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Investigation of the Damages Due to Heavy Earthen Roofs on Masonry Buildings during the Kahramanmaraş Earthquakes

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ABSTRACT

Kahramanmaraş earthquakes, which occurred on 06 February 2023 at 4.17 (Pazarcık) and 13.24 (Elbistan) local time, caused very important structural damages in both urban and rural building stock. This paper deals with field investigations involving structural damages in masonry buildings with heavy earthen roofs after the Kahramanmaraş earthquakes. It also includes location-specific earthquake ground accelerations and response spectra for these earthquakes. 11 provinces were affected by the earthquakes that occurred on the same day, and more than 300,000 buildings were damaged or collapsed. With the examinations made in rural areas, it has been observed that the dominant building stock is masonry buildings and these buildings are mostly built using heavy earthen roofs and wooden beams. Especially in buildings where the wooden beams are not properly connected to the wall, it has been observed that the roof collapses completely or causes out-of-plane damage to the wall as a result of the large moments of inertia it creates. As a result, it has been observed that most of the buildings built in rural areas are not built in accordance with the regulations and are built without any engineering service.

Keywords: Damage, Earthquake, Heavy earthen roof, Kahramanmaraş, Masonry building

Kahramanmaraş Depremlerinde Ağır Toprak Damların Yığma Yapılarda Yol Açtığı Hasarların Araştırılması

ÖZ

06 Şubat 2023 yerel saat ile 4.17 (Pazarcık) ve 13.24 (Elbistan) meydana gelen Kahramanmaraş depremleri hem kentsel hem de kırsal yapı stokunda çok önemli yapısal hasarlara sebep olmuştur. Bu makale, meydana gelen Kahramanmaraş depremleri sonrasında ağır toprak damlara sahip yığma binalarda oluşan yapısal hasarları içeren saha araştırmalarını ele almaktadır. Aynı zamanda bu depremler için il bazlı yer ivmeleri ve tepki spektrumlarını içermektedir. Aynı gün içerisinde meydana gelen depremlerden 11 il etkilenmiş ve toplamda 300.000'den fazla bina hasar görmüş veya çökmüştür. Kırsal bölgelerde yapılan incelemede hakim yapı stokunun yığma bina olduğu ve bu binaların genelde ağır toprak dam ve ahşap kirişler kullanılarak yapıldığı gözlemlenmiştir. Özellikle ahşap kirişlerin duvara bağlantısının düzgün yapılmadığı binalarda çatının tamamen göçtüğü ya da oluşturduğu büyük atalet kuvvetleri neticesinde duvarda düzlem dışı hasara neden olduğu gözlemlenmiştir. Sonuç olarak, kırsal bölgelerde inşa edilen binaların çoğunun yönetmeliklere uygun yapılmadığı ve herhangi bir mühendislik hizmeti almadan inşa edildiği gözlemlenmiştir.

Anahtar Kelimeler: Hasar, Deprem, Ağır toprak dam, Kahramanmaraş, Yığma yapı

INTRODUCTION

Two separate earthquakes occurred at 04:17 and 13:24 local time on 06 February 2023 in the Pazarcık and Elbistan districts of Kahramanmaraş province. The epicenter of the first earthquake is Pazarcık, the second earthquake's epicenter is Elbistan, and the earthquake magnitudes are M_w=7.7 and M_w=7.6, respectively. Many aftershocks occurred after these earthquakes. As a result of both main earthquakes and aftershocks, 11 provinces were significantly affected. The extent of the destruction was much greater, especially in the provinces of Hatay, Kahramanmaraş, and Adıyaman and their districts. These earthquakes have been described as the disaster of the century by causing great economic losses for Turkey, loss of life, and structural damage. The fact that the earthquakes occurred in the same region with very short intervals combined with the soil and structural features adversely affected the damage levels. In the rural areas of 11 provinces affected by earthquakes, the dominant building stock consists of masonry structures.

Masonry structures are generally built by local craftsmen and workers using local materials, without any engineering service. The earthquake resistance of such structures is quite low. Earthen roofs are commonly preferred as roofs in such structures. Wooden roofs can be used on earthen roofs in regions exposed to severe climatic conditions. Heavy earthen roofs can create additional loads in the structure and cause significant damage both on the roof and on the load-bearing walls that form masonry structures [1-4].

