The Fourteenth International Conference on
Computational Structures Technology
23–25 August, 2022 | Montpellier, France

Proceedings of the Fourteenth International Conference on
Computational Structures Technology
Edited by B.H.V. Topping and J. Kruis
Civil-Comp Conferences, Volume 3, Paper 8.2
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.3.8.2

Damage assessment of different Churches in Central Italy

M. Schiavoni[1], E. Giordano[1], A. Ferrante[2], F. Clementi[1] and S. Lenci[1]

[1]Dept. of Civil and Building Engineering, and Architecture, Polytechnic University of Marche, Ancona, Italy
[2]Laboratoire de Mécanique et Génie Civil (LMGC), CNRS, University of Montpellier, Montpellier, France

Abstract

The present work shows the seismic vulnerability analysis of three churches located in Camerino, a village that has reported extensive damages, especially to the monumental historical buildings, after the Central Italy Earthquakes. The churches were studied with local and global analysis, these last were performed using accurate 3D Finite Element Models where the post-elastic behaviour of masonry was considered by Total Strain Crack Model. The study showed as the use of non-linear static analysis is able to reproduce with good approximation the cracks provoke by the quakes.

Keywords: central Italy earthquakes, masonry churches, finite element model, linear dynamic analysis, total strain crack model, non-linear static analysis.

1 Introduction

In this paper are analysed three churches located in Camerino, a village in the crater area of the last 2016 Central Italy Earthquakes. Camerino was exposed to several strong quakes during the centuries, that have provoked numerous damages and victims, the most serious one occurred in 1799 when only Camerino counted 60 victims. Last Central Italy Earthquake, which was characterized by four main shocks with respective epicentres located in Amatrice (Mw=6.0), Campi (Ussita) (Mw=5.9), Colfiorito (Norcia) (6.5) and Capitignano (Mw=5.5), also provoked several failures in the village. Among all the damaged buildings numerous were the recorded damages to ecclesiastic structures that, once again, underlined their vulnerability to quake actions [1–10]. In this study are choose the three mains important churches of Camerino (Figure 1) declared unsafe after the 2016 earthquakes:

- Santa Maria in Via
- San Venanzio
- Santa Maria Annunziata

San Venanzio and Santa Maria Annunziata have a Latin-cross plan, respectively of sizes 39x68 and 29x60m, the first has a bell-tower on the North-Est side of 45m, instead, Santa Maria Annunziata has two in the sides of the facade. Santa Maria in Via is the smallest one, it has an elliptic plant of 28m larger diameter and a bell-tower of 15m.

The study wants to underline the capacity of 3D Numerical Models to reproduce the seismic damage using linear and non-linear analyses. To represent the nonlinear behavior the Total Strain Crack Model is used assigning appropriate constitutive laws in tension, compression and shear.

2 Methods

In this paper, the three churches were analysed considering local and global behaviours following the Italian Guidelines [11,12].

For the local, the structures were divided into macro-elements considering the actual cracks, their capacity was analysed by a kinematic approach comparing the activation acceleration with the PGA waiting for the Limit State of Significant Damage.

To study the global behaviour, instead, the geometries of buildings were reproduced carefully in 3D Models that, subsequently, were discretized by tetrahedral bricks elements using Midas FEA software [13] (Figure 2). This choice is due to the impossibility to simplify these structures for the absence of horizontal floors, openings not aligned, etc. This approach is called Macro-Modelling where no distinctions are made between brick and lime and the material is considered as isotropic, to represent the post-elastic behaviour the Total Strain Crack Model was used assign different constitutive laws. In compression was define a parabolic law, in tension a Hordjik law and a linear behaviour for the shear [14–16], both linear and nonlinear materials parameters were considered by previous investigation and literature data. The Finite Element Models were used to perform linear dynamic analysis and Non-linear static analysis, for the latter two types of inertial distribution forces were assigned following the Italian Code, one proportional to the modal shapes (PushMode) and one proportional to the masses (PushMass). The nonlinear results allowed to extract the capacity curves force-displacement for different control nodes taken on the churches top, they have permit, also, to compare the numerical with the real cracks.

