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Observations from the March 2021 Thessaly Earthquakes: an earthquake engineering perspective for masonry structures

V. Sarhosis[1,7] · C. Giarlelis[2] · C. Karakostas[3] · E. Smyrou[4] · I. E. Bal[4] · S. Valkaniotis[5] · A. Ganas[6]

Abstract

Two strong earthquakes hit Thessaly region on March 3rd, 2021 ($M_w = 6.3$) and on March 4th, 2021 ($M_w = 6.1$). The epicentres of the earthquakes were located at approximately 23 and 29 km respectively NW of Larissa, one of the most populous cities in Greece. Several aftershocks followed thereafter. Although no injuries were recorded, several structures suffered significant damage close to the epicentre, while some others collapsed. Approximately 300 residents of the village of Damasi were transferred to temporary settlements and tents. The event occurred during the COVID19 lockdown and created significant stress and disruption to residents. This paper focuses on the earthquake swarm itself as well as the damages observed in residential buildings, schools, and churches in the earthquake-stricken region. The earthquakes mainly impacted low-rise domestic masonry buildings, while the more modern reinforced concrete structures built following the recent seismic regulations were almost unaffected. The typology of buildings in the region, together with photographs demonstrating the extent of damage are presented herein. Despite the rather satisfactory performance of modern buildings in recent earthquakes in Greece, the preliminary investigations from the Thessaly Earthquakes showed that there is still a significant level of vulnerability in existing masonry building stock constructed using traditional methods and materials. This issue could re-emerge in future earthquakes striking other rural areas of Greece, something that needs to be addressed systematically in the future.

Keywords Visual assessment · Earthquake · Damage · Greece · Masonry

1 Introduction

Earthquakes represent one of the most devastating natural hazards on earth and a major threat to human life, built environment and infrastructure. To understand earthquake risks, the vulnerability of the built environment to earthquake hazard needs to be estimated. Over the last 40 years, significant progress has been made by the scientific community to

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✉ V. Sarhosis
  v.sarhosis@leeds.ac.uk

Extended author information available on the last page of the article

improve design methods and buildings codes. Such studies focused mainly on increasing knowledge of structural design of buildings and structures to extreme loads and the characterisation of seismic hazards with the aim to develop codes and practices for the design and construction of new buildings. However, a large and significant problem remains, and that is our existing buildings and structures which are old, deteriorating and have been designed to past building codes and standards.

On Wednesday 3rd of March 2021, at 10:16 UTC (12:16 local time), a M_w6.3 earthquake struck central Greece, approximately 10 km West of Tyrnavos and 23 kms NW from Larissa, with a focal depth of 8 km. Another, and almost twin in magnitude earthquake (M_w6.1), took place on Thursday, 4th of March 2021, at 18:38 UTC (20:38 local time), at approximately 29 km NW of Larissa. Several aftershocks followed including an event of M_w5.6, which occurred on March 12th and created further damage to structures. The Greek Government declared immediately a state of emergency in the region, whilst first responders reached quickly and played a critical role in humanitarian response. The strong aftershocks contributed to increased stress and anxiety among the inhabitants in the area, forcing several of them to abandon their homes. No fatalities were recorded, while three people were injured due to partial collapse of buildings in Damasi village. Other villages affected were Koutsochero, Tyrnavos, Vlachogianni, Mesochori, Amouri and Verdikousia (see Fig. 1). Economic losses were estimated to be below 1% of GDP of Greece (Lekkas et al. 2021a, b). Strong aftershocks continued for more than a month after the main shock, resulting in further damage in buildings and infrastructure in the region. Figure 1 shows the seismic activity around the epicentre of the earthquake, while the pre-shocks and aftershocks are shown in Fig. 2 in time scale. Also, from Fig. 2, it is evident that there has been some small pre-shock activity (approximately 1–3 days) before the major earthquakes, while the major high frequency after-shock activity lasted for at least 60 days.

This paper aims to provide some insights into the seismic performance exhibited by masonry buildings, schools and churches in the area affected by the Thessaly earthquake sequence of March 2021. The earthquakes mainly impacted low-rise domestic masonry buildings, while the more modern reinforced concrete structures built following the recent seismic regulations were almost unaffected. In particular, this paper discusses the seismicity in the Thessaly basin and surrounding area, the strong ground motion records and how relate to the current seismic codes in Greece, the screening of first structural damages in buildings and the findings from the earthquake damage survey held in Thessaly region only a few days after the twin earthquakes took place. The cases selected herein highlight the main causes of damage and give indications on the vulnerability of existing masonry building stock constructed using traditional methods and materials in the region. Numerous photographs taken during the filed survey have been deposited in Github repository and are freely available to be download (see the link: https://github.com/vsarhosis/Earthquake_Thessaly_Photos_2021.git).

2 Seismicity in Thessaly basin and surrounding area

The region of Thessaly, in Central Greece is characterised by abundant occurrences of Pelagonian crystalline basement rocks, mainly of Paleozoic-Early Mesozoic age. The bedrock geology of the northern Thessaly region comprises a poly-deformed assemblage of gneisses and schists, Mesozoic ultramafic ophiolite fragments and marbles. Thessaly is located in central Greece where crustal extension is dominant (Papazachos et al. 1993;
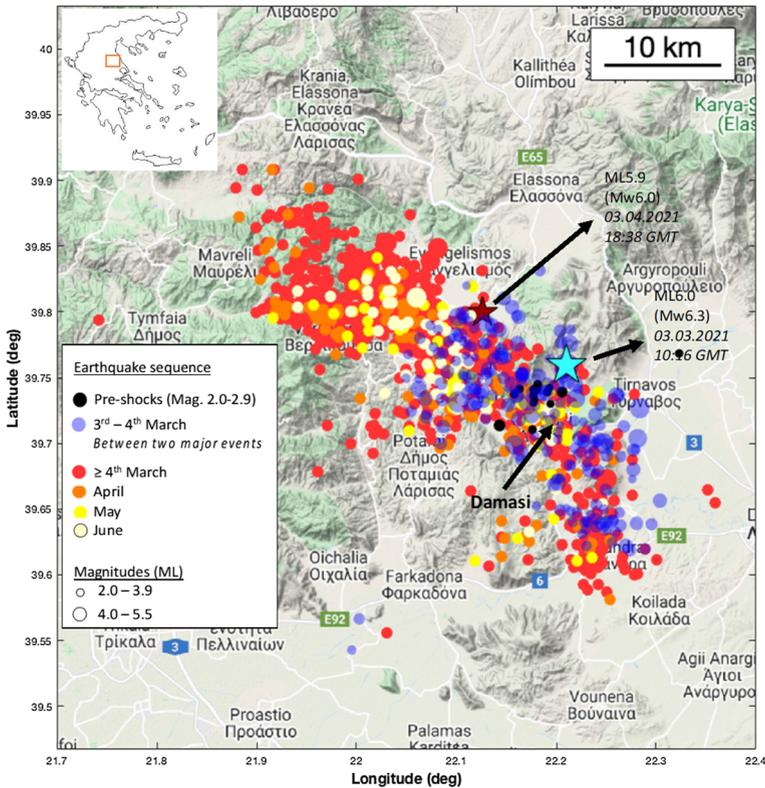
Fig. 1 Regions affected the most during the March 2021 earthquakes in Thessaly and the earthquake epicentres from 1st of March until the end of June (background map: Google Maps; Earthquake sequence of events http://www.geophysics.geol.uoa.gr/stations/maps/recent.html). Affected area is shown in red rectangle in the map of Greece, top-left

Papadimitriou and Karakostas, 2003; Müller et al. 2013; D'Agostino et al. 2020). At the same time, Thessaly is situated at the western end of the North Anatolian Fault Zone (NAFZ; a large strike-slip fault passing through Minor Asia, Turkey, and extending to the Aegean; Taymaz et al. 1991; Hatzfeld et al. 1999), which transfers compression in central Greece through the westwards motion of the Anatolian plate (Taymaz et al. 1991; Briole et al. 2021).