It is necessary to examine existing masonry structures, determine possible earthquake safety, and take precautions accordingly. Rapid evaluation methods can be used to make decisions about the existing building stock [5-7]. Also, there are many studies dealing with the damage to masonry structures after devastating earthquakes in countries with high earthquake risk. Structural damages in masonry structures after earthquakes such as Bilgin et al. [8] 2019-Albania earthquake, Işık et al. [9] 2023-Kahramananmaraş earthquake, Hafner et al. [10], and Ademović et al. [11] 2020-Zagreb earthquake, Karaşin et al. [12], Tondo et al. [13] and Indirli et al. [14] 2009 L'Aquila earthquake, Göçer [15] 2014 Gökçeada earthquake, Furukawa et al. [16] 2015 Gorkha earthquake, Argiento et al. [17] 2016-2017 Central Italy earthquake, Dizhur et al. [18] 2010 Darfield earthquake, Celep et al. [19] 2010-Elazığ earthquake, Işık et al. [20], Günaydin et al. [21], and Nemutlu et al. [22] 2020-Elazig earthquake were evaluated in terms of earthquake and civil engineering. Although heavy earthen roof damages were also mentioned in some of these studies, specifically heavy earthen roof damages were not examined. In this study, the effect of heavy earthen roofs on structural damage was specifically investigated.

Kahramanmaraş earthquakes on 06 February 2023 caused great destruction in many provinces. Earthen roofs form the roof system commonly used in masonry buildings, which constitute a large part of the existing structure stock in rural regions affected by earthquakes. Due to heavy earthen roofs, different levels of damage have occurred both on the roof floors and on the load-bearing masonry walls. In this study, the structural damages caused by heavy earthen roofs in Hatay, Kahramanmaraş, Adıyaman, and different rural parts of these provinces after these earthquakes were specifically examined. Information about the 2023 Kahramanmaraş earthquakes was also given. The part that distinguishes this study from other studies is the analysis of the study in terms of heavy earthen roofs, which are very preferred in rural areas and cause great destruction as a result of these earthquakes.

06 FEBRUARY 2023 KAHRAMANMARAŞ EARTHQUAKES

Kahramanmaraş earthquakes with epicenters in Pazarcık (4:17 local time, M_w=7.7) and Elbistan (13:24 local time, M_w=7.6) affected a total of 11 cities which are Hatay, Kahramanmaraş, Adıyaman, Gaziantep, Malatya, Adana, Şanlıurfa, Osmaniye, Diyarbakır and Kilis and Elazig. The depth of the first earthquake with the Pazarcık epicenter was 8.6 km, while the depth of the second earthquake with the Elbistan epicenter was 7 km. More than 100,000 buildings were damaged or destroyed during the earthquakes that occurred, and more than 50,000 people lost their lives. Some parameters for the 3 stations with the largest PGA values observed in both earthquakes are given in Table 1. The three components of the acceleration records of the 6 selected stations are given in Figures 1 and 2 [23]. As shown in the figures, for station 4614 in the Kahramanmaraş earthquake with Pazarcık epicenter; the highest ground accelerations (a_{max}) were measured as 2016.99 cm/s² in the north-south direction, 2039.20 cm/s² in the east-west direction and 1582.62 cm/s² in the vertical direction, and it is the station with the highest acceleration record in the first earthquake. In the Kahramanmaraş earthquake with Elbistan epicenter, the highest ground accelerations for the station code 4612 were 635.45 cm/s² in the north-south direction, 523.21 cm/s² in the east-west direction and 494.91 cm/s² in the vertical direction, and it was the station with the highest acceleration record in the second main earthquake that took place 9 hours later.

