THE 2012 EMILIA (NORTHERN ITALY) EARTHQUAKE SEQUENCE: AN ATTEMPT OF HISTORICAL READING

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**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 (Imax 7-8 EMS98) assessed through macroseismic field surveys seemed inappropriate to describe the whole range of effects observed, especially those to monumental heritage, that 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 earthquakes 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 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.

**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 epicentre 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 epicentres of the main shocks of 20 and 29 May 2012, historical information provided by the current Parametric Catalogue of 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), that 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 fifty 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 (Grüntal, 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 centres, 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 Imax 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 (Gasperini et al. 2010) (tab. 1) are rather lower than the instrumental magnitude Mw 5.9 of the main shock. In particular the macroseismic magnitude computed from the cumulative intensities at the end of the sequence is Mw 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 catalogue (Fig. 2) (Gruppo di Lavoro 2004; Pasolini et al. 2008) which suggests intensity values ranging from 8 to 9 MCS following a Mw 5.9 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:

a) the 2012 Emilia sequence shows lower intensity values because it affected urban contexts more heterogeneous and much less vulnerable than in the past;

b) 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 catalogue with the Switzerland seismic catalogue, 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 catalogue 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 in the past?**

In the course of time urban settlements have undergone several changes and intensities assessments have been tuned to comply with these changes. It is a fact that most of present Italian urban settlements consist of a delimited old town centre, 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.

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.

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 centres

In order to exclude from our analysis 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 centre was 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 centre 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 1. 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 centres only. In our opinion the latter depict 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 IOTC, where OTC means Old Town Centre) and calculated new macroseismic magnitude.

Within this approach the maximum intensity value 8 MCS was assigned to 7 localities and coincides with I0.

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

The IOTC are on average higher than the IWBS. This trend can be highlighted in Figure 6 where frequency of IWBS and IOTC intensities is reported for different intensity classes.

The IWBS distribution is centered on values lower than the IOTC ones. The mean value for the IWBS intensity distribution is 6.1, while the mean value for the IOTC distribution is 6.7.

The epicentral locations are very similar (Fig. 4 and 5). We computed the macroseismic magnitude either from the WBS and OTC datasets, obtaining respectively Mw 5.3 and Mw 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 MOTC (5.7) is considerably higher than the MWBS (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 regressions line (Pasolini et al. 2008; Gruppo di Lavoro 2004) based upon the 2004 version of the Italian parametric earthquake catalogue (CPTI Working Group 2004). In other words, applying the MCS scale to old town centres only, the gap between assessed and expected intensities decreases.

**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). 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 (Tab. 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 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 1), considering exclusively the damage on monumental buildings (hereinafter IMON).

For instance in San Felice sul Panaro, where the IWBS assessed is 7 EMS98, the intensity based on monumental heritage is IMON =9 MCS.

As regards the macroseismic magnitude, the solution inferred from the data (Gasperini et al., 2010) is MMON =6.0.

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

The white and pale grey bars are the same as in Figure 6 while dark grey 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 (dashed black line) for the WBS distribution it has reached 7.3 MCS value for the IMON (dashed dark grey line). 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 epicentre, calculated by Boxer 4.0 code (Gasperini et al. 2012), differs in respect with those calculated for IWBS and IOTC datasets, and moves eastwards 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 catalogue 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 re-read, 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 concrete, when dwellings were characterized by a more homogeneous seismic vulnerability than nowadays, thus restricting the intensity assessment to old town centres. 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 7-8 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 Figure 9 the three different datasets (WBS in white; OTC in pale grey; MON in dark grey), are simultaneously compared through a radial representation. Each radius corresponds to a different locality. It is evident that MON values are most of times higher than the OTC ones, which in turn are larger than WBS values (the complete scheme of evaluation is in Appendix 1). 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 centre 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.

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 centre, 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 (Gasperini et al. 2010) (Tab. 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.

