# ASSESSMENT OF THE MOST DAMAGED HISTORIC CENTRES OF THE REGION EMILIA ROMAGNA DUE TO THE EARTHQUAKE OF THE 20th AND 29th OF MAY 2012

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*SUMMARY – The Emilia Romagna earthquake of the 20th of May 2012 has damaged some of the historic centres closer to the epicentre of this event. Aftershocks and a second earthquake on the 29th of May 2012 registered in the same region have caused around 30 dead people, 350 of injured people and several damage types to historic assets. In this paper the typical features of the residential constructions in the areas damaged by these earthquakes are introduced and the seismic vulnerability of the Comune of Cento is carried out by using the FaMIVE approach. The same area has also been surveyed by the Italian Civil Protection to assess the safety of the buildings with the aid of AeDES form. The damage scenario observed on site, the safety judgements conducted by AeDES and the forecasted vulnerability obtained by FaMIVE will be illustrated for some building clusters selected in the Comune of Centro.*

*Key words: Emilia Romagna, historic centres, damage scenarios; assessment; seismic vulnerability*

## 1. **Introduction**

On the 20th of May 2012 an earthquake with a magnitude of 5.9 Mw has hit the region of the Emilia Romagna in the North of Italy, causing 7 deaths and significant damage to churches, bell towers and factories. The epicentre was between Finale Emilia and S. Felice sul Panaro (44.800°N 11.192°E), about 36 kilometres north of the city of Bologna. Several aftershocks with a magnitude smaller than 5 Mw occurred in the same area and nine days late the main seismic event another earthquake with a magnitude 5.8 Mw was registered.
The event of the 29th May with the epicentre in Medolla (44.850°N, 11.090°E) at a depth of about 10 kilometres has increased the severity of the damage in the historic and industrial structures and caused other 18 deaths.
In order to assess the seismic damage in the region of Emilia Romagna an inspection campaign has been carried out from the 2nd of June to the 8th of June 2012. The aim of this mission was to identify the most representative features and types of damage of the masonry historic buildings in the areas hit by the earthquakes. For this reason from the 2nd to the 4th of June several historic village and town centres in the region of Emilia Romagna have been surveyed to record the typical construction typology of the region and to document the damage. In the latter part of the mission, from the 5th to the 8th June a more detailed seismic vulnerability assessment was carried out with the support of the Civil Protection in the historic centre of Cento.
In this paper first a description of the typical masonry typology of the region and their damage pattern are described in details. In order to better understand the typical constructions of the Emilia region, several historic centres damaged by the earthquake of the 20$^{th}$ and 29$^{th}$ of May 2012 have been visited from the 2$^{nd}$ to the 4$^{th}$ of June 2012. On the basis of the considerations on the observed features and failure modes introduced in the next sections Cento was then classified as one of the most representative historic centres which has been

surveyed during the campaign. Then the results of the seismic vulnerability assessment of 30 buildings in the historic centre of Cento (FE) performed with the FaMIVE method (D'Ayala & Speranza, 2003, D'Ayala 2005, D'Ayala & Paganoni, 2011) are presented and discussed. Finally the results obtained in terms of failures and damage has been compared with the inventories performed with AeDES survey by the Civil Italian Protection.

## 2. **Inspection Campaign**

The historic centres visited during the campaign are the following: Casumaro, Cento, Finale Emilia, Crevalcore, Camposanto, Rivara, San Felice sul Panaro, Mirandola, Cavezzo, Medolla, and Sant'Agostino, mapped in Figure 1.

