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AN HYBRID METHODOLOGY FOR THE DEFINITION OF LOCALIZED COLLAPSE CURVES FOR UNREINFORCED MASONRY STRUCTURES

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Abstract

The estimation of the potential number of buildings damaged after a seismic event is a fundamental step both for optimal management of resources in the emergency phase and for accurate planning of mitigation measures in time of peace. The collapsed buildings generate the higher damage in terms of human life and economic losses. Also, the collapse of buildings can also cause the interruption of road sections and paths, and consequently limit the rescue by workers and volunteers. Therefore, a localized estimation of possible collapses represents a useful tool in the emergency management planning phase. This assessment depends on the distribution of the building typologies present in the area invested by the earthquake and on their possible answer to the event. This work shows a methodology to build a local vulnerability model for unreinforced masonry structures, which returns collapse curves calibrated on the typological distribution of the buildings of a specific geographical area. This methodology exploits an energy-based modeling of in-plane fragility for 2D ultimate capacity of masonry structures, that provides the collapse acceleration values based on the typological characteristics of the analyzed sample. This analytical application is combined with a data collection activity that provides the frequencies, on the investigated area, of the typological characteristics considered in the modeling. The statistical distribution of the collapse accelerations weighted on the frequency of occurrence of these typological characteristics returns the localized collapse curve.

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1 INTRODUCTION

Italy is a country with very large areas under high seismic hazard. About 40% of its surface, comprised in about 35% of Italian Municipalities, is classified as seismic zone 1 or 2, i.e. It is considered that in a period of 50 years there is a probability greater than 10% that in this area a PGA value of 0.15 g is reached or exceeded. The high seismicity of the Italian territory requires the definition of various analytical tools to quantify the possible damage to buildings, people, and the economy in case of a seismic event. The risk model, understood as an estimate of the possible distribution of damage caused by the expected event, makes use of the convolution of three factors: hazard, vulnerability, and exposure.

The hazard represents the probability that a pre-established seismic event can be reached or exceeded in a pre-established area and in a pre-established time interval.

Vulnerability represents the probability that an element at risk could reach or exceed a fixed level of damage upon the occurrence of a specific seismic event. The exposure represents the quantitative and qualitative distribution of the elements at risk in the investigated area.

Risk and vulnerability assessment at national scale is a topic currently widely addressed in the literature [1, 2, 3, 4, 5, 6, 7, 8, 9], with the aim of providing general analysis to the civil protection department and supporting decisions on the management and distribution of resources on the territory. The need to respond to a national scale makes it necessary to use sometimes imprecise or approximate data, for example the ISTAT data [10] for the definition of exposure, which have the advantage of uniformly covering the entire national territory.

However, when it is asked to respond to requests from local authorities, it is necessary that the hazard, exposure, and vulnerability consider the local features. In this work, therefore, we propose a strategy to the construction of collapse curves for masonry buildings on an analytical basis and calibrated on local data on the Ischia territory.

To this purpose, we made use of a data collection activity to define a sample of about 850 masonry buildings through the PLINIVS survey files to have greater detail both of the typological characteristics of the environment of Ischia, nNeapolitan area particularly sensitive to pre-volcanic seismic events [11], and of their geographical distribution compared to what is reported in the ISTAT database. The seismic behavior class of each building is also defined using the SAVE method [12].

The data collection campaign had the task of defining the occurrence of each building typologies identified in [13], on which an analytical procedure based on the Piecewise Rigid Displacement Method can evaluate the pseudo-static collapse load, correlated to the geometry and construction details of the building. The procedure is specific for masonry structures, as it exploits the Heyman model for Rigid No-Tension materials [14, 15]. In recent years, a large variety of methods based on limit analysis theorems have been developed to evaluate the safety of masonry vaults [16, 17, 18,19], domes [20, 21, 22] and masonry facades [23,24,25,26], and to check the effects of ground settlements [27], with particular attention to the displacement capacity [28,29,30,31].

