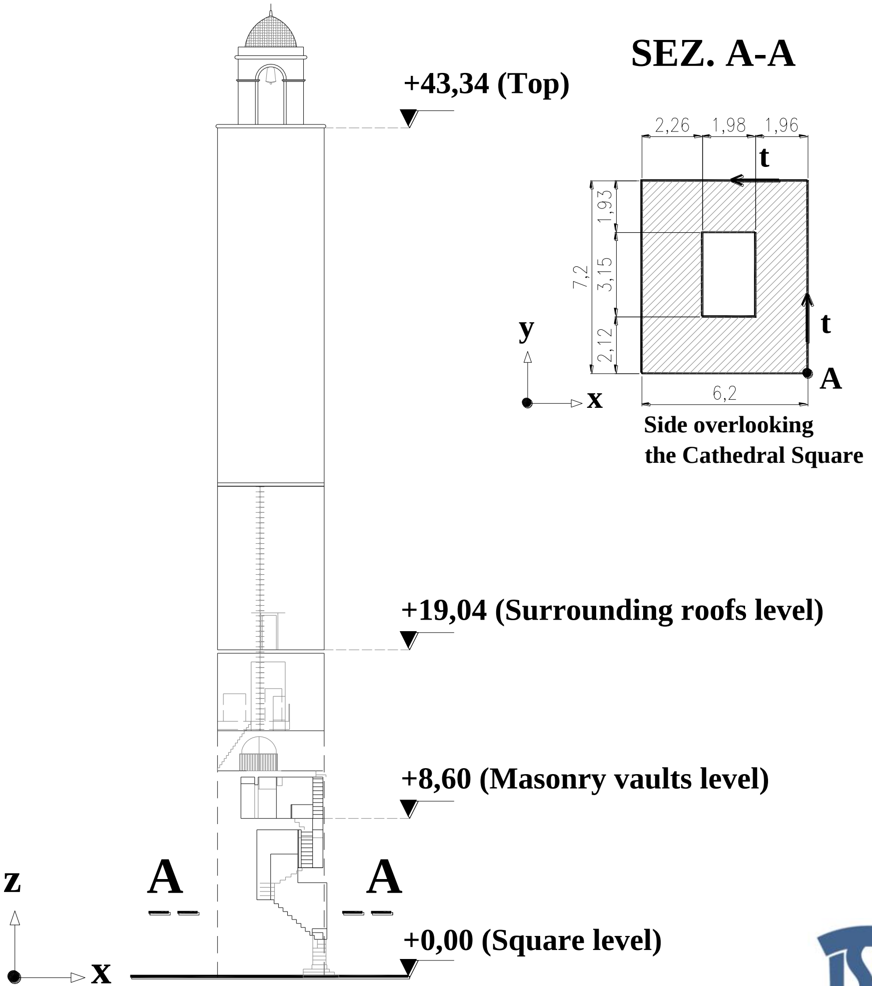
# Safety Indexes

**(Direttiva 9 Febbraio 2011, "Valutazione e riduzione del rischio sismico del patrimonio culturale")**

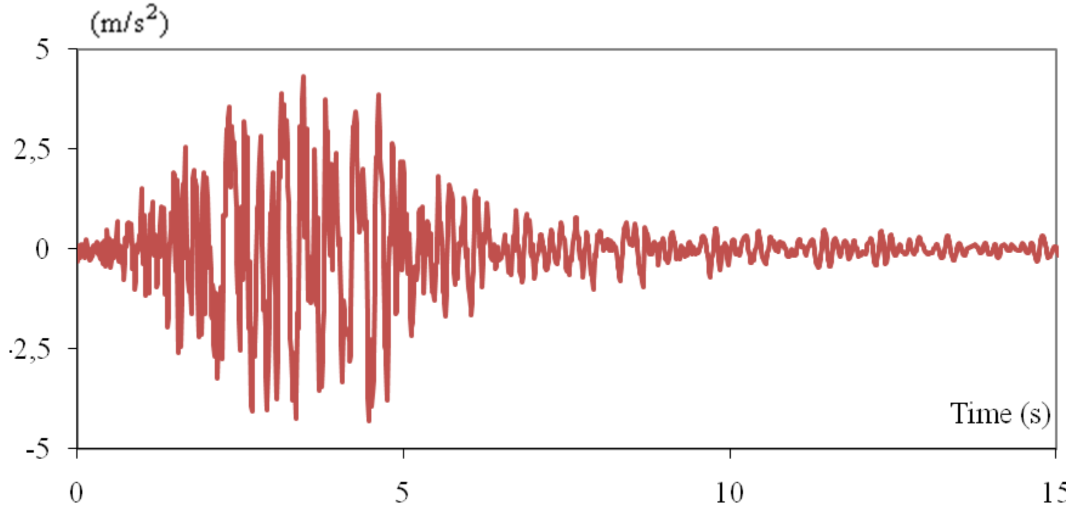
| | *Without reinforcing* | *With reinforcing* |
|---|---|---|
| **PGA** | $f_a = \frac{a_{SLU}}{a_{475}} = \frac{0.75}{1.86} = 0.4$ | $f_a = \frac{a_{SLU}}{a_{475}} = \frac{1.16}{1.86} = 0.6$ |
| **Reference periods** | $I_S = \frac{50}{475} = 0.1$ | $I_S = \frac{140}{475} = 0.3$ |
| **Maximum shear** | $\frac{H_{SLU}}{W} = 0.041$ | $\frac{H_{SLU}}{W} = 0.065$ |

