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Statistical analysis of damages to masonry churches after the 2017 Ischia earthquake

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ABSTRACT

Latest Italian earthquakes have significantly highlighted that heritage masonry buildings, especially churches, are considerably vulnerable to seismic actions. Though usually made of good quality materials, churches are characterized by highly vulnerable structural morphologies and architectural configurations, such as significant dimensions, wide halls, thin long span vaults, slender towering or projecting parts, slender walls with large openings. On 21st August 2017, an earthquake struck the Ischia Island causing several damages to both ordinary and heritage buildings. During the emergency phases after the event, many churches were surveyed and the damage evaluation was carried out by filling in the II level survey form (A-DC) in situ. An interesting database made of 27 churches was, thus, created aimed to carry out detailed analysis of the recorded damages and to realize damage probability matrices, useful to implement fragility curves based on an "observational approach". Both global damage index and activation of mechanisms were investigated. Considerations about the correlation between vulnerability index and observed damage level were also presented. Finally, for a homogenous class of churches, a predictive formulation of the mean damage was assessed and compared with other formulations available in the literature and obtained according to a similar approach.

1 INTRODUCTION

Recent Italian earthquakes, such as the seismic sequences of L'Aquila 2009 and Central Italy 2016-17 (Casapulla et al. 2017, Cescatti et al. 2019, Salzano et al. 2019, da Porto et al. 2012, De Matteis et al. 2014, De Matteis et al. 2016, De Matteis et al. 2019), caused significant damage to heritage masonry structures, in particular churches. The latter resulted to be considerably vulnerable to dynamic actions due to their intrinsic vulnerabilities, such as open plan, high height-to-width ratio, projecting parts, large openings, presence of slender bell towers or belfry, absence of proper transversal connections.

On 21st August 2017, an earthquake with duration magnitude $M_w = 3.9$ hit the Ischia Island, with epicentre in the municipality of Casamicciola Terme. Such an event caused two fatalities and many injured people. Despite the low magnitude, significant damages to masonry and reinforced concrete (RC) buildings was produced (Gruppo di Lavoro INGV 2017). The event, in fact, highlighted the deficiencies of the building stock in Casamicciola Terme and Lacco Ameno municipalities (D'Ambra et al. 2017). Above all, the churches of the island showed numerous damages.

During the emergency phases after the seismic event, several inspections to churches (27) were performed in order to assess the damage induced by the earthquake. In a second phase, the inspected churches were examined again in order to evaluate the vulnerability characteristics, essential for the performance of vulnerability analyses. The in situ surveys were carried out under the joint coordination of the Department of Structures for Engineering and Architecture of the University of Napoli Federico II and "Parthenope", together with the supervision of the

Italian Ministry of Heritage and Cultural Activity and Tourism (MiBACT).

Based on the collected data, the study is firstly aimed to develop a detailed analysis of the constructive typologies (geometry, materials, building techniques, seismic devices) of the inspected churches in order to individuate the most recurrent features. Then, the damage suffered by the inspected churches is examined in detail with refer to both global damage and activation of mechanisms, the damage levels are correlated to vulnerability indexes, and statistical analysis of the observed data are performed by means of Damage Probability Matrices (DPM). Finally, for a homogenous class of churches, i.e. one-nave churches, a predictive formulation for the mean damage index is assessed and compared with other expressions proposed in literature and obtained according to the same observational approach.

2 SEISMICITY OF ISCHIA ISLAND

2.1 *Historical seismicity of the island*

Ischia Island is the emerged part of a volcanic apparatus that, together with *Campi Flegrei* and *Procida Island*, belong to the "*Flegrean Volcanic District*" (Gruppo di lavoro INGV 2017) of the Campania region in the Southern Italy. The island has always been characterized by low magnitude earthquakes, mainly located in the northern part of the island and in *Casamicciola Terme* municipality.

According to the Parametric Catalogue of Italian Earthquakes (CPTI15, Rovida et al. 2016) using the MCS scale (Mercalli-Cancani-Sieberg 1930), 13 earthquakes with magnitude (M_w) higher than 2.9 struck Ischia Island since 1275, as shown in Table 1. This table also lists the maximum macro-seismic intensities (I_{Max}) associated to the historical events recorded since 1275, whose epicentres were located in different municipalities of the island (IS=Ischia, CT=Casamicciola Terme, BA=Barano d'Ischia, SF=Serrara Fontana). The same catalogue reports that the 1883 earthquake ($M_w = 4.3$), which devastated the centre of Casamicciola Terme, was the most destructive one.

Figure 1 shows the macro-seismic intensities historically recorded in the island.

Table 1. Historical seismic events in Ischia (data from CPTI15, Rovida et al. 2016).

Year	Municipality	M_w	I_{max} (epicentral)
1275	IS	4.0	VIII-IX
1557	IS	3.5	VI-VII
1762	CT	3.5	VI-VII
1767	BA	3.5	VI-VII
1796	CT	3.9	VIII
1828	CT	4.0	VIII-IX
1841	CT	3.3	V-VI
1863	CT	2.9	IV
1867	CT	3.0	IV-V
1881	CT	4.1	IX
1883	CT	4.3	IX-X
1980	SF	4.4	V
2017	CT	3.9	VIII

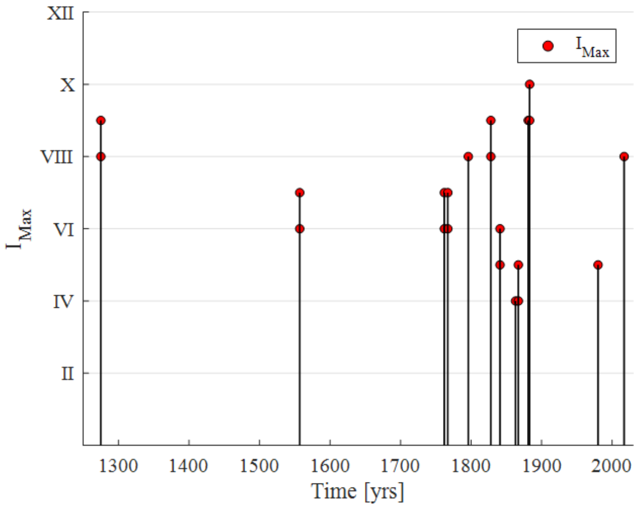


Figure 1. Macro-seismic epicentral intensity I_{max}-time plot for Ischia Island (data from CPTI15).

2.2 *2017 Seismic event*

On 21st August 2017, at 20:57:51 (Italian time) an earthquake of $M_W = 3.9$ struck the Island of Ischia. The earthquake hypocentre was located in Casamicciola Terme municipality at low depth (latitude 40.74°, longitude 13.90°, depth of about 2 km). Some dozens of very small events were recorded (with magnitude less than or equal to 1.0) following the main shock. The earthquake caused two fatalities, and numerous damages to buildings, especially in Casamicciola Terme and Lacco Ameno municipalities.

The main shock was registered by the seismic station called Ischia - Casamicciola Observatory (IOCA) (Luzi et al. 2016). This station is located in Casamicciola Terme (latitude 40.75°, longitude 13.90°), around 500 meters far from the most severe structural collapses that occurred on the island. The station is placed on a class B soil and on a type T1 topographic surface, according to the Eurocode 8 (CEN – EN 1998-1 2005) indications.

Figure 2 reports the E-W component of the accelerogram recorded at the IOCA station, with a registered PGA (Peak Ground Acceleration) of 0.28g.

