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Numerical modelling of the static and seismic behaviour of historical buildings: the church of San Francesco in Lucca

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- The NOSA-ITACA code is a finite element solver 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 for static analyses will be freely downloadable by http://www.nosaitaca.it/it/software/

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$\boldsymbol{E}$ the infinitesimal strain tensor,

$\boldsymbol{T}$ the Cauchy stress tensor,

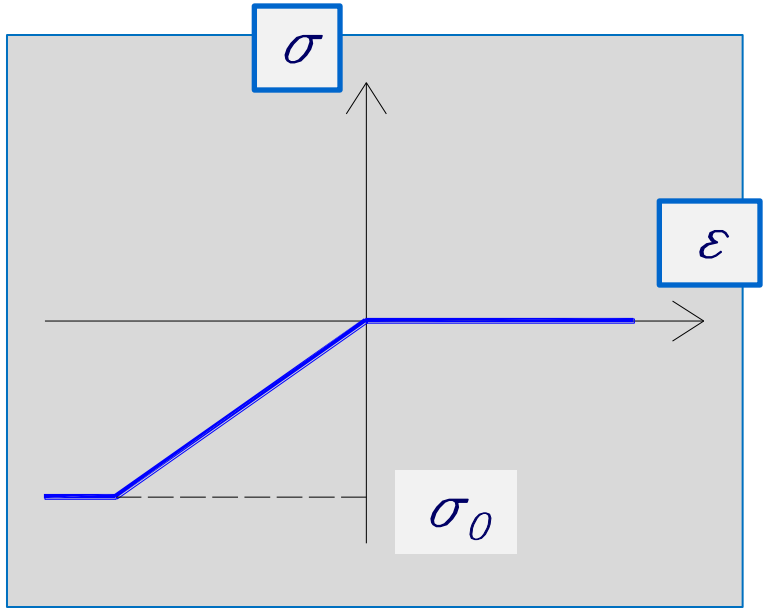
$\boldsymbol{E}^{e}$ the elastic part of the strain,

$\boldsymbol{E}^{f}$ the fracture strain,

$\boldsymbol{E}^{c}$ the crushing strain,

$\mathbf{E}, \nu$ the modulus of elasticity and the Poisson's ratio,

$\sigma_0 < 0$ the masonry maximum compressive stress.



Given E, find E^f, E^c, T such that

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

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

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

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

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

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

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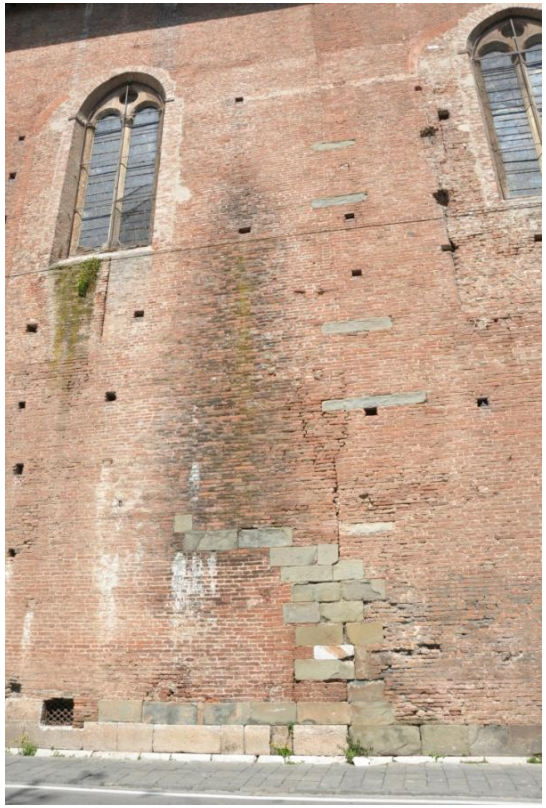
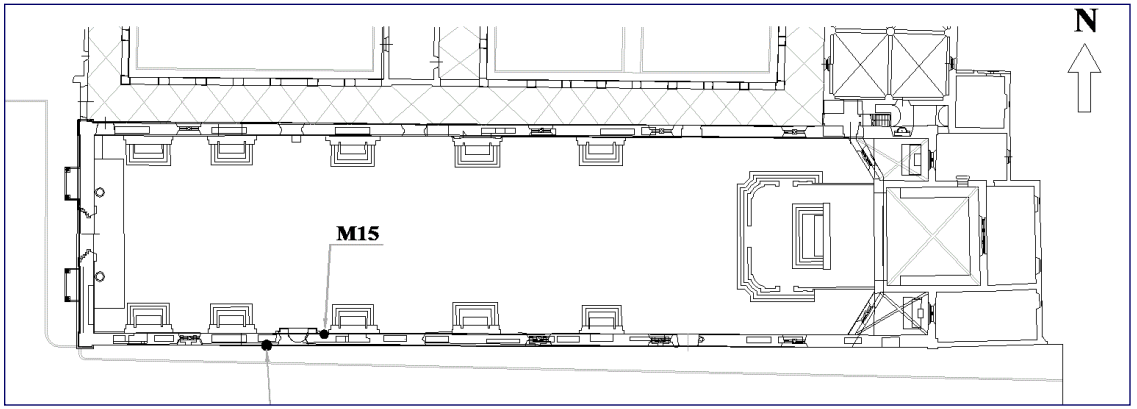
Fondazione
Cassa di Risparmio
di Lucca

The Church of San Francesco





The Church of San Francesco: reinforcement operations

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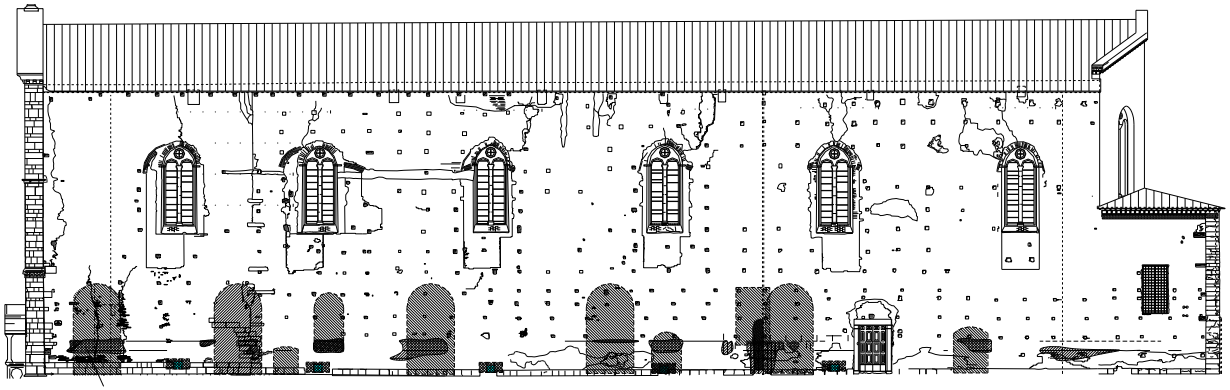
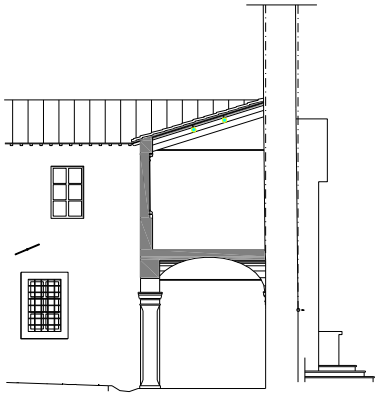
di Lucca

