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Relation between dynamic amplification, structural height and damage in buildings affected by the recent Italian earthquakes

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ABSTRACT

To exploit the purely geometric link between the elastic period of vibration T and the height H (or number of stories) of a building, T was varied from 0 to 0.5 s coinciding with a height between 0 and 12 m (at most the four stories typical of Italian buildings) in order to estimate the spectral accelerations corresponding to acceleration measurements recorded during the earthquakes of L'Aquila, Emilia and central Italy. These estimates were used to calculate the maximum dynamic amplification factors and corresponding heights, called critical heights, that can generate either resonance or appreciable dynamic amplification values. The results showed dynamic amplification values close to 3 for reinforced concrete buildings and 2.5 for masonry buildings independently of the characteristics of the earthquakes. There was a significant coincidence between the structural height of the buildings with greatest recorded damage and the critical height. The basis of the study lies in simple numerical steps carried out with easily obtainable data: for this reason, it can be easily applied to determine the vulnerability of a building according to its structural height.

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KEYWORDS

Dynamic amplification factor; DAF; height; damage; earthquake; seismic risk

1. Introduction

Recent studies have confirmed that the seismic risk to a building is related to its elastic period of vibration and damping (Celebi et al. 2014; Fukuwa et al. 2016), the form of the structure (Whittaker et al. 1999; Mitchell et al. 2003), the constraints (Tsai and Lin 2009), and the duration (Fukuwa and Tobita 2008) and direction of the earthquake's movement (Menghan et al. 2016). The dependence on the building's structural height has been poorly investigated. However, it is known that the destruction mainly affected buildings under 3 stories in the earthquake of Messina (1908) and

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between 6 and 15 stories in that of Mexico City (1985), while others remained practically intact.

If an oscillating building receives dynamic stresses (even small ones) close to its elastic period, the amplitude of vibration can increase considerably: this well-known phenomenon is called dynamic amplification or, in the extreme case, resonance.

Therefore, it is simplistic to exclude the ground-structural height interaction from assessments of vulnerability: since the structural height (or similarly the number of stories above ground) is closely related to the building's elastic period of oscillation, it can be related to the period of the dynamic stress produced by the seismic waves during an earthquake (the ground vibrates in its natural period from about 0.2" for hard soils or rocks up to about 1" for alluvial soils), indicating the "critical" heights at which appreciable dynamic amplifications can occur irrespective of the ground geology. It follows that buildings identical in construction type or materials but of differing heights can suffer differential damage when stressed by the same seismic movement.

Hence, in the study of seismic risk, it is also necessary to evaluate the link between height, dynamic amplification and damage to the building. For this reason, the geometric link between the elastic period of vibration T and the height H (or the number of stories above ground) of the building $T = \alpha H^{\beta}$ was exploited to derive the trend of the dynamic amplification factor DAF, a function of the period T of the earthquake and thus, because of the above-mentioned relation, also of the building's height H . The values of height (or number of stories) that can generate resonance or appreciable dynamic amplification values were extracted from this trend: as mentioned, in these conditions the structure would be subjected to seismic accelerations of amplified intensity with respect to the peak ground accelerations, capable of damaging it or causing it to collapse. These heights (or numbers of stories) have been called "critical."

Three areas of Italy were considered in the present study: L'Aquila, Emilia and central Italy, characterized by strong seismic events between 2009 and 2016. Identified within these areas were some localities with accelerometric recordings and buildings with macroseismic levels of damage not attributable to a site effect.

A rapid topographic survey of the buildings in these localities was conducted to provide information on their geometry (particularly their structural height or number of stories), construction materials, characteristics and, above all, the damage suffered. In total, around 400 buildings that were fairly heterogeneous from both a geometric and constructional point of view were surveyed.

For these areas, the dynamic amplification factors and their corresponding "critical" heights were estimated from the response spectra of the accelerations recorded by stations of the national seismic network - RAN. Then, for each locality, an experimental comparison was made between the structural heights (or numbers of stories) and the critical heights (or critical stories) in terms of the DAF and recorded damage.

A first result showed the same mean maximum values of dynamic amplification for reinforced concrete buildings (= 3) and masonry buildings (= 2.5) in all the areas, demonstrating that the characteristics of the studied earthquakes (depth,