According to the data collected immediately after the earthquake, the registered earthquake was very superficial and characterized by a very strong attenuation effect at short distances, which is a typical effect of volcanic earthquakes (Gruppo di Lavoro INGV 2017).

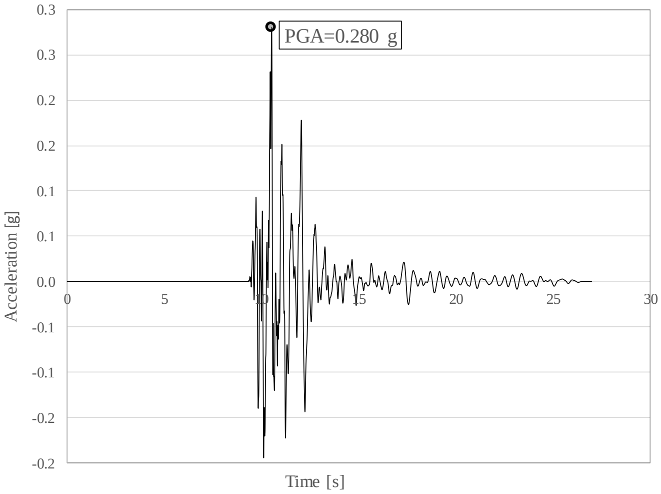


Figure 2. EW component of the accelerogram recorded at IOCA station.

Shake-maps are an useful tool for describing the ground motion parameters, providing an evaluation of the seismic action applied to constructions. Starting from the data recorded in seismic stations, INGV generally provides shake-maps based on attenuation laws defined according to Faenza and Michelini (2010 and 2011). The realization of accurate shake-maps for the August 21st event was particularly difficult. During the event the accelerometer installed at the IOCA station worked correctly and showed a peak acceleration of 0.28g, as shown in Figure 2. However, it is worth noting that the IOCA station is affected by local amplification phenomena (Gruppo di Lavoro INGV 2017). Additionally, the presence of only one reliable recorded accelerometric data in the island and the absence of regional laws for the empirical estimation of soil motion made the estimation of shake-maps particularly complicated. The estimations obtained through INGV shake-maps, indeed, report very low values of PGA (i.e. 0.7%g). These values are not comparable with the PGAs recorded through the IOCA accelerometric station.

2.3 *Macro-seismic survey*

Macro-seismic field surveys were carried out by the emergency group QUEST (QUICK Earthquake Survey Team) of INGV (Azzaro et al. 2017), in collaboration with ENEA, immediately after the earthquake, using the European Macro-seismic Scale (Grunthal 1998), in order to take the heterogeneity of the building stock into account. The inspections were performed all over the island, focusing on the epicentral area. The main aim was assessing damages to buildings and estimating the macro-seismic intensities according to the EMS scale (Grunthal 1998). The EMS intensity scale map is shown in Figure 3.

The surveys were useful for identifying a “red zone” in the district of Casamicciola Terme, close to the epicentre, where most buildings are made of masonry, with absence of reinforcing elements (e.g. tie rods). Moreover, due to the high damages recorded in masonry structures, an overall high vulnerability was found for old masonry buildings (Azzaro et al. 2017). This was attributable not only to the poor quality of masonry, but also to significant structural changes performed in the structural arrangement of the buildings over time.

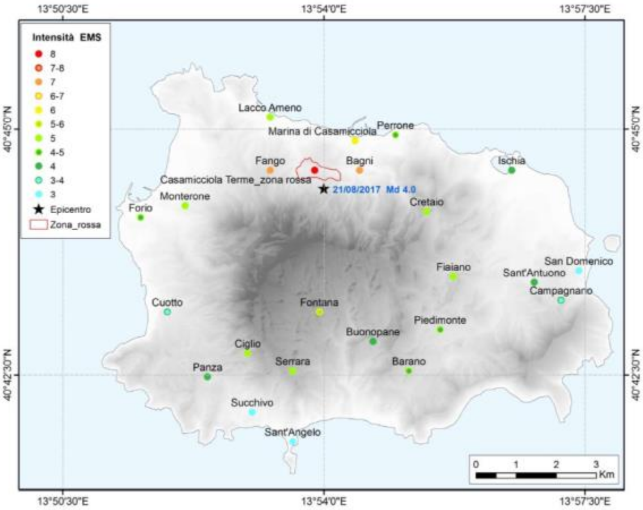


Figure 3. EMS intensity scale (Grunthal 1998), map after the 2017 Ischia earthquake, data from Azzaro et al. 2017.

3 THE ANALYZED CHURCHES

3.1 *Localization and seismic input*

Within the activities carried out by the Universities of Napoli Federico II and “Parthenope”, under the coordination of the Italian Ministry of Heritage and Cultural Activity and Tourism (MiBACT), after the seismic event of 21st August 2017, 27 churches were inspected, whose locations are reported in Figure 4. In particular, the churches were inspected in two phases: the first phase was developed in the post-emergency and was mainly aimed at assessing the overall damage and the usability checks through the A-DC form (MiBACT 2015). The second phase was preparatory to the vulnerability assessment of each church, carried out by filling in the GNDT form (GNDT 2010), where the presence of devices avoiding local failures (e.g. ties) or of vulnerability features can be registered.

According to the location, a value of EMS macro-seismic intensity (I_{EMS}, Grunthal 1998) and PGA were assigned to each church. These assigned values are reported in Table 2 for each church.

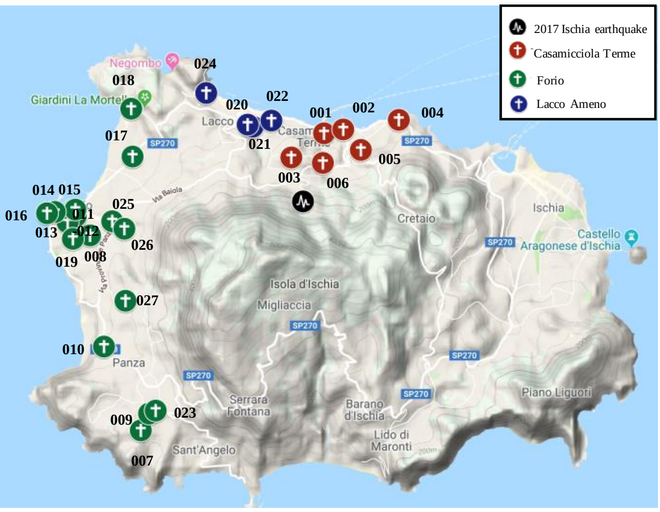


Figure 4. Inspections performed in 27 churches after the event of 21st August 2017.

Table 2. Location of inspected churches with corresponding values of PGA and I_{EMS}.

