

The 2012 Emilia (Northern Italy) earthquake sequence: an attempt of historical reading

L. Graziani · F. Bernardini · C. Castellano ·
S. Del Mese · E. Ercolani · A. Rossi · A. Tertulliani ·
M. Vecchi

Received: 20 March 2014 / Accepted: 30 October 2014 / Published online: 31 December 2014
© Springer Science+Business Media Dordrecht 2014

Abstract In May–June 2012, the Po Valley (Northern Italy) was struck by an earthquake sequence whose strongest event occurred on 20 May (Mw 5.9). The intensity values (I_{\max} 7–8 EMS98) assessed through macroseismic field surveys seemed inappropriate to describe the whole range of effects observed, especially those to monumental heritage, which suffered very heavy damage and destruction. The observed intensities in fact were significantly lower than those we could have expected after a Mw 5.9 event for Italy. As magnitude–intensity regressions are mainly based on historical earthquake data, we handle this issue going back in time and debating the following hypotheses: (a) the 2012 Emilia earthquake sequence shows lower intensity values than expected because the affected urban context is more heterogeneous and much less vulnerable than that in the past; (b) some historical earthquakes, especially those that occurred centuries ago and are provided with little information, could show a tendency to be overestimated in intensity, and consequently in magnitude. In order to give consistency to such hypotheses, we have introduced, as a test, a dual historical reading of the 2012 Emilia earthquake sequence as if it had occurred in the past: the first reading refers to a period prior to the introduction of concrete in buildings assessing the intensity on traditional masonry buildings only. A further historical reading,

assessed by using information on monumental buildings only, was performed, and it can be roughly referred to the XVI–XVII centuries. In both cases, intensity values tend to grow significantly. The results could have a relevant impact when considered for seismic hazard assessments if confirmed on a large scale.

Keywords MCS scale · EMS98 · Emilia 2012 earthquakes · Historical seismology

1 Introduction

On 20 May 2012, at 4:03 local time (2:03 UTC), a damaging earthquake (Mw 5.9) struck a large part of the Po Valley between the cities of Ferrara, Modena, Bologna, and Mantova (Northern Italy). The epicenter was located by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) seismic network ISIDe (2012) at 44.889° N and 11.228° E, approximately 30 km west of Ferrara. The event was preceded by a foreshock that occurred at 01:13 local time (Mw 4.8) and followed by a sequence that lasted for weeks, with six strong shocks with $ML > 5$ (Fig. 1). The strongest occurred on 29 May 2012, at 9:00 local time (Mw 5.7) and 12:55 local time (Mw 5.3), causing additional heavy damage in the western part of the area already hit on May 20.

The area affected by the earthquake sequence of 2012 is characterized by a low-to-moderate level of seismicity. In an area within 30–40 km from the epicenters of the main shocks of 20 and 29 May 2012, historical information provided by the current Parametric Catalogue of

L. Graziani (✉) · F. Bernardini · C. Castellano ·
S. Del Mese · E. Ercolani · A. Rossi · A. Tertulliani ·
M. Vecchi
Istituto Nazionale di Geofisica e Vulcanologia,
Rome, Italy
e-mail: laura.graziani@ingv.it

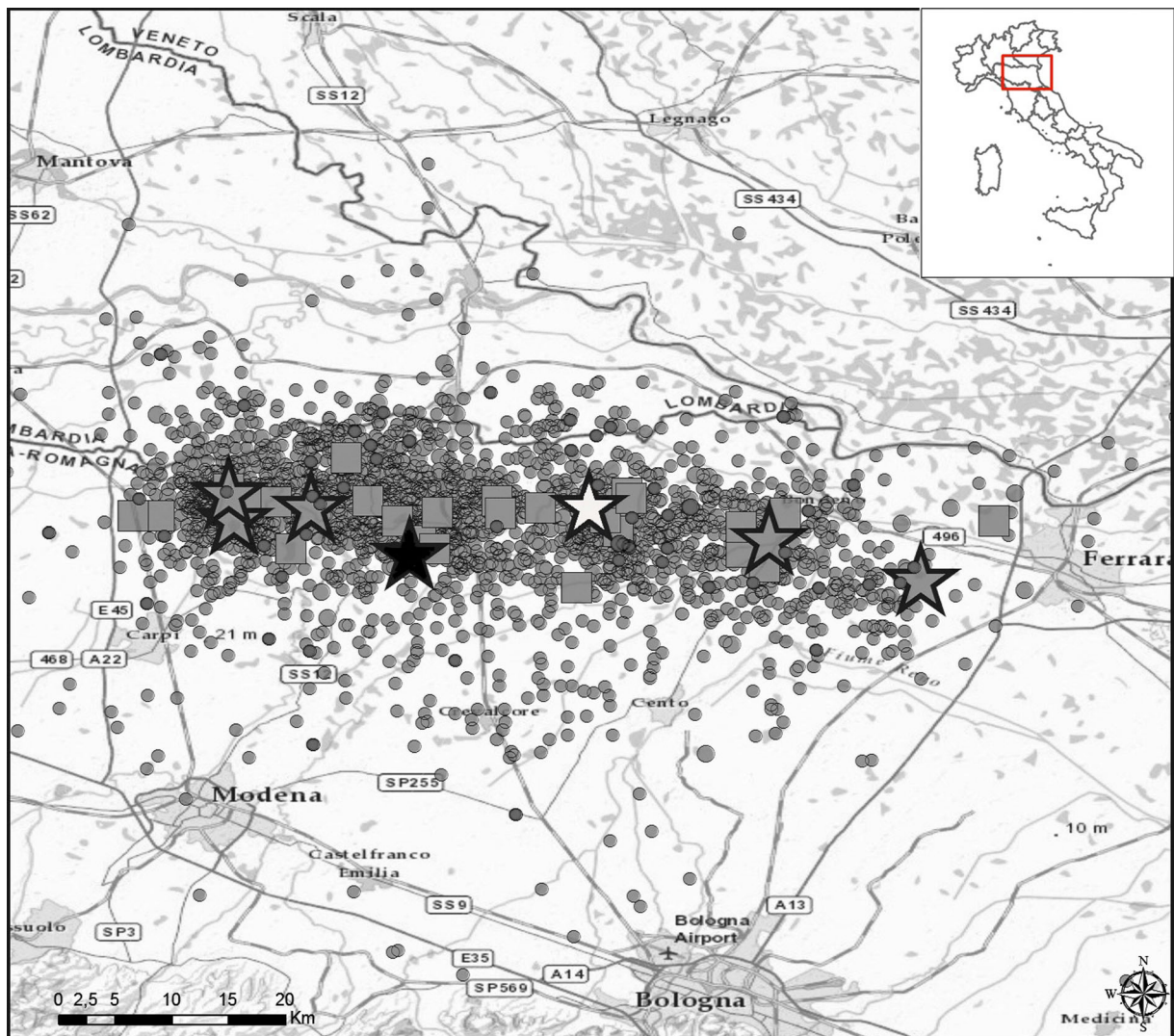


Fig. 1 Map showing the Emilia earthquake sequence (epicenters of events that occurred up to 5 July 2012). *White star* main shock of 20 May (Mw 5.9); *black star* main shock of 29 May (Mw 5.7);

gray stars $M_w \geq 5.0$ aftershocks; *squares* $4.0 \leq M_w < 5.0$ aftershocks; *large dots* $3.0 \leq M_w < 4.0$ aftershocks; *small dots* $M_w < 3.0$ aftershocks (modified after INGV terremoti (2014))

Italian Earthquakes (hereinafter CPTI11, Rovida et al. 2011) does not report any significant event, with the only exception of the event that struck Ferrara on 17 November 1570 (Mw 5.5) (see also Castelli et al. 2012). In the last decades, sporadic small-to-medium magnitude earthquakes have occurred in this sector of the Po Valley, such as the events of 6 December 1986 (Mw 4.6) and 2 and 8 May 1987 (Mw 4.7, 4.6, respectively), which affected the northern sector of the Modena province (Locati et al. 2011; Rovida et al. 2011).

The macroseismic effects of the 2012 Emilia earthquakes have been carefully investigated either according

to European Macroseismic Scale (EMS98, Grünthal 1998; Tertulliani et al. 2012a) or according to the Mercalli-Cancani-Sieberg (MCS, Sieberg 1930) guidelines (Galli et al. 2012); in both cases, the results are very similar.

