Considerations on using MCS and EMS-98 macroseismic scales for the intensity assessment of contemporary Italian earthquakes

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Abstract

The concept of macroseismic intensity arose with the purpose of measuring the strength of an earthquake by the effects it causes on buildings, people, and domestic furnishings. From this perspective, buildings can be considered seismic sensors that record the shaking. Early scales were conceived at a time when buildings were mainly in masonry and therefore they could be used as markers of the intensity in case of earthquakes. Indeed, since they were fairly homogeneous, their level of damage could be considered as an indicator of the shaking level. In recent decades, the evolution of construction techniques have made the MCS scale unsuitable for damage assessment of buildings of various resistance. To overcome this problem the EMS-98 scale was designed. Because the MCS scale is still used in Italy, even in the presence of many reinforced concrete buildings, the purpose of this work is to show that the EMS-98 is the most suitable tool for assessing intensity as it is more consistent with the built environment. Theoretical and real intensity assessments, by both MCS and EMS-98, have been determined and compared, showing that nowadays intensity is a function of the vulnerability. MCS and EMS-98 would be comparable only when the building stock is composed of very vulnerable edifices (generally class A). Finally, thanks to the similarity of the two scales for old and vulnerable buildings, EMS-98 appears fully adequate to investigate historical earthquakes and represents a powerful tool to ensure continuity among earthquakes of different epochs.

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1 Introduction

For 150 years or so, macroseismic intensity has been the tool used by seismologists to describe and classify the effects of ground shaking at a given site during an earthquake. The most widely used scales derive from the 12 degrees Mercalli–Cancani scale (Sieberg 1909), namely the Mercalli–Sieberg (Sieberg 1932), later called Mercalli-Cancani-Sieberg (MCS), the Modified Mercalli (MMI) (Wood and Neumann 1931) and the Medvedev-Sponheuer-Karnik (MSK) (Medvedev et al. 1965). The MCS scale has been widely used in Europe, and is still used in Italy, especially for the evaluation of historical earthquakes. The MMI scale is mainly used in North-America, and the MSK scale was used in Europe between the 1960s and 90 s; in both a formalization of different building types was introduced.

In the macroseismic scales the level of shaking is indicated, in a descriptive form, through a series of typical effects (diagnostics) classified by severity to define type scenarios. The diagnostic elements of the macroseismic scales are generally referred to three groups of observations: transient effects, on people and domestic objects, permanent effects on the built environment, namely damage to buildings, and lastly effects on the natural environment.

While transient and natural environment effects can be considered 'independent' of the time, the diagnostics on the building damage needed some updating. In fact, the built environment has developed since Mercalli's years, especially from the post-World War II period to the present, with the rapid and increasing use of reinforced concrete (RC) in civil constructions.

At the end of the past century, the seismological and engineering communities agreed that a new and updated instrument was necessary to cope with the new and different building types, as well as the wider use of RC, and the increasingly consolidated use of modern seismic codes.

After some years of work (1990–1992) (Grünthal 1993), a reduced group of seismologists comprising G. Grünthal R. Musson, J. Schwarz and M. Stucchi proposed the idea of a vulnerability class which might be predominantly based on construction types.

In 1998, the European Seismological Commission approved the new European Macroseismic Scale, EMS-98, deriving directly from the MSK scale (Grünthal 1998).

The main reasons for a new scale were:

− The need to include new types of buildings, especially those with earthquake-resistant design features, which are not considered by old scale;
− The need to generally improve the description of the scale;
− To design a scale that meets not only the needs of seismologists alone, but also those of civil engineers and other possible users;
− To design a scale that is also suitable for the evaluation of historical earthquakes.

The result is a scale that classifies residential buildings into 6 classes of vulnerability (A–F, from the most to the least vulnerable) and evaluates their damage distribution in five classes (D1–D5: negligible, moderate, substantial to heavy, very heavy damage, and total destruction), adopting qualitative ratings to evaluate the frequencies of buildings with different grades of damage. The EMS-98 is now used world-wide both for historical and recent earthquakes (Silveira et al. 2003; Galea 2007; Tertulliani et al. 2018; Buforn and Udías 2022; Sarabia Gómez et al. 2022; Martin et al. 2022; Triantafyllou et al. 2022;

Tertulliani and Graziani 2022, among the others) and its guidelines have been translated in many languages.

Despite the updating of intensity scales, Italian macroseismic practice has maintained the use of the MCS scale until today. Such use is probably linked to the tradition and necessity to ensure a presumed continuity with the historical earthquake evaluations (Vannucci et al. 2021), since most of the macroseismic data in the Parametric Catalogue of Italian Earthquakes (Rovida et al. 2022) are expressed in MCS scale. Other European countries had instead adopted 'updated' versions of macroseismic scales such as the MSK in the 1970s and later the EMS-98.

Except for a sporadic use of the MSK scale, the MCS scale continued to be used in Italy (i.e. Bottari et al. 1982) from the 1970s to 2000, by introducing, albeit informally, diagnostics related to damage to RC buildings coming from MSK. This practice has not been applied systematically, but it is documented in reports of earthquake surveys of the time (Favali et al. 1980; Spadea et al. 1983; De Rubeis et al. 1991; Gasparini et al. 2011), and its rationale was based on the idea of continuing with the MCS tradition but taking into account new building types. Given these new diagnostics, without related guidelines, the operator had to use a hybrid intensity assessment tool that was not validated by any verification processes.

It is worth mentioning here the MCS version scale proposed by Molin (2009), who introduced modifications to formalize and ensure the linear increase of the observed damage percentages that, in the original MCS, was not regularly organized. This version is still used in Italy for quick earthquake surveys done for civil protection uses because, according to the users (i.e. Molin 2009; Galli et al. 2016), not considering the vulnerability of each single building allows undertaking a more rapid survey, providing the information directly correlated to the damage.

The first experiences with the extensive use of EMS-98 in Italy date back to the 2009 L'Aquila earthquake (Tertulliani et al. 2011) and show the greater ductility of this tool in describing the effects on heterogeneous building stocks.