# The "Rognosa" tower in San Gimignano

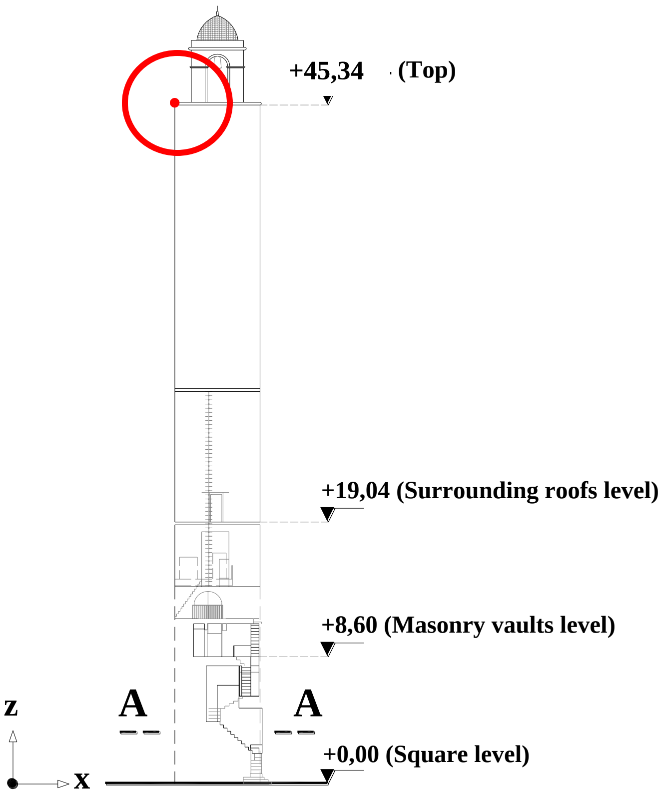


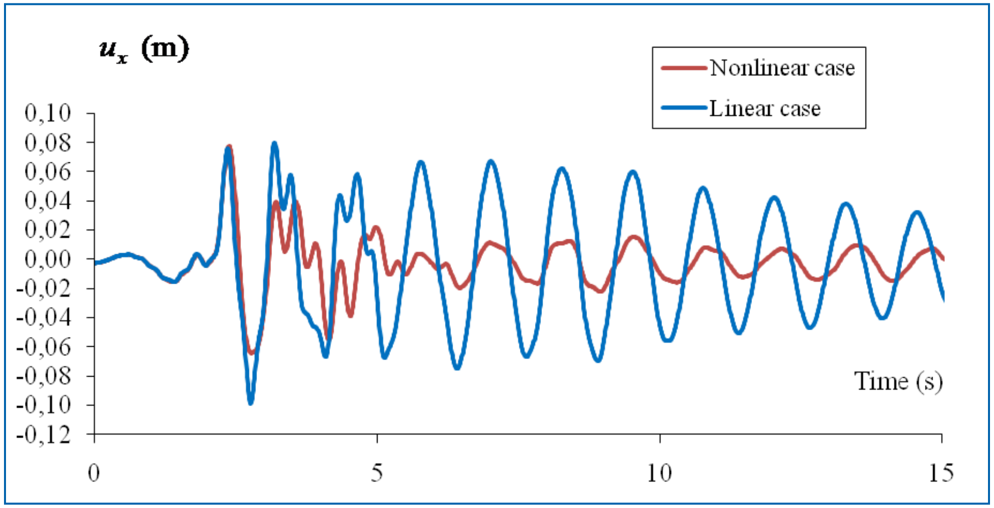
## The "Rognosa" tower in San Gimignano:

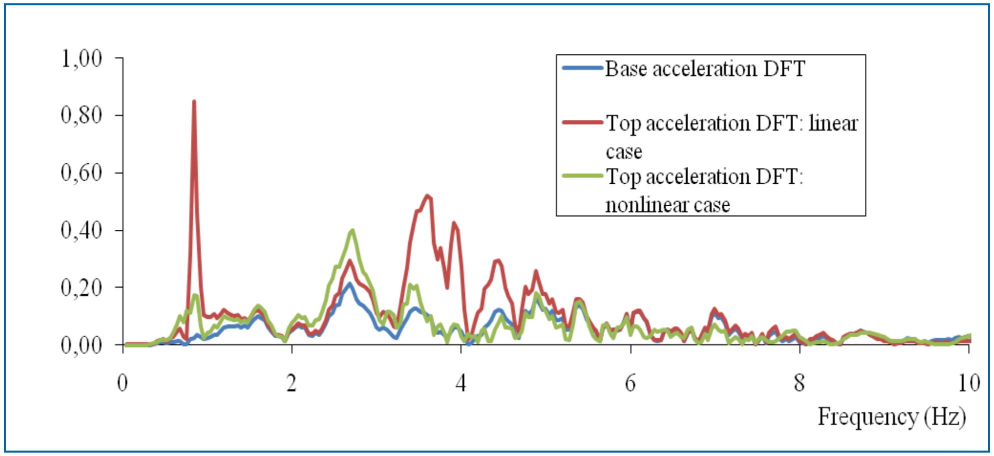
- **Static analysis** The Tower is subjected to