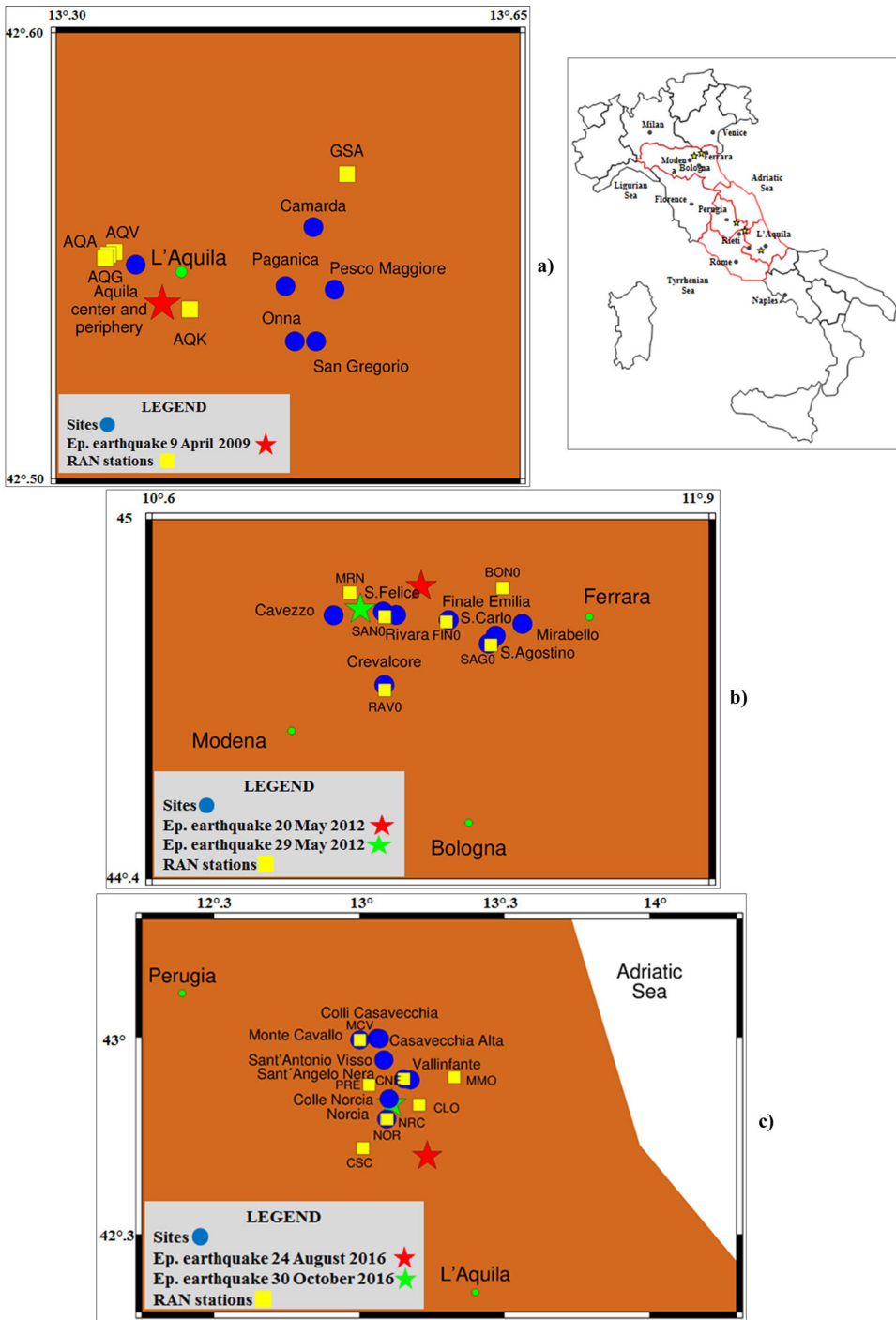


Figure 1. (a) Epicenter of the earthquake of 6 April 2009. Localities and seismic stations. (b) Epicenters of the earthquakes of 20 and 29 May 2012. Localities and seismic stations. (c) Epicenters of the earthquakes of 24 August and 30 October 2016. Localities and seismic stations. Source: Author.

magnitude, duration, etc.) did not influence the DAF value, but only that of the peak ground acceleration. Although the recorded damage differed among the areas (lower in Emilia on account of the resistant buildings, especially residential ones, higher in L'Aquila and central Italy due to the less resistant buildings made of local stone), there was marked coincidence between the structural heights (or stories) and the critical heights (or stories), even though for the southern localities it was not easy to distinguish between the vulnerability associated with the construction materials and building characteristics and that associated with the resonance.

2. The studied areas

2.1. L'aquila area, 2009

The zones of the municipality and province of L'Aquila affected by the earthquake of 6 April 2009 were considered. The details of this event are: time 01:32:40 UTC, duration 40 s, epicenter L'Aquila and surroundings, depth 8.8 km, magnitude 6.3, peak ground accelerations 0.662 g in the N–S direction and 0.558 g in the E–W direction.

The macroseismic damage survey included several localities (Galli et al. 2009) that presented values \geq VIII on the Mercalli-Cancani-Sieberg (MCS) scale (Sieberg 1930), as well as some with effects of degree IX or higher (Tempera 6.73 km, Onna 8.54 km, San Gregorio 9.82 km), even in zones far from the seismic area (Sant'Eusanio Forconese 13.65 km; Villa Sant'Angelo 15.67 km and Castelnuovo 21.25 km, from the epicenter). This mainly regarded residential buildings, with a damage effect attributable to local amplification in the case of Fagnano Alto (km 19.5) and Castelnuovo. In this area, the seismic intensity was not attributed on the EMS-98 scale (Grünthal 1998) and the peak ground acceleration (PGA) values showed a sharp decline already at 15 km from the epicenter (Assergi 0.154 g). For the purposes of this study, seven localities with macroseismic damage on the MCS scale ranging from degree VII to degree X, and at a distance from the epicenter from 0 to 10 km, were identified: they were paired with the RAN seismic stations Aquila Aquilpark (AQK), Aquila Valle (AQV), Aquila Aterno (AQA), Aquila Grilli (AQG) and Gran Sasso (GSA), at distances from 0 to 8 km away (Figure 1(a)).

2.2. Emilia area, 2012

The zones affected by the 2012 earthquake, in particular the provinces of Bologna, Ferrara and Modena, were considered. The strongest seismic events occurred on 20 May 2012: time 2:03:52 UTC, duration 20 s, epicenter between the provinces of Modena and Ferrara, depth 6.3 km, magnitude 5.9, peak horizontal accelerations 0.264 g in the N–S direction and 0.261 g in the E–W direction, and on 29 May 2012: time 07:00:03 UTC, duration 30 s, epicenter in the province of Modena, depth 9.6 km, magnitude 5.8, peak horizontal acceleration 0.296 g. The macroseismic damage surveys revealed intensities between degrees VI and VII on the MCS scale at Bondeno (degree VII), Reno (degree VI–VII), Cento and Finale Emilia (degree VI), Mirandola and San Felice sul Panaro (degree VII). The damage affected edifices like churches, bell towers, civic towers, but especially industrial and agricultural storage buildings.

The residential buildings, both in masonry and reinforced concrete, suffered minor damage (grades 1–2 on the EMS-98 damage classification), with isolated cases of grade 3 and very few collapses (grade 4). In some zones, the macroseismic surveys were performed a second time, revealing an aggravation of the effects in the western part of the area, with an increase of one to two degrees on the MCS scale (Rovereto sulla Secchia and Novi di Modena) and the appearance of localities with effects estimated at degrees V–VI near the Po River (e.g. Castelmassa). In the zones of greatest damage, the seismic intensity was also graded on the EMS-98 scale, with a value of $I > 7$ referred to localities with total or partial collapses, caving in of roofs and masonry structures, wide and deep fissures in masonry buildings and in infill walls of industrial ones. Among these localities, Cavezzo, Concordia and Mirandola presented a substantial aggravation following the tremors of the second event. At other localities, values of $I \leq 7$ were assigned due to the widespread moderate damage, generally concentrated in masonry buildings with vulnerability classes A and B. The greatest effects occurred at San Felice sul Panaro and Finale Emilia, where whole city blocks collapsed, together with severe damage to monumental buildings and old constructions.

Eight localities were chosen for this area: one in the province of Bologna, three in the province of Ferrara and the last four in the province of Modena. They are located from 7 to 30 km from the epicenters and suffered levels of macroseismic damage from degree VI to degree VII on the MCS scale, and from 6 to 7 on the EMS-98 scale, with a worsening between the first and second seismic events. The nearest RAN stations (between 0.5 and 7 km away) are Ravarino temporanea (RAV0), Sant'Agostino temporanea (SAG0), Bondeno temporanea (BON0), San Felice sul Panaro temporanea (SAN0), Mirandola (MRN) and Finale Emilia temporanea (FIN0) (Figure 1(b)). Their recordings refer to the 29 May event; only Mirandola also recorded tremors on 20 May.

