applied sciences

MDPI

Article

Vulnerability and Seismic Exposure of Residential Building Stock in the Historic Center of Alcamo

Piero Colajanni *, Calogero Cucchiara, Jennifer D'Anna, Silvia Pennisi and Salvatore Pagnotta

Department of Engineering, University of Palermo, Viale delle Scienze, 90128 Palermo, Italy; calogero.cucchiara@unipa.it (C.C.); jennifer.danna@unipa.it (J.D.); silvia.pennisi@unipa.it (S.P.); salvatore.pagnotta@unipa.it (S.P.)
* Correspondence: piero.colajanni@unipa.it

Abstract: The influence of exposure evaluation methodology in the assessment of the seismic vulnerability of the residential building stock in the historic center of Alcamo, a town of 45,000 inhabitants in Western Sicily (Italy), hit by an earthquake in 1968, is evaluated in this study. A comparison of exposure estimates on the basis of the description of the residential building stock according to two different approaches is performed. The first, typical of seismic vulnerability assessment procedures at a territorial scale, refers to the description of residential building stock through an accurate typological description, conducted using the CARTIS survey form. The form allows for a detailed description and survey of the prevailing ordinary building types within areas characterized by the homogeneity of the building fabric in terms of age of construction, structural characteristics, construction techniques, and distribution of types. The detailed description of building types allows for the assessment of exposure at the municipal scale based on an estimate of the total number of units and the percentage of each type within each compartment, obtained by interviewing local technicians. The second is based on a similar survey at the building scale, namely, drawing up a form for each building. The comparison of exposure and damage scenarios obtained with the two methods proves that the approximations provided by the compartment-scale survey are compatible with the purposes of an assessment of vulnerability and damage scenarios at the territorial scale.

Keywords: seismic vulnerability; seismic exposure; residential buildings; historic center

check for updates

Citation: Colajanni, P.; Cucchiara, C.; D'Anna, J.; Pennisi, S.; Pagnotta, S. Vulnerability and Seismic Exposure of Residential Building Stock in the Historic Center of Alcamo. *Appl. Sci.* **2023**, *13*, 7092. https://doi.org/10.3390/app13127092

Academic Editor: José Neves

Received: 17 April 2023
Revised: 9 June 2023
Accepted: 11 June 2023
Published: 13 June 2023

1. Introduction

The building fabric of historic town centers is predominantly characterized by masonry constructions, built using construction techniques and criteria handed down over the years by the traditions of good building or, at most, by the "rule of art" [1–3]. In areas where intense seismic events have not frequently occurred, building methods have not developed effective devices to ensure stable buildings against horizontal seismic actions and, for this reason, the constructions are particularly vulnerable. Thus, the planning of retrofitting interventions in these areas cannot disregard an assessment of the seismic risk and vulnerability of the built environment [4,5]. More specifically, a seismic risk assessment should link the built environment's vulnerability to the seismic hazard of the site and its exposure, the latter being described through a conventional measure of the value of assets and human activities potentially affected by a seismic event. Methods for the assessment of seismic vulnerability are largely varied and some of them concern specific sub-assets (RC or masonry buildings); they utilize very different fragility models with accompanying uncertainties, which would provide biased final risk estimations.

Seismic vulnerability analyses can be performed at the building scale, using structural analysis methods, similar to those employed in modern new building designs, which require the use of detailed and accurate structural models [6]. Although their implementation of computational codes can provide reliable seismic-response predictions, it requires a knowledge of the building's geometric and mechanical characteristics, which can only be known through the in-depth development of the knowledge pathway [7], which involves high economic and time burdens.

A comprehensive review of the existing methodologies for the seismic vulnerability assessment of RC and masonry structures can be found in [8–13]. Seismic vulnerability assessment of large portions of man-made territories, such as neighborhoods, historic centers, entire urban centers, or even regions or entire national territories, can be conducted more rapidly, based on information gathered from general census campaigns, such as the ISTAT [14] database, and complementary information obtainable from cursory survey campaigns.

Methods for vulnerability assessments at the territorial scale that have been proposed in the past can be divided into three main categories, namely, empirical, mechanical/analytical, or hybrid methods [8]. Empirical methods are based on the statistical analysis of the damage observed after a seismic event. In general, these methods refer to typological classes and vulnerability indices, which are based on several structural parameters and on geometrical and mechanical characteristics [15]. A review of these methods can be found in [8,16,17].

Mechanical/analytical methods are based on the use of a simplified representation of building mechanical features [15], the latter being the key issue hindering the implementation of this method at the territorial scale. Correlations between building mechanical features, expected damage, and seismic intensity can be assessed through analytical or numerical approaches. To this aim, both approaches evaluate the response of either archetypes of the structures chosen in order to be representative of a building typology or class of building typologies, or a simplified structural scheme with geometrical and mechanical features randomly generated.

Numerical methods based on numerical analyses provide more accurate seismic-response estimates of the expected damage level for each structural type during seismic events of a predetermined intensity, but they require elevated computational efforts, such that these methods are more suitable for the vulnerability assessment of a single building; on the other hand, the analytical approach has less accuracy in terms of seismic-response assessment.

Hybrid methods are formulated by attempting to integrate the potential of the two previously mentioned categories of methods, e.g., by using mechanical models to define correlations between typological characteristics and expected damage, recalibrating them on damage data observed during major seismic events [16,18].

Mechanical methods for assessing seismic vulnerability at a territorial scale employ extremely simplified models of the built environment, most often capable of representing only some of the essential characteristics determining the seismic vulnerability of buildings [19,20], such as the height or number of floors, material mechanical characteristics of vertical structural elements, stiffness and strength of horizontals, and sometimes characteristics of connections between vertical-resistant elements or between the latter and horizontals. Thus "*the reduced capability of a prototype (or a set of them) of representing a more complex building stock and the simplifications inevitably introduced by the structural modelling are the main limitations of the analytical approaches. As a consequence, also the identification of different sources of uncertainty (e.g., in capacity, demand and damage state thresholds) and their quantification can affect the reliability of analytical results. On the contrary, analytical approaches permit to simulate the seismic response of different building types, also analyzing them under high intensity values, for which no or poor empirical data is generally available*" (quoted verbatim from [21]). Empirical methods, based on a typological classification of the built environment, conducted using qualitative information, still play a prominent role in the vulnerability characterization at the territorial scale, since they prove to be especially effective for the vulnerability statistical assessment at the territorial scale, aimed at the allocation of reduced economic resources available for seismic risk mitigation, or for evaluation of damage scenarios for post-earthquake emergency management [19,22,23].

Proof of this is the fact that the Italian Civil Protection Department (ICPD) decided to conduct the latest National Seismic Risk Assessment (NSRA) through a multi-model methodology, where three of the six models are based on an empirical approach [24–26]. Two adopt an analytical approach to derive the fragility curves [18,27] and a third a hybrid approach [23], i.e., a recalibration according to a post-earthquake damage database [28] for masonry buildings only of the macroseismic model [20] used in the present paper.

Regarding exposure, a European model has recently been proposed by [29]. In Italy, at present, NSRA [30] is still evaluated on the basis of the ISTAT database, where construction material, floor number, and construction year only are available. Thus, many researches are trying to supplement the ISTAT census database, collecting data for large-scale assessments (e.g., [31,32]). In this regard, aiming at gathering information specifically devoted to seismic vulnerability assessments that can detect and reveal local structural features, the Italian Protection Department promote, through RELUIS (Italian Network of Academic Laboratory of Earthquake and Structural Engineering), uses of the interview-based CARTIS form.

To date, the CARTIS form has been used to survey approximately 6% of all Italian municipalities, and some Italian researchers are engaged in studies of seismic vulnerability assessment at the territorial scale on the basis of information through the CARTIS card, which has been made available on an online platform [33–35]. The CARTIS form provides a rich description of the structural features of residential building typologies, provided by interviews with technicians with experience in the field of structural construction, who are rooted in the territory and have a thorough knowledge of the construction techniques of the place. However, the numerical data (number of buildings, percentages of each typology) and the percentage of the detailed structural characteristics of each typology are based on a reasonable estimate provided by the interviewed technician and the expert.

In this context, with the aim of investigating the influence that estimates the distribution of structural and typological features provided through the CARTIS form methodology, an assessment of the seismic vulnerability of residential buildings in the historic center of Alcamo is evaluated according to two different approaches: the interview-based CARTIS survey, which is characterized by a survey at the compartment scale, as is described in detail in the Section 2, and a similar survey performed at the building scale, filling in a form containing the indications of the CARTIS form for each building.

2. Methods

In the following sections, the assessment of the exposure, seismic vulnerability, and damage scenarios of the residential building stock in the historic center of Alcamo is performed. Exposure is evaluated according to the two different approaches mentioned above, namely, at the compartment and building scales, while vulnerability and damage distribution assessments are performed according to the macroseismic method [20].

2.1. Exposure: The CARTIS Form

The CARTIS form [36,37] allows for a detailed exposure survey of the prevalent residential building types through the identification of areas characterized by the homogeneity of the building fabric in terms of construction age, structural characteristics, construction techniques, and distribution of typologies; these areas are called "compartments." The detailed description of building types allows for the assessment of exposure at the municipal scale based on an estimate of the total number of units and the percentage of each type within each compartment. The form was compiled on the basis of one or more face-to-face interviews with an expert in seismic engineering and one or more local technicians who have developed, over the years, knowledge of the history and evolution of the urbanization process, construction techniques, materials, and, for more recent buildings, a knowledge of the criteria and rules of design and construction of the built environment.