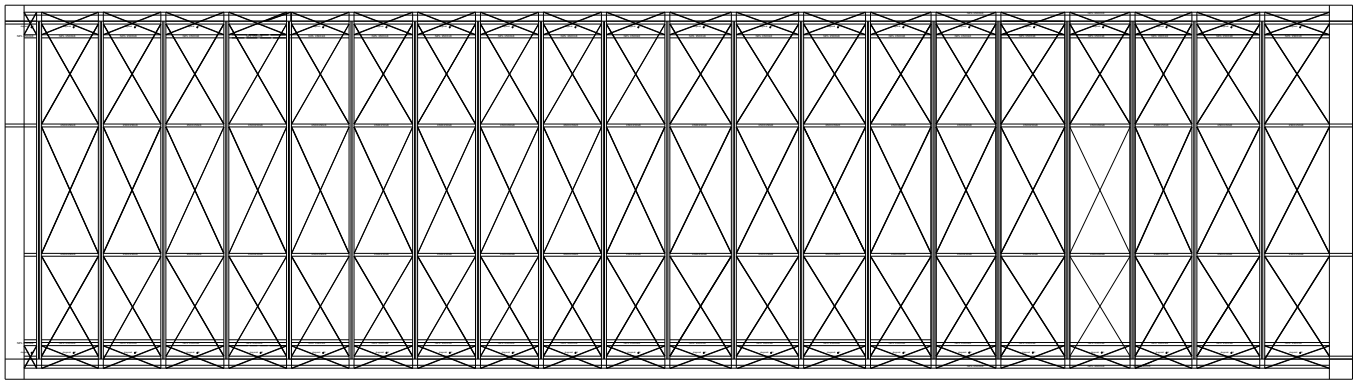
On masonry



On the cloister



On the roof



Evaluation of the seismic vulnerability and the effectiveness of the reinforcement operations

Step 1

- **In situ tests:** geometric survey, flat jacks tests, georadar scans
- **Laboratory tests:** mechanical characterization of materials and soil

Step 2

Numerical model of the existing structure: modal analyses, definition of the horizontal loads, static nonlinear analyses, definition of the collapse loads

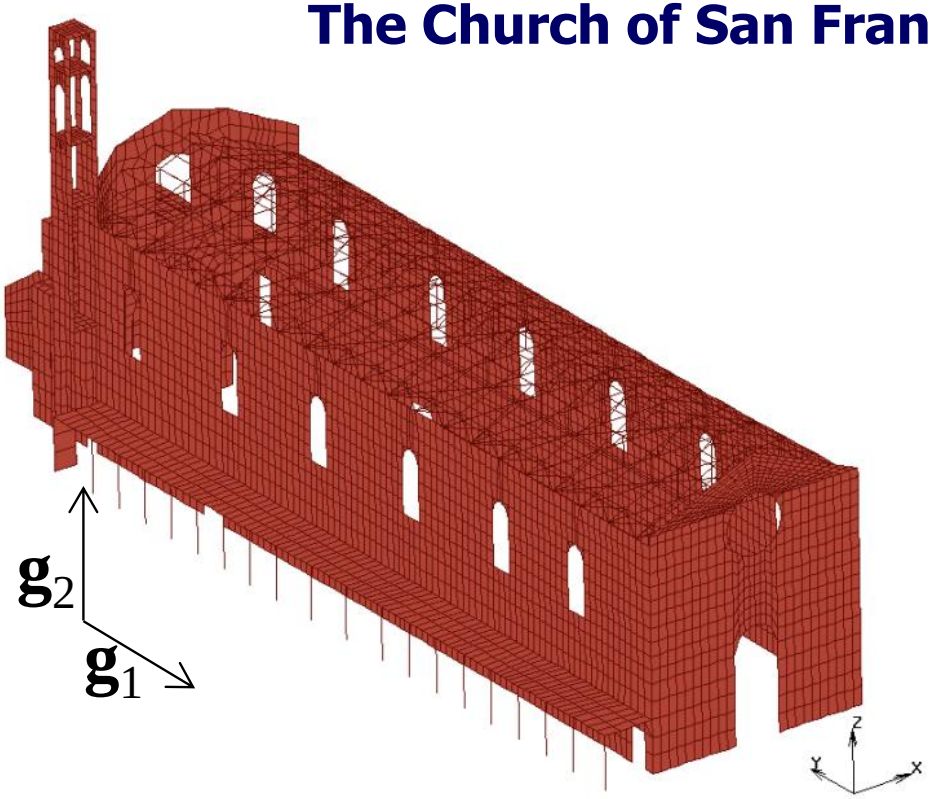
Step 3

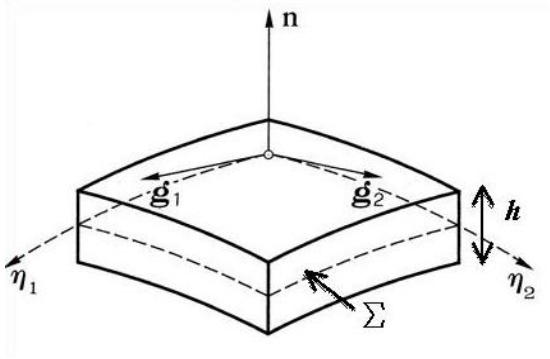
Numerical model of the reinforced structure: modal analyses, definition of the horizontal loads, static nonlinear analyses, definition of the collapse loads

Step 4

Existing and reinforced structure: comparison of numerical results

The Church of San Francesco: The finite element mesh





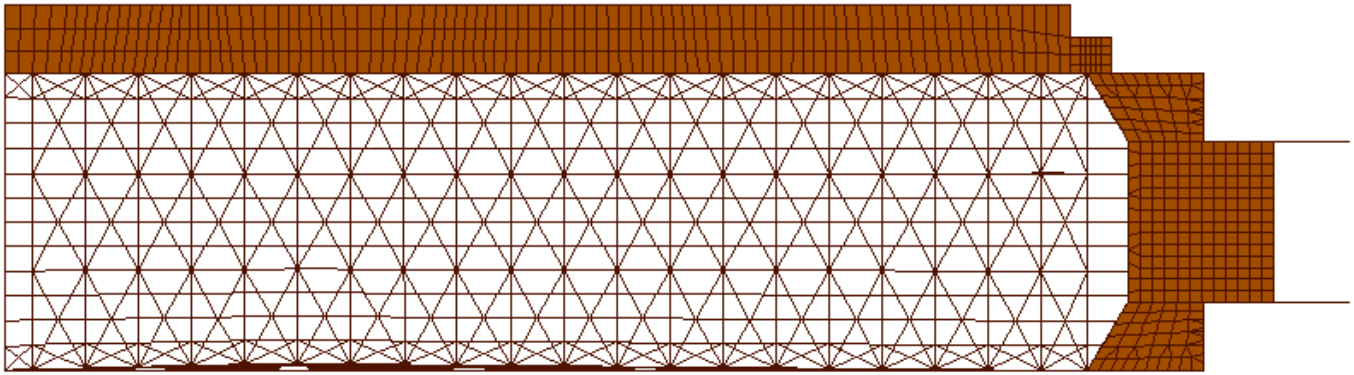
$$\Sigma_\zeta = \{\mathbf{p}' \mid \mathbf{p}' = \mathbf{p} + \zeta\mathbf{n},\ \mathbf{p} \in \Sigma,\ \mathbf{n} = \mathbf{n}(\mathbf{p})\},$$

