

Damage to Ancient Buildings from Earthquakes

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Synonyms

[Archaeoseismology](#); [Archeoseismology](#)

Introduction

Ever since man-made structures have been erected, earthquakes have left their marks on these constructions. The study of earthquake damage can contribute to multidisciplinary efforts to assess parameters of ancient earthquakes from archaeological evidence (archaeoseismology). Initially these studies were aimed at enriching earthquake catalogs; however, recent interest has been targeted to provide quantitative earthquake parameters and describe site effects (Galadini et al. 2006; Sintubin 2011).

Yet, there is widespread skepticism about whether structural damage to man-made constructions, displaced structures, and indications of repair can be used as earthquake indicators. Damage to ancient buildings is often hard to identify, even for experienced archaeologists and engineers (Hinzen 2011). Here we offer a brief overview of earthquake-induced damages observed in ancient structures.

The fabric of the building (masonry, brick, rubble infill between retaining walls, built with or without mortar) has to be thoroughly understood before the analysis and interpretation of archaeoseismological data can be undertaken (Rodríguez-Pascua et al. 2011). Each building material behaves differently under seismic loading; for example, dressed stone walls tend to be rather rigid, while rubble walls have limited elastic properties.

Following the seminal works of Karcz and Kafri (1978) and Stiros (1996), a multitude of studies have listed and illustrated supposed seismic-induced damage of ancient buildings, mostly from the Mediterranean. Korjenkov and Mazor (2003) and Marco (2008) discussed proven or supposed seismic origin of a rich variety of damage features, arranging them in groups of sliding and shifting blocks, fallen columns, chipped block corners, and fractured and deformed walls and floors. Rodríguez-Pascua and his team (2011) established a comprehensive classification of earthquake archaeological effects, of which building damages form the most significant part. However, in-depth analysis, including physical or numerical modeling, is only available for just a few types of structural damage (shifted blocks: Vasconcelos et al. 2006; dropped keystone: Kamai and Hatzor 2008; toppled columns: Hinzen 2009; Yagoda-Biran and Hatzor 2010; for a review, see Hinzen et al. 2011). Complex systems for classifying damage are available (e.g., the genetic approach of Rodríguez-Pascua et al. 2011), but here a simple, descriptive system is used based on the shape of the damage and on whether it involves a single block, multiple blocks, a single wall, adjacent walls, or a whole building.

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Typology of Earthquake-Induced Damages in Ancient Buildings

Archaeoseismology is far from being a science with established methods. However, a few considerations taken into account will help the researcher to recognize, analyze, and interpret earthquake damage in proper context. (1) The older a building, the higher is the chance it has been damaged by seismic activity. (2) Constructions made of meticulously dressed stone provide better records than coarsely worked stone. (3) Buildings neglected since an earthquake offer better record than repaired ones; however, the repair itself can be a source of information on previous structural damage. (4) The history of successive restoration and architectural modification must be understood before seismic analysis is undertaken. In general, ancient structures show no difference in deformation styles than those observed on masonry buildings due to modern earthquakes (Galadini et al. 2006).

Furthermore, finding only one piece of evidence cannot be considered conclusive (Stiros 1996; Mazor and Korjenkov 2001). The identification of different types of deformations, or the repetition of a certain deformation on numerous edifices of a settlement, can be considered as consistent with the occurrence of an earthquake, once other possible natural causes have been excluded (Galadini et al. 2006).

Damage Affecting a Single or Multiple Blocks

The vertical component of a seismic wave moves masonry blocks (ashlars or columns) rapidly up and down. The hammering effect of the upper block on the lower one yields cracks in either or both blocks (Fig. 1a). Penetrating cracks allow a chip, corner, or edge to be separated from the block (Fig. 1b). The direction of the crack is influenced by the lithology of the rock and shape of the block and by direction of hammering. Chipping is not to be confused with rounding or peeling due to weathering as seismically broken chips have sharp edges.

Fractures cutting through two or more blocks are often oriented close to vertical, this being the weakest plane to resist bending forces (Fig. 1c). Fractures through individual blocks are more or less connected to each other, resulting from sudden seismic shaking.