Basic information on the CARTIS form can be found in [33–35], while a detailed description is available in [37]. In [38], it was pointed out that one of the possible sources of uncertainty in the vulnerability estimates based on exposure surveys conducted with the CARTIS form may have derived from the accuracy with which the interviewed technician predicted the distribution of the different types within the identified compartments. Therefore, in the following study, the estimates obtained, as above, defined as the results of surveys conducted at the compartment scale, were compared with the exposure estimates, and subsequent vulnerability estimates conducted through a detailed survey campaign, were performed by filling out a survey form, similar to the one that defines the structural typologies in the CARTIS form, for each of the buildings in the historic center. This second approach, although conducted with some uncertainty related to the hurried nature and limitation of the investigations, which could not take advantage of the inside survey of the typological–structural characteristics of the buildings, made it possible to produce a more reliable estimate of the number of buildings of each type, and of the main characteristics determining seismic vulnerability, such as number of floors, structural regularity in plan and elevation, type of wall texture, stiffness and weight of floors and roofing, degree of connection between structural parts, and state of maintenance.

2.2. Vulnerability and Damage Scenarios: The Macroseismic Method

We then assessed the seismic vulnerability for both the mentioned exposure estimates, using the procedures codified in the macroseismic method [20], briefly summarized below.

Among the most recognized typological–observational methods available in the literature, the macroseismic method proposed by [20] plays a predominant role. The method, unlike most typological–observational methods, is derived from an analysis by probabilistic approaches and the fuzzy set theory of the correlations between typological characteristics and expected damage per seismic event of a given intensity, implicitly contained in the European macroseismic scale EMS98 [39]. In this scale, the residential building stock is characterized through the identification of 15 main structural types (see Table 1), whose seismic vulnerabilities are described by the most probable value of the typological vulnerability index V_I*. The value of the macroseismic vulnerability index V_I for each specific building or specific sub-typology was identified by first assigning the building or sub-typology to one of the 15 typological classes, and then varying the most probable value of the vulnerability index (V_I*) by assigning DVI vulnerability modifiers defined according to detailed characteristics. Using the fuzzy set theory, the authors also derived from the EMS98 scale, for each typology, the range of $V_I^- - V_I^+$ values within which the modified vulnerability index was likely to stay, and the range defined by the boundary values $V_{I\min} - V_{I\max}$ beyond which the index value for an element of that typology could not be assigned.

The assessment of building typology vulnerabilities was a necessary premise for the probabilistic description of the expected damage as a function of the seismic event intensity.

In the macroseismic method [20], the damage description is identified with the description contained in the EMS98 macroseismic scale, which, in addition to the D0 level of no damage, includes the following 5 additional damage levels: D1 mild; D2 moderate; D3 severe, D4 very severe; D5 structural collapse. The qualitative descriptions of damage levels for masonry and reinforced concrete buildings are shown in Figure 1.

Table 1. Characteristic values of the vulnerability index.

Typologies	Code	Building Type	Characteristic Values of the Vulnerability Index				
			$V_{I\,min}$	V_I^-	V_I^*	V_I^+	$V_{I\,max}$
Masonry	M1	Rubble stone	0.62	0.81	0.873	0.98	1.02
	M2	Adobe/earth bricks	0.62	0.687	0.84	0.98	1.02
	M3	Simple stone	0.46	0.65	0.74	0.83	1.02
	M4	Massive stone	0.3	0.49	0.616	0.793	0.86
	M5	U Mansory (old bricks)	0.46	0.65	0.74	0.83	1.02
	M6	U Mansory-r.c. floors	0.3	0.49	0.616	0.79	0.86
	M7	Reinforced /confined masonry	0.14	0.33	0.451	0.633	0.7
Reinforcedconcrete	RC1	Frame in RC (without E.R.D.)	0.3	0.49	0.644	0.8	1.02
	RC2	Frame in RC (moderate E.R.D.)	0.14	0.33	0.484	0.64	0.86
	RC3	Frame in RC (high E.R.D.)	−0.02	0.17	0.324	0.48	0.7
	RC4	Shear walls (without E.R.D.)	0.3	0.367	0.544	0.67	0.86
	RC5	Shear walls (moderate E.R.D.)	0.14	0.21	0.384	0.51	0.7
	RC6	Shear walls (high E.R.D.)	−0.02	0.047	0.224	0.35	0.54
Steel	S	Steel structures	−0.02	0.17	0.324	0.48	0.7
Wood	W	Wood structures	0.14	0.207	0.447	0.64	0.86

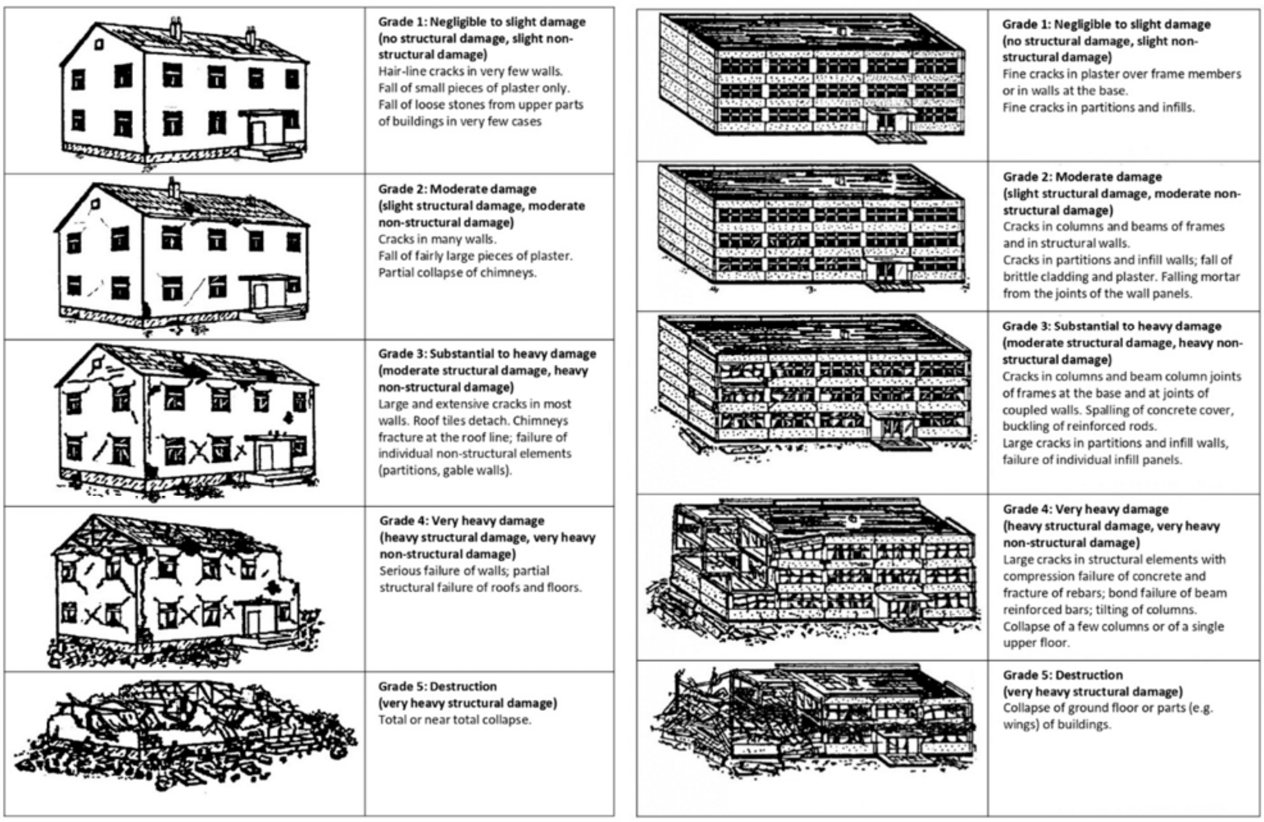

Figure 1. Damage classification.

Based on the V_I value, it is possible to estimate the average damage μ_D per earthquake of macroseismic intensity I (vulnerability curve) by the relationship:

$$\mu_D = 2.5\left[1 + \tan h\left(\frac{I + 6.25V_I - 13.1}{2.3}\right)\right] \tag{1}$$

In order to understand the damage distribution according to the different levels we defined, the probability distribution β (preferred to the more traditional binomial function, as it allows one to represent the variability of damage dispersion) was presented according to the relation:

$$p_\beta(x) = \frac{\Gamma(t)}{\Gamma(r)\Gamma(t-r)} \times \\ \times \frac{(x-a)^{r-1}(b-x)^{t-r-1}}{(b-a)^{t-1}} \tag{2}$$

with Γ Gamma function and $a \le x \le b$, where it is possible to assume $a = 0$, $b = 6$, $t = 8$, and

$$r = t\left(0.007\mu_D^3 - 0.0525\,\mu_D^2 + 0.2875\mu_D\right) \tag{3}$$

Given the damage distribution, it is possible to construct its cumulative function according to the relation:

$$P_\beta(x) = \int_0^x p_\beta(x)dx \tag{4}$$

From this relation, it is possible to evaluate the fragility curves dependent on the intensity I, which express the probability of exceeding the damage level k for a given intensity of seismic action I, through the simple relation:

$$p[D > D_k; I] = 1 - P_\beta(k) \tag{5}$$

Alternatively, it is possible to evaluate the percentage of buildings that experience a predetermined level of damage (damage probability matrices) by taking advantage of the relation that allows one to calculate the probability associated with the damage level k, through the relation:

$$p_k = P_\beta(k+1) - P_\beta(k) \tag{6}$$

Fragility curves can then be expressed as a function of the peak ground acceleration value PGA, by using one of the well-known correlation laws between macroseismic intensity I and PGA values, which can be expressed in the form:

$$a_g = c_1\, c_2^{(I-5)} \tag{7}$$

where c_1 = 0.03 and c_2 = 1.6 can be assumed according to [20], based on [40], or c_1 = 0.043, and c_2 = 1.66 according to [41].