The aim of this work is to show that MCS is no longer suitable for estimating earthquake intensity with respect to the recent built environment, while EMS-98 assessments are the most appropriate for today's scenarios.

Moreover, EMS-98 can also be used, without contraindications, for extremely vulnerable buildings, such as those encountered in the study of historic earthquakes. In the following, we will show theoretical and real examples that highlight differences between MCS and EMS-98 scales in estimating the macroseismic intensity on the present-day building stock.

2 Assessment of macroseismic intensity in MCS and EMS-89 scales

The experiences of assessing macroseismic intensity for earthquakes in recent years in Italy have shown that using the MCS scale is inadequate for current building environments, as it does not allow distinguishing between buildings of different resistance. Indeed, the MCS scale considers common buildings as equally calibrated "seismic sensors," assuming that they have similar resistances. This was true at the time the scale was compiled, and thus made the scale adequate and robust. Today, however, with the numerous buildings with different seismic resistance, the MCS scale has lost its full functionality (Dolce 2019).

Table 1 Damage percentages foreseen by the MCS scale according to Molin (2009)

MCS	D1 Negligible to slight	D2 Moderate	D3 Substantial to heavy	D4 Very heavy	D5 Destruction
VI	(0) **5** (10)	[5]			
VII		(40) **50** (60)			[5]
VIII			(40) **50** (60)	(15) **25** (35)	(0) **5** (10)
IX			(65) **75** (85)	(40) **50** (60)	(15) **25** (35)
X				(65) **75** (85)	(40) **50** (60)
XI					(90) **100**
XII					–

The bold number is the medium value, intended with an uncertainty of 5% or 10% (in round brackets). The value in square brackets indicates [5] the occurrence of occasional damage

Although the MCS and EMS-98 scales can be applied in the same damage scenario, they work differently. Musson et al. (2010) stated that the conversion between scales is neither applicable nor desirable; in fact, to have a real comparison of different scales you need to start with the method of the data assessment.

Macroseismic surveys conducted through the MCS scale allow intensity values to be assigned to damaged localities based on a qualitative estimate of the damage and its spread over the building stock, regardless of its vulnerability levels. Assigning the degree of intensity is quite a fast procedure, because there is no need for a vulnerability classification of individual buildings for the whole site. The description of intensity degrees of the MCS scale, from the original texts and from the synthesis in Sieberg's work (Sieberg 1932), implies an estimation of damage and its frequency, rather indicative, both in terms of severity and quantities of affected buildings.

A modern reading, attempting to ensure a methodological continuity between scales, especially the MSK (Molin 2009), has numerically defined the quantity terms of the MCS scale. For the intensity degrees VI and VII, the scale does not provide a definite specific frequency percentage of damage but uses adjectives (some, few, many, numerous, most) that have been identified with specific percentages (Molin 2009). Starting from the degree VIII upwards, instead, the scale indicates precise quantities (1/4, 1/2, 3/4 of the amount of the building stock) foreseeing a regular increase of the quantities of the observed damage. As for the damage, five levels of increasing severity have been defined, inspired by the MSK scale. This way of reading enables representing the MCS intensity degrees as a table (Table 1). It is worth highlighting that the percentages are meant to be cumulative. For example, at grade IX MCS, 75% damage from level 3 comprises 50% of level 4, which in turn comprises 25% of level 5. In Table 1, for each MCS intensity degree, the expected percentages of damaged buildings are shown according to the five levels of damage.

This way of representing MCS intensity degrees makes comparisons with the EMS-98 easier.

The EMS-98 scale classifies residential buildings into 6 vulnerability classes (A to F, with decreasing level of vulnerability), and evaluates their damage distribution in five classes (D1 to D5: negligible, moderate, substantial to heavy, very heavy damage, and destruction), which accounts for the damage level of both the main structural and non-structural components.
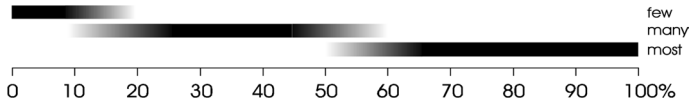
Fig. 1 Definitions of percentage ranges in EMS-98 guidelines and related quantitative adjectives (few, many, most) (Modified after Grünthal 1998)

Table 2 EMS-98 intensity definition according to damage and vulnerability levels

	D1 negligible	D2 moderate	D3 substantial to heavy	D4 very heavy	D5 destruction
V	frew A or B				
VI	many A or B, few C	few A or B			
VII	few D	many B, few C	many A, few B	few A	
VIII		many C, few D	many B, few C	many A, few B	few A
IX		many D, few E	many C, few D	many B, few C	many A, few B
X		many E, few F	many D, few E	many C, few D	most A, many B, few C
XI		many F	many E, few F	most C, many D, few E	most B, many C, few D
XII					all A or B, nearly all C, most D or E or F
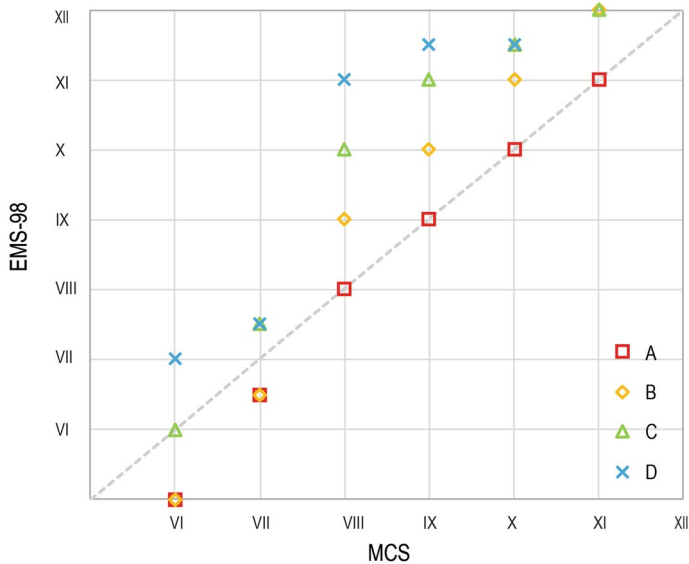
Fig. 2 The graph shows the correspondence between MCS and EMS-98 considering homogeneous building stocks (single vulnerability class). The EMS-98 estimate was derived from the quantities predicted by the MCS scale for a given intensity degree, varying the vulnerability class

