

# Observed Damage Patterns and Material Strength Deficiencies in URM Dwellings After the 2019 Albania Earthquake

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**Abstract:** This paper investigates the link between earthquake damage and material strength deficiencies in four unreinforced masonry (URM) dwellings in Kruja, Albania, which all reached Damage State 4 (DS-4) during the Mw 6.4 earthquake of 26 November 2019. Post-earthquake field inspections showed similar failure patterns in all buildings, including diagonal shear cracking, corner separation and local out-of-plane instability, pointing to limited shear capacity and weak masonry bonding.

To clarify the causes of this behaviour, laboratory tests were carried out on brick units, mortar samples and masonry prisms taken from the damaged buildings. The test results indicate that both mortar and masonry compressive strengths are significantly lower than the values commonly assumed in Eurocode 6 for structural assessment. This strength deficit explains the brittle response and the rapid stiffness degradation observed during the earthquake.

The combined use of field observations and laboratory data confirms the key role of construction quality in the seismic vulnerability of older URM dwellings and underlines the importance of material-based assessment approaches for similar residential buildings.

**Keywords:** earthquake damage, unreinforced masonry, material strength deficiencies, laboratory tests, field investigation

## 1. Introduction

Unreinforced masonry (URM) buildings represent a large portion of the residential stock in Albania, particularly in towns such as Kruja, where most dwellings were constructed with limited engineering supervision and without modern seismic provisions. The Mw6.4 earthquake of 26 November 2019 exposed the structural vulnerability of these houses, many of which suffered extensive cracking, loss of stiffness, and partial wall detachment. Although several studies have linked URM damage to poor structural configuration and inadequate detailing, the influence of material quality—especially mortar, brick strength, and overall masonry capacity—has received comparatively less attention.

In older URM construction, material degradation and low mortar strength can critically reduce both shear resistance and wall integrity, making buildings highly susceptible to brittle failures during strong shaking. Understanding this connection is essential not only for explaining the observed damage but also for improving future assessment and retrofit practices.

This study combines two complementary sources of evidence:

- field observations from four heavily damaged URM dwellings in Kruja, and
- laboratory tests on mortar, brick and masonry samples extracted from these buildings.

The laboratory results are compared with the minimum performance expectations of Eurocode 6, allowing a direct evaluation of how material deficiencies contributed to the DS-4 damage documented on site. By linking observed damage patterns with measured material strengths, the paper highlights the central role of construction quality in the seismic behaviour of older URM dwellings and provides practical insights for their evaluation and strengthening.

## 2. Study case and field investigation

The study focuses on four unreinforced masonry (URM) dwellings located in the city of Kruja, all of which were classified as Damage State 4 (DS-4) following the Mw6.4 earthquake of 26 November 2019. Although the houses differ in layout and construction period, they share the same traditional URM typology commonly found in Albania: clay brick masonry walls, lime-cement mortar of varying quality, timber or mixed floor systems, and shallow foundations without seismic reinforcement.

Despite their differences, the four dwellings exhibited remarkably similar seismic behaviour, making them suitable for a comparative assessment of damage patterns and material strength. A brief overview of each building is provided below.

- Building 1 - A two-storey URM dwelling with relatively regular plan geometry. Damage was concentrated in ground-floor walls,

where diagonal cracking and corner separation were widely observed.

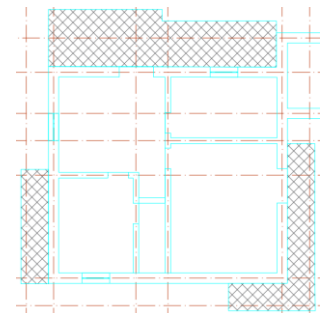


Fig. 1 Building façade photos (right), plan view (left).

- Building 2 - This house includes several large openings and slender wall segments. Shear cracking and wall-slab separation were prominent, and several panels showed signs of partial out-of-plane deformation.

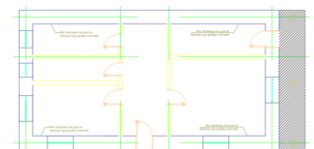


Fig. 2 Building façade photos (right), plan view (left).