Based on the aforementioned relationships, it was possible, based on the seismic hazard estimated by the recent New Technical Standards for Construction [7], to estimate the expected macroseismic intensity for prefixed return periods, thus enabling the assessment of damage scenarios.

3. Exposure of the Historic Center of Alcamo

Figure 2 shows the plan of the historic center of Alcamo, coinciding with areas A1 and A2 of the current general master plan (PRG). The historic center is an area of about 509,000 m^2.

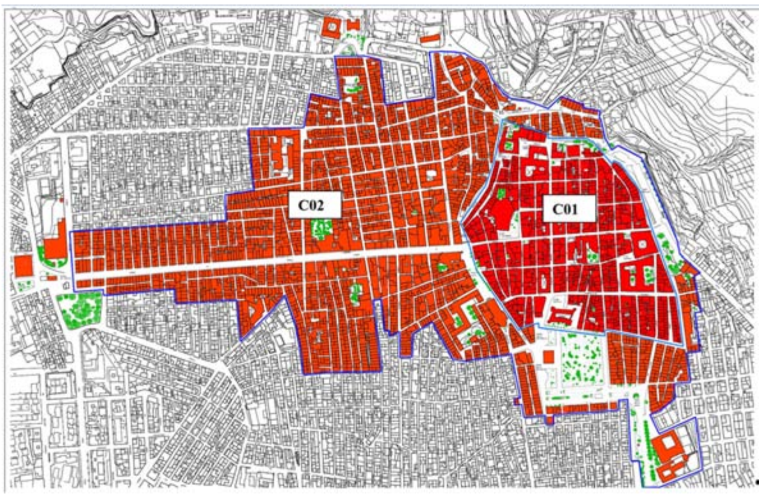

Figure 2. Compartment divisions of the historic center of Alcamo.

To assess the seismic vulnerability, the area was divided into two compartments:

- Compartment C01, originated in the 14th century, called "Historic center: the walled city", coinciding with area A1 of the PRG. The compartment has an extension of 109,280 m^2 and it contains about 640 building units and a population of about 1300 residents;
- Compartment C02, originated in the 16th century, called "Historic center: the ancient quarters", coinciding with area A2 of the PRG. It is an area of about 398,700 m^2 and contains about 2465 building units, with a population of about 5700 residents.

According to the classification presented in the CARTIS sheet [36], three types of masonry buildings and two types of reinforced concrete buildings were initially identified in Compartment C01.

The characteristics of the masonry typologies according to the CARTIS sheet classification criteria, summarized in Figure 3, and the acronyms that identify the typologies are as follows:

- MUR1: included units built before the 1920s, characterized by irregular vertical masonry elements, rough stone with a haphazard texture, without recourse (A2.1), with lime mortar, predominantly 2 or 3 stories, average floor height of less than 3.50 m, average area between 60 and 110 m^2, predominantly irregular configurations in plan, and average irregular configuration in elevation. The average wall thickness of the ground floor was about 50 cm and the average prevailing wall spacing was 3.0 m. The prevailing type of floor slab (90%) was constituted by single plank wood, forming a deformable diaphragm, while the remainder (10%), following renovations, was made of reinforced concrete with prefabricated joists and cast-in-place slab. The stairs, made of stone, were generally made with cantilevered steps or rarely with ramped vaulting. The roofs were wooden, lightweight, with predominantly single pitch (70%), while the remainder show sloping pitches. Buildings were characterized by a lack of adequate buttresses between orthogonal walls and a presence of lintels with reduced flexural rigidity. Sometimes, there were localized reductions in the wall section due to the presence of flues, cavities, or niches. Numerous constructions of this type present irregular forometry with respect to the outer wall box. The roof was usually not adequately connected to the walls. The foundations were superficial and continuous, made of rubble stone. Almost all of these buildings were in aggregate and a high number of buildings were in connection and shared, with the adjacent units, the end-bearing vertical structures. Vulnerability was often increased by location in aggregate, with the floors staggered with respect to the adjoining buildings. Few buildings of this typology have been affected by local interventions, which, in any case, have only resulted in modest seismic improvement.

- The second typology, identified by the acronym MUR2, was built between the early 1920s and 1960. The masonry of the vertical elements was made of pseudo-regular rough-hewn stone without recourses (B2.1). The typology included 2 or 3 floors. Many of the typological–structural characteristics coincided with those of the previous typology. There was a prevalent average spacing of the masonry walls that reached 4 m, a stronger connection between the orthogonal wall and a stringer connection of the roof to the external walls. The stairs were usually made of reinforced concrete ramped slab. The foundations were superficial and continuous, made of rubble stone or squared blocks.
- Finally, the MUR3 typology was the most recent, built until the late 1970s. This typology was made of masonry classifiable as regular squared stone without recourses (C1.1). These buildings presented a greater height, with the number of floors between 3 and 4. About a quarter of the buildings of the typology had cast-in-place brick floors that, constituting a rigid diaphragm, distribute seismic actions on the vertical-resistant elements proportionally to their stiffnesses. Some of the buildings of this typology are made with one-dimensional vertical and horizontal reinforced concrete elements, inserted between the masonry walls, and thus constitute mixed confined masonry structures.
- Among the reinforced concrete structures that have taken the place of buildings that were demolished due to the high degree of deterioration, or saturated the few vacant spaces, the most common typology was CAR1, consisting of buildings built in the 1970s. These buildings had 3–4 stories, a regular configuration in plan and elevation, and frames with infills of substantial masonry. They were equipped with ramped slab staircase and foundations made of a lattice of inverted beams. The buildings are often constructed adjacent to pre-existing buildings, without adequate earthquake-resistant joints, and have first-floor pillar dimensions of no more than 45 cm and structural mesh sizes between 4 and 5 m. The percentage of longitudinal reinforcement of the columns was close to 0.6% and the transverse reinforcement generally consisted of ϕ6 stirrups placed at 30 cm spacing. The state of preservation was in the normal range, since a significant percentage of buildings was subjected to recent maintenance work.
- A small percentage of buildings of the more recent CAR3 typology was also available. These buildings were characterized by 3–4 stories and they were made with the same structural typology as CAR1, but with adequate earthquake-resistant joints. The percentages of longitudinal reinforcement were around 2% and the transverse reinforcement consisted of ϕ6 stirrups with spacing near the nodes of around 15/20 cm.

a. Masonry Characteristics					
A.1.1	IRREGULAR MASONRY	Rounded stone	Without courses	Pebbles with disorganised texture on the facade	○
A.1.2				Pebbles with organised texture on the facade	○
A.1.3			With courses	Pebbles and bricks	○
A.1.4				Pebbles and bricks with brick appeals	○
A.2.1		Rough stone	Without courses	Rubble with disorganised texture on the facade	○
A.2.2				Rubble with organised texture on the facade	○
A.2.3			With courses	Disorganised masonry with roof tiles and limestone	○
A.2.4				Rubble with brick appeals	○
B.1.1	HEWN MASONRY	Slab stone	Without courses		○
B.1.2			With courses		○
B.2.1		Pseudo regular stone	Without courses		•
B.2.2			With courses		○
C.1.1	REGULAR MASONRY	Squared stone	Without courses		○
C.1.2			With courses		○
C.2.0		Bricks			○

Figure 3. Typological classification of masonry according to the CARTIS sheet.

The types found in Compartment C02 were similar to those in Compartment C01, differing in the year of construction, number of floors, some construction details, and intended use, due to the presence of a significant number of buildings partially intended for commercial activities. The main difference between the two compartments, in addition to the abovementioned features, was the different distribution of typologies in the compartments. The MUR1 and MUR2 typologies in Compartment C02 were similar to their counterparts in Compartment C01; although, in both there was a greater number of regular buildings both in plan and elevation. Among the buildings in the MUR2 type of Compartment C02, almost all of the staircases had ramped slabs, and there were far more buildings that underwent local strengthening. The MUR3 type of Compartment C02 differed from its counterpart, Compartment C01, mainly due to the prevalence of rigid horizons made of cast-in-place c.a. floors and the considerable presence (40% of the typology, 11% of the total) of buildings with reinforced concrete piers and curbs inserted into the masonry, thus obtaining a mixed confined masonry structure.

As for the reinforced concrete typologies, CAR1 differed from its counterpart, Compartment C01, due to the presence of a substantial number of buildings constructed in the 1960s, with frames arranged only along one of the two main directions of the building (about 4%). There were frequent ground-floor infills characterized by large openings and only few buildings constructed with isolated plinth foundations. The CAR2 typology of Compartment C02 was also similar to the CAR1 typology of Compartment C01, differing only in some aspects: the construction period, identifiable as the 1980s; the presence (50% of cases) of earthquake-resistant joints in accordance with the standards; a higher amount of longitudinal reinforcements (0.8–1%); and stirrups of diameter of ϕ8, with spacing about 20 cm close to the nodes. In Compartment C02, there were also buildings belonging to the CAR3 type, which are more modern and taller, built from the late 1990s with 4 or 5 floors, with a resistant system and structural characteristics similar to CAR2, classifiable as infilled frame structures with generally sturdy masonry, rarely light, and regular in plan and height dimensions.