From the knowledge of the collapse PGA, grouped for each vulnerability class and their frequencies of occurrence, it was possible to construct the collapse curves for each class, referring to the Ischia area.

2 METHODOLOGY

2.1 Survey Activity

The analysis of the buildings has been carried out through expeditious visual survey and compilation of the First Level form, called PLINIVS, for the collection of parameters affecting the seismic and volcanic vulnerability of buildings, which has been used extensively in previous research.

The information contained in the PLINIVS form can be divided into two groups. The first contains the common parameters used for seismic vulnerability assessment. It provides, in fact, information on the main vertical and horizontal structures, regularity in plan and elevation, age and preservation of the building, and number of floors. The second group, on the other hand, is specific to the behavior of the building because of a volcanic eruption, as it collects information on the elements of vulnerability with respect to fall deposits (roofs) and pyroclastic flows (openings and infills).

The PLINIVS form is described in detail in [32] and can be downloaded at the link [33].

The format of the surveyed data and the coding of the identifiers are organized so that the information collected can be easily entered into the PLINIVS Center data base. The buildings are all georeferenced and reported in a G.I.S. system. The site survey operation has been carried out according to the following procedure:

- Selection of building aggregates to be surveyed.
- Identification, within the aggregate, of individual buildings, (understood as autonomous structural units).
- Subdivision, on the paper map, of each aggregate into buildings and assignment to each listed building of an identification code, consisting of the aggregate code (PROG_ED) and a building code, with progressive numbering within the aggregate (EDIF).
- Completion for each building of the survey form. In it, the building was identified by reporting the aggregate code and the building code.
  If, within the areas to be surveyed, an aggregate has been found that is not shown on the reference map, it is plotted on the paper service map provided and identified by a temporary "new aggregate code." Any subdivisions into multiple buildings are still coded with progressive EDIF identifier.
  If, on the contrary, it has been found that buildings shown on the map are not in fact present, an indication of this is given on the service map.
  If, finally, macroscopic differences in geometry were found between an aggregate on the cartography and the actual situation, appropriate corrections were reported on the service map, and new provisional codes were assigned where necessary.
- Transfer of the material produced in the field to the G.I.S. operators, who reported the subdivisions and any corrections on the cartography and replaced the "provisional aggregate code" with a new unique identifier (PROG_ED)
- Entering the contents of the surveyed sheets into a special data base.
- Linking, through the identification codes, of the collected data to the "shapes" of the G.I.S.

2.2 Vulnerability class assignment

Through the processing of the data collected with the PLINIVS form, each building is assigned its seismic vulnerability class.
Each building surveyed was assigned its seismic vulnerability class according to the European macro-seismic classification E.M.S. (Figure 1), in accordance with the 1st level "SAVE" methodology. This methodology [12] involves the assignment of a base score, depending on the type of vertical structure, which is subsequently updated through the application of modifier coefficients (based on the typological, geometrical, and structural characteristics of the building), the weight of which has been previously calibrated on the seismic damage statistics detected as a result of earthquakes that have occurred in the past. The score arrived at defines the final expeditious assessment of the vulnerability class.

