

## The Lefkada 17 November 2015 ( $M_w$ 6.4) earthquake: strong ground motion and damage distribution

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### ABSTRACT

This work describes the outcome of two field surveys in Lefkada Island, after the 17.11.2015 earthquake of  $M_w$ 6.4 at its southwestern peninsula. Geo-environmental effects were observed throughout the western flanks of the mountain massif, parallel to the activated fault. Structural damage was mainly observed in the epicentral area where macroseismic intensity was assessed as VIII. Both modern and traditional buildings exhibited notable seismic performance. Comparison with the previous earthquake on 14.8.2003 with  $M_w$ 6.2 which occurred ~20 km to the north, shows that structural damage was by ~80% lower during the recent quake, possibly due to enhancement of the buildings after the 2003 event and the spectral content of the strong ground motion, been discrete from the range of the dynamic response of the constructions. The distribution of the damage per building category present in the affected area is presented, based on site surveys and post-seismic usability characterization by the local Earthquake Rehabilitation Organization. The survey highlights the frequent presence of the so-called “pontelo” dual system at both ground floor and two-story stone masonry buildings at the western mountain villages. This structural type, unique within the Greek territory, revealed significant seismic performance and the need of engineering restoration measures is underlined.

*Keywords: Western Greece, Seismic damage, Lefkada buildings, macroseismic intensity*

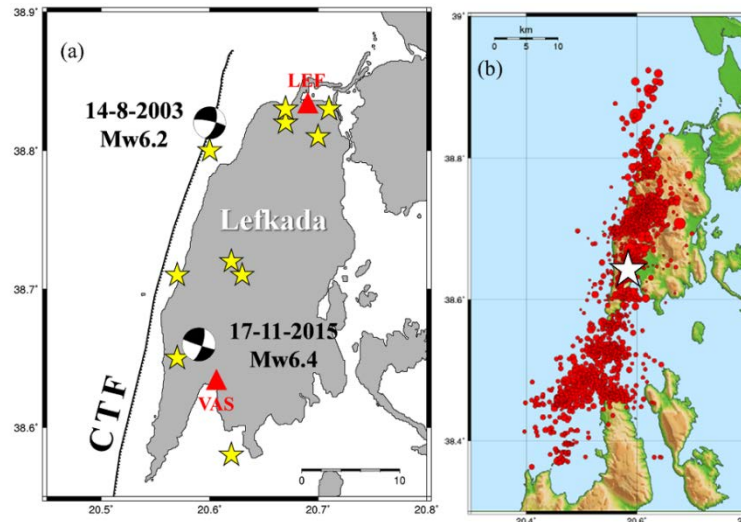
### 1. INTRODUCTION

The present work describes the outcome of two field surveys in Lefkada Island, after the earthquake of  $M_w$ 6.4 on 17.11.2015, organized by the Seismological Laboratory of the National Kapodistrian University of Athens (SL-NKUA), in collaboration with the Institute of Geodynamics of the National Observatory of Athens (GI-NOA) and the Politecnico di Milano (PoliMi).

Lefkada Island is situated at the northwest tip of the Aegean arc, an area of high seismicity rates, having suffered numerous severe earthquakes in the past produced by the prominent Cephalonia Transform Fault (CTF-Figure 1) (Hatzfeld et al. 1995). Most earthquakes in the region were generated at the northwestern part of the island mainly affecting the capital of the island, Lefkada town. The region belongs to the highest zone (III) of the Greek National earthquake design code (EAK 2000, 2003) that predicts a peak ground acceleration of 0.36g.

