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Seismic vulnerability of churches. First results of the study on three façade typologies

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ABSTRACT
The series of seismic events which have struck the Italian territory have allowed the damage observation for different typologies of unreinforced masonry buildings. In particular, churches are constantly studied because of their high vulnerability observed in seismic prone areas. The façade is one of the most vulnerable structural units, called macro-elements. Up to date, three kinematic mechanisms (overturning of the façade, gable mechanism and in-plane mechanism) have been identified for damage and vulnerability assessment procedures.
In this context, this work focuses on the analysis of three façade typologies diffused on the Italian territory. The aim is to evaluate the seismic response of three façade typologies, different for geometry and construction technique, in order to provide a contribution on their seismic vulnerability assessment. The study was performed through non-linear dynamic analyses, recurring to a model constituted of rigid elements connected by springs (RBSM: Rigid Body Spring Model). The RBS-model simulates the out-of-plane behavior and it considers the orthotropic nature of the masonry, assigning phenomenological elastic-plastic laws to the springs.

1 INTRODUCTION

Earthquakes pose a threat to the cultural heritage asset, that in Italy is largely composed of churches. The intrinsic characteristics of this building category makes them highly vulnerable to seismic solicitations. This aspect has been systematically observed and studied after the seismic events occurred in the last decades in Italy, such as the 1976 Friuli, the 1997 Umbria-Marche, the 2002 Molise, the 2004 L'Aquila, the 2012 Pianura Padana, the 2016 Central Italy earthquakes (e.g. Doglioni et al. 1994, Lagomarsino 2004a, Lagomarsino 2004b, Lagomarsino 2009, Sorrentino et al. 2014, Valente et al. 2017, Penna et al. 2019). These experiences brought to the definition of specific methods for the damage and vulnerability assessment. For these evaluations a list of 28 kinematic failure mechanisms have been elaborated and they have been employed in the official damage survey form A-DC (MiBAC, PCM-DPC 2006) and in the recommended procedure for the seismic vulnerability assessment (MiBACT 2011). Some of the mechanisms, enumerated in the list, exemplify the kinematic behaviour of the façade macro-element. Past post-earthquake damage recognitions, have demonstrated that this is one of the most vulnerable part of the church building.

At the same time, numerical codes and software, able to simulate the structural behaviour of masonry structures, have been developed and improved.

In this context, the present work intends to investigate the seismic vulnerability of three configurations of façades that can be found in the Italian territory and that were identified from some post-earthquake recognitions in Central Italy (Parisi et al. 2018, Sferrazza Papa and Silva 2018) and damage consultations from archives. Recurring to a discrete model of rigid elements, connected by springs (RBSM: Rigid Body Spring Model), some non-linear dynamic analyses were performed. This model allows to simulate the damage for out-of-plane modes, considering the orthotropic behaviour of the masonry. This is possible thanks to the phenomenological laws assigned to the elastic-plastic springs (Casolo 2000, Casolo and Uva 2013).

The objective of this paper is to present some initial results of the influence of construction techniques and geometries on the seismic vulnerability of three façades. In this study the façade was considered perfectly connected with the transversal walls. Three church case studies from different geographical areas, with different configurations and construction techniques, were studied, simulating the response to different seismic intensities. The investigated church façades are those relative to San Salvatore in Acquapagana (MC), San Francesco in Tolentino (MC), and San Giovanni Battista in San Giovanni del Dosso (MN). After a short explanation of the RSB-Model, the earthquake strong motions selected for the analyses and the façades case studies are presented. Then, the local model of each façade and the assigned material properties are explained. Finally, the results obtained from the analyses are presented in terms of damage patterns and residual displacements, for each façade typology.

2 OUT OF PLANE RIGID BODY-SPRING MODEL

The seismic response of the masonry church façades was evaluated with an out-of-plane rigid body-spring model (RBSM). According to the RBSM, a façade is discretized in quadrilateral rigid elements connected through elastic-plastic spherical joints (Figure 1). The joints are constituted by two rotational springs, whose behaviour considers the masonry peculiarities at the macroscale. The use of this kind of model is justified by the post-earthquake damage observation of masonry façades. Church façades usually get damaged developing cylindrical yield lines (hinges); for such a reason, the membrane dynamic effects and the in-plane damage mechanisms were neglected in this study.

