16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° XXXX (Abstract ID 3207)

Registration Code: S-G1471534434

DAMAGE PROBABILITY MATRICES FOR EIGHT HISTORIC CENTERS AFTER THE 2009 L'AQUILA EARTHQUAKE

C. Tavani[1], G. Brando [2], G. De Matteis [3], E. Spacone [4]

[1] *Architect, Department of Engineering and Geology, University "G. d'Annunzio" of Chieti-Pescara, Pescara (Italy). email: carmentavani@gmail.com*

[2] *Post-Doc, Department of Engineering and Geology, University "G. d'Annunzio" of Chieti-Pescara, Pescara (Italy). email: gbrando@unich.it*

[3] *Associate Professor, Department of Architecture and Industrial Design, Second University of Naples, Aversa (Italy). email: gianfranco.dematteis@unina2.it*

[4] *Full Professor, Department of Engineering and Geology, University "G. d'Annunzio" of Chieti-Pescara, Pescara (Italy). email: espacone@unich.it*

Abstract

In this paper, the results of a damage reconnaissance activity carried out on eight minor historic centers of Abruzzi after the 6.3 Mw L'Aquila earthquake, occurred on the 6th of April 2009 in the central area of Italy, is presented.

In the first part, minor historic centers belonging to the region interested by the earthquake are described. The main morphological features of these centers, to be ascribed to an historical urban development often carried out according to extemporaneous logics, are discussed. Moreover, the main construction typologies are presented: these are made of poor masonry buildings with many fragility sources and are the result of several transformations and stratifications carried out since the medieval age in order to comply with inhabitants needs, but, mostly, not with structural/seismic matters.

The second part of the paper is focused on the occurred damage scenarios. The most frequent failure mechanisms of macro-elements are shown and the observed damage is classified according to the grades introduced by Grünthal for the definition of the EMS-98 European Macro-seismic scale.

Finally, the revealed frequencies of the observed damage grades are organized in damage probability matrices. These are provided as a useful tool able to quantify effectively the occurred damage and to predict the potential losses that have to be expected for similar historical centers in case of future seismic events.

Keywords: Minor historic centers, Masonry buildings, Damage Probability Matrices (DPMs), Damage Reconnaissance, L'Aquila earthquake.

1. Introduction

The necessity of protecting historic centers exposed to likely catastrophic events derives from the cultural need of preserving the evidence of the past, in order to deliver to future generations a trace of their own history. This statement is particularly true for the large number of minor medieval historic centers of central Italy, characterized by very vulnerable masonry buildings that are threatened by a high seismic hazard.

With the attribute "minor" we commonly classify those small historic centers developed in a poor economic contest and without stringent urban regulations, which are made of buildings conceived according to a spontaneous "architecture without architects" style [1] and built by using rules that local builders mostly applied –apart from residential necessities- for satisfying topography and climate needs instead of anti-seismic requirements [2, 3].

These centers constitute the cultural units -as well as the original and authentic core- of those medieval settlements that form in large part the cultural and historical heritage of Italy; hence, they deserve the maximum attention and care in terms of conservation and protection, in particular against earthquake catastrophic events.

Another reason that makes important to put in the field all the necessary measures for mitigating the seismic risk of minor historic centers is of sociological nature. The direct effects of seismic events of the past on the demography of old Italian towns proved that they are destined to an unavoidable death if strong initiatives aimed at increasing the resilience against seismic events will not be undertaken in the next future. For example, Fig. 1 put in relation the demographic trend registered in the last decades (census data) in eight historic centers of the Italian district of L'Aquila –which are dealt with in this paper- with the earthquakes having a magnitude exceeding 5 that stroke the region. It is evident, for example, that the three events occurred in the fifties, provoked a rapid decrement of inhabitants of the considered towns, which, after ten years were almost halved.

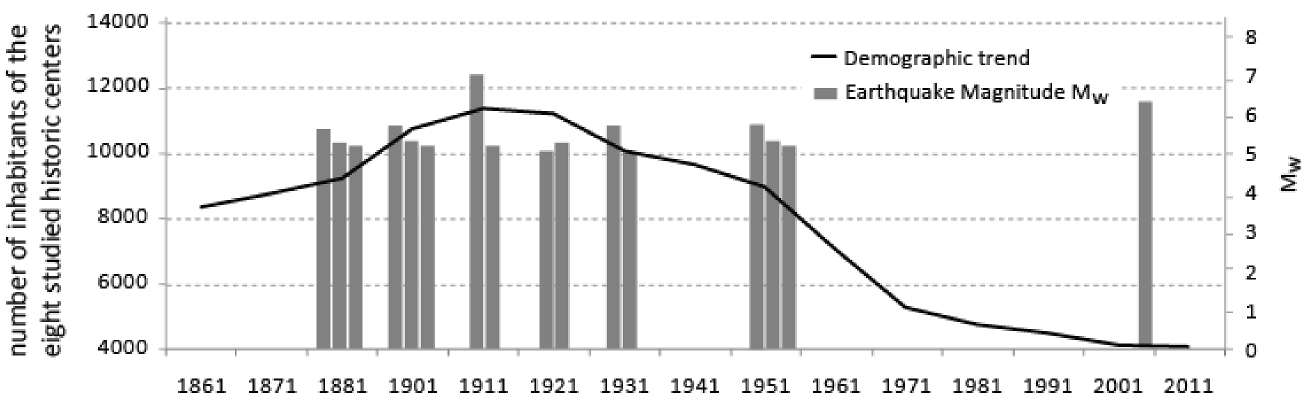


Fig. 1 – Demographic trend vs. historical seismic events in eight historic centers of L'Aquila district

The intrinsic peculiarities of minor historic centers make them really vulnerable to catastrophic seismic events. In fact, these are frequently made of clustered buildings whose current aspect is the result of several additions in both plan and elevation, sometimes carried out by using and superimposing different materials and local constructive techniques. Moreover, the lack of cogent Building Codes and Regulations has often lead, in the course of time, to an irrational expansion of the single building aggregates and of the entire urban layout: frequently the current state of a cluster is originated by the merging of separated clusters by means of buildings erected to fill empty spaces where, formerly, passages were placed (Fig. 2).

The situation described above proves that the evaluation of the real structural and seismic behavior of a building included in a cluster is not easy, as the most influencing sources of vulnerability are often hidden and their behavior barely interpretable. From this point of view, the lesson learnt after a destructive earthquake could represent an unrepeatable, although dramatic, chance to interpret the main construction practices and details used in the historic centers, as well as to appraise possible interventions to be applied with the aim of realizing a general mitigation of the seismic risk.