After the end of the Alpine orogeny (Oligocene), central Greece entered a period of extension (Miocene to recent), as it is situated in the back-arc domain of the Hellenic Arc (Ganas and Parsons 2009). The onset of extensional tectonics resulted in the formation of a series of prominent structural and geomorphic features striking NW–SE, such as the coastal and interior mountain ranges and the late Tertiary sedimentary basins (Caputo and Pavlides 1993). However, the Middle Quaternary-to-present tectonic regime has formed WNW-ESE and E-W high angle, normal faults (Caputo and Pavlides 1993; Pavlides et al. 2004; Ganas 2020). The seismic activity of the E-W & WNW-ESE faults is confirmed by the location of strong earthquakes during the twentieth century (Papazachos et al. 1983; Papastamatiou and Mouyaris 1986; Hatzfeld et al. 1999), and by paleoseismological data (e.g., Palyvos et al. 2010; Tsodoulos et al.
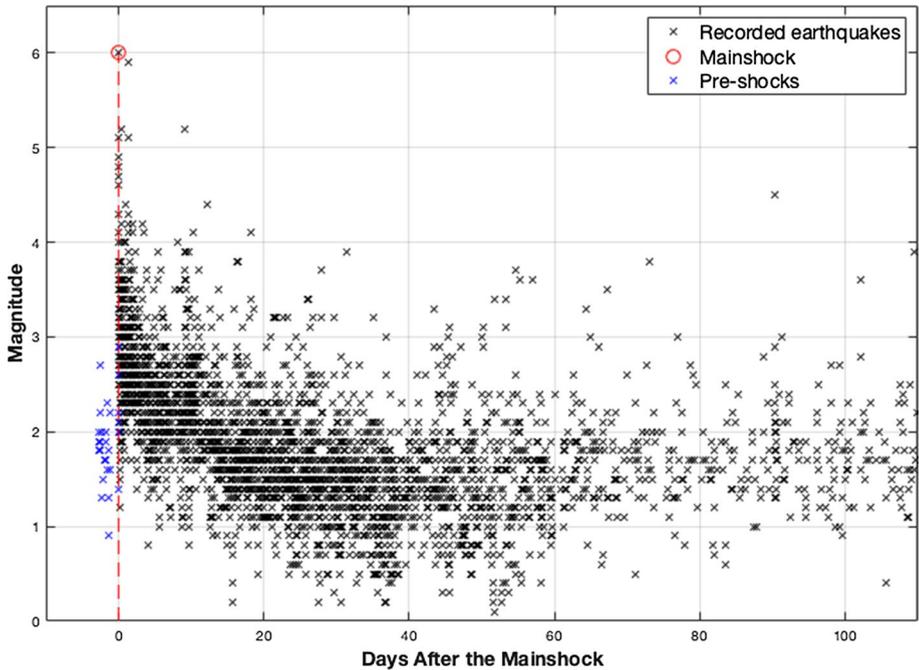
Fig. 2 Seismicity in the Thessaly region along the ruptured fault in March-June 2021

2016). Moreover, GNSS-derived strain rate data for Thessaly (D'Agostino et al. 2020) show an overall N-S orientation of the dilatational strain axis across north Thessaly.

The March 3, 2021, 10:16 UTC (Mw = 6.3) shallow earthquake occurred near Damasi, about 20 km to the northwest of Larissa (Lekkas et al. 2021a, b; Chatzipetros et al. 2021; Ganas et al. 2021; Koukouvelas et al. 2021; Valkaniotis et al. 2021; Tolomei et al. 2021). The following day, a Mw = 6.0 shallow earthquake occurred on March 4, 2021, 18:38 UTC a few km to the NW of the previous event. On March 12, 2021, 12:57 UTC a third event of Mw = 5.6 occurred near the NW edge of the Titarissios river basin. All events are located in the upper crust, with focal depth ranging between 7 and 13 km (Ganas et al. 2021). The co-seismic interferograms showed three main lobes of subsidence, partially overlapping, with a NW-SE to almost E-W orientation (De Novellis et al. 2021; Ganas et al. 2021; Tolomei et al. 2021). The median values of the dip-angles of the moment tensor solutions indicate moderate-dipping normal faulting ($\leq 40°$), in agreement with the results from the inversion of InSAR displacement data and field observations that indicated the activation of three previously unknown normal faults (Ganas et al. 2021). The earthquakes generated numerous secondary phenomena with vast areas of alluvial deposits exhibiting spectacular liquefaction features (Papathanassiou et al. 2021; Valkaniotis et al. 2021). No tectonic surface ruptures were found in the field, in agreement with the modelled, "blind" faults. Figure 3 shows the surface projection of the faults (shaded rectangles) of the three events of March 2021 in Northern Thessaly.
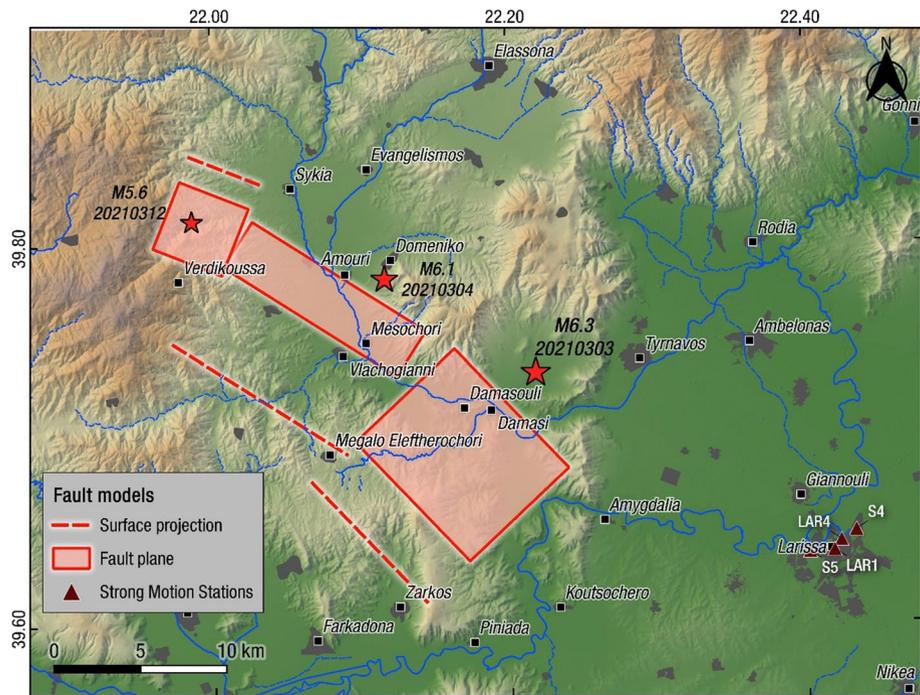
Fig. 3 Surface projection of the fault ruptures (shaded rectangles) of the three events of March 2021 in Northern Thessaly. The earthquake epicentres (Aristotle University of Thessaloniki) are shown as red stars. Dashed red line is the intersection of the fault plane at the surface (when projected up-dip); after Ganas et al. 2021. Crimson triangles show the position of strong motion stations with recorded data (Fig. 4))

3 Strong ground motion records

In the city of Larissa, the recordings of the main shock at four stations (LAR1, LAR4, S1 and S4) were available (Fig. 4). Of these, LAR1 and LAR4 belong to the National Strong Motion Array (installed and maintained by the Institute of Engineering Seismology & Earthquake Engineering ITSAK-EPPO) and the other two belong to the Municipality of Larissa and are maintained by ITSAK-EPPO. Based on available micro-zonation maps and available cross-hole measurements, N_{SPT} tests, and other geophysical investigations in the city of Larissa, it is estimated that the $V_{s,30}$ values are 307 cm/s at LAR1, 313 cm/s at LAR4, 235 cm/s at S4 and 305 cm/s at S5. Based on these estimations, all four stations are classified as Soil Class C according to EC8 (ITSAK-DUTh (2021), ITSAK-EPPO, DUTh, ETAM (2022)).