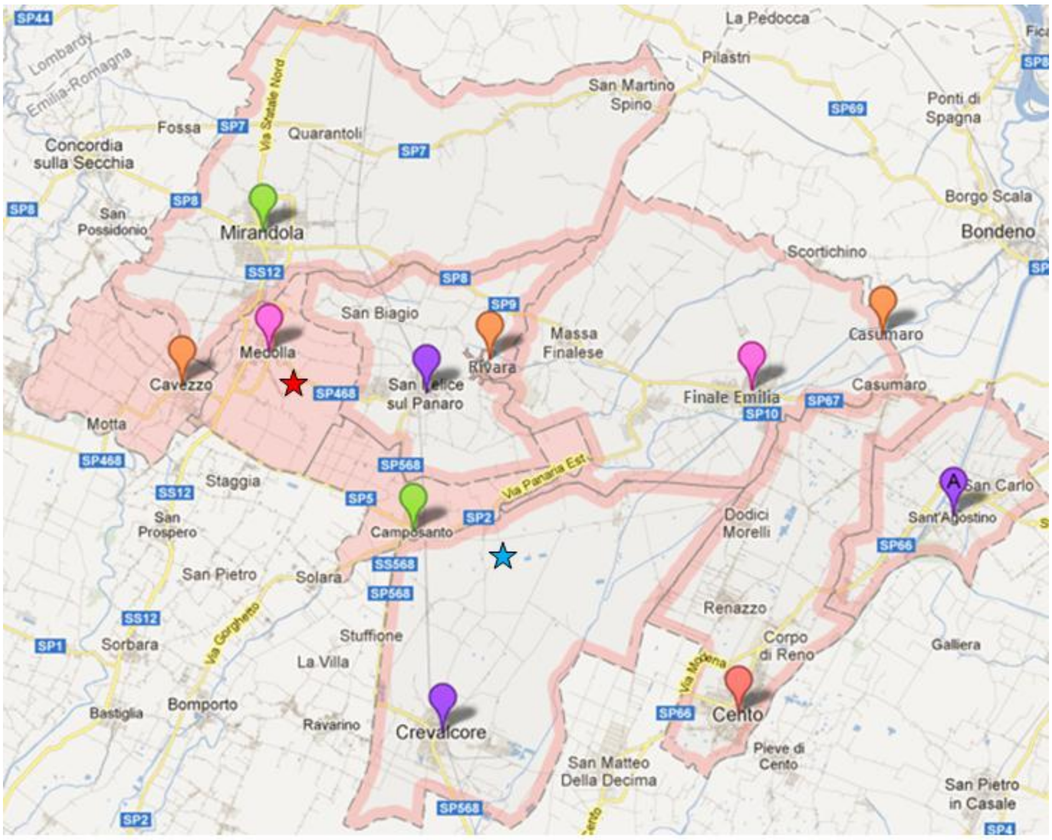



Figure 1: *Mapping of the historic centers visited from the 2nd to 8th June 2012, the blue and red stars point out the epicenter of the first and the second earthquake respectively.*

The initial damage survey was carried out mainly from the street, apart from some buildings which have been entered and inspected, thanks to the support from the Italian Civil Protection.

The towns of Sant Agostino, Finale Emilia, Rivara and San Felice sul Panaro were particularly damaged by the both seismic events. As for the towns of Mirandola, Cavezzo, Medolla and Camposanto located close to the epicentre of the second event, the severity of the damage has increased with the earthquake of the 29th of May. Finally, towns located further away from both the epicentres such as Crevalcore, Cento were also visited in order to compose an informed picture of the damage and disruption caused by the two events which shook Emilia-Romagna, see Figure 2.

The maps of ground shaking for the event of 20th and 29th May, produced by INGV (Istituto

Nazinale di Geofisica e Vulcanologia), [Ref: http://shakemap.rm.ingv.it/shake/7223048150/pga.html], are shown in Figure 3 and Figure 4 with the iso-lines of peak ground acceleration (%g).

| Inspected town | **a)** Distance (km) of the inspected town from the epicenters of the earthquake on the 20th of May 2012 (5.9 Mw) | **b)** Distance (km) of the inspected town from the epicenters of the earthquake on the 29th of May 2012 (5.8 Mw) | **c)** $a_{refg}$ (10% probability of exceedance in 50 years) |
|---|---|---|---|
| Casumaro | 18 | 26 | 0.157 |
| Cento | 18 | 28 | 0.157 |
| Finale Emilia | 15 | 20 | 0.149 |
| Crevalcore | 13 | 20 | 0.157 |
| Camposanto | 12 | 11 | 0.155 |
| Rivara | 17 | 8 | 0.150 |
| San Felice sul Panaro | 18 | 6 | 0.150 |
| Mirandola | 25 | 7 | 0.141 |
| Cavezzo | 18 | 7 | 0.150 |
| Medolla | 21 | 2 | 0.150 |
| Sant'Agostino | 21 | 30 | 0.153 |

Figure 2: *For the inspected towns in a) and b) their distance from the epicenters of the earthquake on the 20th and 29th of May 2012 respectively and in c) their peak ground acceleration $a_{refg}$ (10% probability of exceedance in 50 years), [Ref: www.regione.emilia-romagna.it/geologia/sismica].*

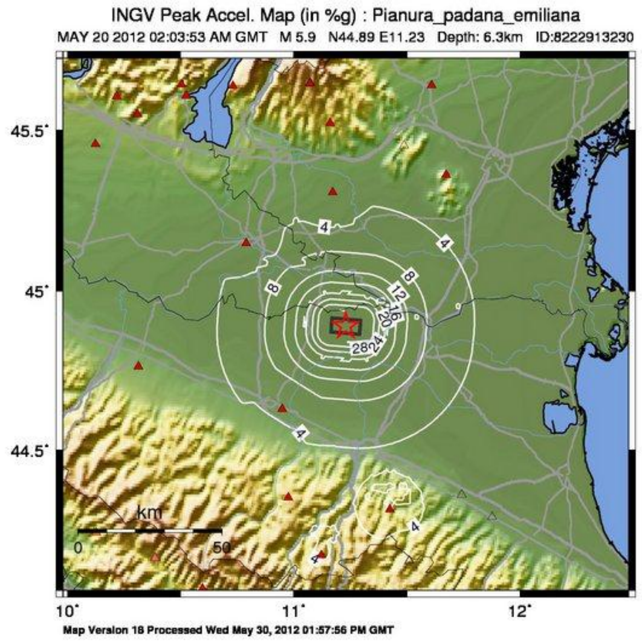



Figure 3: *The map of ground shaking for the event of May 20th event (INGV, 2012c).*

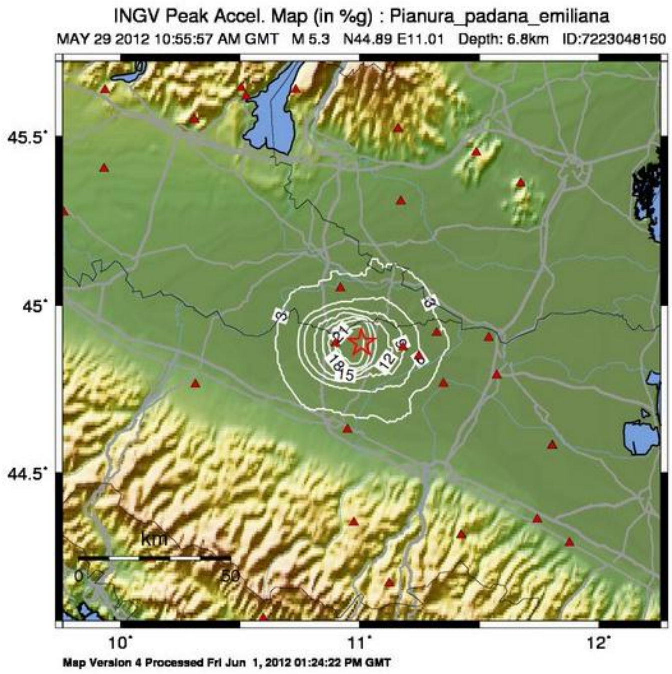



Figure 4: *The map of ground shaking for the event of May 29th event (INGV, 2012c).*