The acceleration response spectrum is a graphic that visualizes earthquake movements and shows the effect of earthquake accelerations on the structure according to periods. Horizontal acceleration spectrum curves with a 5% damping ratio were obtained for 3 directions by using the values obtained from station 4614 for the Kahramanmaraş earthquake with Pazarcık epicenter and station 4612 for the second earthquake in Elbistan (Figure 3). The acceleration response spectrum values in the first earthquake were higher than the values in the second earthquake. According to the selected stations, a steeper and narrower curve was obtained in the first earthquake, while it had a flatter and wider shape in the second earthquake. It can be said that the accelerations increased rapidly in the first earthquake, the structures were exposed to faster and more severe vibrations, and the accelerations increased more slowly in the second earthquake, that is, the structures were exposed to a lower acceleration for a longer period of time.

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Table 1. Parameter of February 06, 2023, Kahramanmaraş Earthquakes

The earthquake with the epicenter of Pazarcık (4:17 local time, M_w =7.7)							
Station Code	**Latitude (N)**	**Longitude (E)**	**Depth (km)**	**PGA-N-S (cm/s²)**	**PGA-E-W (cm/s²)**	**PGA-U-D (cm/s²)**	**Region**
4614	37.48513	37.29775	8.6	2016.99	2039.20	1582.62	Kahramanmaraş-Pazarcık
3129	36.19117	36.1343	8.6	1351.50	1198.74	716.94	Hatay-Defne
3126	36.2202	36.1375	8.6	1178.12	999.38	921.57	Hatay-Antakya
The earthquake with the epicenter of Elbistan (13:24 local time, M_w=7.6)							
Station Code	**Latitude (N)**	**Longitude (E)**	**Depth (km)**	**PGA-N-S (cm/s²)**	**PGA-E-W (cm/s²)**	**PGA-U-D (cm/s²)**	**Region**
4612	38.02395	36.48187	7	635.45	523.21	494.91	Kahramanmaraş-Göksun
4406	38.34388	37.97378	7	467.20	409.31	318.75	Malatya-Akçadağ
4631	37.966325	37.427653	7	337.38	388.61	610.04	Kahramanmaraş-Nurhak

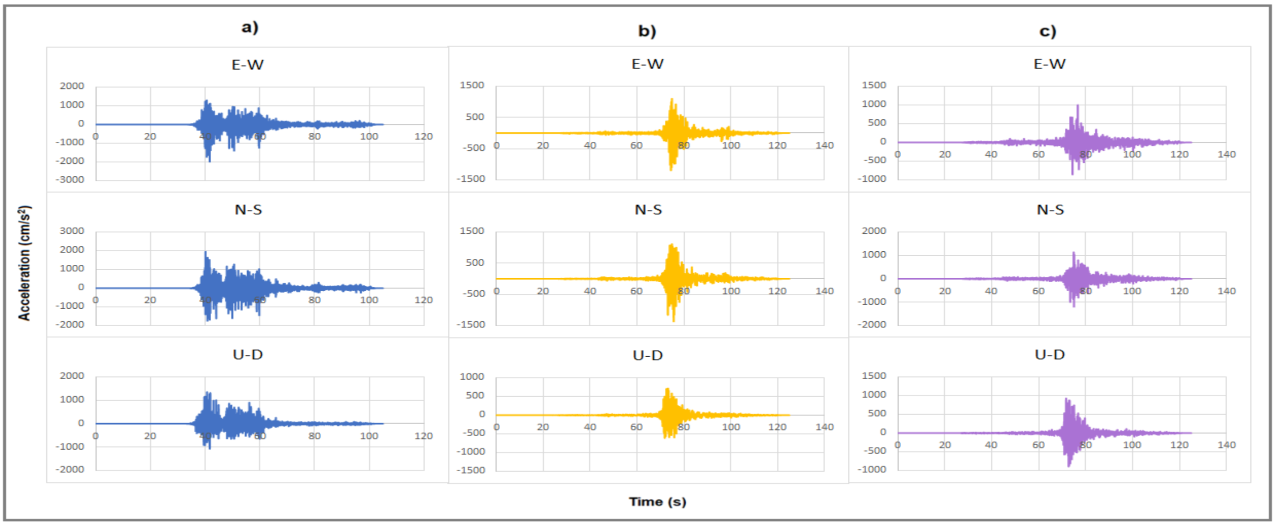

Figure 1. Three components of ground accelerations for the February 06, 2023, Pazarcık, Kahramanmaraş earthquake at a) 4614, b) 3129, and c) 3126 station [23].