2.3. Central Italy area, 2016

The zones affected by the 2016 earthquake were considered, in particular those located in the provinces of Macerata and Perugia. The strongest earthquakes occurred on 24 August 2016: time 01:36:32 UTC, duration 10 s, epicenter in the province of Rieti, depth 4 km, magnitude 6.0, peak horizontal accelerations 0.445 g in the N–S direction and 0.915 g in the E–W direction; on 26 October 2016: time 19:18:06 UTC, duration 15 s, epicenter between the provinces of Macerata and Perugia, depth 8 km, magnitude 5.9, peak horizontal accelerations 0.560 g in the N–S direction and 0.684 g in the E–W direction; and on 30 October 2016: time 06:40:17 UTC, epicenter in the provinces of Perugia and Ascoli Piceno, duration 15 s, depth 10 km, magnitude 6.1, peak horizontal accelerations 0.634 g in the N–S direction and 0.478 g in the E–W direction. In many localities, the effects recorded after 30 October (Galli et al. 2017) were the result of the summation of the damage from previous tremors (Azzaro et al. 2016), especially in the zone between Amatrice and Norcia. Indeed, the damaged zone had significantly extended northward after the 30 October earthquake and the finding of macroseismic effects involved many localities that were lightly affected

previously, especially in the province of Macerata. In many cases, there was an increase of the damage, at times even total destruction, resulting in increases of intensity of up to three degrees on the EMS-98 scale, as occurred in many localities near the epicenter of the 30 October earthquake (Norcia, Castelsantangelo sul Nera, Castelluccio di Norcia and others). For example, Castelluccio di Norcia passed from relatively light damage after 24 August to almost total destruction after 30 October, with an increase in intensity from 6–7 to 9. A few kilometers away, a portion of Arquata del Tronto experienced a major worsening of the situation from 24 August to 30 October, with an increase in intensity from 7–8 to 9. Another significant example concerns Accumoli, which during the quake of 24 August suffered several partial collapses and the total destruction of a few buildings, with an intensity of 8 on the EMS-98 scale. After the 30 October earthquake, there was an estimated intensity of 10, with almost total destruction of more than 80% of the most vulnerable buildings (vulnerability class A) and about 30% of the more robust buildings (class B and higher). The situation was similar at Arquata del Tronto and other towns, with a widespread worsening from 24 August to 30 October, leading to an increase in intensity of one or two degrees. A separate case is San Severino Marche, which although situated very far from the epicenter on terraced alluvial deposits presented a high concentration of severe and very severe damage in houses and apartment blocks of various construction types (reinforced concrete, mixed masonry, blocks). This and many other cases are representative of a probable site effect (Stewart et al. 2017).





In this area, eight localities were considered: six in the province of Macerata and two in the province of Perugia. They are situated from 7 to 30 km from the epicenters of the seismic events and suffered macroseismic damage ranging from degree VI to degree VII on the MCS scale and from 6 to 7 on the EMS-98 scale, with a worsening between the quakes of 24 August and 30 October. The RAN seismic stations near these localities (between 0 and 7 km away) are Norcia (NOR and NRC), Castel Santangelo sul Nera (CNE), Preci (PRE), Castelluccio (CLO), Cascia (CSC), Montemonaco (MMO) and Monte Cavallo (MCV) (Figure 1(c)).

For each locality, a rapid survey of buildings was carried out, concerning the following aspects:

- Historical:
 - building use (residential, industrial-agricultural-artisanal, public [religious or administrative], etc.);
 - year of construction;
 - interventions subsequent to the year of construction (expansions, additions of stories, replacement of horizontal elements, etc.);
 - building context (isolated or attached/adjacent buildings).
- Geometric:
 - planimetric geometry (square or rectangular);
 - roof geometry (flat, single-pitched, dual-pitched, hipped, shed, etc.);
 - eave height and/or number of stories above ground;
 - plan and height regularity;
 - slenderness of the vertical load-bearing structures;



Table 1. "Internal" descriptive numerical scale of damage.

Damage	Value	Description	Some images of damage
Absent	0	No damage	
Low	1	Small number of light superficial fissures in the plaster a few millimeters wide. Horizontal displacements without expulsion of material	
	2	Diffuse light superficial fissures. Limited separations. Falls of small pieces of plaster or stucco not bound to the wall and degraded	
Medium	3	Superficial fissures and some deep fissures 1 cm wide. Damage to the roof. Possible falls of non-structural objects	
	4	Numerous superficial fissures and deep fissures 1 cm wide or wider near the openings (crushing mechanism). Slight separations between floor assemblies and/or staircases and orthogonal walls (of 1 mm). Lesions to the vaults of several millimeters and/or with symptoms of crushing	
	5	Numerous superficial fissures and deep fissures 1 cm wide distributed on parts of the building. Detachments in the secondary framework of the floor assemblies and displacements of up to 1 cm of the main beam supports. Significant damage to the roof with falls of tiles. Visible non-verticalities	
High	6	Structural damage compromising the safety of the residents. Parts of the structure damaged but not in imminent danger	
	7	Structural damage causing instability. Parts of the structure damaged and separated from the body of the building. Significant separations between floor assemblies and/or staircases and walls and between orthogonal walls of ca. 1 cm	
	8	Structural damage compromising stability. Parts of the structure detached by building collapse and partial collapses. Non-verticality with lesions passing through the masonry	
Very high	9	Diffuse structural collapses, but most of the structure still recognizable with danger risk for the residents (instability-dangerousness). Collapse of 50% of the building	
	10	Complete or almost complete collapse	

- distribution of permanent and incidental loads.
- Material:
 - construction material:
 - vertical load-bearing structures (full masonry, hollow masonry, unhewn stone, concrete, reinforced concrete, masonry and reinforced concrete, steel, etc.);
 - horizontal load-bearing structures:
 - floor (floor assemblies in wood, hollow-core concrete, steel and brick, etc.);
 - roof (joists in wood, hollow-core concrete, steel and brick, etc.);
 - stairwells or elevator shafts;
 - structural type (full masonry, frame in reinforced concrete and infill walls, etc.);
- Damage mechanisms:
 - vertical load-bearing structures:
 - inside the plan (buckling, traction shear, thrust shear, crushing, etc.);
 - outside the plan (simple wall overturning, composite wall overturning, total and partial);
 - horizontal load-bearing structures (thrusting roofs, ridge beam hammering, rigid connections at apex associated with poorly resistant facade elements, lack of connections with frame elements, etc.);
 - hammering of adjacent buildings.
- Deformations or damage, with a description and quantification of the earthquake damage using an “internal” descriptive numerical scale shown in [Table 1](#).

The results of the survey of the chosen localities for each area are reported below.

2.4. L'aquila area, 2009

Localities: Aquila center, Aquila periphery, Paganica, Onna, San Gregorio, Camarda, Pescomaggiore. The survey was carried out in June and August 2018, covering a total of 140 buildings uniformly divided among the seven localities. The prevalent building use is residential (99%), with constructions dated between 1900 and 1970. There are a few exceptions dating to the subsequent period and five religious buildings from prior to 1900. Almost all of them (79%) are attached buildings. The planimetric geometry is almost always rectangular. There are no single-pitched roofs, while 20% are flat, 42% dual-pitched and 39% hipped. The heights vary from 3 to 12 meters, with a maximum of 4 stories above ground and the highest percentages with 2 (65%) and 3 stories (26%): the inter-story heights are between 2.75 and 3 m.