Damage Affecting a Single Wall

Where blocks are arranged as walls, two categories of failure occur: *in-plane* failures, where loads act in the plane of the wall, and *out-of-plane* failures, where loads act at an angle to the wall's face.

The most common in-plane failures are *gaps* between shifted blocks (Fig. 1d), produced by lasting vibrations acting parallel to the wall. Cracks can develop across single or multiple blocks, even across whole walls. Brick walls display *diagonal cracks* near doors and windows. Masonry walls – dressed stones being significantly larger than bricks – generally do not display this feature.

Dropped keystones in arches are widely held to be the most reliable evidence of earthquake damage (Kamai and Hatzor 2008) (Fig. 1e). These are formed during horizontal shaking, if there is no significant vertical load (i.e., when higher parts of the building have already collapsed). In multistory buildings, arches in upper floors get damaged, while lower floors do not exhibit damaged arches. Significant vertical loading tends to hold masonry blocks together through high friction at interfaces.

Broken lintels (Fig. 1f) and thresholds occur widely. These features are not firm evidence for seismic shaking because differential settlement of walls due to inadequate foundation can also produce similar structures.

Common out-of-plane failures are *rotated blocks* (Fig. 1g), whose angle or rotation (clockwise or counter clockwise) reflects the direction of strong motion and the friction between adjacent blocks.



Fig. 1 Typology of earthquake-induced damages in ancient buildings. (a) Cracks/fractures within a block (second century AD Palmyra theater, Syria). Photo Kázmér #4281. (b) Chipped edges of column and capital in the sixth-century Euphrasius cathedral, (Poreč, Croatia), damaged by the 1440 earthquake #0080. (c) Through-cutting fractures (repaired) in the eight- to ninth-century Brahma temple of the Prambanan complex, Yogyakarta, Indonesia, caused by the 2006 earthquake #6488. (d) Horizontal shift of large ashlars; vertical joints opened up between them. Shiva temple, Prambanan complex, Yogyakarta, Indonesia. Tape measure extended 20 cm #6498. (e) Dropped ashlars in a Roman arch (Damascus, Syria) #2017. (f) Broken lintels in twelfth-century al-Marqab citadel, coastal Syria #4663. (g) Clockwise-rotated blocks in twelfth-century al-Marqab citadel, coastal Syria #5168. (h) Displaced drums of masonry columns of the fifth-century BC Hephaisteion temple, Athens, Greece #1132. (i) Extruded portion of house wall. Bosra, Syria #4183

Displaced drums in rows of masonry columns (Fig. 1h) are products of either in-plane or out-of-plane seismic loads. Both shifting and rotation of drums occur. Historically, the observation of aligned, fallen monolithic columns has been used to infer directions of earthquake epicenters. However, this interpretation is erroneous, since column alignment in fallen structures can also be produced by heavy storms acting on deteriorated buildings (Ambraseys 2006).

Extruded blocks (Fig. 1i) indicate loads at a high angle to a wall. Displacement occurs along a more-or-less irregular pattern of masonry blocks (mostly without through going fractures), reflecting the failure of the wall core. Masonry maintains coherence during displacement, indicating that not the mortar between blocks but mortar between wall and core maintains wall integrity.