N	Church	ID	LAT	LON	I_{EMS}	PGA [%g]
001	Santa Maria del Buon Consiglio	SMBC	40.749	13.906	VI	0.7167
002	Santa Maria della Pietà	SMP	40.749	13.910	VI	0.7207
003	Santuario Maria SS Immacolata	MSI	40.745	13.900	VIII	0.7170
004	Sant'Antonio di Padova	SAP	40.750	13.920	VI	0.7353
005	San Pasquale Baylon	SPB	40.746	13.913	VII	0.7309
006	Santa Maria Maddalena Penitente	SMMP	40.744	13.906	VIII	0.7171
007	San Gennaro	SG	40.706	13.872	IV	0.7172
008	San Carlo Borromeo	SCB	40.734	13.863	IV	0.7175
009	San Leonardo	SLE	40.709	13.874	IV	0.7173
010	San Francesco Saverio	SFS	40.718	13.865	III-IV	0.7174
011	Santa Maria di Loreto	SML	40.737	13.860	IV-V	0.7083
012	Santa Maria di Loreto - Oratorio	SMLO	40.737	13.860	IV-V	0.7083
013	San Sebastiano	SS	40.736	13.858	IV-V	0.7125
014	San Gaetano	SGT	40.738	13.860	IV-V	0.7038
015	San Francesco d'Assisi	SFA	40.737	13.856	IV-V	0.7062
016	Santa Maria del Soccorso	SMS	40.737	13.854	IV-V	0.7082
017	San Michele Arcangelo (del Purgatorio)	SMAP	40.745	13.871	V	0.6865
018	Santuario San Francesco di Paola	SSFP	40.752	13.870	V	0.6644
019	San Vito	SV	40.733	13.859	IV-V	0.7174
020	Congrega SS Annunziata	CSSA	40.709	13.875	IV	0.7174
021	San Rocco Pio Monte S. Anna	SRPM	40.749	13.893	V	0.7167
022	Santissima Annunziata	SSA	40.750	13.897	V	0.7166
023	Congrega dell'Assunta	CDA	40.750	13.892	V	0.7166
024	Basilica Santa Restituta	BSR	40.754	13.884	V	0.7165
025	San Michele Arcangelo	SMA	40.736	13.867	IV-V	0.7126
026	Santa Lucia	SLU	40.735	13.869	V	0.7172
027	San Domenico	SD	40.725	13.869	IV-V	0.7177

It can be noted that, due to the difficulties of the shake-maps definition for the August 21st seismic event (as mentioned in Section 2.2), the values of PGA provided by the shake-map result significantly lower with respect to the PGA values recorded by the IOCA accelerometer (i.e. 0.28g). This can be attributable to both the intrinsic quick attenuation, typical of superficial volcanic earthquakes, and the local amplification effect of the signal where the IOCA station is located. For these reasons, only the macro-seismic intensities will be considered for the following analysis.

Nevertheless, as already highlighted above, it must be noted that macro-seismic surveys were conducted on ordinary buildings, mainly characterized, for the building stock of Ischia Island, by a high intrinsic vulnerability due to the poor material used (masonry with absence of reinforcing elements) and significant structural changes generally performed to such buildings over time (structural enlargements and/or further raising). For this reason, the assigned macro-seismic intensities could overestimate the actual macro-seismic intensity for the examined churches, which, on the contrary, were characterized by better building techniques in comparison with ordinary buildings. The typical Ischia church is, indeed, made of good material (tuff stone and regular bed joints) and did not show significant damage even in absence of anti-seismic devices (such as tie rods).

A total of 27 surveys were performed on churches in the most damaged areas of the island. As shown in Figure 5, the most inspected municipalities were: Casamicciola (6 churches), Forio (17 churches) and Lacco Ameno (4 churches). Figure 5 summarizes the distribution of the inspected churches for the involved municipalities.

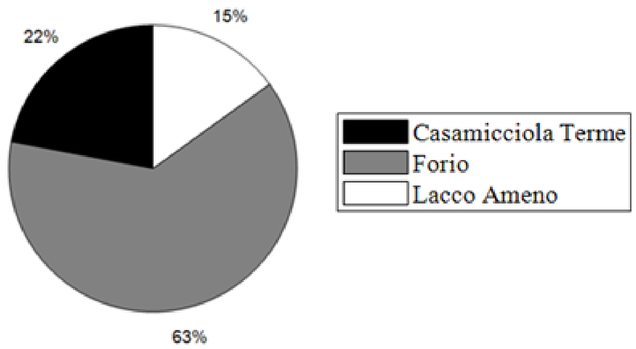


Figure 5. Distribution of the inspected churches among the corresponding municipalities.

3.2 Typological characterization

A preliminary typological characterization of the analysed churches was conducted considering the plan and the spatial compositions, the main structural elements and the range of structural measures.

Out of the 27 inspected churches, 2 churches were excluded from the analysis: the Santuario Maria SS Immacolata and the church of Santa Maria Maddalena Penitente (Casapulla et al. 2019), both located in Casamicciola Terme. The Santuario Maria SS Immacolata is, indeed, a timber-framed masonry church, which is a structural typology significantly widespread throughout the island, mainly for ordinary buildings. Such a building technique started diffusing since XIX century in the Southern Italian regions of Calabria and Campania, after some catastrophic seismic events (e.g. the Casamicciola Terme event of 1883), given its adequacy to resist to seismic actions. The combination of two different materials (wood and stones), indeed, ensures a good performance under seismic actions. Other examples of a similar building technique are the “Pombalino” system in Portugal, the “Dhajji-Dewari” system in South Asia and the “Himis system” in Turkey.

Santa Maria Maddalena Penitente in Casamicciola Terme is a mixed timber-framed and iron-framed masonry church (Casapulla et al. 2019) and is, thus, a unique example of this structural typology in the national construction heritage. The church was totally rebuilt after its collapse under the strong 1883 earthquake. The presbytery and apse areas contain the timber-framed structure, while the nave and the transept are characterized by the iron-framed structure, both embracing the masonry structure made of local green and yellow tuff stones.

The remaining 25 cases were subdivided according to the typologies summarized in Table 3. They have one or three naves, with or without the bell tower adjacent to the main building (only in some cases there are two towers) and with or without the presence of a dome. Due to the greater number of one-nave churches (21 out of 25), the study will focus on this typology.

For the 21 one-nave cases, four churches are shown in Figure 6 as representative of the four different geometry individuated in Table 3.

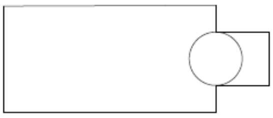
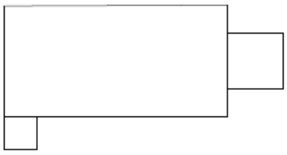
3.3 Geometrical features

Once a typological subdivision of the database was performed considering the plan and the spatial composition of each church, the geometrical features were also analysed.

Table 4 summarizes the mean values of the geometrical characteristics (planimetric surface, A_{mean}, façade height, $H_{facade,mean}$, wall width, s_{mean}, and volume, V_{mean}) for each of the four different types.

The mean values of the plan area for the four types of one-nave churches varies between 97 and 121 m^2. About the façade height, it varies between 8.75 and 12.50 m. The wall width, instead, varies between 0.7 and 0.8 m.

Table 3. Typological subdivision of the churches

Type	1 Nave	3 Naves
 I - Simple	11	-
 II - Dome	3	-
 III - Dome and bell tower	4	4
 IV - Bell tower	3	-


a) b) c) d)

Figure 6. a) Type I: Santa Maria della Pietà church in Casamicciola Terme; b) type II: Santa Maria del Buon Consiglio church in Casamicciola Terme; c) type III: Congrega Santa Maria Assunta church in Lacco Ameno; d) type IV: Santa Maria del Soccorso church in Forio.

Table 4. Mean values of the geometrical characteristics of the one-nave churches.

Type	Geometrical mean values			
	A [m^2]	H [m]	s [m]	V [m^3]
I	121	11.0	0.7	1200
II	111	12.5	0.78	1174
III	97	11.3	0.78	1023
IV	112	8.8	0.80	823

The volume of the church, calculated as the product of the façade height and the plan area, was further investigated in order to find a correlation with the type of bell tower identified.

Figure 7 shows the distribution of the volumes for the 21 one-nave churches and evidences that most of the churches-type I are characterized by a bell gable and a mean volume of 1200 m^3, even if the volumes are very variable (from 300 to 2600 m^3). For the churches of type II and III, the mean volume decreases (about 1173 and 1023 m^3 respectively), while the churches-type IV are the smallest ones (mean volume of 823 m^3) and present integrated bell tower in the façade (as shown in Figure 6d).