its own weight and to the weight of the surrounding buildings
- **Dynamic analysis** The Tower subjected to the Nocera Umbra earthquake in *x* - direction



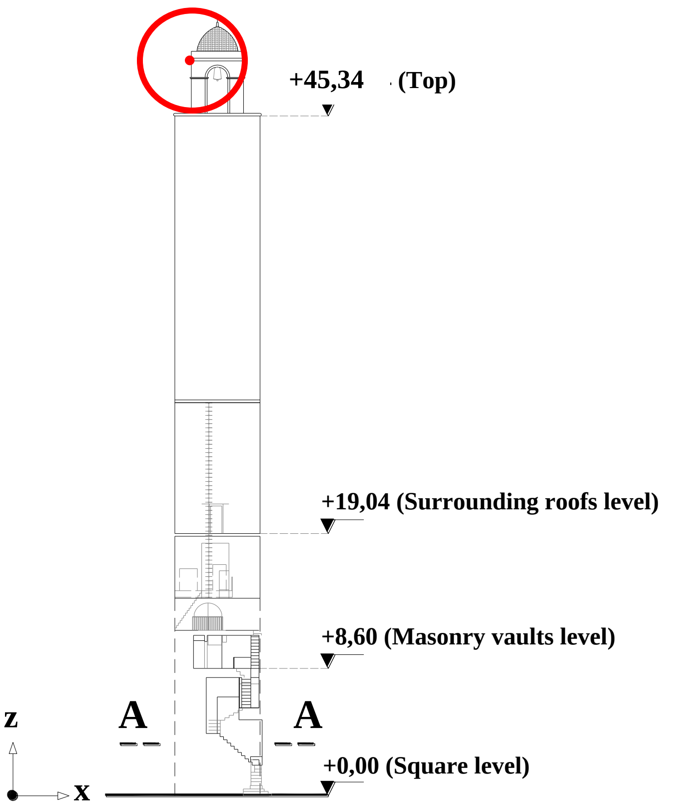
# The "Rognosa" tower in San Gimignano: dynamic analysis