These stations are approximately 21 to 22 km far from the epicentre of the March 3rd earthquake. Time history plots of the recorded accelerations at these stations (records available at http://www.itsak.gr/db/data/strong_motion/after2000/) are given in Fig. 5. From Fig. 5, the largest recorded horizontal acceleration was 0.14 g in the EW direction of the S4 station, the closest to the epicentre (21 km). In comparison, the Mw6.1 earthquake of March 4th caused maximum horizontal accelerations of 0.07 g at the same station, again in the EW direction (the respective plots are not given here due to lack of space).
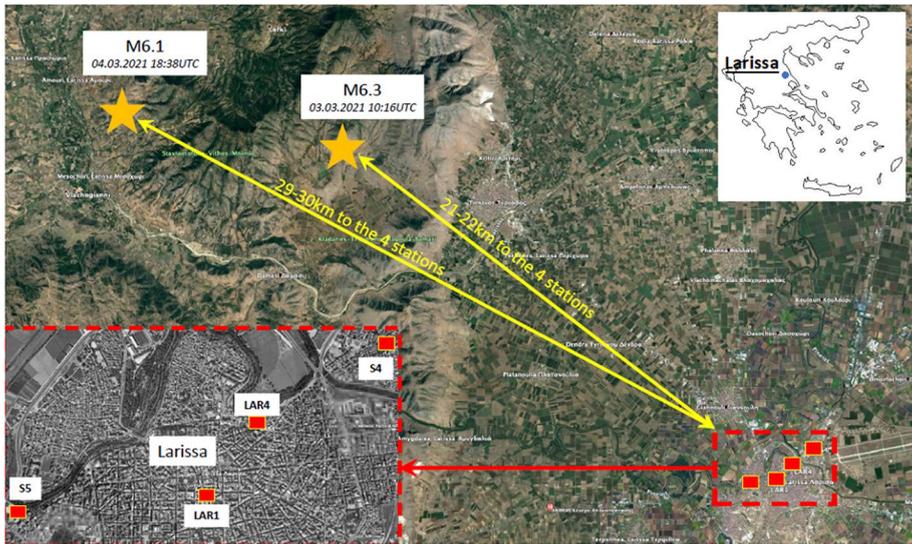
Fig. 4 The closest strong ground motion stations of ITSAK in the city of Larissa

As it will be discussed in the following sections, the structural failures concentrated mostly on rural structures that consisted of low-rise masonry buildings. These are relatively stiff buildings with low fundamental periods of vibration. Although the maximum recorded PGA is relatively small, and below the levels expected by experience to create damage on masonry structures, the extensive damage on buildings was found to be close to epicentre and in particular at the village of Damasi where much higher accelerations than those recorded at S4 in Larissa occurred. When the spectral accelerations in the EW direction were examined (Fig. 5), it can be seen that the recorded motion exhibited responses very close to the modern code levels at short periods. It should be noted that the accelerometers were all in Larissa, which are far from the epicentre. Although there is not record in hand at the rural regions, and closer to the epicentre, one could expect the acceleration response spectra to be closer to or even higher than the modern code levels in the nearfield.

Also, in Fig. 6, the elastic horizontal acceleration spectra ($\zeta = 5\%$) derived from the acceleration records of the March 3rd earthquake are presented and compared to the ones of older and current seismic codes. It should be noted that the first event induced higher accelerations than the second one, therefore only the response spectra in terms of acceleration for the records of the first event are presented herein.

In general, the Thessaly basin was not considered as highly seismic active, hence the Zone 1 and 2 classifications of the region in the latest Seismic Code. It is worth mentioning that the Sofades earthquake was the largest earthquake occurred in the last 100 years in the region. The Sofades earthquake occurred in 1954 and had a magnitude of 7. During the earthquake of Sofades, 25 people died and 157 were injured. In addition, during this earthquake, more than 15,000 structural failures to buildings occurred.
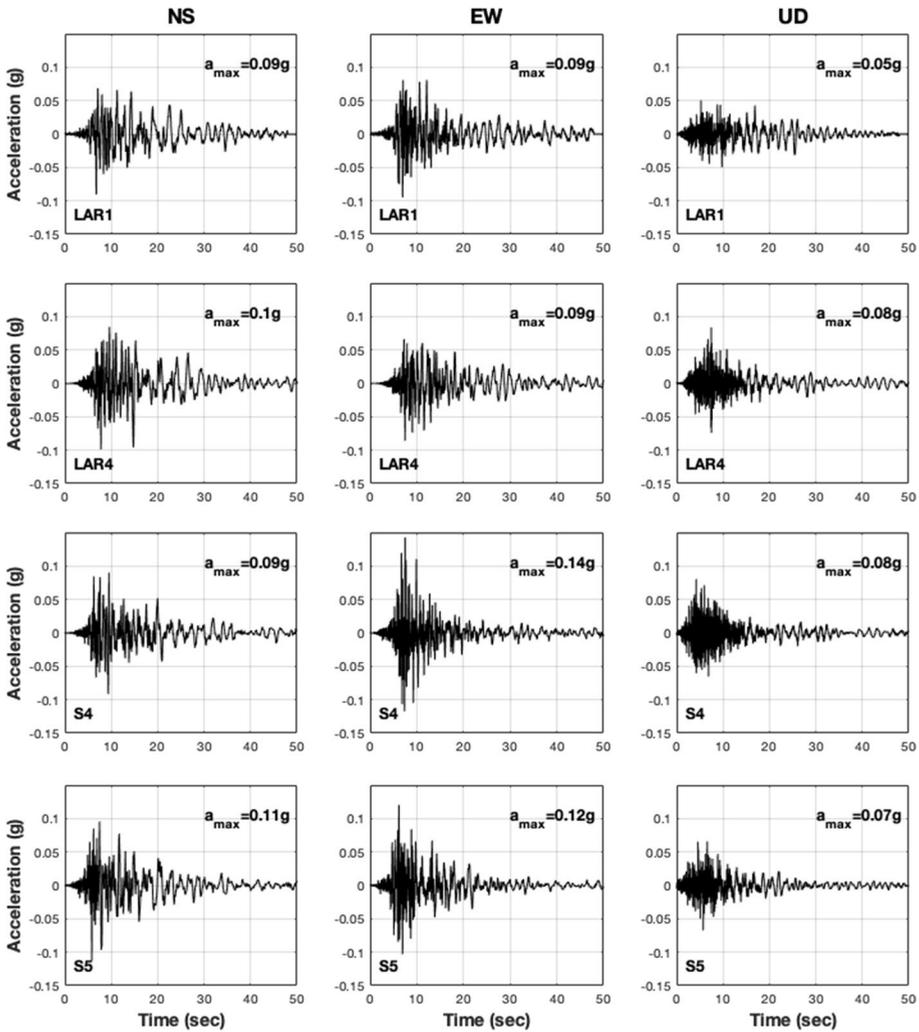
Fig. 5 Time history plots of the mainshock from 4 accelerometers in Larissa, in 21–22 km distance to the epicentre

4 Seismic codes in Greece

The first seismic code of Greece was the 1959 Seismic Code (GSC-1959) (Ministry of Public Works 1959) which prescribed a constant seismic coefficient, i.e., was based exclusively on pseudo-dynamic considerations. The horizontal lines in Fig. 6 correspond to the equivalent response spectrum of the GSC-1959. A constant distribution of the lateral load with a value of $(\varepsilon \times W)$ was considered, where ε is the seismic coefficient of the code, depending on the seismic zone, and W is the gravity load of the structure. The equivalent demand in the realm of modern codes would be a constant response spectrum with $Sd = 1.72 (q \times \varepsilon)$, with 1.72 being an empirical conversion factor between modern and past codes, relating

Fig. 6 5% damped horizontal acceleration elastic response spectra for the **a** NS and **b** EW directions as compared to the demand levels of the 1959 Greek seismic code, as well as the most recent EAK and EC8 design spectra for soil type C
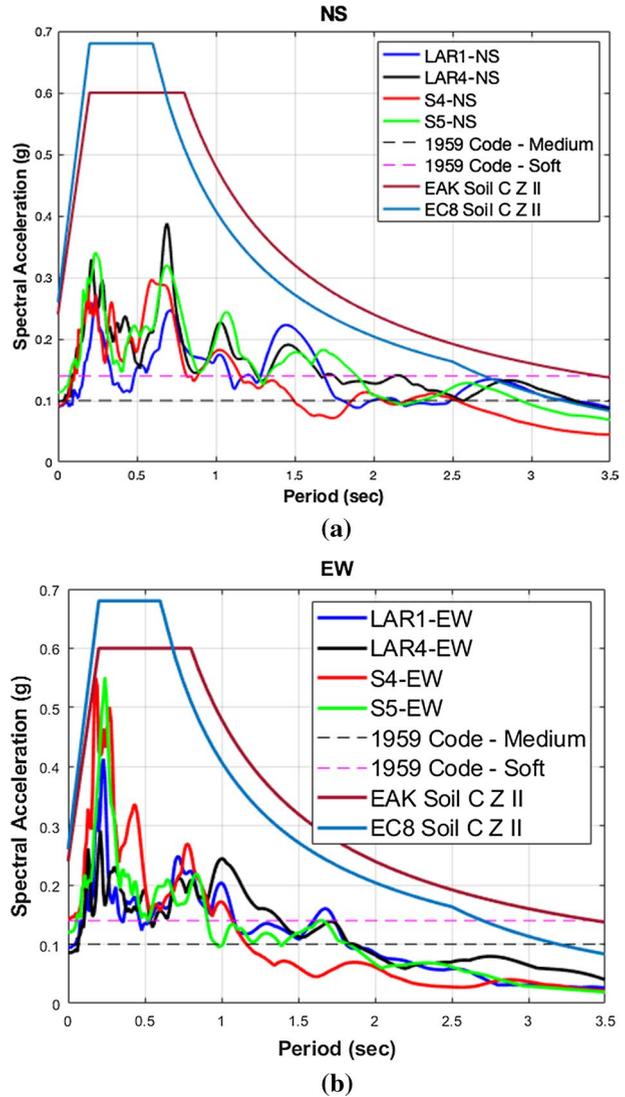
reinforced concrete provisions based on allowable stresses and ultimate strength concepts (Anagnostopoulos et al. 1987).

