Seismic Vulnerability of Rural Masonry Buildings After 2019 Acipayam Earthquake, Denizli, Turkey

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Abstract. Turkey is an earthquake-prone country, and moderate earthquakes hit Acipayam town of Denizli city, located in the western part of Turkey on March 20, 2019 (Mw-5.5). The region is seismically active and, in the past, several earthquakes based on historical archives hit the same region, and some recent modern recordings are available. The March 20 earthquake caused significant damage in the villages of Acipayam, Denizli, where the majority of buildings are masonry buildings, while, the typical building type is cut-stone, adobe and brick masonry-type buildings. The existing buildings suffered damages due to poor building material quality, inadequate design, and detailing. Connection of floor slabs to façade walls are poorly implemented, where in-plane and out-of-plane failures are observed very commonly. Another primary reason for the damage is the poor mortar quality used between masonry units, which lead to masonry walls damages again under in-plane and out-of-plane effects. The most recent Turkish Seismic Code dated 2018, includes a comprehensive chapter on masonry buildings. The general damage observations from Acipayam Earthquake evaluated according to the requirements given in the code and with the lessons taken from past earthquakes, as well.

1. Introduction
Masonry buildings either built by stone or brick units are commonly used in rural areas in Turkey, and these types of structures must be designed and constructed safely against vertical loads as well as earthquake loads. In Turkey, construction of unreinforced masonry buildings is quite common and limited amount of confined masonry buildings co-exist. Unfortunately, in daily practice, masonry buildings are constructed by foremen without receiving proper structural attention. Most foremen do not have sufficient technical training and information about the structural behavior of masonry buildings and the applications in rural areas are generally not officially reviewed/approved during design or construction. As a result, the earthquake resistance of existing unreinforced masonry buildings in rural areas is questionable and these buildings compose a significant part of the weak building stock in such areas. Experience shows that masonry buildings represent quite low seismic performance in Turkey even in moderate level earthquakes. The seismic design codes in Turkey [1-4] have a specific chapter for design and construction of masonry building since 1975. However, unreinforced masonry type construction is most vulnerable to earthquakes in the rural areas of Turkey, which may be attributable to the fact that these buildings did not receive a proper engineering service.
In the present paper the seismic behavior of masonry building after March 20th, 2019 Denizli, Acipayam Earthquake is examined where the masonry buildings are affected at villages of Acipayam. Relevant requirements of the Turkish Building Seismic Code are briefly introduced, the seismic data is given, observed damages are shown and their reasons are discussed in the following parts of this paper.

2. Instrumental seismicity

On 2019, March 20th, Wednesday, at 09:34 local time, a seismic event of Mw 5.5 hit Ucari-Yeniköy (Acipayam, Denizli) region occurred. The seismic epicenter coordinates are given as 37.4313N – 29.431E, and the depth of the epicenter is calculated as 10.76km. The earthquake duration was approximately 11 sec and its epicenter is located between Yeniköy and Ucari, 6.5km east of the center of Acipayam. According to the relevant AFAD report, between 2019, March 2nd and March 20th, total of 50 earthquakes ranging from 0.9 <Mw <3.7 and about 5 hours before the main-shock, Mw 3.7 earthquake occurred in the Acipayam basin. [5].

According to AFAD’s reports 2230 aftershocks ranging from 0.6 <Mw <4.9 were recorded within 25 days after the main earthquake. Within 10 minutes after the main shock, three earthquakes of Mw 4.8, Mw 4.5 and Mw 4.2 occurred with average depths ranging from 6.0 km to 7.0 km in 3 km north of the main shock. The recorded main shock and aftershocks are given in Figure 1.

![Figure 1. Morphotectonic map of the Acipayam basin and 20 March 2019 Acipayam Earthquake main shock and aftershocks (0.9 <Mw <4.6)](image-url)
Out of 152 nearby recording stations, peak accelerations of 361.24 cm/s² at N-S component, 184.42 cm/s² at E-W component and 142.94 cm/s² at the vertical (UD) component were measured at the Acipayam strong-ground motion station, which is 10 km away from the main shock. The distance between the epicenter and the recording stations range from 7 to 399 km. The five closest stations and the measured acceleration values are given in Table 1.