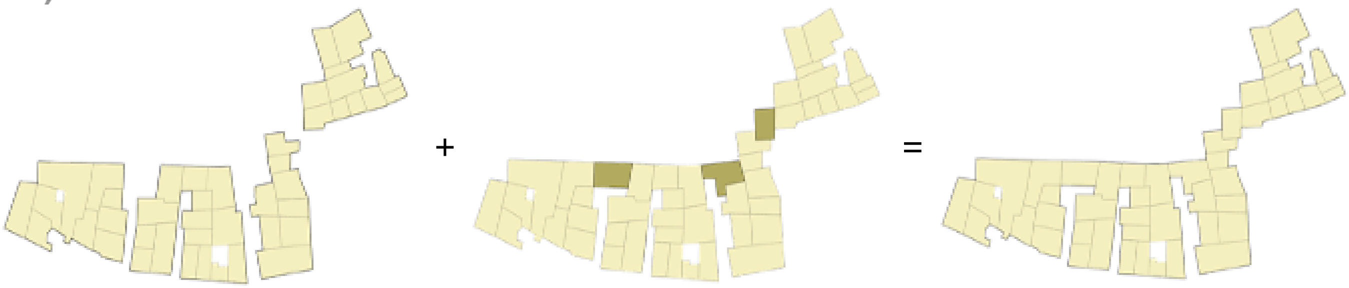


Fig. 2 – A typical cluster of a minor historic center in the Abruzzi region

With this premise, this paper provides a general overview on the damage provoked by the earthquake occurred in 2009 in the Italian region of Abruzzi on eight typical minor historic centers of the hinterland of L'Aquila district.

After a synthetic description of the seismic event that stroke these centers in 2009 (Section 2), the revealed construction typologies are discussed (Section 3). Then, the damage observed during a reconnaissance activity is described in terms of triggered failure mechanisms and quantitatively evaluated (Section 4) according to the grades introduced in [4] by Grünthal for the definition of the European Macroseismic scale EMS-98.

2. The 2009 L'Aquila earthquake

On the 6th of April 2009 a normal-faulting earthquake with moment magnitude 6.3 Mw shook the central part of Abruzzi region. The epicenter was located close to L'Aquila city, with a focal depth of 9.5 km. Several minor events followed, including two aftershocks characterized by moment magnitude higher than 5, on April 7 (5.6 Mw) and April 9 (5.4 Mw). In some areas, horizontal peak ground accelerations of 1.0 *g* were registered, with a strong vertical component likely due to the shallow origin of the earthquake. In addition, many local amplification effects were registered in the surrounding areas [5].

The earthquake was characterized by impulsive features, in particular in the first thirty kilometers from the epicenter [6], with strong vertical components and velocity/displacement demands. Surely, this favored the activation of the large number of out-of-plane mechanisms observed on masonry buildings in historic centers, according to the studies reported in [7, 8, 9].

The earthquake had a dramatic impact on the people community, due to both the loss of human lives (about 300 fatalities) and severe injuries (about 2000 people). In addition, significant (sometimes irremediable) losses have been registered on the cultural and historical heritage [10, 11, 12], formed by churches, monumental buildings and historic centers made of valuable dwellings and palaces, in particular in the city of L'Aquila that, during the last millennium, has represented the cultural, social and business hearth of the whole district [13].

Indeed, after seven years, the situation is slowly returning to normality, but the wounds inflicted by the seismic event, are still bitterly visible. This situation has to be traced back to the intrinsic deficiencies highlighted during the earthquake, namely the poorness of both materials and constructive details and the alterations applied, throughout the centuries, to the original layout of the buildings, which, for the reason already argued in Section 1, were subjected to several transformations and stratifications.

3. Minor historic centers in Abruzzi

The oldest parts of the historic settlements that characterize the inner part of the Abruzzi Region often date back to the eighth/ninth century. Their current aspect is the result of masonry aggregates of small-medium sizes erected around an urban core that is often characterized by the presence of more valuable buildings, such as churches, castles or mansions.

Buildings are mostly made of rubble limestone rocks with thick, weak layers of lime mortar, characterized by a bonding-to-inert ratio of about 0.5. A chaotic pattern is typical for stones with characteristic sizes smaller than 20 cm: in this case the inclusion of both marl and clay-brick pieces is often observed. On the other hand, a more organized texture can be found for bigger stones accounting for around 75% of the wall volume. In both cases, courses are generally absent or, when present, they are not correctly conceived.

Fig. 3 shows some meaningful examples of typical masonry walls. According to the Italian Guidelines "Circolare 617" [14] these are characterized by a compressive strength varying from 1.4 MPa to 2.4 MPa, a tangential ultimate stress ranging from 0.028 MPa to 0.042 MPa, normal and tangential elastic moduli ranging from 900 MPa to 1260 MPa and from 300 MPa to 420 MPa, respectively.