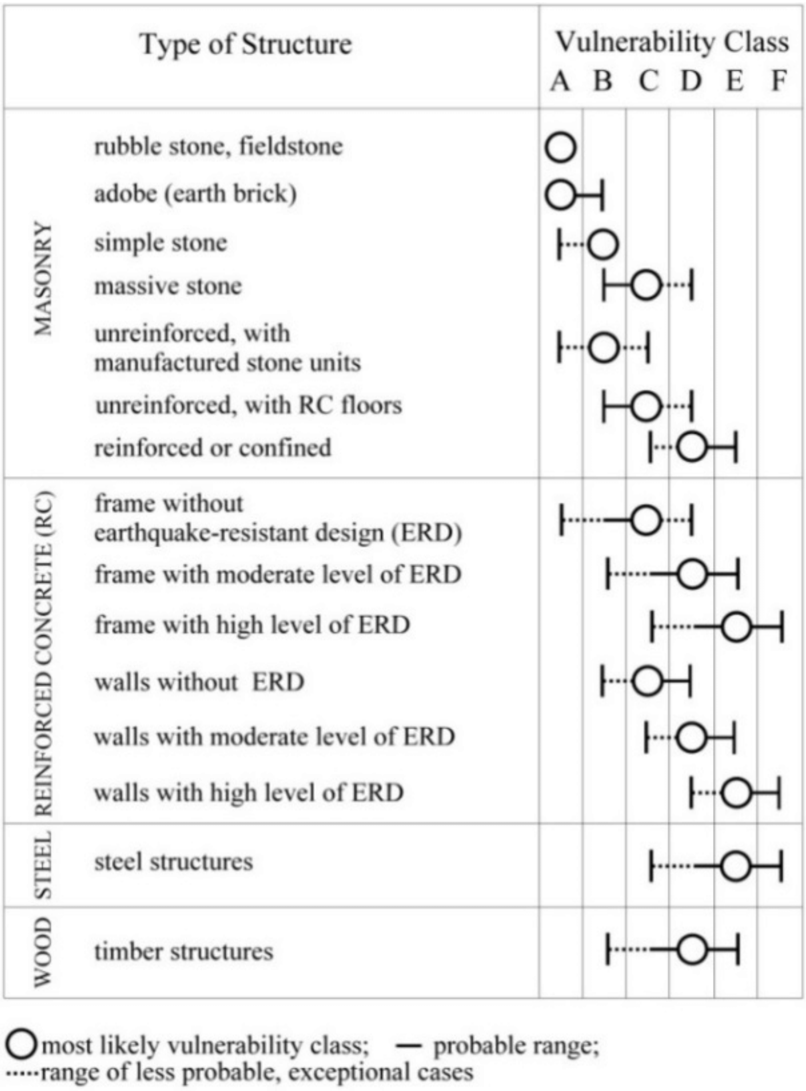

Figure 1. Vulnerability classes defined by the European Macroseismic Scale 1998 [34] (EMS'98).

2.3 Local Collapse Curve construction

Masonry structures are modeled as 2D domains made up of Normal Rigid No-Tension materials, and follow the Heyman assumptions of being non-resistant in traction, rigid and infinitely resistant in compression and to sliding, that is

$$\mathbf{T} \in \mathrm{Sym}^{-}, \qquad \mathbf{E} \in \mathrm{Sym}^{+}, \qquad \mathbf{T} \cdot \mathbf{E} = 0 \tag{1}$$

where **T** **is** the stress tensor, **E** **is** the infinitesimal deformation tensor, Sym^{+} and Sym^{-} are the spaces of positive and negative semidefinite symmetric tensors. The equilibrium and kinematic conditions hold, therefore

$$\begin{gathered} \mathbf{div}\ \mathbf{T} + \mathbf{b} = \mathbf{0} \quad , \ \boldsymbol{x} \in \Omega \\ \mathbf{Tn} = \overline{\mathbf{p}} \quad , \ \boldsymbol{x} \in \partial\Omega_N \\ \mathbf{E} = \frac{1}{2}(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T) \quad , \ \boldsymbol{x} \in \Omega \\ \mathbf{u} = \overline{\mathbf{u}} \quad , \ \boldsymbol{x} \in \partial\Omega_{\mathrm{D}} \end{gathered} \tag{2}$$

with **x** the position vector, $\partial\Omega_N$ and $\partial\Omega_D$ the Neumann and Dirichlet domain boundary, **u** the displacement field, **b** the vector of body loads, defined in the interior of Ω, $\overline{\mathbf{p}}$ the assigned tractions at the Neumann boundary, $\overline{\mathbf{u}}$ the assigned displacements at the Dirichlet boundary.