The earthquakes of Lefkada have been the subject of intense investigations regarding the physics of the seismic sources and the seismic behavior of its buildings (e.g. Touliatos and Vintzileou, 2006), designated as particular earthquake resistant constructions by the European Council Cultural Heritage Unit (Kalantoni et

al., 2013). Much of the research was performed after the Mw6.2 earthquake on 14.8.2003 that stroke the north part of Lefkada, producing moderate damage to its buildings (Karababa and Pomonis, 2011; Kassaras et al., 2014b; 2015) and substantial geotechnical failures (Papathanassiou et al., 2013). The most recent strong earthquake with Mw6.4 occurred onshore at the southwestern part of the island on 17.11.2015, causing slight structural damage and severe secondary effects i.e. landslides, rock falls, road cracks, ground subsidence, liquefaction (Ganas et al., 2016). The 2015 Lefkas earthquake caused slight-moderate structural damage on the island. Two casualties have been reported, due to shaking and rock falls, ~10 injuries and a median of 20 million USD of loss impact, calculated by CEDIM group (Shäfer et al., 2015), mainly attributed to damaged infrastructure due to landslides.



**Figure 1.** (a) Location of major earthquakes with  $M > 6$  (stars) in the area of Lefkada (after Kassaras et al., 2015). Beach-ball diagrams represent focal mechanisms of the 2003 and 2015 earthquakes. Red solid triangles show the position of permanent accelerometric stations. CTF: Cephalonia Transform Fault. (b) Epicenters distribution of the 2015 seismic sequence (Papadimitriou et al., 2016).

## 2. DATA AND METHOD

The data used in this study comprise structural damage observations, geotechnical damage, and strong motion recordings. Structural and geotechnical damage data were obtained during two post-seismic field surveys that were carried out by our research group. The first survey took place immediately after the earthquake, between 19 and 21 November 2015 and the second one during 9-12 January, 2016. Census data available from the EPANTYK Project (2009), entries in the literature (Karababa & Pomonis 2011) testimonies from locals and damage database provided by the local Earthquake Rehabilitation Organization (TAS) were also employed.

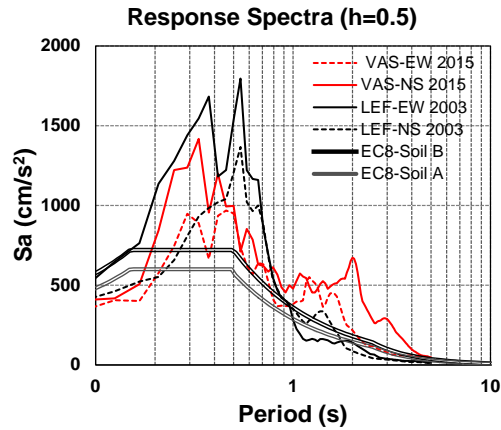
The method used for assessing the macroseismic intensity is based on the combination of damage and vulnerability data proposed by Grünthal (1998) who introduced the European Macroseismic Scale (EMS-98). In order to evaluate the EMS-98 macroseismic intensity at the different parts of the island, the EPPO guidelines (EPPO, 2004) are followed so as to assign color-coding of post-seismic usability inspection to EMS-98 discrete damage grades as following: “Green” – “Safe for Use” – D0/D1, “Yellow” – “Unsafe for Use” – D2/D3 and “Red” – “Dangerous for Use” – D4.

## 3. RESULTS

### 3.1 Strong motion data

The 2015 event was one of the strongest earthquakes reported in the intense seismic history of the area. The value of Peak Ground Acceleration recorded at Vasiliki was equal to 0.36g ([www.itsak.gr](http://www.itsak.gr); Figure 2). The estimated instrumental intensity (<http://shakemaps.ingeoclouds.eu>) ranges from V+ to VII. The strongest