*2.1. Typical features of the residential constructions of the North of Italy*

The mentioned historic centres include a large variety of buildings, varying in height from one (older) to five floors (in this case the buildings are usually refurbished). Typically, the observed buildings are organised in aggregates, distributed linearly along the main streets of the city centre. Within a single aggregate there might be substantial difference in age of the buildings, as it is recognisable from the fact that in some cases façades even though they belong to different buildings, have same opening layouts and same height, while in other

cases there is substantial difference in opening sizes and overall height, with the taller ones and with larger size openings being the most recent.
In a small number of cases, reinforced concrete frame buildings are also present in adjacency to masonry houses. This layout has direct implications on the seismic behaviour of single buildings within clusters, and leaves some of them at severe risk of pounding, as observed on site, see Figure 5.
The surveyed buildings tend to have larger dimension than residential constructions and to be isolated or arranged in a building cluster with small number of buildings.

Figure 5: *Pounding effect due to different heights of buildings in the historic center of Cento.*

In the areas surrounding the surveyed historic centres, it has been observed that most of the buildings are isolated and they are characterised by regular configuration in plan and in elevation. The typical alterations carried out on these constructions, usually are related to the modifications of the original opening layout, extension of the original plan and addition of a storey above the original level, see Figure 5.
Moreover, it has been observed that some of these houses are vacant and others are completely abandoned to their decay, the lack of maintenance and low quality of their original masonry fabric, contributing significantly to their poor structural response to the seismic events; see Figure 6 and Figure 7.


a)

b)

Figure 6: *a) Modification of the original opening layout in the isolated house in the neighborhood of Casumaro (Fe) b) Alteration of the original plan of the isolated house between S. Felice sul Panaro and Rivara.*


a)

b)

Figure 7: *a) Isolated houses between S. Felice sul Panaro and Rivara and b) Isolated house in the neighbourhood of Casumaro characterised by low quality of materials and mortar.*

As for the constructions in the inspected city centres, they have usually commercial activities at the ground floor and residential dwellings at the upper floors. The bearing walls are connected to orthogonal walls and the original alignments are often preserved. The typical alterations of these buildings, observed on site, are the replacement of the original horizontal structures with reinforced concrete slab.

Masonry fabric typologies most frequently observed in the historic centres were brick with regular courses, see
Figure *8*.
The walls usually appear to be very slender, and they are usually double bonds masonry wall. Mortar is typically in lime. Large squared stones are used for quoins both in common buildings and mansions, which improve the structural behaviour of the constructions.
In general, in the historic centres it has been surveyed a good quality of the masonry fabric and high level of maintenance of the buildings. However the slenderness of the façades which characterised most of the historic buildings, inspected on site, has been considered the major cause of several in plane and out plane mechanisms, see Figure 9.

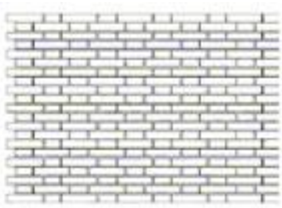
| On-site survey | CNR-GNDT | Annex 2-OPCM3274 | |
|---|---|---|---|
| | | $f_m$ (N/mm2) min-max | $t_m$ (N/mm2) min-max |
|  | Brickwork  | 18.0-28.0 | 0.6-0.92 |

Figure 8: *Mechanical properties of the surveyed typologies of masonry as referred by Italian seismic guidelines and codes. $f_m$ indicates the range of compressive strength, $t_m$ indicates the range of characteristic shear strength.*

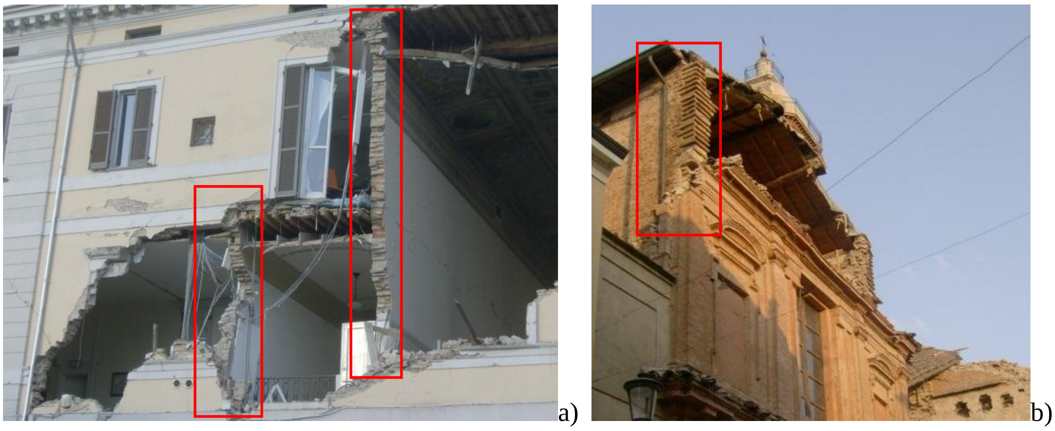



*Figure 9: a) In plane failure of the City Hall in Sant'Agostino b) Out of plane of the building in Curtatone street close to the Cathedral in Mirandola*

Figure 10*: Timber floor and timber roofs inspected in a typical buildings in Emilia Romagna region.*

The original horizontal structures include both masonry vaults and timber floors and roofs; see Figure 10, replaced in recently retrofitted buildings by reinforced concrete. Masonry vaults are usually present at the ground floor and they are often supported by porticoes, see Figure 11.

