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CENTRAL ITALY EARTHQUAKE: A STATISTICAL ANALYSIS OF THE OBSERVED DAMAGE DATABASE

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Abstract

In the last 120 years, Italy has been devastated by seven seismic events that had a magnitude equal to or greater than 6.5. These events have caused substantial economic damage, estimated for the last 50 years at more than 150 billion euros, which has been used for post-event recovery and reconstruction. Therefore, an adequate assessment of the vulnerability of existing construction to define sound seismic risk mitigation strategies is of paramount importance.
In particular, this paper focuses on the analysis of damage observed after the 2016 Central Italy seismic sequence; it presented characters of unprecedented complexity due to the repetition of events, with three shocks of magnitude equal to 6 or greater than 6, and the extension of the affected area.
The activities for post-earthquake damage and usability assessment involved the Italian Civil Protection Department and its technical components, thanks to which more than 89000 residential buildings were surveyed. These data were made available by the Italian Civil Protection Department through the web platform Da.D.O. (Database of Observed Damage). The available data are herein presented and discussed, focusing on damage detected on buildings with different structural typologies and considering the different vertical resistant systems. The observed damage is studied with reference to the most severe seismic events identified during the 2016–2017 earthquake sequence, with the aim of analyzing the effects of cumulative structural damage as a first step towards the implementation of an urban-scale vulnerability model capable of accounting for such effects in selected building typologies.

Keywords: Seismic event, Typological class, Cumulative damage, Survey.

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1 INTRODUCTION

The increasing frequency of strong seismic events and their devastating impact on urban areas have highlighted the urgent need for reliable tools to assess the seismic vulnerability of the built environment. The ability to accurately evaluate the expected damage to buildings plays a crucial role in estimating seismic risk, which is a fundamental input for decision-making in both emergency response and long-term risk mitigation planning [1], [2], [3], [4].

In particular, the definition of fragility functions—which describe the probability of reaching or exceeding certain damage states as a function of seismic intensity—relies heavily on the quality and representativeness of observed post-earthquake damage data. These empirical data are essential not only for calibrating vulnerability models but also for supporting the development of future loss scenarios, which may include both economic losses (e.g., repair costs, loss of function) and social impacts (e.g., displacement, safety concerns).

In this context, various authors have contributed to the development of empirical approaches for the assessment of seismic vulnerability ([5-16]), whose works have provided robust methodologies for correlating observed damage to building typology and seismic intensity. Their studies have also supported national and international strategies for post-earthquake damage surveys and risk assessment.

An additional aspect of increasing relevance is the cumulative effect of multiple seismic events, which can progressively weaken structural systems even in the absence of complete collapse. Some recent contributions [16-18]have begun to explore this phenomenon, emphasizing the need to incorporate damage accumulation into vulnerability assessment frameworks.

This study analyzes post-earthquake data collected through the Italian AeDES forms [20] (Level 1 Form for Post-Earthquake Damage and Usability Assessment and Emergency Countermeasures in Ordinary Buildings), with the aim of investigating the effects of cumulative damage and comparing the seismic performance of different structural typologies.

The analysis focuses on data from the 2016–2017 Central Italy earthquake sequence, which, due to the succession of multiple damaging events, offers a unique opportunity to explore damage accumulation over time.

After an initial overview of the surveyed building stock, the study concentrates on residential buildings, particularly unreinforced masonry and reinforced concrete structures, which are the most representative in the affected area. The results are intended to support future empirical calibration of fragility curves for regional seismic risk assessment.

2 THE 2016-2017 CENTRAL ITALY EARTHQUAKE

The 2016–2017 Central Italy seismic events, referred to by the Italian National Institute of Geophysics and Volcanology (INGV) as the Amatrice-Norcia-Visso seismic sequence, began on August 24, 2016, with two strong earthquakes occurring an hour apart, with epicenters near Accumoli and Norcia. The mainshock (M_w 6.0) severely affected the Lazio, Umbria, Marche, and Abruzzo regions, characterized by complex mountainous terrain, low urbanization, and numerous medieval settlements.

After an initial attenuation phase, the sequence intensified on October 26, 2016, with two events (M_w 5.4 and 5.9) in the Macerata area. The strongest shock occurred on October 30, 2016 (M_w 6.5), with an epicenter between Norcia and Preci, causing widespread and severe damage, among the most destructive in Italy in the past century.

On January 18, 2017, four additional strong shocks (M_w 5.0–5.5) struck the L'Aquila province, further south, marking a new phase of the ongoing seismic crisis.

3 POST-ERTHQUAKE DAMAGE SURVEYS

The number and intensity of seismic events significantly complicated both emergency management and damage assessment. Repeated strong shocks led to cumulative structural damage, challenging standard inspection protocols. Initially, building inspections were carried out by qualified structural engineers using the AeDES form. By late October 2016, around 30,000 inspections had been completed on public, private, and school buildings.

To expedite safety assessments and support reoccupation, a simplified procedure—FAST (Post-Earthquake Rapid Survey for Synthetic Usability)—was introduced with Directive ODCPC no. 405 (10 November 2016). The FAST procedure allowed for rapid assessments to be conducted either on single buildings or on entire areas. The outcome, recorded in a simplified form, aimed to essentially distinguish between usable and unusable buildings due to structural or external risks or, in extreme cases, called for an AeDES survey.

During the Central Italy seismic crisis, a total of 89,268 AeDES forms were collected and digitized. This number corresponds exactly to the total number of inspections carried out on buildings, which represent the Structural Units (US), including repeated assessments performed either after subsequent seismic events or upon request by the property owner due to disagreement with the initial outcome.

The analysis of the number of the total buildings surveyed using the AeDES form by seismic event, as shown in Figure 1, highlights a non-uniform distribution of inspections across the three most severe seismic events. Between August 24, 2016, and October 26, 2016, a total of 29,396 buildings were surveyed, corresponding to 32.9% of the total—reflecting the immediate response to the initial seismic event of August 24. In the subsequent period, from October 27, 2016, to January 17, 2017, the number of inspections decreased, with 19,472 buildings surveyed, accounting for 21.8% of the total. Finally, starting from January 18, 2017, the highest number of inspections was recorded, with 40,397 buildings surveyed, representing 45.3% of the overall total.