Table 2 shows the estimated distributions of the different types in the two compartments obtained through estimates from the interviewed technicians and compared with ISTAT data from the 2001 and 2011 censuses. For the two Compartments, C01 and C02, sub-type MUR2/3_SCA, collecting buildings with masonry walls and cast-in-place RC floors, and sub-typology MUR2/3_CONF, collecting buildings with reinforced concrete floors and mixed confined masonry structure, were generated from the MUR2 and MUR3 typologies. This classification was adopted for reasons that are clarified below.

Table 2. Vulnerability indices and percentages of wall types.

	Tot. Buildings	Typology	%	Tip EMS98	V_I*	Σw_i DVI_M	V_I
C01	640	MUR1	18%	M1	0.873	0.093	0.966
		MUR2	26%	M3	0.74	0.124	0.864
		MUR3	22%	M3	0.74	0.076	0.816
		MUR2/3_SCA	5%	M6	0.616	0.076	0.692
		MUR2/3_CONF	3%	M7	0.451	0.174	0.625
		CAR1	21%	RC1	0.644	−0.02	0.642
		CAR3	5%	RC3	0.324	−0.02	0.322
C02	2465	MUR1	10%	M1	0.873	0.1	0.973
		MUR2	20%	M3	0.74	0.088	0.828
		MUR3	7%	M3	0.74	0.038	0.778
		MUR2/3_SCA	17%	M6	0.616	0.038	0.654
		MUR2/3_CONF	11%	M7	0.451	0.136	0.587
		CAR1	20%	RC1	0.644	0.063	0.707
		CAR2	10%	RC2	0.484	−0.01	0.474
		CAR3	5%	RC3	0.324	−0.03	0.294

The performed analyses showed that (see Table 2), in Compartment C01, there is a prevalence of masonry buildings with pseudo-regular rough-hewn stone MUR2 (26%) or squared MUR3 (22%), with a reduced presence of sub-types MUR2/3_SCA (5%) and MUR2/3_CONF (3%). All of the abovementioned typologies were made of good quality masonry; reduced, however, is the presence of irregular stone masonry irregularly textured MUR1 (18%). There was also a significant presence of reinforced concrete buildings, with the oldest in the CAR1 typology, constituting 21% of the total, and the newest in CAR3, constituting 5%. In Compartment C02, the presence of MUR2 masonry was still significant (20%); however, the overall preponderant was the percentage of types characterized by the presence of reinforced concrete floors (17%) or confined masonry (11%), along with 7% of MUR3. About a third of the buildings in the compartment were made of reinforced concrete (35%), with a predominance of the most vulnerable CAR1 buildings (20%), constructed without an adequate earthquake-proof design. With reference to the height, for buildings in Compartment C01, 58% were 2- or 3-story masonry (44% in C02), while only 15% (14%) were 4-story masonry, a feature that increases their seismic vulnerability.

The reinforced concrete buildings in the two compartments were predominantly 3–4 stories, while only 2.5% in Compartment C02 had more than 4 stories. Although the data on the construction period provided by the ISTAT census and by experts' estimations presented a reduced reliability level, overall, it can be considered that, in the historic center, there is a significant presence of buildings constructed after the 1970s, a period in which the memory of the Belice earthquake of 1968 was alive. This circumstance led to the use of earthquake-resistant features both in the consolidation works of existing buildings (curbs and rigid slabs in RC), as well as in the construction of new buildings with confined masonry, making it possible to reduce their seismic vulnerability. It also favored the construction of RC buildings with anti-seismic designs (frames in two orthogonal directions and lattice foundations with inverted beams).

4. Seismic Vulnerability

The first operation required for the assessment of seismic vulnerability using the Macroseismic method [20] and exposure estimates through the CARTIS form was the assignment to each of the CARTIS types of a corresponding type derived from the EMS-98 macroseismic scale [39].

For typologies MUR1 and MUR2 of both compartments, it was simple to identify the corresponding typologies among those obtained from the macroseismic scale EMS 98; in particular, these were types M1 (rough stone masonry) and M3 (squared stone masonry), respectively. On the other hand, for typology MUR3, it was necessary to derive the two sub-typologies MUR2/3_SCA and MUR2/3_CONF, which, respectively, identified constructions with rigid reinforced concrete floors and constructions with confined masonry. The first of these two sub-typologies can be associated with the M6 typology of the EMS 98 classification, and the second to the M7 typology.

Table 2 summarizes the abovementioned correspondences and the corresponding most-probable values (white values) of the vulnerability index V_I* of the macro-types.

It should be noted that, in order to define the characteristic value of the vulnerability index of CARTIS sub-typologies, it was still necessary to use the vulnerability index modifiers DVI [20]. Behavior modifiers were divided into two broad categories: the first one included regional modifiers of the vulnerability index DVI_R, introduced to take into account the different characteristics of the typologies built in the region or geographical area where the studied building stock was located; this modifier can be assessed based on the characteristics of local construction techniques, thanks to the judgment of an expert. The second category included the behavior modifiers DVI_M that took into account all those characteristics of the building, not strictly characterizing the type, which significantly modified the expected seismic response. Many of them were coded, usually through a statistical regression of the data on the variability of damage detected after real seismic events.

Table 3 presents the values of the modifiers, differentiated for masonry and reinforced concrete structures, according to the level of seismic design.

Table 3. DVI_M vulnerability index modifiers.

Behaviour Modifier	Masonry		Reinforced Concrete			
			Seismic Design Level	Without	Moderate	High
		DVIm		DVIm	DVIm	DVIm
State of preservation	Good	−0.04	Good	-	-	-
	Bad	0.04	Bad	+0.04	+0.02	0
Number of floors	Low (1–2)	−0.08	Low (1–3)	−0.02	−0.02	−0.02
	Medium (3–5)	0	Medium (4–7)	0	0	0
	High (≥6)	0.08	High (≥8)	+0.04	+0.04	+0.04
Structural system	Wall thickness	−0.04 – +0.04	Short columns	+0.02	+0.01	0
	Wall distance		Bow-windows	+0.04	+0.02	0
	Wall connection					
Plan irregularity	Geometry	+0.04	Geometry	+0.04	+0.02	0
	Mass distribution		Mass	+0.02	+0.01	0
Vertical irregularity	Geometry	+0.04	Geometry	+0.04	+0.02	0
	Mass distribution		Mass			
Superimposed floors		+0.04				
Roof	Weight, thrust and connections	+0.04				
Retrofitting interventions		−0.08 – +0.08				
Aseismic devices	Barbican, Foil arches, Buttresses	−0.04				
Aggregate building position	Middle	−0.04	Insufficient aseismic joints	+0.04	0	0
	Corner	+0.04				
	Header	+0.06				
Typological discontinuity		+0.03				
Aggregate building elevation	Taller on 2 sides	+0.04				
	Taller on 1 side	+0.02				
	Shorter on 2 sides	−0.04				
	Shorter on 1 side	−0.02				
Foundation	Different level	+0.04	Plinths	+0.04	0	0
			Isolated beams	−0.04	0	0

A regional modifier was added for typology M7, confined masonry, to account for the fact that confined masonry in Sicily is more often made with calcarenite blocks, instead of the more common and more resistant solid bricks. This modifier had a value of $DVI_{R,M7}$ = +0.06.

The DVI values of the behavior modifiers were attributed to the different typologies by means of weights w_i that indicate the percentages of buildings of the typology that present that particular characteristic. The sum value of the vulnerability index modifiers $\Sigma\, w_i\, DVI_M$ and final values V_I of the characteristic vulnerability index for the CARTIS sub-typologies thus obtained ($V_I = V_I^* + \Sigma\, w_i\, DVI_{M,i}$) are presented in the last two columns of Table 2. It can be seen that, for masonry typologies, the application of the behavior modifiers produced an increase in the vulnerability index. In particular, in Compartment C01, the increase was about 10% of the characteristic value of the EMS98 typology for MUR1 and MUR3 typologies, and 17% for the MUR2 typology, due to a higher percentage of roof spread and a smaller presence of local strengthening interventions. The change in the vulnerability index of confined masonry was particularly significant (38%), due to the presence of the regional modifier $DVI_{R,M7}$. The increases in the vulnerability index in Compartment C02 were smaller, thanks to the reduced irregularities in the plan and elevation and the better connection of roofs to the masonry walls, especially for the MUR2 and MUR 3 types. The changes in the vulnerability index for reinforced concrete types, in both compartments, were extremely small and all negative, except for CAR1 in Compartment C02, due to the absence of seismic joints in accordance with the standards and the presence of a significant percentage of buildings that were irregular in plan and/or elevation or had an irregular distribution of infill.

In order to summarize the difference in seismic vulnerability between the two compartments, it was possible to estimate an average vulnerability index of the compartment through a weighted average, according to the percentages of the presence of the vulnerability indexes of each type. Thus, the values of V_I= 0.747 for Compartment C01 and V_I = 0.696 for Compartment C02 were obtained. The difference was mainly attributable to the higher percentage of reinforced concrete buildings available in Compartment C02 and their lower vulnerability.