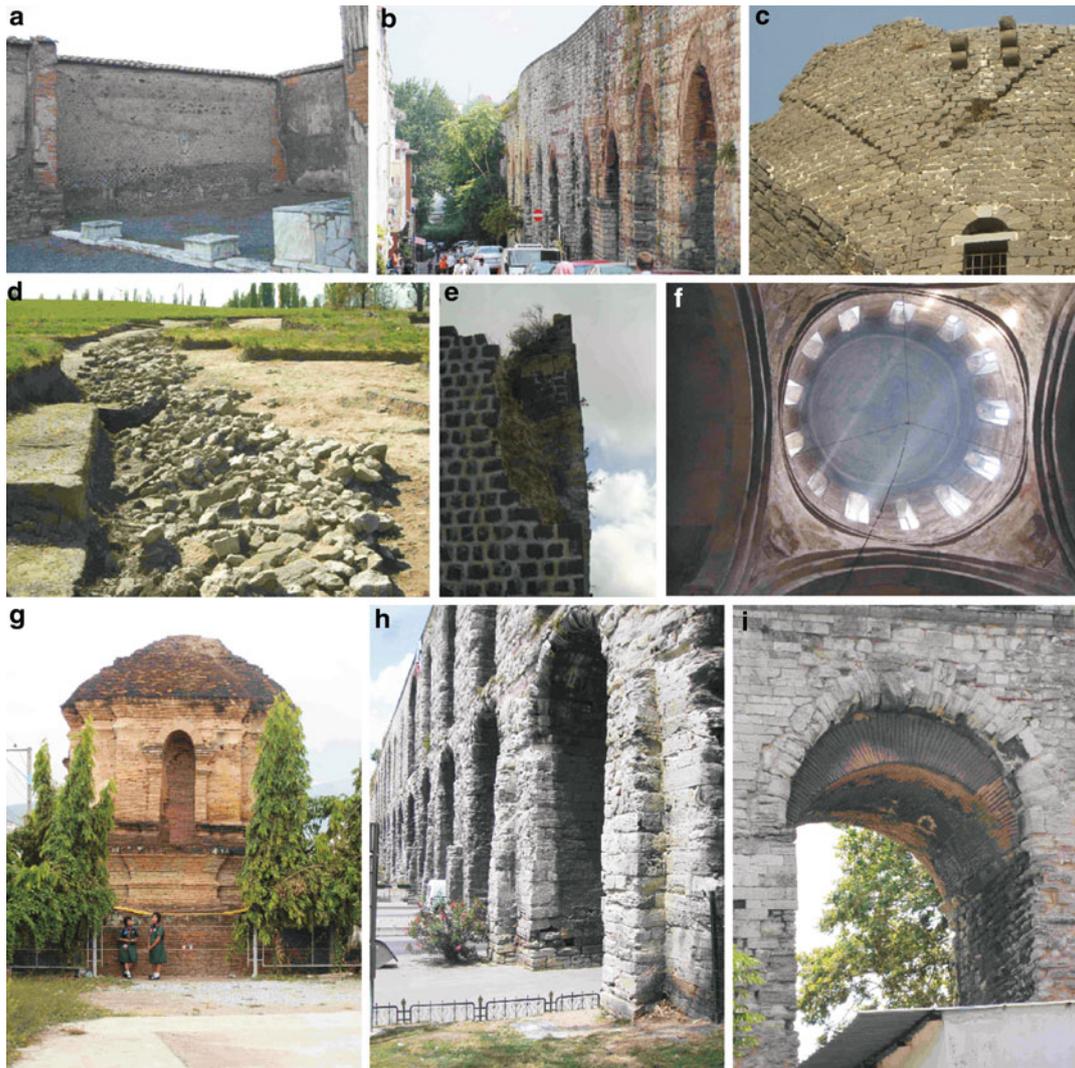


Fig. 2 (a) Arcuate out-of-plane collapse in the market, Pompeii, Italy, repaired before the 79 AD eruption of Vesuvius, which buried the city. Photo: Kázmér #9266. (b) Warped northern side of the Valens aqueduct (Istanbul, Turkey). Completed in 368 AD, several subsequent earthquakes left their traces on the massive construction #0340. (c) V-shaped damage on the SW wall of the twelfth-century donjon of al-Marqab citadel, coastal Syria. The damage was inflicted by the 1202 earthquake (Kázmér and Major 2010) #4589. (d) Fallen masonry fence in the Roman city of Carnuntum (Deutsch-Altenburg, Austria) #5496. (e) Triangular missing parts in corners of walls (al-Marqab citadel, coastal Syria) #4671. (f) Deformed circular dome of fourth- to eleventh-century Samtavro cathedral, Mtskheta, Georgia #1633. (g) Tilted Buddhist stupa (approximately fifteenth century) in Chiang Mai, Thailand. While a single tilted building does not indicate seismic origin, this stupa is one of 21 sites displaying tilting in the city (Kázmér et al. 2011) #3411. (h) Buttresses support the pillars of the Valens aqueduct in Istanbul, Turkey, completed in 368 AD #0335. (i) Valens aqueduct in Istanbul, completed in 368 AD. A brick arch was built to support the weakened stone arch after one of the frequent earthquakes in the region (Istanbul, Turkey) #0335