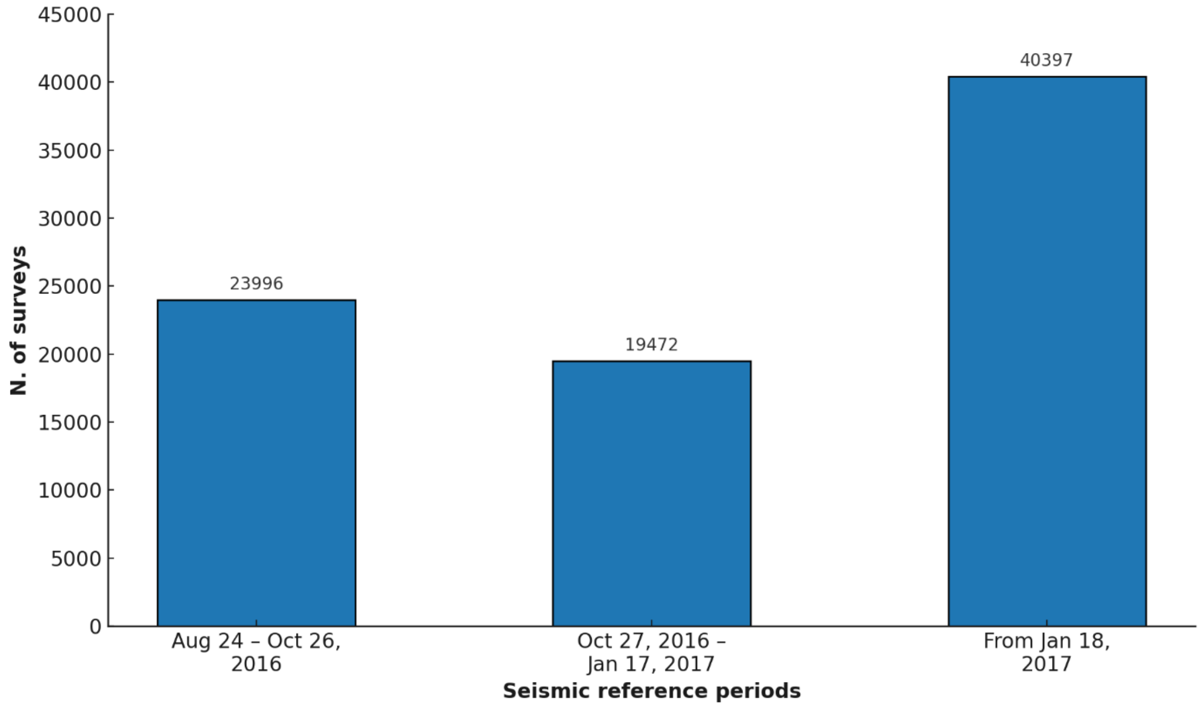

Figure 1 N° of buildings surveyed after the main seismic events.

Based on the data reported in Section 3 of the AeDES form, it is possible to identify the structural typologies; Figure 2 illustrates the distribution of buildings among the various typological classes. Several noteworthy considerations can be drawn from this data:

- prevalence of unreinforced masonry structures (U.R.M.), with 67,281 inspections. This prevalence reflects the characteristics of the built environment in many Italian historic centers, where traditional load-bearing masonry often constructed with stone or brick is predominant;
- reinforced concrete (R.C.) structures registered a total of 10,525 surveyed. Although this typology accounts for a smaller share compared to masonry buildings, it nonetheless represents a substantial portion of the building stock;
- mixed structures (masonry and reinforced concrete): this category comprises 7,361 inspections, indicating a significant number of structures that have undergone partial retrofitting or structural modifications over time, often involving the addition of reinforced concrete elements to existing masonry systems;
- other structural typologies (steel, timber, etc.): with only 1,047 inspections, this category remains marginal. The data suggest that the use of modern, lightweight construction materials is still limited in these regions;
- buildings with unspecified structural typology: for 2,975 inspections, the structural typology was not reported in the survey, highlighting potential gaps in data collection or classification;
- buildings with multiple structural typologies (more than one principal structural system flagged in the form) are registered only in 73 inspections. This suggests two possible explanations: either an error in the compilation of the form, or that hybrid structural configurations involving multiple primary load-bearing materials are actually quite rare.