5. Assessment of Exposure and Vulnerability through Building-Scale Survey

As can be observed from the procedures and data presented above that the exposure estimates conducted with the described procedure were strongly influenced by the estimated percentage of a given type within the compartment. Moreover, the variation in the vulnerability index related to detailing characteristics (influence of modifiers) was significant for masonry types, while this variation was much lower in the case of reinforced concrete structures.

Apparently, a more accurate estimate of exposure and vulnerabilities could be achieved by surveying individual structural units. As is shown, this approach lead to total reliable estimate, only if the survey was performed with great thoroughness, through an inspection of the individual unit from the inside too, and an interview with the owner who could provide details about the construction that could not be obtained by a cursory survey. This procedure was so time-consuming and costly that it was possible to adopt it only for small areas. More frequently and over larger territories, it was possible to conduct a cursory building-scale survey, limited to a photographic survey and an inspection from the outside of the building. In this case, structural features were often not clear, and the survey and attribution of these features were strongly affected by the surveyor's knowledge and skill in correctly identifying elements representative of these features.

Based on these premises, the results of an investigation performed through cursory surveys conducted from the outside of the building are presented. The evaluation was conducted through a complete photographic survey of the units, the support of images from the web, and a subsequent in-depth investigation through additional on-site surveys. The photos and results were reported on a geo-referenced database, which was used as support for the calculation of the vulnerability index of the individual structural unit. The parameters of structural interest that were surveyed were the following: number of floors, number of raised floors, state of preservation, regularities in plan and elevation, type of masonry or type of characteristic framed structure, material of the elevation, type of floors, type of roofing, presence of openings near the eaves, percentage of openings on the ground floor, position in aggregate and interaction with adjacent buildings, presence of earthquake-resistant devices, and presence of seismic strengthening or improvement interventions.

As an example, thematic maps showing the number of floors (Figure 4a) and the state of preservation (Figure 4b) of residential buildings are presented in Figure 4. The former shows the prevalence of 2- and 3-story buildings in Compartment C01, while the percentage of 4-story buildings, which are more vulnerable to seismic action, is significant in Compartment C02. The second map shows a prevalence of good or at least sufficient states of preservation.

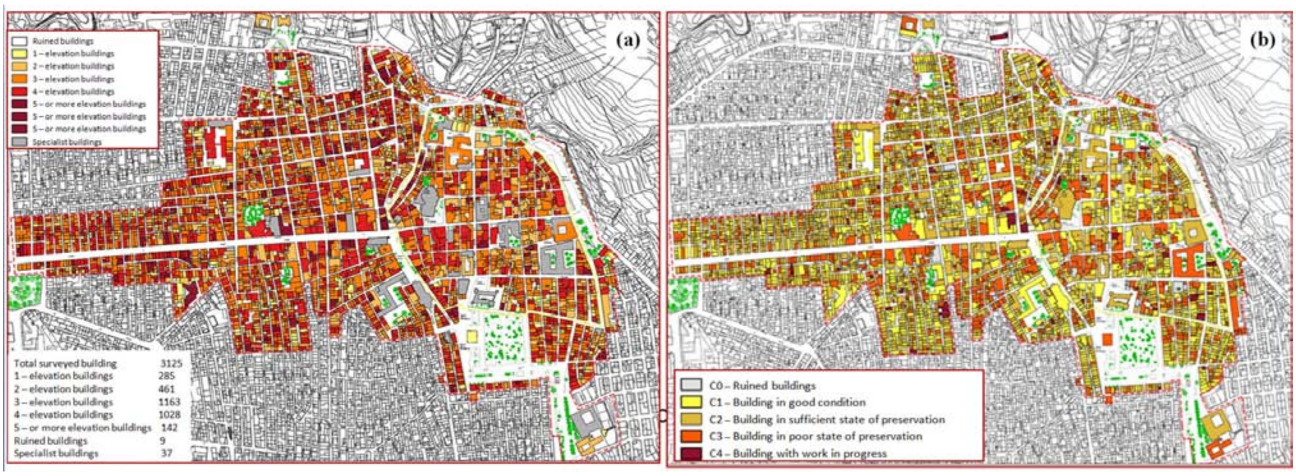

Figure 4. Elevations (**a**) and state of preservation (**b**) of residential building units.

Figure 5a shows the EMS98 types assigned to individual units, represented chromatically according to the vulnerability index.

Figure 5. Surveyed building types (**a**) and vulnerability indices (**b**) according to EMS98.

The units with a plastered elevation, for which the masonry type could not be assigned with a high degree of accuracy, are presented in light blue (Figure 5a). In fact, the architectural characteristics allowed one to identify, with a certain reliability, among the plastered structures, those that were reinforced concrete, while the attribution of masonry typology was not as simple, except in the presence of strongly characterizing typological indicators [38,42]. The high percentage of buildings with plastered walls (31.6%) affected the accuracy of the cursory building-scale survey for the seismic vulnerability assessment.

Aiming at overcoming this problem, based on the previous studies, it was found that the age of construction of the building and the number of floors were among the parameters most correlated with masonry type. Therefore, since only the number of floors could be attributed to the individual building with a high level of reliability, it was chosen to attribute to plastered buildings a value of the most probable vulnerability index V_I* as a function of the number of floors. The value for each number of floors was obtained as a weighted average according to the abundance of buildings of different types and the corresponding most-probable vulnerability indices EMS98.

Table 4a presents the percentages of different types of masonry buildings divided by floors and the value of the most probable vulnerability index attributed to plastered buildings. It can be observed that, as the number of floors increases, the percentage of buildings in the least-vulnerable classes increases, and thus the "initial" value of the most probable vulnerability index decreases as the number of floors increases. This feature should not be confused with the influence of height on a building's seismic vulnerability, which has an opposite correlation, but represents the correlation between the material of the vertical load-bearing elements and number of floors. Table 4b compares the rates of each building typology predicted by the building-scale and CARTIS surveys. The results highlight the difficulty of the building-scale survey in identifying both buildings with confined masonry, which are largely underestimated, and RC buildings designed according to the most recent seismic code. However, the overall estimation rates for masonry buildings provided by the two survey approaches were similar, i.e., 0.73 and 0.67; although, the differences in the distribution across the three different masonry building typologies were quite significant (especially for the MUR3 typology). This circumstance affected the vulnerability estimations since these characteristics significantly reduced the vulnerability of both masonry and reinforced concrete buildings.

Table 4. (**a**) Percentages of masonry building types divided by floors and most-probable vulnerability index for plastered buildings; (**b**) estimated percentage presence types for the entire historic center.

(a)

	M1	**M3**	**M6**	**M7**	
V_I***/floors**	0.837	0.74	0.616	0.511	V_I^{*PI}
1	42%	53%	3%	2%	0.787
2	31%	56%	9%	4%	0.762
3	16%	65%	16%	3%	0.735
4	15%	51%	29%	5%	0.713

(b)

Construction Typology	**Building**	**CARTIS**
MUR1	0.16	0.12
MUR2	0.22	0.21
MUR3	0.20	0.10
MUR23_SCA	0.12	0.15
MUR23_CONF	0.03	0.09
CAR1	0.20	0.20
CAR2	0.08	0.05
CAR3	0.00	0.08

Figure 5b presents the distribution of the most probable vulnerability index estimated once the values of V_I* were attributed to the building with the plastered walls based on the abovementioned procedure. Then, for each unit, the values of the sum of the DVI behavior modifiers were evaluated according to the same criteria used for CARTIS types; their planimetric distributions are represented in Figure 6a. Lastly, the algebraic sum of V_I* and DVI for each individual unit provides the final estimated value of the vulnerability index (Figure 6b).

Figure 6a shows that the buildings with negative values for the behavior modifier DVI are very few and the most can be identified in the zone of the town in which the areas of the city where the detailed characteristics increase the vulnerability. Thus, a comparison between Figures 5b and 6b shows that, overall, the behavior modifiers increase the vulnerability estimate as well as the areas of the historic center that are characterized by the greatest vulnerability.

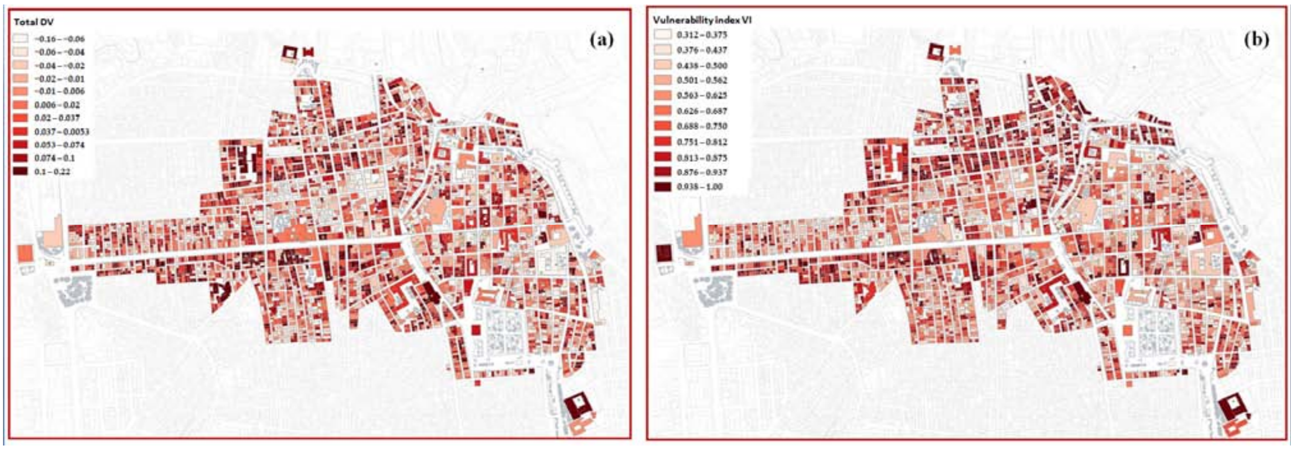

Figure 6. Distributions of (**a**) behavior modifiers; (**b**) vulnerability indices.