Figure 11: *Masonry vaults supported by porticoes observed on the ground floor of the buildings.*

The presence of porticoes at the ground floor, see Figure 12, where shops and building's entrances are located, is the most representative feature of the constructions in t this region. Indeed this element of discontinuity of the façades is also common to many other provinces and region of Northern Italy, as it had been already identified in a vulnerability study of Serravalle and Vittorio Veneto in the Veneto region (Bernardini et.al, 2008).
As many other historic centres in seismic prone areas, cross ties are a common feature, and they are inserted into the masonry, just below the floor level or above the openings, with metallic elements resting on the surface of the façades to improve the connections between orthogonal walls and between walls and horizontal structures, see Figure 13. As for the trust generated by the vaults of the porticoes, this is also usually taken care of by the introduction of anchors, longitudinally and transversally which contribute to restrain the façades against out-of plane leaning or rocking, see Figure 14.

a) b)

Figure 12: *Porticoes in a) Malagodi street and in b) Provenzali street in the historic centre of Cento.*

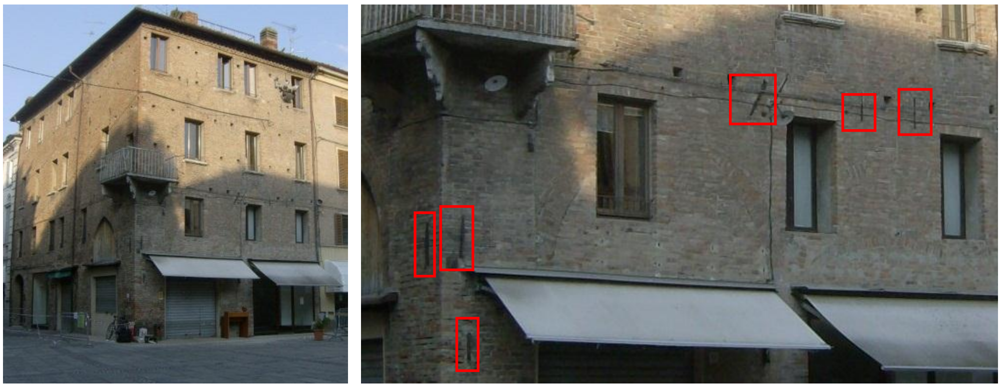


Figure 13: *Metallic elements on the façades of the buildings on the corner between Costituente square and Volturno street in Mirandola*


a)

b)

Figure 14*: a) Metallic elements and anchors in the arches of the façades of the building on the corner between Costituente Square and Felice Cavallotti street in Mirandola b) Anchors in the arches of the façade in Cesare Battisti street in Mirandola.*

*2.2. Seismic damage and failure modes assessment*

The seismic damage assessment has been carried out on site by establishing a correlation between constructions details and damage types from visual inspections of a larger number of buildings. Both parameters related to the observed behaviour have been inspected, as mentioned in the previous section, from the street, for reasons linked to safety and security concern.

The types of damage observed in the several areas of Emilia Romagna region has pointed out that the partial or total overturning of the façade; see Figure 15; is usually caused by the following issues:

- poor quality of the connections between the entire walls or part of them
- poor quality of the masonry fabric and mortar
- lack of connection between horizontal structures and bearing walls lack of maintenance of masonry

Figure 15*: Examples of out of plane in the historic center of Mirandola.*

Differently from what usually considered in unreinforced masonry walls with regular opening, the occurrence of a recurring pattern of diagonal X shaped cracks in the spandrels or in the piers is not the only most common in plane failure. Indeed, the horizontal structures being not rigid in their plane, since they are in timber or masonry vaults, the redistribution among the piers of the lateral actions depend on their connections with internal walls and position of their timber beams or on the groin of the vaults (Casapulla & D’Ayala, 2006 and

Novelli & D'Ayala, 2012).
This involves that some piers being more vulnerable than others might be failing in a combination of bending and shear, rather than just shear; see Figure 16.
As for those restrained buildings, the constraining action is active when ties are regularly spaced over the façade, and correctly anchored and connected through to the orthogonal walls or to the floor structures. In case the ties are not properly anchored and the unstrained length of the façade is considerable respect to its thickness, it has been observed that a central trapezoidal portion of this façade, under the effect of the seismic action, tends to shift outwards, see Figure 17.

a) b) c) d)

Figure 16*: Examples of in plane mechanism in a) and b) historic center of Mirandola and in c) city hall of Sant'Agostino. d) Sketch related to the identified mechanism (D'Ayala and Speranza, 2003).*

a) b) c) d)

Figure 17*: Examples of Out of plane of the top level in a) and b) Mirandola, c) Rivara and in d) sketch related to the identified mechanism (D'Ayala and Speranza, 2003).*