The buildings always present both plan and height regularity, and the distribution of permanent-incidental loads is generally uniform; however, it should be noted that because of the prevalent rectangular geometry and joists arranged in a single direction (the shorter length) the structures were subjected to torsion.

For the residential buildings, the prevalent building material is local hewn stone (89%) followed by full brickwork (15%) and concrete blocks (3%). In only two cases the structures are made of reinforced concrete with light brick infill walls. The

external walls are two-headers thick, bonded with low consistency bedding mortar; some of them present high degrees of slenderness. The external surface is almost always plastered to hide the uneven pattern of the usually irregular stonework, with obvious separations: when the plaster is missing, the joints of the exposed stonework are in lime stucco. There are also reinforcements of a different material from that of the original wall and poorly joined to it.

In 25% of cases, the floor assemblies are in wood (especially for buildings in historical centers and in attached/adjacent buildings) with main beams in simple support (there are no stiffening elements on the vertical walls), while in 61% of cases they are in hollow-core concrete (for the isolated and recently constructed buildings) and in 20% in steel and brick, never staggered with orientation parallel to the shorter plan length. The roof joists reflect the types of floor joists and are mainly in wood (90% versus 10% concrete or steel with brick). In all the buildings, with the exception of the single-story ones, there are staircases either in reinforced concrete or in wood. They are almost never in a central position in terms of the plan and in a few cases are located externally.

The most common damages were found on the vertical masonry walls (in 50% of cases), on the floor assemblies (17%) and on the roof joists (25%). The main failure consisted of ruptures, separations in the corners of the walls, lesions on the gables, detachments, longitudinal fissures of the joists and differential subsidence, on both the vertical and horizontal structures. The most frequent damage mechanisms were manifested within the plan of the external walls, including buckling, traction shear (in most cases) and thrust shear. In isolated cases there were also crushing mechanisms (vertical lesion) where the construction material was inadequate. A large percentage of damage mechanisms (49%) also occurred outside the plan, both by simple overturning, highlighted by inclinations, or by composite overturning highlighted by separations due to rotation between joists and walls. Some damage mechanisms were also found on the staircases. The most frequent damage mechanism in dual-pitched roofs was hammering of the ridge beam (60%), shown by separations and lesions on the gable, while in four-pitched roofs it was thrusting of the roofs (40%). Other damages occurred by building hammering, given the high percentage of adjacent buildings.

2.5. Emilia area, 2012

Localities: S.Felice sul Panaro, Cavezzo, Rivara, Crevalcore, Finale Emilia, S.Agostino, S.Carlo, Mirabello. The survey was conducted in September 2018, covering a total of 100 buildings. The building use is mainly residential (77%), with 15% built before the end of the nineteenth century, 51% between 1900 and 1950 and the rest afterwards. There is an equal percentage of isolated and attached/adjacent buildings. The planimetric geometry is almost always rectangular. There are very few flat or single-pitched roofs: almost all are dual-pitched (50%) and hipped (35%), while the rest (12%) are the “shed” type, typically in industrial buildings. The heights vary from 3 to 12 m, with a maximum number of 4 stories above ground and the highest percentages with 2 stories (32%) and 3 stories (42%); the inter-story heights range between

3 and 5 m. There are equal incidences of regularity, both of plan and height (less than 6% of the buildings are irregular), and the distribution of permanent-incidental loads is generally uniform.

For the residential buildings, the prevalent building material is full masonry, one-header or two-headers thick (rare cases with three-headers), bonded with cement mortar or hydraulic lime mortar. In all the industrial buildings, reinforced concrete prevails, although iron is absent. The floor assemblies are in wood in 59% of cases (especially for buildings in historical centers and in attached/adjacent buildings) with main beams in simple support; hollow-core concrete and bond beams are used in 36% of cases (for isolated and newly constructed buildings), while steel and brick assemblies are found in only 5% of cases, never staggered and always arranged parallel to the shorter plan length, which means that the barycenter of weights almost never coincides with that of the resistances (stiffness–shiftiness). The roof joists reflect the types of floor joists with a prevalence of wood (69% versus 31% hollow-core concrete).

For the industrial buildings, the construction material is reinforced concrete and the prevalent structural type is prefabricated reinforced concrete frame with vertical infill walls in either concrete panels or light brickwork. Flat concrete roofs predominate.

In all the buildings, except for the single-story ones, there are staircases (either in reinforced concrete or iron) or elevator shafts, almost never in a central position in terms of the plan.

The most common damages were found on the vertical masonry walls (in 50% of cases), on the floor assemblies (33%) and on the roof joists. The main failure consisted in fissures or inclinations, lesions on the gables, separations in intersections, longitudinal fissures of the joists and differential subsidence, both on the vertical and horizontal structures. Consequently, the most frequent damage mechanisms (buckling and traction shear) were within the plan of the external walls. There were lower percentages of damage mechanisms outside the plan, mainly due to simple overturning highlighted by inclinations, and on the horizontal structures (staircases and floor assemblies). In the roofs, the most frequent damage mechanisms were found in dual-pitched ones (hammering of the ridge beam in 12% of cases, with lesions on the gable) and in the four-pitched ones (thrusting of the roof in 58% of cases) with signs of separation along the intersections of the walls.

2.6. Central Italy area, 2016

Localities: Pie' Del Colle, Norcia, Castel Sant'Angelo sul Nera, Vallinfante, Visso, Colli di Casavecchia, Casavecchia Alta, Montecavallo. The survey was carried out at the beginning of August, with data collected for 131 residential buildings located in the zones affected by the earthquake of 30 October 2016. These localities have buildings constructed mainly in the first half of the twentieth century (56%) and only 2% of them prior to that century. They are prevalently for residential use (95%) and 56% of them are adjacent buildings (historical centers). Historical buildings are in masonry, mainly regular and calcareous sandstone that is usually unhewn and formed

by river pebbles of very irregular size and grade, with low-quality mortars (peripheral localities). More recent buildings are constructed in regular full brickwork with bedding mortar.

The same locality can have both brick buildings, with hollow-core concrete floor assemblies and roofs (40% of the cases) in good maintenance conditions, and poorly maintained local-stone buildings, with floor assemblies and roofs in wood, in steel and brick or sometimes in masonry vaults. In some cases, there are masonry buildings with relatively recent interventions, such as superimposition of a bond beam or a reinforced concrete roof on a local-stone facade. From the geometric point of view, the heights vary from 3 to 12 m, with a maximum of 4 stories (inter-story heights between 3 and 3.5 m) although mostly 2 stories (54%). The prevalent planimetric geometry is rectangular, with greater plan and height regularity in percentages up to 80%. The stairwells and elevator shafts are almost never in a central position, and the distribution of permanent-incident loads and masses is generally uniform. The survey revealed that some buildings had undergone partial seismic improvement with the introduction of tie rods. The roof geometry is dual-pitched (70%) and four-pitched (17%).