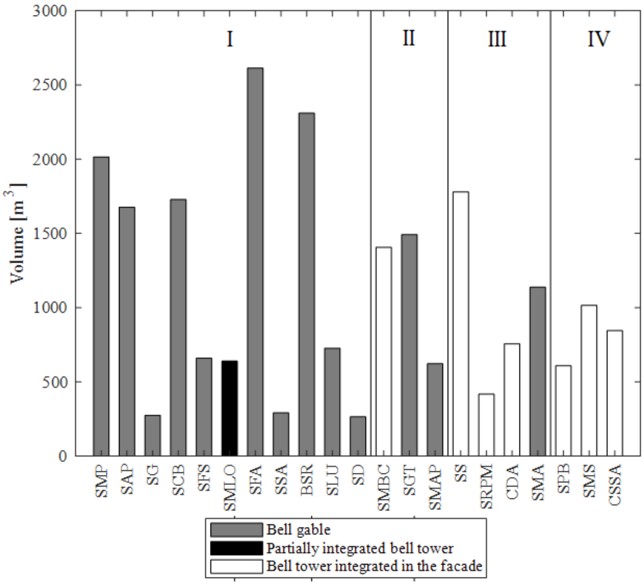


Figure 7. Distribution of the volume for different types of one-nave churches and bell tower type.

3.4 *Damage detection*

The main aim of the technical inspections performed in the first phase, immediately after the August 21st event, was to fill in the A-DC survey form (MiBACT 2015) providing usability checks for the churches after the earthquake. The form gives the possibility of defining 6 usability outcomes: safe, partially safe, safe with precautions, temporarily unsafe, unsafe for external cause, unsafe. Figure 8 reports the usability outcomes distribution for the 21 one-nave churches collected according to the assigned macro-seismic intensity. Within such inspections, the 17 churches with a macro-seismic intensity $I_{EMS} \leq V$ were mostly “safe” or ”safe with precaution” (94%), while only 1 church located in Forio municipality was “unsafe”. Only three churches attained a macro-seismic intensity I_{EMS} = VI and were “safe” or “safe with precautions”. Finally, only one church located in Casamicciola Terme (San Pasquale Baylon church) was characterized by a higher value of macro-seismic intensity (I_{EMS} = VII); nevertheless this church was declared safe with precautions. This result can be due to the overestimation of the macro-seismic intensity for that church, as previously discussed.

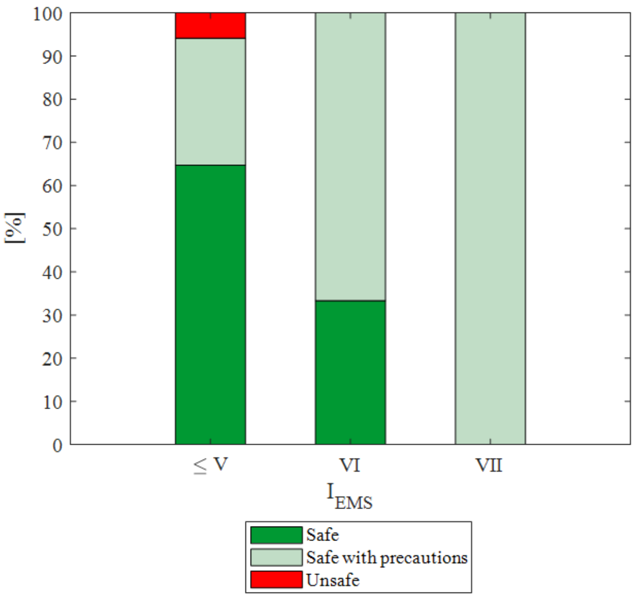


Figure 8. Usability outcomes distribution for 21 one-nave churches.

In order to quantify the actual damage, the A-DC survey form also provides a damage index i_d defined according to the analysis of 28 damage mechanisms to a number of macro-elements (i.e. the façade, the colonnade, the vaults, the chapels, the apse, the transept, the dome and the bell tower). The objective is to verify their activation and the level of damage reached (D1-D5), defined according to the EMS scale (Grunthal 1998) and related to i_d as presented in Section 4. The global damage index is expressed by the formulation:

$$i_d = \frac{1}{5} \cdot \frac{\sum_{k=1}^{n} d_k}{n} \tag{1}$$

where n is the number of activated mechanisms and d_k is the level of damage recorded for each activated mechanism and varies from 0 to 5.

The values of damage index i_d for the 21 inspected one-nave churches are reported in Figure 9 as a function of the macro-seismic intensity. The assessed damage index varies between 0 and 0.35, that means that the inspected structures suffered an overall slight damage. It is worth noting that the highest damage level was reached for churches with $I_{EMS} \leq V$, as it was also evidenced by the usability checks reported in Figure 8.

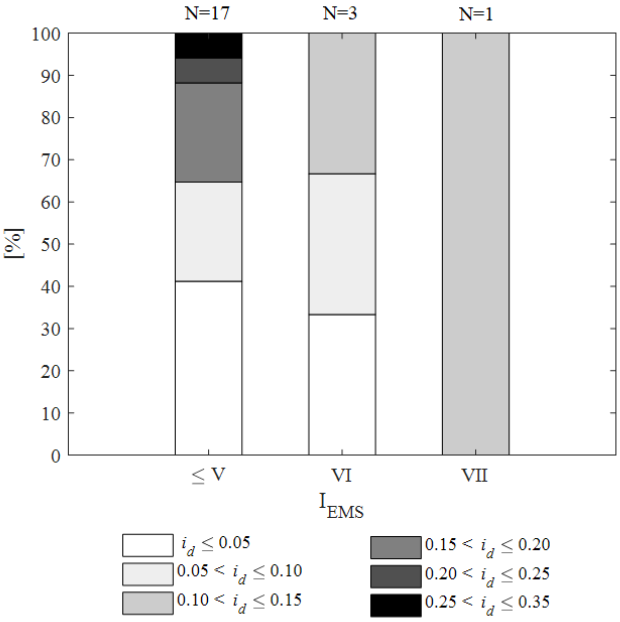


Figure 9. Damage index distribution for 21 one-nave churches.

3.5 *Vulnerability assessment*

In order to perform a vulnerability assessment of the inspected churches, a second phase of surveys was carried out in order to achieve information necessary to define the vulnerability index (i_v) given by the Italian Guidelines on Cultural Heritage (Italian Ministry of Heritage and Cultural Activity and Tourism, 2011). The A-DC form (MiBACT 2015) does not provide, indeed, the possibility to add information related to vulnerability indicators.

In order to do that, each church and the 28 mechanisms described in the A-DC form (MiBACT 2015) were inspected twice. The assessment of i_v requests the definition, for each potential mechanism, of a fragility indicator ($v_{k,i}$) and of a possible protection device indicator ($v_{k,p}$). The effectiveness of these indicators is registered with a score ranging from 0 to 3 (the maximum effectiveness corresponds to a score of 3). The vulnerability index is, thus, calculated as:

$$i_v = \frac{1}{6}\cdot\frac{\sum_{k=1}^{28}\rho_{k,i}\cdot(v_{k,i}-v_{k,p})}{\sum_{k=1}^{28}\rho_{k,i}}+\frac{1}{2} \qquad (2)$$

where $\rho_{k,i}$ is the weight attributed to each mechanism (i.e. 0 for the mechanisms not activated or for the lack of the macro-element, while it varies between 0.5 and 1 in the other cases).