The EMS98 survey was performed on a total of 87 localities with the specific goal of describing, as accurately as possible, the damage scenario for each locality. It was possible to define the intensity distribution for the 20 May event in about 50 localities, surveyed before the occurrence of the 29 May shocks. The assessment of EMS98 intensities is based on the observations of

damage suffered by the residential building stock, previously classified in typology and vulnerability classes. The intensity assessment is based on the percentage of the different damage grades suffered by each vulnerability class. Damage on monumental and special buildings was reported too, although it is not considered for the estimation of intensity, as suggested by the guidelines of the EMS98 scale. Such kind of buildings have the characteristic of being unique or very few in one place, and therefore, they cannot be computed in a statistical way as other building typologies (Grünthal 1998).

The MCS survey was performed in 190 localities, 52 before the 29 May shocks, with the main intent of defining, as quickly as possible, the area of major damage (Galli et al. 2012) for civil protection purposes. The main difference between the use of EMS98 and MCS scales lies in the fact that the latter assesses the intensity value on the base of a comprehensive scenario, without detailing building types, damage grades, and quantities, considered individually by EMS98.

In broad terms, we can confirm that most of the damage was concentrated in old town centers, where the historic monumental buildings were heavily struck. Most of the total or near collapses involved both manufacturing plants (industrial warehouses, farmhouses, barns) and monumental buildings (fortresses, churches, and towers or belfries). Dedicated investigations confirmed that the historical/monumental building stock suffered the major damage as demonstrated in Modena et al. (2013). On the other side, the residential building stock did not suffer much damage: generally from light to moderate (Penna et al. 2013). As a result, in many sites, severe destruction was clustered in a general scenario of light damage. The final estimate leads to moderate intensity values: the maximum intensity value assigned is I_{max} 7–8 for the EMS98 as well as for the MCS. As a consequence, the values of macroseismic magnitude calculated both from EMS98 and MCS intensity data (Tertulliani et al. 2012a; Galli et al. 2012) by means of the code Boxer 4.0 (Gasparini et al. 2010) (Table 1) are rather lower than the instrumental magnitude M_w 5.9 of the main shock. In particular, the macroseismic magnitude computed from the cumulative intensities at the end of the sequence is M_w 5.3. Such results instill doubt that the assessment is not appropriate.

This discrepancy can also be found on the analysis of the magnitude-intensity recent regression lines based upon the CPTI catalog (Fig. 2) (Gruppo di Lavoro 2004; Pasolini et al. 2008) which suggests intensity values ranging from 8 to 9 MCS following a M_w 5.9

Table 1 Intensity values (EMS and MCS) and macroseismic magnitudes related to the 20 May shock and the cumulative effects for the whole sequence (last $M > 5$ aftershock that occurred on 3 June 2012)

	M_w (instr.)	I EMS	M_w EMS ^a	I MCS	M_w MCS ^a
20/5/2012	5.9	7	5.1	7	5.1
Cumulative	-	7-8	5.3	7	5.1

^a Macroseismic magnitudes are computed by Boxer 4.0 (Gasparini et al. 2010)

earthquake, significantly higher than the intensity values assessed for the Emilia seismic sequence.

What are the possible causes of such discrepancy? Considering that the regression is mainly based on historical earthquakes, some possible hypotheses arise:

1. The 2012 Emilia sequence shows lower intensity values because it affected urban contexts more heterogeneous and much less vulnerable than those in the past;
2. Some historical earthquakes, especially those occurred ages ago and provided with little information, could tend to be overestimated due to the scarcity of data available.

Those topics were recently analyzed by Rong et al. (2011), comparing CPTI catalog with the Switzerland seismic catalog, revealing that the Italian side magnitudes were significantly higher by 0.5–0.6 unit, especially for small-to-moderate earthquakes. They conclude that a possible cause was the use of different catalog sources and an overestimation of pre-1975 earthquake intensity. Analogously, Hough (2013) demonstrates that intensity values of historical North American earthquakes, based on fragmentary accounts, can lead to overestimation, considering the most severe rather than representative effects. In the following paragraphs, we will try to clear up such questions and give a response to them.

2 Is it true that the 2012 Emilia earthquakes show lower intensity values because they affected a context more heterogeneous and much less vulnerable than that in the past?

In the course of time, urban settlements have undergone several changes, and intensity assessments have been

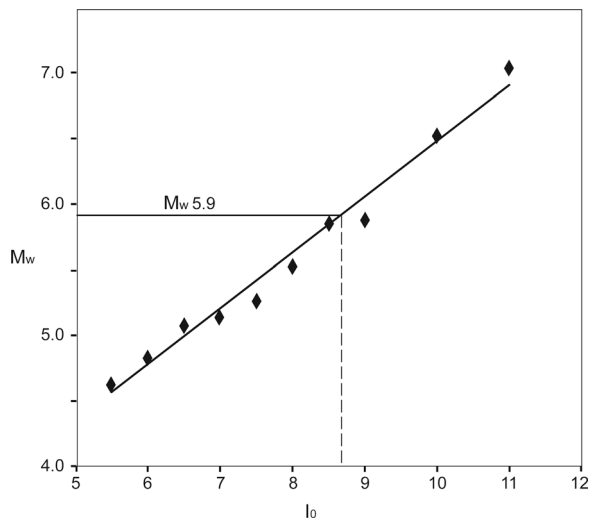


Fig. 2 Magnitude-intensity regression line after CPTI04 (redrawn from Gruppo di Lavoro 2004). Magnitude of the 20 May 2012 Emilia earthquake and expected intensity are also indicated

tuned to comply with these changes. It is a fact that most of present Italian urban settlements consist of a

delimited old town center, with mostly stone or masonry buildings, and a large modern expansion area, mostly composed of reinforced concrete buildings. Therefore, building typologies characterized by different vulnerability levels coexist within the same settlement, with the result of a high variability of damage in the same locality (Meroni et al. 2000; ISTAT 2001). Modern intensity assessments take into account the whole building stock, oldest and newest, considering their own statistical weight. As a consequence, towns with recent developments show an overall reduced vulnerability in respect to those that have not experienced any changes in times. Moreover, the estimation of the intensity in a recent town is assessed on an urban sample that is considerably more developed, as compared to the past; therefore, the whole damage is spread out over a larger building sample. These changes could contribute to lower intensity values in comparison with those assessed for earthquakes that occurred ages ago, when settlements were smaller and building stock was theoretically more vulnerable.



Fig. 3 Example of the analysis applied to the town of Mirandola. The central part of the town (*inside the polygon*) is well distinguishable also from the aerial view and represents the old town of Mirandola. In this part of the city, both residential and monumental

buildings are masonry structures (clay bricks). The residential stock is almost entirely composed by old traditional two-story brick houses, with negligible presence of concrete buildings

To demonstrate the above statement to be true, we have tried to handle the 2012 Emilia earthquake as if it had occurred in the past before the recent building development. As the macroseismic survey performed in EMS98 (Tertulliani et al. 2012a) provided us with a detailed dataset, where buildings are classified according to vulnerability typologies, we assessed the damage on the historical building stock only, adopting the same methodology used to study historical earthquakes.

Basically, to obtain a building stock similar to one of the past, we filtered our data discarding recent buildings (reinforced concrete buildings), and we analyzed the filtered data in the frame of the MCS scale, traditionally still used in Italy to examine historical earthquakes. This approach allows us to assess the effects as a whole, without considering building types, damage grades, and quantities individually.