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

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

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



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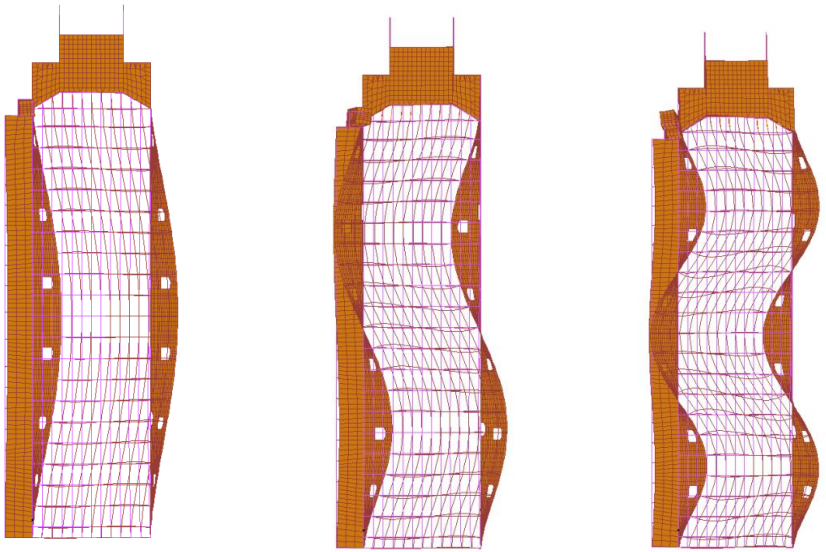
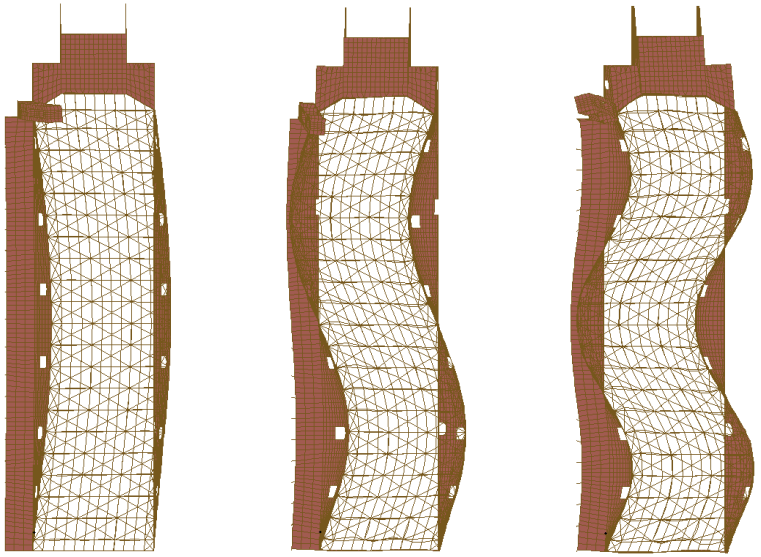
The Church of San Francesco: modal analyses

Without reinforcing

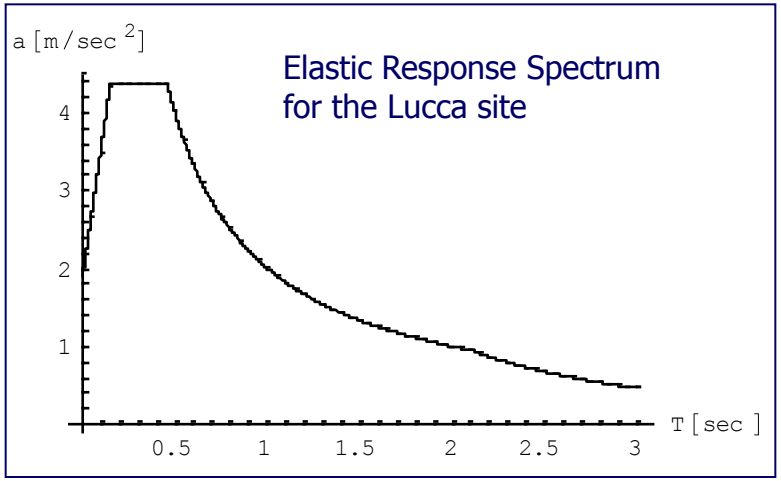


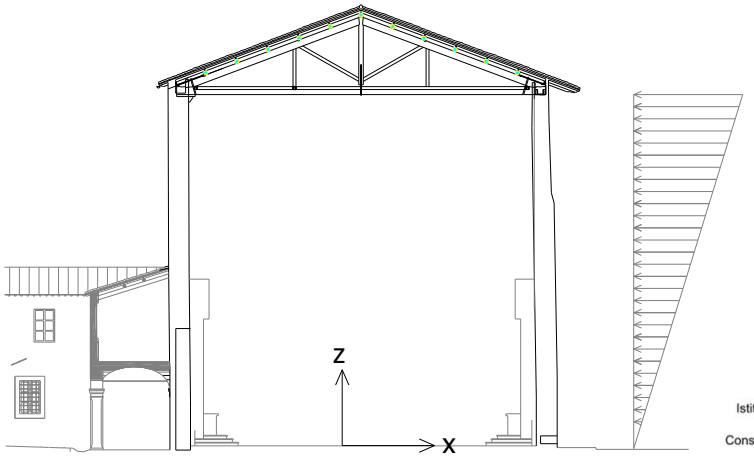
T1=1,26 s

With reinforcing



T1r=1,04 s





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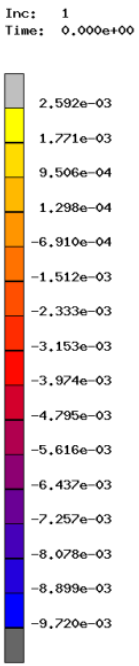
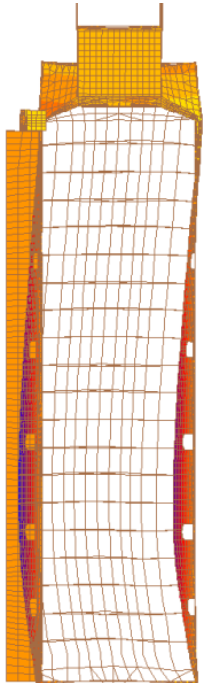
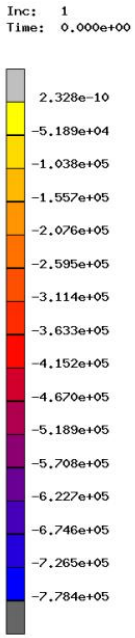
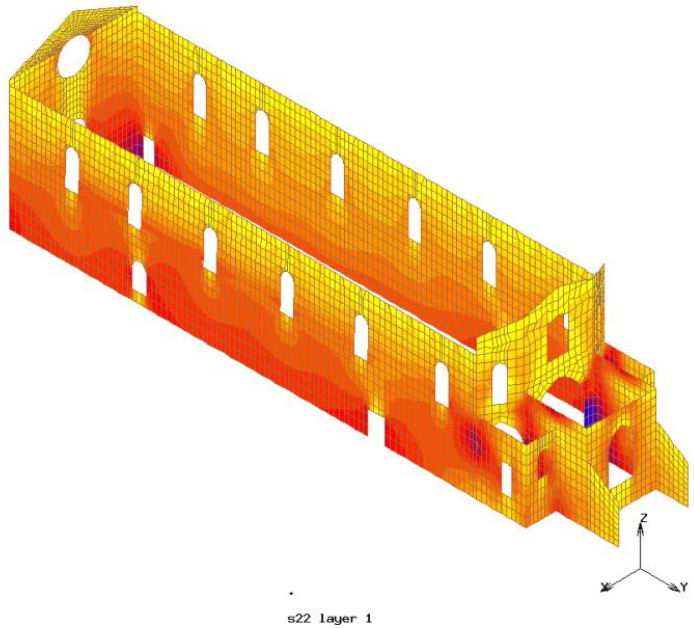
The Church of San Francesco: permanent loads