Table 5 summarizes the mean values of the vulnerability indexes calculated for the churches of each municipality and distinguished for one- and three-nave churches. The values of i_v varies in the range of 0.41-0.59, with an overall mean value of $i_{v,\text{mean}}$ = 0.503, which means a medium vulnerability for the set of examined churches.

The one-nave churches of Lacco Ameno are characterized by the highest vulnerability (i.e. i_v=0.551). As an example, in the Santa Restituta church (i_v=0.58), the presence of large openings and a high slenderness have provided significant sources of vulnerability (Figure 11a). However, this church is characterized by a damage index i_d=0, that means that the church did not suffer any damage; this outcome is probably related to its distance from the epicentre and the strong attenuation effect that characterized the earthquake (see Section 2.2).

Table 5. Mean value of vulnerability index (i_v) for each municipality and church type.

Type	$i_{v,\text{mean}}$			
	Casamicciola Terme	Lacco Ameno	Forio	All
One-nave churches	0.492	0.551	0.485	0.499
Three-nave church	-	-	0.525	0.525

In order to check if a correlation between vulnerability and damage does exist, the damage index i_d is plotted in Figure 10 as a function of the vulnerability index i_v for both one-nave (21) and three-nave (4) churches, according to the different municipalities to which each church belongs. Moreover, the values of i_d are associated to the EMS damage levels D_k (Grunthal 1998): D0 for i_d < 0.05, D1 for 0.05 < i_d < 0.25, D3 for 0.25 < i_d < 0.40.

For i_d > 0.20 it was not possible to find a clear trend of the damage index with the vulnerability index, also because of the few data available. Nevertheless, for i_d < 0.20 an increasing trend of the damage index with the vulnerability index can be identified, especially for the one-nave churches, even if several inconsistencies are present and discussed in the following.

The two churches with i_d > 0.2 are one-nave churches and are located in Forio (San Michele Arcangelo del Purgatorio with 0.33 and Santa Maria di Loreto – Oratorio with 0.23). The first church suffered severe shear damage to the lateral wall and apse (Figure 11b), in addition to the numerous cracks on the vault of the central nave. The latter one also suffered damage to the vault of the central nave (Figure 11c). Nevertheless, in both cases the intrinsic characteristics of the churches did not highlight significant vulnerability sources (i_v = 0.5), except for the lack of anti-seismic safety devices.

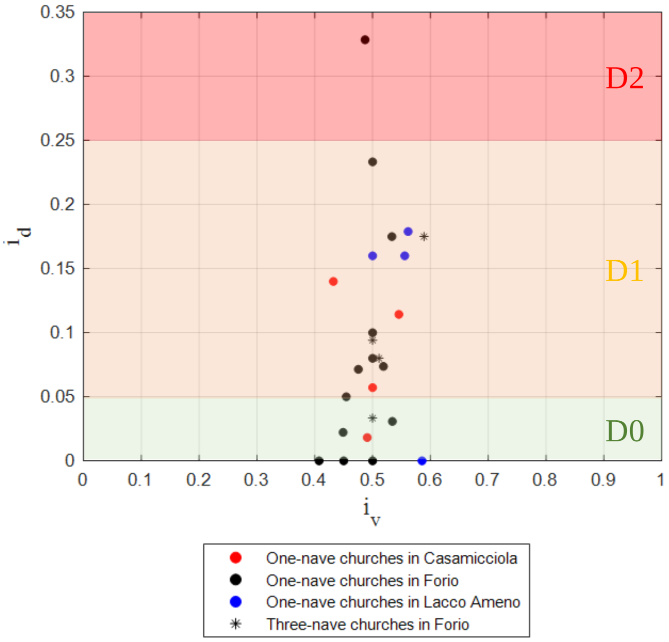


Figure 10. Damage index vs. vulnerability index for 21 one-nave churches and 4 three-nave churches located in different municipalities of Ischia Island.

On the other hand, the three one-nave churches of San Gennaro, San Francesco Saverio and San Michele Arcangelo, located in the same municipality, did not show any damage, resulting in a 0 damage index and being characterized by i_v=0.4-0.5.

The other church having i_d=0 is the one-nave Basilica of Santa Restituta located in Lacco Ameno, previously examined.

Within the churches with i_d < 0.2, four churches are located in Casamicciola, i.e. the epicentre of the event, and and increasing trend of i_d with i_v can be detected, with exception of the

San Pasquale Baylon church, having the lowest i_v and the highest i_d and, as mentioned in Section 3.4, the highest macro-seismic intensity (I_{EMS}=VII). A similar trend is followed by the one-nave churches in Forio.

The three-nave churches (4 cases) are all located in the Forio municipality (San Leonardo, Santa Maria di Loreto, San Francesco di Paola and San Vito). Three of them were characterized by a low damage index ($i_d < 0.1$) with i_v about 0.5, while the Santa Maria di Loreto church had i_d=0.17 and i_v=0.58, i.e. the highest value in the set of examined churches. Such a church is, indeed, characterized by a wide area (A=221.27 m^2) that could have caused an intrinsic higher vulnerability of the church.

a)

b) c)

Figure 11. a) Santa Restituta church in Lacco Ameno; b) Shear damage in San Michele Arcangelo church in Forio; c) Cracks on the vault of the central nave of Santa Maria di Loreto - Oratorio church in Forio.

3.6 Analysis of activated mechanisms for one-nave churches

The A-DC survey form (MiBACT 2015) analyses also the possibility of activating the 28 mechanisms listed in Table 6. The analysis was carried out with only reference to the one-nave churches in order to have a more homogenous set of data.

The correlation between the potential and activated mechanisms in the 21 inspected one-nave churches of Ischia Island is shown in Figure 12. This figure highlights that some mechanisms, such as M3 and M6 (shear mechanism in the façade and shear mechanism in the nave lateral walls, respectively), present the highest percentages of occurrence (45-55%), followed by M1 (overturning of the façade, 40%).

Table 6. Damage mechanisms defined in the A-DC survey form (MiBACT 2015).

Mechanism	Description
M1	Overturning of the façade
M2	Overturning of the gable
M3	Shear mechanism in the façade
M4	Porch and narthex.
M5	Transversal vibration of the nave
M6	Shear mechanism in the nave lateral walls
M7	Longitudinal vibration of the central nave
M8	Vaults of the central nave
M9	Vaults of the lateral naves
M10	Overturning of the transept façade
M11	Shear failure in the transept walls
M12	Vaults of the transept
M13	Kinematic chain in the triumphal arches
M14	Collapse of the dome and the Tiburio
M15	Collapse mechanism of the lantern
M16	Overturning of the apses
M17	Shear failure in the apses and presbytery walls
M18	Vaults of the apses and of the presbytery
M5	Transversal vibration of the nave
M19	Hammering and damage in the nave roof
M20	Hammering and damage in the transept roof
M21	Hammering and damage in the apses roof
M22	Overturning of the chapels walls
M23	Shear failure in the chapel walls
M24	Collapse mechanism in the chapel vaults
M25	Interaction between elements of different behaviour
M26	Overturning of the standing out elements
M27	Global collapse of the bell tower
M28	Mechanism in the bell cell

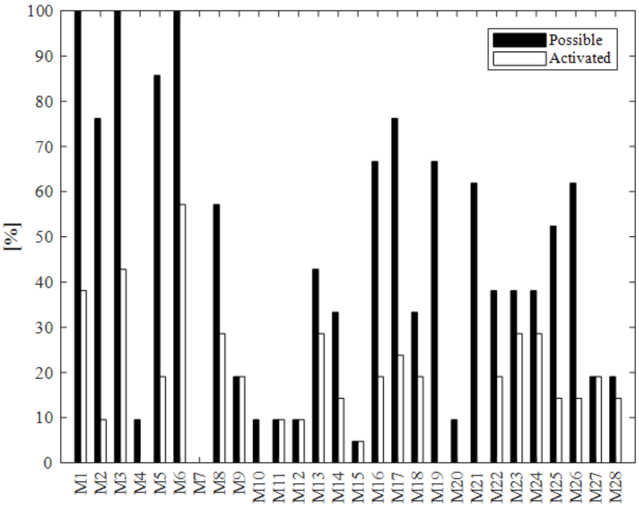


Figure 12. Percentage of potential and activated mechanisms for the 21 one-nave churches.