6. Comparison of Compartment- and Building-Scale Surveys

Table 5 shows, for the entire historic center, the effect of the behavior modifiers on the evaluation of the vulnerability indexes for the different types estimated with the building-scale analysis (for non-plastered buildings).

Table 5. Vulnerability index values estimated by the building-scale survey.

	MUR1	MUR2	MUR3	MUR23_SCA	MUR23_CONF	RC1	RC2
Most prob. Vuln. Index VI	0.873	0.740	0.740	0.616	0.511	0.644	0.484
Average prob. Index VI	0.870	0.753	0.770	0.643	0.537	0.653	0.494
Standard Deviation	0.081	0.077	0.090	0.073	0.078	0.071	0.065
Coeff. of Variation	0.093	0.103	0.117	0.113	0.145	0.109	0.131
Min	0.653	0.530	0.560	0.456	0.331	0.504	0.344
Max	1.000	1.000	1.000	0.846	0.659	0.904	0.644
Variation Range	0.347	0.470	0.440	0.390	0.328	0.400	0.300
Variation of av. Value %	0.389	1.698	4.101	4.421	5.077	1.323	2.105
Variation range %	60.252	36.486	40.541	36.688	35.812	37.888	38.017

The table shows the statistical parameters (mean, standard deviation, coefficient of variation, lower and upper extremes and width of the variation range, percent change in the mean value, and percent of the width of the variation range with respect to the mean value) of the vulnerability index for each of the CARTIS types. The percentage values of the variation range, ranging from 35.8% for MUR2/3SCA up to 60.2% for MUR1, show that the influence of modifiers at the building scale is very significant on the individual building. However, it produces a modest average value of V_I for the typological class. Excluding the effect of the regional modifier, the greatest variation in the average value was found for the MUR2/3_CONF typology and was 5.1%, while it was only 0.4% for the MUR1 typology. A comparison with the influence of modifiers estimated with the compartment-scale survey, highlighted by the results shown in Table 2, shows that, in this case, the influence on the V_I value is significant, being equal to 22% for MUR2/3_CONF (excluding the rate due to the regional modifier), standing at values close to 10% for most masonry types and with smaller variations for reinforced concrete types. These circumstances had relevant repercussions on the expected mean damage (vulnerability curve) and damage distribution (fragility curve) estimations as the intensity of the seismic event changes for each building typology; however, the influence was greatly reduced when an overall assessment of the expected damage was performed.

7. Results

The results obtained based on the compartment-scale survey, using the procedure described above, are initially shown. Figure 7a compares the average damage curves, as the macroseismic intensity changes, for the typologies of the historic center, obtained with the vulnerability index evaluated by the compartment- (solid line) and building- (dotted line)-scale surveys, respectively. The curves show, for fixed seismic event intensity, the greater expected damage in higher-vulnerability masonry buildings (MUR1), the lower propensity for damage in buildings with RC on good-quality masonry (MUR23_SCA), the effectiveness of masonry confinement in reducing the expected damage (MUR3_CONF), which is close to that expected in non-seismically designed RC buildings (CAR1), and the reduced damage expected in RC buildings designed in accordance with the recent earthquake-resistant legislation (CAR3). A comparison between the curves obtained with the two different scales of the survey campaign highlights the significant increase in the average damage expected for the masonry types, above all for the more vulnerable MUR1 and MUR2, for the survey at the compartment scale, and the negligible variation for reinforced concrete buildings.

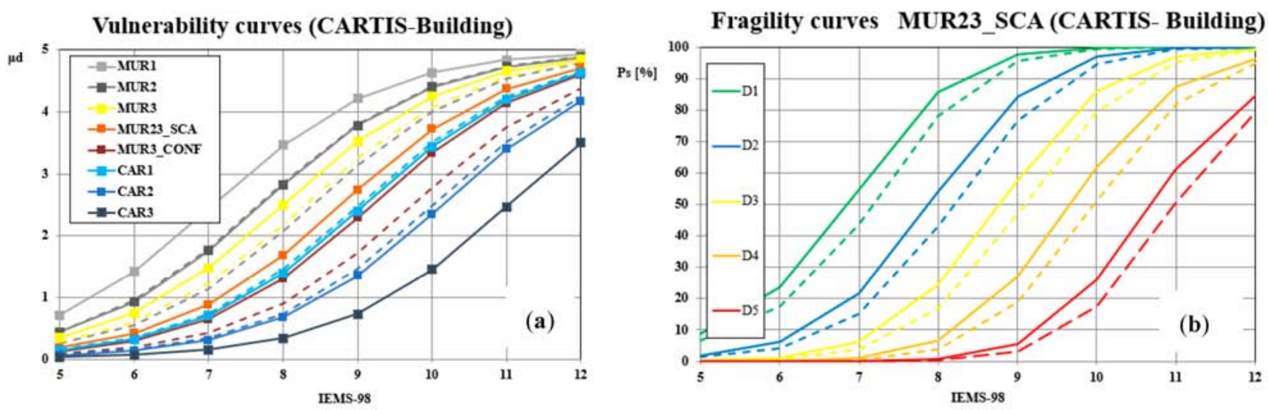

Figure 7. Curves of average damage (**a**) and probability of damage level exceedance (**b**) as macroseismic intensity changes for vulnerability indexes evaluated by compartment- (solid line) and building (dotted line)-scale surveys.

The fragility curves for masonry buildings with reinforced concrete slabs MUR23_SCA in Figure 7b show how, through the damage distribution probability function presented in Equation (2), it is possible to predict, for each masonry type, the probability to exceed a given damage level as the macroseismic intensity varies. The increase in the vulnerability index obtained with the survey campaign at the compartment scale compared to that at the building scale presented, as a consequence, a similar increase in the probability of damage overcoming for all levels of damage.

The expected damaged based on the compartment-scale survey, using the procedure described above, are initially shown. In more detail, Figure 8 shows the maps of the mean values of the expected damage for two different macroseismic intensity levels, evaluated based on the data derived through the building-scale survey. The first one, for macroseismic intensity I = 6 (Figure 8a), roughly corresponding to an earthquake with a return period RP = 30 years, shows that moderate damage is expected for this seismic intensity. In the second one, related to macroseismic intensity I = 9 (Figure 8b), slightly higher than that corresponding to a return period of 975 years, the number of buildings experiencing substantial-to-severe damage, with moderate structural damage and severe nonstructural damage ($D \geq 3$), is significant.

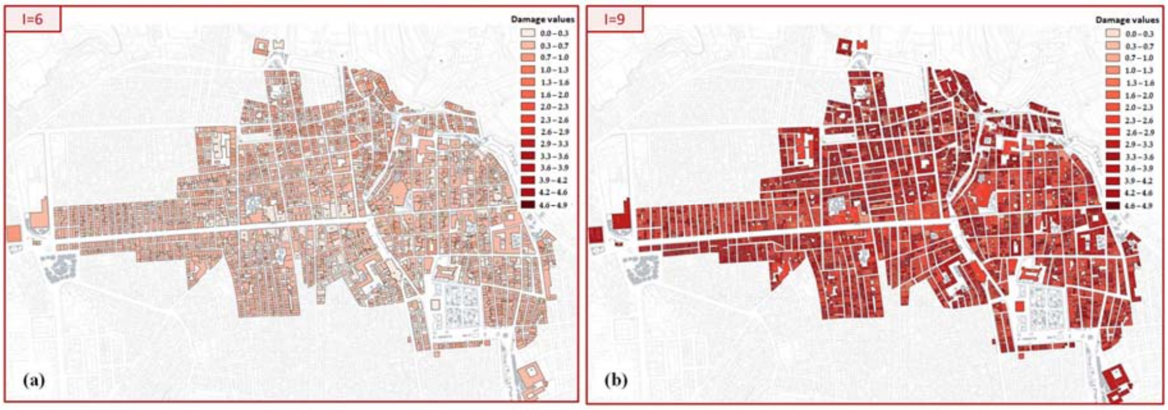

Figure 8. Expected damage for seismic events of different macroseismic intensity levels: I = 6 (**a**) and I = 9 (**b**).

Taking advantage of the relationship presented in Equation (7), which links the macroseismic intensity to the seismic acceleration peak value, and the seismic hazard estimation provided in the present Technical Standards for Construction (MIT, 2018), assuming that, in a simplified way, the entire historic center is built on category-B soil (stratigraphic amplification coefficient S = 1.2), it was possible to provide an estimate of the foreseeable damage for seismic events with return periods RP of 30, 50, 475, and 975 years, whose corresponding to peak values of the acceleration at the foot of the structure are: 0.04, 0.05, 0.14, and 0.19 g (g = gravity acceleration).