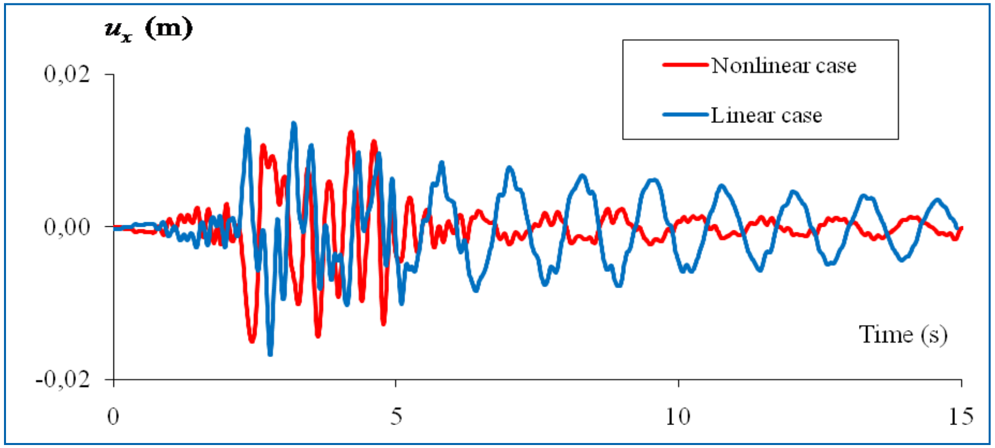



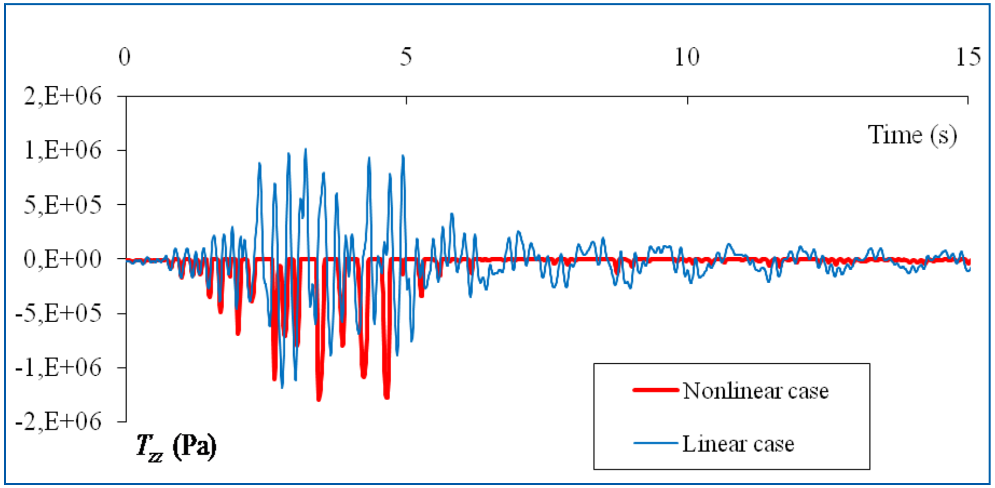



# Tower vertical section




# The bell chamber

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