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FINITE ELEMENT MODELLING FOR SEISMIC ASSESSMENT OF EXISTING MASONRY CHURCHES – PART I: GLOBAL ANALYSES

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Abstract

To date, seismic vulnerability and risk assessment of cultural heritage is a very discussed topic. Particular attention is paid to existing masonry churches, constructions having relevant dimensions and realized with traditional techniques based on empirical rules. As demonstrated by the last earthquakes, these constructions are very vulnerable with respect to the seismic lateral actions, even if of moderate magnitude. For this reason, numerical simulations on existing masonry churches have become essential in order to properly predict their seismic response, even if highly challenging because of the complexity of the construction details and involved materials. Among these, the Finite Element Modelling represents a valid tool, allowing to obtain realistic computational solutions with respect to different seismic scenarios. This paper aims at investigating the global seismic behavior of two existing masonry churches located in Italy and in Romania. Non-linear dynamic analyses are performed by means of 3D FEM models, with the aim of investigating the influence of the ground motion vertical component in the global non-linear response of the churches considered. The numerical results are illustrated and commented, highlighting the differences between the results obtained without and with the ground motion vertical component. In a companion paper, local seismic analyses are carried out on some architectural portions of the case studies considered.

Keywords: Finite element modelling, Global analyses, Seismic risk, Existing masonry churches, Vertical ground motion.

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1 INTRODUCTION

To date, the preservation of historical cultural heritage is a particularly highly discussed topic in literature. Cultural heritage is very vulnerable to natural disasters due to time-aging, old construction techniques, and even poor maintenance. History and traditions associated with cultural heritage are invaluable, and their destruction can compromise information sources of past societies and ruin cultural icons. Furthermore, the impact that natural disasters can have on cultural heritage is directly connected to economic losses [1, 2].

Among natural threats, recent seismic events have caused serious damage to existing buildings, especially masonry ones, appearing to be very vulnerable to horizontal loads [3]. Existing masonry buildings represent a large part of the actual cultural heritage in the world. They are built following empirical construction techniques known as "rules of art", resulting in a very high strength to vertical loads, but vulnerability to dynamic actions. Collapse under seismic action is due to rigid-fragile global behavior of these kinds of structures, characterized by massive masonry walls, light and flexible diaphragms, structural heterogeneity and low transversal connections [4].

It follows that it is really important for authorities to assess the seismic vulnerability of the existing built heritage, considering the number and complexity of masonry buildings, in order to focus the limited economic resources on the most vulnerable ones, especially if they are located in earthquake-prone areas [5]. Numerical Finite Element Modelling (FEM) represents a valid tool for simulating the behavior of existing masonry buildings under seismic action, by reading the effects of different seismic scenarios considered [4, 6, 7]. Referring to multilevel methodologies on seismic vulnerability, and indirectly on seismic risk [8], global behavior evaluation should be intended as a more refined approach to investigate selected case studies after territorial assessments [9, 10].

This work focuses on the seismic behavior assessment of two existing masonry churches, located respectively in Italy and in Romania. The preliminary results here presented are obtained carrying out Non-Linear Dynamic Analyses by means of FEM numerical models including also the vertical component of the seismic action. Concerning this, recent studies [4, 11, 12], have shown that the vertical component in near-field earthquakes substantially modifies the structural behavior of existing unreinforced masonry buildings.

First, the two case studies and the seismic history of the areas where they are located are presented. Secondly, the FEM numerical models' implementation into the MIDAS FEA NX 2024 (v1.1) environment [13] and the assumptions made for performing the analyses are reported. Finally, the first results are illustrated and commented on. Furthermore, local seismic analyses on some architectural portions of the case studies considered are carried out in a companion paper [14].

This study presents preliminary findings from ongoing research assessing the seismic vulnerability of existing churches, with a comparative analysis carried out for Italian and Romanian masonry churches.