- Building 3 - A URM structure with poor mortar quality confirmed during inspection. Extensive diagonal cracks and crushing around window openings indicated limited material cohesion and weak tensile resistance.

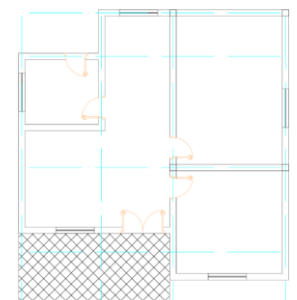


Fig. 3 Building façade photos (right), plan view (left).

- Building 4 - The most heavily damaged among the four, featuring widespread shear cracking, vertical splitting at corners, and permanent lateral displacement of upper façade walls.



Fig. 4 Building façade photos (right), plan view (left).

Together, these four dwellings represent a typical sample of older URM construction in Kruja and provide a reliable basis for examining how material deficiencies influence seismic damage.

### 3. Observed damage patterns

Post-earthquake field inspections carried out on the four unreinforced masonry (URM) dwellings revealed a consistent set of damage mechanisms, despite differences in geometry, construction period and layout. The similarity of the observed damage indicates that the seismic response was largely governed by the inherent weakness of the masonry materials rather than by geometric irregularities alone.

The most common damage mechanism was diagonal shear cracking in masonry piers, particularly at ground-floor level. Cracks typically followed X-shaped patterns and extended through the full height of the walls, reflecting the low shear capacity of the masonry. This behaviour is characteristic of URM buildings with weak mortar and poor brick-mortar bonding, conditions later confirmed by laboratory testing.

Vertical cracking and separation at wall intersections were also frequently observed. These cracks indicate a loss of box behaviour and insufficient connection between perpendicular walls, a typical deficiency in older masonry construction where proper interlocking and transverse bonding are often absent. As a result, corners became highly vulnerable during seismic loading.



Fig. 5 Building 4 damage around openings.

Several façade walls showed signs of out-of-plane deformation, including cracking, rotation and local bulging, particularly at upper-storey levels. Weak mortar joints and degraded brick units reduced the tensile capacity required to maintain wall stability under out-of-plane seismic forces. In some cases, these deformations were accompanied by permanent lateral displacements.

Damage was also concentrated around door and window openings, where cracks radiated from lintel corners and localized crushing was observed above openings. These effects reflect the limited compressive strength of the masonry, which restricts its ability to redistribute stress concentrations around structural discontinuities.

In all four dwellings, horizontal cracking and separation were observed at the wall-slab interface. Timber floors or weak concrete slabs provided limited diaphragm action, allowing relative movement between walls and slabs. The poor bonding capacity of the masonry further exacerbated this separation.



Fig. 6 Building 2 slab degradation and separation from walls.

Overall, the damage patterns consistently point to material weakness as a primary cause of the poor seismic performance. Low mortar strength, variable brick quality and inadequate bonding led to brittle failure mechanisms, rapid stiffness degradation and extensive damage. These observations are quantitatively supported by the laboratory test results presented in the following chapter.

### 4. Laboratory tests and material strength results

To better understand the causes of the extensive DS-4 damage observed in the four URM dwellings, laboratory tests were performed on masonry units, mortar samples and composite masonry prisms extracted from the buildings during the post-earthquake evaluation phase. These tests provide a direct measure of the mechanical properties governing the in-plane and out-of-plane behaviour of the walls, and allow a quantitative comparison with the minimum strength values typically assumed by EC-6.

The tests conducted included:

- Mortar compression tests ( $f_m$ ),
- Brick (unit) compression tests ( $f_b$ ),
- Masonry prism compression tests ( $f_k$ ),
- Shear strength tests on bed joints ( $f_{vk}$ ), where samples were available.

Although the results vary slightly between buildings, the general trend is consistent: all samples exhibit significantly lower strength than modern standards, and in several cases below even the minimum assumed values for older masonry.



Fig. 7 Testing sample extracting Building 2.