Problem (1)-(2) constitute a Boundary Value Problem, and can be formulated in terms of the minimization of two different functionals: the Total Potential Energy E, and the Total Complementary Energy E_c. The minimization of the Total Potential Energy provides the solution in terms of displacements and deformations; the minimization of the Total Complementary Energy, on the contrary, provides the solution of the BVP in terms of the stress field.
In this contribution we pursue the first path, and introduce the Total Potential Energy as

$$\mathrm{E} = -\int_{\partial\Omega_N} \overline{\mathbf{p}} \cdot \mathbf{u}\ ds - \int_{\Omega} \mathbf{b} \cdot \mathbf{u}\ da \tag{3}$$

The solution is found as

$$\mathrm{E}(\mathbf{u}^0) = \min_{\mathbf{u} \in K} \mathrm{E}(\mathbf{u}) \tag{4}$$

where K is the set of kinematically admissible displacement fields, that is

$$K = \{\mathbf{u} \in \mathrm{R}^2 \ \text{s.t.}\ \mathbf{E} = \frac{1}{2}(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T),\ \ \mathbf{E} \in \mathrm{Sym}^{+}, \mathbf{u} = \overline{\mathbf{u}}\,\} \tag{5}$$

A load distribution $(\overline{\mathbf{p}}, \mathbf{b})$ is admissible if the Total Potential Energy is bounded from below, that is, the formation of mechanisms is prevented. The existence of a minimum, therefore, depends on the size of the set K, which, in turn, depends on the given external loads.
We consider both fixed and variable external loads, as

$$\mathbf{b} = \mathbf{b}_{\mathrm{g}} + \lambda\, \mathbf{b}_{\perp} \quad , \quad \overline{\mathbf{p}} = \overline{\mathbf{p}}_{\mathrm{o}} + \lambda\, \overline{\mathbf{p}}_{\perp} \tag{6}$$

λ being a scalar multiplier, $\mathbf{b}_{\mathrm{g}}$, $\overline{\mathbf{p}}_{\mathrm{o}}$ the fixed part of the volumetric and boundary loads, and $\mathbf{b}_{\perp}$, $\overline{\mathbf{p}}_{\perp}$ the variable part. It is customary, in seismic application, to consider the seismic action as pseudo-static loads orthogonal to the gravitational direction.

Therefore, the definition of the Total Potential Energy can be reformulated as depending on λ, as

$$\mathrm{E}_\lambda = -\int_{\partial\Omega_N} (\,\bar{\mathbf{p}} = \bar{\mathbf{p}}_o + \lambda\,\bar{\mathbf{p}}_\perp)\cdot\mathbf{u}\; ds - \int_{\Omega} (\mathbf{b}_g + \lambda\,\mathbf{b}_\perp\,)\cdot\mathbf{u}\; da \tag{7}$$

whose solution is found through:

$$\mathrm{E}_\lambda(\mathbf{u}^0) = \min_{\mathbf{u}\in K} \mathrm{E}_\lambda(\mathbf{u}) \tag{8}$$

The computation of the maximum admissible load therefore consists in the search of the maximum scalar multiplier for which the Total Potential Energy is bounded from below, as

$$\lambda_c = \max_{\lambda\in R^+} \min_{\mathbf{u}\in K} \mathrm{E}_\lambda(\mathbf{u}) \tag{9}$$

2.4 PRD discretization strategy

The solution of Problem (9) can be found through the Piecewise Rigid Displacement (PRD) method [35], a numerical strategy based on the discretization of the domain in rigid blocks Ω_j, as shown in Figure 2.