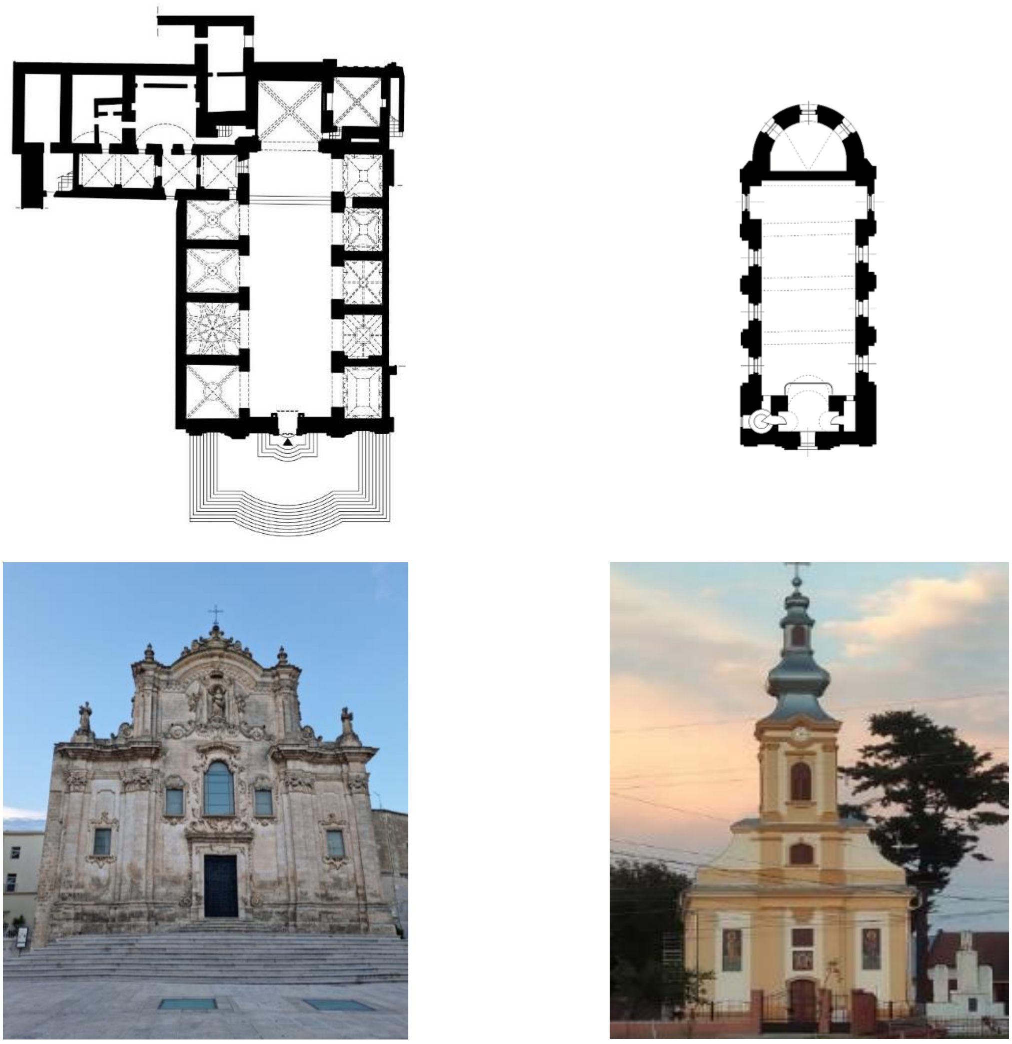
2 CASE STUDIES

The selected case studies are two existing masonry churches. The first one is named "Saint Francis of Assisi Church" (in Italian "Chiesa di San Francesco d'Assisi" – Figure 1a) and located in Matera, a city in the Basilicata Region, in the south of Italy. The current Italian Seismic Hazard Map provides the point-by-point seismic hazard over the entire national territory, expressed by means of the expected maximum horizontal acceleration. For the whole municipal territory of Matera, with a probability of exceedance of 10% in 50 years on rigid and flat soil, the seismic hazard map provides a horizontal ground accelerations in the range of a_g =

0.100g to a_g = 0.175g. Specifically, rare events of modest magnitude have been observed in proximity of the city, while the local effects of some earthquakes originating in more distant seismic areas appear more relevant. The most critical episodes affecting the municipality of Matera are those of 1845, 1978 and 1990, all classified by the MCS4 scale between grade VI and VII [15].

The second analyzed case study is the "Jesus Resurrection Church" (in Romanian "Biserică Învierea Domnului" – Figure 1b), located in the municipality of Belinț, in the north-western Romanian region of Banat, on the border with Hungary and Serbia. The Banat region suffered more than 600 earthquakes since 1773, and six of them had a magnitude ranging between Mw = 5.0 and Mw = 5.7. This region is characterized by shallow earthquakes of crustal type, with focal depths between 1 and 35 km and epicenters in the entire Banat region. It was also observed that in the last earthquakes the vertical component was not negligible [4, 16, 17].

The current Seismic Hazard Map adopted in Romania refers to the expected maximum ground acceleration for a mean return period of 225 years (20% in 50-year probability of exceedance). In particular, for Belinț municipality where Jesus Resurrection Church is located, the expected ground acceleration corresponds to a_g = 0.15 g [16, 17].



a) b)

Figure 1: Plan and main façade pictures of: a) Saint Fransis of Assisi Church in Matera; b) Jesus Resurrection Church in Belinț.

2.1 Saint Francis of Assisi Church in Matera

Saint Francis of Assisi is a Catholic church made of regular masonry of squared blocks in local calcarenite stone, improperly called "tufo". It was built between the 13th and 17th centuries, with a gradual extension from an initial layout coinciding with the present belfry. The single-nave environment was built as the first extension, then chapels were gradually added on the left side, embodying four spans of the existing convent, and finally five chapels on the right side were built. The current configuration dates back to the 17th century and the subsequent Baroque process was implemented in the original Romanesque layout during the 18th century [18], as visible from the main façade and interior stucco works. The actual plan of the church can be enclosed in a rectangle measuring about 22 m by 37 m.