Only 14% of the surveyed buildings were undamaged, while among those damaged the highest percentage (49%) were attached/adjacent buildings due to the hammering effect between neighboring structures. The commonest lesions were on the vertical walls (in 84% of the total) and on the roof joists (23%), with only 12% in the floor assemblies. The main failure was the presence of fissures or inclinations, lesions on the gables, separations at intersections, detachments, longitudinal fissures of the joists and differential subsidence, both on the vertical and horizontal structures mainly due to both the mechanical characteristics and the slenderness of the walls. The most frequent damage mechanisms were within the plan of the external walls and included buckling, traction shear and thrust shear (63%). A lower percentage of damage mechanisms occurred outside the plan, mainly due to simple overturning highlighted by inclinations, and on the horizontal structures (staircases and floor assemblies). In the roofs, the most frequent damage mechanisms were found in the dual-pitched ones (hammering of the ridge beam with lesions on the gable in 17%).

3. Data processing

The relation between the elastic period of vibration T and the height H of the building is as follows (Chopra 1995):

$$T = \alpha H^\beta \quad (1)$$

T is expressed in seconds and H in meters.

In ATC3-06 (ATC 1978), β is set at 0.75 and α at 0.06. Subsequently, in SEAOC-88 (SEAOC 1996), the value of α was changed to 0.073 and rounded to 0.075 in the European regulation EC8 (CEN 2004). In the last twenty years, the choice of α and β coefficients has been made on the basis of experimental data (Goel and Chopra 1997; Hong and Hwang 2000), with α set according to the construction material.

Table 2. L'Aquila Area. Earthquake of 6 April 2009 01:32:40 UTC M_w 6.3.

RAN	d_e (km)	PGA mean (g)	T_d (sec)	T (sec) $\zeta = 5\%$	DAF max $\zeta = 5\%$	T (sec) $\zeta = 8\%$	DAF max $\zeta = 8\%$
AQK	0	0.341	13	0.140	3.0	0.142	2.5
AQV	4.9	0.622	8	0.110	2.8	0.108	2.4
AQG	5.4	0.553	8	0.050	1.8	0.050	1.6
AQA	5.4	0.437	8	0.056	3.3	0.056	2.5
GSA	14.6	0.154	9	0.102	3.9	0.104	3.0
				Mean	3.0	Mean	2.4
				Variance	0.6	Variance	0.3

Maximum and mean DAF for reinforced concrete and masonry buildings.

In an equivalent manner, the following relation applies:

$$T = 0.1 N \quad (2)$$

where N is the number of stories. This relation is indicated in NEHRP (1994) and is recommended for buildings up to 12 stories and with inter-story heights not less than 3 m.

In this study, relation (1) was used with the α coefficient set at 0.05 for masonry and at 0.075 for reinforced concrete, as recommended by the Italian legislation (NTC 2018). By the inversion of (1), H was calculated according to the period T : in particular, T was varied from 0" to 0.5" with increments of 0.002" to obtain the corresponding H between 0 and 12.5 m (heights typical of Italian buildings, especially masonry ones – Istat 2018). The spectral accelerations were extracted in the interval from 0" to 0.5": their relation to that of zero height (coinciding with the PGA) represents the dynamic amplification factor – DAF. The spectral accelerations were derived from processing of the accelerometric records (with sampling at 200 Hz) of the seismic stations indicated for each area, as the mean of the pseudoaccelerations in the N–S and E–W components. The raw data were filtered with the Butterworth bandpass algorithm of order 3 or 6 and variable range from 0.1 to 50 Hz (Stearns and David 1996; Lynn and Fuerst 1998; Boore and Akkar 2003). All the spectra were processed with a dedicated code in Matlab environment, setting a damping ratio ζ of 5% for reinforced concrete buildings and 8% for masonry buildings.

For each of the three study areas, the maximum dynamic amplification factors at the spectral acceleration peak (Gatti 2018a) were calculated (at this time, no attention was paid to the critical height H).

These first data processing results are reported in Tables 2–4 according to the distance from the epicenter, to the PGA (in g) (mean of the two N–S and E–W components) recorded by the RAN station, to the significant duration T_d (Trifumac and Brady 1975) of the earthquake, and to the elastic period of vibration T (in seconds), both for reinforced concrete and masonry buildings. The mean value and its variance are also indicated in the tables (Tables 2, 3 and 4).

Subsequently, the same spectrograms were used to calculate the dynamic amplification factors for T values for heights of 2.70, 2.85 and 3.00 m which correspond, for masonry structures alone, to single-story buildings (Class I); T values for heights of 5.50, 5.75 and 6.00 m, i.e. two-story masonry buildings (Class II); T values for heights of 8.50, 8.75 and 9.00 m, i.e. three-story masonry buildings (Class III); T values for

Table 3. Emilia Area. Earthquake of 29 May 2012 07:00:03 UTC $M_w = 5.8$.

RAN	d_e (km)	PGA mean (g)	T_d (sec)	T (sec) $\zeta = 5\%$	DAF max $\zeta = 5\%$	T (sec) $\zeta = 8\%$	DAF max $\zeta = 8\%$
MRN	2.0	0.280	8	0.186	3.0	0.16	2.3
SANO	4.0	0.202	7	0.174	3.0	0.176	2.4
RAVO	15.0	0.079	14	0.314	2.6	0.314	2.2
FINO	16.0	0.235	9	0.242	2.6	0.238	2.2
MRN (°)	17.0	0.295	6	0.268	3.2	0.272	2.6
SAGO	25.0	0.077	19	0.292	3.3	0.290	2.6
BONO	26.0	0.032	19	0.168	3.9	0.168	3.2
				Mean	3.1	Mean	2.5
				Variance	0.2	Variance	0.1

Maximum and mean DAF for reinforced concrete and masonry buildings.

(°) Earthquake of 20 May 2012 02:03:52 UTC M_w 5.9.

Table 4. Central Italy Area. Earthquake of 30 October 2016 01:36:32 UTC M_w 6.0.

RAN	d_e (km)	PGA mean (g)	T_d (sec)	T (sec) $\zeta = 5\%$	DAF max $\zeta = 5\%$	T (sec) $\zeta = 8\%$	DAF max $\zeta = 8\%$
NOR	4.9	0.329	13	0.872	3.2	0.900	2.6
NRC	5.4	0.412	10	0.232	4.1	0.234	3.2
CNE	7.0	0.406	8	0.436	2.5	0.438	2.1
PRE	7.9	0.297	12	0.096	2.9	0.096	2.4
CLO	8.2	0.568	10	0.374	2.8	0.376	2.2
CSC	15.9	0.164	9	0.172	3.6	0.174	2.8
MMO	18.9	0.200	13	0.264	3.0	0.266	2.3
MCV	19.2	0.352	12	0.116	3.6	0.118	2.8
				Mean	3.2	Mean	2.5
				Variance	0.3	Variance	0.1

Maximum and mean DAF for reinforced concrete and masonry buildings.

heights of 11.50, 11.75 and 12.00 m, i.e. four-story masonry buildings (Class IV). The calculations were performed for each of the seismic stations.