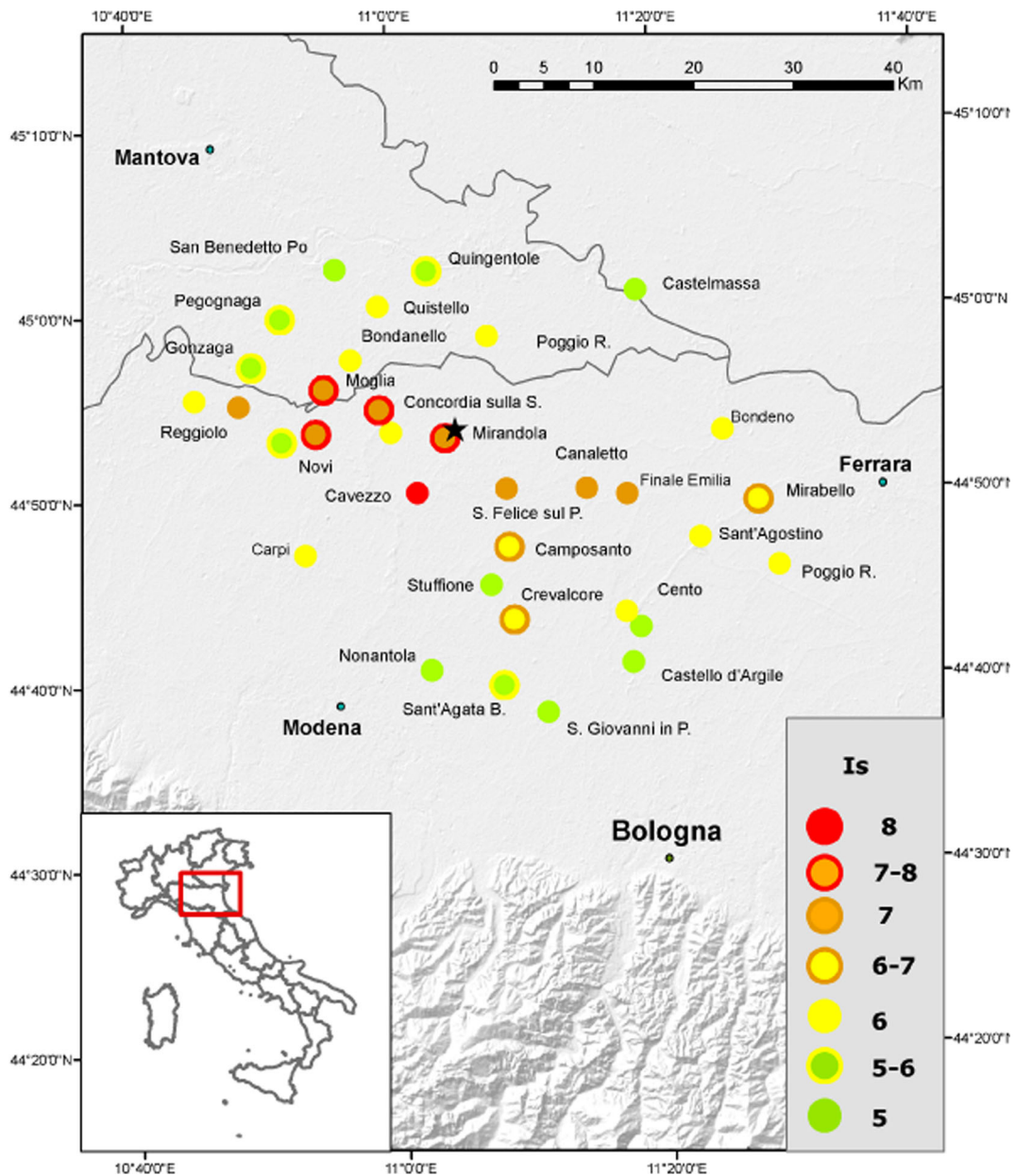


Fig. 4 Cumulative intensity distribution for the whole building stock (I_{WS} EMS98). *The black star* represents the macroseismic epicenter computed by Boxer 4.0 code (Gasperini et al. 2010)

The two steps, (a) discarding recent buildings and (b) analyzing the data with a MCS approach, can be viewed as a sort of historical reading of the earthquake. We believe that the historical reading represents a reliable method to read a present-day earthquake in the perspective of a comparison with the historical seismicity of the area.

2.1 The historical reading: a macroseismic analysis of earthquake effects in old town centers

In order to exclude from our analysis the recent urban development, we restricted our investigation to stone and the masonry buildings only. More precisely, we selected those localities for which a delimited old town center was

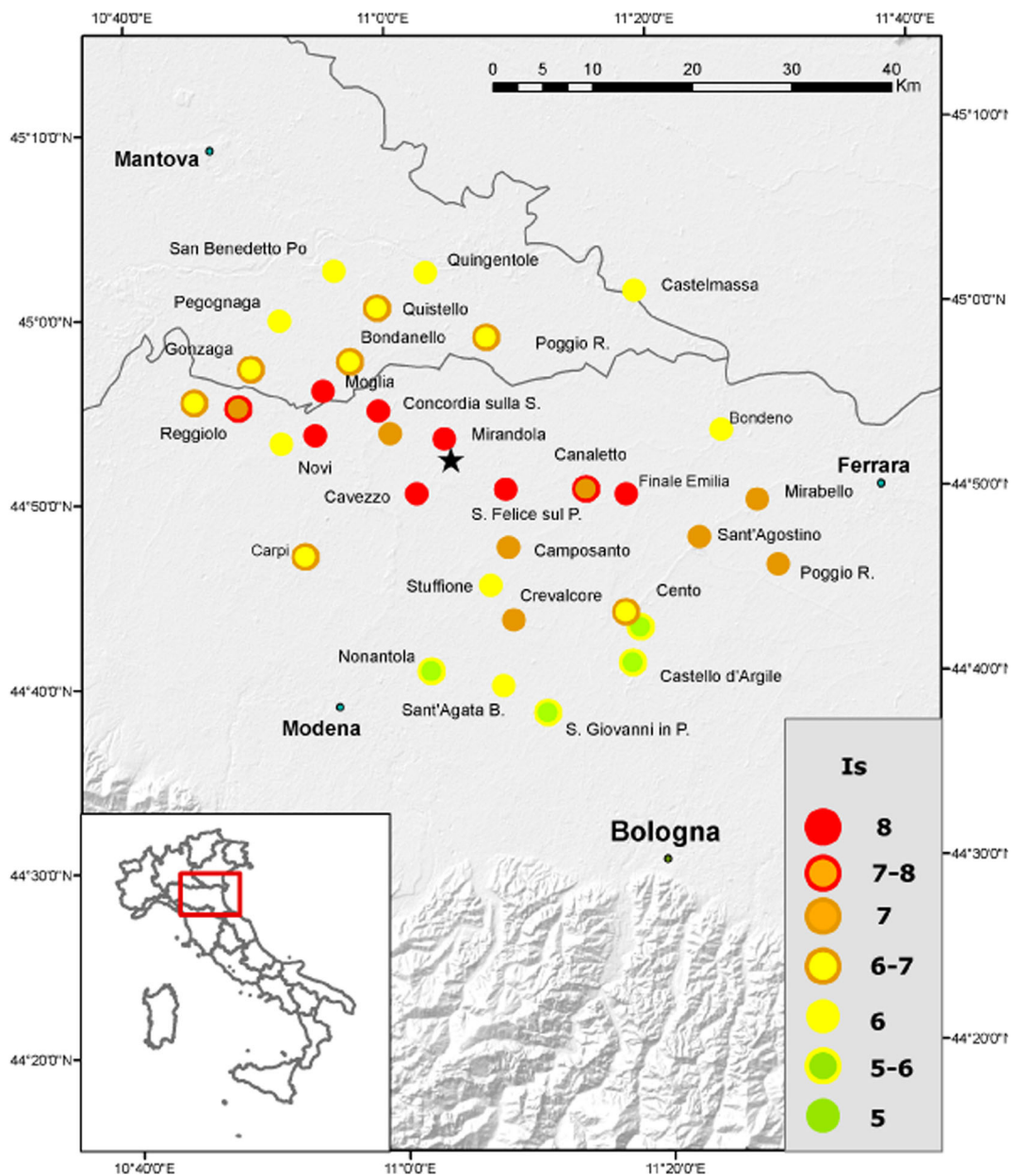


Fig. 5 Cumulative intensity distribution for the old town centers (I_{OTC} MCS). The black star represents the macroseismic epicenter computed by Boxer 4.0 code (Gasperini et al. 2010)

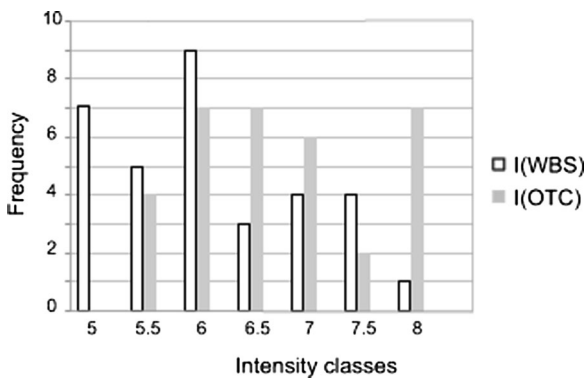


Fig. 6 Frequency of IWBS and IOTC intensities for different intensity classes

clearly distinguishable (Fig. 3), with a homogeneous building stock and negligible presence of concrete buildings.

Out of 87 localities, 33 display the useful characteristics for our analysis, having the old town center well identifiable. Data collected during our surveys were then examined in order to evaluate the intensity in terms of MCS scale. The results are shown in Appendix. For each locality, the WBS row displays EMS98 results (WBS stays for whole building stock); we believe that this scale is the most robust tool to depict the effects of a present earthquake. The OTC row is the new set of data that represents the effects of the 2012 Emilia earthquake on old town centers only. In our opinion, the latter depicts the effects of an earthquake that struck the very same area of the Emilia seismic sequence, but as if it had occurred before the introduction of concrete in building. From this new dataset, we assessed new intensity values according to the MCS scale (hereinafter named I_{OTC} , where OTC means old town center) and calculated new macroseismic magnitude.