The church is characterized by walls from 0.80 m to 1.70 m thick, realized according to core-and-veneer masonry where two layers are interposed by a cavity filled with incohesive material and connected by transversal blocks. The central nave is covered with a ceiling made of metal girders and clay planking built in the 20th century to replace an existing wooden floor and to mask the original wooden truss roof, which still exists [18]. All the other environments are covered by 0.25 m thick vaults differing in shapes and dimensions, belonging to the two big families of cross vaults and pavilion vaults.

As to the conservation state, materials degradation due to capillary rising and infiltration from the roofs is mainly observed; nevertheless, some short vertical cracks on the apse and belfry walls and on the lower part of the triumphal arch piers are registered. Furthermore, the belfry environment is affected by several cracks probably due to overloads, and for safety reasons a wooden shoring system was constructed.

On the main façade, the outer left wall and the apse wall, an undocumented intervention is observed, consisting of the mortar injections within the masonry. This intervention was supposed to consolidate the masonry and improve its mechanical performance [19].

2.2 Jesus Resurrection Church in Belinț

Jesus Resurrection is an Orthodox church made of local clay bricks. It is an isolated church with a single-nave rectangular plan (which can be enclosed in a rectangle measuring 11.30 m by 28.80 m) with a circular apse, whose year of construction dates back to 1797.

The perimeter walls are made of plain brickwork and vary in thickness from 0.70 m to 1.70 m. The nave is covered by a system of 0.30 m thick ribbed vaults alternated with depressed arches. The main façade has a characteristic bell tower centrally placed, terminating in a wooden spire above the belfry. The roofing of the nave is made of a system of wooden pseudo-trusses and planking, giving it a very pronounced slope. Both the roofing of the nave and the belfry are finished with galvanized sheet metal covering.

Recently (from 2014 to 2020) the church was subjected to restoration, which involved the foundation waterproofing, the replacement of fixtures, plasterwork, roofing and drainage system, and the filling of sub-vertical cracks occurring on the transept and nave walls, in correspondence of the openings.

3 PRELIMINARY FEM ANALYSIS

The preliminary FEM models of the two churches are obtained with solid meshes by means of MIDAS FEA NX 2024 (v1.1). The masonry material is implemented with the Concrete Smeared Crack Model (CSCM), by considering compression, tension and shear stress-strain relationships, as reported in Table 1. In the CSCM the compressive behavior is simulated with a typical elasto-plastic isotropic model, having parabolic hardening and softening branches. As for the tensile behavior, the cracks are simulated by regulating the stress and the stiffness at the integration point, without reconfiguring the mesh. The tension function has an exponential softening. Furthermore, the model takes into account the material damage and the cracks opening. Finally, after cracking the shear stiffness is reduced by a shear retention factor β (assumed equal to 0.05).

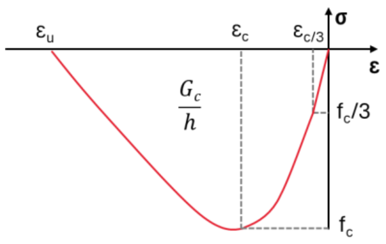
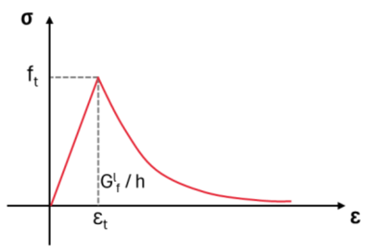
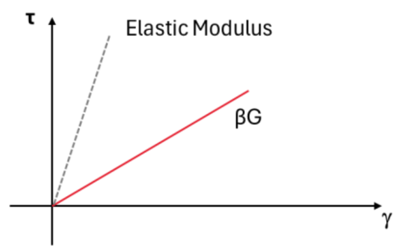
Compression function	Tension function	Shear function
		

Table 1: Functions considered for masonry smeared crack model [16].

As regards the Saint Fransis of Assisi Church, only masonry elements are modelled, according to the numerical values reported in Table 2. Vaults filling, ceilings and roofs are considered only as load applied on vaults or on walls, depending on the case. As for the Jesus Resurrection Church, all masonry and wooden components are modelled following parameters reported in Table 3, except the nave roofs, that are considered only as load applied on perimetral walls. Both churches are assumed to be fully fixed to the ground.

Non-Linear Dynamic Analysis, also indicated as Non-Linear Time History Analysis (NTHA), is implemented considering: for the Saint Fransis of Assisi Church the accelerograms of the Irpinia earthquake occurred in 1980 (Figure 2a); for the Jesus Resurrection Church the accelerogram of the Banloc earthquake occurred in 1991 (Figure 2b). Time History is carried out till 3.15 sec, with an increment of 0.05 sec per each analysis step. Figure 2a and Figure 2b report the vertical component recorded, too.

The performed preliminary analyses on the two churches are: NTHA by applying the accelerogram along only the horizontal X direction (NTHA_X), and the NTHA by simultaneously applying the accelerograms along the horizontal X direction and the vertical Z direction (NTHA_X+Z).