Table 3 Percentage of buildings in each damage level in the case of MCS intensity equal to VIII degree

VIII	D1	D2	D3	D4	D5
Building stock			25%	20%	5%

Table 4 Damage quantitative terms for a locality with only class A vulnerability buildings

	D1 negligible	D2 moderate	D3 substantial to heavy	D4 very heavy	D5 destruction
VIII				many A	few A

The EMS-98 scale also adopts qualitative ratings to evaluate the frequencies of buildings with different degrees of damage, for each vulnerability class and for each macroseismic intensity (V to XII), but the quantitative adjectives are related to specific ranges of percentages (Fig. 1). Table 2 shows the definition of the intensity degrees according to the quantities of damaged buildings, for each class of vulnerability and for the five grades of damage. For instance, the scale defines that intensity degree VI has occurred when "damage of grade 1 is sustained by many buildings of vulnerability class A and B; a few of class A and B suffer damage of grade 2; a few of class C suffer damage of grade 1" (Grünthal 1998, p. 18).

To see how the two scales work, we can compare the definition of intensities for the degree VIII. The choice of degree VIII is motivated by the regular damage progression that starts from this degree VIII of the MCS scale; this makes a clear comparison with the EMS-98 quantities possible (Fig. 1).

First, we consider a hypothetical locality that suffered damage referable to intensity VIII MCS. At this location, comprising, for example, 100 buildings, we can use data in MCS to assess the EMS-98 intensity degree.

According to the MCS statement, 50% of buildings sustain D3 + D4 + D5, 25% D4 + D5 and 5% D5, so that by splitting in each grade of damage it can be represented as in Table 3.

Likewise, the VIII EMS-98 intensity degree for a locality comprising only vulnerability class A buildings, is shown in Table 4:

The damage scenarios represented by Tables 3 and 4 are nearly the same, except for the 25% D3, which is not represented in Table 4. Indeed, in the EMS-98 intensity degrees, usually only the two highest damage grades for a particular vulnerability class are mentioned (Grünthal 1998), and the missing 25% (many) of D3 can be assumed as the proportionate number of buildings that had suffered lower grades of damage not made explicit in the intensity degree definition.

In any case, we can say that if the hypothetical locality consists of 100 buildings belonging to vulnerability class A, then the macroseismic intensity will be VIII in both the MCS and EMS-98 scales.

Instead, if the 100 buildings belong to vulnerability class B the MCS intensity will remain VIII, while the EMS-98 intensity will increase to IX degree, as defined in Table 5.

Considering the progressiveness of the EMS-98 scale and decreasing the vulnerability class, we will see an increase in the gap between MCS and EMS-98 intensity assessments. This pattern can be repeated by diminishing the vulnerability class up to class D (buildings

Table 5 Damage quantitative terms for a locality with only class B vulnerability buildings

	D1 negligible	D2 moderate	D3 substantial to heavy	D4 very heavy	D5 destruction
IX				many B	few B

Table 6 Comparison of the MCS and EMS-98 intensities assessment for hypothetical localities with buildings in only one class of vulnerability (A-D)

Building stock	MCS	EMS-98
100% class A	VIII	VIII
100% class B	VIII	IX
100% class C	VIII	X
100% class D	VIII	XI

with earthquake resistant design, ERD), where the EMS-98 intensity reaches degree 11 (Table 6).

This simple example shows that the damage sustained by increasingly less vulnerable buildings, due to the shaking increase, determines a variation of EMS-98 intensity, a variation that the MCS scale cannot recognize. The EMS-98 maintains its efficiency irrespective of the quality of the building stock; on the contrary, the MCS scale, not considering the building vulnerability, can no longer provide an adequate estimate of the macroseismic intensity related to the building resistance. The degree XII is excluded from this progression as every manmade construction is destroyed.

Repeating this reasoning for the other degrees of intensity, and assuming that the building stock varies in vulnerability class from time to time, yields the graph in Fig. 2.

It is worth highlighting that starting from intensity VIII and for vulnerability classes more resistant than class A, MCS systematically produces intensities lower than EMS-98. This tendency cannot be found for intensities lower than VIII and even tends to reverse for classes A and B. This is particularly manifest in the case of intensity V EMS-98, which expects light damage in a few buildings of class A and B that can be identified in intensity VI MCS. On the contrary, ERD buildings (class D) do not contribute to the intensity assessment for degrees lower than VII. Below the damage-threshold (I < V) MCS and EMS-98 produce the same results (Tertulliani 1995; Musson et al. 2010).

2.1 Evidences from field survey data

As theoretically illustrated above, the MCS scale is not sensitive to variations in building vulnerability. In this section, we present some intensity assessments on field survey data coming from different macroseismic campaigns during Italian earthquakes. The considered localities (Fig. 3) are Santa Rufina (Abruzzo region), Gualdo (Marche region), Accumoli (Lazio region), San Biagio and Spina (Umbria region), struck by damaging earthquakes occurring in L'Aquila in 2009, Tevere Valley in 2009 and Central Italy in 2016, respectively (Galli Camassi 2009; Arcoraci et al. 2010; Tertulliani et al. 2016a, 2016b; Rossi et al. 2019; Graziani et al. 2019).

During the inspections in the villages, vulnerability classes and degrees of damage were assessed; the results are shown in Table 7. The distribution, as a percentage, of buildings with the same grade of damage provides the estimation of MCS intensity. The percentage

Fig. 3 Map with the studied localities

value of D2 is used to assess MCS intensity lower than VIII, otherwise it is not accounted for in the assessment (values in brackets in Table 7).

The EMS-98 intensity is obtained after accounting for the distribution of degree of damage, expressed in quantitative adjectives, for each vulnerability class evaluated for each residential building.

The examples in Table 7 show that the two scales provide similar results when the building stock is composed of many vulnerable buildings (with vulnerability class A), as in the case of Accumoli. In Santa Rufina and Gualdo, the EMS-98 intensity is one degree higher than the MCS intensity because of the scarcity of buildings with high vulnerability. The similarity of the results for San Biagio and Spina cases can be explained by the low intensity range (VI and VII), where the behavior of the two scales is not linear (see Fig. 2).