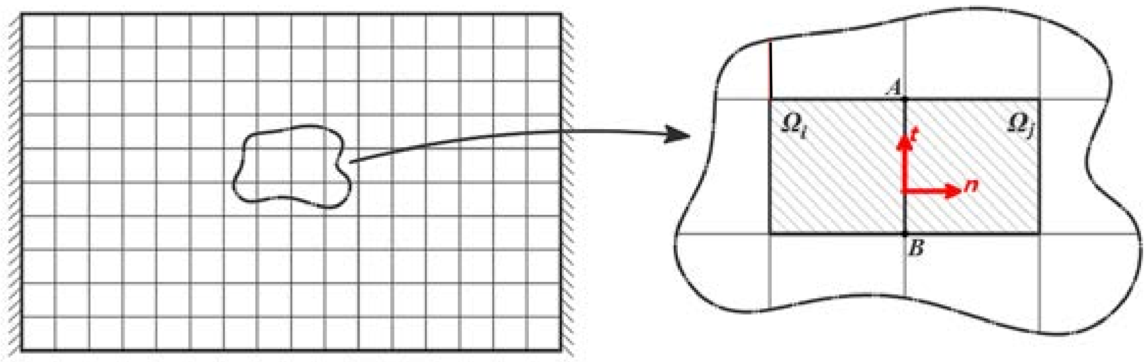

Figure 2. PRD discretization of a rectangular domain

The rigidity of each subdomain Ω_j implies that the deformation is concentrated only at the frontiers between blocks, and on the Dirichlet boundary. Therefore, it is expressed through a singular deformation $\mathbf{E}^s$, as

$$\mathbf{E} = \mathbf{E}^s = \mathrm{e}\;\delta[\Gamma]\mathbf{n}\otimes\mathbf{n} \tag{10}$$

where e is the intensity of the singular deformation, Γ is its support, which coincides with the interface between block, $\delta(\Gamma)$ is the Dirac delta distribution, and $\mathbf{n}$ is the direction normal to the interface boundary.

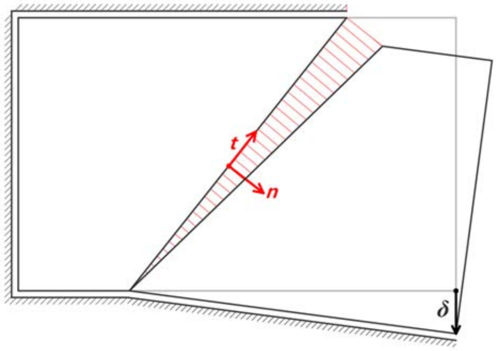

Figure 3. Admissible displacements in PRD

The admissibility of the deformation, given the PRD formulation, is enforced through the admissibility of the displacements at the interface (see Figure 3), that can occur only in detachment, as

$$\mathrm{v} = (\mathbf{u}^+ - \mathbf{u}^-)\cdot\mathbf{n} \geq 0 \tag{11}$$

where $\mathbf{u}^+$ and $\mathbf{u}^-$ are the nodal displacements of two adjacent blocks; the no-sliding conditions is enforced through:

$$\mathrm{w} = (\mathbf{u}^+ - \mathbf{u}^-)\cdot\mathbf{t} = 0 \tag{12}$$

$\mathbf{t}$ being the tangential direction at the interface.
Collecting all the interface and considering all the blocks of the discretization, the set of admissible displacement field is given by

$$K^{PRD} = \{\hat{\mathbf{u}} \in \mathrm{R}^{\mathbf{n}} \text{ s.t. } \mathbf{A}\hat{\mathbf{u}} \geq \mathbf{0}\text{ },\mathbf{B}\hat{\mathbf{u}} = \mathbf{0}, \hat{\mathbf{u}} = \bar{\mathbf{u}}\text{ }\} \tag{13}$$

and the solution in terms of the collapse multiplier is found as

$$\lambda_c^{PRD} = \max_{\lambda\in R^+}\min_{\hat{\mathbf{u}}\in K^{PRD}} \mathrm{E}_\lambda(\hat{\mathbf{u}}) \tag{14}$$

3 OUTCOMES

3.1 Typological Characterization of the Island of ISCHIA

Within the framework of the VIRA 2019 convention stipulated between the PLINIVS Study Center and the Department of Civil Protection, a data collection campaign was carried out on the Ischia Island territory covering a sample of 1,528 buildings. These buildings are distributed on the six Ischian municipalities and the three main vertical typologies (masonry, R.C., other) as reported in Table 1.
The built PRD method works on masonry structures only, so 860 buildings have been considered for the local vulnerability model. With respect to the typological characteristics used in the developed PRD method (vertical typology, horizontal typology, number of floors and openings) the surveyed masonry buildings distribution is reported in Table 2.