Calcarenite stone masonry properties	
Model type: Concrete smeared crack - Isotropic	
ρ Density (kg/m^3)	1800
E Normal elastic modulus (N/mm^2)	2256
G Tangential elastic modulus (N/mm^2)	902.4
v Poisson's ratio	0.25
f_c Compressive strength (N/mm^2)	3.84
f_t Tensile strength (N/mm^2)	0.384
G_c Compressive fracture energy (N/mm)	6.144
G_f Tensile fracture energy (N/mm)	0.011
h Mesh size (mm)	500

Table 2: Saint Francis of Assisi Church: squared stone blocks masonry mechanical properties [20, 21, 22].

Brick masonry properties		**Softwood properties**	
Model type: Concrete smeared crack - Isotropic		Model type: Elastic - Isotropic	
ρ Density (kg/m^3)	1800	ρ Density (kg/m3)	290
E Normal elastic modulus (N/mm^2)	2350	E Normal elastic modulus (N/mm^2)	7000
G Tangential elastic modulus (N/mm^2)	940	G Tangential elastic modulus	440
v Poisson's ratio	0.25	h Mesh size (mm)	300
f_c Compressive strength (N/mm^2)	2.35		
f_t Tensile strength (N/mm^2)	0.235		
G_c Compressive fracture energy (N/mm)	3.760		
G_f Tensile fracture energy (N/mm)	0.007		
h Mesh size (mm)	300		

Table 3: Jesus Resurrection Church: brick masonry and softwood mechanical properties [16].

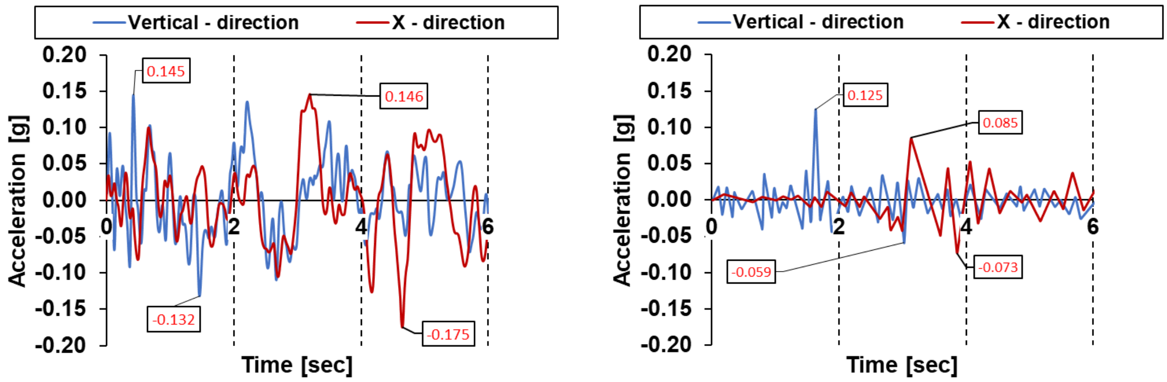


Figure 2: Earthquake accelerograms registered during the earthquakes of: a) Irpinia, 1980; b) Banloc, 1991.

4 RESULTS DISCUSSION

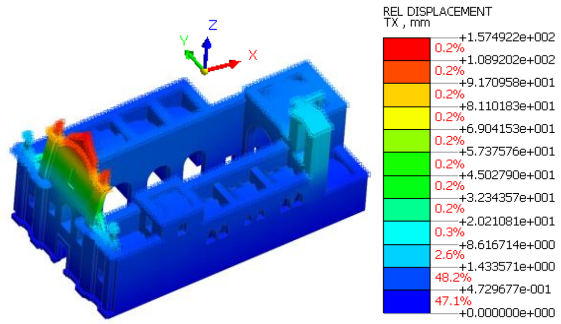
Preliminary results obtained from NTHAs on the two case studies are reported in this section. NTHAs are preliminary conducted along the horizontal X direction, without (NTHA_X) and with the vertical seismic action (NTHA_X+Z). For brevity, per each NTHA the following results are shown:

- The maximum relative displacement along the positive X direction (indicated as +TX).
- The minimum relative displacement along the negative X direction (indicated as –TX).
- The maximum axial principal stress (indicated as S-PRINCIPAL A).
- The minimum axial principal stress (indicated as S-PRINCIPAL C).
- The crack status of the church at the end of NTHA.

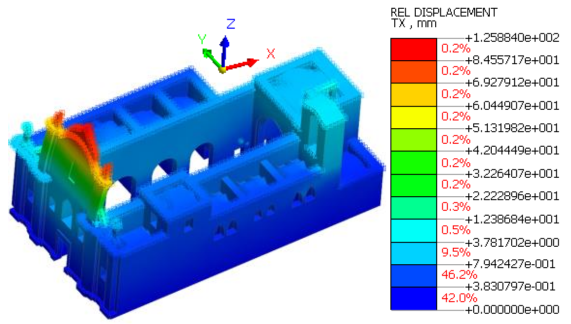
4.1 Saint Francis of Assisi Church in Matera

In Table 4 results carried out for the NTHA_X and NTHA_X+Z analyses are reported. As for the maximum and minimum relative displacements, a reduction can be observed in displacement once the Z component is considered. On the other hand, there is an important increase in tensile axial stresses and a more extensive crack pattern in the NTHA_X+Z analysis compared with NTHA_X. Finally, it can be deduced that the portion of the church most involved is the upper part of the façade. Moreover, the tensile and the compressive strengths (f_t = 0.384 N/mm^2; f_m = 3.84 N/mm^2) are both exceeded.