The DAF values calculated for the three heights in each class were averaged and the mean dynamic amplification factor \widehat{DAF} and the corresponding “critical” height H_c (m) for reinforced concrete buildings and critical story P_c for masonry buildings were extracted.

These second data processing results are reported in Tables 5–10, along with the spectral acceleration value A_g (in g), as the product $\widehat{DAF} \times \text{PGA}$ (the latter reported in Tables 2–4), for each area and each RAN station.

For each locality considered, the results of the structural geometric survey were used to relate the mean recorded damage in all buildings with damage greater than 5 (according to the value reported in Table 1) to the mean structural height H_m (for industrial buildings) and/or story P_m (for residential buildings).

Tables 11–13 report the name of the localities, their distances from the epicenter, the percentage of buildings with damage greater than 5 (Table 1), the mean damage D_m , the mean structural height H_m and/or story P_m , as well as the nearest seismic station and the distance from it. The tables (Tables 11, 12 and 13) are reported by area: industrial buildings were only considered for the Emilia area (Table 12).

4. Resources and discussion

Finally, for the localities in the three areas, the mean height H_m (for industrial buildings) and/or mean story P_m (for residential buildings) reported in the preceding

Table 5. L'Aquila Area. Earthquake of 6 April 2009 01:32:40 UTC M_w 6.3.

RAN	\widehat{DAF}	H_c (m)	A_g (g)
AQK	1.8	6	0.614
AQV	2.1	6	1.306
AQG	1.6	6	0.884
AQA	2.2	6	0.961
GSA	3.2	6	0.493

\widehat{DAF} , critical height H_c and spectral acceleration A_g . Reinforced concrete buildings $\alpha = 0.075$, $\beta = 0.75$ and $\zeta = 5\%$.

Table 6. L'Aquila Area. Earthquake of 6 April 2009 01:32:40 UTC M_w 6.3.

RAN	\widehat{DAF}	P_c	A_g (g)
AQK	1.7	2	0.579
AQV	1.8	2	1.120
AQG	1.3	2	0.719
AQA	2.0	2	0.874
GSA	2.7	2	0.416

\widehat{DAF} , critical story P_c and spectral acceleration A_g . Masonry buildings $\alpha = 0.05$, $\beta = 0.75$ and $\zeta = 8\%$.

Table 7. Emilia Area. Earthquake of 29 May 2012 07:00:03 UTC $M_w = 5.8$.

RAN	\widehat{DAF}	H_c (m)	A_g (g)
MRN	2.5	6	0.700
SANO	2.8	3	0.565
RAVO	2.0	6	0.158
FINO	2.0	6	0.470
MRN (°)	3.1	6	0.914
SAGO	3.0	6	0.231
BONO	2.3	6	0.074

\widehat{DAF} , critical height H_c and spectral acceleration A_g . Reinforced concrete buildings $\alpha = 0.075$, $\beta = 0.75$ and $\zeta = 5\%$.
(°) Earthquake of 20 May 2012 02:03:52 UTC M_w 5.9.

Table 8. Emilia Area. Earthquake of 29 May 2012 07:00:03 UTC $M_w = 5.8$.

RAN	\widehat{DAF}	P_c	A_g (g)
MRN	2.5	2	0.700
SANO	2.2	3	0.444
RAVO	1.9	3	0.150
FINO	1.9	2.5	0.447
MRN (°)	2.4	3.5	0.708
SAGO	2.3	3.5	0.177
BONO	2.8	2	0.090

\widehat{DAF} , critical story P_c and spectral acceleration A_g . Masonry buildings $\alpha = 0.05$, $\beta = 0.75$ and $\zeta = 8\%$.
(°) Earthquake of 20 May 2012 02:03:52 UTC M_w 5.9.

Table 9. Central Italy Area. Earthquake of 30 October 2016 01:36:32 UTC M_w 6.0.

RAN	\widehat{DAF}	H_c (m)	A_g (g)
NOR	2.0	6	0.658
NRC	3.7	6	1.524
CNE	2.2	6	0.893
PRE	1.9	6	0.564
CLO	2.7	9	1.533
CSC	2.1	6	0.344
MMO	2.8	6	0.560
MCV	1.6	6	0.563

\widehat{DAF} , critical height H_c and spectral acceleration A_g . Reinforced concrete buildings $\alpha = 0.075$, $\beta = 0.75$ and $\zeta = 5\%$.

Table 10. Central Italy Area. Earthquake of 30 October 2016 01:36:32 UTC M_w 6.0.

RAN	\widehat{DAF}	P_c	A_g (g)
NOR	1.8	3.5	0.592
NRC	3.0	2.5	1.236
CNE	1.8	2	0.730
PRE	2.2	2	0.653
CLO	1.85	3.5	1.051
CSC	2.6	2	0.426
MMO	2.3	3	0.460
MCV	2.1	2	0.739

\widehat{DAF} , critical story P_c and spectral acceleration A_g . Masonry buildings $\alpha=0.05$, $\beta=0.75$ and $\zeta=8\%$.

Table 11. L'Aquila Area. Earthquake of 6 April 2009 01:32:40 UTC M_w 6.3. Locality, percentage of buildings with damage greater than 5, mean structural story P_m , mean damage D_m and seismic station.

Locality	d_e (km)	% Residential buildings Damage > 5	P_m	D_m	Seismic station	d Locality-Seismic station (km)
Aquila center	1.3	100	2.5	10.0	AQK	0.5
Aquila periphery	3.9	19	2	5	AQG-AQV-AQA	0.6
Paganica	7.7	64	2.1	7.1	AQK	6.1
Onna	8.5	72	2.3	8.2	AQK	6.8
San Gregorio	9.8	75	2.3	9.0	AQK	8.1
Camarda	10.5	46	1.8	6.0	GSA	3.9
Pescomaggiore	10.7	53	1.8	7.4	GSA	4.9

Table 12. Emilia Area. Earthquake of 29 May 2012 07:00:03 UTC $M_w = 5.8$.