Within this approach, the maximum intensity value 8 MCS was assigned to seven localities and coincides with I_0 .

EMS98 macroseismic intensities from Tertulliani et al. (2012a) (I_{WBS}) and MCS intensities (I_{OTC}) are plotted in Figs. 4 and 5, respectively. It has to be pointed out that we refer to the cumulative intensity due to the whole sequence effects.

The I_{OTC} are on average higher than the I_{WBS} . This trend can be highlighted in Fig. 6 where frequency of I_{WBS} and I_{OTC} intensities is reported for different intensity classes.

The I_{WBS} distribution is centered on values lower than the I_{OTC} ones. The mean value for the I_{WBS} intensity distribution is 6.1, while the mean value for the I_{OTC} distribution is 6.7.

The epicentral locations are very similar (Figs. 4 and 5). We computed the macroseismic magnitude either from the WBS and OTC datasets, obtaining, respectively, M_w 5.3 and M_w 5.7. The macroseismic magnitude from WBS dataset coincides with that reported in Table 1 computed from the whole original dataset. The result shows that M_{OTC} (5.7) is considerably higher than the M_{WBS} (5.3).

In the light of these results, we can affirm that, if the 2012 Emilia earthquake had occurred in the past (for example in the XIX century, that is to say a period antecedent to the use of concrete in building), we would have assessed intensities on average higher than those assessed for a present-day event. This kind of historical reading of the 2012 Emilia earthquakes shows results that are consistent with the current magnitude-intensity regression line (Pasolini et al. 2008; Gruppo di Lavoro 2004) based upon the 2004 version of the Italian parametric earthquake catalog (CPTI Working Group 2004). In other words, applying the MCS scale to old town centers only, the gap between assessed and expected intensities decreases.

Table 2 Ferrara earthquake of 17 November 1570: examples of the interpretation key used by Guidoboni et al. (2007) for the localities of Francolino and S. Maria Codifume, and relative intensity assessments

Locality	Original text	Synthesis	Intensity MCS
Francolino (FE)	“Oratory of S. Antonio. The church needs restoration and daubing. The roof has to be mended” (Maremonti 1574)	Oratory of S. Antonio. Damage to the walls and to the roof.	6
Santa Maria Codifume (FE)	“Oratory of Santa Maria Maddalena. The floor of the church has to be tiled with stone, the roof to be tiled [...] so as the belfry in danger of collapsing in need of restoration” (Maremonti 1574)	The S. Maria Maddalena church suffered heavy damage to the roof and the belfry, in danger of collapsing.	7–8

Table 3 2012 Emilia earthquake sequence: two examples of the 1570 interpretation key application for the localities of San Giovanni in Persiceto and Bondanello and relative intensity assessments

Locality	Field survey report	Intensity MCS
San Giovanni in Persiceto (BO)	“Two Churches slightly damaged, one statue collapsed	6
Bondanello (MN)	“The Esaltazione della Croce church is heavily damaged, with extensive cracks both on the façade and on the back. The bell tower, in danger of collapsing after the recent aftershocks, has been demolished.”	7–8

3 Scarcity of data and overestimation of historical earthquakes: the 1570 Ferrara earthquake as an interpretation key

Historical and monumental buildings (i.e., fortresses, churches, bell towers, and historical palaces) are not considered truly representative of the macroseismic intensity affecting a given area or single settlement. It is not unusual that churches turn out to be the only affected buildings in a given locality struck by a moderate seismic event. In fact, this kind of buildings usually has its own particular vulnerability to ground shaking and shows a higher tendency to be damaged by earthquakes (Cattari et al. 2013). That is why modern macroseismic scales (i.e., EMS98, but also MCS) suggest caution against considering only such kind of buildings for the intensity assessment.

However, it is also true that historical/monumental buildings often have a particular importance (i.e., artistic, religious, cultural, or even political/administrative).

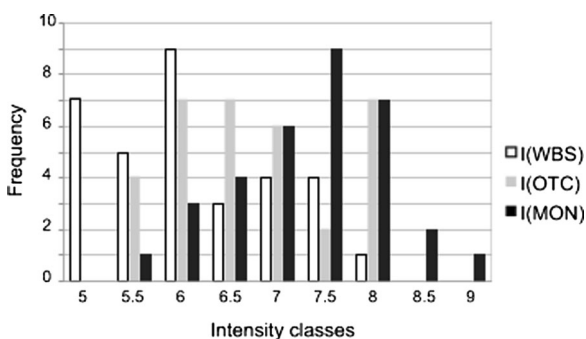


Fig. 7 Frequency of I_{WBS} , I_{OTC} , and I_{MON} intensities for different intensity classes; (white for WBS [whole building stock], pale gray for OTC [old town centres], dark gray for MON [monumental buildings])

So, they usually are under a sort of magnifying glass; consequently, they tend to receive particular attention from reporters, chroniclers, or observers. It is quite frequent that historical sources tend to mention effects on monumental buildings rather than effects on simple dwellings, on the base of the occasional extreme effects only. Indeed, to assess intensity through scarce data and descriptions referred to particular kind of buildings only is one of the main challenges of historical seismology (Musson 1998; Ferrari and Guidoboni 2000; Bakun et al. 2011; Hough 2013). Could this condition affect the earthquake scenario and lead to overemphasize the image of the earthquake impact?

To test this hypothesis, we first of all needed a historical earthquake to be used as key of interpretation, with intensity points estimated almost exclusively from damage to monumental buildings.

The 1570 Ferrara earthquake has the suitable characteristics, as its site and location resemble those of the 2012 event, and above all, its accounts are mainly related to effects on monumental heritage.

This event was carefully studied by Guidoboni et al. (2007). The 17 November 1570 main shock (Mw 5.4) started a complex seismic sequence that lasted until 1574. In the city of Ferrara, most of the buildings suffered severe structural damage and a few totally collapsed; the major damage was sustained by churches, bell towers, and monumental palaces.

In this study, Guidoboni et al. (2007) assessed the intensity of most localities starting from a poor documentation. In fact, excluding Ferrara which is well documented, 32 localities out of 35 have intensity equal or greater than 6 MCS and are documented through only one source very often referring to a single monumental building. This source is a transcription of a coeval account of the apostolic visit of Cardinal Maremonti (Maremonti 1574) and reports the damage produced by the earthquake on religious buildings.

On the base of these reports, we deduced the interpretative scheme used by Guidoboni et al. (2007) for the assessment of the intensity (Table 2). In Table 2, two examples of intensity assignment from Guidoboni et al. (2007) are given: In the first row, the assessed intensity is 6 MCS for a damage that can be mended; in the second row, the assessed intensity is 7–8 MCS for heavy damage to the roof and the belfry, in danger of collapsing.

The following step is the attempt to apply the same scheme to the 2012 Emilia earthquake, as a further and more extreme historical reading, in order to see how the