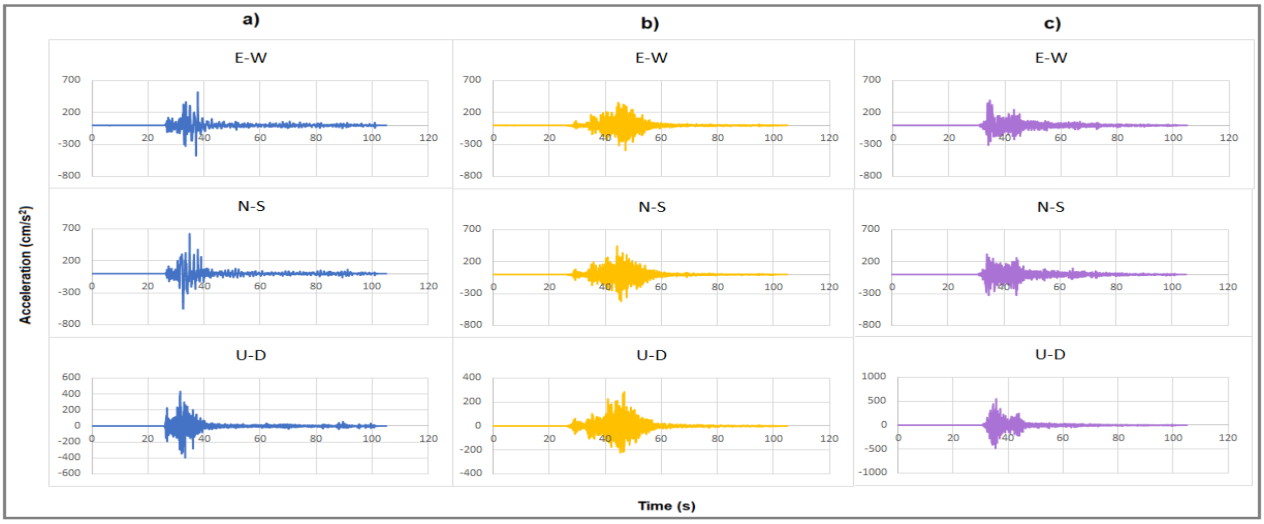

Figure 2. Three components of ground accelerations for the February 06, 2023, Elbistan, Kahramanmaraş earthquake at a) 4612, b) 4406, and c) 4631 station [23].

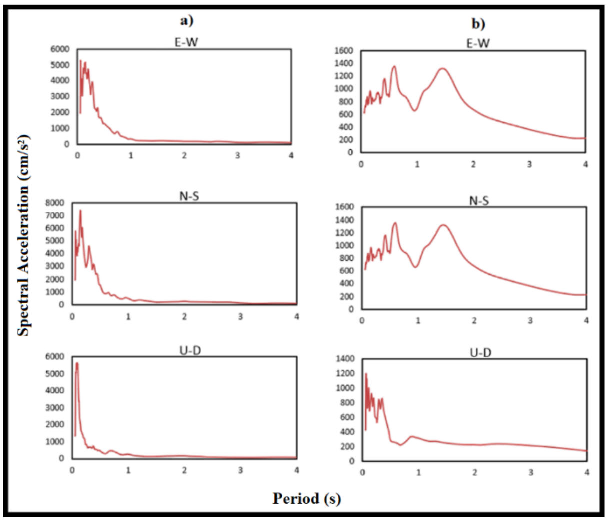

Figure 3. Acceleration Response Spectrum of E-W, N-S, and U-D components February 06, 2023, Pazarcık and Elbistan (Kahramanmaraş) earthquakes a) for 4614 station, b) for 4612 station

TYPES OF EARTHEN ROOFS and FORMS OF CONSTRUCTION IN RURAL AREAS

The masonry buildings constructed in rural areas are commonly formed by combining the building materials found in the region. However, these structures are built without material tests and necessary controls. In addition, it causes the structures not to comply with the standards required in the design of the connection areas and therefore not to provide sufficient load transfer. This means that the masonry structures in these regions do not show sufficient strength under earthquake forces. 86.7 percent of the buildings in the earthquake zone are reinforced concrete. 2.4 percent of the buildings are steel, 3.5 percent are masonry, and 3.6 percent are prefabricated. Although the level of masonry structures, which is the most problematic category in terms of earthquake resistance, remains numerically low, it is the type of structure with the highest damage rate [24].