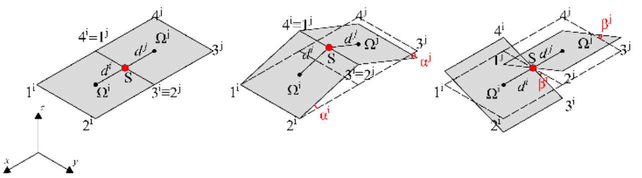


Figure 1. Bending and twisting deformation of two connected rigid elements.

A discrete model, as in this case the RBSM, allows to reduce the computational effort for a non-linear dynamic analysis (Kaway 1978). The non-linearities are concentrated in the springs and the degrees of freedom are just 3n, where n is the number of the mesh elements. Furthermore, the model considers the following specificities of masonry: the very low tensile strength; the dependence of the shear strength on the vertical compression stress; the progressive mechanical degradation; and the orthotropy combined with the texture effects.

Each pair of rigid elements is connected by a bending and a twisting spring, whose behaviour is defined through a moment-curvature ($M-\chi$) relation. The average curvatures of the springs χ_f and χ_t are defined as:

$$\begin{Bmatrix}\chi_f\\ \chi_t\end{Bmatrix} = \frac{1}{d^i+d^j}\begin{bmatrix}\cos\vartheta & \sin\vartheta\\ -\cos\vartheta & \cos\vartheta\end{bmatrix}\begin{Bmatrix}\alpha^j-\alpha^i\\ \beta^j-\beta^i\end{Bmatrix} \qquad (1)$$

Where: d^i and d^j are the distances of the connection point from the centres of gravity of the two connected elements i and j; α^i and β^i are the rotations, of the i-element, around the y and the x axis respectively.

The bending springs control the relative rotation around the edge, whereas the twisting ones control the relative rotation around the normal to the edge in the plane of the elements. The moment-curvature law of the bending springs considers the different masonry behaviour for rotation around an horizontal and a vertical axis. In fact, the rotation around an horizontal axis is influenced by the vertical compression stress and by the interlocking among the masonry leaves. In case of a multi-leaf masonry wall, widely diffused in the Italian cultural heritage, the moment for an assigned value of curvature $M_t^h(\chi)$ is equal to the sum of the moments in the l leaves $M_i^h(\chi)$, as if they were completely uncoupled, plus an additional value that considers the interlocking among the leaves $M_c^h(\chi)$.

$$M_t^h(\chi) = \sum_{i=1}^{l} M_i^h(\chi) + M_c^h(\chi) \qquad (2)$$

The rotation around the vertical axis is influenced by the shear response of the bed joints. The spring law considers the vertical compression stress, the friction coefficient ϕ and the number of bed joints in the representative volume element (dashed black lines in the figure), function of the block dimension (Figure 2) (Casolo and Milani 2013). This aspect is considered through a shape coefficient ρ. Finally, for the twisting springs an average of the bending spring laws is considered.

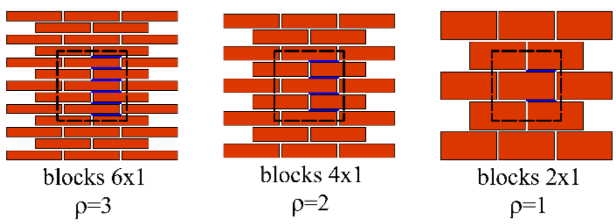


Figure 2. Influence of the brick geometry on the horizontal bending response.

3 DESCRIPTION OF THE CASE STUDIES

3.1 San Francesco in Tolentino (MC)

Figure 3. The façade of San Francesco in Tolentino (MC).

The church of San Francesco is located in Tolentino (MC). This church has a rectangular and regular plan. It has niches on both sides of the nave and massive buttresses in correspondence of the arches, giving rhythm to the nave. One of the buttresses, per each side of the nave, is built against the façade, increasing the stiffness of this macro-element. The church was built in XIII century, with the last transformations in the XVIII century, related to the vault system of the nave. The façade of this church clearly shows the brick texture, relegating the plaster to the pilasters and the cornices (Figure 3). The masonry wall of the façade is made of thin bricks with a dimension of 24x4 cm. The thickness of the façade wall is about 95 cm and, in absence of non-destructive tests (NDT), it was considered for the aim of this study as a single leaf wall. This hypothesis was elaborated in consequence of some damage observations of historical buildings, of the same period, located in the same urban centre.