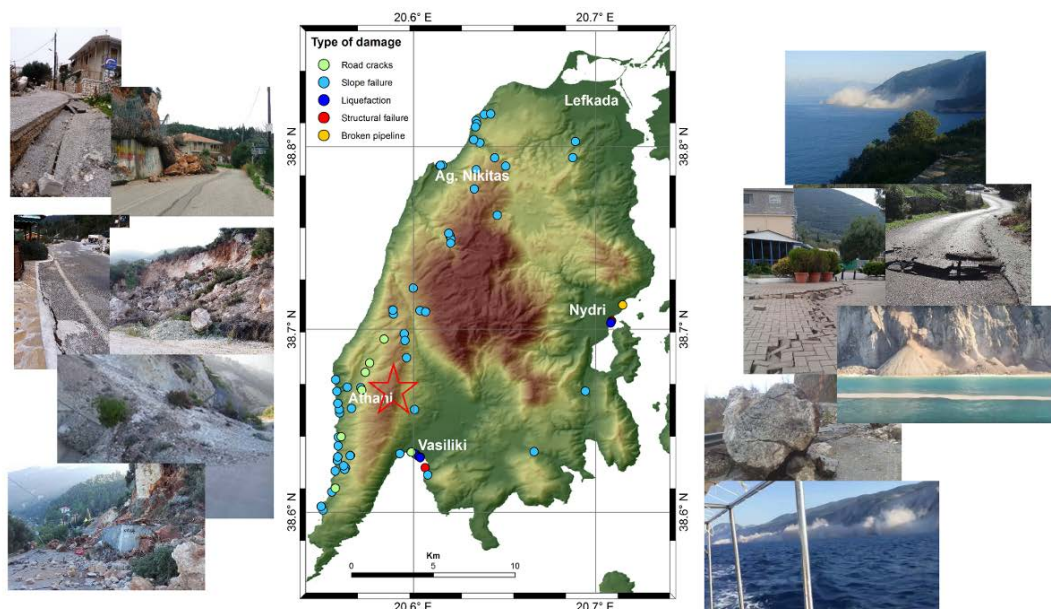
aftershock with Mw5.1 occurred 4 km to the SW of the main-shock about 1:20 hours later. A major aftershock with Mw4.9 that occurred on 18.11.2015, ~20 km north of the epicentral area was intensively felt in the Lefkada capital at the northernmost part of the island (LEF in Figure 1) causing slight structural damage. The spectral amplitude for the 2003 earthquake reached 1.7g at ~0.5sec with another significant peak at 0.25sec, while the one of 2015 presents one cycle of strong shaking of 1.4g at 0.25sec. Recordings for both earthquakes exceed the values of the design spectra for soil categories A and B predicted by the current seismic code (EAK-2000).



**Figure 2.** Comparison of horizontal pseudo-acceleration spectra of the earthquakes of 2003 and 2015 with design spectra for soil types A and B (ITSAK, 2015; CEN, 2004).

### 3.2 Geo-environmental effects

Environmental Seismic Intensity (ESI-07, Michetti et al., 2007) was assessed VIII-IX (Ganas et al., 2015). No primary fault surface ruptures were observed in the field; secondary earthquake effects outbreaks were extensive at the western part of the island including ground failures, rock falls, landslides (mainly slope failures), coastal or dock's cracks and soil liquefaction (Figure 3).



**Figure 3.** Distribution of geotechnical damage across the island (modified after Ganas et al., submitted to Tectonophysics). The red star denotes the epicenter of the M6.4 earthquake (bbnet.gein.noa.gr).

The dominant geo-environmental effects triggered by the 2015 Lefkada earthquake were related to slope failures. The highest ESI-07 of the order VIII-IX was observed within the area delineated by the villages of Dragano – Athani – Porto Katsiki and Egremnoi beach and along the road of Tsoukalades - Ag. Nikitas (Figure 3) related with slope failures, rock falls, rock mass slides, shallow landslides. This zone is

susceptible in triggering such phenomena due to the combination of high elevation and steep slopes with the highly fracture rock mass due to tectonic activity (Papathanassiou et al., 2013).

The earthquake severely affected the recently constructed pier and quay of Vasiliki, where the recorded PGA was equal to 0.36g (ITSAK, 2015). Small-scale liquefaction-induced ground failures were mainly concentrated along the southern coastal zone between Vasiliki and Ponti. Cracks on paved roads were observed along the road network at the central and western part of the island, mainly within the above mentioned zone. In general, ground openings were found to be increased during the second survey, due to deformation from aftershocks. Settlements and soil deformations were often the reason for structural damage on masonry walls, especially the ones founded on inclined ground. In addition, the watering and sewage system of Agios Nikitas presented functionality problems. Underground tubes subjected to high lateral and axial deformations due to ground failures.