The area struck by the earthquake belongs to two seismic zones, Zone II for the metropolitan Larissa area and Zone I for the severely hit Elassona area. For the former, where the accelerometers were located, the base shear seismic design coefficient was set equal to $\varepsilon = 0.08$ and 0.12, for medium (type B) and soft soils (type C), respectively. Should a value of 1.50 be adopted for the behaviour factor (a reasonable approximation both for the unreinforced masonry structures and for the older generation of RC structures in Greece built without capacity design considerations), then the elastic spectrum acceleration Sa is equal to 0.21 and 0.32 respectively. It should be noted that since soil type classification at that time was rarely based on geotechnical investigation but on an engineering rough guess,

overestimating the soil stiffness was very common, i.e., in many cases type B factor was used for soft soils.

The 1959 Seismic Code was revised considerably in 1985 (Ministry of Public Works 1984) introducing several new provisions that increased the ductility of the structures and the requirement for using frame analysis for multi-storey buildings instead of the one-storey-model analysis prescribed in the 1959 code. A new seismic code, based on ultimate strength was introduced in 1995 (NEAK) and it was revised in 2000 (with a new seismic hazard map for Greece adopted in 2003) (EAK2000) (OASP2000) resulting to code provisions that are close to the ones of Eurocede 8 (EC8, 2004). In Fig. 6a, the response spectrum for an ordinary structure in Larissa metropolitan area following the Greek seismic code 2000 (GSC-2000), still in force for new structures in parallel with EC8, is plotted for soil type C. In Fig. 6a, the code prescribed peak ground acceleration is A = a g = 0.24 g, the importance factor is considered as $\gamma_I = 1$, and the behaviour factor is taken as q = 1 (elastic response spectra). It should be noted that in the GSC-2000 there is no explicit amplification factor applied depending on the soil type, however, while the maximum spectral values ('plateau' of the response spectrum) are the same, different period ranges within which they occur are prescribed for each soil type.

Finally, in Fig. 6, the requirements of EC8 in terms of elastic response acceleration spectra are presented for soil type C. For the EC8 acceleration spectra the parameters used are the same as for the GSC-2000 regarding the code prescribed peak ground acceleration, the importance factor, and the behaviour factor. The soil factor was taken as 1.15 for soft soil.

5　Method description of the field survey on building damages and findings

In order to gain valuable information from the site, and even from the more rural areas hit by the earthquake, and despite restrictions due to COVID19 pandemic, a damage investigation team was organised and visited the earthquake affected region. The post-disaster structural damage assessment was based on ground surveying method. It was necessary to identify the damage using a building-by-building approach, so most building damage assessments reviewed on a foot-on-ground approach. This detailed inspection was the most reliable and generated invaluable information about the damage condition, material behaviour and seismic performance of building stock in the region. Our in-situ structural observations were not limited to the mechanism of structural failure of single buildings but the scale of damage to structures at regional level. Local phenomena, such as the increase in observed damage close to alluvial riverbeds, was used in intensifying the inspections in those regions for getting a better picture of the underlying reasons of damage. However, inspection inside the buildings as well as at foundations were not possible.

Before the site visit, information about the building stock in the area was identified through the 2011 Census and the Hellenic Statistic Authority (Hellenic Statistic Authority 2015). According to that, 28% of the buildings were constructed before 1960, i.e., were designed without considering any seismic code provisions. Another 50% of the buildings were designed following the first seismic code provisions GSC 1959, which largely underestimate the seismic hazard. Also, 12% of the buildings were built between 1985 and 2000, a period in which the seismic codes were changing to become stricter. However, for the biggest part of that period the seismic hazard was still underestimated. Only 10% of the

buildings were constructed after 1996, clearly following modern regulations and design rules.

The first screening of damage undertaken by public authorities in the first week after the major earthquakes demonstrated that several domestic properties and some public buildings were severely damaged, including eight churches and a school in Damasi in which students were in the building during the earthquake. Figure 7 and Table 1 shows the outcome of the first rapid post-earthquake examination in buildings conducted the first week after the mainshock of the 3rd of March 2021 in the Municipality of Elassona. In total, 768 buildings were inspected by the Natural Disaster Impact Rehabilitation Directorate in Greece (DAEFK). The purpose of the inspection was to assess post-earthquake damage and group the buildings into three categories: (a) Green; (b) Yellow; and (c) Red. Buildings marked with green were those that were suitable for use; buildings marked with yellow were unsuitable for use until the building will be repaired; while buildings with a red mark were those in which the possibility of collapse is high, the entrance is forbidden or the building has already collapsed during the earthquake. From the conducted inspection, 368 buildings were marked as Green, 297 marked as Yellow and 103 marked as Red. The village with the most damage in buildings was Amouri with 27 buildings marked Red,
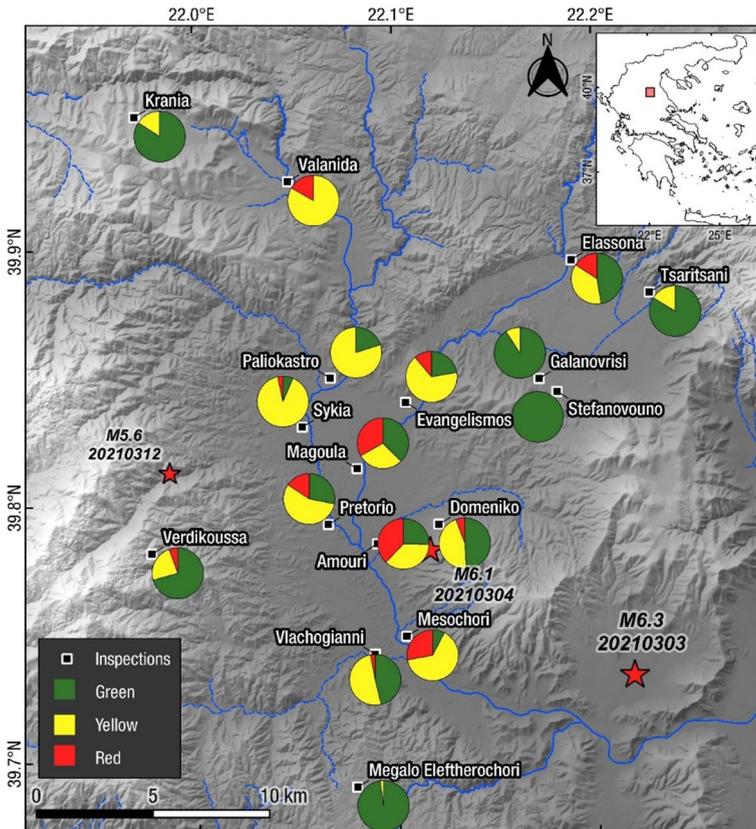

Fig. 7 Dsitributed of green, yellow and red tagged buildings after the inspections conducted until 12th of March 2021

Table 1 Buildings inspections with the accompanied geological conditions per region

Building Inspection

Settlement	Green	Yellow	Red	Geological conditions
Krania	16	3	–	*Bedrock, valley fill sediments*
Valanida	1	5	–	*Fluvial terraces*
Elassona	9	7	3	*Quaternary fluvial and fan deposits*
Paliokastro	3	12	–	*Quaternary alluvial deposits*
Sykia	2	28	1	*Fluvial terraces, quaternary deposits*
Magoula	26	20	23	*Fluvial terraces, quaternary deposits*
Verdikoussa	77	26	6	*Metamorphic bedrock*
Vlachogianni	31	34	2	*Metamorphic bedroc, fluvial terraces*
Megalo Eleftherochori	48	1	–	*Metamorphic bedrock*
Mesochori	7	60	26	*Quaternary fluvial and fan deposits*
Amouri	18	26	27	*Fluvial terraces*
Domeniko	26	24	3	*Metamorphic bedrock*
Evangelismos	2	6	1	*Quaternary fluvial and fan deposits*
Stefanovouno	18	–	–	*Metamorphic bedroc, alluvial deposits*
Tsaritsani	36	7	–	*Quaternary fluvial and fan deposits*
Pretorio	18	36	10	*Fluvial terraces, quaternary deposits*
Galanovrisi	30	3	–	*Metamorphic bedroc, alluvial deposits*

followed by Mesochori with 26 buildings marked Red. In addition, from the 25 schools inspected in Elassona, 11 were found to be usable while 14 unusable. Also, the Elassona Health Centre was inspected and deemed usable while the Magistrate's Court was temporarily unsuitable. In Tyrnavos Municipality, 26 school buildings were usable and 13 unusable. Also, the Agricultural Clinic of Tyrnavos was inspected and deemed usable. In Palamas, 25 school buildings were usable and 6 unusable, while in Farkadone 17 school buildings were usable and 14 unusable (Lekkas et al. 2021a, b). From the above it is clear that the schools in the region suffered significant damage and the State should take actions to identify schools vulnerable to earthquakes at a national level and future-proof them from similar events.