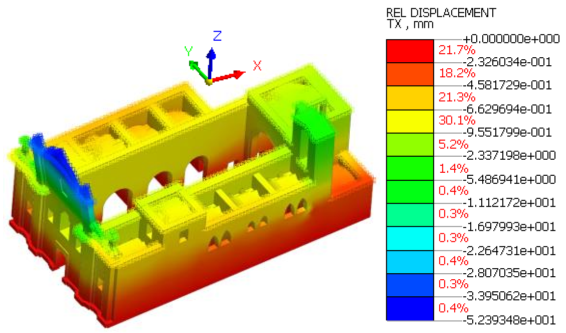
NTHA_X	**NTHA_X+Z**



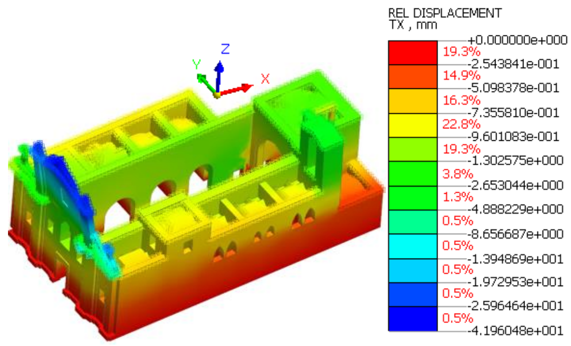
NTHA_X_max displ +TX = + 157.49 mm



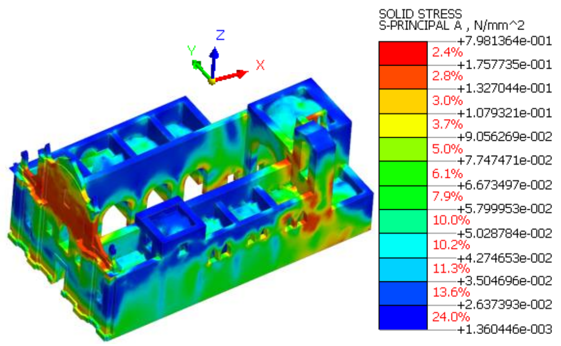
NTHA_X+Z_max displ +TX = + 125.88 mm



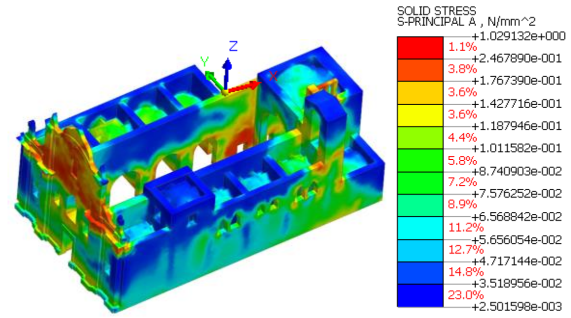
NTHA_X_min displ –TX = - 52.39 mm



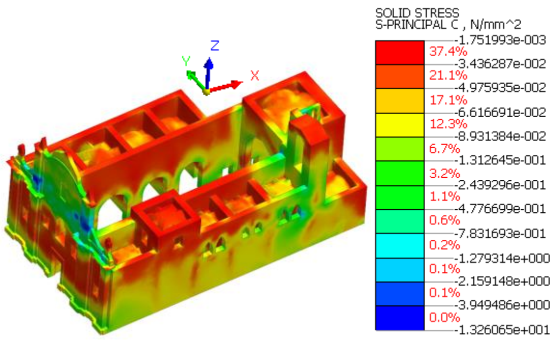
NTHA_X+Z_min displ –TX = - 41.96 mm



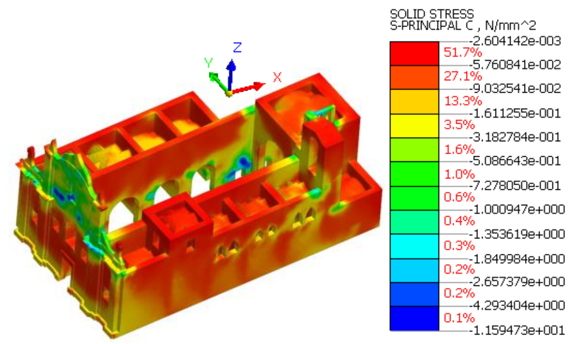
NTHA_X_max S-P. A = + 0.798 N/mm^2



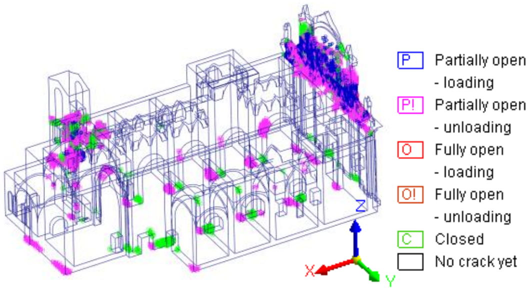
NTHA_X+Z_max S- P. A = + 1.029 N/mm^2



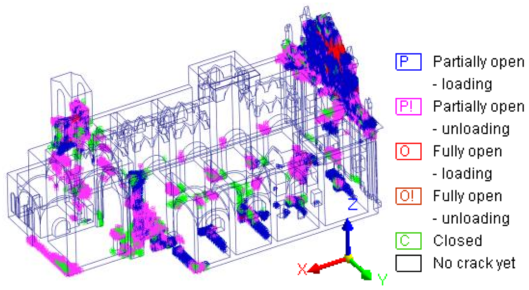
NTHA_X_min S-P. C = - 13.26 N/mm^2



NTHA_X+Z_min S-P. C = - 11.59 N/mm^2



NTHA_X_Crack status at 3.15 sec



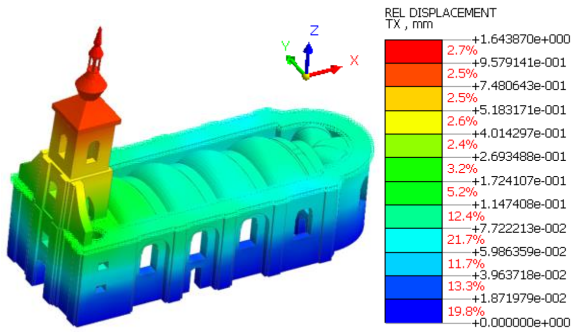
NTHA_X+Z_Crack status at 3.15 sec

Table 4: Saint Fransis of Assisi Church: NTHAs without (X) and with vertical component (X+Z).