3 Forecasting the intensity values

Since the difference between EMS-98 and MCS intensity seems to depend on the vulnerability distribution of the locality struck by the earthquake, it may be useful to predict where this difference will be greater and to identify a priori the settlement typologies, and conditions, for which the two scales provide different assessments.

For this purpose, we used the National Institute of Statistics (ISTAT) (2011) data on residential buildings to estimate the distribution of vulnerabilities of some localities. We used large-scale vulnerability estimation models, generally accepted by the

Table 7 Field survey data coming from macroseismic campaigns carried out following damaging earthquakes in recent years (Galli Camassi 2009; Arcoraci et al. 2010; Tertulliani et al. 2016a, b; Rossi et al. 2019; Graziani et al. 2019). Intensity assessments on MCS scale (upper part of the table)

EVENT–locality Damage %	Central Italy (2016) Accumoli	L'Aquila (2009) Santa Rufina	Central Italy (2016) Gualdo	Tevere valley (2009) San Biagio	Tevere valley (2009) Spina
D2	(23)	(12)	18	19	35
D3+D4+D5	62	54	35	11	14
D4+D5	28	39	9	2	1
D5	7	28	–	–	–
I MCS	VIII	VIII-IX	VII	VI-VII	VII
Vulnerability					
D2 moderate	*few A, many B, many C*	*few B, many C*	*many B,* **few C**	*many B, many C*	*many A, many B,* **many C**
D3 substantial to heavy	*many A,* **many B,** *few C*	*few A, many B,* **many C**	**many A, Many B, Many C**	**many B**	**many A, many B, few C**
D4 very heavy	**many A, few B**	**few A, many B**	**most A,** *few B*	**few B**	**few B**
D5 destruction	**few A**	**most A, many B, few C**			
I EMS-98	VIII	IX-X	VIII	VII	VII
Δ I	0	1	1	0.5	0

The intensity assessment on EMS-98 (lower part of the table) is done using mainly the quantities related to the two highest damage grades for a given vulnerability class (in bold). Δ I represents the difference I EMS-98–I MCS

scientific community, to assess the damage distribution, and then proceeded with the estimate of the MCS and EMS-98 intensities as per definition.

3.1 ISTAT data

To assess the building vulnerability at an urban scale, we use the census data for residential housing provided by ISTAT, homogeneously collected every 10 years on the entire national territory. These data allow a reliable estimate of the total number of buildings. Edifices are described by multiple characteristics: structural typology, date of construction or renovation, number of floors, position in the block, state of repair and quality of maintenance (Table 8). The last parameter is deduced indirectly from the presence of efficient installations (e.g. plumbing systems, connections to the sewage system, domestic hot water supply, etc.).

The ISTAT data on residential buildings are provided at a census section resolution (a subdivision of the municipality); since the information is provided in a disaggregated way (e.g. number of buildings of a specific type, with a certain age and a given number of floors), it is possible to use it for the vulnerability assessment. In this way, the ISTAT data allow grouping buildings into 6 classes (A to F of the EMS-98 intensity scale) by assigning a score of vulnerability (e.g. Bernardini et al. 2008).

Despite significant limitations, the census data are useful to take into account the considerable urban growth occurring during last century in Italy, though there are areas in the country with a scarce building development or even affected by depopulation, for instance rural districts or mountain villages (e.g. in the Apennines). Moreover, as often happens in the case of rapid urban development, the vulnerability level of more or less recent buildings is difficult to characterize because of the need to know their age (i.e. year of construction) to link with the relevant technical rules. The characterization at a municipal scale of buildings of the last 30 years is therefore a critical step in our analysis.

For this reason, different methods for estimating vulnerability are examined in the following.

Table 8 Typological parameters of the buildings, according to ISTAT census data

Structural typology	Building age	Number of floors	Isolated or contiguous	Maintenance status
Masonry	Before 1919	1 or 2	Isolated	Good
Reinforced concrete	From 1919 to 1945	From 3 to 5	Contiguous	Bad
Soft first storey building	From 1946 to 1960	More than 6		
Other typology	From 1961 to 1971			
No info	From 1972 to 1981			
	From 1982 to 1991			
	From 1992 to 2001			
	After 2001			

3.2 Vulnerability assessment methods

The first step is to assign a vulnerability level to the buildings in the municipalities of the investigated area. The scientific literature presents various methodologies for generating a vulnerability/damage scenario for built-up areas impacted by an earthquake; each method combines variables in different ways. These approaches differ on the method of assessing a building's vulnerability: they often use different parameters—more or less detailed—and relationships calibrated on different databases, but they all arrive at classifying the vulnerability (and damage) levels according to the European Macroseismic Scale (EMS-98) definition.

In this work, we used three methods for vulnerability assessment. The first, proposed by Di Pasquale et al. (2005), derives from a series of already tested approaches, based on the relationships between structural types and age classes of the buildings. It is still widely used (e.g. by Lucantoni et al. (2001) and Borzi et al. (2019) for its robustness and ease of application, as it uses only two ISTAT parameters (type of construction and age of the buildings).

With reference to the new methods, recently revised in the framework of the National Risk Assessment for Italy developed by the Department of Civil Protection (DPC) (Dolce et al. 2021), we also adopted the Lagomarsino et al. (2021) methods for masonry buildings and Rosti et al. (2021) for RC buildings. These procedures make use of most of the parameters of Table 8.

For the vulnerability classification of the RC buildings, the most recent methods consider the year of seismic classification, after which the adoption of more restrictive seismic standards is conceivable. In the study-area (Central Italy), the seismic classification was adopted mainly in 1915, 1927 and 1935, but such early dates do not guarantee an adequate level of resistance. The residential stock can therefore be grouped into the 6 vulnerability classes of EMS-98 scale. Trusting in the robustness of the first method and on the high level of detail of the other two, we have applied all of these, averaging the results by a simple medium value on the numbers of buildings.