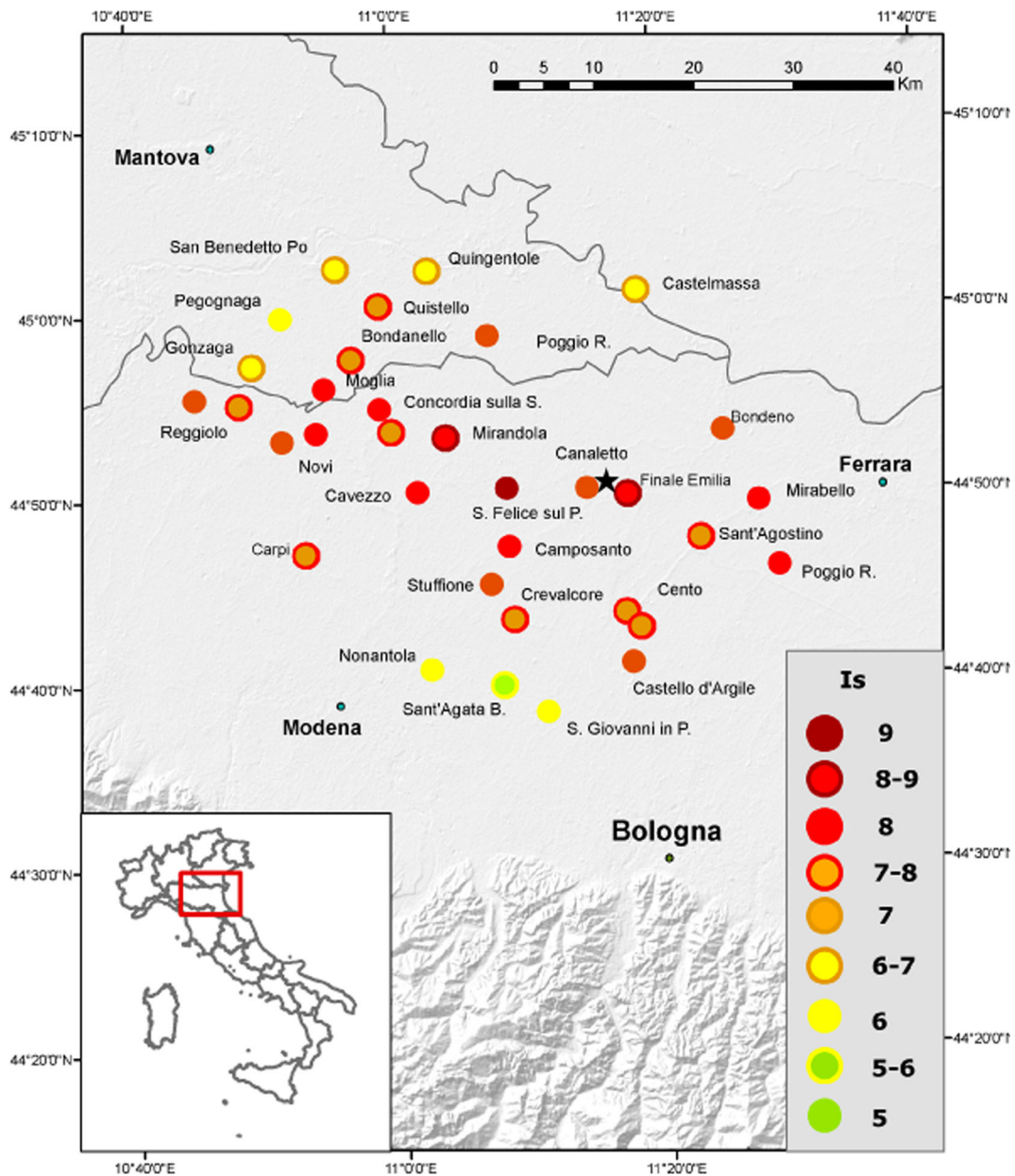


Fig. 8 Cumulative intensity (I_{MON}) distribution. *The black star* represents the macroseismic epicenter computed by Boxer 4.0 code (Gasperini et al. 2010)

scenario of that earthquake changes. Therefore, we filtered the data from the EMS98 macroseismic survey (Tertulliani et al. 2012a) selecting information related to monumental buildings only (see the examples in Table 3).

In synthesis, we suppose that if the 2012 Emilia earthquake had happened in XVI century, very likely the only information preserved would have been those about important buildings such as monumental and public buildings.

The results of this procedure show a general increase of the assessed intensities (Appendix), considering exclusively the damage on monumental buildings (hereinafter I_{MON}).

For instance, in San Felice sul Panaro, where the I_{WBS} assessed is 7 EMS98, the intensity based on monumental heritage is $I_{MON}=9$ MCS.

As regards the macroseismic magnitude, the solution inferred from the data (Gasperini et al. 2010) is $M_{MON}=6.0$.

In Fig. 7, the frequency of intensities of the three methods (WBS, OTC, MON) is reported for different intensity classes.

The white and pale gray bars are the same as in Fig. 6 while dark gray bars represent the frequency of intensities assessed on monumental damage for different classes. The mean value has considerably increased, and starting from 6.1 MCS for the WBS distribution, it has reached 7.3 MCS value for the I_{MON} . Even in this case, the results of the historical reading, selecting only the damage on monumental buildings, are consistent with the (magnitude-intensity) regression relationships (Fig. 2).

The macroseismic epicenter, calculated by Boxer 4.0 code (Gasperini et al. 2012), differs in respect with those calculated for I_{WBS} and I_{OTC} datasets and moves eastward due to the intensity increase in the easternmost localities (Fig. 8).

4 Discussion and conclusions

The aim of the present work is to discuss the fact that the intensity values observed during the 2012 Emilia

earthquakes were lower than we could expect for an Italian Mw 5.9 earthquake (see Pasolini et al. 2008; Gruppo di Lavoro 2004; Gasperini et al. 2010). As magnitude-intensity relationships are derived from seismic catalog records, mainly based on historical earthquakes, the suspect that some biases could have affected their intensity assignments leading to inflated assessments (Rong et al. 2011) arose. In fact, several recent studies carried out to revise historical events came to drop original intensity values (see for instance Hough et al. 2000; Tertulliani et al. 2012b; Hough 2013; Huysken and Fujita 2013). To tackle this issue, the effects of the 2012 Emilia earthquake were historically reread, as if the event had occurred in historical times. Such exercise can represent an advice on how interpretations of documentary sources can condition the assessment of a historical earthquake.

Starting from the damage survey (Tertulliani et al. 2012a) on the whole present-day building stock, developed during centuries, we have filtered the macroseismic information in order to obtain datasets representing different historical times. At first, we considered a time period before the use of reinforced

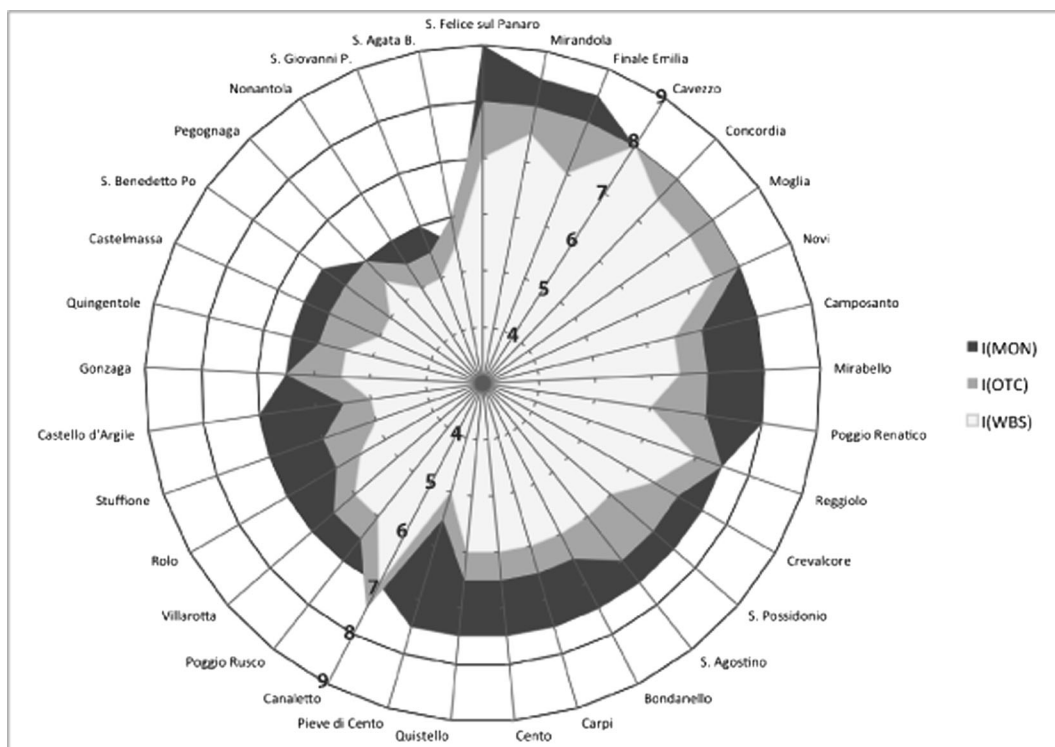


Fig. 9 A radial representation showing the comparison between the three different intensity datasets (WBS white, OTC pale gray, and MON dark gray)