Other out-of-plane mechanisms (such as the overturning of the apses, M16, or chapels, M22) show a lower probability of occurrence (20%). More frequent mechanisms (30% of occurrence) were M8, M23, M24 related to damages to the vaults of the central nave or to chapels walls and vaults.

In Section 5, a more detailed study is reported for the most recurrent mechanisms, i.e. the in-plane ones.

4 STATISTICAL ANALYSIS OF THE COLLECTED DATA: GLOBAL DAMAGE RECORDED ON CHURCHES

4.1 DPMs

Damage Probability Matrices (DPMs), based on the statistical elaborations of damage observed in the inspected churches, are presented for the set made of 21 one-nave churches. DPMs are aimed to perform a vulnerability analysis providing a direct correlation between the observed damage (through the damage index, i_d) and the seismic action in terms of macro-seismic intensity, I_{EMS}. The use of these matrices was firstly introduced in Italy starting from 1980 Irpinia earthquake (Braga et al. 1982) aimed at performing vulnerability analysis and forecasting an expected damage. For a reliable representation of data, a homogeneous class of vulnerability should be associated to each matrix. For this reason, the 21 one-nave churches were considered only. As previously discussed, they are characterized by an overall mean vulnerability index $i_{v,\mathrm{mean}}=0.499$ with a small variation ($i_{v,\mathrm{min}}=0.407$ and $i_{v,\mathrm{max}}=0.585$) and, thus, they can be considered as representative of a homogeneous class of buildings with a medium vulnerability.

In order to define DPMs, the damage index i_d obtained from A-DC form (MiBACT 2015) is transformed into a discrete variable, establishing a correlation with the six EMS damage levels (Grunthal 1998), as proposed by Lagomarsino and Podestà (2005) and shown in Table 7.

Table 7. Correlation between the EMS damage levels and the damage index intervals (Lagomarsino and Podestà 2005).

Level of damage	0	1	2	3	4	5
Damage index i_d	0 ↓ 0.05	0.05 ↓ 0.25	0.25 ↓ 0.4	0.4 ↓ 0.6	0.6 ↓ 0.8	0.8 ↓ 1

Figure 13 reports the DPMs obtained for two different intervals of macro-seismic intensities ($I_{EMS} \leq$ V and $I_{EMS} >$ V). It has to be noted that most of the churches (17 out of 21) belong to the lower macro-seismic intensity interval (see also Section 3.4). Figure 13 also highlights that 41% of churches characterized by low macro-seismic intensity and 25% of churches characterized by high macro-seismic intensity suffered damage level D0. Most of the churches with both low and high macro-seismic intensity (i.e. 53% and 75% respectively) reached damage level D1, while only about the 5% of churches with $I_{EMS} \leq$ V reached a higher level of damage (damage level D2, corresponding to a damage index i_d=0.25÷0.4).

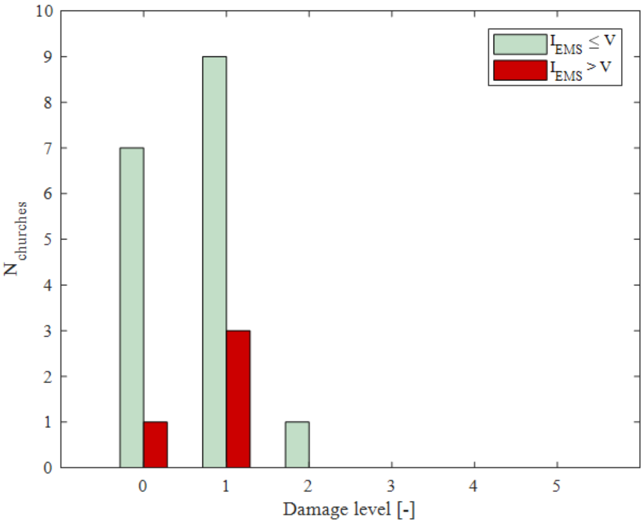


Figure 13. DPMs for the 21 one-nave churches and different values of macro-seismic intensity.

The mean damage for the one-nave churches is estimated for different values of macro-seismic intensity and is listed in Table 8.

Table 8. Mean damage for one-nave churches.

I_{EMS}	III-IV	IV	IV-V	V	VI	VII
Mean damage	0	0.20	0.50	0.74	0.33	0.50

4.2 *Assessment of the global mean damage*

In order to provide predictive models for the vulnerability assessment, the mean damage values observed for the one-nave churches of Ischia are compared in Figure 14 with data coming from other studies. In particular, the observational data related to the following previous studies were considered:

- 375 churches affected by Umbria-Marche 1997 earthquake (Lagomarsino et. al 2004).
- 633 one-nave churches affected by 2016-17 Central Italy earthquake (Cescatti et al. 2019, Salzano et al. 2019);
- 68 one-nave churches affected by 2016-17 Central Italy earthquake (De Matteis et al. 2019).

Figure 14 shows that the data related to the 2017 Ischia earthquake are not reliable for high values of macro-seismic intensity. In fact, for $I_{EMS} \leq V$ the mean damage is in agreement with the trends of data referred to the other databases (De Matteis et al. 2019, Cescatti et al. 2019, Salzano et al. 2019 and Lagomarsino and Podestà 2004), while for $I_{EMS}>V$ there is a decrease of mean damage for increasing values of macro-seismic intensities. As already commented above, the macro-seismic intensity assignment is generally performed considering the damage assessment of the ordinary buildings, which in the case of Ischia Island are made with poor masonry and other intrinsic vulnerabilities due to structural modifications over time. By contrast, historical buildings were made of better quality masonry (tuff stones and regular bed joints). This may have led to an overall overestimation of the macro-seismic intensities for the churches of Ischia and, thus, to values of mean damage not in agreement with the trend observed for lower intensity values.

It is also important to note that the considered macro-seismic intensity scales are not the same for all represented data; in fact, in the case of Ischia surveys, only the values according to the EMS macro-seismic scale were available (Azzaro et al. 2017), while for all the cited studies (De Matteis et al. 2019, Cescatti et al. 2019, Salzano et al. 2019 and Lagomarsino and Podestà 2004), the MCS macro-seismic scale (Mercalli-Cancani-Sieberg 1930) was considered as reference. Nevertheless, past studies have shown the comparability of the two macro-seismic scales (Casapulla et al. 2017 and Cescatti et al. 2019).

The observed mean damage is compared with the two following correlations both provided by (Lagomarsino et. al 2004):

$$\mu_D = 2.5 \cdot [1 + \tanh(\alpha \cdot I - \beta)] \tag{3}$$

$$\mu_D = 2.5 \cdot \left[1 + \tanh\left(\frac{I + 3.4375 \cdot \bar{\iota}_v - 8.9125}{3}\right)\right] \tag{4}$$

In Eq. (3), α and β are correlation parameters, which implicitly consider the intrinsic vulnerability of the structure, I is the macro-seismic intensity, and $\bar{\iota}_v$ is the mean vulnerability index.