3 Results

The first analyses performed were the linear dynamics, they were used to identify the main modal shapes and compare their periods with those recorded during the 30th October 2016 shook. Observing the Figure 3 it is evident as the accelerations recorded at Camerino the 30th October were high especially in North direction, being double

respect the expected acceleration for this type of structures, Class II and ordinary buildings, for Limit State of Significant Damage (SLSD or SLV in Italian).
The Figure 3 shows that the bell-towers are involved in all the cases, due to their particular conformation. The Latin-cross churches have as other weak elements the lateral walls nave, whereas, the elliptic church has the façade. Comparing the periods, it is evident that the main shapes are near the acceleration peaks, indeed, all these elements presented spread cracks after the 2016/17 quakes Figure 4.
After this first proof of model dependability the non-linear analyses were carried out using the arch-length Method and the initial stiffness method, imposing the following parameters:

- Maximum number of iterations of load increment: 100;
- Maximum analysis number of sub-steps: 1000;
- Minimum analysis number of sub-steps:5;
- Initial load factor 0.1;
- Energy norm tolerance 10^-3.

The curves force-displacement obtained have shown different capacities in X and Y direction and for PushMass e PushMode analysis. For example, the Santissima Annunziata church is more resistant in Y-Direction (longitudinal Direction) respect X-Direction (transversal-Direction).
To verify the models capacity to reproduce the real behaviours, also the cracks obtain by non-linear static analyses were compared with the real ones that occurred. In Figure 5 it is possible to see that in Santa Maria in Via church and in Santissima Annunziata church the cracks are recreated with good approximation.

4 Conclusions and Contributions

The paper analysed three churches located in Camerino, a village that suffered serious damages from the last Central Italy Earthquake. The churches analysed are: (i) the Santa Maria in Via Church, (ii) Santa Maria Annunziata Church and (iii) San Venanzio Church, all of them were considered unsafe after the quakes, at present, only San Venanzio church was reopened on 16th December 2019.
The most damaged was Santa Maria in Via that the 26th October suffered the bell-tower collapse, this event had a strong resonance in Italy because it destroyed a nearby building.
These earthquakes showed again the high vulnerability of these type of structures and that their failure can be dangerous for the near structures. To preserve them and to prevent uncontrolled failures it is necessary to identify their vulnerability to intervene as soon as possible.
This aim is here presented using kinematic analyses on macro-element, dynamic linear analyses and nonlinear static analyses on 3D Finite Element Models. The study showed as this type of modelling is useful to identify the most vulnerable elements and to evaluate their seismic capacities.
The cracks obtain by non-linear static analysis shown the reliability of numerical models with some approximations that could be overcome with dynamic non-linear analyses even it will require more computation time.