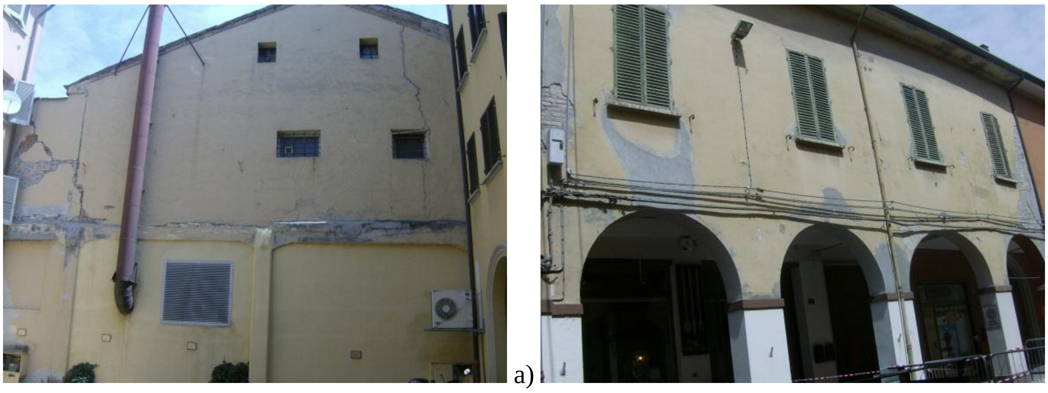
In some buildings, for which more detailed inspection has been carried out, it has been observed that timber plates are often used in order to prevent the façade from moving out from the top floor. However, it has been noted that the presence of this element might cause out of plane of the top level in cases the timber plate is not well connected and continuous along the top of the wall (see Figure 18)
Quoins have also been identified in several historic buildings, see Figure 19. These restraining elements are effective to guarantee box behaviour of the building. However the efficiency of these elements is limited when coupled with poor masonry fabric or internally unconnected masonry. It should also be noted that in some cases the quoins might be only

veneers inserted in the architectural rather than structural purposes.
In some cases, in particular for those buildings with commercial activities at the ground floor the damage is concentrated from the second level, since the ground floors are often refurnished with a new structure, usually made in RC frames, see Figure 20.

a) b)

Figure 18: *a) Typical timber plate found at roof level in the historic center of Cento and b) out of plane of the related façade due to the discontinuity of the timber plate.*

Figure 19: *Typical quoins on both edges of the façades. The building on the corner between Guglielmo Marconi street and Costa street in Crevalcore suffers of shears on the spandrels.*



a) b)

Figure 20: *a) South west and b) north west façades of the building in Malagodi street n.8 in the center of Cento.*

In summary, within the inspected historic city centres, the number of the total collapses is minor, while the number of proportions or partial collapses of upper storeys is perhaps greater than would been expected. In a minority of cases total collapsed of the façades has been observed, and these are usually associated to buildings having specific vulnerabilities, mainly due to

- Intrinsic weaknesses of the materials;
- Inappropriate restraining or repairing interventions;
- Lack of maintenance of the restraining elements such as anchors and timber plates present in the existed building;
- Substitution of the original slabs with heavier horizontal structures.

Although the number of undamaged masonry buildings is very modest, the majority suffer either minor damage or structural repairable damage.

## 3. Seismic vulnerability of the historic centre of Cento

A more accurate assessment of the damage has been carried out in the historic centre of Cento in the province of Ferrara, since this town has a high concentration of construction typologies representative of this region. This historic centre was mainly damaged by the second event on the 29$^{th}$ May 2012, indeed several streets, in particularly the areas around to the Estense castle, were cordoned off for the safety of the habitants.
The surveys have been performed to collect the data required by the vulnerability model FaMIVE (D'Ayala & Speranza, 2003, D'Ayala 2005, D'Ayala & Paganoni, 2011) for the evaluation of the failure modes of approximately 30 buildings in the cluster mapped in Figure 21. The same buildings were also surveyed by the Italian Civil Protection for access clearing by using AeDES form (D.P.C.M. 23 February 2006 (G.U. 7.3.2006, n. 55 and O.P.C.M n. 3753, Gazzetta Ufficiale, 7th April 2009, n. 81, (2) in Italian).


Figure 21*: Historic centre of Cento and mapping of the inspected buildings.*

The distribution of collapse load factors (λ), calculated for the selected buildings is shown in Figure 22 with a median value of 0.32g and standard deviation of 0.11g. This result is obtained assuming that connections of the façades with the side walls are good, as per the observation on site. The median value of maximum lateral capacity of the sample can be compared with the $a_{refg}$ (10% probability of exceedance in 50 years) for the Comune di Cento provided by http://www.isesd.cv.ic.ac.uk/ESD/ for the seismic assessment of structure in third level analyses. The peak ground acceleration for the Comune of Cento, classified in zone III in the OPCM n. 3274 / 2003, is 0.157g, with a maximum elastic spectral amplification of 2.7 for a period of T=.2 sec.; such values justify the good response of the buildings observed on site. Such performance is also confirmed by the results of the survey for the occupant safety carried out by the Italian Civil Protection using the AeDES form, according to which only few buildings fall in the category of partially or totally unfit for use.

Figure 23 shows that in-plane failure is the most common for the inspected buildings, with 67% of façades failing for in plane mechanism, 16% for soft storey, 13% for out of plane and 3% for combined mechanism, in which both the façade and the side wall participate in the overturning.