In the field observations made in rural areas after earthquakes, it was observed that earthquake damage occurred according to the construction style of the roofs and the materials used. The structural members built to protect the buildings against external influences such as snow, rain, wind, hot, and cold and to limit the space are called roofs. Roofs are constructed by using various types of building materials together.

The climatic conditions of the region where the building will be built and local construction technologies are effective factors in deciding the shape and material of both the structure and the roof to be used in the building [25]. In addition, elements such as gutters and vertical pipes are used as complementary roof elements in roof design [26]. While these elements increase the durability of the structures against external factors, they also contribute to the longevity of the structures.

Flat earthen roofs have been widely used as roofs in masonry structures in rural areas affected by the Kahramanmaraş earthquakes that occurred on February 06, 2023. In some regions, wooden roof systems were built on flat earthen roofs. Different types of earthen roof typologies are shown in Figure 4.

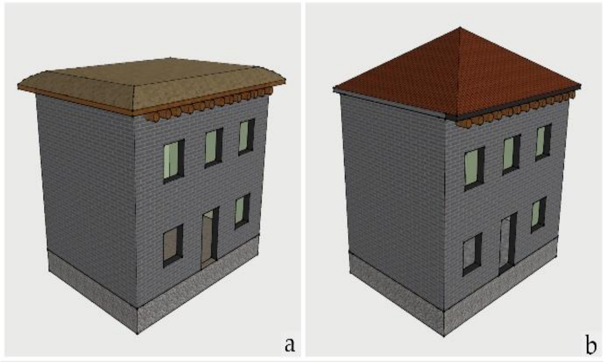

Figure 4. Different typologies of constructed earthen roofs; a) Flat earthen roofs b) Earthen roofs with roof rafters

Earthen roofs built for roof purposes from the earthquake zone are constructed by going through the following stages;

• Wooden beams are placed in a circular section on the outer and inner wall tops. Wooden beams are generally obtained from poplar wood.

• Flat veneer boards are placed on the wooden beams without interruption in order to make the wooden beams look aesthetically pleasing from the inside and to prevent the soil material from spilling down. Nails provide the connection between these two members.

• Reeds obtained from the region are placed on the boards by building them as poles or wickers.

• Local soil laying is done on the reeds. The first layer consists of mud with chaff. On top of this, the material obtained with a mixture of clay, salt, and water is laid.

• The soil, whose construction is completed in this way, is left on the roof for 1 or 2 days and then compacted by logging. The compressed soil is polished over the roof with the help of a hand roller to ensure fewer voids. In general, this process takes between 7-15 days. As a result, a compacted roof cover with a smooth surface is obtained.

• The edges of the flat roof constructed are chamfered, allowing the precipitation to flow over the roof. In order to discharge the waters caused by the deflections that occur over time, a gutter drain is performed in some regions. On roofs covered with wood, the outer wall is raised and the edges of the roof are placed on the wall.

• Seasonal periodic maintenance-repair interventions are carried out. The soil mortars added during these maintenances bring a plus load to the roof. By transferring the section with the clayey top layer every 2-3 years, the excess load is removed and the atmospheric effects are prevented from penetrating the interior.

The cross-sections of heavy earthen roofs commonly used in masonry buildings in rural areas and their representation on a sample structure are shown in Figure 5.