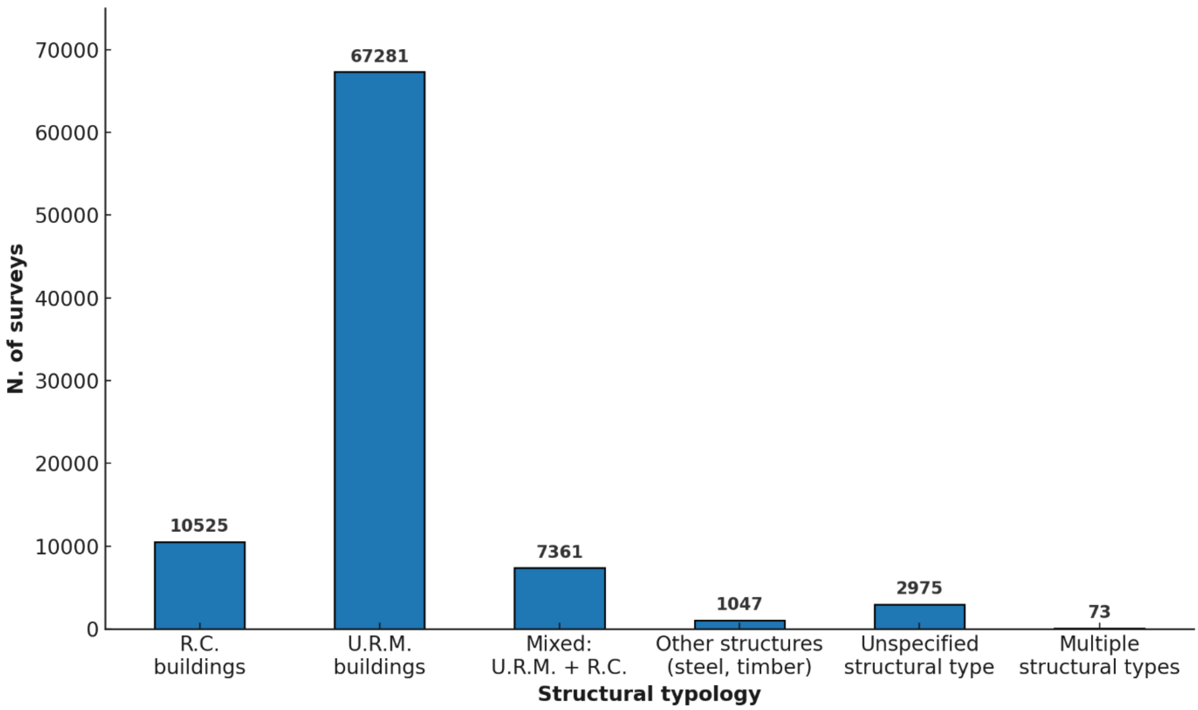

Figure 2 N° of surveys on buildings with different structural typologies.

4 RESIDENTIAL BUILDING STOCK OVERVIEW

A total of 67,281 surveys on masonry residential buildings and 6,276 surveys on reinforced concrete residential buildings were recorded through the AeDES forms following the 2016–2017 Central Italy seismic sequence. The temporal disaggregation of the data provides an opportunity to analyze how the observed damage evolved over the course of the seismic sequence and to investigate the potential cumulative effects of repeated seismic events on different structural typologies.

Focusing on masonry buildings, 22,853 were surveyed in the first period (from August 24 to October 26, 2016), followed by 13,895 in the second period (from October 27, 2016 to January 17, 2017), and 30,530 in the third period (from January 18, 2017 onward). The data show a significant increase in the number of assessments after the last most severe event, which may be attributed both to the occurrence of additional seismic events and to the progressive expansion of the survey activities over time linked to the transfer of surveying operations to regional and reconstruction offices.

As for reinforced concrete residential buildings, 1,797 were surveyed during the first period, 1,439 in the second, and 3,040 in the third. The distribution follows a similar pattern to that observed for masonry buildings, with nearly half of the total number of assessments carried out after January 18, 2017. This temporal trend reinforces the need to explore the extent to which cumulative damage may have influenced usability assessments and structural conditions, particularly in cases where buildings were subjected to multiple seismic shocks before being inspected.

5 DAMAGE ASSESSMENT IN RESIDENTIAL BUILDINGS

The following analysis focuses on the municipalities of Amatrice, Accumoli, and Arquata del Tronto, which were among the most severely affected by the 2016–2017 Central Italy seismic sequence. According to the Italian Department of Civil Protection, these municipalities were subject to systematic and comprehensive surveys after the three most severe seismic events, making them particularly suitable for a detailed investigation of post-earthquake damage in residential buildings.

The damage information considered in this study is derived from Section 4 of the AeDES form, which classifies damage levels as follows: D0: no damage, D1: slight damage, D2–D3: moderate to heavy damage (grouped), D4–D5: - very severe damage to collapse (grouped).

For each structural component—vertical structures, floors, stairs, roof, infills, and partitions—the extent of the damage is also recorded, distinguishing three categories of affected area: less than 1/3, between 1/3 and 2/3, and more than 2/3 of the component's surface.

In order to perform a consistent analysis and comparison of the damage severity, the AeDES data are converted into the EMS-98 damage scale [21], which defines six levels of damage from D0 (no damage) to D5 (collapse). Appropriate conversion rules are applied separately for unreinforced masonry and reinforced concrete (R.C.) buildings to account for their specific structural behaviors, as described in the following subsections.

In the following sections, cumulative damage distributions will be presented separately for the two main structural typologies, starting with U.R.M. buildings, followed by R.C. buildings. The analysis aims to explore how repeated seismic events influenced structural degradation and contributed to increased vulnerability.

5.1 Residential Unreinforced Masonry Buildings

The analysis of U.R.M. residential buildings represents a fundamental step in understanding the impact of the 2016–2017 Central Italy earthquake sequence on the most prevalent structural typology in the affected areas. In order to assess the severity and progression of damage, the information collected in Section 4 of the AeDES form was converted to the EMS-98 damage scale using the conversion method proposed by Rota et al. (2008) [6], which has become a widely accepted approach for the global damage state (DS) for masonry structures.

In this method, the global damage grade of a building is defined as the maximum level of damage observed among three key structural components: vertical structures (load-bearing walls), floors, and roof.

This approach reflects a conservative yet effective representation of the building's overall structural condition, as damage to any of these main elements can significantly compromise safety and usability.

The cumulative damage distributions are analyzed considering the three most severe seismic events identified in § 2, focusing on the municipalities of Accumoli, Amatrice, and Arquata del Tronto, where detailed and repeated surveys allow a consistent comparison of damage evolution over time.