6 Structural damage in buildings

One of the basic principles of earthquake resistant design is that earthquakes have the tendency to pinpoint the buildings' weak points. The strong earthquakes and aftershocks of March 2021 in Thessaly revealed that the performance of reinforced concrete buildings was generally good and consistent with the level of expectation for the level of shaking. Some minor damages were observed mainly in non-structural elements such as infill walls. However, the strong shaking in the region exposed the vulnerability of the low-rise masonry dwellings made of local stone, clay fired bricks and low bond strength mortar joints (in most places mud mortar). Also, some of the buildings affected by the earthquakes form part of the architectural heritage of the region. Thus, it is imperative that a policy is developed to "*retain and strengthen*", rather than "*demolish and replace*" them. Strengthening

should be undertaken with care and by qualified engineers according to earthquake engineering principles and a vision to "*build-back better*". Also, reconstruction should be made with a view to preserve their architectural features and optimise reuse or high-grade recycling as per the principles of circular economy. This section presents the main observations and findings from the earthquake damage survey held in Thessaly, by members of the research team, only a few days after the twin earthquakes took place. The building typology in Thessaly is briefly reviewed and the field observations in the villages of Damasi, Tyrnavos, Mesochori and Koutsochero are discussed. The cases selected below are to highlight only the main observations from the rapid assessments and the macroscopic structural surveys. Numerous photographs are available freely as supplementary material to this manuscript and have been deposited at github: https://github.com/vsarhosis/Earthquake_Thessaly_Photos_2021.git

6.1 Reinforced concrete buildings

The response of the reinforced concrete buildings when subjected to earthquakes is highly dependent on the distribution of stiffness and mass in both the horizontal and vertical direction (Chopra, 2017). Typical damage was related to non-structural elements such as infill walls, i.e., separation of the infill walls from the concrete frame. In other cases, out of plane displacement and cracking due to bending were observed (Fig. 8). In addition to out-of-plane infill behaviour, the building in Fig. 8 shows shear damage in the column potentially due to the impact of the infill with the supporting column. Assuming that the structure did not have infill walls, the loss of the supporting column may have resulted to partial or even full progressive collapse of the bare reinforced concrete frame. However, the presence of masonry infill walls restrains the development of partial or progressive collapse

Fig. 8 Damage of infill walls in a RC building due to out of plane bending and shear damage in the column due to in plane infill behaviour in Damasi

mechanism. Such phenomena have been observed in the experiments carried out by Brod-sky et al. (2017) which concluded that a sound consideration of this interaction effect may contribute to the design of more robust buildings with improved ability to respond to the event of loss of a supporting column.

Figure 9 shows another example of in-plane shear failure of a poorly confined masonry wall in Mesochori. Cracking in masonry presents a diagonal shear crack formed in a zig-zag pattern.

Despite the fact that a large portion of RC buildings suffered only non-structural dam-age, severe damages had also occurred, as shown in Fig. 10 and 11.

Severe damages to RC buildings were observed mainly in soft-storey ground floors (called pilotes in Greek, see Fig. 10a). These are buildings mainly designed and con-structed before 1985. The lack of shear reinforcement accompanied with loss of stiffness due to open ground floors led to shear failures of columns and beam to column joints, see Fig. 10. Lack of appropriate horizontal reinforcement (stirrups) resulted in buckling of the longitudinal rebars of the columns (Fig. 10c). The strong beams remained undamaged, while severe damage and plastic hinges developed at the top of the columns. In other cases, where not enough reinforcement installed, diagonal shear cracking was observed in shear walls, see Fig. 11.

6.2 Masonry buildings

Masonry is a brittle and anisotropic material which is strong in compression and weak in tension (Hendry 1998; Lourenco 1998). Cracks in masonry may not open uniformly. In fact, cracks may open and close according to the type of stresses applied to them (Sar-hosis et al. 2016). Typically, cracks greater than 0.2 mm in width are visible to the naked

Fig. 9 In plane shear failure of poorly confined masonry wall due to door opening in Mesochori

Fig. 10 Strong beam-weak column of a residential building in Damasi

eye. In masonry buildings, the walls are the most vulnerable structural components to the horizontal seismic forces. There is a significant amount of unreinforced masonry buildings in Thessaly region. The preliminary damage assessment presented here is based on the patterns of cracks and dislocations observed on the exterior of the buildings, since access to the interior was not allowed at the time of the visit.

6.2.1 Residential buildings

Residential masonry buildings are either single- or two-storey and were made of uncoarsed random rubble (irregularly shaped) stone masonry and/or clay masonry units. Their typical
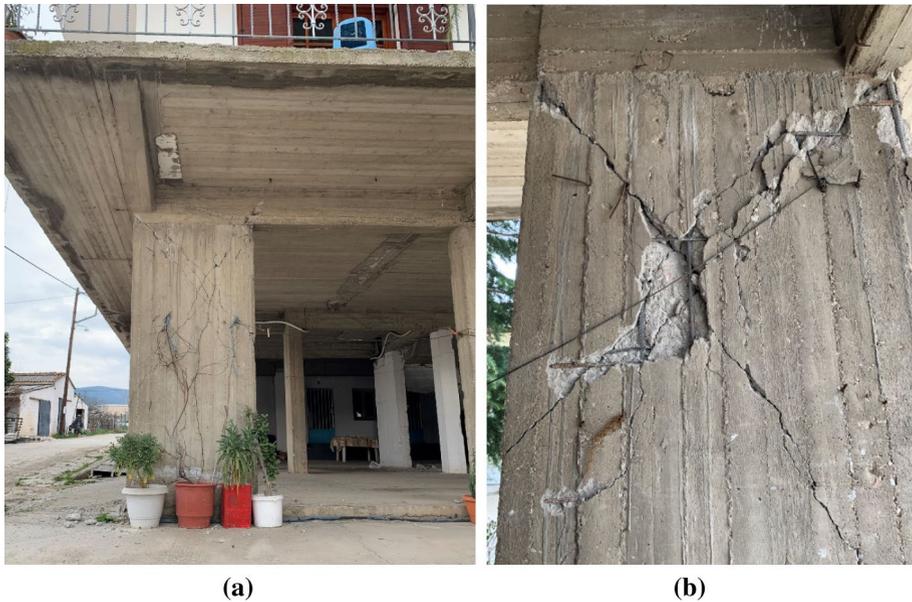
(a)   **(b)**

Fig. 11 "X" shaped failure of a shear wall located near the top in a RC building **a** face of the shear wall; **b** back of the shear wall at the corner of the building

plan is either square or elongated rectangular with the large side often being longer than twice the length of the smaller side. Typically, walls are two-leaf and their thickness ranges usually from 0.4 m to 0.6 m. In general, there is no transversal interlocking of masonry units between the two leaves of the masonry walls that would allow improved shear bearing capacity and enhance the in-plane and out-of-plane strengths of the wall. Despite other apparent weaknesses, the outer corner intersections (edges) of the walls are usually well constructed with interlocking semi-dressed stones. As it will be shown later, the bonding pattern and mortar characteristics affected the structural capacity of these masonry buildings. Also, residential buildings in the region are characterised by large openings with or without horizontal timber or masonry arched lintels. Roofs are made of timber trusses, covered with ceramic red tiles. On the top of the masonry, there is usually a twin lintel band for the connection of the wooden roof with the stone structures. However, in some cases, there are intermediate lintel bands (chainage) of wood or other material that would significantly increase the seismic capacity of the buildings. Floors are typically made of timber joists covered with wooden planks for flooring. In other cases, buildings were made of multi-leaf rubble stone at the ground floor and the upper storey made of clay bricks (Fig. 12). Residential masonry buildings in the region suffered the most damage. The extent of damage varied from one building to the other and from region to region. These buildings were constructed without following any structural regulations. In addition, they are old and not sufficiently preserved; in some cases, the structures suffered from pre-existing ground settlements and small out-of-plane deformations.