### 3.3 Building inventory and structural damage

The island has displayed considerable resilience during strong earthquakes thanks to a local traditional construction practice, which incorporates elements for earthquake resistance (e.g. Karababa and Guthrie, 2007). Local constructions involving a timber secondary load-bearing system have been the subject of several studies (Tonna, 2014; Kassaras et al., 2015, among others). Table 1 summarizes the main characteristics of six building categories found in Lefkada.

**Table 1.** Structural typologies and vulnerability assignment (Karababa & Pomonis, 2011; Kassaras et al., 2014b). Asterisks denote the new elements highlighted in this work.

Typology	Description	Vulnerability class	%
<i>Reinforced concrete frame (RC)</i>	Without ERD (<1960)	C	2.5%
	With moderate ERD (1960-1994)	D	20%
	With high ERD (>1995)	E	22%
<i>Load-bearing stone masonry (LBSM)</i>	With thick wall sections, flexible timber diaphragms, mainly built prior to 1960	A or B depending on maintenance	30%
<i>Timber frame structures (TF)</i>	With locally supplied timber, flexible timber diaphragms, mainly built between 1946-1960	B to D depending on maintenance	4%
<i>Dual load-bearing stone masonry and timber frame structures (LBSM-TF)</i>	Dual system of load-bearing stone walls in the ground floor, timber columns supporting upper storey floor as secondary structural system (local so-called “pontelo”), upper story constructed with infilled timber frames	A to C depending on maintenance	10%
<i>Mixed load-bearing masonry &amp; Reinforced concrete structures (LSBM-RC)</i>	Mixed system of load-bearing stone or brick walls confined with reinforced concrete vertical and horizontal elements, so called “nucleus”, timber joist boars or cast in-situ slabs, mainly constructed between 1960-1985	B to C depending on construction period and maintenance	10%
<i>Load-bearing stone masonry with internal load carrying timber columns (LBSM-TC)*</i>	With stone load-bearing walls, secondary internal structural system supporting floors/roof in timber columns (“pontelo”)	A or B* (same vulnerability as LBSM but safer for users)	2%*

*ERD: Earthquake Resistant Design Code provisions*

The LBSM-TC type (Table 1) was detected only in the internal part of the island. Its main difference with the LBSM-TF construction, is that the upper story is not timber, but stone masonry of 60 to 100 cm thickness with interior vertical load bearing timber columns that extend to the ground, while joists and trusses constitute the floor and roof flexible system. In case of failure of the walls, the secondary timber frame system offers the necessary for the seismic zone alternative transfer path of the vertical loads. Following the well-known technique of LBSM-TF buildings (Vintzileou et al., 2007a) the floors and roofs are hyperstatically supported, providing a “shelter” to the residents in case of collapse of the vulnerable perimeter

walls. The seismic performance of this LBSM variation follows the typical LBSM pattern, as it will be explained below (3.3.2.3) and thus equal vulnerability (\*) has been assumed. Traces of this structural typology date back to the local building tradition and history of the 18<sup>th</sup>-19<sup>th</sup> century. Combination with the post-seismic observation that structural elements of different material offer dissimilar response, necessary for capturing the unpredicted seismic excitations, probably led to the generation of this typology.

The first post-earthquake building inspection was conducted immediately after the main shock by engineers of the local Earthquake Rehabilitation Organization (TAS). The main criterion for the damage state characterization is the safety of the users based on the estimation of the post-seismic bearing capacity of the buildings, as well as any non-structural elements posing hazardous conditions. Damage state distribution inferred from the post-seismic survey per settlement is illustrated in Figure 4. Panel A in Figure 4 presents the spatial distribution of the damage due to the 14.8.2003 earthquake, as it has been registered by Karababa and Pomonis (2011). Figure 4B displays the registered damage state after the 17.11.2015 event. It is worth mentioning that damage inspection is typically undertaken upon the building owner request, consequently, it is assumed that “unchecked” buildings present no damage, despite the probability of erroneous decision by the owner.