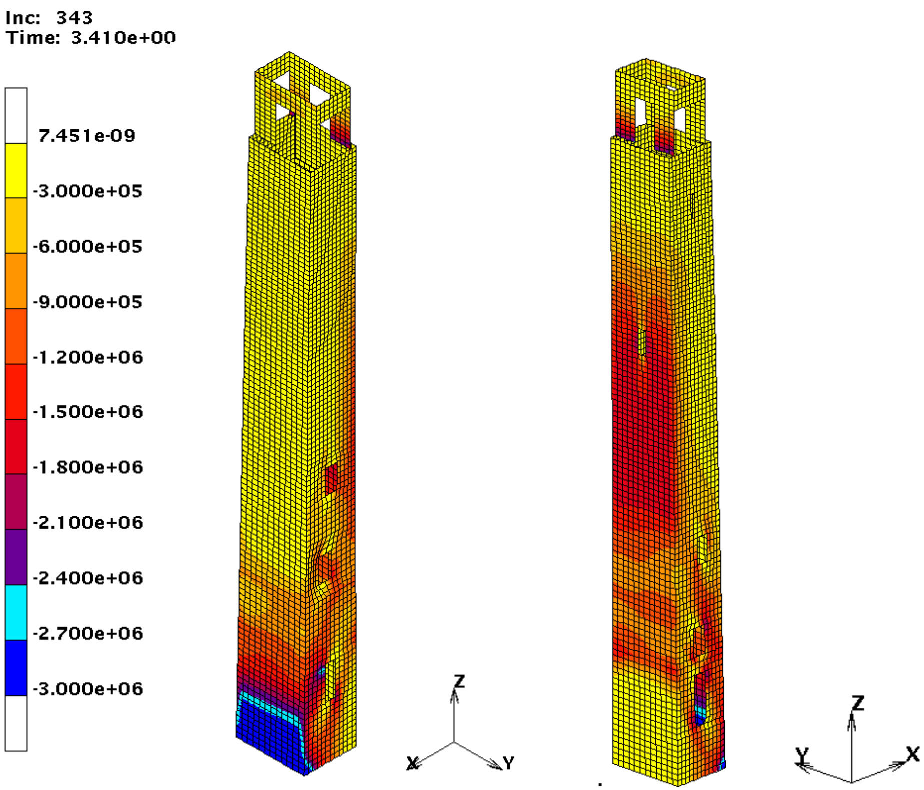
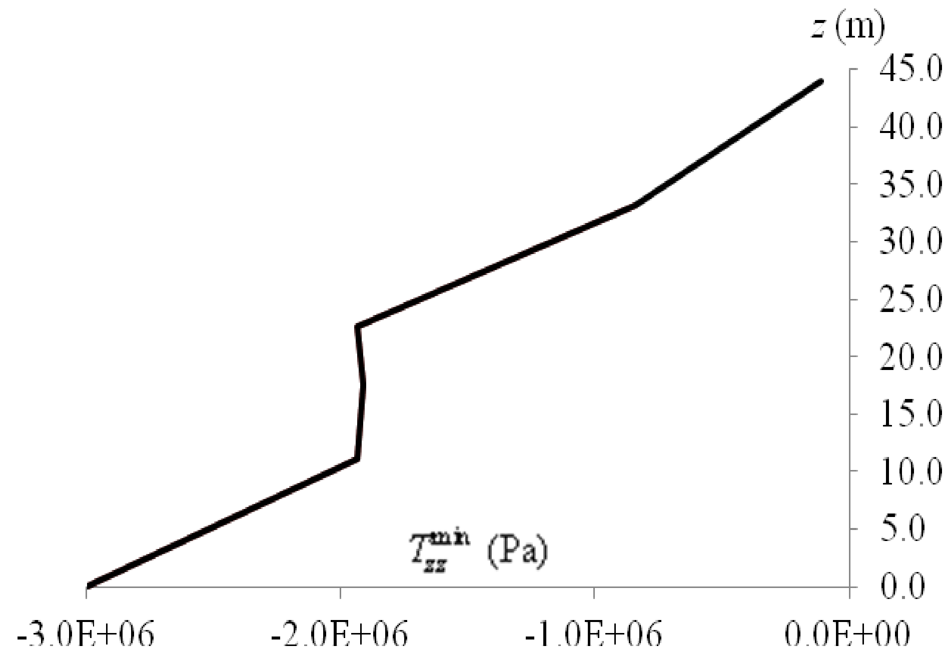
# The "Rognosa" tower in San Gimignano: dynamic analysis