Structural inspections carried out a few days after the earthquake demonstrated that poor material quality of multi-leaf masonry walls was the main reason of structural damage in several buildings. In particular, out of plane partial or complete collapse of walls was the main failure mode in most of the residential unreinforced masonry

Fig. 12 Masonry house with large openings and wooden lintels above openings in Tyrnavos. The ground floor is made of stone masonry while the first floor is made of clay bricks

buildings in Damasi and Mesochori. Figure 13 shows some examples of out-of-plane failure of masonry walls. It is evident from Fig. 13 that, although the thickness of the walls is adequate, these were constructed using mud as mortar, which is of very low strength and thus vulnerable to earthquake shaking (Lourenço 1998). Despite the fact that Fig. 13 does not show a serious damage in the form of partial or total collapse, parts of the wall falling on the street causes many other secondary issues, such as blocking the passage of large rescue vehicles and damaging civilian cars.

Lack of maintenance contributed in many cases to increase in the seismic vulnerability of the existing masonry buildings in the region. Other reasons for the development of such out-of-plane failures are the absence of horizontal binding elements and inadequate connections at wall intersections, see Fig. 14. These uncoursed walls have two exterior vertical layers (called wythes) of large stones, filled in between with loose stone rubble and mud mortar. Although someone could consider such stone masonry buildings robust due to their large wall thickness, in effect this is not the case. Such buildings are one of the most deficient building systems from an earthquake-resistance point of view. The excessive wall thickness and the absence of connection between the two wythes of the wall, as well as the use of round stones instead of regular shaped ones
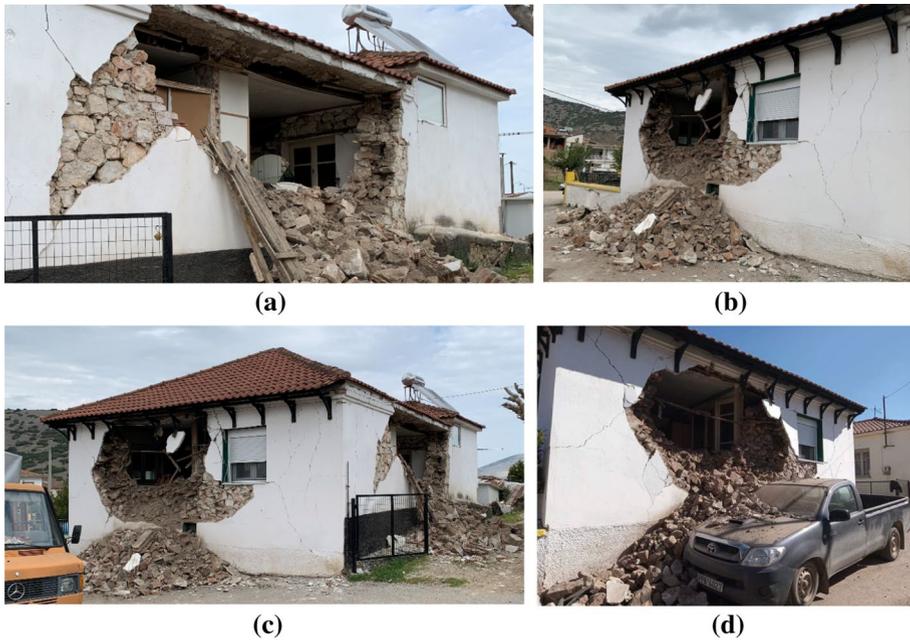
Fig. 13 Out of plane collapse of masonry walls in Damasi, Greece

Fig. 14 Typical uncoursed random rubble stone masonry walls found in buildings in Thessaly region **a** view of the inner part of the thick wall; **b** cross-section of the wall (average thickness of walls is 0.5 m)

could split the wall into two vertical layers. Often outward bulging of the vertical wall layer was encountered.

In addition, most of the buildings in the region did not have any ring beam below the roof, while they lacked stiff in plane diaphragms at the floor and roof level. Figures 15 and 16 show buildings with loosely connected walls and no rigid top floor or RC ring beam. The poor wall to roof connection together with the poor quality of stone arrangement and mortar strength contributed to their collapse during the earthquake. It is also believed that the later added rigid RC slabs (partially supported on RC columns on one side and on the

Fig. 15 Out of plane collapse due to poor connection between the roof and the underlying masonry and no rigid top floor, Damasi, Greece

Fig. 16 Pounding failure due to different dynamic characteristics of structural components

masonry walls on the other) at the entrance of the buildings in the region, meant for rain protection or shading, contributed to the out of plane damage of the original low strength masonry walls. In fact, these additions were quite common among the masonry buildings in the affected area, see Figs. 15 and 16.

In other cases, the ring beam used by engineers to allow connectivity of the walls was ineffective. Figure 17 shows an example of an ineffective ring beam constructed with three

Fig. 17 Lack of an effective ring beam

layers of clay masonry units with a stronger mortar, which is a rather unfortunate design choice. The higher masonry ring beam may have caused redistribution of vertical compressive stresses and some parts of the masonry wall below, could result in becoming unloaded and prone to being unstable during the earthquake. In addition, the high stiffness of the masonry ring beam, which is able to carry large axial and bending forces has modified the natural vibration mode of the masonry walls and generated local high stresses in the masonry walls below the ring beam (Borri et al. 2016; Faella 2020). From Fig. 17, the lack of anchoring of the ring beam with the load bearing walls to resist loads from horizontal direction and the lack of strengthening of the wall are the main causes of the partial collapse.

Another type of damage observed was that of bulging and delamination of the walls due to their outward buckling. The main reason for delamination was the absence of through stones or connection between the two-leaf walls as well as due to weak bonding between the outer wall and fill material. Delamination was mainly observed at the upper part of the walls. Since the space between the interior and exterior walls was filled with small stones and rubble bonded with mud mortar, connection between the two walls was inadequate. Figure 18 shows examples of delamination of masonry walls in buildings found in Meschohori. It is worth mentioning that delamination was formed in a trapezoidal shape. In some cases, delamination was observed only at the masonry walls (Fig. 18a), while in others it was a combination of the masonry walls and wall to wall intersections (Fig. 18b).

Based on the aspect ratio of unreinforced masonry elements, excessive bending and shear can produce in-plane failure. From the visual survey it was evident that diagonal shear cracks developed in walls with openings during the earthquake. Such cracks initiated from the centre of the pier and propagated towards the corners. Depending on the quality of mortar, cracks passed through the mortar joints or in other cases pass through the units and mortar joints. Several masonry buildings had suffered damage to walls, in the form of double-diagonal shear (X) cracking, which is a common weakness of unreinforced masonry walls in shear. When a full diagonal shear crack occurs during an earthquake, the

Fig. 18 Delamination of **a** the upper part; and **b** entire wall of a masonry buildings in Mesochori

triangular sections of the cross-diagonal crack become unstable, and eventually it may lead to collapse with aftershocks. Typical, examples of diagonal shear cracks in load-bearing walls caused by the earthquake in Thessaly are shown in Fig. 19.

Figure 20 also shows pounding of the RC building slab into the masonry wall of the adjacent building. The RC slab of the reinforced concrete building penetrated in the corner of the masonry buildings at the wall to roof connection and created damage.

In addition, it was observed that severe vertical cracks and gaps formed and propagated along the height of bearing wall intersections, see Fig. 21a and b. Such damage was attributed to the lack of the horizontal diaphragms. Structural integrity formed due to the inadequate connections between the bearing walls at the wall intersections and between the bearing walls and the roof. From Fig. 21 the lack of diagonal shear cracks is evident which denotes that the walls acted independently along the in-plane and out-of-plane direction under the earthquake.

6.2.2 School building of Damasi

In Thessaly, school buildings are large in dimension and typically symmetrical. Usually, such buildings were constructed using high quality details e.g., connection between

Fig. 19 Shear cracks due to diagonal tension in domestic masonry buildings in Mesochori

Fig. 20 Pounding between adjacent RC and masonry buildings

(a) **(b)**

Fig. 21 Vertical cracks at corners of the buildings denotes the lack of diaphragmatic action of the roof and floor systems (Lekkas et al. 2021a, b)

walls, lintels above window and door openings, beams, or bands at various heights etc. The failures observed in school buildings in Thessaly follow the typical damage typology of the masonry residential buildings. The extent of damage in the school of Damasi which was built in 1938 is shown in Fig. 22. Sixty-three students and their ten teachers were fortunately unharmed when some masonry walls locally collapsed. From Fig. 22, it can be observed that parts of the load bearing walls of the building failed in the out of plane direction while some diagonal shear cracks are evident between the window openings of the ground floor. Also, the front face of the school suffered more damage compared to the back side. This was due to the fact that more openings existed at the front of the school in which classes were located as opposed to the back side of the school in which there was the corridor to the classes. In the interior of the building, major diagonal shear failure at the masonry walls as well as separation of coating material from the masonry walls and overturning of chairs, desks and equipment occurred. The structure

Fig. 22 **a** Front view of the school from the 1940s; **b** front view of showing shear cracks and out of plane failure of the masonry walls; **c** rear view showing extensive shear failure of the piers between openings

(a)

(b)

(c)

was characterised as unsuitable and was demolished a couple of weeks after the first strong earthquake.