A sample of the damaged building stock has been investigated during our field trips, mainly concentrated at the most severely hit areas of Dragano, Athani, Komilio, Agios Petros. In-situ observations allowed the estimation of the macroseismic intensities. Additional damage data per construction material type, were provided by TAS. “Yellow” tagging has been attributed to all types of building categories, whereas “Red” tagging can only be found at traditional LBSM structures. Interestingly, 20% of “Yellow” buildings are RC buildings that correspond to 2% of the total RC buildings of the island.

EMS-98 intensity was estimated based on the combination of the extent of damage for different vulnerability typologies. Due to the limited number of TF buildings in the meizoseismal area and the absence of LBSM-TF from EMS-98 guidelines (Grunthal, 1998), only LBSM and RC buildings have been used with appropriate expert judgment and case-by-case considerations. Given the absence of detailed information in TAS data regarding the erection year of RC buildings, vulnerability C has been assumed for RC damaged typology present in most of the villages, with poor detailing and limited or absent ER Design. Site survey confirmed that RC buildings prior to 1995 were the ones mostly affected. LSBM-TC typology was not included among the damaged structures. The damage distribution for both vulnerability classes made possible the estimation of the macroseismic intensity through a weighted mean approach (Pomonis et al., 2014).

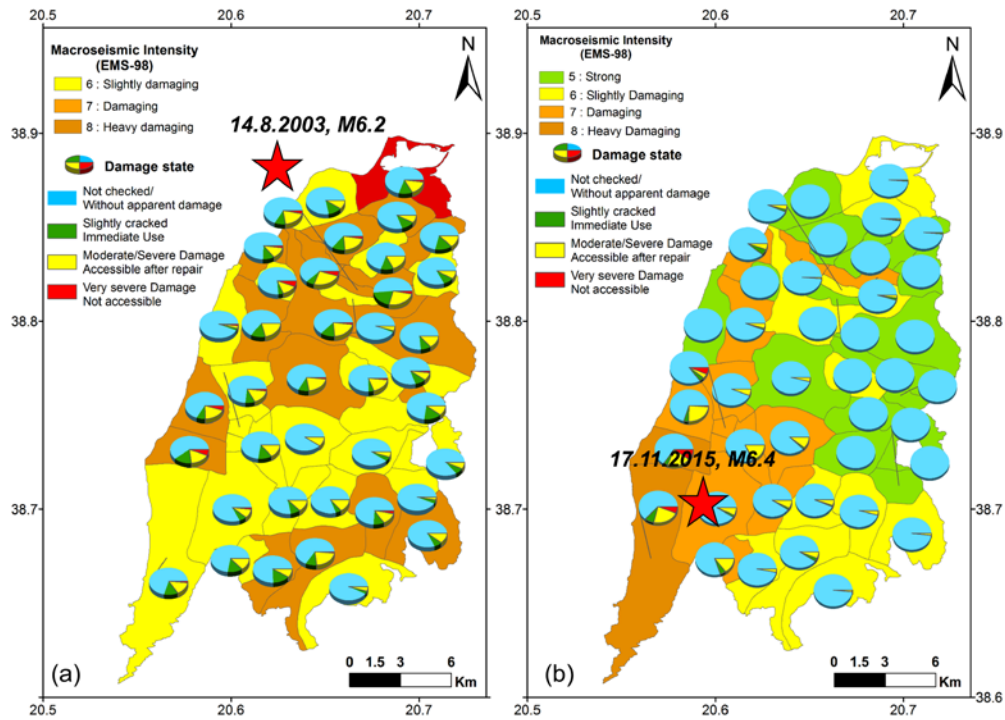
Figure 4 presents the results of the macroseismic survey according to the EMS-98 provisions for the 2003 earthquake (Karababa & Pomonis, 2011) and according to the present study’s findings. Maximum intensity of the order of VIII has been concluded for the meizoseismal region of SW peninsula of the island, where an important percentage of LBSM buildings has been very heavily damaged. Comprehensive decisions have been made upon the quantitative definitions “few”, “many”, “most”, considering the small data sample and the range of the statistical uncertainties. Secondary earthquake effects are not taken into account for the intensity estimation. Figure 5 presents the distribution of damage characterization per structural typology and the macroseismic intensities across the island, based on the TAS inspection protocols.