The damage form for this church, filled after the 2016 Central Italy earthquake, reports the following levels of damage according to EMS-98 (Grunthal et al. 1998): 2 (moderate damage) for the overturning of the façade and 3 (severe damage) for the gable mechanism.

3.2 San Giovanni Battista in San Giovanni del Dosso (MN)

Figure 4. The façade of San Giovanni Battista in San Giovanni del Dosso (MN).

The church of San Giovanni Battista in San Giovanni del Dosso (MN) is an example of baroque church. Other churches of this style were found among the damaged churches after the 2012 Pianura Padana earthquake. The church was built in the 1616 and it is a three nave church. The façade is characterized by a central principal entrance in axis with the rose window and two secondary doors symmetrically disposed per each side and corresponding to the lateral naves. Moreover, one cornice separates the first from the second order of the openings, and another distinguishes the second order from the lofty gable. An arch, built against the façade, is the last element of a repetitive structure of arches and vaults that covers the central nave. The façade has a rhythm associated with the pilasters (Figure 4). The masonry wall of the façade is made of thin bricks organized with a regular pattern that were visible from photos taken inside the church at the roof level. Also in this case, in absence of non-destructive tests (NDT), the masonry section was considered constituted of just one single leaf.

The damage form for this church, filled after the 2012 Pianura Padana earthquake, reports the following levels of damage: 4 (extremely severe damage) for overturning of the façade and 5 (collapse) for the gable mechanism.

3.3 *San Salvatore in Acquapagana (MC)*

Figure 5. The façade of San Salvatore in Acquapagana (MC)

The church of San Salvatore in Acquapagana (MC) is an example of the medieval typology, diffused in Central Italy. The church was built in XI century, it has a single and symmetric nave with the entrance in axis with the square apse. The roof is a light timber one. The façade reflects the simplicity of the church with a hut shape and a simple white stone portal (Figure 5). The masonry wall of the façade consists of three leaves with some cross-stone blocks. The external leaves are made of square stones, joined by thin layers of mortar, arranged to form a regular pattern (Sferrazza Papa and Silva 2018).The façade is 90 cm thick, while the lateral walls are 83 cm.

The damage form for this church, filled after the 2016 Central Italy earthquake, reports the following levels of damage: 2 (moderate damage) for the overturning of the façade and 3 (severe damage) for the gable mechanism.

4 SELECTED STRONG GROUND MOTIONS

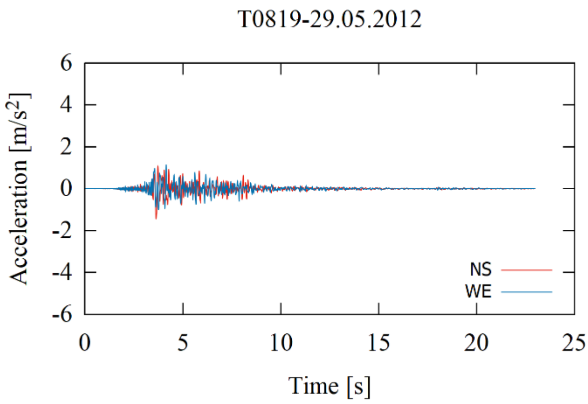
For the non-linear dynamic analyses, three different registered accelerograms were considered. Two of them belong to the 2012 Pianura Padana earthquake sequence and one to the 2016 Central Italy earthquake. Table 1 reports the information of the considered accelerograms. The accelerograms are characterized by increasing values of peak ground acceleration (PGA). These values reflect the Italian seismic classification for moderate and high seismicity (OPCM 2006).

Table 1. Data of the registered accelerograms obtained from the ITACA database (Luzi et al. 2019).

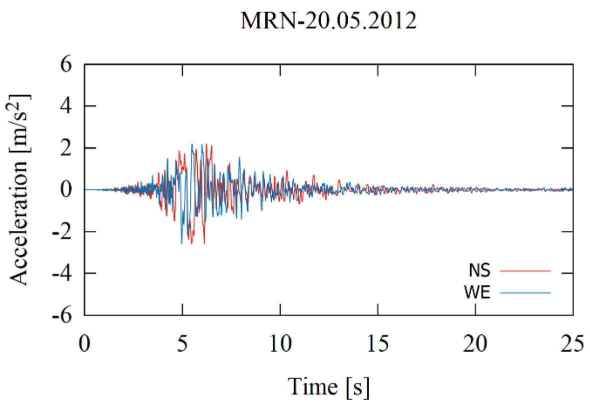
Seismic Event	29/05/2012 h 11:00 Northern Italy	20/05/2012 Emilia	30/10/2016 Central Italy
Station	Novi di Modena (T0819)	Mirandola (MRN)	Castelluccio di Norcia (CLO)
Soil type EC8	C	C	A
Epicentral distance (km)	6.6	16.1	7.8
Magnitude (Mw)	5.5	6.1	6.5
PGA (g)	0.146	0.264	0.582