## Compressive stress $T_{zz}$

At time t=3,41 s:



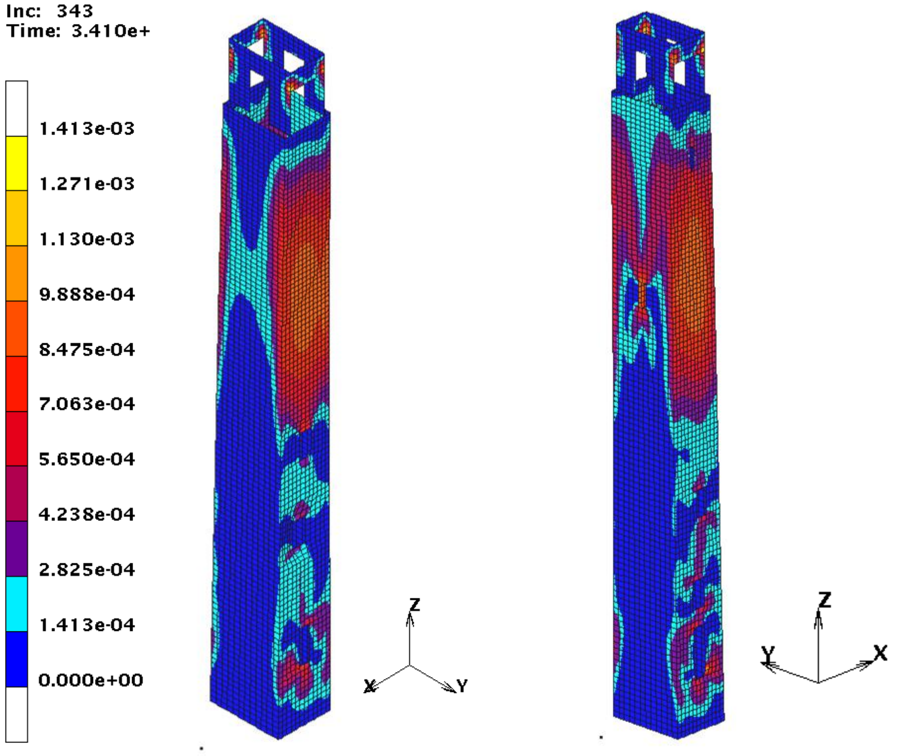

Minimum values reached during the analysis :



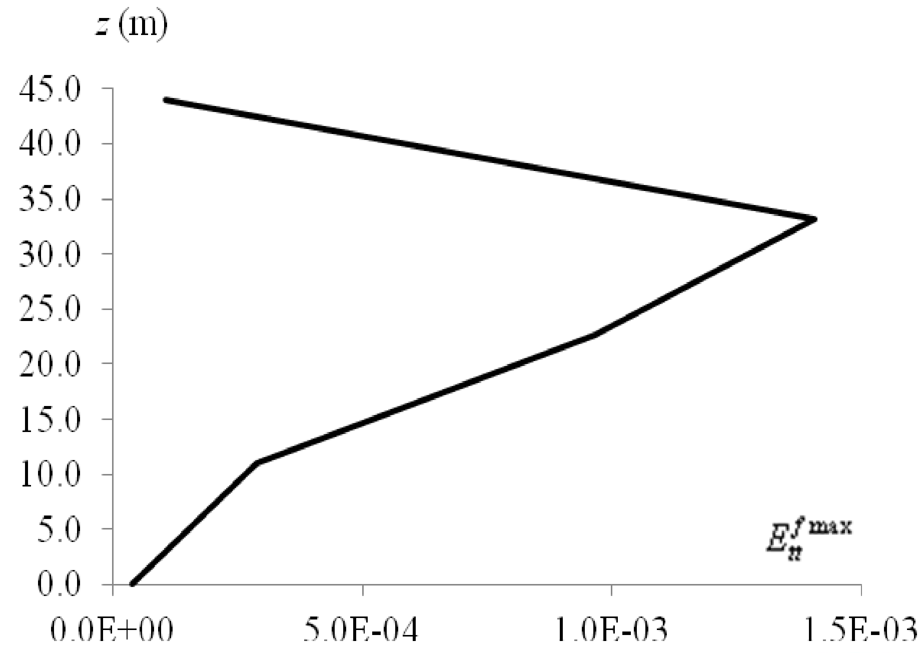
## The "Rognosa" tower in San Gimignano: dynamic analysis