### **3.3.1 Reinforced concrete buildings**

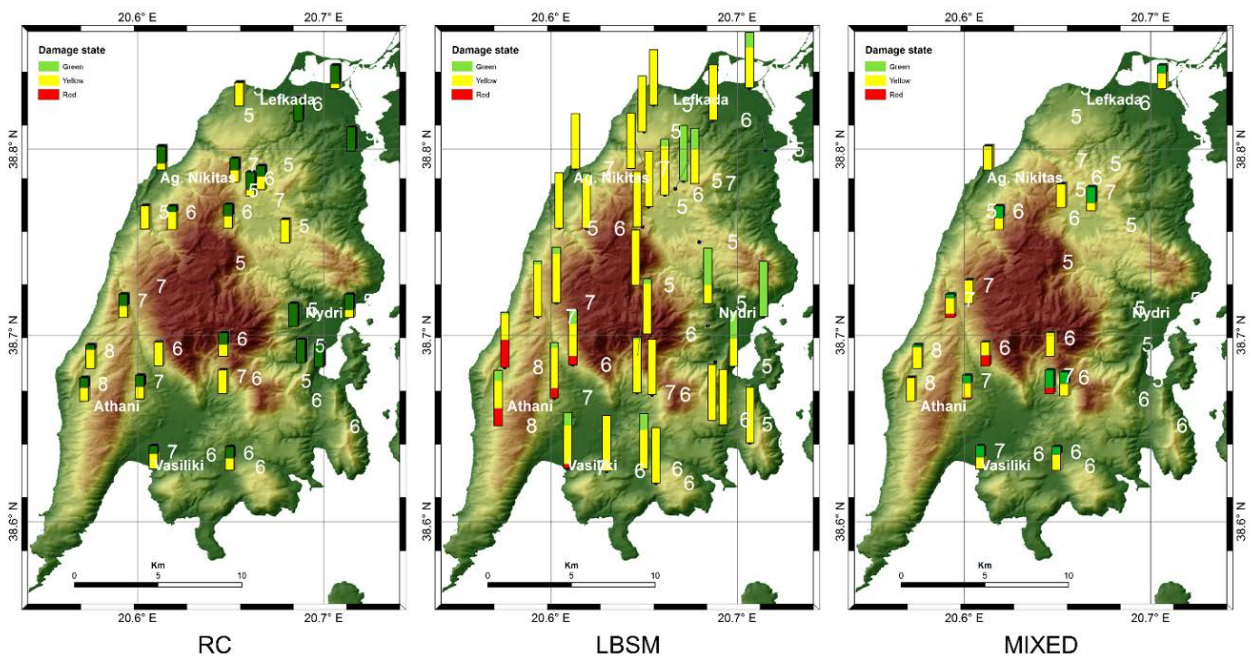
Their vulnerability, after EMS-98 is medium (C class or higher). Only few of these buildings have been registered as “Yellow”. Damaged RC buildings are mainly concentrated in the meizoseismal area of the southwestern peninsula. These are RC infilled frame one-to-two story buildings, constructed before 1995, following the premature ERD provisions of the first official Greek Seismic Code. This fact, in addition with arbitrary constructions, erroneous interventions, improper structural finishing and materials of questionable quality (Vintzileou et al., 2004) resulted for some cases in low seismic performance during the earthquake.