For the Umbria and Marche churches, in Lagomarsino and Podestà (2004), Eq. (4) was considered with $\bar{\iota}_v = 0.4$ and $I=I_{MCS}$. The following equation was obtained and plotted in Figure 14:

$$\mu_D = 2.5 \cdot \left[1 + \tanh\left(\frac{I - 7.5375}{3}\right)\right] \tag{5}$$

In De Matteis et al. (2019), Eq. (4) was used with an average vulnerability index, $\bar{\iota}_v = 0.479$ and $I=I_{MCS}$. The following equation was obtained and plotted in Figure 14:

$$\mu_D = 2.5 \cdot \left[1 + \tanh\left(\frac{I - 7.2659}{3}\right)\right] \tag{6}$$

The fitting of Eq. (6) with the observational data of De Matteis et al. (2019) is quite good, but clearly lower than that of Eq. (5) with the data of Lagomarsino and Podestà (2004), since the coefficients 3.4375 and 8.9125 were assessed on the Umbria and Marche churches.

For the one-nave churches of Ischia, considering the more reliable data for $I_{EMS} \leq V$ only, the fitting of the parameters α and β of Eq. (3), the mean vulnerability index, $\bar{\iota}_v$= 0.499, and the macro-seismic intensity $I=I_{EMS}$ introduced in Eq. (4) provide the following equations:

$$\mu_D = 2.5 \cdot [1 + \tanh(0.7363 \cdot I_{MCS} - 4.5448)] \tag{7}$$

$$\mu_D = 2.5 \cdot \left[1 + \tanh\left(\frac{I - 7.1972}{3}\right)\right] \tag{8}$$

Curves corresponding to Eqs. (7) and (8) are plotted in Figure 14. A good fitting is shown for the observational data in the case of Eq. (6), while Eq. (8) provides an unreliable fitting since the numerical coefficients are the ones given by

Lagomarsino and Podestà (2004) and are not assessed on the observational points. Clearly, Eq. (7) is strongly conditioned by the few available data for low damage values and, thus, the prediction could not be reliable for μ_D higher than 1 (i.e. corresponding to $I_{EMS} > V$).

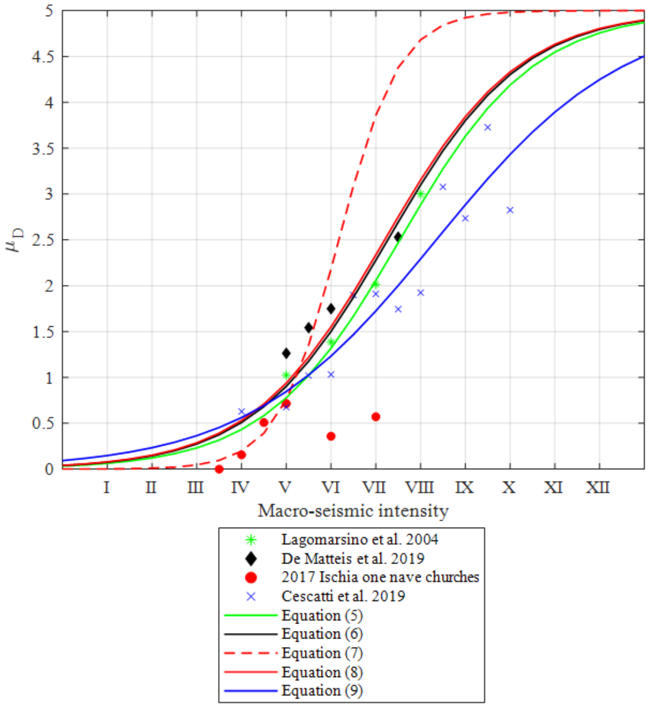


Figure 14. Vulnerability curves for Ischia one-nave churches compared with existing literature correlations.

Finally, for the 633 central Italy one-nave churches examined by Cescatti et al. (2019) and , Salzano et al. (2019), only Eq. (3) was used, since the values of i_v were not available. The fitting of the parameters α and β in Eq. (3), with $I=I_{MCS}$, provided the following correlation:

$$\mu_D = 2.5 \cdot [1 + \tanh(0.2375 \cdot I_{MCS} - 1.9828)] \quad (9)$$

Eq. (9) is characterized by a good fitting with the observational data of central Italy one-nave churches and furnishes mean damage meanly lower than that provided by Eqs. (5) and (6).

Moreover, it can be noted that the observational data of Ischia churches and the provisions given by Eq. (7) for $I_{EMS} \leq V$ are always lower than the predictions fitted on other databases, evidencing again the possibility of an overestimation of the macro-seismic intensity for such a set of churches. Conversely, for $I_{EMS} > V$, the provisions of Eq. (7) are higher than the ones giver by other equations, but, as already evidenced, Eq. (7) cannot be considered for $I_{EMS} > V$, due to the lack of reliable observational data.

5 STATISTICAL ANALYSIS OF THE COLLECTED DATA: LOCAL DAMAGE RECORDED ON CHURCHES

5.1 *DPMs*

Damage Probability Matrices (DPMs) were also computed for the most recurrent mechanisms of the 21 Ischia one-nave churches.

As shown in Section 3.5, the most recurrent mechanisms for the reduced sample of one-nave churches are the ones related to the in-plane shear mechanisms (in particular, M3 and M6).

DPMs are obtained for both mechanisms M3 (Figure 15) and M6 (Figure 16) subdividing the sample according to the two intervals of macro-seismic intensity already considered ($I_{EMS} \leq V$ with 17 churches, and $I_{EMS} > V$ with 4 churches).

Figure 15 shows that the maximum damage level is D2. Most of the churches reached D0 and D1 levels (94% and 75% for $I_{EMS} \leq V$ and $I_{EMS} > V$, respectively), while a very low percentage of churches reached the D2 level (6% and 25% for $I_{EMS} \leq V$ and $I_{EMS} > V$, respectively).

Figure 16 shows that for $I_{EMS} > V$ all the four churches reached the D0 and D1 level, while for $I_{EMS} < V$, the 88% of churches reached D0 and D1 and only 12% reached the D2 level.

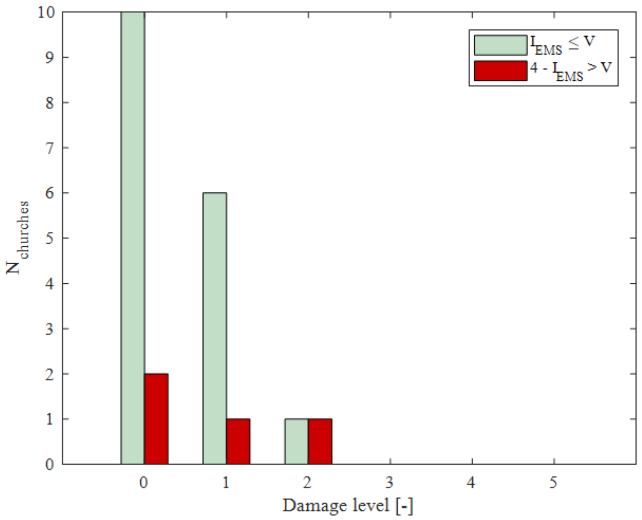


Figure 15. DPMs for M3 - Shear mechanism in the façade, according to two intervals of macro-seismic intensity.