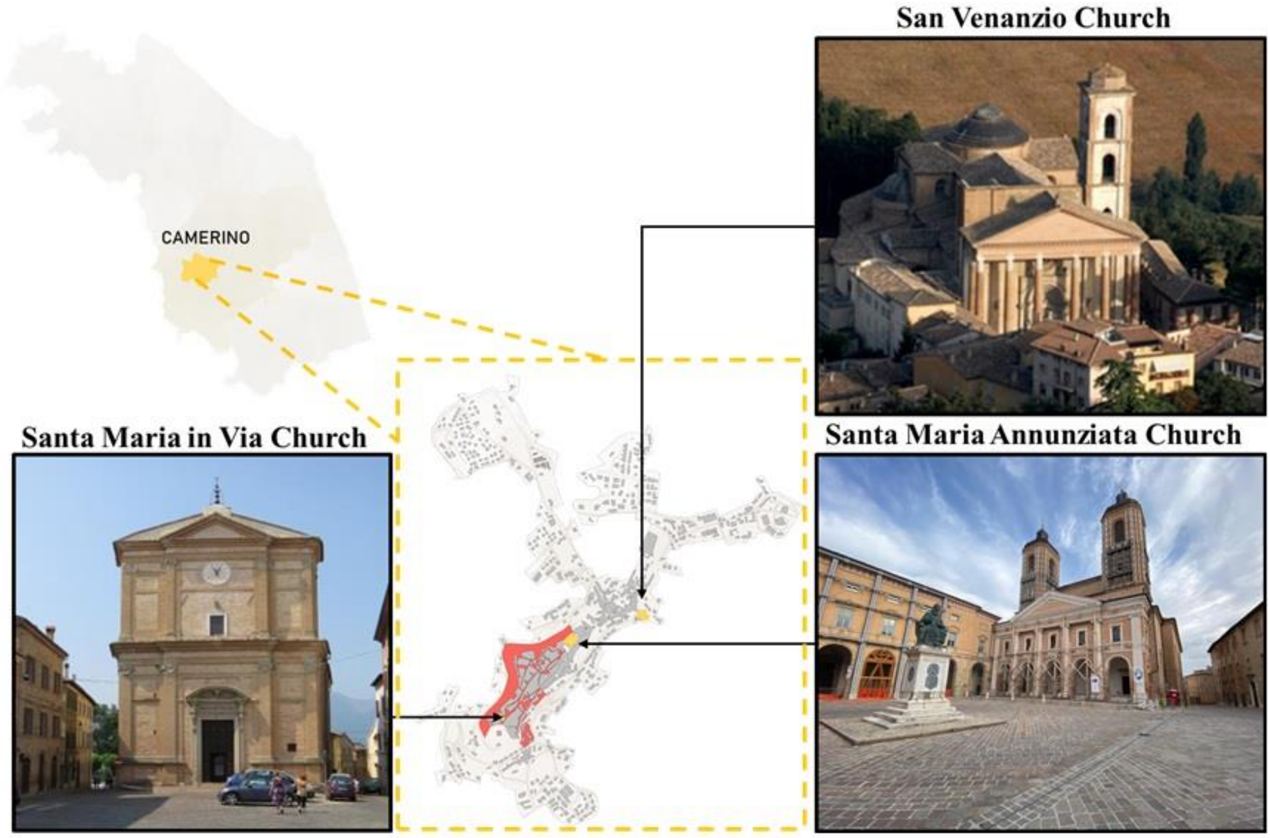

Figure 1: Geographical localization of the churches analysed.

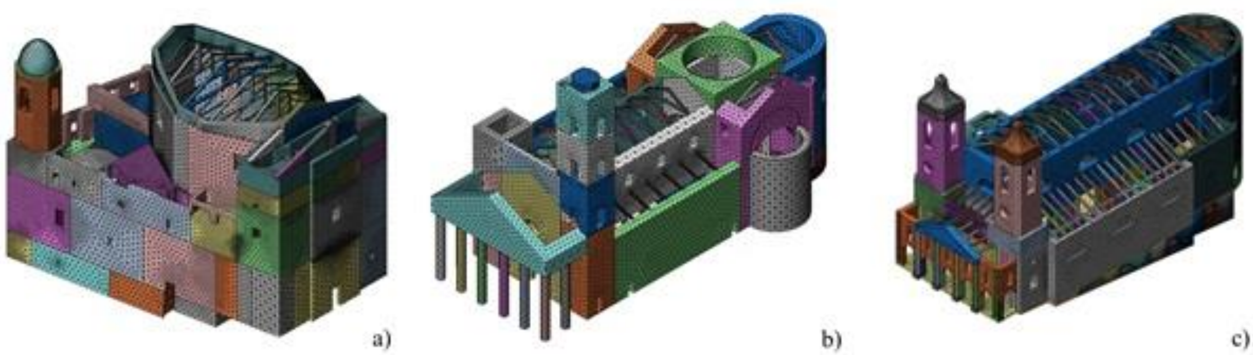

Figure 2: Numerical models of a) Santa Maria in Via; b) San Venanzio; b) Santa Maria Annunziata.