6.2.3 Churches

Several churches were severely damaged during the earthquake in Thessaly. Churches are not only places of religion gatherins but centres of social activities for the local communities. Churches play an important role in the social behaviour of citizens which is amplified in an event of an earthquake. From the earthquake engineering point of view, it is interesting to study churches due to their peculiar architecture and thus dynamic response.

Most of the churches in Thessaly were made of good workmanship masonry walls that suffered significant, but repairable damage. In some cases, complete re-construction of parts of the churches is essential. Inversely, arches and hemispherical domes, and in particular those with large span/diameter, were poorly constructed and not well connected to the main structural elements of the churches. Movement and deformation induced from earthquakes' actions can disturb the equilibrium and cause instability. To avoid such issues, the loads need to be distributed uniformly. Figure 23 shows cracking at the arches supporting the dome in churches in Tyrnavos. Such arches which are in fact "relieving arches" were built inside the solid masonry walls to influence instability of the dome and reduce the weight at the top. These arches transfer the weight of the dome to either side of the opening (i.e., at the slender pillar). To resist the horizontal seismic movement, pillars must have enough strength/width to keep the resultant lateral forces within limits. When this is not the case, shear failure at the pillars is observed, which could also lead to cracking of the arches (see Fig. 24). Figure 24 shows temporary measures and scaffolds placed a few days after the earthquake to keep the dome in place and avoid its collapse due to aftershock activity. In addition, spandrel failure was found to be influenced by the lintels above openings. It was observed that lintels made of timber failed in flexure while the ones made of shallow masonry arches or flat arches failed in shear. Such observations coincide with laboratory tests preseted at (Beyer and Dazio 2012; Sarhosis et al. 2015).

Masonry bell towers present peculiar behaviour during an earthquake due to their unique characteristics such as the slenderness (height over length ratio) and shape. Bell towers in the region of Thessaly are typically isolated towers commonly built adjacent to churches. They were mainly built to withstand vertical loading induced by self-weight, not providing for adequate lateral performance under earthquake loads. Their wall thickness used to be determined by rules of thumb which led to enormous thicknesses, in some cases even 2 m. Such structures are typically over 100 years old, are deteriorating and have large and heavy bells on the top which makes them extremely vulnerable to suffer a sudden collapse during an earthquake. Damage in bell towers observed after the earthquake in Thessaly are shown in Fig. 25.

Several strong aftershocks occurred caused further damage or collapse to churches. Progression of damage depends on the mainshock-aftershock sequence but also on the type and seismic capacity of the structure. Therefore, it is important to efficiently forecast how
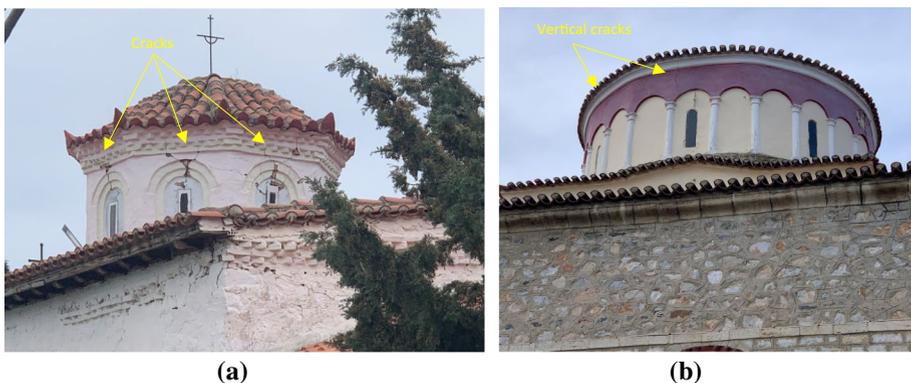

| (a) | (b) |

Fig. 23 Vertical cracks in arches and domes: **a** profitis Hlias in Tyrnavos; **b** Panagia Faneromeni in Tyrnavos
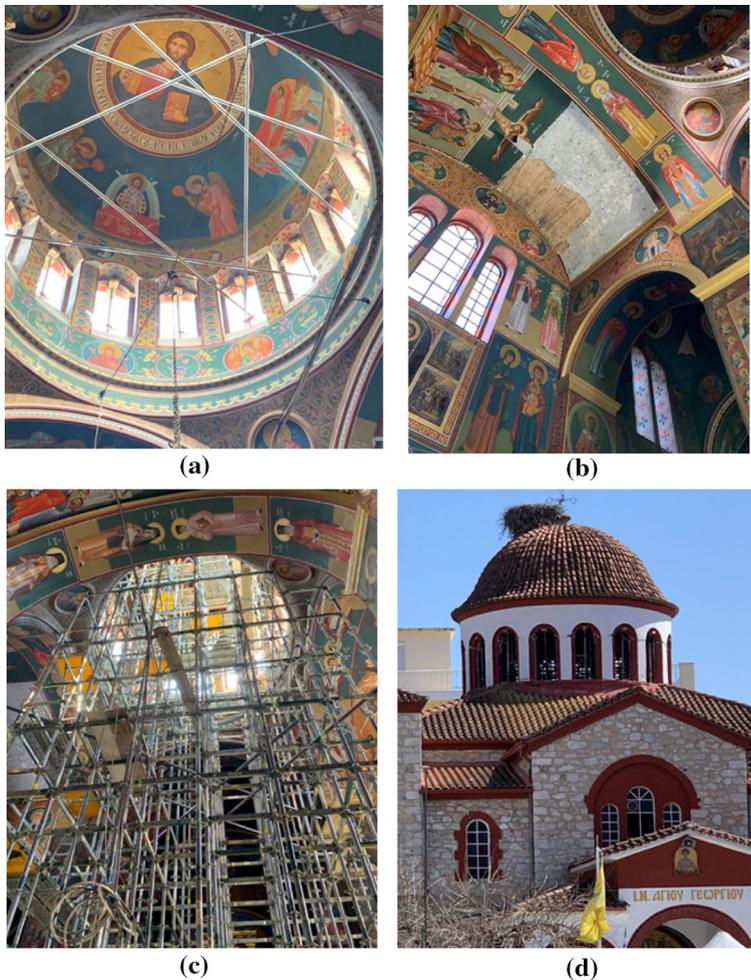
Fig. 24 Church of Agios Georgios in Tyrnavos: **a** Lateral springing thrust of the arches resulted in shear cracks in the slender piers supporting the wooden dome; **b** non-structural damages; **c** scaffolding for supporting of the arch dome; **d** external view

these already-compromised structures will perform during the next aftershock, or during a follow-up major seismic event. In order to address these dangers in the aftershocks time, the use of remote sensing and robots for search and rescue operations could be implemented (Sarhosis et al. 2016, 2021). In Fig. 26a the progressive collapse of the bell towers in the church of Agios Dimitrios at Mesochori can be seen. As a result of the aftershocks, the towers, the triangular gabion wall (metopi) and the kiosk in front of the church collapsed.

Figure 27 is an example of an effective retrofitting scheme to improve connection of the roof and the walls applied to a church in Tyrnavos. The reinforced concrete ring beam effectively kept the connectivity of the peripheral walls of the building and the roof together. In order for the retrofitting scheme to be effective, reinforced concrete ring beams should be introduced to avoid excessive increase in weight and stiffness

Fig. 25 **a** Bell tower of church of Agios Ioannis in Tyrnavos before the 3/3/2021 event (source: Tirna-vospress.gr); **b** out of plane failure after the earthquake; **c** and **d** shear diagonal cracks between openings at the bell tower of the church of Agia Paraskevi in Tyrnavos

as well as tangential stresses development between the ring beam and the wall, which could lead to sliding of the ring beam and desegregation of the masonry wall (Frumento et al. 2006). Due to the difference in stiffness between the reinforced concrete beam and masonry, local strengthening of the upper part of the wall is required using post installed grouted bars or rods.

On the other hand, Fig. 28a shows a corner failure of the load bearing walls of a church due to out of plane movement which can lead to façade separation, while in Fig. 28b shear cracks occurred due to the large openings. Such cracks propagated from the window and door openings to the roof.