The North-South (NS) and East-West (EW) components of the considered accelerograms are reported in Figure 6. For all the ground motions, the NS component has higher values of acceleration than the EW. For this reason, the NS accelerogram was applied to the façade and the EW to the lateral walls. In Figure 6, the elastic response spectra of the recorded accelerograms are compared with the response spectra of the church sites according to the Italian Building Code (NTC 2018).

Figure 7 shows that the CLO-30.10.2012 spectral accelerations are higher than the ones defined by the code in the three church sites for the Ultimate Limit State (SLU). Furthermore, comparing the three response spectra for the three churches, the different seismic hazard for the three sites can be evaluated.



(a)



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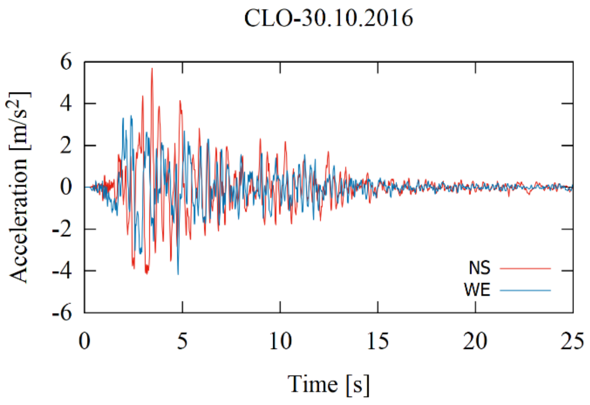


(c)

Figure 6. The accelerograms used for the dynamic non-linear analyses registered in (a) Novi di Modena, (b) Mirandola and (c) Castelluccio di Norcia.

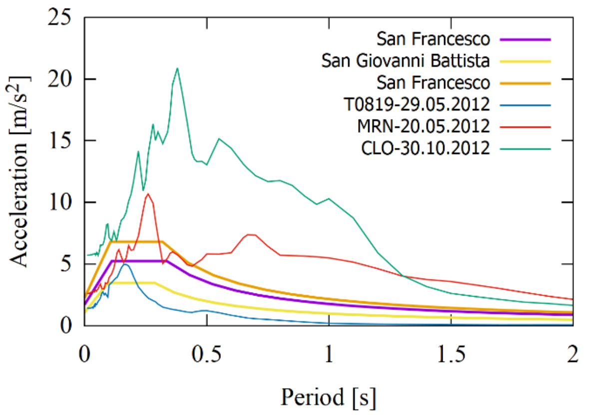


Figure 7. The elastic response spectra of the NS component of the considered accelerograms. The purple, yellow and orange lines are the response spectra reported by the Italian building code for ultimate limit state in the three church sites.

5 NUMERICAL MODELS

In this section, the models of the three façades are described, with their specificities. For each church a perfect connection between the lateral walls and the façade was assumed. For this reason, the transversal displacement of the façade was constrained by the lateral walls.

5.1 *San Francesco*

The façade of San Francesco in Tolentino has an average thickness of 95 cm, with two large buttresses at the corners. For this reason, the bending interaction with the lateral walls was neglected (Figure 8).

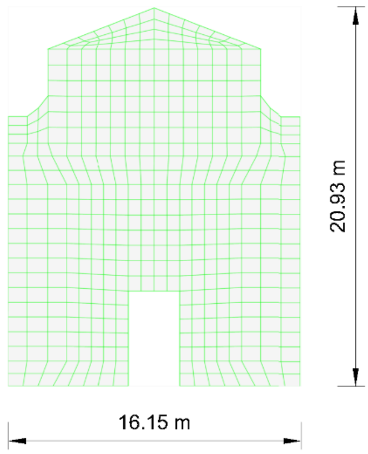


Figure 8. Mesh of the façade of San Francesco used for the analyses.