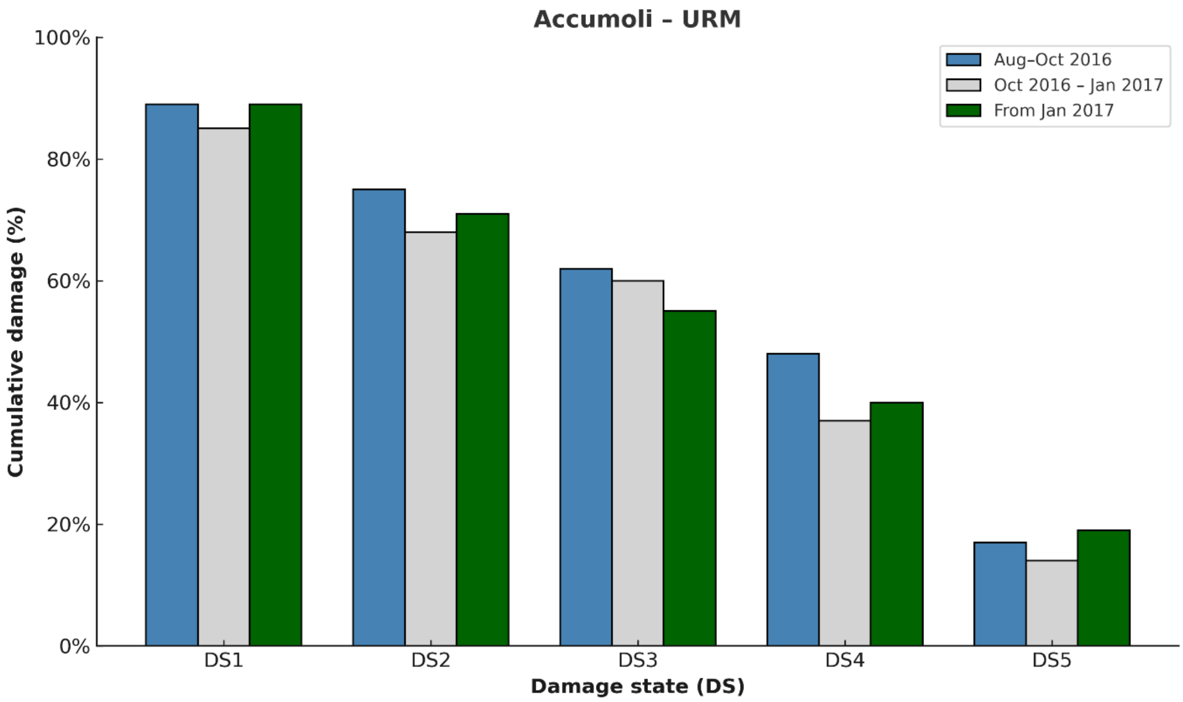

Figure 3 Cumulative Damage Distribution URM– Accumoli

Figure 3 shows the cumulative damage distribution across the five damage states (DS1–DS5) for the municipality of Accumoli, disaggregated considering the three most severe seismic events. The data highlight a significant level of damage affecting the building stock, consistent with field observations and previous studies that identified Accumoli as one of the most severely impacted areas during the Central Italy seismic sequence.

The cumulative damage curves remain relatively high after each most severe event and for all damage states, particularly for DS1 and DS2, where more than 85% and 70% of surveyed buildings respectively exhibit damage levels equal to or exceeding those thresholds. A progressive decline is observed for more severe damage states, with DS5 (collapse) involving around 15–19% of surveyed buildings, depending on the reference seismic event considered.

It is important to note that the apparent reduction in cumulative damage observed after the second and the third most severe seismic events, especially at higher damage states, may be partially attributed to survey limitations. Specifically, buildings that collapsed or were deemed inaccessible after the second mainshock were often not surveyed again, leading to a potential underrepresentation of the most heavily damaged structures in subsequent assessments. This factor must be carefully considered when interpreting damage progression over time, as it may introduce a downward bias in the damage estimates.

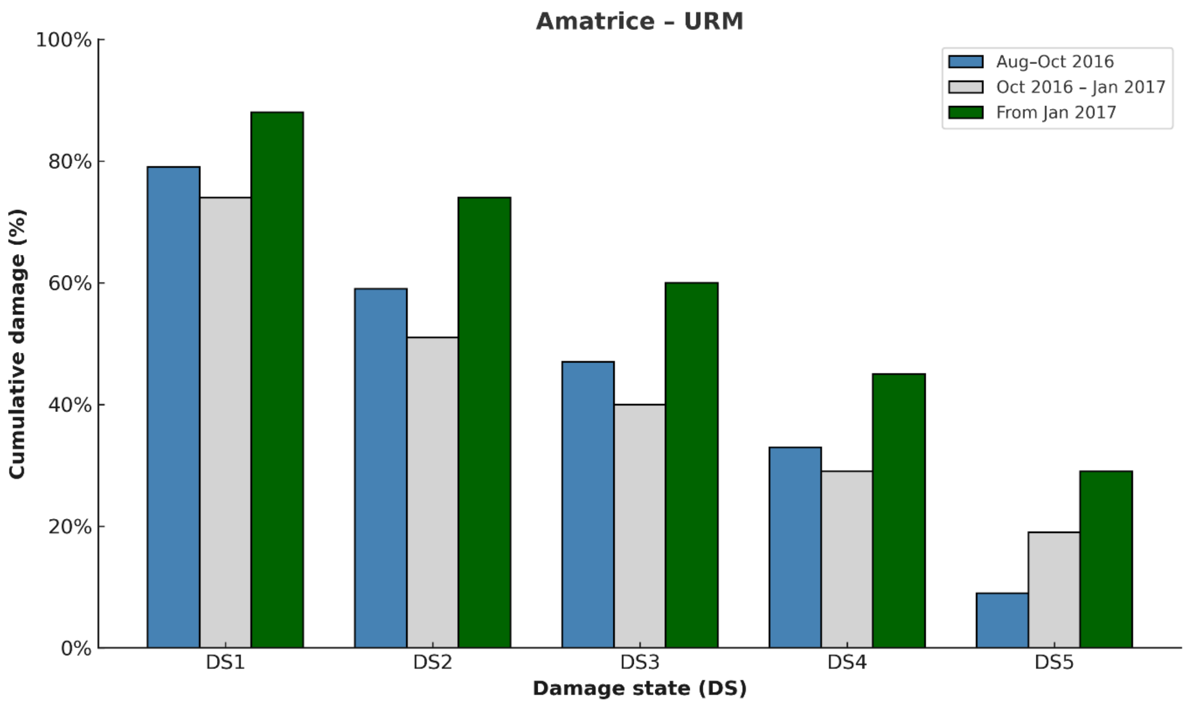

Figure 4 Cumulative Damage Distribution URM– Amatrice

The cumulative damage distribution for the municipality of Amatrice (Figure 4) reveals a marked progression of structural damage after the three seismic events considered. The data show a consistent increase in the percentage of buildings experiencing higher damage states, particularly after the most severe seismic event (from January 2017 onward), where the share of buildings reaching DS4 and DS5 rises significantly compared to earlier phases. This trend reflects the cumulative impact of repeated seismic loading on an already weakened building stock and is consistent with the well-documented severity of damage observed in Amatrice, one of the most affected municipalities during the Central Italy earthquake sequence. It is worth noting that the apparent escalation in damage levels may, in part, be influenced by the loss of buildings due to collapse after the second mainshock, which could have led to underrepresentation in subsequent surveys. Nonetheless, the increase in cumulative damage percentages, particularly at the most severe levels (DS4–DS5), supports the interpretation of a progressive deterioration of structural integrity and highlights the need to consider damage accumulation when assessing post-seismic vulnerability