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APPENDIX

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

| **Locality** | **Damage reports** | **I** |
| --- | --- | --- |
| San Felice sul Panaro | WBSThe small old town centre, suffered heavy damage, very small compared to the recent development. 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** |
| OTCThe 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 collapseChurch: total collapse2 Churches: partial collapseClock tower: partial collapseCommemorative stone crackedPillar and capitals collapse | **9** |
| Mirandola | WBSThe 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** |
| OTCWidespread 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 collapseS. Giacomo della Roncole: church partial collapse S. Franchesco d'Assisi church and belbry near total collapseMerlons collapsed. City wall collapse  | **8.5** |
| Finale Emilia | WBSThe 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** |
| OTCWidespread 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** |
| MON Widespread heavy damage on monumental buildingsCastle: partial collapseTower: total collapseTown hall partial collapse of the clock towerCity wall large extensive cracks, partial collapseCathedral: partial collapseMadonna del Rosario church: large and extensive cracks2 Churches partially collapsedChurch: pinnacles collapseChurch capitals collapse and large and extensive cracks2 Belfries: large and extensive cracks Monumental building large and extensive cracksTheatre roof tiles detach, failure of individual non-structural elementsCollapse perimetral pillars. | **8.5** |
| Cavezzo | WBSLarge 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 collapsed a few totally collapsed. | **8** |
| OTCSome 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** |
| MONStructural failure of the roof church and collapse of belfry cusp. | **8** |
| Concordia sulla Secchia | WBSThe 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** |
| OTCWidespread 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** |
| MON The Conversione di San Paolo church: roof collapsedBelfry damaged  | **8** |
| Moglia | WBSThe 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** |
| OTCWidespread 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. Collapse perimetral walls.  | **8** |
| MONChurch partially collapsed. Town hall roof partially collapsed, extensive cracks on the facade.  | **8** |
| Novi | WBSThe 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** |
| MONClock tower collapsed | **8** |
| Camposanto | WBSMany buildings suffered moderate damage (cracks in many walls) some buildings with large and extensive cracks. Few building of concrete slightly damaged.  | **6.5** |
| OTC Widespread chimneys collapse observed. Many buildings suffered moderate damage (cracks in many walls) some buildings with large and extensive cracks. | **7** |
| MONChurch partially collapsed (gable and roof).Belfry with large and extensive cracks | **8** |
| Mirabello | WBSFew 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 craks, roof tiles dislocation, chimney collapse) | **7** |
| MON2 Churches partially collapsedBelfry bent on one side. | **8** |
| Poggio Renatico | WBSFew 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 collapsedChurch: roof tiles detach, large and extensive cracksBelfry collapsedFornisini tower: large and extensive cracks | **8** |
| Reggiolo | WBSMany 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. | **7** |
| OTCWidespread moderate damage, many buildings suffered substantial to heavy damage (roof tiles detach, chimneys collapse) few partial collapses observed in old scruffy buildings. | **7.5** |
| MONSmall church partially collapsedCastle: large and extensive cracks, some isolated collapseTheatre: cracks on the gableBelfry damaged | **7.5** |
| Crevalcore | WBSFew 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** |
| OTCWidespread moderate damage, some buildings suffered substantial to heavy damage (roof tiles detach, chimneys collapse) | **7** |
| MONTheatre: 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** |
| San Possidonio | WBSThe old town centre, suffered substantial to heavy damage. The recent development less affected. Few concrete buildings slightly damaged.  | **6** |
| OTCSome 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** |
| MONChurch and belfry seriously damaged.  | **7.5** |
| Sant'Agostino | WBSFew building of class B suffered light to moderate damage. Few concrete buildings slightly damaged. | **6** |
| OTCSome 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) | WBSMany buildings of class B lightly damaged few moderately. Sporadic cases of substantial to heavy damaged buildings of class A and B. | **6** |
| OTCWidespread light damage, some buildings moderately damaged. Sporadic cases of substantial to heavy damaged buildings (roof tiles detach, chimneys collapse observed). | **6.5** |
| MONThe 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** |
| Carpi | WBSMany buildings of class A and B slightly damaged, few moderately damaged. | **6** |
| OTCWidespread 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** |
| MONCathedral: 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** |
| Cento | WBSFew buildings of class B moderately damaged. Sporadic light damage in concrete buildings. | **6** |
| OTCMany buildings moderately damaged, fall of large pieces of plaster, sporadic cases of large extensive cracks, some roof tiles detach and chimey failures. | **6.5** |
| MON San Lorenzo church partial failure of the roof, cusp failure of the belfry.  | **7.5** |
| Quistello | WBSExcluding sporadic cases partial collapse in old scruffy buildings, few buildings of class B moderately damaged.  | **6** |
| OTCSome 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 | WBSSporadic moderate damage observed in the old town centre.  | **5** |
| OTCSporadic roof tiles detach and cracks on chimeys observed. Recent development not affected. | **5.5** |
| MONChurch: partial failure of the roof Some cracks in the arcades. | **7.5** |
| Canaletto | WBSMany 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** |
| OTCSporadic 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** |
| MONSmall church with large cracks. | **7** |
| Poggio Rusco | WBSFew buildings of class B moderately damaged, few concrete buildings slightly damaged. | **6** |
| OTCSporadic roof tiles and pieces of plaster detachments observed | **6.5** |
| Church with large and extensive cracks in the apses and on the walls.Cracks on the belfry | **7** |
| Villarotta | WBSFew buildings of class B suffered light to moderate damage. Few buildings of class A with roof tiles detach and chimney failures. | **6** |
| OTC Some buildings with roof tiles detach and chimney failures. Fall of large pieces of plaster observed. | **6.5** |
| MONChurch with large and extensive cracks on the facade. Castle merlons damaged | **7** |
| Rolo | WBSFew building of class A and B slightly damaged, few moderately damaged. | **5.5** |
| OTC Light and scarcely spread damage. Sporadic failure of chimney observed | **6** |
| MONChurch facade failure, cracks on the belfry | **7** |
| Stuffione | WBSExcluding light and scarcely spread damage in the old town centre, no damage was reported in recent development. | **5** |
| OTC Light and scarcely spread damage. Sporadic failure of chimney observed | **6** |
| MONThe tower of Ronchi Castle collapsed.Small church partially collapsed  | **7** |
| Castello d'Argile | WBSExcluding few buildings with cracks on plaster in the old town centre, no damage was reported in recent development. | **5** |
| OTCFew buildings with cracks on plaster | **5.5** |
| MONChurch few large cracks and facade detachment, roof damaged. | **7** |
| Gonzaga | WBSFew buildings of class B suffered light to moderate damage. Sporadic structural damage in the old town centre observed.  | **5.5** |
| OTCFew buildings with moderate structural damage. Buildings with cracks on plaster.  | **6.5** |
| MONCracks on the arcades. Church moderate structural damage  | **6.5** |
| Quingentole | WBSExcluding sporadic moderate damage observed in the old town centre, no damage observed in recent development. | **5.5** |
| OTCSporadic failure of chimney and roof tiles detach observed, some cracks on plaster. | **6** |
| MONChurch collapse of decorative ornaments  | **6.5** |
| Castelmassa | WBSExcluding sporadic light damage observed in the old town centre, no damage observed in recent development. | **5** |
| OTCSporadic chimney failure, and cracks on buildings | **6** |
| MONCotogni theatre with cracks on the arcadesSome cracks on the church and belfry | **6.5** |
| San Benedetto Po | WBSLight damage observed in the old town centre, no damage observed in recent development.  | **6** |
| OTC Light and scarcely spread damage.  | **6** |
| MON Churches, Cathedral and Abbey slightly damaged  | **6.5** |
| Pegognaga | WBSFew buildings of class B with light to moderate damage | **5.5** |
| OTC Light and scarcely spread damage. Sporadic failure of chimney observed | **6** |
| MONThe theatre facade and town hall with cracks | **6** |
| Nonantola | WBSExcluding very light damage observed in the old town centre, no damage observed in recent development | **5** |
| OTC Hairy like cracks in buildings | **5.5** |
| MONChurch slightly damaged. Town hall with hairy like cracks | **6** |
| San Giovanni in Persiceto | WBSExcluding few buildings of class B lightly damaged no damage observed in recent development | **5** |
| OTC Hairy like cracks in buildings | **5.5** |
| MON 2 Churches slightly damaged, one statue collapsed | **6** |
| Sant'Agata Bolognese | WBSExcluding light and scarcely spread damage in the old town centre no damage observed in recent development | **5.5** |
| OTC Light and scarcely spread damage. Sporadic failure of chimney observed. Hairy like cracks in buildings | **6** |
| MON Church closed to the public with preexisting cracks.An ancient mill with few cracks  | **5.5** |