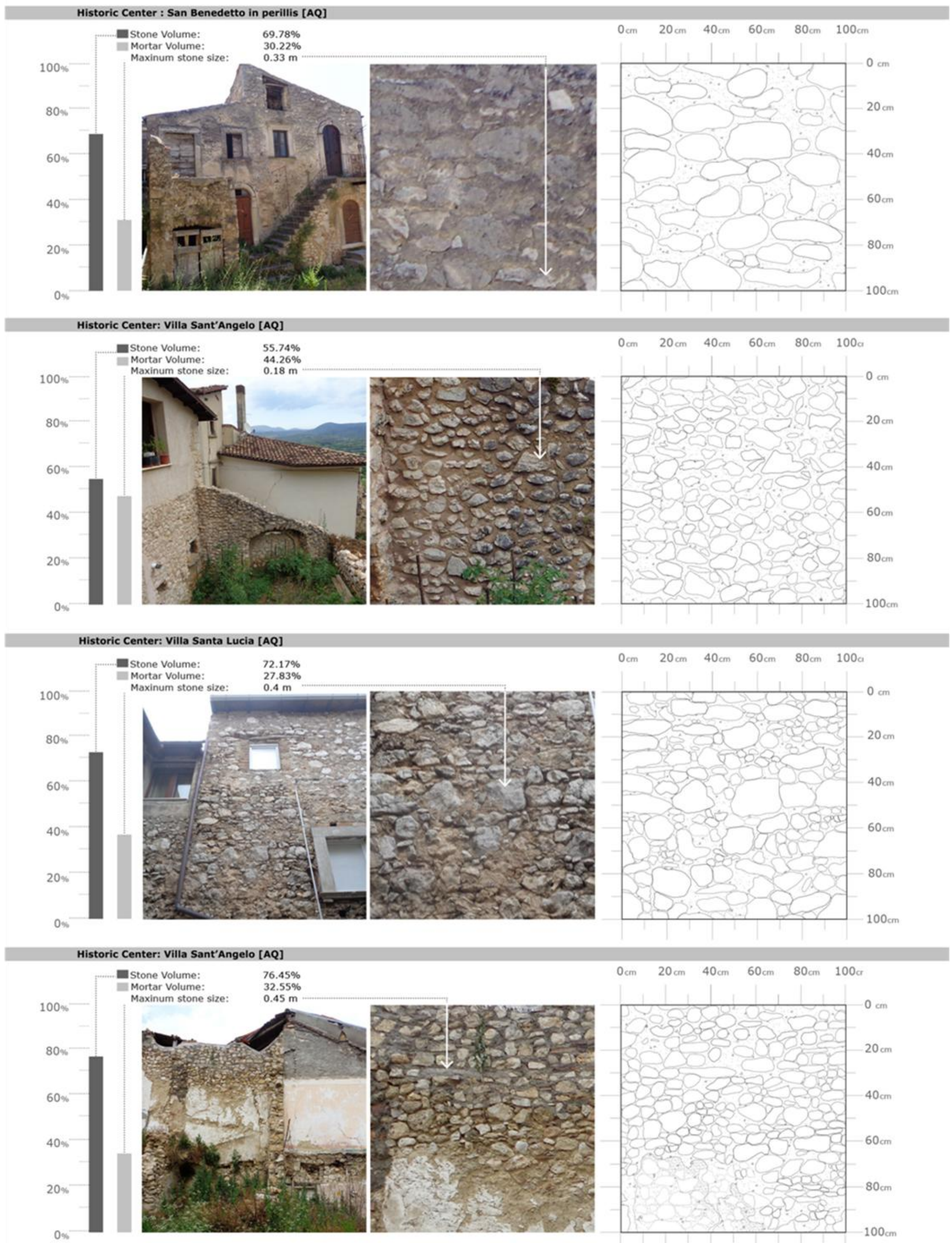


Fig. 3. Masonry typologies revealed in minor historic centers of Abruzzi

Through the thickness, there are usually three leaves: walls are generally characterized, for about 1/3 of their transversal dimension, by an internal “sacco” consisting of earth and rubble stones, which separates two external stone and mortar leaves with transversal thickness ranging from 15 cm to 30 cm. The external leaves are not generally connected by through elements. In most cases, effective quoins, when present, can be observed at the lower storeys. Internal transversal walls are rarely connected with orthogonal walls.

Anti-seismic measures can be found in centers hit by past strong earthquakes. Iron ties were often inserted to prevent out-of-plane overturning of external walls and façades. These are characterized by different details, mostly of the anchor plates (Fig. 4a), depending on the period in which they were applied to the original walls of the buildings. Moreover, in some cases, the presence of buttresses is clearly evident (Fig. 4.b) while, for some specific buildings, “scuci and cuci” interventions can be read in the wall pattern (Fig. 4.c). Mortar injections and reinforced concrete plaster (fig. 4.d) have been applied only seldom.


a)


b)


c)


d)

Fig. 4. Anti-seismic strengthening interventions observed in some of the studied minor historic centers: (a) Iron ties with different type of anchor plates and (b) buttresses observed in San Benedetto in Perillis; (c) “Scuci and Cuci” intervention in Bazzano and (d) Reinforced plaster in Castelvecchio Subequeo

4. The damage observed on eight historic centers

4.1 General

After the 2009 seismic event, a damage reconnaissance activity on more than 1000 buildings belonging to eight minor historic centers of the inner Abruzzi has been carried out. Namely, the minor centers inspected were: Sant’Eusanio Forconese, Villa Sant’Angelo, Bazzano, San Demetri né Vestini-Cavantoni, San Demetrio né Vestini-Colle Valicella, Villa Santa Lucia degli Abruzzi, Castelvecchio Subequo, San Benedetto in Perillis. All these villages belonged to the so-called seismic crater, which is the area of Abruzzi region evidenced in Fig. 5a that was significantly stroke by the earthquake, so that the Italian Government funded its Reconstruction. In Fig. 5b an enlarged view of the area is proposed with the eight studied centers. For these the macro-seismic magnitude measured in the Mercalli-Cancani-Sieberg (MCS) and their position with respect to the epicenter is shown.

The reported MCS intensities have been extracted by the evaluation provided by the Italian Civil Protection in the aftermath of the seismic event. Indeed, after the damage reconnaissance activity described in this paper we confirmed the MCS intensities proposed by the Italian Civil Protection, except for one case. In fact, for the center of San Benedetto in Perillis, we found several collapses that do not justify the assigned MCS intensity of 5.5 (Fig. 6).