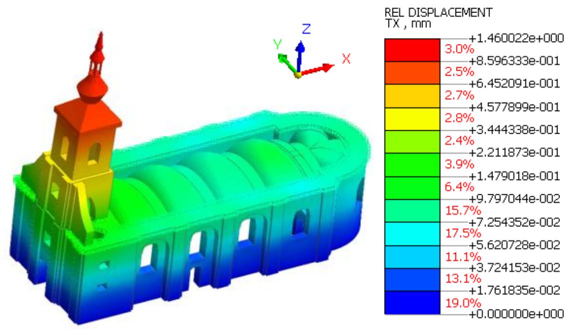
4.2 Jesus Resurrection Church in Belinț

In Table 5 results carried out for the NTHA_X and the NTHA_X+Z analyses are reported. As for the maximum and minimum displacements, a reduction can be observed in displacement once the Z component is considered, too. On the other hand, there is a modest increase in axial stresses and a slightly more extensive crack pattern in the NTHA_X+Z analysis compared with NTHA_X. Finally, it can be deduced that the portion of the church most involved in this case is the bell tower. Cracks occur at the bell tower base, on the opposite side of the façade, since the tensile stress (NTHA_X_max S-P. A = + 0.284 N/mm^2; NTHA_X+Z_max S-P. A = + 0.287 N/mm^2) exceeds the tensile strength (f_t = 0.235 N/mm^2).