For the material properties, the values for “masonry with solid bricks and mortar”, reported in the Italian Building Code (Circolare n° 7 del 21 Gennaio 2019), were adopted. For the horizontal bending behaviour, the friction coefficient was assumed equal to 0.4 and, considering the bricks geometry (24x4 cm), a shape coefficient equal to 3 was assumed. Figure 9 reports the obtained moment-curvature relationships for different levels of vertical compression.

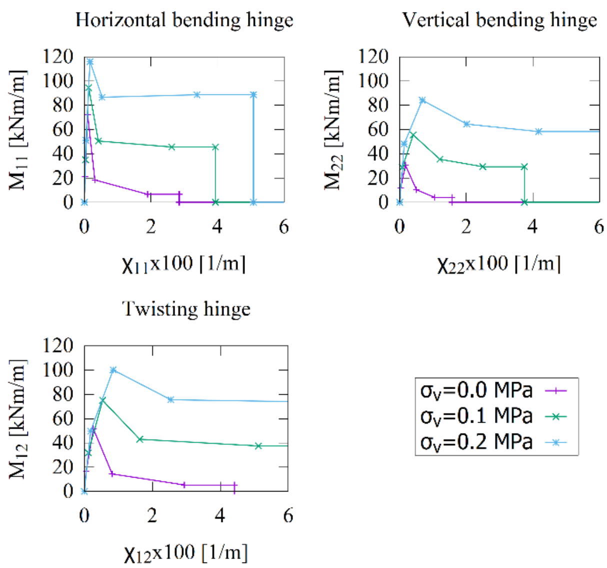


Figure 9. Façade of San Francesco. Piecewise moment-curvature relationships of the bending and twisting rotational springs, for different levels of vertical compression stress σ_v. The points are called, for increasing value of the curvature, E,Y, U, S and Crack point.

5.2 *San Giovanni Battista*

The façade of San Giovanni has an average thickness of 60 cm, that increases in the pilasters to 70 cm. In this case, the bending interaction with the lateral walls of the first order was considered. The lateral walls were modelled up to the first buttress, for an average length of 4.70 m, as reported in Figure 10. The connection between lateral walls and façade, on one side, constrains the out-of-plane displacements of the walls and on the other side, allows to transfer bending moments between the walls but does not transfer twisting moments. The thickness of the façade was increased up to 140 cm in correspondence of the arch to consider its stiffening contribute.

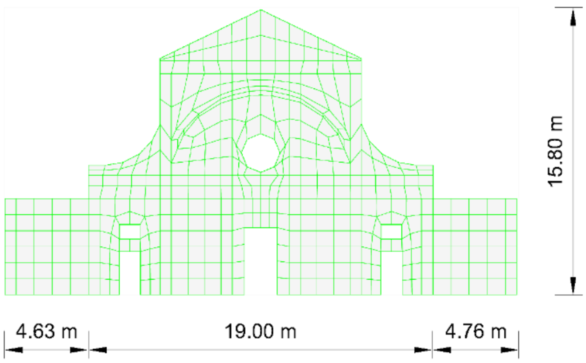


Figure 10. Mesh of the façade of San Giovanni Battista considered for the analyses.

For the materials, the same values of San Francesco were adopted. However, in this case, the shape coefficient ρ was assumed equal to 2, considering that in average the bricks are 24x6 cm. Figure 11 reports the obtained moment-curvature relationships for different levels of vertical compression.

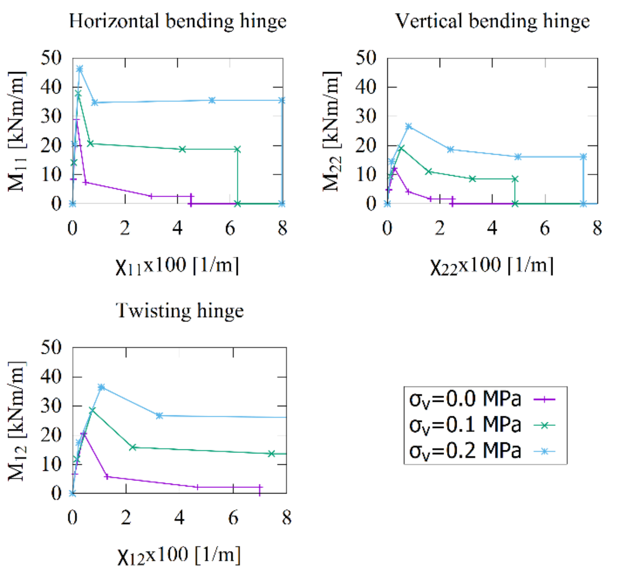


Figure 11. Façade of San Giovanni Battista. Piecewise moment-curvature relationships of the bending and twisting rotational springs, for different levels of vertical compression stress σ_v. The points are called, for increasing value of the curvature, E,Y, U, S and Crack point.