concrete, when dwellings were characterized by a more homogeneous seismic vulnerability than nowadays, thus restricting the intensity assessment to old town centers. The results of this first step revealed that very likely the intensity of the 2012 Emilia earthquake would have been larger, with the maximum intensity from 7 to 8 MCS for many localities (Fig. 6). The second step is another leap in the past, when the records on damage on special monumental buildings were often the only information that could be retrieved in historical accounts about earthquake effects. In this case, the 2012 Emilia earthquake would have been classified as a strong earthquake with damage effects up to 9 MCS degree. Our journey back in time demonstrates that starting from intensity 7.5 EMS assessed on the present building stock (WBS), we have evaluated growing intensity values both for masonry building stock (XIX century-like; OTC) and monumental heritage (XVI century-like; MON). In Fig. 9, the three different datasets (WBS in white; OTC in pale gray; MON in dark gray) are simultaneously compared through a radial representation. Each radius corresponds to a different locality. It is evident that MON values are most of the times higher than the OTC ones, which in turn are larger than WBS values (the complete scheme of evaluation is in Appendix). This is particularly evident for localities such as San Felice sul Panaro, Mirandola, Finale Emilia, Camposanto, Mirabello, Stuffione, and some more. On the other hand, Cavezzo represents a very peculiar case, where intensity values from the three readings tend to coincide (8 MCS and EMS). This is mainly due to the fact that heavy damage in Cavezzo affected several modern reinforced concrete buildings as well as monumental and older ones, resulting in similar scenarios. Unlike Cavezzo, a few localities (i.e., Canaletto, and to a minor extent also S. Agata Bolognese) show MON and WBS intensity values both identical and slightly lower than the OTC one, because of the heavier damage affecting several masonry buildings in the old town center in comparison with damage observed in churches. In several cases, like Reggiolo, Concordia sulla Secchia, Novi, Moglia, Pegognaga, Gonzaga, MON and OTC values coincide, while WBS intensities are comparatively lower. Such cases occur in localities where damage both to monumental and masonry buildings (relatively old ones mainly in ancient town centres) is comparable, whereas outer modern expansion areas, mostly composed of reinforced concrete buildings, show much slighter damage levels.

Table 4 Macroseismic magnitudes calculated from WBS, OTC, and MON intensity data

	I_{\max}	I_0	Epicentral coord (Lat–Lon)	M_w^a
I_{WBS} EMS	8	7.5	44.866–11.017	5.3
I_{OTC} MCS	8	8	44.875–11.027	5.7
I_{MON} MCS	9	8.5	44.847–11.148	6.0

^a Macroseismic magnitudes are computed by Boxer 4.0 (Gasparini et al. 2010). The instrumental magnitude M_w of the main shock of Emilia 2012 earthquake was 5.9 (ISIDe 2012)

Apart from the peculiar cases of Cavezzo, Canaletto, and Sant’Agata Bolognese, we can highlight a sort of general trend: All the surveyed localities show the increase of the intensity values as we narrow down the reference damage scenario from the whole building stock to the old town center, and from the latter to the special monumental buildings.

It is evident that such variations of the intensity assessment for different building stocks result in a different calculated magnitude. As for the 2012 Emilia case, to evaluate the difference in magnitude, we computed macroseismic magnitudes by means of the code Boxer 4.0 (Gasparini et al. 2010) (Table 4). The difference of one degree in intensity entails a change in the macroseismic magnitude of 0.7.

The exercise here presented, on only one case, opens a substantial issue and would deserve a larger-scale effort to systematically validate such preliminary results. Anyway, it is evident that the size of the discrepancies here shown could have a significant impact when considered for seismic hazard assessments (Ambraseys and Douglas 2004; Rong et al. 2011). This issue is therefore well framed in the growing and renewed interest in the interpretation of key historical earthquakes that might have been overestimated and play a crucial role for the calibration of intensity prediction relations.

In conclusion, we emphasize the need to define more homogeneous criteria in the interpretation of original accounts to reduce possible biases in the assessment of historical intensity.

Acknowledgements The authors wish to thank L. Cucci and R. Camassi for their useful comments which helped to improve the manuscript. The authors also wish to express their cordial thank to I. Cecic and the anonymous reviewer for their constructive suggestions.

Appendix

Table 5 Complete scheme of evaluation used for the WBS, OTC, and MON datasets

Locality	Damage reports	I
San Felice sul Panaro	WBS The old town centre, very small compared to the recent development, suffered heavy damage. The latter is characterized by moderate damage in few concrete buildings with cracks in partition and infill walls, and in many buildings of class B (cracks in many walls). In few buildings of class B roof tiles detach and large and extensive cracks observed.	7
	OTC The small old town centre, suffered heavy damage. Total and partial collapse of some old scruffy buildings. Widespread substantial to heavy damage, failure of individual non-structural elements, roof tiles detach, large and extensive cracks. Chimneys failures observed.	8
	MON Total and partial collapse of monumental buildings: Castle: partial collapse Church: total collapse Two churches: partial collapse Clock tower: partial collapse Commemorative stone cracked Pillar and capitals collapse	9
Mirandola	WBS The old town centre suffered substantial to heavy damage. The recent development less affected. Few concrete buildings with cracks in partition and infill walls. Substantial to heavy damage in few buildings either of class C or class B. Few buildings of class B and many of class A with large and extensive cracks and roof tiles detach. Some old scruffy buildings partially collapsed.	7.5
	OTC Widespread substantial to heavy damage, almost all buildings suffered heavy damage, with large and extensive cracks. Some old scruffy buildings partially collapsed, one totally collapsed. Widespread roof tiles detach and chimneys collapse observed.	8
	MON Widespread heavy damage on monumental buildings Cathedral: partial collapse S. Giacomo della Roncole: church partial collapse	8.5

Table 5 (continued)

Locality	Damage reports	I
Finale Emilia	S. Franchesco d'Assisi church and belfry near total collapse Merlons collapsed City wall collapse	
	WBS The old town centre suffered substantial to heavy damage. The recent development less affected. Moderate damage in few buildings of class C and in many of class B. Substantial to heavy damage in few buildings of class B with large and extensive cracks and roof tiles detach. Some old scruffy buildings partially collapsed.	7
	OTC Widespread substantial to heavy damage, almost all buildings suffered heavy damage, with large and extensive cracks. Partial and total collapse of some old scruffy buildings. Widespread roof tiles detach and chimneys collapse observed.	8
Cavezzo	MON Widespread heavy damage on monumental buildings Castle: partial collapse Tower: total collapse Town hall partial collapse of the clock tower City wall large extensive cracks, partial collapse Cathedral: partial collapse Madonna del Rosario church: large and extensive cracks Two churches partially collapsed Church: pinnacles collapse Church capitals collapse and large and extensive cracks Two belfries: large and extensive cracks Monumental building large and extensive cracks Theatre roof tiles detach, failure of individual non-structural elements Collapse perimetral pillars	8.5
	WBS Large village with a very small town centre. Few concrete buildings partially collapsed sporadically the collapse is total. Excluding these cases, the majority of concrete buildings suffered moderate damage. Few buildings of class B partially collapsed or suffered substantial to heavy damage. Many buildings of class A partially collapsed, a few totally collapsed.	8

Table 5 (continued)

Locality	Damage reports	I
Concordia sulla Secchia	OTC Some good buildings suffered very heavy damage with partial and total collapses, and some with extensive cracks. Partial and total collapse of some old scruffy buildings. Widespread roof tiles detach and chimneys collapse observed.	8
	MON Structural failure of the roof church and collapse of belfry cusp.	8
	WBS The old town centre, suffered substantial to heavy damage. The recent development less affected. Substantial to heavy damage in many buildings of class B and in few buildings of class C. Many concrete buildings with cracks in partition and infill walls. Few buildings of class B and class A partially collapsed. Occasionally some old and scruffy buildings totally collapsed.	7.5
	OTC Widespread substantial to heavy damage, most buildings of the old town centre damaged, many with large and extensive cracks. Some buildings partially collapsed. Widespread roof tiles detach and chimneys collapse observed.	8
Moglia	MON The Conversione di San Paolo church: roof collapsed Belfry damaged	8
	WBS The old town centre, suffered substantial to heavy damage. The recent development less affected. Few concrete buildings with cracks in partition and infill walls. Substantial to heavy damage in few buildings of class C and in many of class B and A. Few buildings of class B and A with partially collapsed.	7.5
	OTC Widespread substantial to heavy damage, many buildings suffered heavy damage, with partial collapses and extensive cracks. Widespread roof tiles detach, chimneys collapse and some roof failure observed. Part of perimetral walls collapsed.	8
	MON Church partially collapsed. Town hall roof partially collapsed, extensive cracks on the facade.	8

Table 5 (continued)