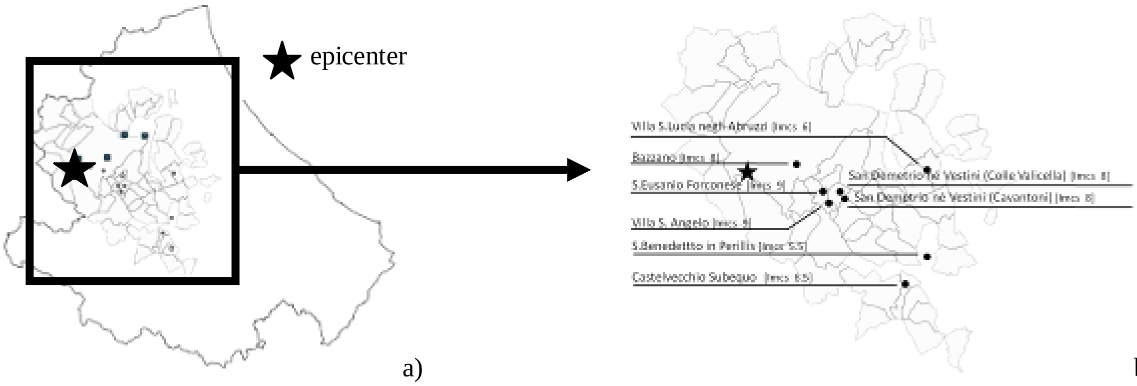


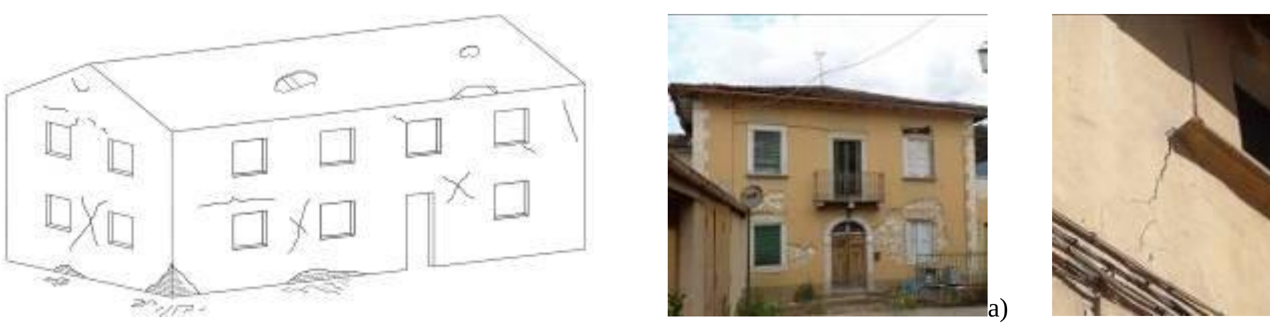
Fig. 5. a) Seismic crater of the 2009 L'Aquila earthquake; b) the eight studied historic centers

Fig. 6. The observed buildings' collapses in San Benedetto in Perillis

The studied centers have been selected according to the criterion of being representative, in terms of urban layout, building typologies and vulnerability sources, of almost all the minor historic centers of the inner Abruzzi. Buildings have the same masonry layout, with walls constructed according to the same poor techniques. Moreover, for some of the studied centers, specific situations that could provoke an increased vulnerability, because of local amplification effects, have been included. For example, with the choice of San Benedetto in Perillis, it has been possible to include in the studied stock of buildings those situations characterized by man-made caves beneath existing constructions, which are typical for some centers in Abruzzi.

4.2 Observed Failure Mechanisms

During the reconnaissance activities several failure mechanisms were observed. Mainly, they concerned the masonry in-plane behavior (Second Mode mechanisms), with cracks mostly developed in diagonal direction (Fig. 7a), in particular near openings (Fig. 7b).



a) bb)

Fig. 7. Second Mode Mechanism observed in (a) Villa Sant'Angelo and (b) in San Demetrio-Cavantoni

Many out of plane mechanisms were observed in case of lack of ant seismic devices able to restrain them, such as iron ties, or buttress or connection with transversal walls. In Fig. 8, one of the revealed complete overturning of one of the external walls is depicted. This was also favored by the slenderness of the masonry, as well as by the lack of floor or roof system able to act as a diaphragm.

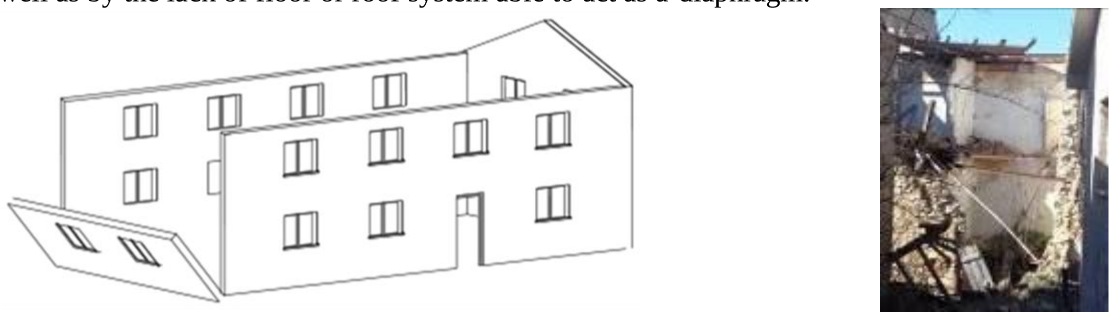


Fig. 8. Complete overturning of a perimeter wall in Sant'Eusanio Forconese

Moreover, the lack of a transversal connection through the walls, entailed the trigger of overturning mechanisms of their external leaves, when these were characterized by a very limited thickness and were made of rubble stones with a chaotic texture. An example is given in Fig. 9, where a partial tilting of the external leaf of the façade of a building in Bazzano is shown. Also, the collapse of the external leaf for flexural mechanisms, in case of restraining ring beams or iron ties at the floor or intermediate levels, was often observed. An example is shown in Fig. 10, which show a case reported in Villa Santa Lucia.

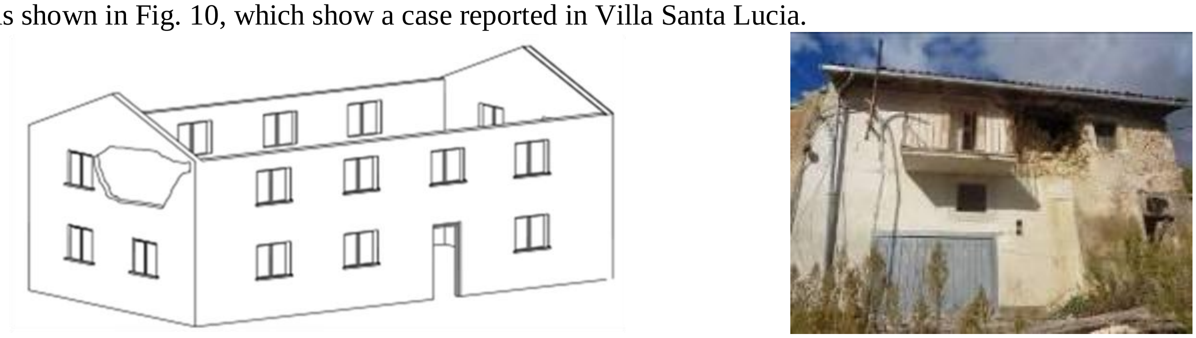


Fig. 9. Partial overturning of the external leaf of a perimeter wall of a masonry building in Bazzano