Post-seismic survey allowed the damage assessment of the order of Grade 2-3. Totally, 95 buildings are “yellow” tagged, according to the inspection protocols provided by TAS. More specifically, cracks in RC elements (beams, columns, joints) are inspected in different extent, while spalling of concrete cover and buckling of rebars for some limited cases have been reported (Figure 6a-b). The most common failure is

related to abruption and cracking of infill panels (Figure 6c), as well to damage of the roof cover. Non-structural damage, such as cracks in partition walls, fall of brittle cladding and mortar (Figure 6c), account for damage assessment of Grade 2. Other source of damage was the static ground deformation, which has not been possible to be assimilated by the separate footings, especially of the older buildings. As far as the response of RC buildings located at more remote epicentral distances is concerned, failures were mostly generated by earthquake secondary effects, such as landslide, slope failure and mutual pounding of adjacent buildings due to insufficient seismic joints.



**Figure 4.** Distribution of Post-seismic characterization by TAS and EMS Intensity estimation per settlement of the island for the (A) 2003 earthquake (after Karababa & Pomonis, 2011) and (B) 2015 earthquake.



**Figure 5.** Damage distribution across the island for the RC, LBSM and mixed buildings (stacked charts), and macroseismic intensity estimates (numbers) deduced from the TAS data. The length of the charts is proportional to the number of buildings.

### 3.3.2 Traditional buildings

#### (1) Timber frame structures (TF)

Their vulnerability, following EMS-98 guidelines, ranges between B and D depending on their maintenance state (Table 1). This typology is present mainly in the capital of Lefkas, where the ground motion was found to be of moderate size. None of these buildings has been majorly affected by the earthquake, with the exception of few abandoned ones with a very poor state of health. Regular shape, light mass and structural flexibility have contributed to a favorable seismic behavior.



**Figure 6.** (a-b) Damage to the columns and beam column joints of RC buildings; (c) Large cracks at infill panels in Athani.

#### (2) Dual load-bearing stone masonry and timber frame structures (LBSM-TF)

This construction type is found throughout the island and represents a historically earthquake-resistant structure, uniquely encountered in Lefkada (Vintzileou et al., 2007b). Kassaras et al. (2014) suggest a vulnerability class better than B for the sum of the surveyed buildings and better than C for the majority of them. For the purposes of the current study, a pre-seismic/post-seismic cross-check inspection has been performed for several buildings.

The damage analysis performed for several cases at various locations, showed different structural behavior during the seismic event. This may be attributed to the state of preservation and the characteristics of the structural components, depending on the period of construction given the design improvement with time and the quality of the stone-timberwork. Damage is found to be mainly concentrated at the ground floor, being significantly stiffer, with the presence of diagonal shear cracks, initiating at the wall openings (doors, windows). The infill material of the upper timber frame structure has been also cracked and dismantled in some cases. Several “Yellow”-tagged samples of this typology have been registered, mainly at the meizoseismal area. Few LBSM-TF buildings are characterized “Red”, with vertical deviation of the timber framework and extensive cracking of the stone walls.



**Figure 7.** The crack pattern surveyed for the traditional LBSM-TF typology: (a) A previously damaged house in Lefkada town with in-plane diagonal shear cracking; (b) Building in Ag. Petros with wall angle detachment due to soil subsidence; (c) “Red” tagged building in Athani.

In several cases, previously damaged unrepaired structures presented worsening of their state jeopardizing the risk for the surrounding area (Figure 7a). No essential structure-related collapse mechanisms have been detected. On the contrary, co-seismic ground deformation is found to affect the stiff ground floor producing severe cracking of the masonry wall (Figure 7b-c). Interestingly, buildings with severely damaged stone masonry walls and/or large lateral displacement of the timber upper story did not collapse (Figure 7d), implying for the satisfactory seismic performance and integrity of the secondary “pontelo” system.