Displacements u_x

Stresses T_{22}

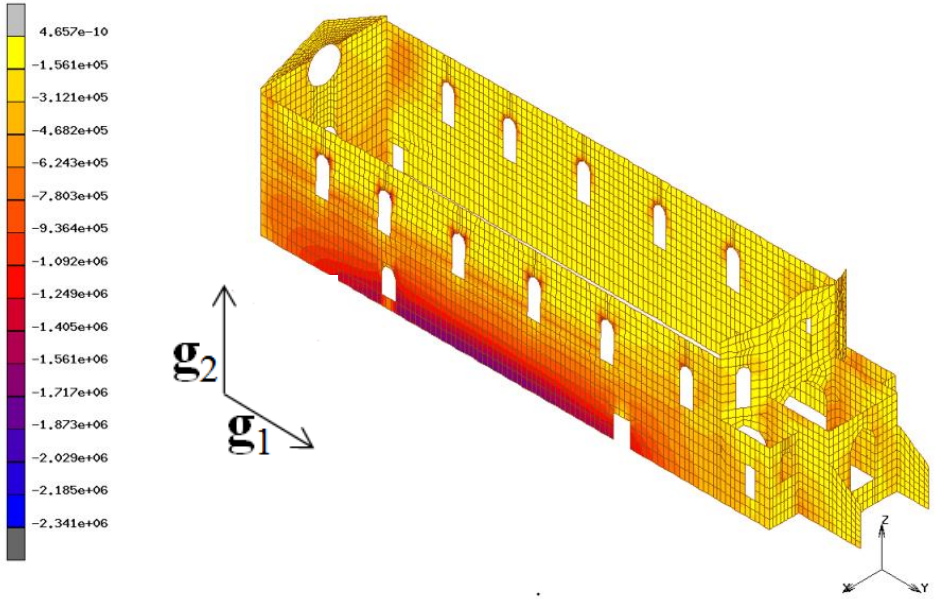
The Church of San Francesco: evaluation of the seismic vulnerability

Stresses T_{22}

SLU

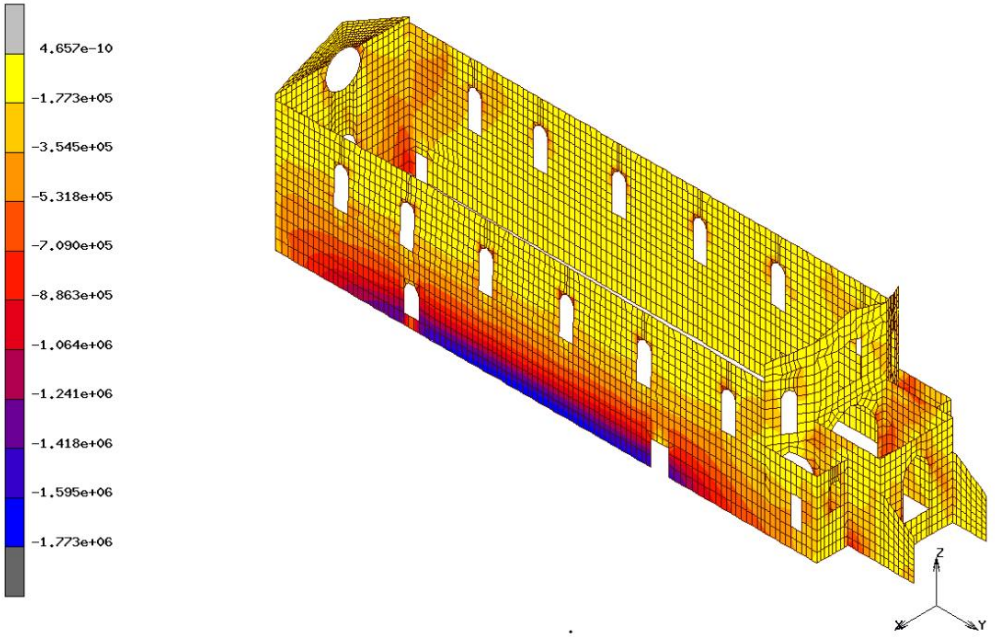
Without reinforcing

Hu=4,1% Weigth



With reinforcing

Hu=6,5% Weigth



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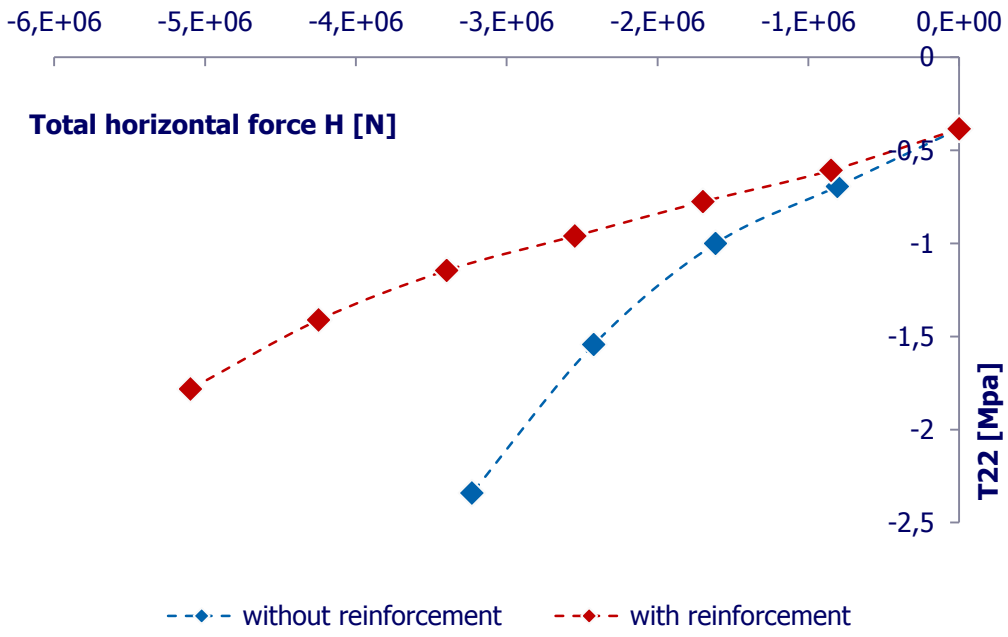
The Church of San Francesco: evolution of the maximum values of normal stresses