3.2.1 Method 1

This method, adopted by the Department of Civil Protection to assess seismic risk in Italy (Di Pasquale et al. 2005), subdivides the building stock into four vulnerability classes (A, B, C1 and C2) by correlating the type of construction and age. Table 9A lists the vulnerability class as a function of the horizontal and vertical structural elements. A correlation between vulnerability class and the age of masonry buildings (Table 9B, adapted from Braga et al. 1982), has been obtained through a statistical study of a sample of about 50,000 dwellings after the 1980 Irpinia M_W 6.8 earthquake. The RC buildings are classified into the C2 vulnerability class if built before 1980 (in the case of municipalities classified in the seismic zone before that date), or D otherwise.

3.2.2 Method 2

The former method elaborated by Lagomarsino and Giovinazzi (2006), based on the expert appraisal that is implicit in the EMS-98 definition, was recently revised (Lagomarsino et al. 2021). The post-earthquake damage data, collected in the aftermath of earthquakes

Table 9 **A** Vulnerability classes vs. horizontal and vertical structural elements. **B** Vulnerability classes vs. age for masonry buildings (modified from Di Pasquale et al. 2005)

A

Horizontal structure	Vertical structure			R.C
	Masonry walls			
	Field stone	Hewn stone	Bricks	
Vaults	A	A	A	\
Wood	A	A	B	\
Steel & vaults	B	B	C1	\
Reinforced concrete	B	C1	C1	C2-D

B

Age	Vulnerability class [%]		
	A	B	C1
<1919	74	23	3
'19–'45	52	40	8
'46–'60	25	47	28
'61–'71	4	31	65
'72–'91	2	19	79

occurring in Italy in the period 1976–2012, were organized in the Da.D.O. database (Dolce 2019) and used for the new calibration. As a result, a vulnerability classification of buildings into four distinct categories, from A to D, is defined for masonry structural types, depending on the age and number of floors. Table 10 shows the percentage of buildings in the different vulnerability classes; it gives a clear picture of how the vulnerability changes with the age of construction and number of floors (L = 1 or 2 floors; M = 3 or 5 floors; H = more than 5 floors).

3.2.3 Method 3

The approach elaborated by Rosti et al. (2021), specifically developed for RC buildings, derives empirical fragility curves based on the data of Da.D.O. database (Dolce 2019), that provides information on the building position, characteristics and damage detected on

Table 10 Percentage of vulnerability classes in each ISTAT masonry sub-types, depending on age and building heights (L/M/H) (from Lagomarsino et al. 2021)

ISTAT	<1919			1919–1945			1946–1961			1962–1981			>1981		
	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
A	60	40	90	10		40									
B	40	60	10	90	80	60	40	50	70						
C					20		60	50	30	60	80	100		10	20
D										40	20		100	90	80

different structural components. Fragility curves for two vulnerability classes, C2 and D, further subdivided into three classes of building height (L, M, H), are obtained.

3.3 Examples of intensity assignments

In this section, a few examples of MCS and EMS-98 intensities calculation are presented. Knowing the number of buildings in a locality is sufficient to assign the value of MCS intensity, according to its definition (Table 1). ISTAT provides the number of residential buildings in each locality.

To assign the EMS-98 intensity values, on the other hand, it is necessary (a) to estimate the vulnerability distribution of residential buildings and (b) to quantify the qualitative measures "few, many, most" of the damage in Fig. 1. To quantify the qualitative adjective of the EMS-98 scale definition, we introduced three numerical alternative values, expressed in percentages, (min, med, max, see Table 11), codifying the linguistic quantity of the EMS-98 scale.

The vulnerability distribution was estimated as the average value of the three vulnerability distributions obtained with the methods described above. Indeed, we used that of Di Pasquale et al. (2005) for its robustness and ease of application and the two others for their best level of detail and for having been calibrated on the most recent data.

For each intensity degree, the quantities of damaged buildings were assessed using the EMS-98 intensity definition (Table 2), integrating the quantities of buildings not explicitly considered.

Following the numerical approach based on a fuzzy set theory by Bernardini et al. (2007), it is possible to extrapolate a description of the foreseen damage distribution by integrating the missing quantities to complete the definitions provided by the scale.

For example, buildings of class A, in the case of intensity VIII, are distributed (see Table 2) in D4 (many A) and D5 (few A). The definition does not specify how to distribute the remaining buildings of vulnerability A. Implicitly, they will suffer damage of levels below D4, therefore it seems apt to assign the remaining buildings (many A) in grade D3. The same integration was carried out for intensities IX, X and XI, also for the other vulnerability classes not explicitly defined by the EMS-98 scale.

3.3.1 Accumoli

The village of Accumoli (in the province of Rieti, in the Lazio Region) was chosen because the number and the quality of buildings surveyed during the 2016 macroseismic campaign, in its historic center, was comparable to that reported by Istat (2011) data in the corresponding census Section (163 and 121 respectively).

At the time of the 2016 earthquake, the locality was characterized by an abundance of old and very vulnerable buildings, probably due to the constant population decrease that

Table 11 Numerical scores codifying the linguistic quantity definitions of the EMS-98 scale, adopted by the authors

	Few	Many	Most
Min	5	15	55
Med	10	35	75
Max	15	55	95

Table 12 Vulnerability distribution of the buildings of the historical centre of Accumoli, calculated both from ISTAT data and from the 2016 macroseismic survey data (Graziani et al., 2019)

Accumoli	Istat (2011)	Survey 2016
Buildings	121	163
Masonry	99.2%	
r.c. + pilotis	0.8%	
other	0.0%	
A	46.0%	52.2%
B	44.3%	40.5%
C	8.9%	7.4%
D	0.9%	0.0%

Table 13 Number of Forecasted Damaged Buildings (FDB) in the historical centre of Accumoli, for each intensity degree, in both MCS and EMS-98 intensity scales

ACCUMOLI ISTAT 2011	121 buildings		
Intensity	Damage indicator	FDB for MCS	FDB for EMS-98
VIII	D3+D4+D5	(48) **61** (73)	(31) **70** (109)
IX	D3+D4+D5	(79) **91** (103)	(38) **87** (136)
X	D4+D5	(79) **91** (103)	(49) **84** (119)
XI	D5	(109) **121**	(31) **44** (57)

Bold numbers are the medium values, and those in round brackets are the minimum and maximum values. Shaded cells indicate the similar number of FDB for the same intensity degree

began after 1911, the most populous year, and continued until the 1980s with a drop of about 80%. From 1910 to 2011, the municipality was hit by 7 damaging events (I≥6) and was included in the Italian seismic classification since 1927.