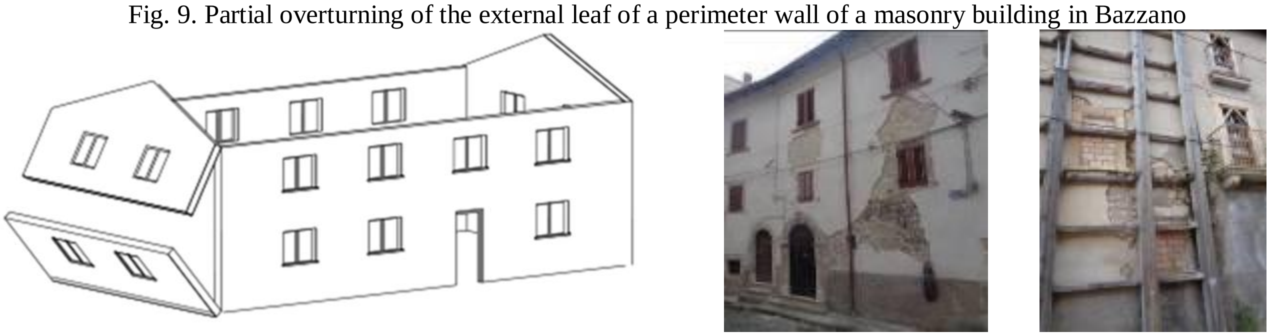


Fig. 10. Out-of-plane flexural mechanisms of the external leaf of a perimeter wall equipped with iron ties of a masonry building in Castelvecchio Subequo

The presence of openings in the transversal walls favored overturning mechanisms also in case of good inter-connection of the tilted walls at their edges. An example is given in Fig. 11, where an "overturning with side wing" observed in Sant'Eusanio Forconese is shown.

4.3 Damage Probability Matrices

The reported damage on the whole inspected buildings was classified according to the criteria by Grünthal [4] for the definition of the European Macroseismic scale EMS-98.

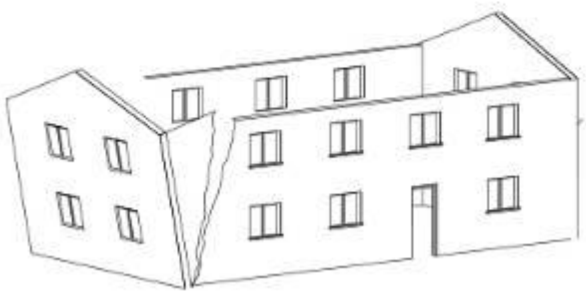


Fig. 11. Partial overturning of the external leaf of a perimeter wall of a masonry building in Sant'Eusanio Forconese

Six damage levels, D_k, each one associated to a damage level *Dk*, ranging from 0 to 5, are defined according to this scale: (*i*) *Level D0:* no damage; (*ii*) *Level D1*: negligible to slight structural damage, with hair-line cracks in very few walls and fall of small pieces of plaster only; (*iii*) *Level D2*: slight structural damage and moderate non-structural damage, with cracks in many walls and with fall of fairly large pieces of plaster, with partial collapse of chimneys; (*iv)Level D3*: moderate structural damage and heavy non-structural damage, with large and extensive cracks in most walls, with roof tiles detachment; chimneys fracture at the roof line, and/or failure of individual non-structural elements (partitions, gable walls) and/or activation of the first out-of-plane mechanisms; (*v*) *Level D4*: heavy structural damage and very heavy non-structural damage, with serious wall failures and partial structural failure of roofs and floors; (*vi*) *Level D5*: very heavy damage to both non-structural and structural parts, with total or near total collapse of the whole building.

In Fig. 12, the Damage Probability Matrices (DPMs) reporting the frequencies of the damage grades occurred on 750 inspected buildings are given in order to represent quantitatively the occurred scenarios. To this purpose, the entire stock of buildings has been divided in two vulnerability classes that during the earthquake showed different seismic behaviors and different damages. The first class (Class I, Fig. 12a) is made of 586 buildings characterized by the fact that they were not subjected to retrofitting or strengthening anti-seismic interventions (iron ties, reinforced plasters, reinforcement applied to spandrels, etc.) during their life. Contrarily, the second vulnerability class (Class II, Fig. 12b), is composed by all the 750 buildings of the studied stock, and include both non-strengthened and strengthened buildings.

Always with reference to Fig. 12, it is shown that the revealed frequencies for the vulnerability "Class I" are well fitted by the binomial probability distribution given in eq. (1)

$$p_k = \frac{5!}{k!(5-k)!} \cdot \left(\frac{\mu_D}{5}\right)^k \cdot \left(1 - \frac{\mu_D}{5}\right)^{5-k} \tag{1}$$

where k is and integer corresponding to the observed damage grade (0 for *D0*, 1 for *D1*, 2 for *D2*,......,5 for *D5*), and μ_D is the mean value of the revealed frequencies, namely the unique parameter, reported in the figures, on which the binomial distribution depends. On the contrary, in Fig. 12b, the above result has not been observed: this outcome is surely to be deepened, as it seems that the variation of the original layout of the building produces scattered behaviours that do not allow to catch the damage scenario by a simply probabilistic distribution.

The graphs given in Fig. 12 for the whole population of buildings analyzed during the reconnaissance activity are further reproduced in Figs. 13-19 for the single studied historic centers. Also in this case, the binomial distribution seems to be able to capture well the damage frequencies observed for buildings belonging to the first vulnerability class, except two cases, namely Villa Sant'Angelo and San Demetrio né Vestini-Cavantoni, for which the number of investigated was very low (below fifty buildings) due to the fact that a large part of these historic centers was not accessible because of the restricted areas imposed by the Italian Civil Protection. Also, it is to be highlighted that for the historic center of San Benedetto in Perillis, only buildings belonging to the first vulnerability class have been investigated. In fact, on these historic center, few not relevant strengthening interventions have been revealed.