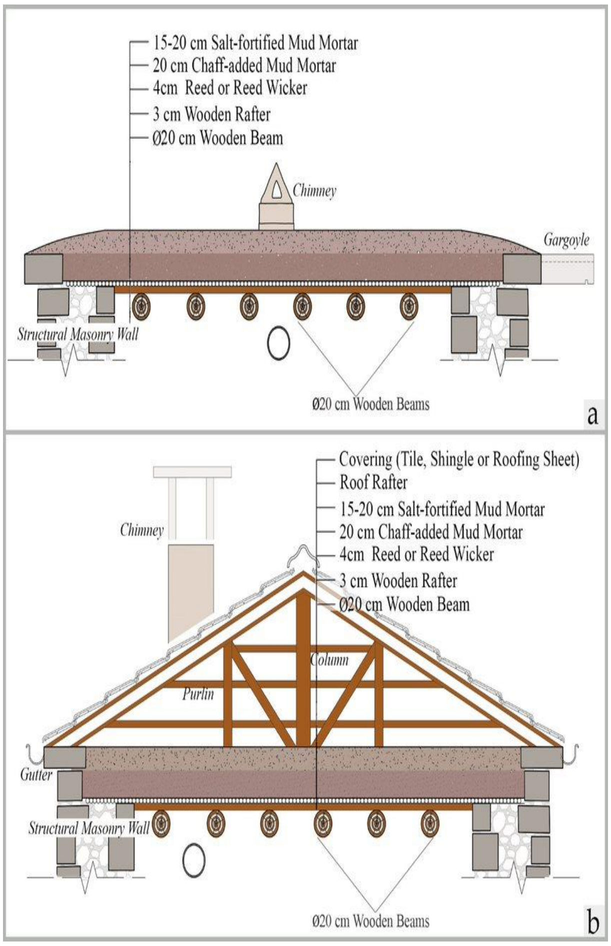

Figure 5. Examples of earthen roof cross-sections; a) flat earthen roof b) earthen roof with roof rafter

DAMAGES OBSERVED ON HEAVY EARTHEN ROOFS DURING THE EARTHQUAKE

Roofs in masonry buildings commonly used in rural regions are usually built using heavy earthen roofs and wooden girders. The lower layers are compressed and the roofs become heavier as a new layer is added to them, especially when the seasons change. During the earthquake, heavy earthen roofs caused substantial damage to both themselves and the load-bearing walls. [27-30].

As a result of the observations made in rural areas after the Kahramanmaraş earthquakes, the fall down of the heavy earthen roofs made the structures unusable. Such heavy earthen roofs, in conjunction with the vertical acceleration part of the earthquake, push the load-bearing walls in/out of the plane during the earthquake. Thus, these walls, which have poor in/out-of-plane stiffness and insufficient connection to the roof, are unable to transfer the load appropriately, suffer an abrupt loss of strength, and collapse together with the roof. In buildings with lightweight cover or metal material on the roof and used for warehouses/barns etc., the collapse was relatively less. Completely collapsed earthen roofs are shown in Figure 6.

Figure 6. Examples of completely collapsed earthen roofs

It has been researched that heavy earthen roofs increase the lateral forces by 10-15% during the earthquake [31] and due to collapses on weak roofs, it has seriously damaged the load-bearing walls. The area's hefty clay roofs were constructed from wooden logs and a substantial coating of soil. Due to the impact of climatic and environmental factors, earthen roofs are compacted by adding new soil layers each season to protect them from rain and melting snow. As a result, the already-heavy clay roof becomes even heavier, which causes the walls to be forced in and out during the earthquake with considerable force and causes the walls on the building's vulnerable side to fall. In the examinations made in rural areas after the Kahramanmaraş earthquakes, it was observed that the roof collapsed due to the earthquake and the walls displayed out-of-plane failure (Figure 7). Another damage observed in structures with heavy earthen roofs is the partial collapse of the roofs (Figure 8).

In structures with heavy earthen roofs, the collapse of a part of the roof forced the wall on the collapsed side to out-of-plane behavior and it was observed that the wall in that area also collapsed (Figure 9).

Figure 7. Example of load-bearing wall damages

Figure 8. Example of partial collapse damage of heavy earthen roofs

Figure 9. Load-bearing wall damages due to partial collapse of heavy earthen roofs

Wooden beams are positioned at specific intervals on the underside of the soil layer in buildings with earthen roofs. The aged wooden logs are gradually replaced by fresh ones. The wooden girders, which are subjected to heavier loads during earthquakes and wear out over time, reducing their bearing capacity, are unable to handle the additional horizontal load and are prone to varying degrees of damage as a result of the increased roof mass. Furthermore, increased loads will harm beams that are not properly supported on the roof and load-bearing walls, perhaps causing them to perform at levels that would cause a collapse. Examples of such damage are shown in Figure 10.