The Church of San Francesco: evaluation of the seismic vulnerability

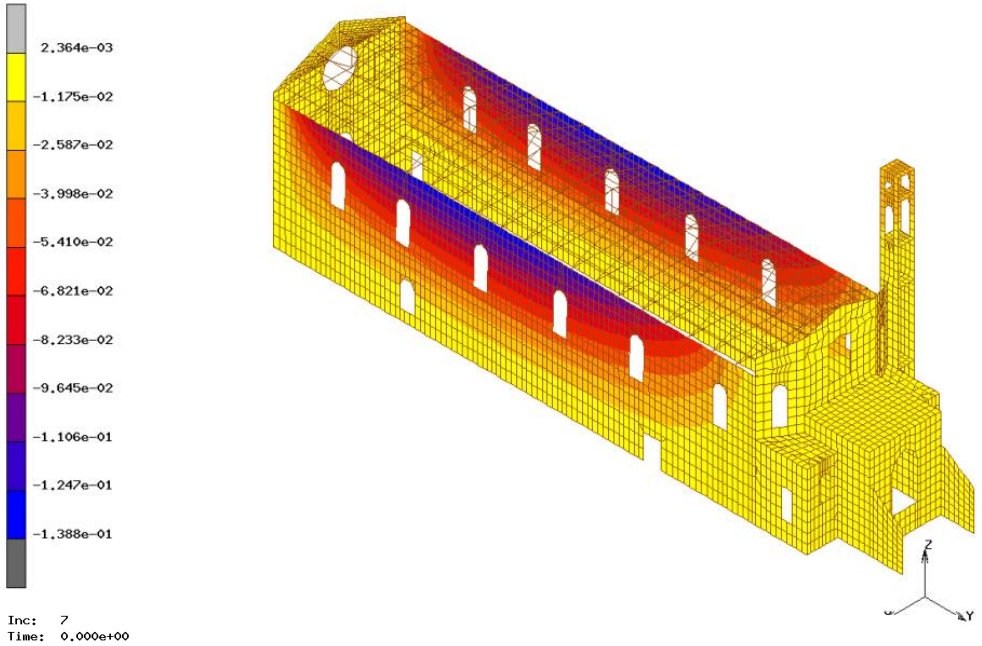
Displacements u_x

SLU

Without reinforcing

H_U=4,1% Weigth

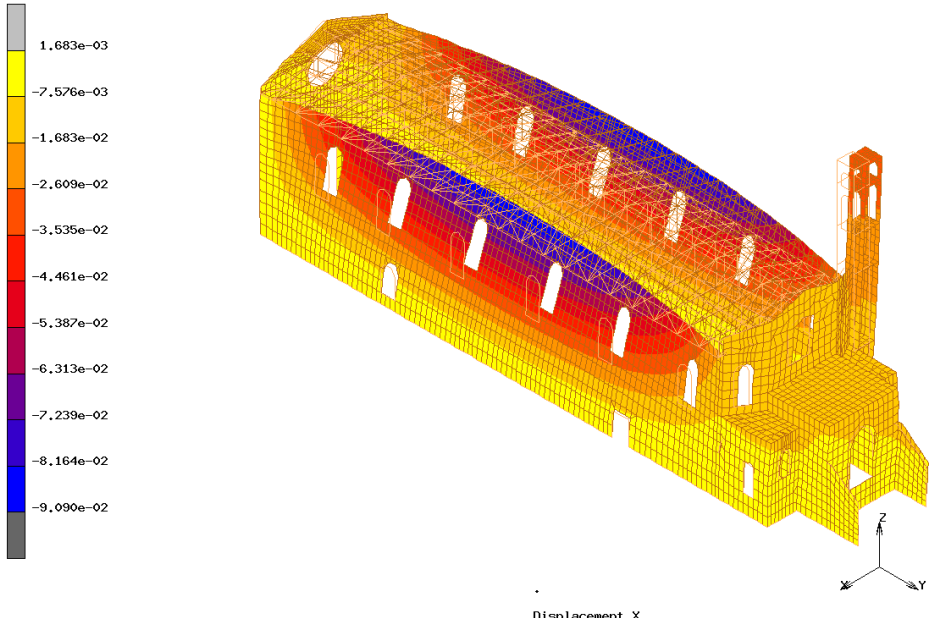
U_{xmax}/h= 0,0078



With reinforcing

H_U=6,5% Weigth

U_{xmax}/h= 0,005



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The Church of San Francesco: evaluation of the seismic vulnerability

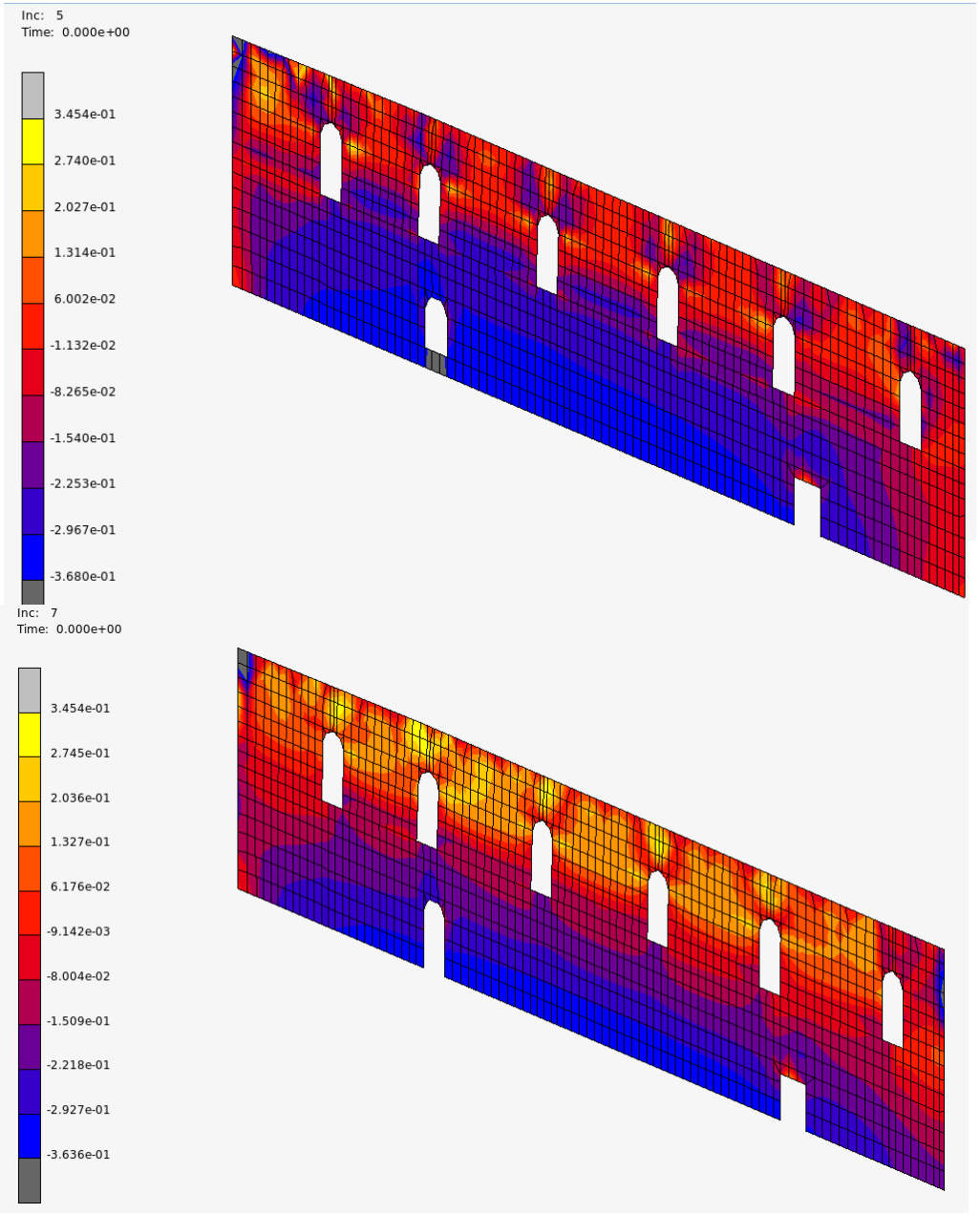
Eccentricities e_{22}

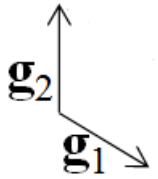
SLU

Without reinforcing

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

With reinforcing





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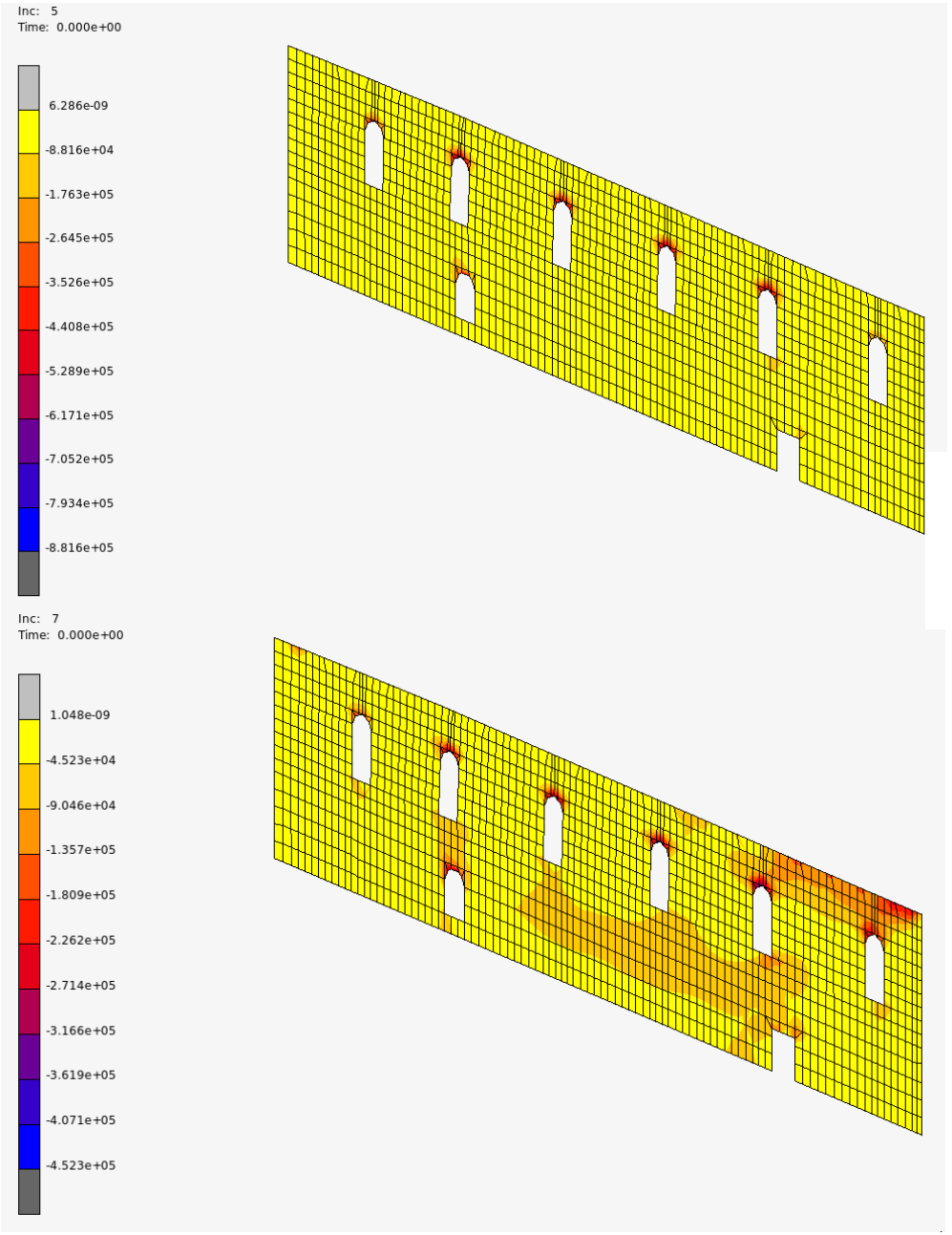
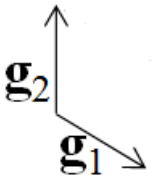
Stresses T_{11}