Table 12 shows the percentage distribution of buildings typology according to ISTAT 2011 data. The vulnerability distribution of the same buildings, calculated from ISTAT data according to the vulnerability assessment methods described in Sect. 3.2, is compared with that of the macroseismic campaign data (Graziani et al., 2019).

With reference to the MCS intensity scale definition (Table 1), we define some useful damage indicators for the comparison between the MCS and EMS-98 scales, illustrated in Table 13. For example, according to the definition of grade VIII MCS, 50% of all the buildings suffer damage levels higher than D2, therefore the damage indicator will be (D3+D4+D5) (Table 3).

Likewise, the estimate of the VIII EMS-98 is depicted, obtained considering the vulnerability distribution of buildings following ISTAT 2011 (Table 12), the numerical score "med" of Tab. 11 that codifies the linguistic quantity definition "few-many-most", and the quantities reported (in Table 2) to define the EMS-98 intensity degree. The number of buildings with damage level D5 is calculated as 10% of buildings with class A vulnerability (few A, in Table 2); those with damage level D4 are the sum of 35% A buildings and 10% B buildings B (many A, few B); those with D3 damage are 35% B buildings and 10% C buildings (many B, few C), and so on for the other damage levels.

As mentioned in Sect. 2, only the quantities related to the two highest damage grades, for a particular vulnerability class, are specified in the definition of EMS-98 intensity degrees. This means that there are some buildings with vulnerability class A not shown in

Table 2, but we assumed that they have suffered a damage level D3 at least. This assumption is congruent with that generally made by other authors (e.g. Bernardini et al. 2007) in the assessment of complete damage distributions.

The comparison between the number of Forecasted Damaged Buildings (FDB) for MCS and EMS-98 obtained from the same damage indicators is shown in Table 13. In the specific case, the prevalence of buildings with high vulnerability (class A and B) produces similar intensity estimates in both MCS and EMS-98 scales: the sum D3 + D4 + D5, calculated in terms of EMS-98 intensity, gives a number of buildings equal to 70, comparable with that calculated according to the intensity of the MCS scale (61). The same happens for intensity degrees IX and X (see shaded cells in Table 13).

It should be noted that the damage indicators change according to the definitions of the MCS intensity degrees (in fact, grade X assumes that 75% of all buildings suffer damage D4 + D5, while grade XI assumes that all buildings undergo damage D5). Bold numbers are the medium values within the range of the expected number of buildings for each damage indicator obtained by using the min and max values of Table 1.

3.3.2 Folignano

The municipality of Folignano (province of Ascoli Piceno, Marche region) is halfway between the highly urbanized Adriatic coast and the historic centers of the Apennines. Just over 50 km from Accumoli, it represents a very different urbanized reality. Indeed, this town has been characterized by a strong demographic growth that has seen its population triple from 1971 to 2011. There is not much data about the earthquakes that affected the town: the maximum recorded intensity was VII-VIII MCS in 1943. The vulnerability estimation models (by the method illustrated in the previous paragraph) show that buildings are mostly class C (70–80%), with lower percentages (5–15%) of buildings in the most vulnerable classes A and B. There are only a few buildings with low vulnerability (class D) since the year of seismic classification of the municipality is very recent (2003).

The comparison between the number of FDB of the same damage indicators in MCS and EMS-98 scale is shown in Table 14: the damage indicator for the VIII MCS displays a number of damaged buildings (473) very close to the number of damage indicator for the IX EMS-98 (460). This means that with those quantities the two intensity assessments can differ by about one degree, due to the high prevalence of buildings in class C. Comparing the damage indicators for other intensity levels one can see that the MCS assessment tends to be systematically lower than the EMS-98 ones.

Table 14 Number of FDB in Folignano, for each intensity level, in both MCS and EMS-98 intensity scales

FOLIGNANO ISTAT 2011 945 buildings			
Intensity	Damage indicator	FDB for MCS	FDB for EMS-98
VIII	D3+D4+D5	(378) **473** (567)	(74) **156** (239)
IX	D3+D4+D5	(614) **709** (803)	(203) **460** (716)
X	D4+D5	(614) **709** (803)	(213) **455** (697)
XI	D5	(851) **945**	(162) **339** (515)

Bold numbers are the medium values, and those in round brackets are the minimum and maximum values. Shaded cells indicate the similar number of FDB for the same intensity degree.

Table 15 Number of FDB in Alfedena, for each intensity level, in both EMS-98 and MCS intensity scales

ALFEDENA ISTAT 2011 999 buildings			
Intensity	Damage indicator	FDB for MCS	FDB for EMS-98
VIII	**D3 + D4 + D5**	(400) **500** (599)	(22) **45** (69)
IX	**D3 + D4 + D5**	(649) **749** (849)	(104) **226** (348)
X	**D4 + D5**	(649) **749** (849)	(363) **660** (957)
XI	**D5**	(899) **999**	(87) **186** (286)

Bold numbers are the medium values, and those in round brackets are the minimum and maximum values

3.3.3 Alfedena

The last considered case is the municipality of Alfedena, in the province of L'Aquila, in Abruzzo. It is a mountain municipality and, like Accumoli, was affected by severe depopulation (almost -60% from 1921 to 2011). Even Alfedena has been included in the Italian seismic classification for a long time (since 1915). In 1984, it was hit by two earthquakes of grade VII and VIII MCS, which made it necessary to proceed with an important reconstruction action. For this reason, the municipality is characterized by a notable presence of buildings with low vulnerability level: more than 65% of buildings have vulnerability D (very low), 30% have vulnerability C, while buildings of the most vulnerable classes A and B are very scarce.

The theoretical assignment of the intensities provides the indication of a constant difference between the MCS and EMS-98 intensities values greater than one degree (Table 15).