Table 1. Surveyed buildings distribution on the Ischian municipalities and vertical typologies

Municipality	masonry	R.C.	other	TOTAL
Barano d'Ischia	82	10	14	**106**
Casamicciola Terme	260	113	68	**441**
Forio	186	66	60	**312**
Ischia	232	79	115	**426**
Lacco Ameno	85	27	44	**156**
Serrara Fontana	15	3	69	**87**
TOTAL	**860**	**298**	**370**	**1528**

Table 2. Surveyed buildings distribution on the Ischian municipalities and vertical typologies

vertical typology	buildings
irregular stone	59
regular stone	90
tuff masonry	600
filled brick	102
hollow brick	9
TOTAL	**860**

number of floors	buildings
1 floor	273
2 floors	409
3 floors	153
4 floors	14
5 floors	1
TOTAL	**850**

horizontal typology	buildings
timber floor, without ties	23
timber floor with ties	3
steel without ties	133
reinforced concrete	620
vaults without ties	24
vaults with ties	8
TOTAL	**811**

openings	buildings
< 10%	97
10 - 25%	344
25-30%	342
30-50%	19
TOTAL	**802**

Analysis of the surveyed buildings shows a prevalence of buildings of good quality from a seismic point of view. With reference to the vertical structure, the predominant type is tuff (600 out of 860 buildings), material typical of the island and volcanic in nature that has good mechanical properties. With regard to the horizontal structures, a prevalence of buildings with rigid reinforced concrete floors is observed (620 buildings of 811 with horizontal structure reported). This type of horizontal structure promotes the distribution of seismic action among the load-bearing walls and greatly improves the overall behavior of the structure. Buildings can, moreover, be considered mainly low-rise: in fact, about 80 percent of the sample has fewer than three stories. In addition, no buildings with more than 50% openings were found.
Consistent with the good quality of typological characteristics found in the data collection campaign, the application of the SAVE method returned 51 buildings in class A (6% of the total), 43 buildings in class B (5% of the total) and 766 buildings in class C (89% of the total).

3.2 Collapse Curves for the Island of Ischia

According to the typological characteristics of the detected buildings, their distribution on the 750 possible typologies obtained by the PRD method has been derived and a collapse PGA

value has been associated. On Ischia Island, 86 typologies have been found. Considering the buildings distribution on the vulnerability classes and on the PGA values, an occurrence has been determined as the number of buildings associated to a PGA value of the considered class and the total number of buildings of the class.
The cumulative probability of collapse associated to a PGA value of a specific class has been defined as the sum of all occurrences of typologies that collapse for lower PGA value of the considered one. In Tables 3-5, the cumulative percentage associated to the PGA value of vulnerability class A, B and C are reported respectively.

Table 3. Cumulative percentage of collapse for buildings in class A

class	PGA	buildings	occurrence of typology	cumulative percentage
A	0.02	1	0.02	0.02
A	0.04	3	0.07	0.09
A	0.06	7	0.14	0.23
A	0.07	15	0.30	0.52
A	0.08	17	0.34	0.86
A	0.16	1	0.02	0.89
A	0.21	3	0.07	0.95
A	0.22	2	0.05	1.00

Table 4. Cumulative percentage of collapse for buildings in class B

class	PGA	buildings	occurrence of typology	cumulative percentage
B	0.14	5	0.11	0.11
B	0.15	2	0.05	0.16
B	0.18	5	0.11	0.27
B	0.19	3	0.08	0.35
B	0.20	2	0.05	0.41
B	0.23	2	0.05	0.46
B	0.27	5	0.11	0.57
B	0.34	1	0.03	0.59
B	0.35	13	0.30	0.89
B	0.40	1	0.03	0.92
B	0.44	1	0.03	0.95
B	0.45	2	0.05	1.00