The overall data for the entire historic center derived from the compartment-scale analysis are shown for four different seismic action return periods in Figure 9a.

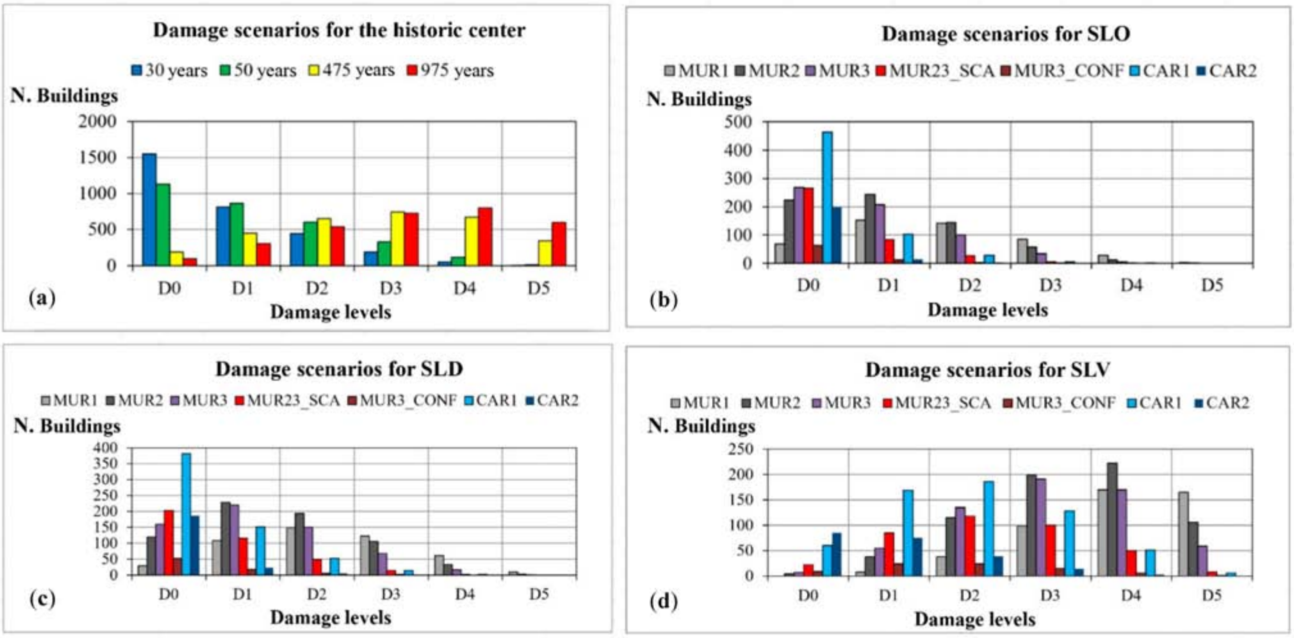

Figure 9. Damage scenarios: (**a**) historic center; (**b**) SLO (RP = 30 years); (**c**) SLD (RP = 50 years); (**d**) SLV (RP = 475 years).

The figure shows that, for RP = 50 years, 20% of buildings suffer significant damage to non-structural elements ($D \geq 3$), while, for RP = 475 years, more than one third of buildings suffer severe structural damage and very severe non-structural damage ($D \geq 4$). Figure 9c, which shows the damage distribution among the different types for a seismic event with RP = 475 (corresponding to the Life Protection Limit State SLV) points out that masonry types with deformable horizontals (MUR1, MUR2, and MUR3) are those that particularly suffer significant damage to the structural elements. A significant number of reinforced concrete structures designed without anti-seismic measures (CAR1) suffer moderate structural damage, while only about 50 of these and an equal number of confined masonry structures suffer severe structural damage. For the more recent reinforced concrete types, a significant number of buildings with moderate or greater structural damage is not expected.

In Table 6, the percentage difference of the damage distribution in the buildings in the historic center evaluated by the survey at the compartment scale and the survey at the building scale, respectively, is presented. The greatest increases in the expected damage percentage were observed for high structural damage (D5) for return periods of the seismic action equal to or longer than 475 years. For a seismic action return period of 50 years, there was an increase of 2.29% of buildings suffering from moderate structural damage (D3). However, overall, the variation in expected damage was compatible with the overall degree of uncertainty that characterized these damage scenarios.

Table 6. Percentage difference of the distribution of damage to buildings in the historic center evaluated by survey at the compartment scale compared to the survey at the building scale.

RP	D0	D1	D2	D3	D4	D5
30 years	−3.43	−1.10	2.00	1.77	0.69	0.07
50 years	−1.11	−3.68	0.76	2.29	1.47	0.26
475 years	4.43	−1.61	−4.34	−3.26	1.01	3.77
975 years	3.91	0.23	−3.14	−4.52	−1.43	4.95

Red color indicates positive variation, green color indicates negative variation.

8. Conclusions

An investigation of the seismic exposure and vulnerability of the historic center of Alcamo was performed, based on the building stock characterization according to two approaches: the first approach, consistent with the CARTIS form procedure, required the subdivision of the historic center into compartments, which are homogeneous zones in terms of building characteristics distribution.

The second approach was based on a cursory survey of the characteristics of each individual building, conducted through external inspections. The reliability of the data gathered by the two procedures was discussed, highlighting that each of the two procedures presents weaknesses. In more detail, the results obtained by the survey at the compartment scale are strongly dependent on the estimate of the percentage of each typology distribution within the compartments, and the descriptions of the typologies features that characterize the expected seismic behavior have major influences on the attributed vulnerability indexes. It was highlighted that, for the case study, it leads one to predict a significant increase in vulnerability, especially for the oldest and most-vulnerable masonry types. By contrast, the variations in the vulnerability index produced by the behavior modifiers for exposure assessment campaigns conducted at building scales, while significantly influencing the vulnerability of the single building, tended to compensate for all the buildings in the compartment, resulting in average vulnerability values close to those predicted by compartment-scale analyses.

The subsequent evaluation of the expected damage distribution, as a function of the seismic intensity, together with the seismic hazard characterization provided by the earthquake codes, at present, allowed for the derivation of damage scenarios. The latter, although evaluated under simplifying assumptions that reduced their accuracy, proved that the overall exposure estimates provided by the vulnerability survey at the two different scales, although with some discrepancies, were comparable.

Author Contributions: Conceptualization, methodology, data curation, writing: P.C., C.C., J.D., S.P. (Silvia Pennisi) and S.P. (Salvatore Pagnotta); funding acquisition, P.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Italian Department of Civil Protection, within the ReLUIS-DPC 2022–2023 Research Project, grant number CUP B73C22000960005.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Campisi, T.; Colajanni, S.; Saeli, M. Fabbricare nel recinto di pietra. Tipologie edilizie e sistemi costruttivi della città storica. In *Alcamo. Studi, Piani e Progetti per il Centro Storico*; Franco Angeli srl: Milan, Italy, 2021; pp. 33–58.
2. Fatta, G.; Campisi, T.; Vinci, C.; Saeli, M. Modica: La fabbrica della città. In *Modica: Contributi per il Recupero e la Riqualificazione del Centro Storico*; 40 due Edizioni: Palermo, Italy, 2016; pp. 140–199.
3. Borri, A.; Corradi, M.; De Maria, A. The failure of masonry walls by disaggregation and the masonry quality index. *Heritage* **2020**, *3*, 1162–1198. [CrossRef]
4. Colajanni, P.; Cucchiara, C.; D'anna, J.; La Mendola, L. Criteri e tecniche di valutazione e riduzione della vulnerabilità sismica del centro storico. In *Modica: Contributi per il Recupero e la Riqualificazione del Centro Storico*; 40 due Edizioni: Palermo, Italy, 2016; pp. 201–237.
5. Tempesta, G. Seismic retrofit of historical masonry walls by means of natural basalt fiber strips system (BFRP). Pre-modern concepts and innovative materials. In *MATEC Web of Conferences*; EDP Sciences: Les Ulis, France, 2018; Volume 242, p. 01014.
6. Follador, V.; Carpanese, P.; Donà, M.; da Porto, F. Effect of retrofit interventions on seismic fragility of Italian residential masonry buildings. *Int. J. Disaster Risk Reduct.* **2023**, *91*, 103668. [CrossRef]
7. MIT. Ministry of Infrastructure and Transport, Update of the Technical Standards for Construction (NTC18), Published in the Official Gazette no. 8 of 20 February 2018 (Ordinary Supplement no. 8). 2018. Available online: https://www.gazzettaufficiale.it/eli/gu/2018/02/20/42/so/8/sg/pdf (accessed on 9 June 2023). (In Italian).
8. Calvi, G.M.; Pinho, R.; Magenes, G.; Bommer, J.J.; Restrepo-Vélez, L.F.; Crowley, H. Development of seismic vulnerability assessment methodologies over the past 30 years. *ISET J. Earthq. Technol.* **2006**, *43*, 75–104.
9. Rossetto, T.; Ioannou, I.; Grant, D.; Maqsood, T. *Guidelines for Empirical Vulnerability Assessment*; GEM: Pavia, Italy, 2014. [CrossRef]
10. Rossetto, T.; Ioannou, I.; Grant, D.N. *Existing Empirical Fragility and Vulnerability Relationships: Compendium and Guide for Selection*; GEM Foundation: Pavia, Italy, 2013.
11. D'ayala, D.; Meslem, A.; Vamvatsikos, D.; Porter, K.; Rossetto, T.; Crowley, H.; Silva, V. *Guidelines for Analytical Vulnerability Assessment of Low/Mid-Rise Buildings*; Global Earthquake Model: Pavia, Italy, 2014.
12. Maio, R.; Tsionis, G. *Seismic Fragility Curves for the European Building Stock*; JRC Technical Report; European Commission: Brussels, Belgium, 2015.
13. Lagomarsino, S.; Cattari, S. Fragility functions of masonry buildings. In *SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk: Buildings, Lifelines, Transportation Networks and Critical Facilities*; Springer: Dordrecht, The Netherlands, 2013; pp. 111–156.
14. ISTAT. 15° Censimento Generale della Popolazione—Dati Sulle Caratteristiche Strutturale della Popolazione, delle Abitazioni e Variabili. Available online: http://www.istat.it/it/archivio/104317 (accessed on 10 May 2020). (In Italian).
15. Romano, F.; Zucconi, M.; Imperatore, S.; Ferracuti, B. Advancements in Seismic Vulnerability Assessment Methodologies for RC Buildings at Territorial Scale. In *Advancements in Seismic Vulnerability Assessment Methodologies for RC Buildings at Territorial Scale*; Pisa University Press: Pisa, Italy, 2017; pp. 303–313.
16. Dolce, M.; Prota, A.; Borzi, B.; da Porto, F.; Lagomarsino, S.; Magenes, G.; Moroni, C.; Penna, A.; Polese, M.; Speranza, E.; et al. Seismic risk assessment of residential buildings in Italy. *Bull. Earthq. Eng.* **2021**, *19*, 2999–3032. [CrossRef]
17. Yepes, C.; Silva, V.; D'Ayala, D.; Rossetto, T.; Ioannou, I.; Meslen, A.; Crowley, H. The global earthquake model physical vulnerability database. *Earthq Spectra* **2016**, *32*, 2567–2585. [CrossRef]
18. Donà, M.; Carpanese, P.; Follador, V.; Sbrogiò, L.; da Porto, F. Mechanics-based fragility curves for Italian residential URM buildings. *Bull. Earthq. Eng.* **2020**, *19*, 3099–3127. [CrossRef]
19. Donà, M.; Carpanese, P.; Follador, V.; da Porto, F. Derivation of mechanical fragility curves for macro-typologies of Italian masonry buildings. In Proceedings of the 7th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Crete, Greece, 24–26 June 2019; pp. 1691–1706.
20. Lagomarsino, S.; Giovinazzi, S. Macroseismic and mechanical models for the vulnerability and damage assessment of current buildings. *Bull. Earthq. Eng.* **2006**, *4*, 415–443. [CrossRef]
21. Masi, A.; Lagomarsino, S.; Dolce, M.; Manfredi, V.; Ottonelli, D. Towards the updated Italian seismic risk assessment: Exposure and vulnerability modelling. *Bull. Earthq. Eng.* **2021**, *19*, 3253–3286. [CrossRef]
22. Lagomarsino, S.; Cattari, S. Seismic vulnerability of existing buildings: Observational and mechanical approaches for application in urban areas. In *Seismic Vulnerability of Structures*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2013; pp. 1–62.