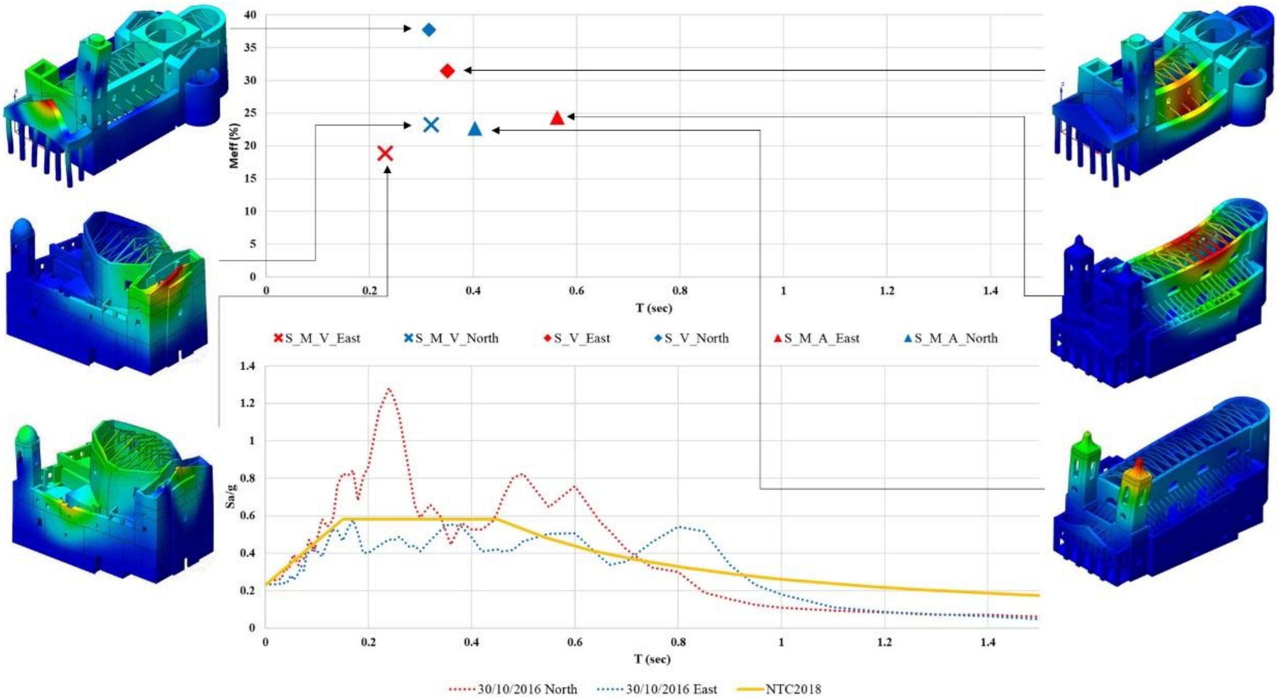

Figure 3: Distribution of principal modal shapes in the North and East directions and comparison with the pseudo-acceleration response spectra of the main shock of Central Italy 2016-2017 seismic sequence.

Figure 4: Some cracks after the Central Italy Earthquake, a) Partial collapse of one façade side of Santa Maria in Via; b) Cracks spread on the walls and the vault of San Venanazio; c) Crack in correspondence of the Clock of one Santissima Annunziata bell-tower.

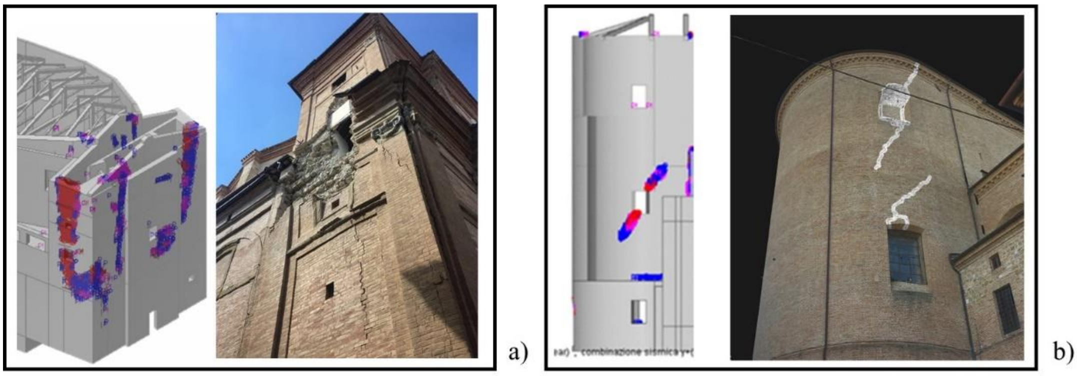

Figure 5: Correspondence between numerical and real cracks for a) Santa Maria in Via; b) Santa Maria Annunziata.

References

[1] F. Clementi, A. Ferrante, E. Giordano, F. Dubois, S. Lenci, Damage assessment of ancient masonry churches stroked by the Central Italy earthquakes of 2016 by the non-smooth contact dynamics method, Bull. Earthq. Eng. (2019). doi:10.1007/s10518-019-00613-4.