The cumulative damage distribution for Arquata del Tronto (Figure 5) indicates a clear and progressive deterioration of the building stock over the course of the seismic sequence. Damage percentages increase consistently across all damage states after the third most severe event (from January 2017 onward), with particularly marked rises in the most severe categories. After the last most severe seismic event, 64% of surveyed buildings had reached at least DS4, and 45% had experienced DS5-level damage, a substantial increase compared to earlier most severe seismic events. These figures suggest a high vulnerability of the built environment, likely exacerbated by the cumulative effects of repeated seismic events and the presence of already weakened or partially damaged structures. As with other heavily impacted municipalities, the interpretation of this damage progression must account for possible data gaps, particularly the absence of post-collapse surveys for buildings destroyed after the second mainshock. Nonetheless, the steep rise in cumulative damage levels in the final phase reinforces the importance of considering repeated shaking effects and long-term degradation when assessing post-seismic safety and planning reconstruction efforts.

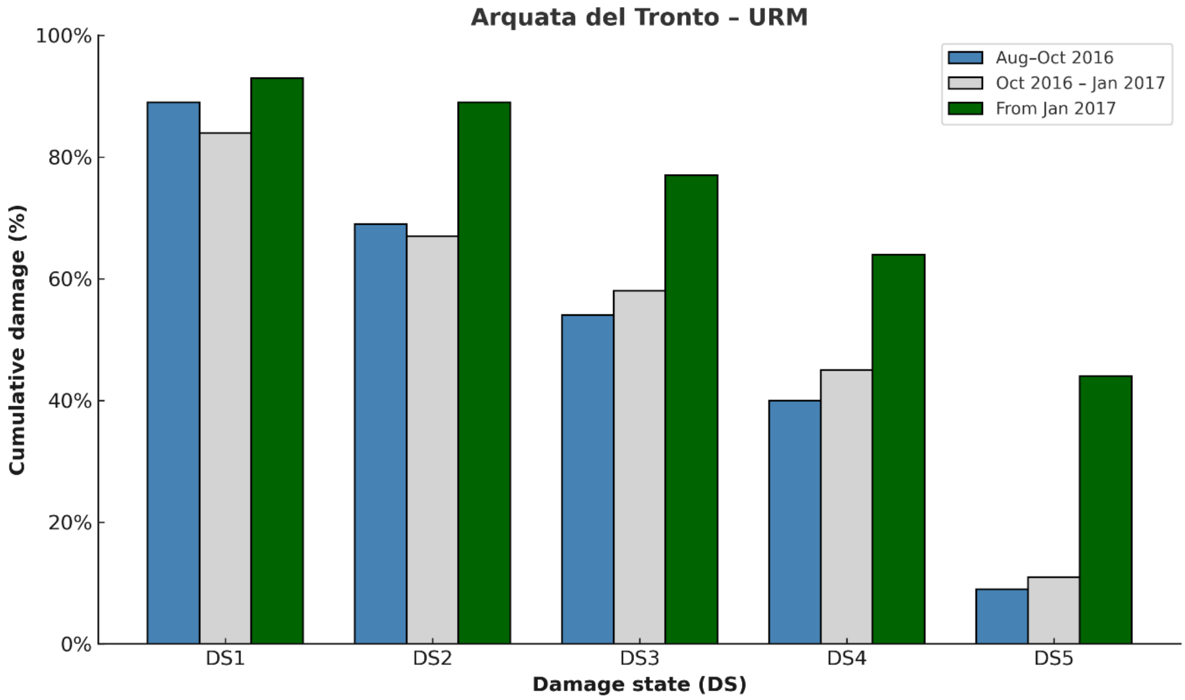

Figure 5 Cumulative Damage Distribution URM – Arquata del Tronto

5.2 Residential Reinforced Concrete Buildings

For reinforced concrete residential buildings, the conversion of damage levels reported in the AeDES forms to a global damage state according to the EMS-98 scale was carried out using the method proposed by Del Gaudio et al. (2017) [5]. This approach defines the global damage state as the maximum damage level observed among two key components: vertical structural elements, and infills and partitions.

This methodology is widely acknowledged and adopted within the scientific community, particularly because it captures a fundamental aspect of R.C. building behavior: the significant role of infill panels in the overall damage process. Unlike in masonry buildings, where infills are an integral part of the load-bearing system, in R.C. structures, they are non-structural elements that nonetheless strongly influence —when properly integrated into the structural framework— the seismic response and the perceived level of damage. Therefore, their inclusion in the damage assessment is essential to provide a more realistic representation of the building's condition after an earthquake.

In analogy with the analysis carried out for unreinforced masonry buildings, the following sections present the cumulative damage distributions for R.C. structures in the three most affected municipalities—Accumoli, Amatrice, and Arquata del Tronto— after the three most severe seismic events defined earlier.

The cumulative damage distribution for R.C. buildings in Accumoli (Figure 6) highlights a clear increase in the extent of damage over the three seismic events. In the first period (Aug–Oct 2016), most buildings fall into the DS1 (slight damage) state (~65%), with relatively low values for the higher damage states. In the second period (Oct 2016 – Jan 2017), the distribution remains similar for DS1 and DS2, but an increase is observed in DS4 (severe damage), suggesting that the later shocks triggered additional degradation in a subset of buildings. After the most severe seismic event (from Jan 2017), there is a significant increase in DS1 (reaching nearly 78%) and a more evident shift towards higher damage states, particularly DS2 and DS3, which may reflect the accumulation of damage from repeated events and the vulnerability of non-structural elements, such as infills. The proportion of buildings reaching DS5 (collapse) appears limited after the three most severe seismic events; however, this may be partially misleading, as collapsed buildings are typically excluded from subsequent surveys even though some were directly documented by Civil Protection Department teams, albeit with a rather high degree of uncertainty in correctly identifying the structural typology. Moreover, considering that Accumoli suffered extensive destruction following the October events, the actual severity of damage may be underrepresented in the dataset. This highlights the importance of interpreting cumulative damage distributions in light of data collection limitations, especially when assessing the overall impact on the built environment.