4 Analysing the results and application on a large scale

A practical application of the previous considerations is the identification, a priori, of areas in which the two scales provide different results compared to others where the two intensity scales are comparable, as in the case of Accumoli.

To this end, it is advisable to analyse the distribution of buildings in Italy, using a few parameters of the ISTAT data as proxies of the vulnerability of the buildings. For a large-scale analysis, one can assume a correspondence between the vulnerability classes and the typological characteristics (RC or masonry) of the buildings, as well as some considerations on their construction period.

Therefore, by analyzing these last two parameters it is possible to characterize the territory at a national level.

On observing the residential buildings in the Italian territory, we can affirm that in the last 100 years the building typologies have changed radically. Residential masonry buildings have been built for centuries with local materials and with techniques established by experience that were only brought into question by major natural events. These types of buildings were gradually replaced by those in RC, starting from the middle of the last century. Considering the social and economic context, it is possible to highlight the immediate reconstruction efforts after the Second World War in 1945, followed by the themes of urbanization, land speculation and real estate markets of the 1950s.

Figure 4 shows the distribution of buildings by type (masonry, RC and other types) in the time interval of about one hundred years, from the 2011 ISTAT census. It is notable
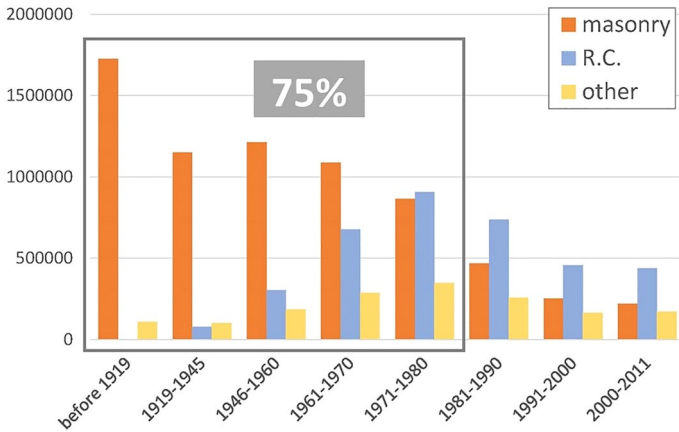
Fig. 4 Temporal distribution of buildings in masonry, RC, and other structural types from pre-1919 until 2011
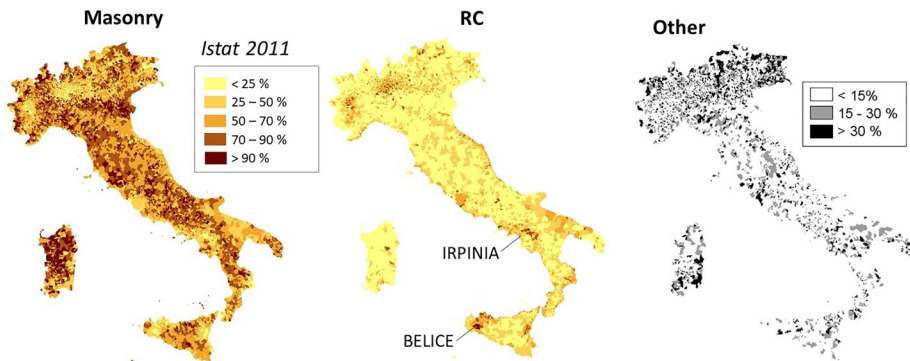

Fig. 5 Percentage distribution of masonry, RC and other buildings in the Italian territory, according to ISTAT (2011) data

that the use of masonry was still predominant until the 1970s and was subsequently super-seded by that of RC.

Reinforced concrete, "considered cheaper and more versatile than masonry" (Borzi et al. 2021) was widely used in Italy in the 1960s, when the growth of industrial districts and development pressures on the historical fabric of the city became prevalent. Initially, the RC typology proved particularly vulnerable, due to the lack of proper seismic design that was successively enforced after damaging earthquakes (Borzi et al. 2021). The first RC design code (Regio Decreto Legge 1939) remained in force for over 30 years until 1972 when a new code was issued (Norme Tecniche 1972), hence the RC buildings in Italy have often been divided into these two distinct classes: pre-and post-1970 (Crowley et al. 2009).

Seismic design and seismic classification of the Italian territory have often gone hand in hand, but it was only at the beginning of the twenty-first century that the entire terri-tory was classified and important changes in the structural design were adopted in 2003 by the Ministerial Ordinance n. 3274 (OPCM/3274, 2003). Following the publication of
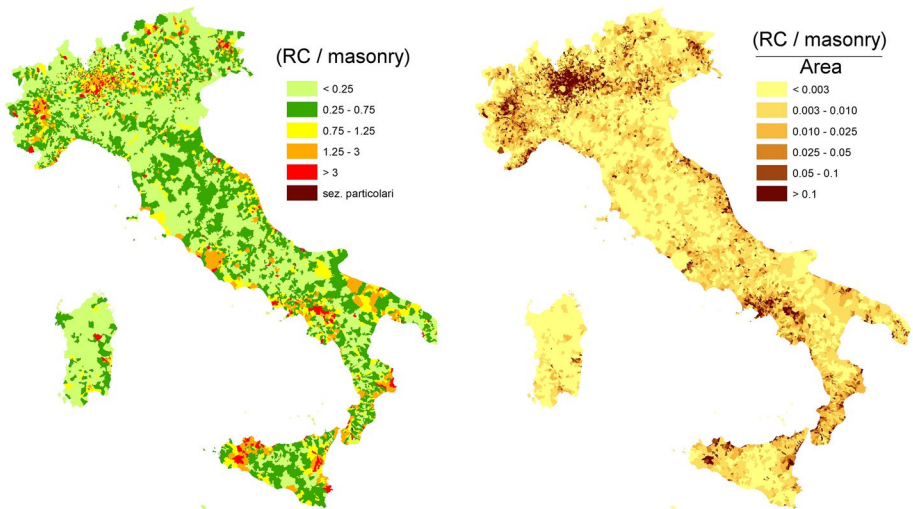
Fig. 6 RC/M map: distribution of the ratio between number of RC and masonry buildings (left). RC/M maps normalized for the municipality area (right)

the seismic hazard map MPS04 (Gruppo di Lavoro MPS 2004, 2011), the New Technical Standards for Construction (Norme Tecniche per le Costruzioni (NTC) 2008) were released in 2008, and successively updated (Norme Tecniche per le Costruzioni (NTC) 2018), following the publication of the seismic hazard map MPS04 (Gruppo di Lavoro MPS 2004; Stucchi et al. 2011).