SLU

Without reinforcing

With reinforcing





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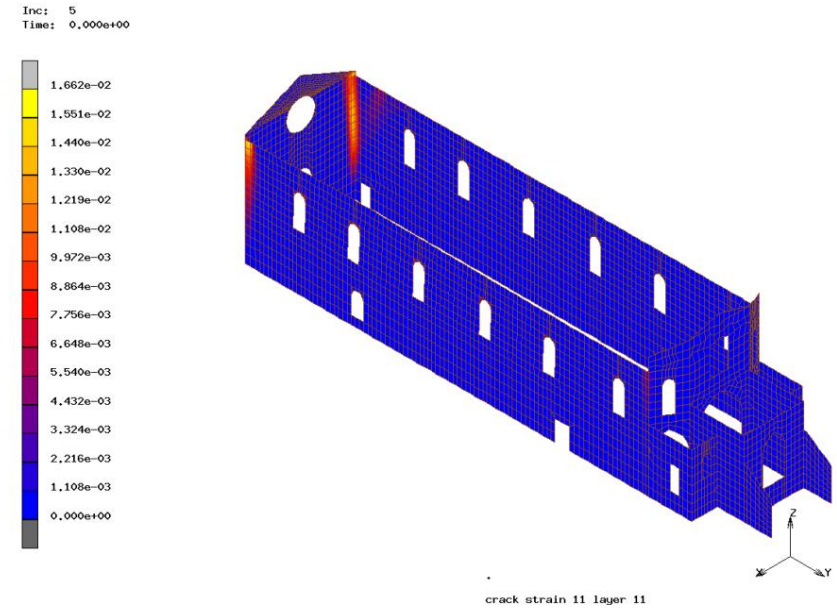
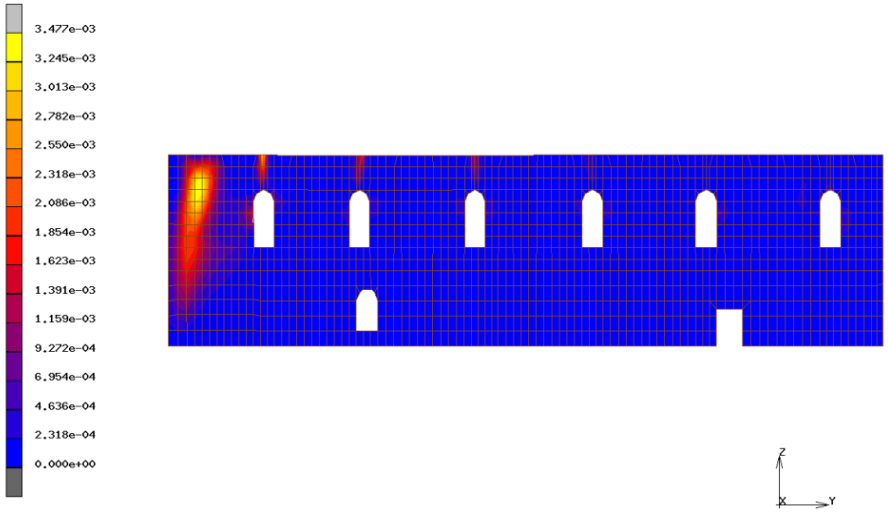
Without reinforcing





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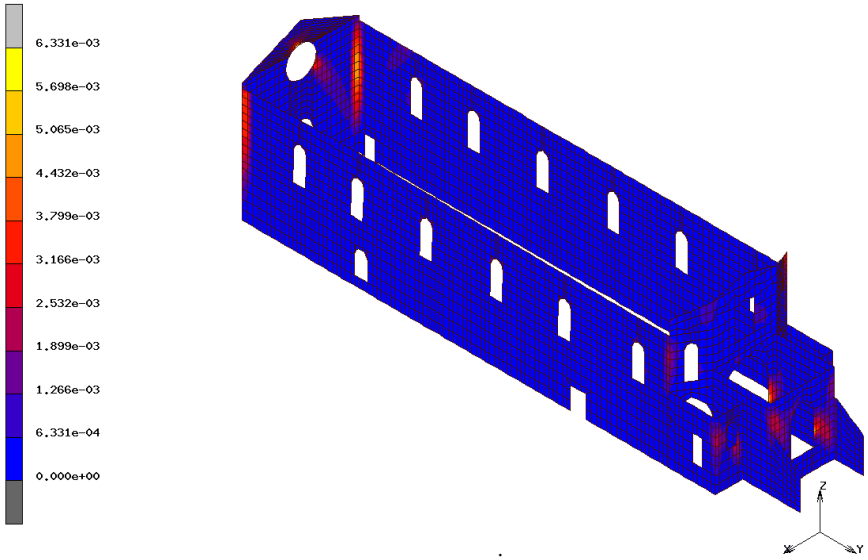
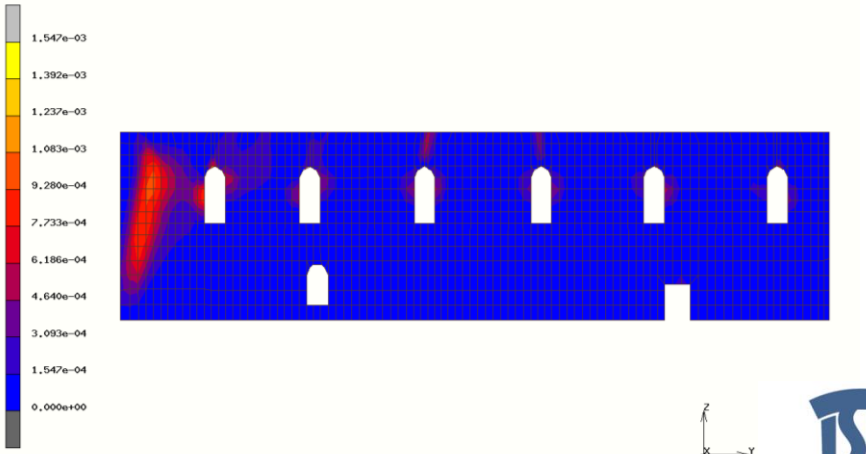
Fracture strains E^{f}_{11}