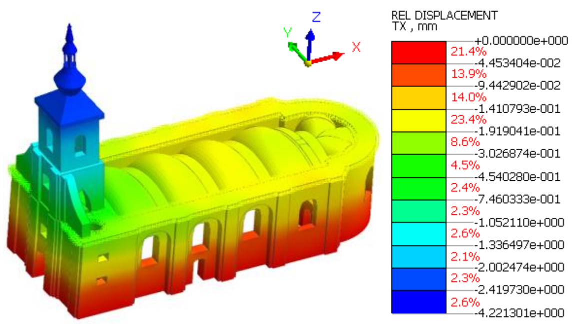
NTHA_X | **NTHA_X+Z**



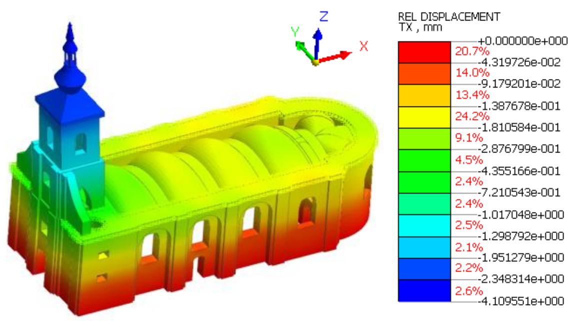
NTHA_X_max displ +TX = + 1.643 mm



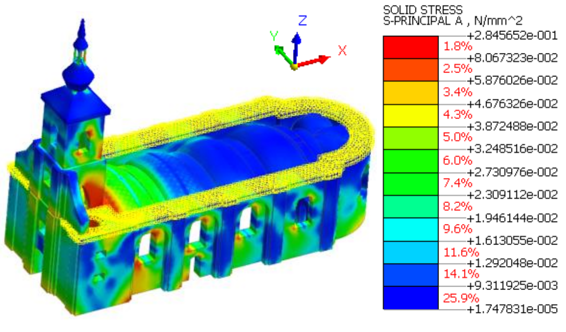
NTHA_X+Z_max displ +TX = + 1.460 mm



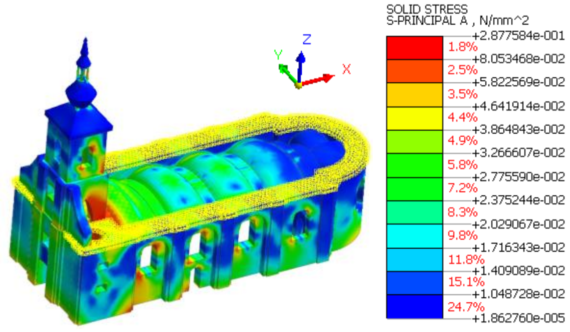
NTHA_X_min displ –TX = - 4.221 mm



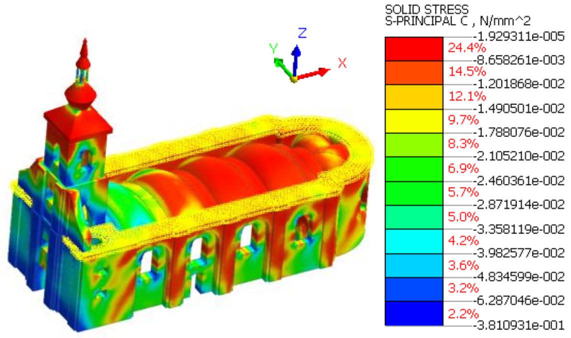
NTHA_X+Z_min displ –TX = - 4.109 mm



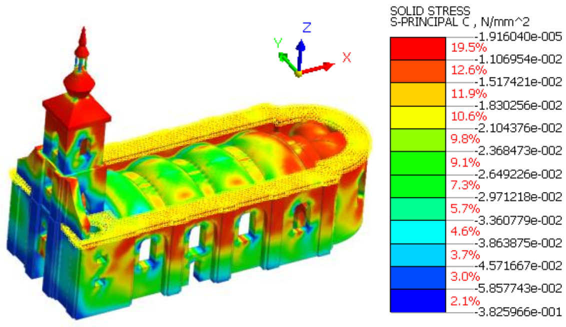
NTHA_X_max S-P. A = + 0.284 N/mm^2



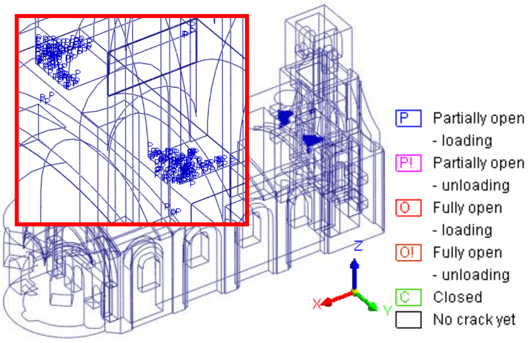
NTHA_X+Z_max S- P. A = + 0.287 N/mm^2



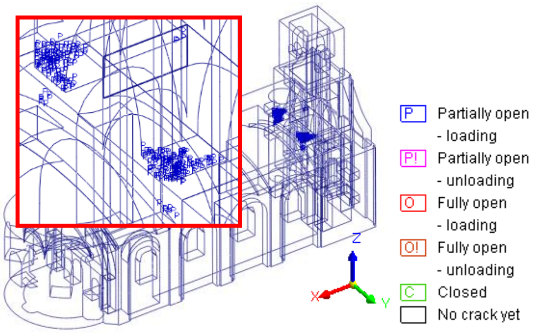
NTHA_X_min S-P. C = - 0.381 N/mm^2



NTHA_X+Z_min S-P. C = - 0.382 N/mm^2



NTHA_X_Crack status at 3.15 sec



NTHA_X+Z_Crack status at 3.15 sec

Table 5: Jesus Resurrection Church: NTHAs without (X) and with vertical component (X+Z).

5 CONCLUSION

In this work, preliminary results on the seismic behavior of two existing masonry churches located in Italy and Romania have been shown. Non-Linear Time History Analyses have been conducted by without and with the vertical component, in order to highlight how this component may affect the horizontal response during an earthquake. Preliminary results show that, by considering the vertical component, an increase in the axial stresses and the extent of the crack pattern are obtained. In the future, it is intended to further investigate the seismic behavior of these two case studies by also considering the horizontal Y component of the accelerogram and its combination with the vertical one.

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REFERENCES

[1] V. Despotaki, V. Silva, S. Lagomarsino, I. Pavlova, and J. Torres, Evaluation of Seismic Risk on UNESCO Cultural Heritage sites in Europe, *International Journal of Architectural Heritage*, vol. 12, no. 7–8, pp. 1231–1244, Nov. 2018, doi: https://doi.org/10.1080/15583058.2018.1503374.

[2] J. Taboroff, Cultural heritage and natural disasters: incentives for risk management and mitigation, in *Managing disaster risk in emerging economies*, vol. 2, ch. 7, pp. 71–79, 2000.