Locality	d_e (km)	% Residential buildings		% Industrial buildings			H_m (m)	D_m	Seismic station	d Locality-Seismic station (km)
		Damage > 5	P_m	Damage > MRN (°)	H_m (m)	D_m				
S.Felice sul Panaro	4.2	35	3.0	6.3	100.0	5	8.2	SANO	1.0	
Cavezzo	5.1	56	2.6	7.1	100.0	6	5	MRN MRN (°)	5.2	
Rivara	6.7	63	2.4	7.2	0.0	–	–	SANO	2.1	
Crevalcore	14.8	100	2.3	9.3	0.0	–	–	RAVO	1.0	
Finale Emilia	16.4	59	2.8	5.5	0.0	–	–	FINO	0.5	
S.Agostino	24.6	50	2.0	6.0	0.0	5	6.3	SAGO	0.5	
S.Carlo	25.5	0	–	–	100	5	8	SAGO	2.0	
Mirabello	30.5	50	2.5	5.0	100	5	7.5	SAGO	7.0	
	BONO	7.6								

Locality, percentage of buildings with damage greater than 5, mean damage D_m , mean structural story P_m (residential buildings), mean structural height H_m (industrial buildings) and seismic station.

(°) Earthquake of 20 May 2012 02:03:52 UTC M_w 5.9.

tables (Tables 11–13) were compared with the “critical” heights H_c and stories P_c , obtained from the RAN seismic stations closest to them (Tables 5–10).

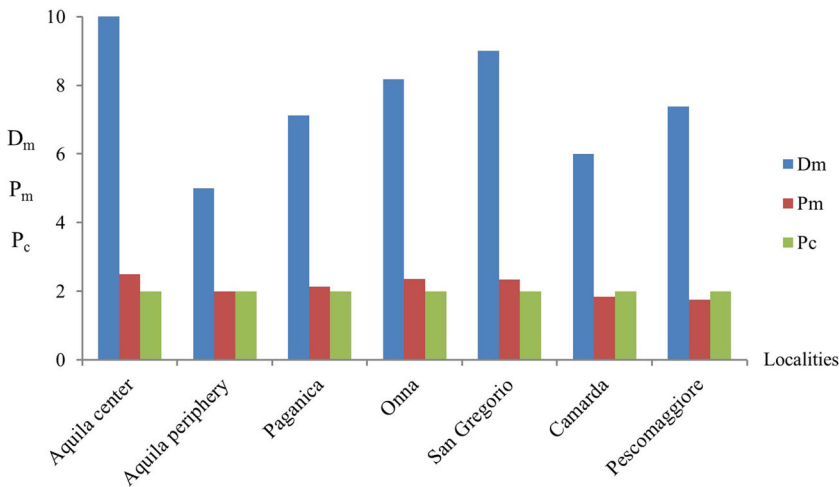
Figure 2 reports, for the seven localities in the L'Aquila Area, the values of D_m for buildings with damage > 5 in relation to the number of structural stories P_m and the number of critical stories P_c (corresponding to the highest dynamic amplification factor \widehat{DAF}) for the earthquake of 6 April 2009. Almost identical values of P_m and P_c were found in the two-story buildings in each locality, confirming for that type building a correlation between the greatest recorded damage and the highest value of the dynamic amplification factor.

In this case, there is no single value of P_c that coincides with P_m . San Felice, Cavezzo, Mirabello and Finale Emilia show exact or close coincidence of the two

Table 13. Central Italy Area. Earthquake of 30 October 2016 01:36:32 UTC M_w 6.0.

Locality	d epicenter (km)	% Buildings Damage > 5	P_m	D_m	Seismic station	d Locality- Seismic station (km)
Pie' Del Colle	1.5	50	2.1	8.8	NRC	5.7
Norcia	4.5	54	2.2	7.4	NOR	0.1
Castelsantangelo sul Nera	7.8	71	2.8	9.6	CNE	0.3
Vallinfante	8.5	88	2.3	8.0	CNE	1.8
Visso	12.5	43	2.7	9.3	CNE	7.8
Colli di Casavecchia	18.6	62	2.4	8.4	MCV	5.0
Casavecchia Alta	19.0	90	2.2	9.2	MCV	5
Montecavallo	20.0	25	2.0	5.0	MCV	0.1

Locality, percentage of buildings with damage greater than 5, mean structural story P_m , mean damage D_m and seismic station.


Figure 2. L'Aquila Area. Earthquake of 6 April 2009 01:32:40 UTC M_w 6.3. Locality, mean damage $D_m > 5$, mean structural story P_m and critical story P_c . Source: Author.

values for buildings of three or two and half stories. In other localities, the two values are one unit lower or higher.

Figure 3(b) presents the results concerning D_m for industrial buildings with damage > 5, structural height H_m and critical height H_c for five of the eight localities in the Emilia Area. The coincident values of H_m and H_c found in correspondence of 5 and 6 m (except for only one locality) confirm the perfect correlation between the greatest damage and the highest value of dynamic amplification factor.

Industrial buildings: locality, mean damage $D_m > 5$, mean structural height H_m (m) and critical height H_c (m).

For the surveyed buildings in the Central Italy Area (all of the residential attached/adjacent type), there is good coincidence of the P_m and P_c in buildings with two stories (Figure 4). In other words, for every locality, this type of building shows the highest values of dynamic amplification factor.

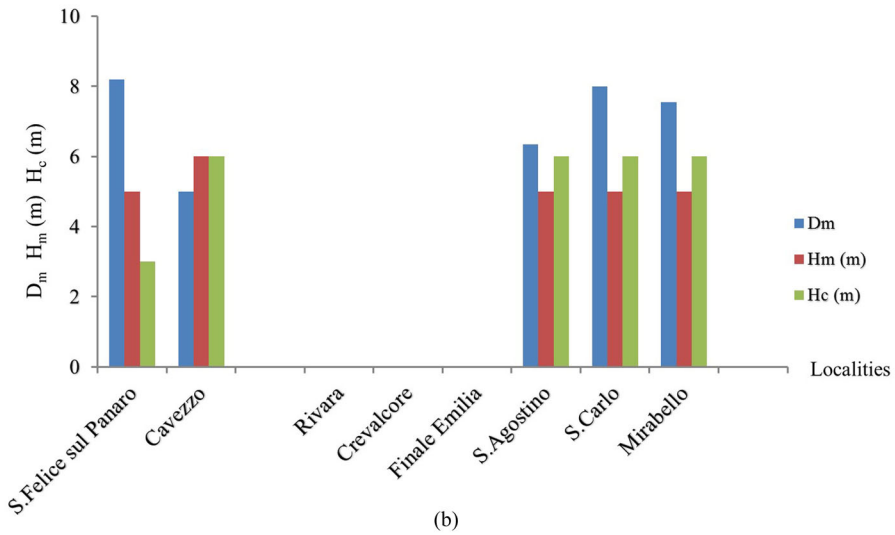
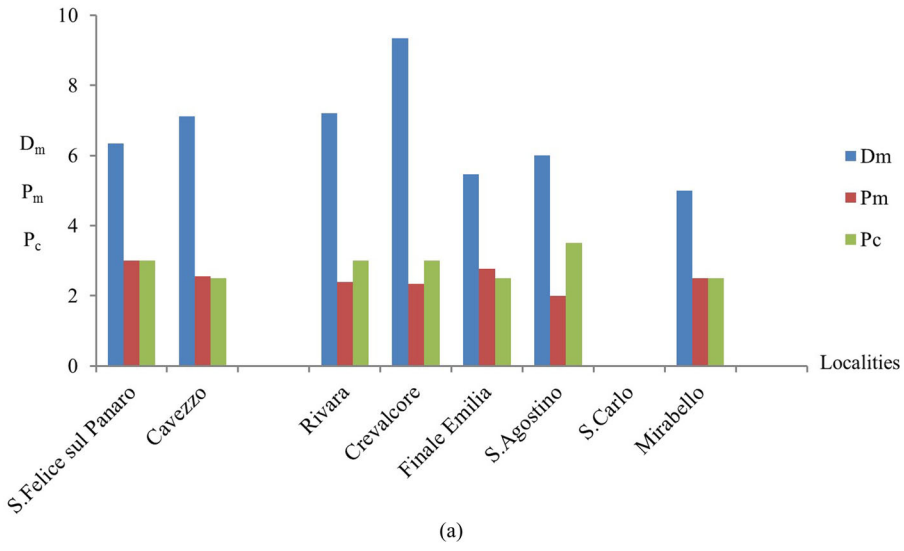