# Tangential fracture strain $E^{f}_{tt}$

At time t=3,41 s:




Maximum values reached during the analysis :

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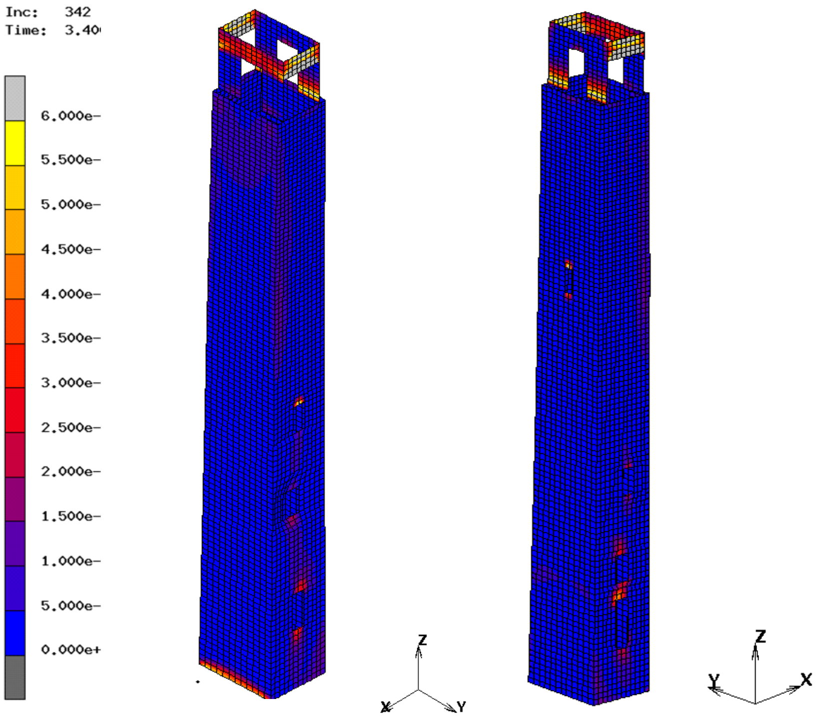
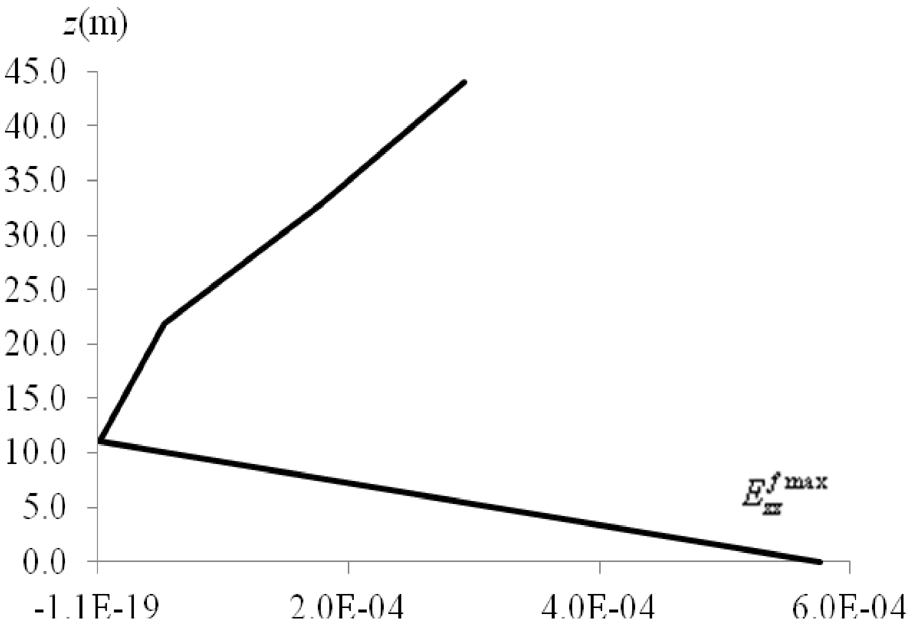
## The "Rognosa" tower in San Gimignano: dynamic analysis