5.3 *San Salvatore*

The façade of San Salvatore has an average thickness of 90 cm. It was assumed that the external leaves, made by square stones, are 20 cm thick, with an inner core of poor mechanical properties of 50 cm. The material parameters of the external leaves were assumed in agreement with the values for "masonry with square stone blocks", reported in the Italian Building Code (Circolare n° 7 del 21 Gennaio 2019). Figure 13 shows the obtained moment-curvature relationships for different levels of vertical compression.

Also in this case, it was considered the collaboration of the lateral walls (83 cm thick) with the façade. The longitudinal walls were modelled up to the first buttresses, for an average length of 3.50 m, as reported in Figure 12.

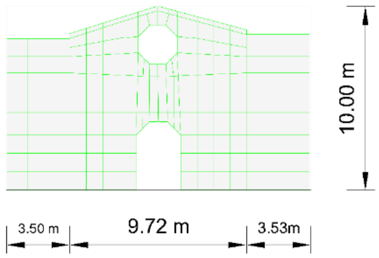


Figure 12. Mesh of the façade of San Salvatore used for the analyses.

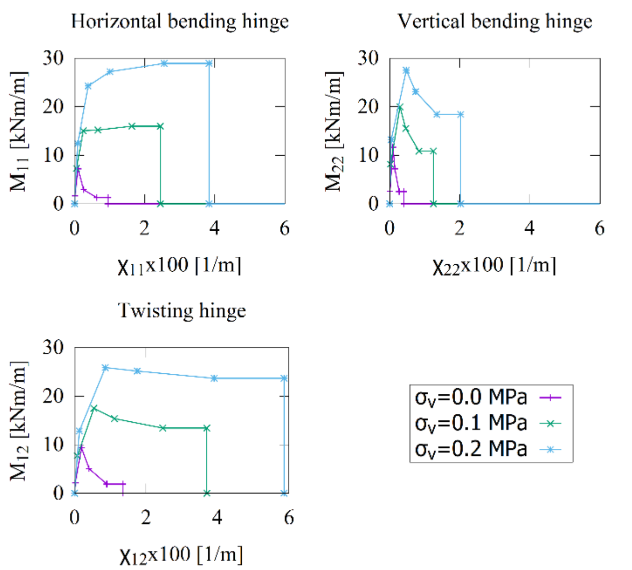


Figure 13. Façade of San Salvatore. Piecewise moment-curvature relationships of the bending and twisting rotational springs, for different levels of vertical compression stress σ_v. The points are called, for increasing value of the curvature, E,Y, U, S and Crack point.

6 RESULTS

The results of the non-linear dynamic analyses are reported in terms of displacement of a control point (the highest point of the façade) and damage