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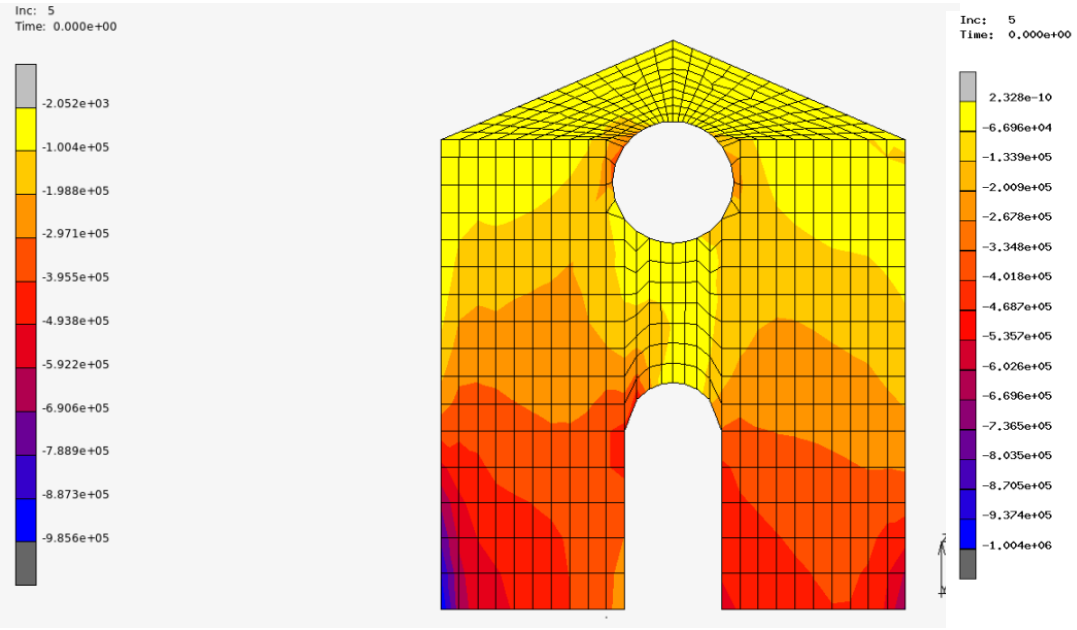
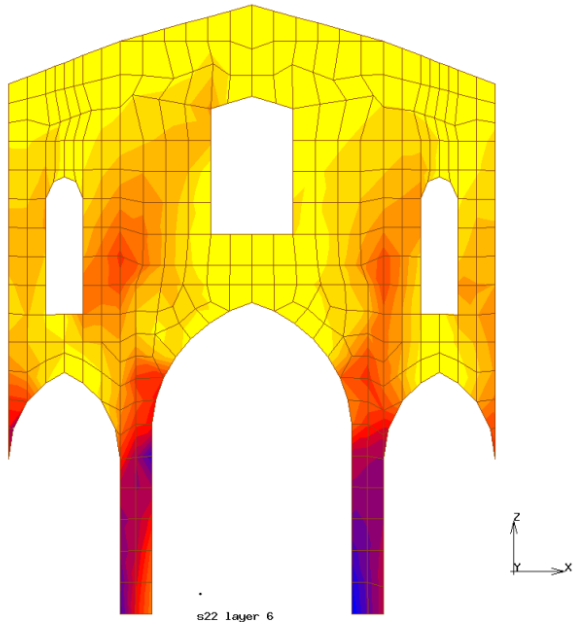
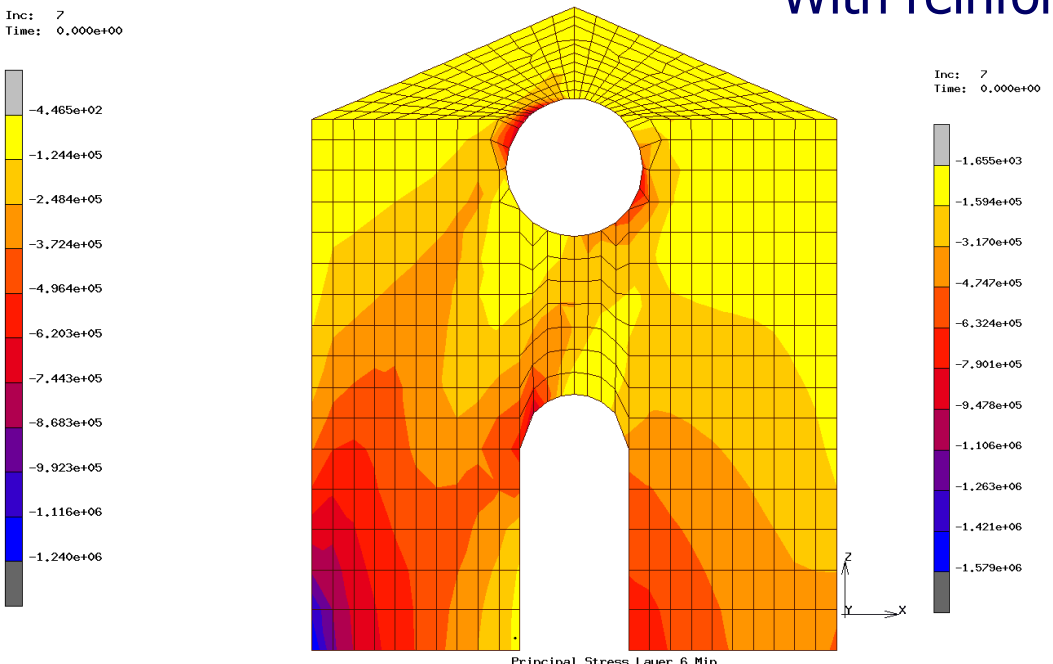
Without reinforcing