Table 1. Measured accelerations in the closest five stations.

| Code | City     | Station | Latitude | Longitude | N-S    | E-W    | U-D    | Distance (Repi) |
|------|----------|---------|----------|-----------|--------|--------|--------|-----------------|
| 2017 | Denizli  | Acıpayam| 37.5300 (N) | 29.3500 (E) | 361.24 | 184.42 | 142.94 | 7               |
| 1505 | Burdur   | Tefenni | 37.3161 (N) | 29.7790 (E) | 26.37  | 14.33  | 14.97  | 34              |
| 2026 | Denizli  | Tavas   | 37.2787 (N) | 29.0248 (E) | 14.02  | 15.49  | 14.84  | 40              |
| 2011 | Denizli  | Kınıklı | 37.7372 (N) | 29.1006 (E) | 15.04  | 12.23  | 8.01   | 44              |
| 2002 | Denizli  | Merkez  | 37.8125 (N) | 29.1111 (E) | 11.92  | 15.32  | 11.39  | 50              |

2.1. Acceleration Values

The acceleration recordings of the main shock for the three main directions obtained at Acipayam station are shown in Figure 2. According to the record, the effective duration is calculated as 7.7 seconds (The time duration between 5% and 95% of Arias Intensity).

Figure 2. The acceleration recordings of main shock (Acipayam station)

Following Figure 3 shows the acceleration spectrum calculated for the N-S and E-W components of Acipayam record in comparison with the acceleration design spectra of the main shock location. The design spectra are given for the 475 years and for the 72 years return period seismic levels (DD-2 and DD-3, respectively) where the soil type is assumed to be ZC class. The figure shows that the main shock results with their spectral values those are smaller than the design level seismic motions. Although Acipayam Earthquake spectrum is larger than the DD-3 spectral level under which Limited Damage performance level is expected according to the current Turkish seismic code [6].
Figure 3. Acceleration spectra of Acipayam Earthquake and comparison with design spectra [6].

3. Earthquake Resistant Design Rules of Masonry Buildings
From past to this day Turkish seismic codes [1-4] contain modern design and assessment rules on reinforced concrete and also masonry buildings. It is easy to state that Turkish seismic codes are quite comprehensive in terms of seismic design for quite a long time. The code requirements have been similar to those of the related Euro Codes and the codes in the US. On the other hand, the lacking of inspection of building projects at design and construction stages; either reinforced concrete or masonry type of buildings seems to be the main reason of seismic failure. The essential rules on masonry building design in Turkish Seismic Code 2007 [3] can be summarized as follows:

Turkish Seismic Code 2007 states that all masonry buildings should comply with the minimum requirements such as the restriction on the number of stories in a masonry building or the dimensions of the door or window openings. The code also states the requirements regarding the lengths and the thickness of the load bearing walls, the transversely unsupported lengths of the structural walls and the dimensions of the lintels and the tie beams. Minimum requirements for the structural design and construction of the masonry buildings and moreover simple seismic analysis for masonry buildings is also provided by the code. Finally, normal and shear stress control on the masonry walls are required by the code, as well.

In the code, the number of stories of a masonry building is constrained depending on the seismic region of the building in question. In the high risk seismic zones, the maximum number of allowed stories is limited to 2, while 3 or 4 story masonry buildings can be built in zones with lower seismic risk. Meanwhile, a masonry building is allowed to contain a basement floor and/or a roof floor covering maximum 25% of the normal floor area.

The masonry units used in the walls are allowed to be solid and hollow clay or concrete blocks having maximum 35% pore ratio. The minimum allowed compressive strength of the units is 5MPa by assuming the total cross-section of each unit. However, natural stones with minimum compressive strength of 10MPa can be implemented in the walls of a basement floor. Minimum thickness of the masonry walls are also given in the code depending on the seismicity level.

The ratio of the total length of the masonry walls in two orthogonal directions excluding the openings to the floor area should be larger than 0.20 I m/m². Here I is the building importance factor and is taken as 1.0 for residential buildings as an example. Masonry walls should be laterally supported against out of plane deformations at an interval of less than 5.5 m in the high risk seismic
zones and 7.5 m in the other zones. If this unsupported length condition is not satisfied, vertical tie beams should be provided at least every 4.0 m including the corners along the masonry wall. However, in this case, the unsupported length cannot be longer than 16.0 m under any circumstance.

Window and door openings should not be closer than 1.5m and 1.0m to the corners in high-risk seismic zones and lower risk zones, respectively. Meanwhile the openings shouldn’t be close to each other more than 1.0m and 0.8m in high-risk seismic zones and lower risk zones, respectively. When vertical tie beams are provided in each side of a masonry wall, the aforementioned minimum length requirements regarding the openings are allowed to be reduced by 20%. These openings should not be closer than 0.5 m to any support of the masonry wall. Lintels above the window or the door openings should be supported on each side at least 0.2 m and 15% of the lintel clean span.