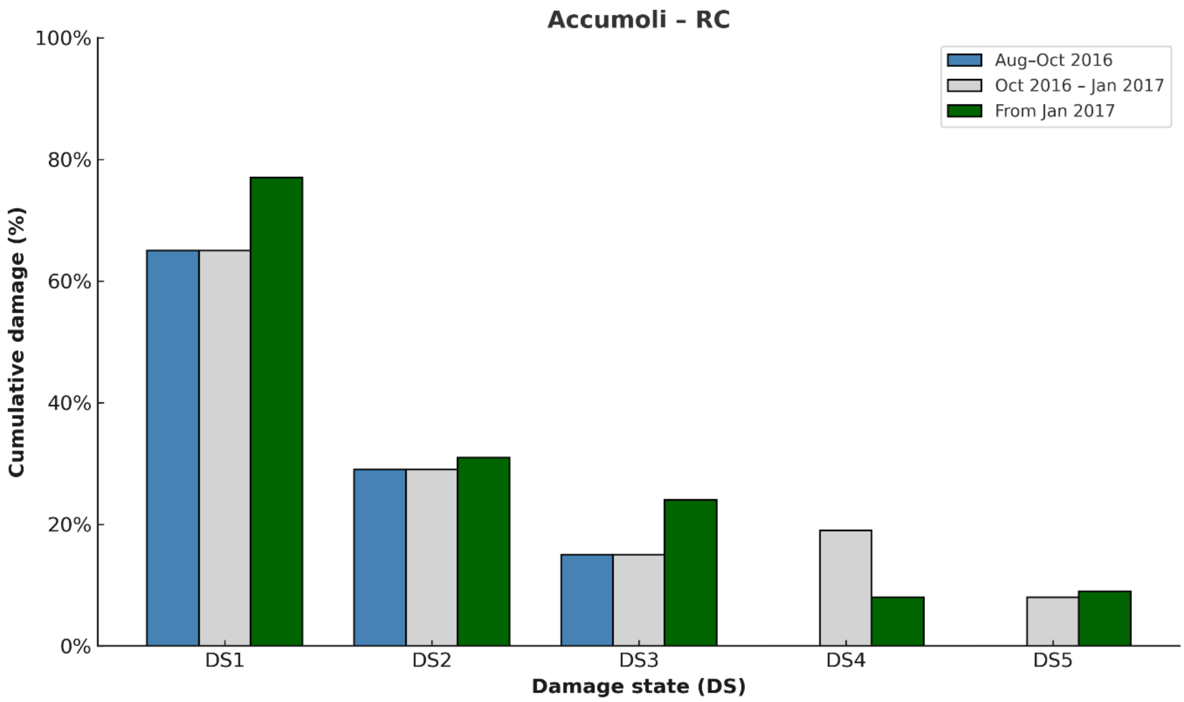

Figure 6 Cumulative Damage Distribution RC – Accumoli

The cumulative damage distribution for R.C. buildings in Amatrice (Figure 7) reveals a progressive increase in damage after the three most severe seismic events. During the first period

(August–October 2016), most buildings are classified in DS1 (slight damage) (~61%), with a smaller portion reaching DS2 and DS3, and very limited cases in higher damage states.

In the second period (October 2016 – January 2017), a notable change is the appearance of damage states DS4 and DS5, which were absent in the initial surveys, indicating that the later shocks triggered more severe damage in a subset of buildings.

In the third period (from January 2017), the distribution continues to shift, with a further increase in DS1, reaching nearly 80%; a marked rise in DS2 and DS3, suggesting accumulation of damage; and a clearer presence of DS4 and DS5, though still limited in absolute terms.

These trends highlight how repeated seismic events accentuated the vulnerability of R.C. buildings. As in Accumoli, the exclusion of collapsed buildings from subsequent surveys may lead to a partial underestimation of the actual extent of severe damage.

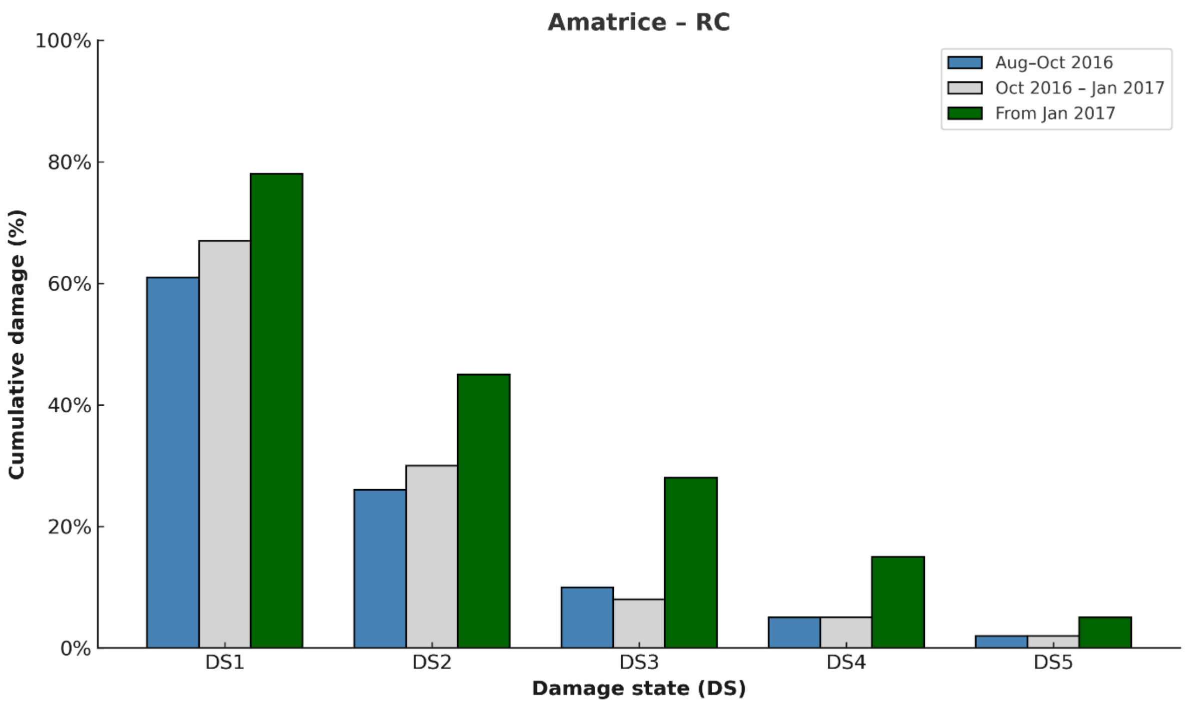

Figure 7 Cumulative Damage Distribution RC – Amatrice

The cumulative damage distribution for R.C. buildings in Arquata del Tronto (Figure 8) presents a different evolution compared to the other municipalities. During the first period (August–October 2016), the damage was primarily concentrated in DS1 (around 65%) and DS2, with a very limited presence in the higher damage states.