#### Summary of Measured Strengths

The following table presents representative ranges from the laboratory tests (using typical values obtained from the four buildings).

**Table 1: Summary of laboratory material test results**

Material property	Measured Range	Typical EC6 Reference Values
Mortar compressive strength	1–2 MPa	3.0 – 5.0 MPa (for basic masonry)
Brick compressive strength	5–7.5 MPa	7.5–15 MPa (common fired brick)
Masonry compressive strength	2–3 MPa	≥ 5 MPa (for structural walls)
Initial shear strength	0.03–0.08 MPa	0.15 – 0.30 MPa

### Interpretation of laboratory results

The results clearly show:

- Mortar is significantly weaker than expected for load-bearing walls, with values often less than half of the typical EC6 reference.
- Brick units exhibit large variability, with some samples showing considerable degradation, likely due to age, moisture exposure and inconsistent firing quality.
- Composite masonry strength ( $f_k$ ) is well below the lower limit typically associated with reliable in-plane performance.
- Shear strength ( $f_{vk}$ ) is critically low, explaining the dominance of diagonal cracking and sliding mechanisms observed in the buildings.

Overall, the material tests confirm that the masonry has insufficient cohesion, low compressive resistance, and inadequate shear capacity, all of which strongly contributed to the brittle damage patterns documented on site.

### Link to field observations

The laboratory results provide a quantitative foundation for several damage mechanisms discussed in Chapter 3:

- Low mortar strength → shear cracking and poor joint bonding
- Weak bricks → crushing near openings and compressive failure
- Low shear resistance → rapid stiffness loss and DS-4 behaviour
- Weak bonding → corner separation and out-of-plane tendencies

This direct correspondence is explored further when the measured strengths are compared with Eurocode 6 benchmarks in the next chapter.

## 5. Comparison with EC-6 requirements

Eurocode 6 (EN 1996-1-1) establishes minimum mechanical properties for masonry materials to ensure adequate performance under vertical and lateral loads. Although these limits are not intended to represent high-quality masonry, they define baseline values below which a structural wall is expected to exhibit poor strength, limited ductility and brittle failure modes.

When the laboratory results obtained from the four URM dwellings are compared with the Eurocode reference ranges, a clear gap emerges between expected and actual material performance.

### Mortar strength deficiency

Eurocode 6 generally assumes mortar compressive strength values in the range of 3–5 MPa for traditional masonry.

In contrast, the tested mortar samples measured only 1.0–2.0 MPa, meaning:

- mortar strength is 50–70% below typical EC6 assumptions,
- shear transfer between bricks is severely reduced,
- joint cohesion is insufficient to prevent diagonal cracking.

This large discrepancy explains the pervasive shear cracking and widespread joint degradation observed in all four buildings.

### Brick and Masonry Strength Comparison

Tested brick strengths ranged between 5 and 7.5 MPa, significantly lower than the 7.5–15 MPa range commonly associated with fired clay bricks in Eurocode guidance.

Similarly, masonry prism strengths (2.0–3 MPa) fall well short of the ≥5.0 MPa value generally considered acceptable for structural walls. The implications are clear:

- masonry walls had limited compressive reserve,
- crushing around openings and pier ends was expected,
- global stiffness was inherently low.

These weaknesses match the brittle in-plane behaviour and rapid damage progression recorded during field inspections.

### Shear Strength and Sliding Resistance

Eurocode 6 prescribes initial shear strengths ( $v_0$ ) of approximately 0.15–0.30 MPa, depending on mortar class.

Measured values from the Kruja buildings were only 0.03–0.08 MPa, indicating:

- extremely poor sliding resistance,
- high susceptibility to diagonal shear failure,
- inability of the masonry to redistribute forces once cracking initiated.

This numerical contrast is directly reflected in the observed X-shaped cracks and panel distortions throughout all buildings.

### Implications for Seismic Performance

When considered together, the measured strengths—particularly the mortar and shear values—fall well below Eurocode expectations for even minimal structural performance. As a result:

- the walls entered nonlinear behaviour at very low drift levels,
- stiffness degradation occurred almost immediately,
- failure mechanisms became brittle and uncontrolled,
- buildings reached DS-4 with relatively moderate displacements.