4. Damages and failure modes of unreinforced masonry buildings

The typical failure modes of unreinforced buildings, that have been widely observed in actual seismic surveys, can be given as follows [7,8]:

- In-plane and out-of-plane damages of masonry walls.
- Insufficient diaphragm behaviour/strength at floor and/or roof level.
- Lack of anchorage (connection) of floors and roof to the masonry walls.

In the rural areas, the unreinforced masonry buildings are generally constructed without following the crucial earthquake design requirements given in the relevant codes, and these type of buildings are recognized as the type of buildings that are most vulnerable to moderate or strong seismic events. The past earthquakes have shown that, main reasons of damages observed in unreinforced masonry buildings, such as the ones given above, have repeated in earthquakes such as Dinar Earthquake 1995 [8-10] or the Acipayam earthquake 2019. Irregularities in the plane and vertical direction, over-sized openings and lack of material and construction quality, are other essential damage reasons.

5. Observed Damages from Acipayam Earthquake 2019

The earthquake, that has been effective in more than 20 villages, has caused severe damage especially in the villages of Apa, Ucarı, Kirca, and Karahüyük. However within Acipayam town-center significant damage has not been observed. The earthquake caused 44 houses to collapse, 303 heavily and 225 lightly to damage, according to a study by AFAD [11]. In total 572 masonry houses lacking engineering service more than 50 years old built of adobe and rubble stone with mud mortar in the rural area collapsed and heavily to lightly damaged. In general, the northern and southern walls of the masonry houses in the villages located in the north-northwest of the epicenter damaged and collapsed. A few mosques built of rubble with mud mortar were severely damaged and the minarets of a mosque were toppled. There was no damage to the buildings that received proper engineering services and the buildings with timber structural systems. There were no casualties and injuries in the earthquake except a few animal causalities and injuries.

The on-site technical inspection of numerous masonry buildings in Acipayam area and its districts has revealed that the main causes of damages observed in masonry buildings during an earthquake could be classified as follows:

- Use of masonry units and mortar not following the standards,
- Poor construction quality and unfilled joints between masonry units,
- Insufficient of wall integrity,
- Inadequate connections between walls at corner joints,
- Insufficient connection between the roof plane, floors, and walls,
- Lack of stiffness (diaphragm behavior) in the floor and/or roof plane,
• Inadequate wall area in two orthogonal directions of plan,

The moderately and heavily damaged unreinforced masonry buildings built in the rural area are shown in Figures 4-9 as follows.

Figure 4. Damaged unconfined masonry building, inadequate connection at corner and poor mortar between masonry units

Figure 5. Seismic damage caused by insufficient connection between masonry wall and roof

Figure 6. Seismic damage in a masonry building built by adobe units; out of plane failure of façade walls; lack of connection between masonry walls at floor and roof levels; insufficient plane rigidity of floors and roof.
Figure 7. Collapsed of a masonry building

Figure 8. Out of plane failure of façade wall of a masonry building having adobe units and slender timber floors

Figure 9. A heavily damaged unreinforced masonry building having stone and adobe masonry units.

6. Conclusions
In Acipayam, Denizli region, a moderate earthquake occurred on 2019 March 20th, Wednesday, at 09:34 local time having Mw 5.5 and PGA 0.3949g. Fortunately, there were no casualties, but some un-engineered unreinforced masonry buildings located in surrounding villages of Acipayam suffered moderate to substantial damages. The reasons for these damages were similar to those observed in the past earthquakes, such as; the use of substandard masonry units and mortar, poor construction quality and unfilled joints between masonry units, lack of integrity of walls (lack of horizontal tie beams),
inadequate connections between walls at corner joints, lack of connection strength between floors, roofs and walls, lack of stiffness in the floor and in the roof plane and inadequate wall area in the two directions can be listed as the main reasons for the observed damages. Lessons learned from past earthquakes once more yield that unreinforced masonry buildings should be constructed by receiving proper engineering services. Turkish seismic codes provide comprehensive approaches for the design of masonry buildings and the observed damages in some buildings were because these buildings were not designed according to the code requirements. To improve the earthquake performance of masonry buildings mentioned above arrangement of horizontal tie beams on the masonry walls at floor and roof levels and sufficient vertical tie columns within the walls (confined masonry), avoiding poor quality of material and construction, and providing proper connections between walls and floor and roof levels are recommended.

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