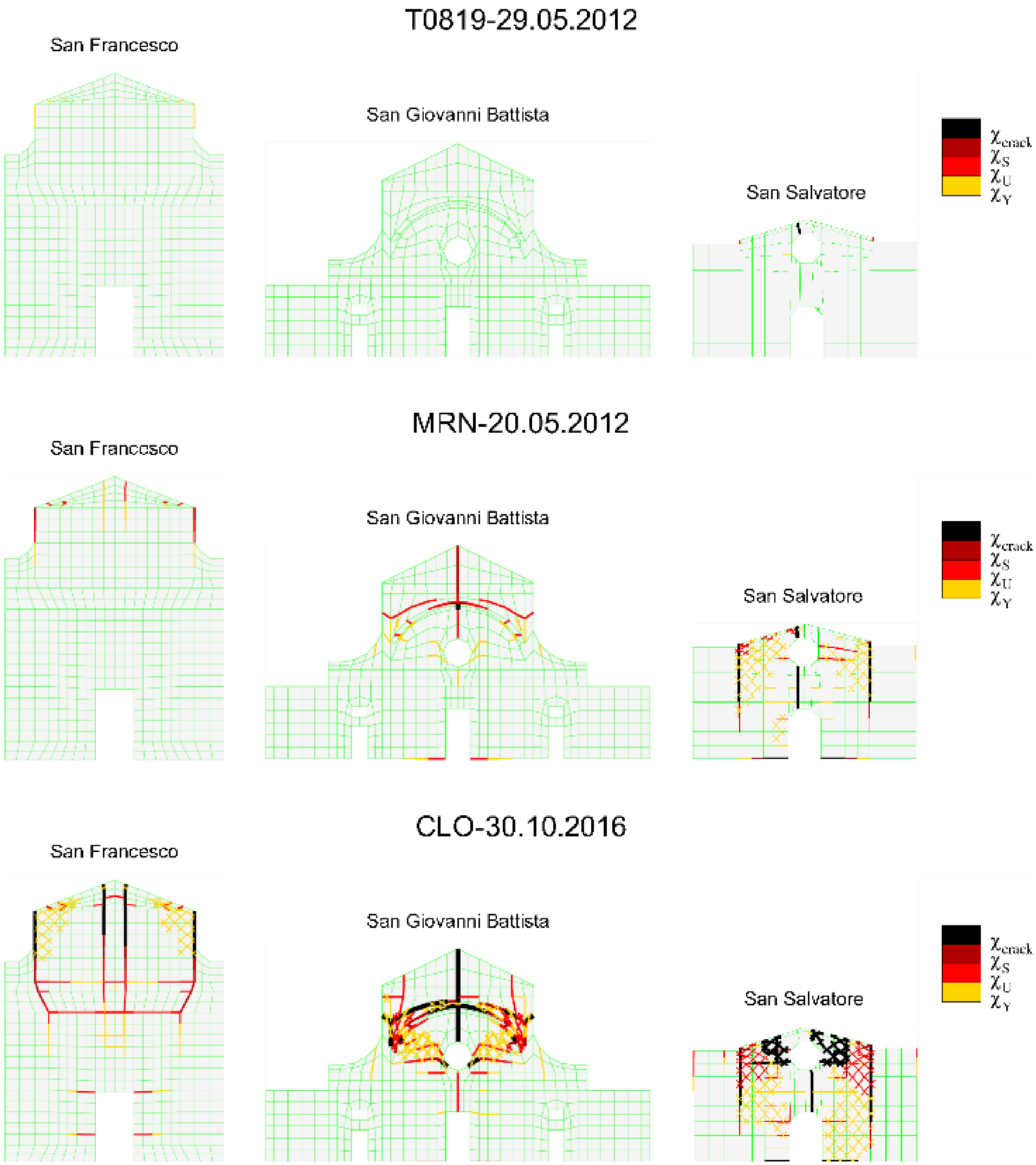


Figure 14. Damage patterns obtained for the three façades applying the three accelerograms with increasing values of the PGA: T0819-29.05.2012 (PGA=0.15g), MRN-20.05.2012 (PGA=0.26g), CLO-30.10.2016 (PGA=0.58g).

patterns. The damage state is plotted in terms of maximum average curvatures reached in the connections. If the maximum bending curvature is higher than the Y-point curvature a straight coloured line is plotted along the side. On the contrary, if the twisting curvature exceeds the Y-point curvature, a coloured cross is plotted in the connection point.

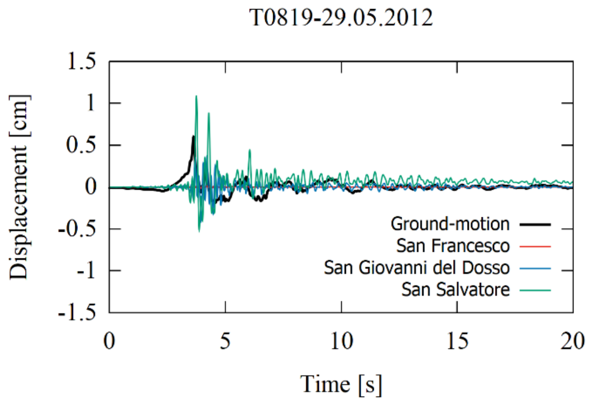
The damage maps (Figure 14) show that for the two strong motions with the highest values of PGA (MRN-20.05.2012 and CLO-30.10.2016) the façade of San Salvatore is the most damaged with several springs that reach the crack curvature value. The damage is concentrated around the rose window and at the intersection with the lateral walls. A prevalent mechanism of façade overturning was observed for the Mirandola accelerogram. Whereas, for the Castelluccio di Norcia accelerogram (PGA=0.58g), the overturning of the gable, over the rose window, was also observed.