Figure 10. Damages due to insufficient support of wooden beams on heavy earthen roofs

Examples of damage to structures that were forced by the additional forces from heavy earthen roofs but did not reach the collapse mechanism are shown in Figure 11. The reason for this is that the wooden beams are well supported on the walls they sit on, but with the addition of a new soil layer to the building during the season transitions (with the additional roof load), deflections have occurred due to the insufficient size of the wooden beams.

Figure 11. Examples of wooden beams forced to collapse

Heavy earthen roofs in the earthquake zone are constructed in two different ways. Examples of cracking and partial collapse damage occurring on flat heavy earthen roofs are shown in Figure 12.

Figure 12. Example of the structural damage on flat earthen roofs

Another application used in the earthquake zone is to build wooden roof rafters on heavy earthen roofs. Different levels of damage have occurred on earthen roofs in such structural systems (Figure 13).

Figure 13. Examples of damage to earthen roofs with wooden roof rafters

In some masonry structures, reinforced concrete bond beams are used under the earthen roofs. The lack of sufficient interlocking between this bond beam and the earthen roofs and insufficient reinforced concrete strength, which was built without any engineering service, caused damages. An example of this type of damage is shown in Figure 14.

Figure 14. Structural damage despite the use of reinforced concrete bond beams

In the examinations carried out in the region, samples of heavy earthen roofs that were not damaged at all were also found. Examples of heavy earthen roofs that have never been damaged are shown in Figure 15.

Figure 15. Example of heavy earthen roof with no damage

The schematic representation of the structural damage caused by heavy earthen roofs as a result of the field investigations is given in Figure 16.

It has been compared within the framework of the rules in the last two earthquake regulations used in Turkey regarding the slab made in masonry structures. The rules regarding the slab in the 2007 Earthquake Code are as follows;

- The slabs of masonry structures will be RC slabs or ribbed slabs with dimensions and reinforcements designed according to the rules in TS-500.
- The masonry buildings whose slabs do not comply with the above rule will be constructed in all earthquake zones, with a maximum of two floors, if any, without counting the basement. In such buildings, the horizontal bond beams under the slabs will be made according to the criteria given in the regulation. Buildings with adobe

walls, on the other hand, will be built with at most one storey without counting the basement.

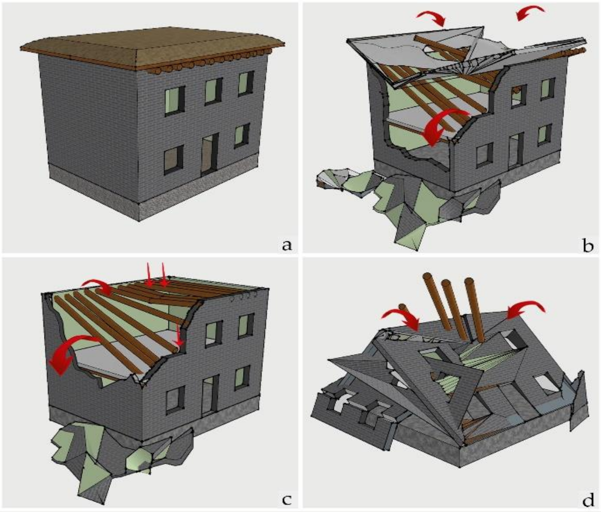

Figure 16. Schematic representation of structural damage observed in heavy earthen roofs. a) Undamaged masonry structure b) Heavy earthen roof damage and resulting damage to walls c) Insufficient support in wooden beams and forced to collapse d) Complete collapse

•Roofs of masonry structures can be made as reinforced concrete terrace roofs and wooden or steel roofs.

• The connections of the wooden roof equipment with the horizontal bond beams on the floor and load-bearing walls will be made according to the rules given in TS-2510 (Figure 17).

• If the height of the roof wall sitting on the horizontal bond beam on the top floor is greater than 2.0 m, vertical and inclined beams should be made.

• Roofs of adobe masonry buildings will be made as light as possible, with eaves that exceed the outer walls by 500 mm at most.