Locality	Damage reports	I
Novi	WBS The old town centre suffered very heavy damage. The recent development less affected. Few concrete buildings with cracks in partition and infill walls. Substantial to heavy damage in few buildings of class C and in many of class B and A. Partial collapse in few buildings of class B and in many buildings of class A observed.	7.5
	OTC Some buildings suffered very heavy damage with partial collapses. Substantial to heavy damage in many buildings	8
Camposanto	MON Clock tower collapsed	8
	WBS Many buildings suffered moderate damage (cracks in many walls) some buildings with large and extensive cracks. Few building of concrete slightly damaged.	6.5
Mirabello	OTC Widespread chimneys collapse observed. Many buildings suffered moderate damage (cracks in many walls) some buildings with large and extensive cracks.	7
	MON Church partially collapsed (gable and roof). Belfry with large and extensive cracks	8
	WBS Few buildings of class B suffered either moderate damage (cracks in many walls) or substantial to heavy damage. Few buildings of concrete suffered either moderate damage (cracks in many walls) or substantial to heavy damage.	6.5
	OTC Some buildings suffered substantial to heavy damage (large extensive cracks, roof tiles dislocation, chimney collapse)	7
Poggio Renatico	MON Two churches partially collapsed Belfry bent on one side.	8
	WBS Few buildings of class B suffered slight to moderate damage, few concrete buildings slightly damaged.	6
	OTC Very few partial collapses. Some buildings with large and extensive cracks, roof tiles detach, chimneys collapse. Few with slight to moderate damage.	7
	MON Castle collapsed	8

Table 5 (continued)

Locality	Damage reports	I
Reggiolo	Church: roof tiles detach, large and extensive cracks Belfry collapsed Fornisini tower: large and extensive cracks WBS	7
	Many buildings of class A suffered substantial to heavy damage (roof tiles detach, chimneys collapse) few partial collapses observed in old scruffy buildings. Many buildings of class B moderately damaged, few suffered substantial to heavy damage.	
	OTC Widespread moderate damage, many buildings suffered substantial to heavy damage (roof tiles detach, chimneys collapse) few partial collapses observed in old scruffy buildings.	7.5
	MON Small church partially collapsed Castle: large and extensive cracks, some isolated collapse Theatre: cracks on the gable Belfry damaged	7.5
Crevalcore	WBS Few buildings of class A and B suffered substantial to heavy damage, many suffered moderate damage (cracks in many walls). Few concrete buildings moderately damaged.	6.5
	OTC Widespread moderate damage, some buildings suffered substantial to heavy damage (roof tiles detach, chimneys collapse)	7
	MON Theatre: keystone collapsed the facade is in danger of collapse Bologna and Modena Gates are damaged and bent on one side, big decorative elements collapsed. San Silvestro church: gable damaged, partial failure of the roof. Columns of the arcades damaged.	7.5
	WBS The old town centre, suffered substantial to heavy damage. The recent development less affected. Few concrete buildings slightly damaged.	6
San Possidonio	OTC Some buildings suffered substantial to heavy damage, one very heavy damaged. Roof tiles detach observed. Sporadic partial collapse in old scruffy buildings. Moderate damage observed.	7
	MON Church and belfry seriously damaged.	7.5

Table 5 (continued)

Locality	Damage reports	I
Sant'Agostino	WBS Few building of class B suffered light to moderate damage. Few concrete buildings slightly damaged.	6
	OTC Some buildings with large and extensive cracks, roof tiles detach, chimneys collapse. Few with slight to moderate damage.	7
	MON Town hall very heavily damaged with partial structural failure of roof and floors. Church and belfry with large and extensive cracks.	7.5
Bondanello (Moglia)	WBS Many buildings of class B lightly damaged few moderately. Sporadic cases of substantial to heavy damaged buildings of class A and B.	6
	OTC Widespread light damage, some buildings moderately damaged. Sporadic cases of substantial to heavy damaged buildings (roof tiles detach, chimneys collapse observed).	6.5
Carpi	MON The Church is heavily damaged with extensive cracks both on the facade and on the back. The bell tower, in danger of collapsing after the recent aftershocks, has been demolished.	7.5
	WBS Many buildings of class A and B slightly damaged, few moderately damaged.	6
	OTC Widespread light damage, many buildings with hairy like cracks, some moderately damaged. Sporadic cases of substantial to heavy damage in old scruffy buildings with roof tiles detach and chimney collapse.	6.5
Cento	MON Cathedral: facade gable with large and extensive cracks, collapse of some decorative ornaments. The tower of the castle partially collapsed San Francesco church: partial failure of roof and floors.	7.5
	WBS Few buildings of class B moderately damaged. Sporadic light damage in concrete buildings.	6
	OTC Many buildings moderately damaged, fall of large pieces of plaster, sporadic cases of large extensive cracks, some roof tiles detach and chimney failures.	6.5

Table 5 (continued)

Locality	Damage reports	I
Quistello	MON San Lorenzo church partial failure of the roof, cusp failure of the belfry.	7.5
	WBS Excluding sporadic cases partial collapse in old scruffy buildings, few buildings of class B moderately damaged.	6
	OTC Some buildings moderately damaged, roof tiles detach and chimney failures observed. Sporadic partial collapse in old scruffy buildings.	6.5
	Church: apses collapse Town hall and art gallery damaged	7.5
Pieve di Cento	WBS Sporadic moderate damage observed in the old town centre. Recent development not affected.	5
	OTC Sporadic roof tiles detach and cracks on chimneys observed.	5.5
	MON Church: partial failure of the roof Some cracks in the arcades	7.5
Canaletto	WBS Many buildings of class A suffered substantial to heavy damage (roof tiles detach, chimneys collapse) with partial collapses observed in old scruffy buildings. Many buildings of class B moderately damaged, few suffered substantial to heavy damage.	7
	OTC Sporadic buildings suffered heavy damage, with partial collapses and large and extensive cracks. Widespread roof tiles detach, chimneys collapse. Few partial collapses observed in old scruffy buildings.	7.5
	MON Small church with large cracks	7
	WBS Few buildings of class B moderately damaged, few concrete buildings slightly damaged.	6
Poggio Rusco	OTC Sporadic roof tiles and pieces of plaster detachments observed	6.5
	Church with large and extensive cracks in the apses and in the walls Cracks on the belfry	7
	WBS Few buildings of class B suffered light to moderate damage. Few buildings of class A with roof tiles detach and chimney failures.	6

Table 5 (continued)

Locality	Damage reports	I
Rolo	OTC Some buildings with roof tiles detach and chimney failures. Fall of large pieces of plaster observed.	6.5
	MON Church with large and extensive cracks in the facade Castle merlons damaged	7
	WBS Few building of class A and B slightly damaged, few moderately damaged	5.5
Stuffione	OTC Light and scarcely spread damage. Sporadic failure of chimney observed	6
	MON Church facade failure, cracks on the belfry	7
	WBS Excluding light and scarcely spread damage in the old town centre, no damage was reported in recent development.	5
Castello d'Argile	OTC Light and scarcely spread damage. Sporadic failure of chimneys observed	6
	MON The tower of Ronchi Castle collapsed Small church partially collapsed	7
	WBS Excluding few buildings with cracks in plaster in the old town centre, no damage was reported in recent development.	5
	OTC Few buildings with cracks in plaster	5.5
Gonzaga	MON Church: few large cracks and facade detachment, roof damaged	7
	WBS Few buildings of class B suffered light to moderate damage. Sporadic structural damage in the old town centre observed.	5.5
	OTC Few buildings with moderate structural damage. Buildings with cracks in plaster.	6.5
Quingentole	MON Cracks in the arcades Church moderate structural damage	6.5
	WBS Excluding sporadic moderate damage observed in the old town centre, no damage observed in recent development.	5.5
	OTC Sporadic failure of chimneys and roof tiles detach observed, some cracks in plaster.	6

Table 5 (continued)

Locality	Damage reports	I
Castelmasa	MON	6.5
	Church collapse of decorative ornaments	
	WBS	5
	Excluding sporadic light damage observed in the old town centre, no damage observed in recent development.	
	OTC	6
	Sporadic chimney failures, and cracks in buildings	
San Benedetto Po	MON	6.5
	Cotogni theatre with cracks in the arcades	
	WBS	6
	Some cracks in the church and belfry	
	Light damage observed in the old town centre, no damage observed in recent development.	
	OTC	6
	Light and scarcely spread damage.	
Pegognaga	MON	6.5
	Churches, Cathedral and Abbey slightly damaged	
	WBS	5.5
	Few buildings of class B with light to moderate damage	
	OTC	6
	Light and scarcely spread damage.	
	Sporadic failure of chimneys observed	
Nonantola	MON	6
	The theatre facade and town hall with cracks	
	WBS	5
	Excluding very light damage observed in the old town centre, no damage observed in recent development	
	OTC	5.5
	Hairy like cracks in buildings	
San Giovanni in Persiceto	MON	6
	Church slightly damaged	
	WBS	5
	Town hall with hairy like cracks	
	Excluding few lightly damaged buildings of class B, no damage observed in recent development	
	OTC	5.5
	Hairy like cracks in buildings	
Sant'Agata Bolognese	MON	6
	Two churches slightly damaged, one statue collapsed	
	WBS	5.5
	Excluding light and scarcely spread damage in the old town centre no damage observed in recent development	
	OTC	6
	Light and scarcely spread damage.	
	Sporadic failure of chimneys observed.	
	Hairy like cracks in buildings	

Table 5 (continued)

Locality	Damage reports	I
	MON	5.5
	Church closed to the public with preexisting cracks	
	An ancient mill with few cracks	

For each locality, the WBS (whole building stock) row displays the EMS98 concise damage reports (from Tertulliani et al. 2012a): class A indicates very old and poorly maintained masonry buildings; class B indicates maintained masonry buildings (mostly bricks); class C indicates reinforced concrete buildings (Grünthal 1998).