For the same two accelerograms, the façade of San Giovanni Battista results widely damaged. In this case, the damage is more severe above the arc, with the formation of an almost horizontal yield line and the consequent overturning of the tympanum. This damage is the same that occurred during the 2012 Pianura Padana earthquake. Furthermore, a vertical hinge cuts the middle of the façade getting to the rose window.

The façade of San Francesco is the least damaged by these two events. For the same two accelerograms, the damage is concentrated in the second order of the façade with the formation of vertical hinges at the intersection with the lateral walls and in the centre of the façade, as in a mechanism of overturning of the gable.

For the Novi di Modena accelerogram (T0819-29.05.2012), that has spectral accelerations lower than those reported in the Code, all the façades are almost undamaged. The only exception is represented by San Salvatore where a vertical hinge above the rose window is severely over the elastic limit. Only in this case, the façade of San Francesco is more damaged than the one of San Giovanni Battista, two vertical hinges are already activated at the intersection with lateral walls of the second order.

The different seismic response is also confirmed by the history of displacement of the highest point of the façade, selected as control point (Figure 15). The San Salvatore façade is the only one that shows considerable increasing residual displacements for the three seismic solicitations. On the contrary, the stiff San Francesco façade shows very little displacements, independently from the seismic solicitations.



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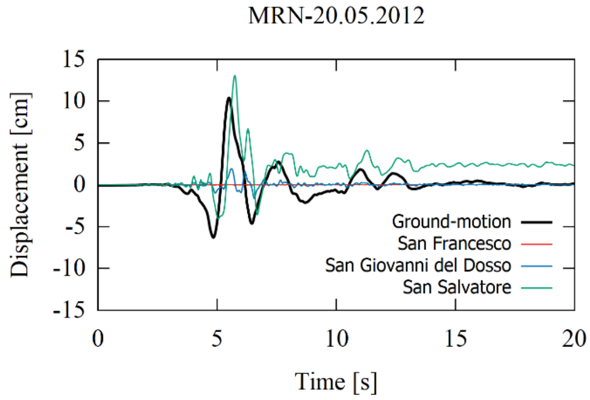

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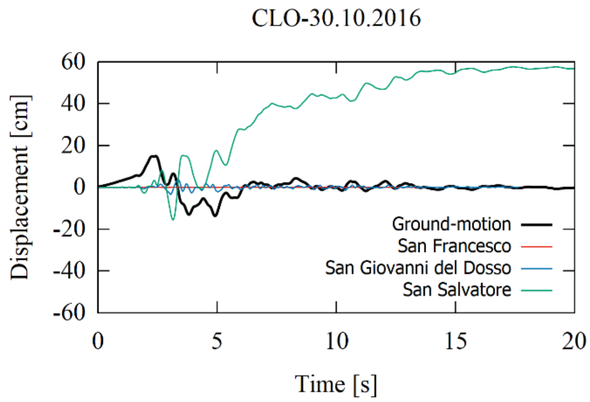

(c)

Figure 15. History of displacement of the highest point of the façades for the different seismic events: (a) Novi di Modena, (b) Mirandola and (c) Castelluccio di Norcia.

7 CONCLUSIONS

This preliminary study has investigated the seismic response of three different church façades, representative of some typologies widely diffused on the Italian territory. The obtained results provide a contribution on the seismic vulnerability assessment, focusing on the construction technique and the façade geometry.

The seismic response was evaluated through non-linear dynamic analyses for three registered accelerograms with increasing values of PGA. For the analyses, an out-of-plane rigid body spring model was used, allowing to consider, through phenomenological laws, the different behaviour of masonry for vertical and horizontal bending, with a limited computational effort. Only the façade macro-element was modelled assuming a perfect connection with the lateral walls.

The results of the non-linear dynamic analyses show that the construction technique influences the seismic response of the church façades. A three-leaf masonry wall is more vulnerable to out of plane loads than a single leaf one. This is due to the scarce connection among the leaves. Hence, the façade of San Salvatore, that is the least slender, seems the most vulnerable.

The façade configuration is defined not only by its geometry but also by the presence of some local elements like arcs, pilasters and buttresses. The façade is stiffened by these elements, that influence its structural response. In fact, the façade of San Francesco that is the highest one, is less vulnerable than the one of San Giovanni Battista. This is due to a thicker wall and two big buttresses on the corners.

Finally, the rose window and the gable confirm to be the most vulnerable parts of the façade, when the connection with the lateral walls is guaranteed.

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