23. Lagomarsino, S.; Cattari, S.; Ottonelli, D. The heuristic vulnerability model: Fragility curves for masonry buildings. *Bull. Earthq. Eng.* **2021**, *19*, 3129–3163. [CrossRef]
24. Rosti, A.; Rota, M.; Penna, A. Empirical fragility curves for Italian URM buildings. *Bull. Earthq. Eng.* **2020**, *19*, 3057–3076. [CrossRef]
25. Rosti, A.; Del Gaudio, C.; Rota, M.; Ricci, P.; Di Ludovico, M.; Penna, A.; Verderame, G.M. Empirical fragility curves for Italian residential RC buildings. *Bull. Earthq. Eng.* **2020**, *19*, 3165–3183. [CrossRef]
26. Zuccaro, G.; Perelli, F.L.; De Gregorio, D.; Cacace, F. Empirical vulnerability curves for Italian masonry buildings: Evolution of vulnerability model from the DPM to curves as a function of acceleration. *Bull. Earthq. Eng.* **2020**, *19*, 3077–3097. [CrossRef]
27. Borzi, B.; Onida, M.; Faravelli, M.; Polli, D.; Pagano, M.; Quaroni, D.; Cantoni, A.; Speranza, E.; Moroni, C. IRMA platform for the calculation of damages and risks of Italian residential buildings. *Bull. Earthq. Eng.* **2020**, *19*, 3033–3055. [CrossRef]
28. Dolce, M.; Speranza, E.; Giordano, F.; Borzi, B.; Bocchi, F.; Conte, C.; Di Meo, A.; Faravelli, M.; Pascale, V. Da.D.O.—A web-based tool for analyzing and comparing post-earthquake damage database relevant to national seismic events since 1976. In Proceedings of the XVII Congresso Nazionale ANIDIS "L'Ingegneria Sismica in Italia", Pistoia, Italy, 17–21 September 2017.
29. Crowley, H.; Despotaki, V.; Rodrigues, D.; Silva, V.; Toma-Danila, D.; Riga, E.; Karatzetzou, A.; Zugic, Z.; Sousa, L.; Ozcebe, S.; et al. Exposure model for european seismic risk assessment. *Earthq. Spectra.* **2020**, *36*, 252–273. [CrossRef]
30. Italian Civil Protection Department. National Risk Assessment 2018. Overview of the Potential Major Disasters in Italy. Updated December 2018. 2018. Available online: https://www.protezionecivile.gov.it/static/5cffeb32c9803b0bddce533947555cf1/Documento_sulla_Valutazione_nazionale_dei_rischi.pdf (accessed on 9 June 2023).
31. Cacace, F.; Zuccaro, G.; De Gregorio, D.; Perelli, F.L. Building Inventory at National scale by evaluation of seismic vulnerability classes distribution based on Census data analysis: BINC procedure. *Int. J. Disaster Risk Reduct.* **2018**, *28*, 384–393. [CrossRef]
32. Zuccaro, G.; Cacace, F. Seismic vulnerability assessment based on typological characteristics. The first level procedure "SAVE". *Soil Dyn. Earthq. Eng.* **2015**, *69*, 262–269. [CrossRef]
33. Polese, M.; Gaetani d'Aragona, M.; Prota, A. Simplified approach for building inventory and seismic damage assessment at the territorial scale: An application for a town in southern Italy. *Soil Dyn. Earthq. Eng.* **2019**, *121*, 405–420. [CrossRef]
34. Polese, M.; Di Ludovico, M.; Gaetani d'Aragona, M.; Prota, A.; Manfredi, G. Regional vulnerability and risk assessment ac-counting for local building typologies. *Int. J. Disaster Risk Reduct.* **2020**, *43*, 141400. [CrossRef]
35. Brando, G.; Cianchino, G.; Rapone, D.; Spacone, E.; Biondi, S. A CARTIS-based method for the rapid seismic vulnerability assessment of minor Italian historical centres. *Int. J. Disaster Risk Reduct.* **2021**, *63*, 102478. [CrossRef]
36. Zuccaro, G. *Inventory and Vulnerability of the Residential Building Stock of the National Territory, Risk Maps and Socio-Economic Losses*; I.N.G.V./G.N.D.T.—National Institute of Geophysics and Vulcanology/National Group for Earthquake Defense: L'Aquila, Italy, 2004. (In Italian)
37. Zuccaro, G.; Dolce, M.; De Gregorio, D.; Speranza, E.; Moroni, C. La scheda CARTIS per la caratterizzazione tipologico-strutturale dei comparti urbani costituiti da edifici ordinari. Valutazione dell'esposizione in analisi di rischio sismico (The CARTIS form for the typological-structural characterization of urban areas with ordinary buildings. Exposure assessment in seismic risk analysis). In Proceedings of the 34th National Conference GNGTS (Gruppo Nazionale di Geofisica della Terra Solida), Trieste, Italy, 17–19 November 2015; pp. 281–287. (In Italian).
38. Colajanni, P.; Cucchiara, C.; D'Anna, J.; Di Gesaro, G.; Pagnotta, S.; Pennisi, S. Effect of the different data survey scale on assessment of seismic exposure and vulnerability of the historic center of Caltabellotta. In Proceedings of the XVIII Convegno Nazionale ANIDIS L'Ingegneria Sismica in Italia, Ascoli Piceno, Italy, 15–19 September 2019.
39. Grunthal, G. European macroseismic scale 1998. *Cah. Cent. Eur. Géodyn. Séismol.* **1998**, *15*, 1–97.
40. e Cauzzi, F. Macroseismic intensities for seismic scenarios estimated from instrumentally based correlation. In Proceedings of the First European Conference on Earthquake Engineering and Seismology, Geneve, Switzerlan, 3–8 September 2006. paper 569.
41. Margottini, C.; Molin, D.; Serva, L. Intensity versus ground motion: A new approach using Italian data. *Eng. Geol.* **1992**, *33*, 45–58. [CrossRef]
42. Colajanni, P.; e Pennisi, S. Caratteristiche tipologico-strutturali per la valutazione della vulnerabilità sismica nel centro storico di Caltabellotta tra persistenze e trasformazioni. In *Caltabellotta Studi e Ricerche sul Centro Storico*; Maggioli Editore: Sant'Arcangelo di Romagna, Italy, 2020. (In Italian)