• No earthen roof will be built in the first and second-degree earthquake zones. In the third and fourth-degree earthquake zones, the soil cover thickness of the earthen roof cannot be greater than 150 mm. Roofs of adobe structures can be made as wooden trusses or reinforced concrete slabs.

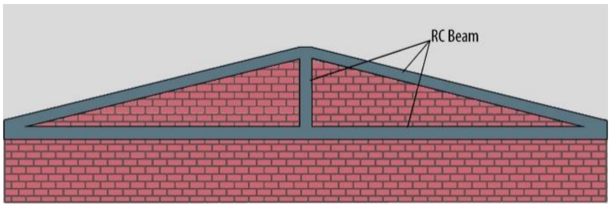

Figure 17. Roof, horizontal, and vertical bond beams.

In the currently used Turkish Building Earthquake Code (TBEC-2018) [32], the construction of earthen roofs is strictly prohibited. In this situation;

• Reinforced concrete slabs with a thickness of at least 100 mm will be made to provide the rigid diaphragm effect in unreinforced masonry buildings, reinforced masonry buildings, and confined masonry buildings. These slabs should be supported on horizontal bond beams with a cross-section height of at least 300 mm and with 6φ12 longitudinal, φ8/150 mm transverse reinforcements. The width of the horizontal bond beams will be at least as much as the wall thickness. The vertical spacing of the horizontal bond beams shall not exceed 4 m.

While it was stipulated in the previous regulation that heavy earthen roofs should not be built only in 1st and 2nd-degree earthquake zones, it was stated that earthen roofs could be built in other earthquake zones. However, heavy earthen roof is prohibited with the current regulation.

Within the scope of this study, the roofing detail proposed by the authors in a way that does not remove the aesthetically old appearance is shown in Figure 18.

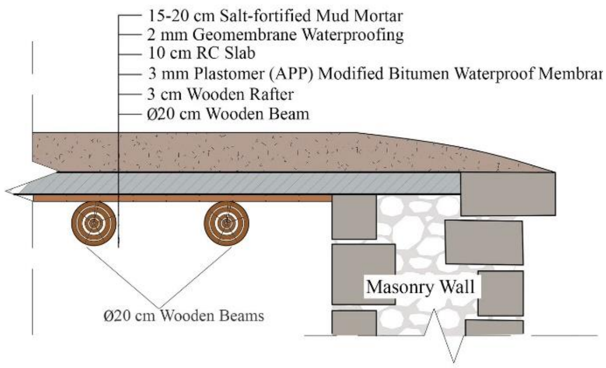

Figure 18. Recommended roof slab section

Buildings can be modeled using the finite element method to obtain information about their structural behavior. [33-36]. In order to make comparisons between building behaviors, the traditional roof system and the roof system suggested by the authors can be modeled with the finite element method in future studies.

CONCLUSIONS

Within the scope of this study, structural damages in heavy earthen roofs, which are commonly used in masonry structures, due to the Kahramanmaraş earthquakes that occurred on February 06, 2023, at 9-hour intervals were investigated.

Earthen roofs, which are already heavy in masonry structures that do not receive any engineering service, become even heavier with additional soil due to maintenance and repairs during seasonal transitions. Heavier earthen roofs create additional seismic forces and cause structural damage at different levels. In buildings with heavy earthen roofs, the rate of destruction is higher when the use of low-strength materials, the inability to provide the necessary and sufficient connection between the walls, and the excessive number of doors and windows openings. Although it is completely prohibited by the latest earthquake regulation, it is still used in some regions. In this context, the building control mechanism should also be implemented in rural areas. Currently, building inspection operates only for urban buildings. For all kinds of buildings to be built in rural areas, building inspection should be made effective from the design stage to the start of operation. Therefore, if there is any structural damage to the heavy earthen roof structures commonly used in rural areas, demolition of these structures should be recommended.

Generally, the damages that occur in heavy earthen roofs, the construction of masonry structures without any engineering service, the high self-weight of earthen roofs, an additional weight due to maintenance and repairs in seasonal transitions, not using horizontal reinforced concrete bond beams on load-bearing walls, insufficient support between the load-bearing wall and roof slab, the errors in determining the size and spacing of wooden beams, and aging of wooden beams over time can be listed.

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