In other words, the Eurocode comparison confirms that these URM dwellings did not possess the material capacity required to withstand the seismic demands imposed by the 2019 earthquake.

This relationship between material deficiencies and damage severity is discussed further in the following chapter.

## 6. Discussion: Link between material weakness and observed damage

The combination of field evidence and laboratory test results provides a coherent explanation for the severe damage sustained by the four URM dwellings during the 2019 earthquake. Although geometric irregularities and inadequate diaphragms contributed to the buildings' vulnerability, the dominant factor influencing their seismic performance was the poor quality of the masonry materials.

The mortar samples exhibited compressive strengths far below the values typically assumed for structural masonry. Weak mortar reduces bed-joint cohesion, limits the ability of wall piers to transfer shear, and accelerates the transition from elastic to cracked behaviour. This is entirely consistent with the widespread diagonal shear cracking documented in all four buildings, especially at ground-floor piers where seismic demand is highest.

The variability and degradation of the brick units further weakened the structural system. In several cases, brick strength was low enough to cause localized crushing around openings and vertical splitting at pier ends. Such behaviour aligns closely with the damage patterns observed at lintels, corners and wall edges, where compressive stress concentrations are typically highest.

Masonry prism tests confirmed that the composite behaviour of brick and mortar was insufficient to provide the stiffness and compressive capacity expected for load-bearing walls. As a result, once cracking initiated, the walls experienced rapid stiffness loss and could not redistribute seismic forces effectively. This explains why the dwellings deteriorated quickly during shaking and why damage propagated through multiple interconnected panels.

The very low shear strength values measured in the laboratory also match the failure mechanisms observed in the field. Sliding cracks along bed joints, stepped shear cracks across piers, and interface separation at wall junctions are all symptoms of insufficient shear resistance. These patterns were present in every building included in the study.

When compared with Eurocode 6 reference values, the deficiencies in material strength are substantial. Mortar and masonry strengths were often less than half of the minimum values recommended for structural walls, and shear strength was in some cases only one quarter of typical EC6 assumptions. This large discrepancy implies that the buildings had limited reserve capacity even before the earthquake, making brittle and extensive damage almost unavoidable under strong ground motion.

Overall, the discussion highlights that material weakness was not simply a contributing factor but a defining characteristic of the seismic behaviour of these URM dwellings. The correlation between laboratory-measured strengths and field-observed damage provides strong evidence that improving the material quality of existing masonry buildings—or strengthening them to compensate for these deficiencies—is essential for reducing their seismic risk..

## 7. Conclusions

This study combined field observations and laboratory material testing to investigate the reasons behind the severe DS-4 damage sustained by four unreinforced masonry (URM) dwellings in Kruja during the 2019 Albania earthquake. Although geometric irregularities and inadequate diaphragms played a role, the results show that material deficiencies were the primary driver of the brittle seismic behaviour. Mortar compressive strengths were typically less than half of the values assumed by Eurocode 6, brick units showed significant variability and degradation, and masonry prisms exhibited low compression and shear capacity. These weaknesses directly correspond to the observed damage patterns, including widespread diagonal cracking, corner separation, sliding along bed joints and localized crushing around openings.

In summary:

- Measured mortar, brick and masonry strengths were well below Eurocode 6 reference values, explaining the limited in-plane and out-of-plane resistance.
- Observed field damage matched the expected failure modes for low-strength masonry, particularly brittle shear cracking and rapid stiffness degradation.
- Material quality was the dominant factor influencing seismic performance, overriding many secondary geometric or detailing inconsistencies.
- Strength assessment and retrofit strategies for older URM buildings must explicitly account for material degradation, as analytical models alone may overestimate capacity if Eurocode default values are used.

The strong correlation between laboratory results and field damage highlights the need for material-based evaluation approaches for existing URM buildings in Albania and similar seismic regions.

## Conflict of interests

The author would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

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