The *arcuate collapse* of walls (Fig. 2a) is sign of loads acting at high angle to a wall that is confined (fixed) at both ends. Wall terminations (usually supported by cross walls) maintain their full elevation, while the free-standing middle part loses coherence and collapses during heavy vibration.

A *warped wall* is produced by out-of-plane loads acting at high angle to the wall (Fig. 2b). Warping can be to one or both sides. Thick walls made of Roman concrete can behave this way,

while thin walls collapse in arcuate form (Fig. 2a). Generally, there is no change of wall geometry at foundation level.

A *V-shaped extrusion* near the top of a cylindrical building (Fig. 2c) indicates strong motion in the direction of extrusion.

Fallen walls lying on the ground are more-or-less preserving original coherence (Fig. 2d). A seismic load acting at a high angle to a wall can cause simultaneous collapse along the full length of the structure.

Damage Affecting Adjacent Walls

Triangular collapses in the corners of walls (Fig. 2e) are due to differential loading of perpendicular walls. Shaking in different directions at the same time shears off the masonry joints, allowing collapse of the weakened corner.

Simple *deformed geometrical structures deformed* (rectangular to parallelogram, circular to elliptical, etc.) (Fig. 2f). These features are hard to recognize, since deformations are subtle: parallels and right angles deviate a few degrees only (higher deformation would yield total collapse).

Whole Buildings

Tilted buildings are signs of uneven loading of subsoil (Fig. 2g). When seismic vibrations act on water-saturated soil, it loses coherence and behaves like a fluid. Building foundations – losing support during liquefaction events – suffer differential settlement, tilting, and collapse. Traces of total failure are mostly removed, but minor tilting – not affecting the use of the building – is often left unrepaired.

Very rarely a building – if built across an active fault – is sheared by fault movement. The displaced walls indicate the sense and cumulative offset of the fault since construction time. Walls are either displaced along a single fault (i.e., Vadum Iacob crusader tower, Israel: Ellenblum et al. 1998) or along a splay of faults, where the building maintains integrity, but the floor plan gets deformed (i.e., St. Simeon monastery, Syria: Karakhanian et al. 2008).

Repairs

Ruins of completely collapsed buildings are usually removed after an earthquake. Moderate damages are repaired on the spot, and additions, new walls, *buttresses* (Fig. 2h), *reinforced arches* (Fig. 2i), and other *supporting structures* can be identified as evidence of past earthquakes. Repairs are often built of different, often inferior material (Fig. 2i: brick arc supporting a stone arch), poorly fitted to masonry patterns, obstructing windows – these are features of repair following structural damage.

Study of damaged ancient buildings is a major source of evidence for past earthquakes: various seismic parameters (e.g., date, intensity, strong motion direction) can be assessed from a careful, critical study. However, before anyone jumps head-fast into archaeoseismology, here is a cautionary note: attributing seismic origin to observed damage needs careful consideration and exclusion of all other potential causative agents (Ambraseys 2006).

Summary

Damage to ancient buildings is a major source of information about the parameters of past earthquakes (date, intensity, strong motion direction, just to name a few). Features to aid in the identification of seismic damage are briefly described and illustrated and arranged in a simple, descriptive system. Deformations affecting single and multiple blocks of dressed masonry, single walls, adjacent walls, and whole buildings record evidence of seismic damage. Their recognition, careful analysis, and distinction from other types of damage (by aging, warfare, poor construction, etc.) need thorough and systematic study but provide much needed data on past earthquakes.

Cross-References

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