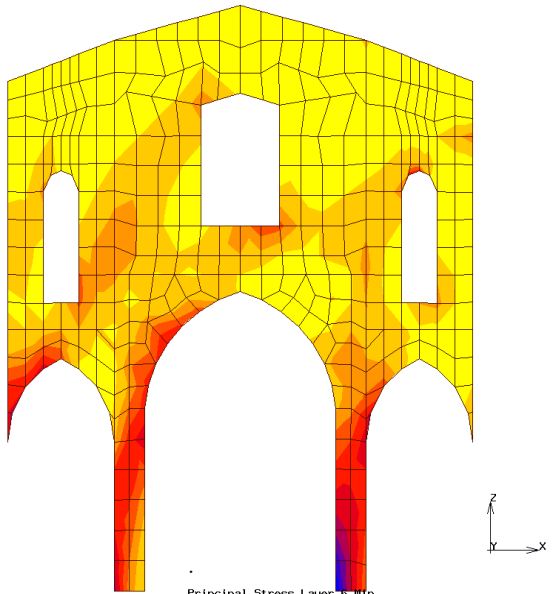




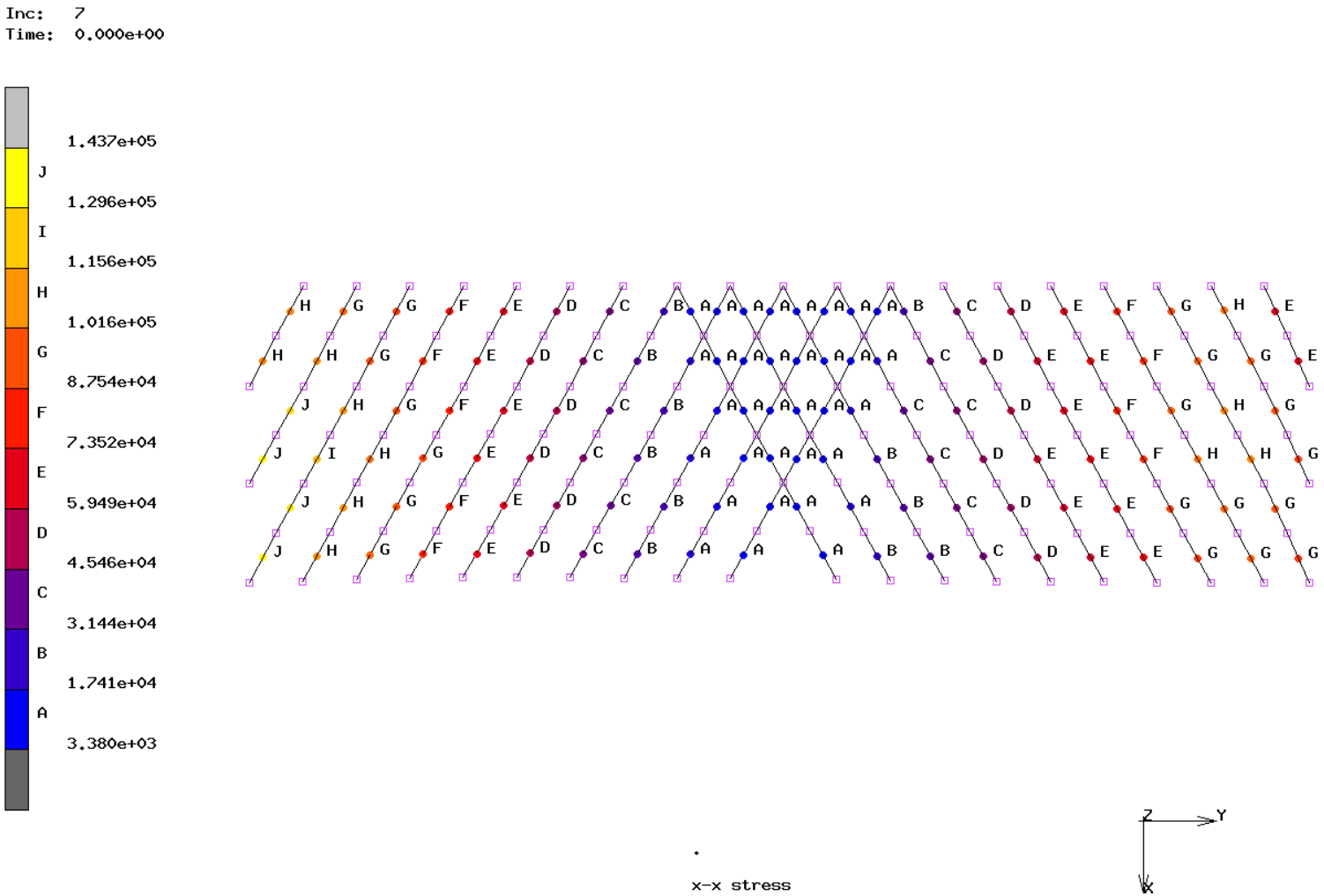
With reinforcing

Stresses T_{22}

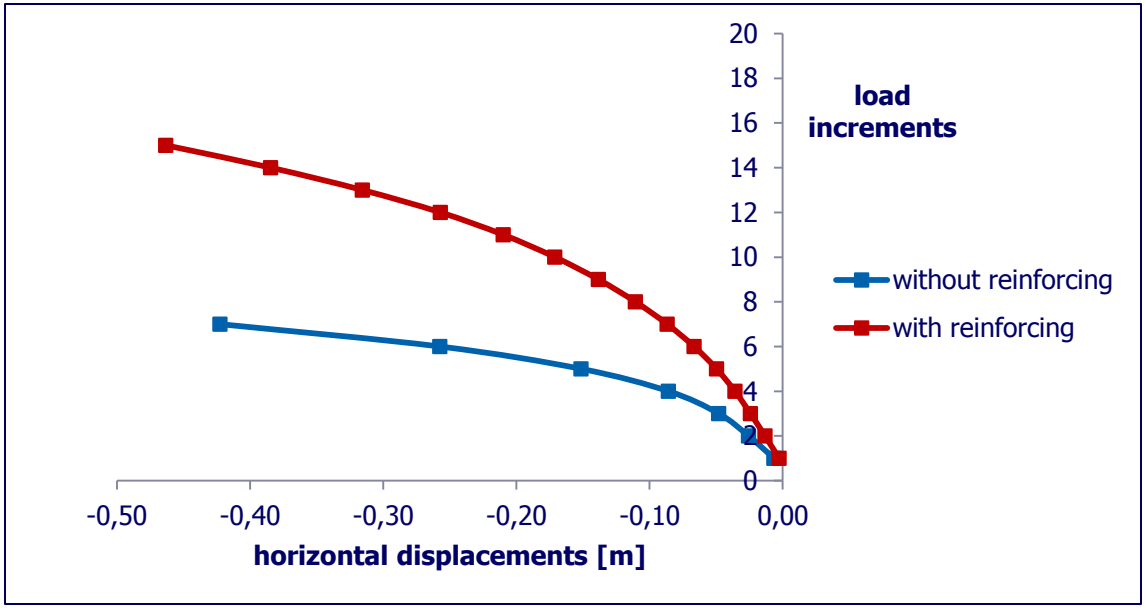




Normal force in the windbracing at the ultimate limit state



The Church of San Francesco: evaluation of the seismic vulnerability



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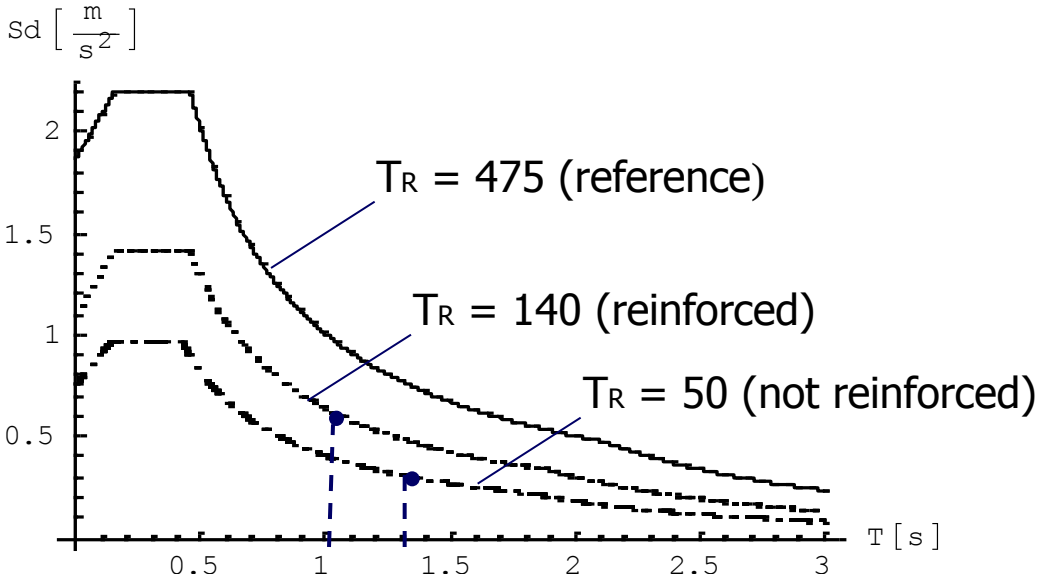
Without reinforcing ***With reinforcing***

$$f_a = \frac{a_{SLU}}{a_{475}} = \frac{0.75}{1.86} = 0.4 \quad \Rightarrow \quad f_a = \frac{a_{SLU}}{a_{475}} = \frac{1.16}{1.86} = 0.6$$

$$I_S = \frac{50}{475} = 0.1 \quad \Rightarrow \quad I_S = \frac{140}{475} = 0.3$$

$$\frac{H_{SLU}}{W} = 0.041 \quad \Rightarrow \quad \frac{H_{SLU}}{W} = 0.065$$



Conclusions

- The NOSA - ITACA code is a finite element code for static and dynamic nonlinear analyses of masonry structures. The version for static analyses 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.
- A case study has been presented in which the seismic vulnerability of the church of San Francesco in Lucca is assessed by means of a nonlinear static analysis 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.

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