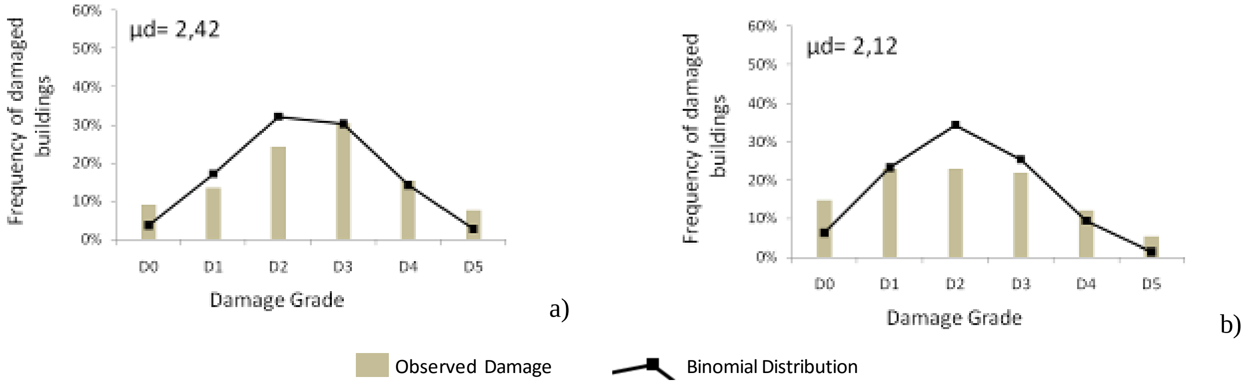


Fig. 12. DPMs for the whole stock of buildings: (a) Vulnerability "Class I" and (b) Vulnerability "Class II"

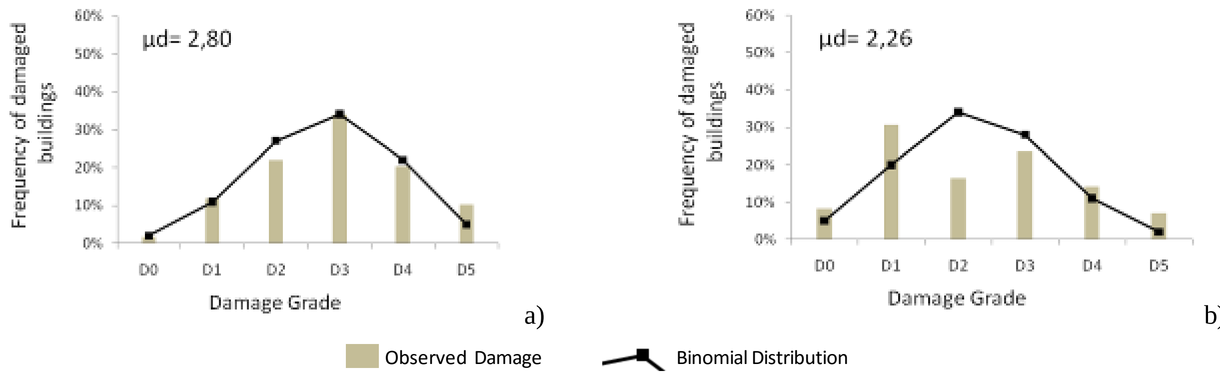


Fig. 13. DPMs for Bazzano (I_{MCS}=8): (a) Vulnerability "Class I" and (b) Vulnerability "Class II"

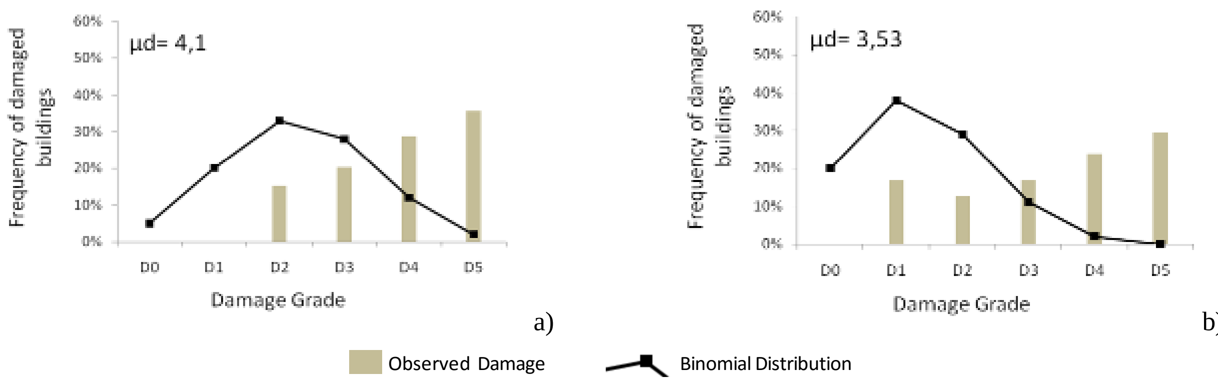


Fig. 14. DPMs for Villa Sant'Angelo (I_{MCS}=9): (a) Vulnerability "Class I" and (b) Vulnerability "Class II"

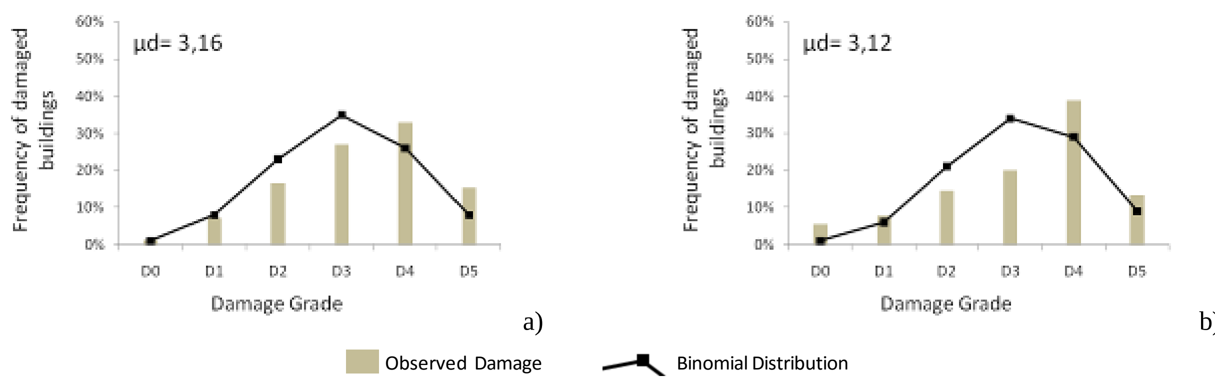


Fig. 15. DPMs for Sant'Eusanio Forconese (I_{MCS}=9): (a) Vulnerability "Class I" and (b) Vulnerability "Class II"