A substantial shift occurs in the second period (October 2016 – January 2017), where a significant increase is observed in DS2 and DS3, accompanied by the emergence of DS4 and DS5. This suggests that the shocks of late October—particularly the event of October 30th—had a severe impact on the R.C. building stock in Arquata, more so than in the previous phase.

In the third period (from January 2017), the trend appears to partially reverse: the percentage of buildings in DS1 increases, while the higher damage states slightly decrease compared to the second period. This behavior might reflect the possible exclusion of severely damaged or collapsed structures already assessed after the first two most severe seismic events or demolished after the earlier events.

As for the other municipalities, these results highlight the need for careful interpretation of cumulative damage data, which depend not only on the actual progression of structural damage but also on the modalities and timing of post-earthquake surveys.

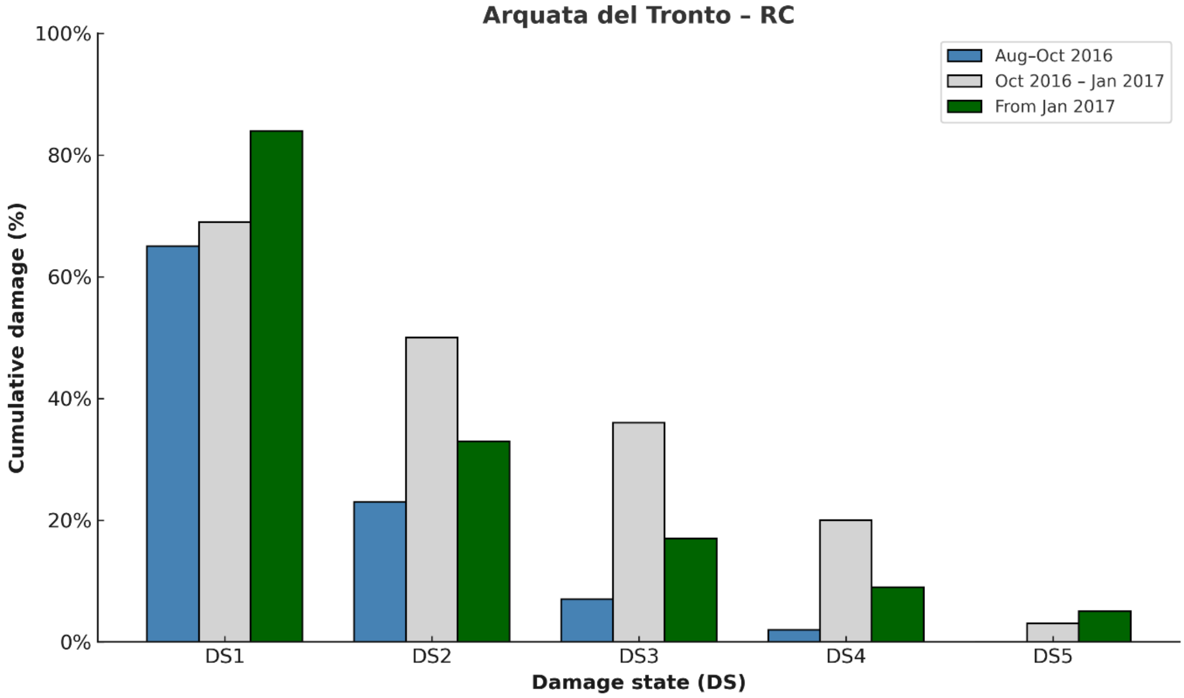

Figure 8 Cumulative Damage Distribution RC – Arquata del Tronto

6 CONCLUSIONS

This study presented a statistical analysis of post-earthquake damage data collected through AeDES forms following the 2016–2017 Central Italy seismic sequence. The analysis focused on residential buildings, with particular attention to the two main structural typologies in the affected area: unreinforced masonry and reinforced concrete structures.

Starting from a general overview of the surveyed building stock and its typological classification, the study concentrated on the three municipalities most severely impacted by the seismic sequence—Accumoli, Amatrice, and Arquata del Tronto. For each, cumulative damage distributions were examined over the three most severe seismic events. The conversion of AeDES damage data into the EMS-98 scale allowed for a standardized and comparative evaluation of structural damage levels.

For unreinforced masonry buildings, the analysis revealed a widespread and severe level of damage, with a large proportion of buildings reaching advanced damage states (DS4–DS5), particularly following the last event of the seismic sequence. The results confirm the high vulnerability of traditional masonry construction and the progressive degradation of structural performance due to repeated seismic shaking.

In the case of R.C. buildings, damage levels were generally lower than UMR for initial events; they were mainly DS1 and DS2. However, significant shifts toward higher damage states were observed after the second and third main seismic event of the sequence, especially in Amatrice and Arquata del Tronto, indicating that repeated seismic events had a significative cumulative impact even on structures and non-structural elements with nominally higher seismic capacity. The inclusion of non-structural elements—infills and partitions—in the damage assessment proved essential for accurately capturing the extent of degradation in R.C. buildings.

The comparative analysis between the two typologies shows that masonry buildings experienced more widespread and severe damage overall, whereas R.C. buildings demonstrated greater initial resistance but they were still susceptible to cumulative effects over time. In both cases, the progression of damage highlights the need to consider not only the severity of individual events, but also the combined impact of multiple shocks.