Table 5. Cumulative percentage of collapse for buildings in class C

class	PGA	buildings	occurrence of typology	cumulative percentage
C	0.19	55	0.07	0.07
C	0.21	5	0.01	0.08
C	0.23	1	0.00	0.08
C	0.23	9	0.01	0.09
C	0.24	75	0.10	0.19
C	0.25	1	0.00	0.19

C	0.25	1	0.00	0.19
C	0.27	129	0.17	0.36
C	0.29	5	0.01	0.37
C	0.29	2	0.00	0.37
C	0.29	9	0.01	0.38
C	0.30	5	0.01	0.39
C	0.30	2	0.00	0.39
C	0.31	9	0.01	0.40
C	0.32	25	0.03	0.44
C	0.33	32	0.04	0.48
C	0.34	2	0.00	0.48
C	0.34	144	0.19	0.67
C	0.35	42	0.05	0.72
C	0.37	2	0.00	0.73
C	0.38	1	0.00	0.73
C	0.38	6	0.01	0.74
C	0.39	29	0.04	0.77
C	0.43	43	0.06	0.83
C	0.44	5	0.01	0.84
C	0.45	23	0.03	0.87
C	0.46	35	0.05	0.91
C	0.47	46	0.06	0.97
C	0.48	20	0.03	1.00
C	0.53	2	0.00	1.00

The couple of point PGA-cumulative percentage value have been reported in diagram for each vulnerability class, and exploiting a Least Square Method, the collapse curves have been derived. The results are reported in Figures 4-5-6 for vulnerability class A, B and C respectively.