As concerns the territorial distribution, the areas with older buildings are those of the North-Western Alps or in the Central and Southern Apennines and specifically some mountainous areas that have been affected in the years by the depopulation phenomenon: in such situation, the masonry building heritage has not been preserved and today represents an element of considerable vulnerability.

On the other hand, areas such as Irpinia or Belice (Fig. 5), having been affected by strong earthquakes in the last century that prompted the reconstruction or restoration of entire villages or part of them, has led to a less vulnerable renovated building heritage.

Comparing the relative distribution of masonry and RC (Fig. 5), it is evident that the most recent urbanized areas, characterized by the predominance of RC buildings, are located on the coastline with a vocation for tourism, in the most economically active districts in the north and in the major cities. Figure 5 also shows the distribution of the typology defined by ISTAT as "other" which are constructions in steel, wood or mixes (RC and masonry).

The ratio RC/M between the number of RC and masonry buildings was calculated to produce a summary map of the previous considerations and a useful working tool (Fig. 6 on the left). Buildings classified as "other" were distributed between the two classes, in proportion to their numerousness.

It may first be assumed that a less than 0.25 RC/M ratio can identify areas in which the EMS-98 intensity assessments can still be compared with the historical assessed values: in these areas the presence of RC buildings is much lower than the masonry ones. Instead, the areas with RC/M > 1.25 are those in which an MCS intensity assignment is inadequate and risks leading to underestimated intensity data.

Figure 6 (right) is the normalization of the RC/M ratio on the municipal area since municipalities with older and more vulnerable buildings generally extend over a large area. The map is therefore just a different representation to better highlight the critical areas (the darker ones) in case of assigning the MCS intensity.

Although this map is rather approximate and can be considered valid only for large-scale considerations, a certain correspondence can be found between this and the published vulnerability maps (Zuccaro 2004; Lucantoni et al. 2001).

5 Conclusions

The Italian current building stock has changed profoundly since the first macroseismic scales were established more than a century ago, making the MCS scale outdated today. The MCS is a scale designed at a time when buildings were more or less homogeneous and therefore they could be considered, in good approximation, as seismic instruments that were calibrated in the same way. Thus, when subjected to an earthquake they showed comparable damage for comparable ground motions. This makes MCS intensity only a function of damage.

The current diversity of buildings, in a given town or village, results in variability in earthquake resistance depending on the type of building. EMS-98 was created with the aim of taking this diversification into account by introducing the parameter of building vulnerability for the purpose of intensity assessment. This means that intensity depends not only on damage, but also on the vulnerability of buildings.

Because the MCS scale is still used in Italy, even in the presence of recently constructed buildings, the purpose of the work is to demonstrate that the EMS-98 is the most suitable tool for assessing intensity as it is more consistent with the built reality. In this paper, we analyzed the impact of the evolution of Italian building stock on macroseismic scales application.

We initially analyzed the theoretical behavior of the two scales: this analysis shows that in general the two scales provide comparable estimates when the building stock has a high vulnerability (class A), i.e. it is the same or very similar to the typical pre-World War II building stock. On the contrary, in presence of increasing percentages of less vulnerable buildings, up to and including ERD buildings, MCS estimates are systematically lower than those in EMS-98. This behaviour is observed for intensity equal to or greater than VIII. This is intuitively related to the fact that more resistant buildings are damaged by greater shaking, and thus for the same amount of shaking, the severity of damage is directly proportional to the building's vulnerability. For the MCS scale, the buildings have roughly the same resistance, so the scale itself fails to interpret the difference in shaking required to damage buildings with less vulnerability. The EMS-98 scale, on the other hand, includes the diagnostic elements describing a differentiated building stock, so the damage-shaking proportionality due to vulnerability can be interpreted: ultimately, the more resistant the buildings, the greater the observable difference between the intensities assigned with the two scales.

The considerations on the comparison of the intensity values assigned on real and theoretical cases on the validity of the MCS and EMS-98 intensity scales, can lead to useful indications in the case of macroseismic surveys. We have theoretically demonstrated that the dependence of intensity on vulnerability, in those locations where the built environment is mainly represented by class C, D buildings and higher, can lead to differences

greater than one degree between the assessments on the two scales. Since the difference of the two scales is highly dependent on vulnerability, it is possible to highlight a priori those localities or areas, depending on the building characteristics, where the only estimate of intensity in EMS-98 terms finds a reasonable field of application and where, vice versa, that in terms of MCS intensity would give underestimated values. These are all areas of more recent construction, where the prevalent buildings are in RC or good quality masonry and where the historic centers have been renovated.

Until a few years ago, most of the renovations only took place after earthquakes, while recently financial policies in Italy have been implemented to reduce the vulnerability of buildings as a general practice. This has led to the creation of an ever-improving building stock, for which the MCS scale will be increasingly difficult to apply.

What has been presented so far suggests a further consideration on the use of the EMS-98 for the intensity assessment of Italian historical earthquakes: it can be reasonably assumed that the vulnerability of buildings constructed from several centuries to about 60 years ago may in the great majority be assignable to Class A. This means that evaluating an historical earthquake in EMS-98 is analogous to the evaluation of a recent earthquake in a location with old or poor constructions. Therefore, the use of EMS-98 for the study of old earthquakes is consistent with previous assessments in MCS. In conclusion, the use of the MCS or EMS-98 for historical earthquakes would be no different, while the continued use of the MCS for modern earthquakes is not recommended because it may lead to inhomogeneity in the evaluation between historical and recent earthquakes.

Finally, in our opinion, today the EMS-98 is the more useful and robust tool to perform reliable estimations of macroseismic intensity in whatever evaluation context.

Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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