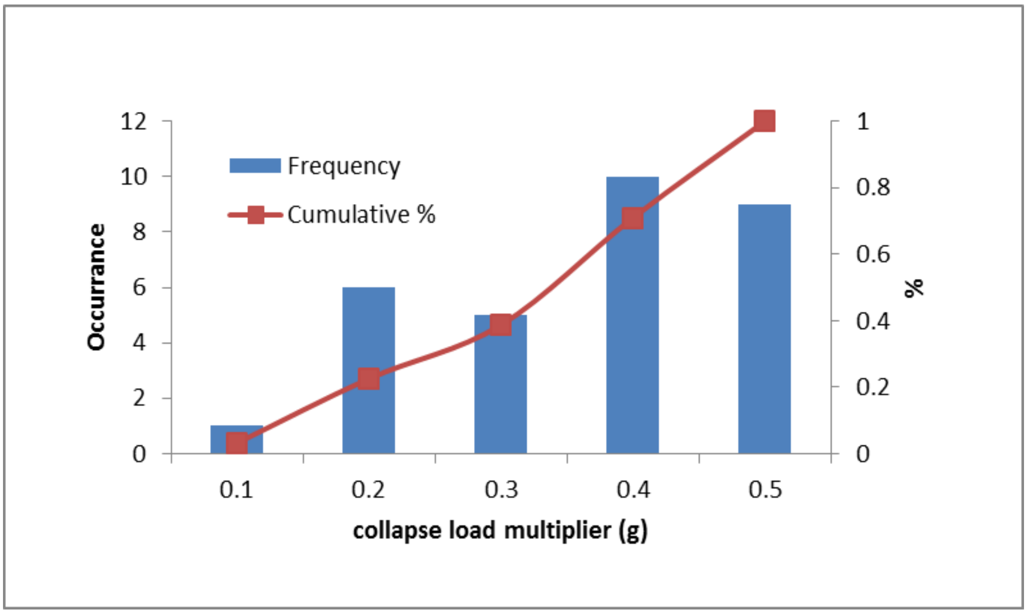



*Figure 22: Collapse load factors multiplier (g) distribution calculated on the selected historic buildings of Cento.*

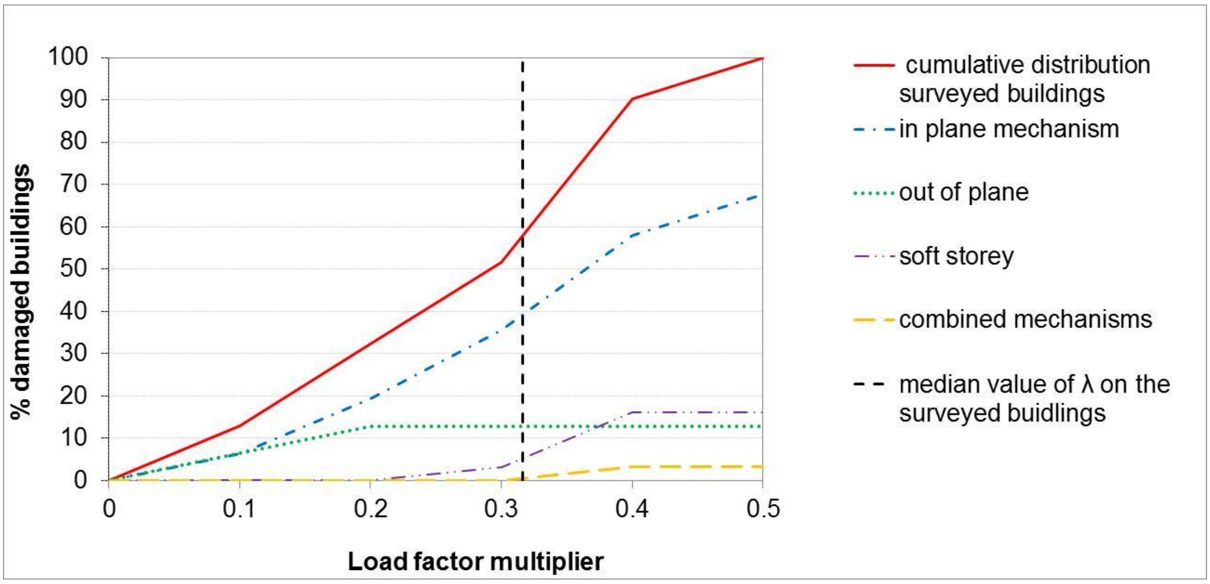



Figure 23*: Load factor multiplier (λ) distribution in the surveyed sample in the historic centre of Cento.*

Overturning of the entire façade due to lack of connections between orthogonal walls is unlikely to occur, as it was observed on site, see Figure 17. Indeed the only out-of-plane failures identified by FaMIVE as critical mechanisms, involve only modest portion of the upper part of the façade (mechanism G).

The presence of anchors in the porticoes reduces the vulnerability of the façades to the soft

storey; indeed only when the porticoes are not restrained or the restraining elements are not properly anchored the value of λ for this collapse mechanism decreases and becomes comparable with the lateral capacity of the structure for other in plane mechanisms.
Since FaMIVE is a limit state approach which calculates the structural performance of a building in case of failure, while AeDES is an assessment method, which identifies the safety of a building on the basis of the post-earthquake surveys, the comparison between the two methodologies has been carried out by correlating AeDES classification on the surveyed buildings with the vulnerability levels identified by FaMIVE, as it is illustrated in Figure 24. This comparison points out that 80% of the buildings classified as "A" in AeDES are not particularly vulnerable to seismic events according to FaMIVE which assigns a medium vulnerability to these buildings. As for the buildings classified as B and C, classes which identify a partial safety of the buildings, FaMIVE assigns to those a high vulnerability.
Moreover it has been observed that the few inspected buildings classified as unsafe by AeDES, class E, are not particularly vulnerable for FaMIVE. This incongruence is justified since those buildings considered unsafe by AeDES were already unfit for use before the earthquake.