The OTC row is the new set of data that represents the effects of the 2012 Emilia earthquake on old town centers only. The MON row is the new set of data that represents the effects of the 2012 Emilia earthquake on monumental buildings only

References

- Ambraseys NN, Douglas J (2004) Magnitude calibration of north Indian earthquakes. *Geophys J Int* 159:165–206. doi:10.1111/j.1365-246X.2004.02323.x
- Bakun WH, Gómez Capera A, Stucchi M (2011) Epistemic uncertainty in the location and magnitude of earthquakes in Italy from macroseismic data. *Bull Seismol Soc Am* 101(6): 2712–2725. doi:10.1785/0120110118
- Castelli V, Bernardini F, Camassi R, Caracciolo CH, Ercolani E, Postpischl L (2012) Looking for missing earthquake traces in the Ferrara-Modena plain: an update on historical seismicity. *Ann Geophys* 55:4. doi:10.4401/ag-6110
- Cattari S, Degli Abbatì S, Ferretti D, Lagomarsino S, Ottonelli D, Tralli A (2013) Damage assessment of fortresses after the 2012 Emilia earthquake (Italy). *Bull Earthq Eng* doi:10.1007/s10518-013-9520-x
- CPTI Working Group (2004) *Catálogo Parametrico dei Terremoti Italiani, versione 2004 (CPTI04)*, INGV, Bologna. doi:10.6092/INGV.IT-CPTI04 <http://emidius.mi.ingv.it/CPTI04/>. Accessed 13 January 2014
- Gruppo di Lavoro (2004) *Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM 3274 del 20 marzo 2003. Rapporto Conclusivo per il Dipartimento della Protezione Civile*, INGV, Milano-Roma, aprile 2004, 65 pp. appendice.1, in Italian
- Ferrari G, Guidoboni E (2000) Seismic scenarios and assessment of intensity: some criteria for the use of the MCS scale. *Ann Geophys* 43(4):707–720
- Galli P, Castenetto S, Peronace E (2012) The MCS macroseismic survey of the Emilia 2012 earthquakes. *Ann Geophys* 55:4. doi:10.4401/ag-6163
- Gasperini P, Vannucci G, Tripone D, Boschi E (2010) The location and sizing of historical earthquakes using the attenuation of macroseismic intensity with distance.

- Bull Seismol Soc Am 100:2035–2066. doi:[10.1785/0120090330](https://doi.org/10.1785/0120090330)
- Gasperini P, Lolli B, Vannucci G, Boschi E (2012) A comparison of moment magnitude estimates for the European-Mediterranean and Italian regions. *Geophys J Int* 190: 1733–1745. doi:[10.1111/j.1365-246X.2012.05575.x](https://doi.org/10.1111/j.1365-246X.2012.05575.x)
- Grünthal G (ed) (1998) European Macroseismic Scale 1998 (EMS-98). European Seismological Commission, subcommission on Engineering Seismology, working Group Macroseismic Scales. Conseil de l'Europe, Cahiers du Centre Européen de Géodynamique et de Séismologie, 15, Luxembourg
- Guidoboni E, Ferrari G, Mariotti D, Comastri A, Tarabusi G, Valensise G (2007) CFTI4Med, Catalogue of Strong Earthquakes in Italy (461 B.C.-1997) and Mediterranean Area (760 B.C.-1500). INGV-SGA <http://storing.ingv.it/cfti4med/>. Accessed 13 January 2014
- Hough SE (2013) Spatial variability of “Did you feel it” intensity data: insights into sampling biases in historical earthquake intensity distributions. *Bull Seismol Am Soc* 103:2767–2781. doi:[10.1785/0120120285](https://doi.org/10.1785/0120120285)
- Hough SE, Ambruster JG, Seeber L, Hough JF (2000) On the modified Mercalli intensities and magnitudes of the 1811–12 New Madrid earthquakes. *J Geophys Res* 705:23,839–23,864
- Huysken KT, Fujita K (2013) A reevaluation of the intensities of the Northern Illinois earthquake of 1909. *Bull Seismol Am Soc* 103:2810–2823. doi:[10.1785/0120130003](https://doi.org/10.1785/0120130003)
- INGV terremoti <http://ingvterremoti.wordpress.com/2012/07/05/terremoto-in-pianura-padana-aggiornamento-5-luglio/>. Accessed 13 January 2014
- ISIDE Working Group (INGV) (2012) Italian seismological instrumental and parametric database <http://iside.rm.ingv.it>. Accessed 13 Jan 2014
- ISTAT (2001) www.istat.it. Accessed 13 Jan 2014
- Locati M, Camassi R, Stucchi M (eds) (2011) DBMI11, the 2011 version of the Italian Macroseismic Database. Milano, Bologna, <http://emidius.mi.ingv.it/DBMI11>. Accessed 13 Jan 2014
- Maremonti Giovanni Battista (1574) *Visitatio Generalis Apostolica*. In: Marzola M 1976. *Per la storia della chiesa ferrarese nel secolo XVI (1497–1590)*, Torino, vol. 2, in Italian
- Meroni F, Petrini V, Zonno G (2000) Distribuzione nazionale della vulnerabilità media comunale. In: A. Bernardini, (A cura di), *La vulnerabilità degli edifici: valutazione a scala nazionale della Vulnerabilità sismica degli Edifici ordinari*, GNDT-CNR, Roma, Maggio 2000, pp. 105–131+n. 4 mappe allegate e CD-ROM, in Italian
- Modena C, Da Porto F, Bettiol G, Giaretton M (2013) Monumental historical building—preservation of buildings of historic and artistic interest in emergency post-earthquake. *Progettazione Sismica* 03:211–221, in Italian
- Musson RMW (1998) Inference and assumption in historical seismology. *Surv Geophys* 19:189–203
- Pasolini C, Albarello D, Gasperini P, D'Amico V, Lolli B (2008) The attenuation of seismic intensity in Italy, part II: modeling and validation. *Bull Seismol Soc Am* 98(2):692–708. doi:[10.1785/0120070021](https://doi.org/10.1785/0120070021)
- Penna A, Morandi P, Rota M, Manzini CF, da Porto F, Magenes G (2013) Performance of masonry buildings during the Emilia 2012 earthquake. *Bull Earthq Eng*. doi:[10.1007/s10518-013-9496-6](https://doi.org/10.1007/s10518-013-9496-6)
- Rong Y, Mahdyiar M, Shen-Tu B, Shabestari K (2011) Magnitude problems in historical earthquake catalogues and their impact on seismic hazard assessment. *Geophys J Int* 187:1687–1698. doi:[10.1111/j.1365-246X.2011.05226.x](https://doi.org/10.1111/j.1365-246X.2011.05226.x)
- Rovida A, Camassi R, Gasperini P, Stucchi M (eds.) (2011) CPTI11, Parametric catalogue of Italian earthquakes, 2011 version, Milano, Bologna <http://emidius.mi.ingv.it/CPTI>. Accessed 13 Jan 2014
- Sieberg A (1930) *Geologie der Erdbeben*. *Handbuch der Geophysik* 2(4):550–555, in German
- Tertulliani A, Arcoraci L, Berardi M, Bernardini F, Brizuela B, Castellano C, Del Mese S, Ercolani E, Graziani L, Maramai A, Rossi A, Sbarra M, Vecchi M (2012a) The Emilia 2012 sequence: a macroseismic survey. *Ann Geophys* 55(4):679–687. doi:[10.4401/ag-6140](https://doi.org/10.4401/ag-6140)
- Tertulliani A, Cucci L, Rossi A, Castelli V (2012b) The 1762 October 6 earthquake in the Middle Aterno Valley (L'Aquila, Central Italy): new constraints and new insights, *Seism Res Lett* 11, 83, 6:1068–1077