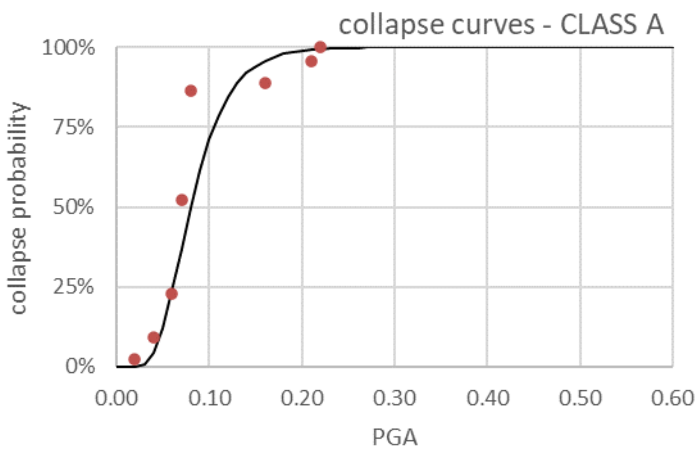

Figure 4. Collapse curve for building in class A of the Island of Ischia

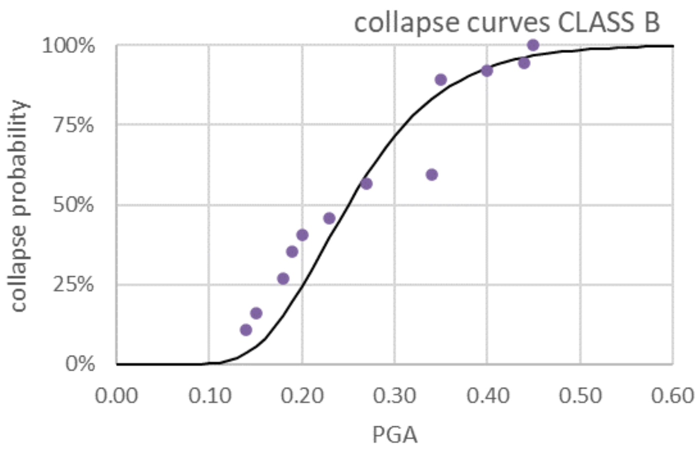

Figure 5. Collapse curve for building in class B of the Island of Ischia

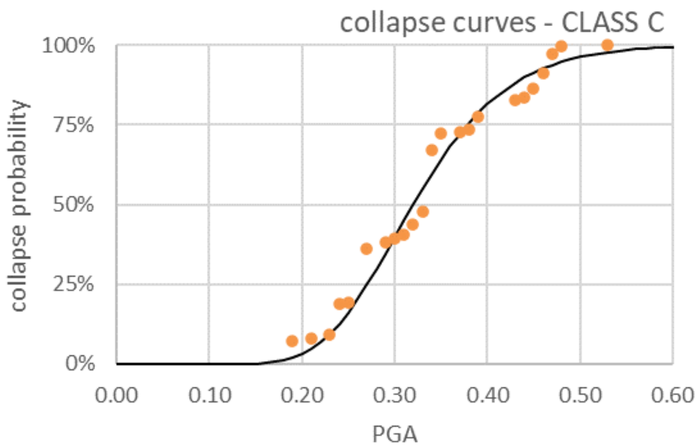

Figure 6. Collapse curve for building in class C of the Island of Ischia

4 COMPARISONS

The local collapse curves have been compared with the global collapse curves obtained in [13]. The outcomes are shown in Table 6 with respect to mean μ and standard deviation σ in Figure 7 in terms of curves. It is shown that the local collapse curves have a worst behaviour with respect to the global one. although the Ischia area is made up mostly of class C buildings, a prevalence of less performing buildings is evident.

Table 6. Mean and Standard Deviation of the collapse curves derived with local (Ischia) and global distribution of the modeled typologies.

parameters	local curves (ISCHIA)			global curves		
	class A	class B	class C	class A	class B	class C
μ	0.080	0.250	0.320	0.135	0.285	0.457
σ	0.400	0.320	0.250	0.645	0.408	0.271

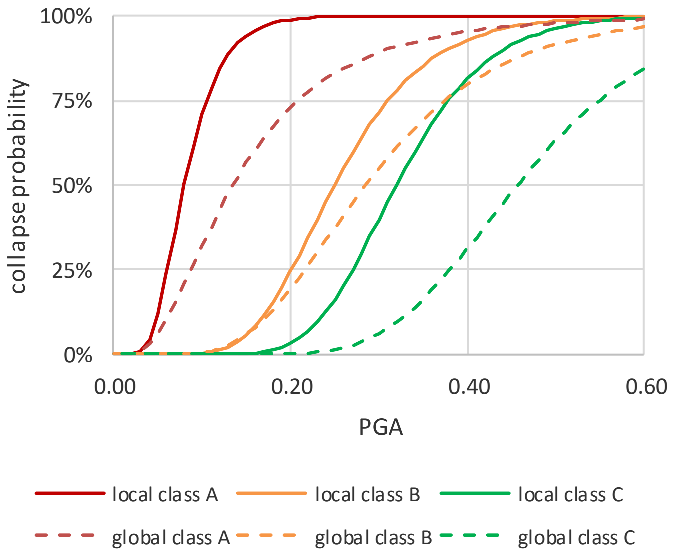

Figure 7. Collapse curves derived with local (Ischia) and global distribution of the modeled typologies.

5 CONCLUSIONS

In the context of emergency management, knowledge of a possible distribution of collapses on the territory defines a fundamental element for the decision-making choices by the authorities. Several works are present in the literature to provide support on a national scale.
However, localized knowledge of the phenomenon represents a very important tool for local authorities to better manage the operational phase of the emergency. This article demonstrates a procedure for calibrating a localized vulnerability model for unreinforced masonry buildings. The methodology makes use of an analytical procedure which, based on the typological characteristics considered, returns the PGA value capable of activating the collapse mechanism. This methodology was combined with a data collection activity of the Ischia area which provided the frequency of occurrence of the typologies considered in the modeling. Furthermore, exploiting literature criteria for defining the vulnerability class of buildings based on their typological characteristics, it was possible to determine a localized collapse curve for each vulnerability class.
The results obtained were compared with previous works, in which the frequency of occurrence of the building typologies had not been taken into consideration. It has been shown that the local distribution of building typologies can significantly affect the construction of the curve.
Future developments foresee the calibration of regionalized curves on the basis of data obtained from data collection campaigns, and a validation of the vulnerability model through impact analysis.

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