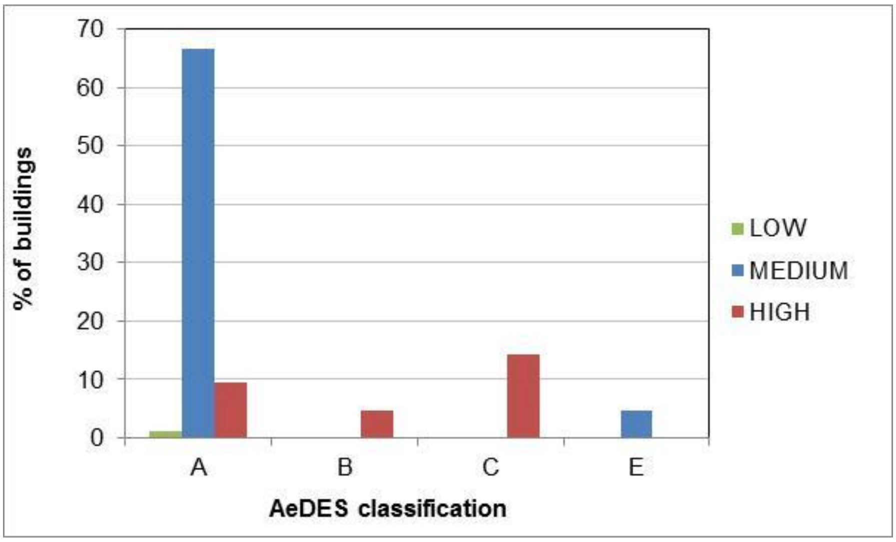
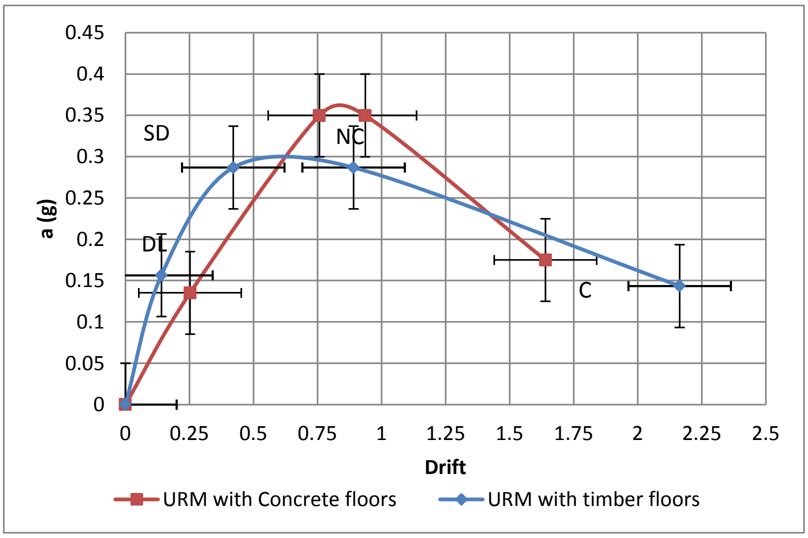


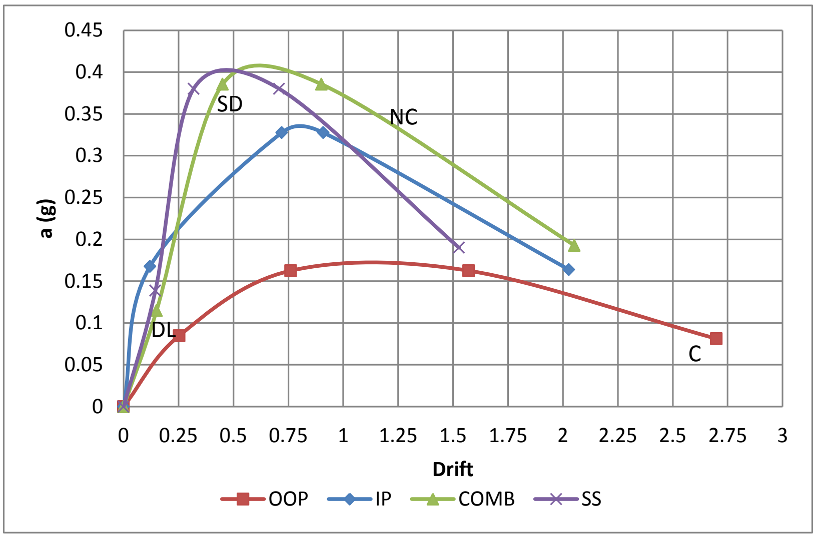

Figure 24: *Comparison between the damage scenario classified by AeDES and the vulnerability level obtained by FaMIVE of the historic centre of Cento.*