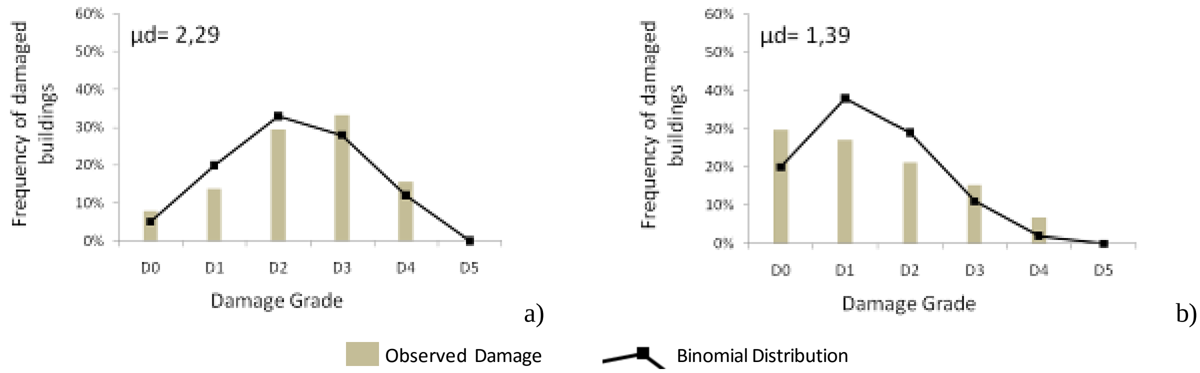


Fig. 16. DPMs for Castelvecchio Subequo (I_{MCS}=6.5): (a) Vulnerability “Class I” and (b) Vulnerability “Class II”

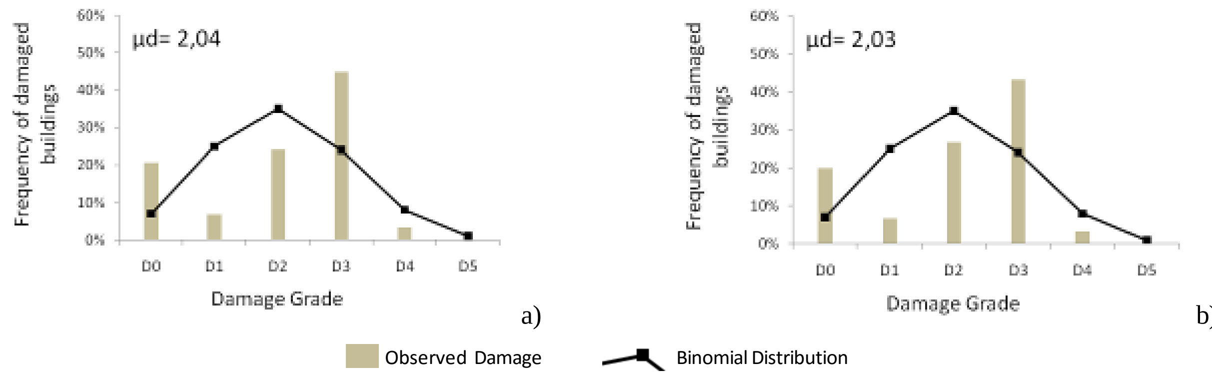


Fig. 17. DPMs for San Demetrio né Vestini-Cavantoni (I_{MCS}=8): (a) Vulnerability “Class I” and (b) Vulnerability “Class II”

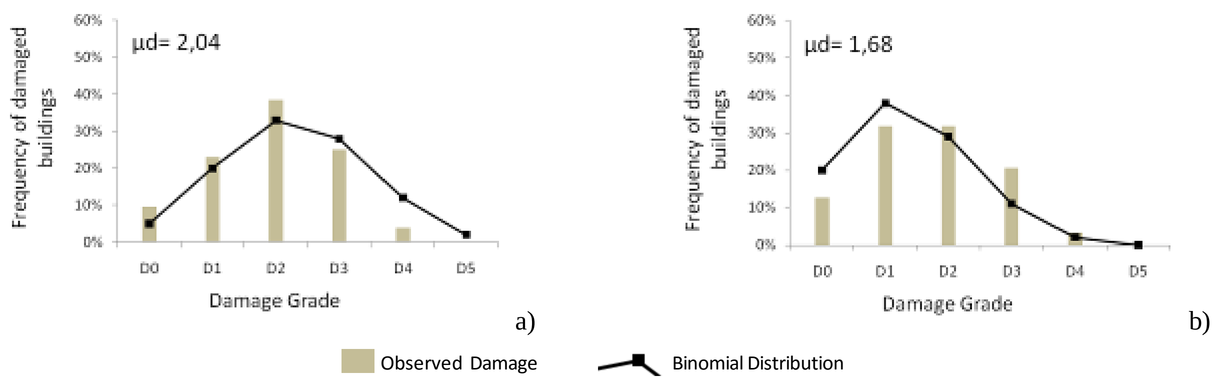


Fig. 18. DPMs for San Demetrio né Vestini (I_{MCS}=8) -Colle Valicella: (a) Vulnerability “Class I” and (b) Vulnerability “Class II”

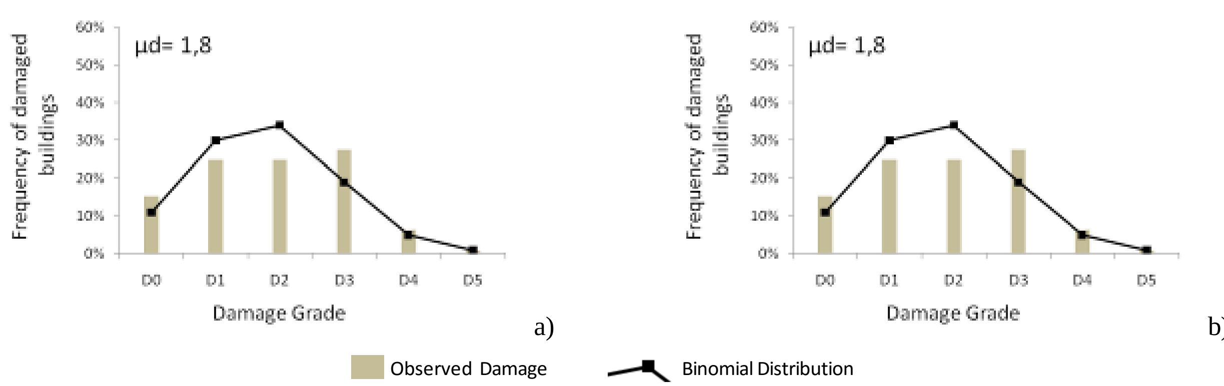


Fig. 19. DPMs for Villa Santa Lucia degli Abruzzi (I_{MCS}=6): (a) Vulnerability “Class I” and (b) Vulnerability “Class II”