[2] E. Giordano, F. Clementi, A. Nespeca, S. Lenci, Damage Assessment by Numerical Modeling of Sant’Agostino’s Sanctuary in Offida During the Central Italy 2016–2017 Seismic Sequence, Front. Built Environ. 4 (2019). doi:10.3389/fbuil.2018.00087.

[3] G. De Matteis, M. Zizi, Preliminary Analysis on the Effects of 2016 Central Italy Earthquake on One-Nave Churches, in: 2019: pp. 1268–1279. doi:10.1007/978-3-319-99441-3_136.

[4] G. Milani, M. Valente, Failure analysis of seven masonry churches severely damaged during the 2012 Emilia-Romagna (Italy) earthquake: Non-linear dynamic analyses vs conventional static approaches, Eng. Fail. Anal. 54 (2015) 13–56. doi:10.1016/j.engfailanal.2015.03.016.

[5] A. Ferrante, F. Clementi, G. Milani, Dynamic Behavior of an Inclined Existing Masonry Tower in Italy, Front. Built Environ. 5 (2019). doi:10.3389/fbuil.2019.00033.

[6] A. Formisano, G. Vaiano, F. Fabbrocino, G. Milani, Seismic vulnerability of Italian masonry churches: The case of the Nativity of Blessed Virgin Mary in Stellata of Bondeno, J. Build. Eng. 20 (2018) 179–200. doi:10.1016/j.jobe.2018.07.017.

[7] E. Giordano, F. Clementi, A. Barontini, M. Giovanna, E. Chatzi, F. Luís, Damage detection and optimal sensor placement in health monitoring of “ Collegiata di Santa Maria ” in Visso (Central Italy) Damage detection and optimal sensor placement in health monitoring of “ Collegiata di Santa Maria ” in Visso (Central Italy), (2019) 44–53.

[8] E. Giordano, A. Ferrante, E. Ribilotta, F. Clementi, S. Lenci, Damage

Assessment of San Francesco Church in Amandola Hit by Central Italy 2016-2017 Seismic Event, Key Eng. Mater. 817 (2019) 627–633. doi:10.4028/www.scientific.net/KEM.817.627.
[9] A. Ferrante, E. Ribilotta, E. Giordano, F. Clementi, S. Lenci, Advanced Seismic Analyses of “Apennine Churches” Stroked by the Central Italy Earthquakes of 2016 by the Non-Smooth Contact Dynamics Method, Key Eng. Mater. 817 (2019) 309–316. doi:10.4028/www.scientific.net/KEM.817.309.
[10] E. Ribilotta, E. Giordano, A. Ferrante, F. Clementi, S. Lenci, Tracking Modal Parameter Evolution of Different Cultural Heritage Structure Damaged by Central Italy Earthquake of 2016, Key Eng. Mater. 817 (2019) 334–341. doi:10.4028/www.scientific.net/KEM.817.334.
[11] Ministero delle Infrastrutture e dei Trasporti, DM 17/01/2018 - Aggiornamento delle “Norme Tecniche per le Costruzioni” (in italian), (2018) 1–198.
[12] M. delle infrastrutture e dei trasporti, Circolare 21 gennaio 2019 n. 7 C.S.LL.PP. Istruzioni per l’applicazione dell’aggiornamento delle “Norme Tecniche per le Costruzioni” di cui al D.M. 17/01/2018 (in Italian), Suppl. Ord. Alla G.U. n. 35 Del 11/2/19. (2019).
[13] Midas FEA, Analysis and Algorithm Manual, (2016).
[14] J.G. Rots, Smeared and discrete representations of localized fracture, Int. J. Fract. 51 (1991) 45–59. doi:10.1007/BF00020852.
[15] P.B. Lourenço, Recent advances in masonry modelling: micromodelling and homogenisation, in: Multiscale Model. Solid Mech. Comput. Approaches, 2009: pp. 251–294. doi:10.1142/9781848163089_0006.
[16] J.G. Rots, R. de Borst, Analysis of Mixed-Mode Fracture in Concrete, J. Eng. Mech. 113 (1987) 1739–1758. doi:10.1061/(ASCE)0733-9399(1987)113:11(1739).