# Fracture strain $E^f_{zz}$

At time t=3,41 s:




Maximum values reached during the analysis :

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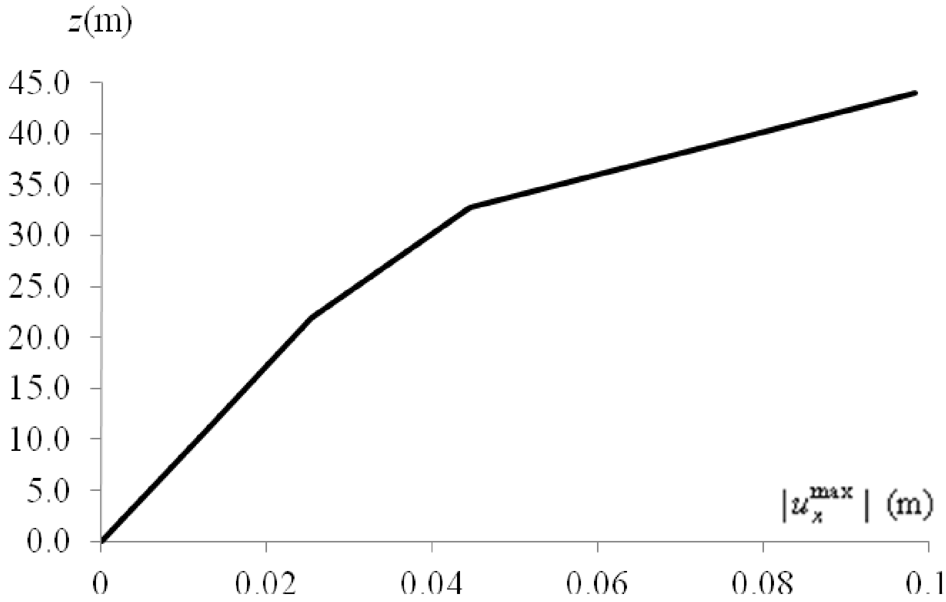
# Displacements $u_x$

Maximum values reached during the analysis:



# Conclusions

• The NOSA-ITACA project aimed to upgrade the NOSA code and disseminate the use of numerical tools in the field of maintenance and restoration of the architectural heritage.

• The NOSA - ITACA code is a finite element code for static and dynamic nonlinear analyses of masonry structures. It will be freely downloadable by the end of the year.

•Masonry is modelled by means of a masonry-like constitutive equation with zero tensile strength and finite or infinite compressive strength.

•Some cases have been presented in which the seismic vulnerability of the church of San Francesco in Lucca and of the "Rognosa" tower in San Gimignano are assessed by means of a nonlinear static and dynamic analyses conducted via the NOSA–ITACA code.

The financial support of the Region of Tuscany (project "Tools for modelling and assessing the structural behaviour of ancient constructions: the NOSA-ITACA code", PAR FAS 2007-2013) is gratefully acknowledged.

# The Church of San Francesco: evaluation of the seismic vulnerability