Figure 3. (a) Emilia Area. Earthquakes of 29 May 2012 07:00:03 UTC M_w 5.8 and 20 May 2012 02:03:52 UTC M_w 5.9. Residential buildings: locality, mean damage $D_m > 5$, mean structural story P_m and critical story P_c . (b) Emilia Area. Earthquakes of 29 May 2012 07:00:03 UTC M_w 5.8 and 20 May 2012 02:03:52 UTC M_w 5.9. Industrial buildings: locality, mean damage $D_m > 5$, mean structural height H_m (m) and critical height H_c (m). Source: Author.

Conclusions

A first result reveals a mean maximum dynamic amplification value of 3 for reinforced concrete buildings and 2.5 for masonry buildings in the three areas. This means that the characteristics of the earthquakes (depth, magnitude, duration, etc.) did not influence the DAF, but only the value of peak ground acceleration. If this result were to be verified, the industrial and residential buildings, with their elastic period of vibration close to that of the ground, would undergo accelerations

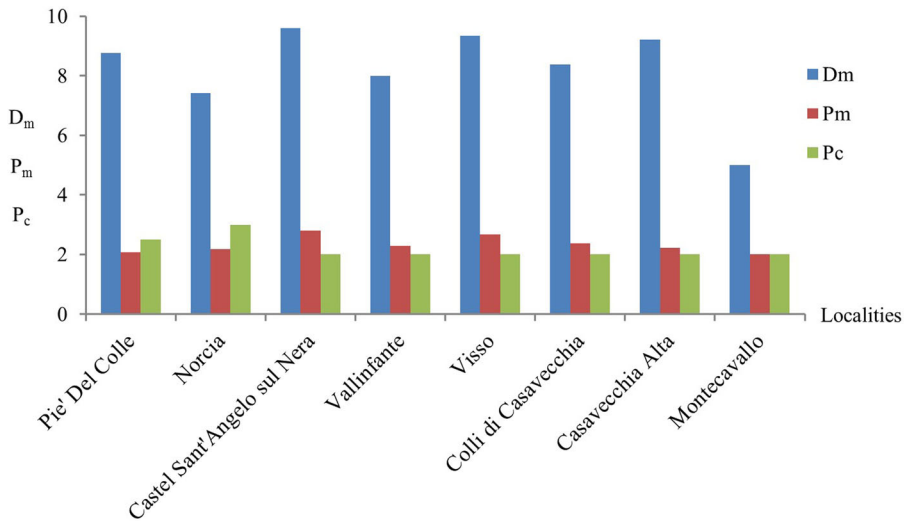


Figure 4. Central Italy Area. Earthquake of 30 October 2016 01:36:32 UTC M_w 6.0. Locality, mean damage $D_m > 5$, mean structural story P_m and critical story P_c . Source: Author.

respectively three or two and a half times higher than the maximum acceleration recorded on the ground (which, for the seismic stations in this study, reached the maximum peak of 0.662 g).

Regarding the relation between height or number of stories and damage, we must distinguish between the study areas:

- L'Aquila Area: 140 buildings were surveyed, and almost all of them were residential and, in a high percentage, attached/adjacent. More than two thirds of the building damage was concentrated in the medium (19%), high (27%) and very high (24%) categories, with only 35% in the low one. The buildings have high vulnerability due to poorly resistant and relatively slender external walls as well as low stiffness of the frame. Hence, residential buildings with mean damage greater than 5 represent the highest percentage (from 43% at Camarda, with mean damage of 6, to 100% at Aquila center, with mean damage of 10). For all the localities, the buildings with greatest damage were the two-story ones, i.e. those in which the critical second story corresponded to the highest dynamic amplification factor.
- Emilia Area: about 100 buildings were surveyed and 25% of them were industrial ones. The recorded damage was mainly in the medium-low categories (20% low and 40% medium), with 35% in the high category and only 5% in the very high one. The greatest damage levels were found among the industrial buildings (medium and high with a mean of 7.5), with lesser damage in the residential ones (low and medium with a mean of 4.5). The damage was more limited in the residential sector due to construction types characterized by full masonry and hollow-concrete floor assemblies stiffened with bond beams. Therefore, within the limits of what is stated for this type of building, the story with greatest recorded damage was not uniform as in the previous case, but rather was between the second and third story with differentiation from locality to locality. In general, the fit with the

critical story was consistent, with the sole exception of Sant'Agostino. In contrast, the industrial buildings (the result of prefabrication in the 1970s that favored systems with isostatic constraints resistant to horizontal forces due to friction alone) presented damage much greater than 5 (Table 1) in correspondence with a mean structural height of 5–6 m. With the exception of a single locality, 6 m was also the critical height, i.e. the one at which the greatest dynamic amplification factor was found.

- Central Italy Area: all of the 131 surveyed buildings were residential, most of them attached/adjacent. Seventy per cent of the damage was medium (20%), high (19%) or very high (31%), with values almost always exceeding 8. For all localities, the buildings with greatest damage were the two-story ones, i.e. those with the highest dynamic amplification factor. The causes were the same structural deficiencies reported for the L'Aquila area.

The limits of the present study are:

- the difficulty in distinguishing the vulnerability due to construction materials and characteristics from that associated with resonance, especially in the L'Aquila and Central Italy areas characterized by low-quality materials;
- a non-rigorous dependence of T on H and the value of ζ , as demonstrated in recent works by the present author (Gatti 2018b, 2018c).

Nonetheless, these are not valid reasons to reject the theoretical foundation of the study: based on simple numerical steps carried out with easily obtainable data, namely seismic recordings (already available in areas with historical seismicity) and heights of buildings, it could be applicable to signal situations of vulnerability of buildings where extensive or timely controls are still insufficient to define a practical and rapid method for the detection of small-scale seismic risk related to structural heights.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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