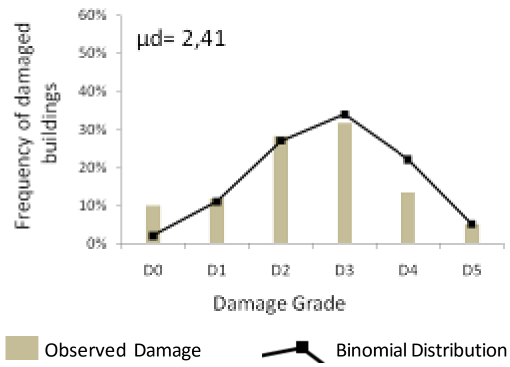


Fig. 20. DPMs for San Benedetto in Perillis (I_{MCS}=5.5): (a) Vulnerability "Class I" and (b) Vulnerability "Class II"

5. Conclusions

In this paper the main outcomes of a damage reconnaissance activity carried out after the 2009 L'Aquila earthquake on eight historic centers belonging to the "seismic crater", namely that area near the epicenter that was strongly stricken during the seismic event, have been presented.

After an analysis of the inspected constructive typologies, mostly made of medieval masonry buildings belonging to clusters originated and transformed in the course of time in an extemporaneous and not always logical way, the most recurrent damage types provoked by the earthquake have been described. Then, the observed damage has been classified according to the grades introduced by Grünthal for the definition of the European Macroseismic scale EMS-98. Hence the frequencies of these grades have been organized into Damage Probability Matrices, which represent a useful way to represent synthetically and quantify the occurred damage scenarios. The analysis has been done by subdividing the observed buildings into two vulnerability classes, according to the presence or absence of strengthening interventions applied during the building life, for both the entire population of inspected buildings and for the buildings of the single studied historic center.

The obtained results put in evidence that for the first vulnerability class, that is the class formed by buildings without strengthening interventions, the damage scenarios are well interpretable by a binomial distribution, provided that the unique parameter needed, namely the mean damage grade, is obtained by a population of buildings that is statistically representative. On the contrary, for buildings belonging to the second vulnerability class, the result described above has not been found, this highlighting that, evidently, the variation of the original layout of the building produces scattered behaviors that cannot be predicted by a simply probabilistic distribution.

It must be highlighted that the obtained outcomes are particularly important, in terms of seismic risk assessment at territorial level, as the eight studied historic centers are representative of several situations that can be found not only in Abruzzi, but also in a larger area of the central part of Italy, which is particularly threaten by a high seismic hazard.

4. Acknowledgements

This study has been developed in the framing of the Italian Research Project 2014-2018 ReLUIS, funded by the Italian Civil Protection.

5. References

[1] May, J., Reid, A. (2010). *Architecture without architects*, Rizzoli ed., Bologna. ISBN: 8817037850. 192 pages.

[2] Maietti, F. (2008). *Centri Storici Minori* (*Minor historic Centers)*, Progetti di Recupero e Restauro del Tessuto Urbano fra Identità Culturale e Salvaguardia. Maggioli ed., ISBN: 8838746567-9788838746567. 279 pages.

[3] De Berardinis, P., Rotilio, M., Marchionni, C., Friedman, A. (2014). *Improving the energy-efficiency of historic masonry buildings. A case study: A minor centre in the Abruzzo region*, Italy (2014) Energy and Buildings, 80, pp. 415-423.

[4] Grünthal G ed. (1998). *European Macroseismic Scale 1998*. Cahiers du Centre Europèen de Gèodynamique et de Seismologie. Conseil de l'Europe, Conseil de l'Europe.

[5] Di Giulio G., Marzorati S., Bergamaschi F. et al. (2011). *Local variability of the ground shaking during the 2009 L'Aquila earthquake (April 6, 2009-Mw 6.3): The case study of Onna and Monticchio villages*. Bulletin of Earthquake Engineering, 9 (3), pp. 783-807.

[6] Chioccarelli, E., Iervolino, I. *Near-source seismic demand and pulse-like records: A discussion for L'Aquila earthquake* (2010) Earthquake Engineering and Structural Dynamics, 39 (9), pp. 1039-1062.

[7] Doherty, K. (2000). *An investigation if the weak links in the seismic load path of unreinforced masonry buildings*. Ph.D thesis. University of Adelaide.

[8] Costa, A. A., Arêde, A., Costa, A., Guedes, J., & Silva, B. (2012). *Experimental testing, numerical modelling and seismic strengthening of traditional stone masonry: comprehensive study of a real Azorian pier*. Bulletin of Earthquake Engineering, (10), 135–159.

[9] Ferreira, T.M., Vicente, R., Mendes da Silva, J. A. R., Varum, H., Costa, A. (2013). *Seismic vulnerability assessment of historical urban centres: case study of the old city centre in Seixal, Portugal*. Bulletin of Earthquake Engineering, October 2013, Volume 11, Issue 5, pp 1753-1773.

[10] Criber, E., Brando, G., De Matteis, G. (2015). *The effects of L'Aquila earthquake on the St. Gemma church in Goriano Sicoli: part I—damage survey and kinematic analysis*. Bulletin of Earthquake Engineering, 13 (12), pp. 3713-3732. DOI 10.1007/s10518-015-9793-3

[11] Brando, G., Criber, E., De Matteis, G. (2015). *The effects of L'aquila earthquake on the St. Gemma church in Goriano Sicoli: part II—fem analysis*. Bulletin of Earthquake Engineering, 13 (12), pp. 3733-3748. DOI 10.1007/s10518-015-9793-3

[12] Tashkov, L., Krstevska, L., Naumovski, N., De Matteis, G., Brando, G. (2010). Ambient vibration tests *on three religious buildings in Goriano Sicoli damaged during the 2009 L'Aquila earthquake* (2010) COST ACTION C26: Urban Habitat Constructions under Catastrophic Events - Proceedings of the Final Conference, pp. 433-438.

[13] De Matteis, G., Criber, E., Brando, G. (2016). *Damage Probability Matrices for Three Naves Masonry Churches in Abruzzi Based on the Experience of the 2009 L'Aquila Earthquake*. DOI:10.1080/15583058.2015.1113340. In International Journal of Architectural Heritage. Volume 10, Issue 2-3, 2016, Pages 120–145 - ISSN:1558-3066

[14] Circolare n. 617 02/02/2009. *Istruzioni per l'applicazione delle ''Norme tecniche per le costruzioni, di cui al D.M. 14/01/2008''* [Italian].