(3) *Load-Bearing Stone Masonry Buildings (LBSM, LBSM-TC, LBSM-RC)*

Their vulnerability according to EMS-98 ranges between class A and C. A close correlation between the damage state and the assigned vulnerability has been confirmed for these structural typologies. These typologies, routinely found across the meizoseismal area, exhibited quite good behavior during the earthquake. Although 65% of “Yellow” tagged buildings and 88% of “Red” tagged buildings, correspond to LBSM typology, their seismic response is considered satisfactory in overall, given the multitude of this typology across the epicentral area and the variety of material quality and preservation conditions.

All variations of LBSM buildings present a similar behavior/failure pattern. Separation of walls at intersections (

Figure 8a), cracking and tilting of wall panels, diagonal in-plane cracks initiating from weak areas, delamination of wall wyths loosely interlocked, are some of the failures detected in different extent. Disruption of the roof tiled cover have been detected, leading to either “Green” or “Yellow” characterization.

The “pontelo” system of the LBSM-TC buildings, partially discharges the bearing walls and avoids the push out of the roof rafters imposed to the masonry walls. However, the frequent absence of roof anchorage to the perimeter walls doesn’t protect them from toppling. In many cases, the “pontelo” internal structure has been proven to have remained intact, when the perimeter walls follow the damage pattern of typical LBSM configuration (

Figure 8b). The LBSM-RC buildings presented an overall enhanced structural behavior thanks to ring concrete beams with light reinforcement, or mortar bandages, at the lintels or roof level.



**Figure 8.** (a) LBSM “yellow” tagged building with separation of walls intersection; (b) characteristic damage of a single floor LBSM-TC; (c) LBSM-RC remained intact after earthquake



**Figure 9.** (a) Collapsed church of Agia Paraskevi in Athani; (b) Collapsed kiosk near Athani.



Special reference should be made to the case of Agia Paraskevi church in Athani; the RC ring roof joist applied during rehabilitation and strengthening works has been proven to pose fatal burden on the old deteriorated timber load-bearing system (pontelo), which thereafter was not able to resist to gravity loads during strong ground shaking, leading to its total collapse (Figure 9a). This effect implies that interventions at traditional structures should be thoroughly scheduled so as to avoid cancelling of effective traditional earthquake resistant performance. Moreover, the collapse of an arbitrarily constructed tavern kiosk (Figure 9b) emphasizes that life threat is pronounced whenever design and construction is not undertaken by experts.

## 5. SUMMARY AND CONCLUSIONS

The 2015 Lefkada earthquake produced extended geotechnical and limited structural damage. Geotechnical damage was mainly due to the geology and topography of the area. Structural resilience highlights the traditional anti-seismic architecture of Lefkada. Our study releases some interesting features summarized as following:

- **LBSM buildings:** The majority of the observed damage is attributed to these structures (LBSM, LBSM-TC, LBSM-RC), regarding mainly cracking of the masonry walls. However, our investigation revealed the satisfactory performance of the internal secondary timber load-bearing system for LBSM-TC, even after partial collapse of the external walls. In addition, LBSM with ring beams (LBSM-RC) presented an exceptional behavior, confirming that the achievement of box-action is crucial for masonry structures.
- **LBSM-TF** structures, representative of the unique traditionally earthquake-resistant technique, demonstrated once again a satisfactory performance with limited damage at the masonry walls of the ground floor and dismantling of the infill material of the timber frame.
- **TF buildings:** They have been found as the most resilient typology, besides their sparsity in the epicentral area.
- **RC buildings:** Few of them located close to the epicenter have been slightly-to-moderately affected. In general they have responded elastically with localized damage imposed to structural and non-structural elements, often due to secondary earthquake effects.

Concluding, the significant seismic performance of the vernacular constructions, unique within the Greek territory, is emphasized in this work. Given these exceptional properties, together with their outstanding harmonization with the natural landscape, engineering protective/restoration measures are strongly recommended.

### Acknowledgements

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