Fig. 26 Church of Agios Dimitrios at Mesochori **a** view from the 1980s; **b** before the earthquake; **c** after the main event of 3/3/21; **d** after the aftershocks on 10/03/21

Fig. 27 Example of good quality RC ring beam which ensured connectivity of walls in a church in Tyrnavos

Fig. 28 Damages (within the red ellipses) in the corner and perimeter wall of churches at **a** Damasi (church of Agios Nikolaos); and **b** Tyrnavos (church of Agia Paraskevi)

Figure 29 shows the Church of St Nicolas in Koutchocheron. As we can see from Fig. 29b the eastern wall of the church collapsed in an out of plane mode. This may be attributed, among others, to the existance of three large openings at the altar (Fig. 29a), a not so typical architectural feature (most Greek Churches have one opening at the altar only). Also, Fig. 29c shows an extension of the church with a RC covered walkway in contact with the southern wall of the church for operational reasons. Diagonal "X" shaped cracks of the infill walls of the walkway as well as separation of the newer walls with the existing ones of the church occurred during the earthquake. Several non-structural damages were also observed in Fig. 29d. Finally, Fig. 29e and f shows the total collapse of the older, Agios Nikolaos chapel (built in late 1700s), next to the newer church. The chapel was made of stone masonry connected with low in bond strength mud mortar. Also, the timber roof simply resting on top of the perimeter walls without any capacity of resisting any out of plane actions of the upper part of the walls but rather transfer horizontal forces which led to collapse of the walls.

7 Lessons learned from the earthquake damage survey

The earthquake of Thessaly in 2021 highlighted the vulnerability of existing masonry dwellings in Greece. The lessons learned from the earthquake damage survey in Thessaly region can be summarised as follows:

- The earthquake damage to masonry buildings was severe, whereas damage to RC buildings was limited, which demonstrates the effectiveness of the new design codes and standards. However, although RC framed buildings performed well for this earthquake, caution is necessary related to future hazards in the region because the 2021 earthquake is not necessarily the worst-case scenario.
- Performance of masonry buildings was poor due to bad quality of construction typologies, materials and lack of maintenance.
- Some buildings that were severely damaged by the mainshock eventually collapsed due to major aftershocks. Therefore, further studies are required to enable engineers

Fig. 29 Church of Agios Nikolaos at Koutchochero: **a** before the earthquake (picture taken from Google maps-street view), **b** North side of the church after the earthquake of March 2021; **c** west side of the church; **d** non-structural damages inside the church; **e** older, Agios Nikolaos chapel; **f** interior of the chapel of Agios Nikolaos

   to assess the capability of aftershock forecasting and building evacuation procedures, as well as for protecting the life of the responders serving in the region throughout the whole seismic sequence.
- The building damage in Thessaly was localised to specific areas even within the same village. Therefore, it is expected that the building collapse sites were affected by local soil characteristics and/or structural deficiencies, thus micro-zonation studies to better capture the local site characteristics would provide valuable insights.

- Out-of-plane collapses were often observed in masonry structures in the region. Such walls may even be free on to top if the roof diaphragm is not sufficient, leading thus to even lower out of plane strength.
- Based on previous seismological suggestions, Larissa and Tyrnavos areas are considered to be in seismic zone 2, with a design peak ground acceleration equal to 0.24 g. The Elassona area, which was severely hit by the seismic event on the other hand, lies in seismic zone 1, with a design peak ground acceleration equal 0.16 g. Based on the data provided by the earthquake and the increased seismic hazard of the Elassona area. the seismic hazard of the Ellassona area may need to be upgraded in a future revision of the seismic code.
- Futureproofing the seismic vulnerability of schools and hospitals is of paramount importance and the government needs to urgently act on this. The priority should be given older, and especially masonry school structures.
- The existing disaster management plans were in general effectively implemented after the 3/3/2021 earthquake. The villages and the affected people were reached soon after the main event by the authorities and respective national disaster relief agencies, and building tagging started soon after.
- Fortunately, several rehabilitation strategies are currently available for strengthening existing masonry structures. These mainly focus on: a) improving connections using anchor rods, tie rods etc.; b) stiffening floor diaphragms e.g., by using timber planks or panels, cast in reinforce concrete etc.; and c) enhancing masonry material properties e.g., deep joint repointing, installation of reinforced plasters etc. Further information about different seismic retrofitting techniques for masonry, can be found, among others, in Wang et al. (2018), Frumento et al. (2006), Corradi et al. (2019) and Guerrini et al. (2021).

8 Conclusions

The earthquake on the 3rd of March 2021 in Thessaly needs to be analysed carefully to better understand the phenomenon and its vulnerability to the rural buildings stock. Although the modern seismic codes, which are in effect in Greece since 1984, can protect the buildings from major earthquakes, rural construction, public buildings made in lower or no seismic standards such as schools, and historical building stock are still vulnerable to medium to large magnitude earthquakes. Although there are no strong ground motion records from the mountainous areas of the effected region, the indications show that the accelerations response in short periods could be higher than the anticipated in the modern codes. This paper presented important earthquake field observations in Thessaly in the aftermath of the consecutive earthquakes of $M_w = 6.3$ and $M_w = 6.1$, on March 3rd and 4th, respectively. Damage investigation data were collected in 3 to 7 days after the main shocks, and thus a first hand damage observations were recorded very quickly. Data and geo-referenced photos obtained have been shared publicly and are freely available to be downloaded for educational and research purposes. To gain an improved understanding of the damage observed during the earthquakes in Thessaly, the regional seismicity in the region was reviewed and available pre-shock and aftershock data and ground motion data were proceeded and discussed.

The main mode of failure observed on masonry buildings was the out-of-plane overturning of the long side of the masonry buildings, while cases of total collapse were also

observed. In some cases, delamination of masonry wall layers was observed, followed by out of plane failure of only one leaf (usually the exterior one) for double leaf stonework. This is attributed to the lack of interlocking between the leaves. The masonry walls on the short sides of the building usually experienced in-plane shear cracks and rather rarely out-of-plane failure. In several cases the diaphragm action was not sufficient either at the level of the floors or at the roof level. For timber floors this may happen due to insufficient connections of the wood beams to the walls or due to lack of stiffness of the wood floors as a result of rotting. As far as the roof is concerned, this is the result either of a complete lack of a timber or RC belt at the crown of the masonry or of a half width band that lies only on the inner leaf of the masonry at its crown. The latter takes place for architectural reasons so as the belt is not visible at the facade. The result is that the outer leaf of the masonry is not connected to the roof diaphragm leading to the delamination of the masonry and the out of plane failure of the outer leaf.

Another factor that led to failures was the poor quality of the bonding mortars. Their deterioration due to aging in combination with the lack of maintenance, led to a decline of their strength (especially for clay mortar). Also, in some cases masonry buildings that were in contact with newer RC buildings (i.e. without seismic joint) experienced damage as a result of pounding. This should be expected due to the different stiffness of the two structures and therefore the different fundamental periods of vibration. The phenomenon was also observed in the cases of horizontal extension of masonry buildings with newer additions made of RC. Special mention should be made of the following rather frequent case of pounding. In several buildings a later semi open entrance area was added made of reinforced concrete. This additional structure consists of columns bearing a reinforced concrete slab often without beams. The slab is usually located at a lower level than the roof of the building, so a pounding effect could take place.

It should be noted that the post-earthquake structural observations in this paper do not include response of foundations and their possible role in the overall picture, because site investigation of foundation elements was not possible within the short time available in the post-event reconnaissance visit.

Declarations

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Authors and Affiliations

V. Sarhosis[1,7] · **C. Giarlelis[2]** · **C. Karakostas[3]** · **E. Smyrou[4]** · **I. E. Bal[4]** · **S. Valkaniotis[5]** · **A. Ganas[6]**

[1]   School of Civil Engineerinag, University of Leeds, Leeds LS2 9JT, UK

[2]   EQUIDAS Consulting Engineers, Athens, Greece

[3]   Institute of Engineering Seismology & Earthquake Engineering, Research Unit of Earthquake Planning & Protection Organization, 55535 Thessaloniki, Greece

[4]   Hanze University of Applied Sciences, Research Centre Built Environment NoorderRuimte, Zerkineplein 7, Groningen, Netherlands

[5]   Department of Civil Engineering, Democritus University of Thrace, 67100 Xanthi, Greece

[6]   National Observatory of Athens, Institute of Geodynamics, Lofos Nymfon, Thission, 11810 Athens, Greece

[7]   Chair of Analysis and Restoration of Structures of Architectural Heritage in the UK (ISCARSAH-UK), London, UK