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

**FIGURES CAPTIONS**

**Fig. 1** Map showing the Emilia earthquake sequence (epicentres 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); grey stars: Mw≥5.0 aftershocks; squares: 4.0≤Mw<5.0 aftershocks; large dots: 3.0≤Mw<4.0 aftershocks; small dots: Mw<3.0 aftershocks (modified after - INGV terremoti)

**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

**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.

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

**Fig.5** Cumulative intensity distribution for the old town centres (IOTC MCS). The black star represents the macroseismic epicentre computed by Boxer 4.0 code (Gasperini et al. 2010)

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

**Fig. 7** Frequency of IWBS , IOTC and IMON intensities for different intensity classes; dashed lines represent the mean value for each distribution (black for WBS [whole building stock], pale gray for OTC [old town centres], dark grey for MON [monumental buildings])

**Fig.8** Cumulative intensity (IMON) distribution. The black star represents the macroseismic epicentre computed by Boxer 4.0 code (Gasperini et al. 2010)

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

**TABLES**

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).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | Mw (instr.) | I EMS | Mw EMS\* | I MCS | Mw MCS\* |
| 20/5/2012 | 5.9 | 7 | 5.1 | 7 | 5.1 |
| cumulative | - | 7-8 | 5.3 | 7 | 5.1 |

\* macroseismic magnitudes are computed by Boxer 4.0 (Gasperini et al., 2010)

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 Codifiume, 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 ” (*Marzola, 1976) | Oratory of S. Antonio. Damage to the walls and to the roof. | 6 |
| Santa Maria Codifiume (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” (*Marzola, 1976) | 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 |

Table 4

Macroseismic magnitudes calculated from WBS, OTC and MON intensity data

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Imax | I0 | Epicentral coord (Lat - Lon) | Mw\* |
| IWBS EMS | 8 | 7.5 | 44.866 - 11.017 | 5.3 |
| IOTC MCS | 8 | 8 | 44.875 - 11.027 | 5.7 |
| IMON MCS | 9 | 8.5 | 44.847 - 11.148 | 6.0 |

\* Macroseismic magnitudes are computed by Boxer 4.0 (Gasperini et al., 2010). The instrumental magnitude Mw of the main shock of Emilia 2012 earthquake was 5.9 (ISIDe, 2012).