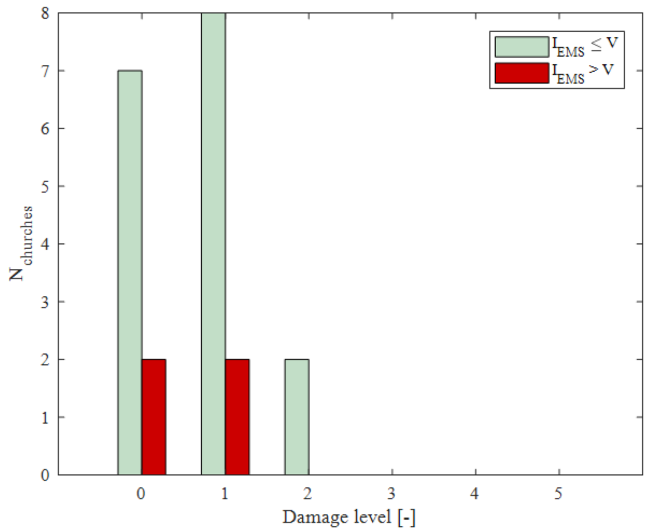


Figure 16. DPMs for M6 - Shear mechanism in the nave lateral walls, according to two intervals of macro-seismic intensity.

5.2 *Assessment of the mean damage for mechanisms*

Vulnerability curves, correlating the observed mean damage to the macro-seismic intensity, were also obtained for the mechanisms M3 and M6, as plotted in Figure 17 and reported in Table 9.

M3 and M6 (shear mechanism in the façade, and shear mechanism in the nave lateral walls, respectively) are the most frequent in the surveyed churches, characterized by a highest mean damage. Those mechanisms were activated in over 50% of churches (Casapulla et al. 2019).

Table 9 summarizes the mean damage for both the mechanisms M3 and M6 on one-nave Ischia churches. In both cases, an increasing trend of mean damage for $I_{EMS} \leq V$ is evident.

Table 9. Mean damage for the mechanisms M3 and M6 on one-nave churches.

I_{EMS}	M3	M6
III-IV	0	0
IV	0	0.33
IV-V	0.57	0.71
V	0.67	1.0
VI	0.33	0.33
VII	2.0	1.0

In Figure 17, the following theoretical laws are also plotted:

- for M3:

$$\mu_D = 2.5 \cdot [1 + \tanh(0.7983 \cdot I_{MCS} - 4.8759)] \quad (10)$$

- for M6:

$$\mu_D = 2.5 \cdot [1 + \tanh(0.6920 \cdot I_{MCS} - 4.1198)] \quad (11)$$

Eqs. (10) and (11) are obtained using Eq. (3) and fitting the parameters α and β, only considering the more reliable data related to macro-seismic intensities $I_{EMS} \leq V$. Also for these cases, indeed, data related to $I_{EMS} > V$ were excluded because of the inconsistencies described above

Eqs. (10) and (11) could be useful for providing the mean damage reached with in-plane mechanisms M3 and M6 according to different macro-seismic intensities.

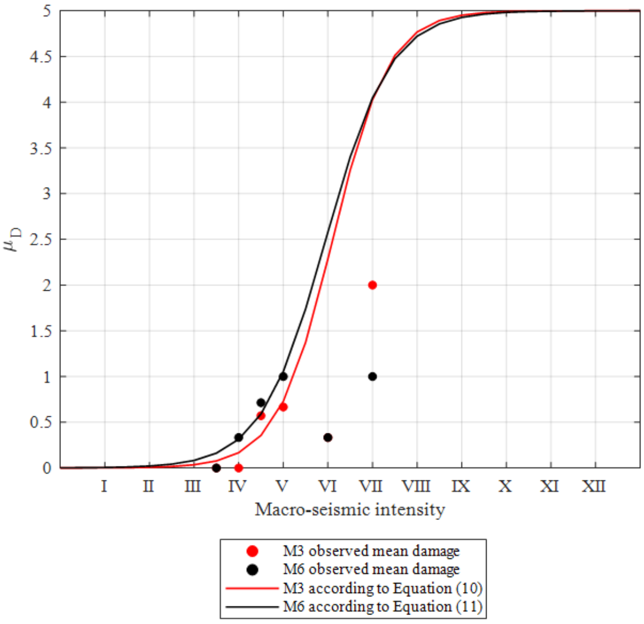


Figure 17. Vulnerability curves for the mechanisms M3 and M6 in the 21 Ischia one-nave churches.

6 CONCLUSIONS

The earthquake that struck the Ischia Island on 21st August 2017 caused significant damages to churches and masonry buildings in Forio, Lacco Ameno and Casamicciola Terme municipalities. The 2017 event was very superficial and characterized by a very strong attenuation effect at short distances; this, together with the lack of historical attenuation laws of volcanic earthquakes, led to an unreliable construction of shake-maps. On the other hand, macro-seismic field surveys were carried out by the emergency group QUEST, providing an EMS intensity scale map, very useful for obtaining a combined measure of the earthquake intensity and damage recorded.

Thanks to two phases of in situ surveys realized after the seismic event of 2017, a database of 27 churches was created. Firstly, a typological description of the inspected churches, considering the plan and spatial compositions, the main structural elements and the range of structural measures of the churches, was carried out. Four typologies of churches were identified: with one (21) or three (4) naves, with or without the bell tower adjacent to the main building (only in some cases there are two towers) and with or without the presence of a dome. In general, the churches of Ischia Island have a simple geometry.

Successively, a detailed study of the geometry of the inspected churches was performed with reference to plan area, façade height and wall width.

The comparison of the damage indexes and the usability outcomes with the macro-seismic intensities for the one-nave churches evidenced that churches were mostly "safe" or "safe with precaution" and only 1 church was unsafe.

A vulnerability characterization of the one-nave churches was also performed, showing that, in all the examined cases, the vulnerability index varies between 0.4 and 0.6. An increasing trend between the damage index and the vulnerability index was identified for $i_d < 0.20$, even if some inconsistencies were evidenced.

Damage Probability Matrices (DPMs) were obtained for $I_{EMS} \leq V$ and $I_{EMS} > V$. Mostly, churches reached a damage level lower or equal to D1.

The mean damage for the Ischia one-nave churches is compared with literature data and literature regression laws, showing that the data are not reliable for $I_{EMS} > V$. Conversely, for $I_{EMS} \leq V$, the mean damage observed in the Ischia one-nave churches is in agreement with the trend of the observational data of other databases, which were characterized by higher macro-seismic intensities, but is lower than the predictions provided by existing correlations assessed on other databases.

All the analyses confirmed some inconsistencies in the data of churches with $I_{EMS} > V$. These inconsistencies may be caused by an overestimation of the macro-seismic intensity assigned to each church, defined considering the damage on Ischia ordinary buildings, characterized by an overall higher vulnerability (poor masonry and significant intrinsic vulnerabilities).

The study of the potential and activated mechanisms was carried out, highlighting that some mechanisms, such as M3 and M6 (shear mechanism in the façade and shear mechanism in the nave lateral walls, respectively), presented the highest percentage of occurrence (45-55%).

DPMs and vulnerability curves were also obtained considering the mechanisms M3 and M6. DPMs showed that for all the examined churches the damage reached for the two mechanisms was lower or equal to D2. As for the global damage, also the regression laws related to the mean damage of M3 and M6 were reliably assessed only for low values of macro-seismic intensity ($I_{EMS} \leq V$).

Following studies will be aimed at setting up fragility curves for the one-nave homogeneous class of churches, in order to define the best strategies for interventions.

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