These findings suggest that cumulative damage is a real and measurable phenomenon that deserves further investigation. Future studies should focus on refining typological classification—both unreinforced masonry and reinforced concrete structures—based on meaningful parameters such as construction timespan and number of stories. Moreover, to develop robust vulnerability and risk models, it is essential to associate observed damage levels with appropriate seismic intensity measures, enabling a more accurate correlation between ground motion and structural performance.

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REFERENCES

[1] M. Dolce *et al.*, "Seismic risk assessment of residential buildings in Italy," *Bulletin of Earthquake Engineering*, no. 0123456789, 2020, doi: 10.1007/s10518-020-01009-5.

[2] A. Masi, S. Lagomarsino, M. Dolce, V. Manfredi, and D. Ottonelli, *Towards the updated Italian seismic risk assessment: exposure and vulnerability modelling*, no. 0123456789. Springer Netherlands, 2021. doi: 10.1007/s10518-021-01065-5.

[3] B. Borzi *et al.*, "IRMA platform for the calculation of damages and risks of Italian residential buildings," *Bulletin of Earthquake Engineering*, vol. 19, no. 8, 2021, doi: 10.1007/s10518-020-00924-x.

[4] V. Silva, H. Crowley, H. Varum, and R. Pinho, "Seismic risk assessment for mainland Portugal," *Bulletin of Earthquake Engineering*, vol. 13, no. 2, pp. 429–457, 2014, doi: 10.1007/s10518-014-9630-0.

[5] C. Del Gaudio *et al.*, "Empirical fragility curves from damage data on RC buildings after the 2009 L'Aquila earthquake," *Bulletin of Earthquake Engineering*, vol. 15, no. 4, pp. 1425–1450, 2017, doi: 10.1007/s10518-016-0026-1.

[6] M. Rota, A. Penna, and C. L. Strobbia, "Processing Italian damage data to derive typological fragility curves," *Soil Dynamics and Earthquake Engineering*, vol. 28, no. 10–11, pp. 933–947, 2008, doi: 10.1016/j.soildyn.2007.10.010.

[7] A. Rosti, M. Rota, and A. Penna, "Empirical fragility curves for Italian URM buildings," *Bulletin of Earthquake Engineering*, vol. 19, pp. 3057–3076, 2021, doi: 10.1007/s10518-020-00845-9.

[8] S. Lagomarsino, S. Cattari, and D. Ottonelli, “The heuristic vulnerability model: fragility curves for masonry buildings,” *Bulletin of Earthquake Engineering*, vol. 19, no. 8, pp. 3129–3163, Jun. 2021, doi: 10.1007/s10518-021-01063-7.

[9] F. da Porto *et al.*, “Comparative analysis of the fragility curves for Italian residential masonry and RC buildings,” *Bulletin of Earthquake Engineering*, vol. 19, no. 8, 2021, doi: 10.1007/s10518-021-01120-1.

[10] M. Zucconi and L. Sorrentino, “Census-Based Typological Damage Fragility Curves and Seismic Risk Scenarios for Unreinforced Masonry Buildings,” *Geosciences (Basel)*, vol. 12, no. 1, p. 45, Jan. 2022, doi: 10.3390/geosciences12010045.

[11] M. Zucconi, F. Romano, and B. Ferracuti, “Typological fragility curves for RC buildings: influence of damage index and building sample selection,” *Eng Struct*, vol. 266, no. 58, p. 114627, Sep. 2022, doi: 10.1016/j.engstruct.2022.114627.

[12] A. Shabani, M. Kioumarsi, and M. Zucconi, “State of the art of simplified analytical methods for seismic vulnerability assessment of unreinforced masonry buildings,” *Eng Struct*, vol. 239, p. 112280, Jul. 2021, doi: 10.1016/j.engstruct.2021.112280.

[13] V. Cima, V. Tomei, E. Grande, and M. Imbimbo, “Fragility curves at regional basis for unreinforced masonry buildings prone to out-of-plane mechanisms: the case of Central Italy,” *Structures*, vol. 34, no. November, pp. 4774–4787, Dec. 2021, doi: 10.1016/j.istruc.2021.09.111.

[14] M. Zucconi, M. Di Ludovico, and L. Sorrentino, “Census-based typological usability fragility curves for Italian unreinforced masonry buildings,” *Bulletin of Earthquake Engineering*, pp. 1–20, Mar. 2022, doi: 10.1007/s10518-022-01361-8.

[15] M. Zucconi, R. Ferlito, and L. Sorrentino, “Typological Damage Fragility Curves for Unreinforced Masonry Buildings affected by the 2009 L’Aquila, Italy Earthquake,” *The Open Civil Engineering Journal*, vol. 15, no. 1, pp. 117–134, May 2021, doi: 10.2174/1874149502115010117.

[16] A. Shabani, M. Zucconi, D. Kazemian, and M. Kioumarsi, “Seismic fragility analysis of low-rise unreinforced masonry buildings subjected to near- and far-field ground motions,” *Results in Engineering*, vol. 18, no. June, p. 101221, Jun. 2023, doi: 10.1016/j.rineng.2023.101221.

[17] M. E. Rodriguez, “The interpretation of cumulative damage from the building response observed in Mexico City during the 19 September 2017 earthquake,” *Earthquake Spectra*, vol. 36, no. 2_suppl, 2020, doi: 10.1177/8755293020971307.

[18] M. Di Ludovico *et al.*, “Cumulative damage to school buildings following the 2016 central Italy earthquake sequence,” *Bollettino di Geofisica Teorica ed Applicata*, vol. 60, no. 2, 2019, doi: 10.4430/bgta0240.

[19] L. M. Massone, D. Aceituno, and J. Carrillo, “Cumulative damage in RC frame buildings – The 2017 Mexico earthquake case,” *Advances in Computational Design*, vol. 8, no. 1, 2023, doi: 10.12989/acd.2023.8.1.015.

[20] C. Baggio *et al.*, *Manuale per la compilazione della scheda di 1° livello di rilevamento danno, pronto intervento e agibilità per edifici ordinari nell’emergenza post-sismica (AeDES)*, 2nd ed. (in Italian), 2014.

[21] G. Grünthal, *Cahiers du Centre Européen de Géodynamique et de Séismologie: Volume 15 – European Macroseismic Scale 1998*. Luxembourg: European Center for Geodynamics and Seismology, 1998.