[3] M. Zizi, J. Rouhi, C. Chisari, D. Cacace, and G. De Matteis, Seismic Vulnerability Assessment for Masonry Churches: An Overview on Existing Methodologies, *Buildings*, vol. 11, no. 12, p. 588, Nov. 2021, doi: https://doi.org/10.3390/buildings11120588.

[4] N. Chieffo, M. Mosoarca, A. Formisano, P. B. Lourenço, and G. Milani, The effect of ground motion vertical component on the seismic response of historical masonry buildings: The case study of the Banloc Castle in Romania, *Engineering Structures*, vol. 249, p. 113346, Dec. 2021, doi: https://doi.org/10.1016/j.engstruct.2021.113346.

[5] A. Lo Monaco et al., Seismic assessment of typical historical masonry churches in the Banat region, Romania - Part II, in *Procedia Structural Integrity (2023)* - XIX Conference of Associazione Nazionale Italiana di Ingegneria Sismica (ANIDIS 2022), Sep. 11-15, 2022, doi: https://doi.org/10.1016/j.prostr.2023.01.261.

[6] G. Milani, Lesson learned after the Emilia-Romagna, Italy, 20–29 May 2012 earthquakes: A limit analysis insight on three masonry churches, *Engineering Failure Analysis*, vol. 34, pp. 761–778, Dec. 2013, doi: https://doi.org/10.1016/j.engfailanal.2013.01.001.

[7] M. Valente & G. Milani, Seismic response and damage patterns of masonry churches: Seven case studies in Ferrara, Italy, *Engineering Structures*, vol. 177, pp. 809–835, Dec. 2018, doi: https://doi.org/10.1016/j.engstruct.2018.08.071.

[8] A. Lo Monaco, A. Ranaldo, R. Sulla, and M. D'Amato, Overview of multilevel seismic risk assessments on existing buildings - *22nd International Conference on Numerical Analysis and Applied Mathematics (ICNAAM 2024)*, Crete, Greece, Sep. 11-17, 2024. *In press.*

[9] M. D'Amato & R. Sulla, Investigations of masonry churches seismic performance with numerical models: application to a case study, *Archives of Civil and Mechanical Engineering*, vol. 21, no. 161, 2021, doi: https://doi.org/10.1007/s43452-021-00312-5.

[10] A. Lo Monaco et al., Seismic response of historical masonry churches: the case of the Banat Romanian region, in ECCOMAS Procedia (2023) - *9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*

(COMPDYN 2023), Athens, Greece, Jun. 12-14, 2023, pp. 1669–1686, doi: 10.7712/120123.10510.20637.

[11] G. Rinaldin, M. Fasan, S. Noé, and C. Amadio, The influence of earthquake vertical component on the seismic response of masonry structures, *Engineering Structures*, vol. 185, pp. 184–193, Apr. 2019, doi: https://doi.org/10.1016/j.engstruct.2019.01.138.

[12] F. Di Michele, C. Cantagallo, and E. Spacone, Effects of the vertical seismic component on seismic performance of an unreinforced masonry structures, *Bulletin of Earthquake Engineering*, vol. 18, no. 4, pp. 1635–1656, Mar. 2020, doi: https://doi.org/10.1007/s10518-019-00765-3.

[13] CSPFEA - Engineering solutions, Midas FEA NX 2024 (v1.1).

[14] A. Ranaldo, A. Lo Monaco, M. D'Amato, R. Gigliotti, and M. Mosoarca, Finite element modelling for seismic assessment of existing masonry churches – Part II: local analyses - *10th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2025)*, Rhodes Island, Greece, Jun. 15-18, 2025.

[15] Municipality of Matera and Civil Defense Basilicata Region, Report on hazard scenarios. Municipal Civil Defense Plan (in Italian), Matera, Feb. 2017. Accessed: Mar. 3, 2025. [Online]. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.comune.mt.it/wp-content/uploads/2024/01/A.2.1-Relazione-sugli-scenari-di-rischio.pdf.

[16] A. Lo Monaco et al., Seismic assessment of Romanian Orthodox masonry churches in the Banat area through a multi-level analysis framework, *Engineering Failure Analysis*, vol. 153, no. 107539, Nov. 2023, doi: https://doi.org/10.1016/j.engfailanal.2023.107539.

[17] Romanian Design Code P100-1/, Ministry of Regional Development Public Administration and European Funds, 2013 (in Romanian).

[18] AA.VV., Matera Saint Francis Square. Origin and evolution of an urban area, *BMG*, Matera, 1986 (in Italian).

[19] I. Hafner, T. Kišiček, and M. Gams, Review of Methods for Seismic Strengthening of Masonry Piers and Walls, *Buildings*, vol. 13, no. 1524, 2023.

[20] Giuffrè A. & Carocci C., Codice di pratica per la sicurezza e la conservazione dei Sassi di Matera, *Edizioni La Bautta*, Matera, 1997 (in Italian).

[21] G.U. n. 35, Circular n.7 - NTC 2018, 2019 (in Italian).

[22] Code CEB-FIP Model. 1990. Comité Euro-International Du Béton (CEB), 1993.