Figure 24 shows that the classification provided by Civil Protection results in only 4% of the inspected buildings in class E: unfit for use, and 13% in class C: partially unfit for use, while 13% is classified as B: temporary not safe or safe if repairing interventions are carried out and 70% as A: safe.
The FaMIVE procedure also produces output in terms of capacity curves. Given the way in which the data are collected and the fact that the analysis is based on limit state analysis approach, such capacity curves are particularly useful if considered as representative average behaviour of a class or subclass of buildings with an associated standard deviation, defining the aleatoric uncertainty, within the sample analysed.
The capacity curves are shown in Figure 25 for the two major groups of construction typologies identified: unreinforced fired brick masonry with timber floors and roof, and unreinforced fired brick masonry with concrete floor slabs and roof. Figure 25a shows that on average the buildings with concrete slab floors have greater lateral capacity but reduced ultimate ductility and most importantly a relatively brittle behaviour, when compared with the less strong but more ductile timber floor structures. Figure 25b shows the average

capacity curve with the indication of the limit state representative points for class of failure mechanism, out-of-plane (OOP), in-plane (IP), combined (COM) and soft-storey (SS). The out of plane mechanism are in this case, as stated before, local mechanisms of upper spandrel overturning, concentrated at the top floor level, and usually triggered by low level of lateral acceleration. However as they involve a modest portion of the façade they are considered in the class of low vulnerability. The soft-storey curve has a capacity higher than the in-plane one, but brittle, while the combined mechanism has higher capacity and similar ductility to the in-plane mechanism.



a)



b)

Figure 25*: a) Capacity curves for buildings with unreinforced fired brick masonry with timber floors and roof and b) Capacity curves for buildings with and unreinforced fired brick masonry with concrete floor slabs and roof.*

Finally in Figure 26 the performance points for the limit state of structural damage, associated to the life safety condition in EC8 is compared with the 475 years return period acceleration displacement elastic response spectrum, with the peak ground acceleration $a_{ref}$ (10% occurrence of exceedence in 50 year), provided by http://www.isesd.cv.ic.ac.uk/ESD/.
The nonlinear spectrum for a ductility value of 2 is also provided for reference. This is calculated using the N2 method approach (Fajfar et al. 2000), recommended by Eurocode 8 part 3for assessment of seismic performance of existing buildings. It can be seen that most

representative points are located above and on the right hand side of both curves and only a minority is below the red curve, indicating that the performance of these buildings will be worse than just structural damage. It should also be noted that the $a_{ref}$ for 475years is greater than the value indicated for Cento on the shaking map of Figure 3 and Figure 4. This analysis confirms the relatively low level of damage and good performance identified by the on-site survey and the FaMIVE analysis.

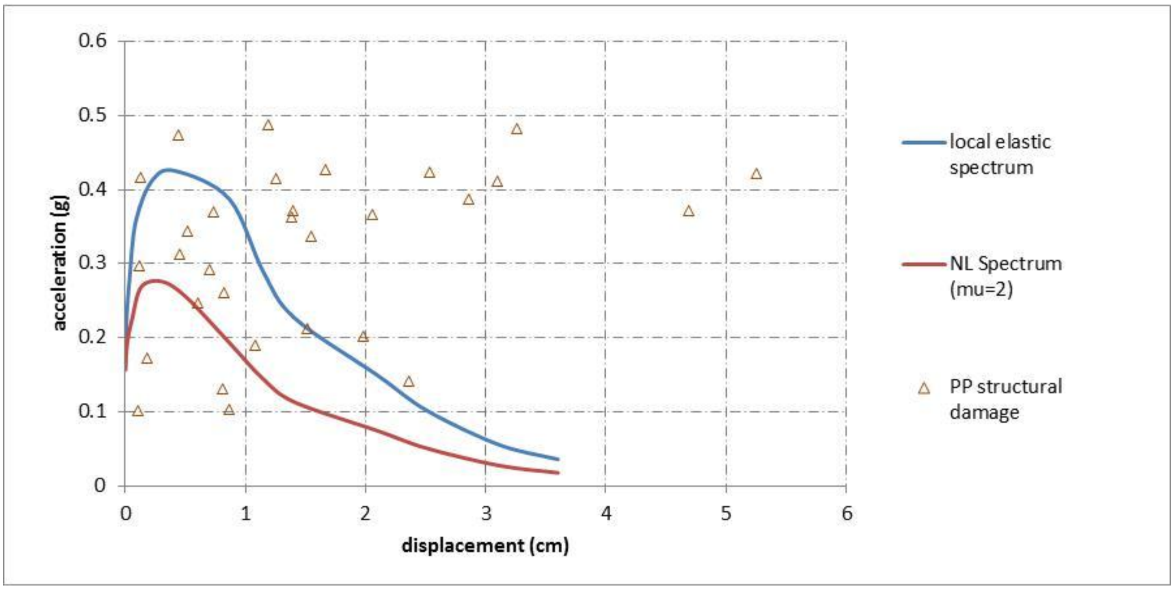



Figure 26: *Comparison between the performance points for the limit state of structural damage, , associated to the life safety condition in EC8 and the 475 years return period acceleration displacement elastic response spectrum, with the peak ground acceleration aref (10% occurrence of exceedence in 50 year), provided by http://www.isesd.cv.ic.ac.uk/ESD/.*

## 4. **Conclusion**

In the present work the typical constructions of the Emilia Pianura Padana, observed during damage assessment of the historic centres hit by the earthquake of the 20th and 29th May 2012 in Emilia Romagna region, were described.

Since the historic centre of Cento, in the province of Ferrara has been classified as one of the most representative towns among the visited locations hit by the earthquakes a more detail data collection for a group of buildings in the historic centre has been carried using two methods:

- FaMIVE methodology to assess the seismic vulnerability
- AeDES approach to assess safety and access of the buildings.

The damage assessment performed on site has pointed out that a good performance has characterised most of the buildings. Moreover the same observation has also been confirmed by the judgments of the Italian Civil Protection which has used the AeDES form to assess the conditions of the structures.

The seismic vulnerability calculated by FaMIVE has identified in-plane failure as the most common failure mode for the buildings selected in the historic centre of Cento, and the good performance of the restraining elements in the porticoes, which do not allow that the façades fail for soft storey.

5. **Acknowledgements**

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