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Seismic response of structures and infrastructure facilities during the Lefkada, Greece earthquake of 14/8/2003

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Abstract

A strong ($M = 6.2$) earthquake struck the island of Lefkada (also called 'Lefkas') in western Greece on August 14, 2003. In this paper the seismic behaviour of the buildings and infrastructure in the region, as established by numerous in situ investigations by the research team, is presented. For an integrated presentation, first some basic seismological issues are given, as well as a short description of failures of geotechnical nature. Buildings in the area are classified according to their structural system, and the response and damage observed in each structural category is presented. The response spectra of the strong ground motion are compared with both contemporary and past Greek seismic code provisions, and their effect on damage observed is discussed. The distribution of damage in the meisoseismal area is also presented and discussed. Analytical investigations on the seismic response of two representative buildings (a traditional and a reinforced concrete one) help in explaining observed damage and in gaining insight on various factors that mitigated the earthquake consequences. Finally, a short overview of the emergency management measures taken is also presented.
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Keywords: Lefkada earthquake; Seismic response of structures; Structural damage

1. Introduction

On August 14, 2003 at 08:15 local time (05:15 GMT) a strong earthquake of magnitude $M = 6.2$ occurred close to the island of Lefkada in Western Greece. The earthquake was strongly felt in the rest of the Ionian islands (Cephalonia, Zakynthos, Ithaki etc) and in an extensive area of the mainland. The earthquake was recorded by several accelerographs of the national permanent strong motion network in the area, which were installed, serviced and monitored by the Institute of Engineering Seismology and Earthquake Engineering (ITSAK). The Ionian islands area is one of the most earthquake-prone in Greece, and was always classified in Greek Seismic Codes among those with the highest seismic hazard. At the time of the seismic event, the island of Lefkada was estimated to be inhabited by approximately 60,000 tourists, besides the 22,500 permanent residents. Fortunately no human loss occurred, while about 45 injuries were reported, most of them from free-falling roof tiles and other nonstructural elements. Serious structural damage to buildings was rather limited, given the intensity and proximity (∼12 km) of the earthquake epicenter to the town of Lefkada, the island's capital, where a peak ground acceleration of $a_g = 0.42g$ was recorded at the accelerograph installed at the town hospital. One reinforced concrete (R/C) building collapsed, while damage to other structures in the area was limited to local failures of structural and nonstructural components that fortunately did not lead to building collapses. A considerable number of marine infrastructures were affected moderately to heavily by the strong ground motion, while traffic on a large part of the road network at the western part of the island was disrupted for several days due to a significant number of landslides and rock falls.

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From the very day of the main event and for more than two months afterwards, scientists (seismologists and civil engineers) from ITSAK were present at the island, recording the aftershock activity and assessing damage to buildings, marine structures and road networks. The results of these in situ investigations on structures are presented in this paper. For a better understanding of the event, a short description of the most important seismological and geotechnical issues pertaining to the earthquake and its consequences is given. A description of damage to different structural types of the existing building stock is presented, along with explanations of the various factors that caused it. These evaluations are based both on macroscopic examinations, and on dynamic analyses of typical buildings of the area, which were conducted at ITSAK for a better assessment of the seismic behaviour of structures. Finally, an overview of the emergency management measures taken by the authorities is presented.

2. Seismological issues

The earthquake, of magnitude $M = 6.2$, occurred on August 14, 2003 at 08:15 local time (05:15 GMT). The hypocenter coordinates, as computed by the Geophysical Laboratory of Aristotle University of Thessaloniki, were 38.76° N 20.60° E and its focal depth ∼10 km. Long before the mainshock, digital accelerographs maintained by ITSAK and belonging to the permanent National Strong Motion Network were installed, seven of which recorded the mainshock [1]. The closest ($R \sim 12$ km) to the main event accelerograph (station LEF1, see Fig. 1) was the one installed at the hospital of Lefkada town, where a peak ground acceleration $a_g = 0.42g$ was recorded (Fig. 2). In the transverse horizontal and vertical directions respective PGAs of $0.34g$ and $0.19g$ were recorded. The seismic sequence can be associated [2] with dextral strike-slip faulting along the Cephalonia Transform Fault [3], comprising the distinctive Cephalonia and Lefkada faults, with the latter running parallel to the western coast of the island of Lefkada. An extensive investigation of the seismotectonic properties of the area (seismic history in the region, mainshock mechanism, seismic sequence of the event etc) can be found in Karakostas et al. [2] The long duration of the event (estimated bracketed duration of 18 s) [1], combined with the high PGA values, list this earthquake as one of the most intense ever recorded in Greece.

3. Geotechnical issues

The earthquake had a significant number of geotechnical impacts, something rather uncommon in past Greek earthquakes. The western part of the island is mountainous, with steep slopes towards the western coast. The mountain

Fig. 1. The island of Lefkada. The epicenter of the mainshock of August 14, 2003 is denoted by star. Permanent strong motion stations of ITSAK in the towns of Lefkada (LEF1) and Preveza (PRE1) are denoted by dark squares. The location of Lefkada island is denoted by the dark circle in the inset map of Greece.

slopes are less steep towards the eastern part of the island (Fig. 1).

The soil structure beneath Lefkada town is classified as low quality (soil categories C and in some cases X according to the Greek Seismic Code (EAK2000)–soil categories C and E according to Eurocode 8/2002 [1,4]. Also, mainly in the old historical district of the town the water table is very high (less than 1.5–2 m beneath ground surface).

Due to either poor soil conditions or steep morphology, several failures pertaining to geotechnical aspects were observed [1], among which:

- Damage to port and marine structures (docks, seawalls, breakwaters, etc) in Lefkada town and at Lygia, Nydri and Vasiliki villages due to ground settlement and lateral spreading of loose surface soil layers and poorly compacted fills behind the seawall facilities. (Fig. 3).
- Liquefaction and consequent loss of strength, ground settlements and lateral spreading in the broader area of the castle of the town of Lefkada as well as in Nydri village.
- Landslides and rock falls on both natural and cut slopes mainly at the western side of the island along the road network joining the town of Lefkada with the villages of Tsoukalades, Agios Nikitas, Kathisma, Kalamitsi, Chortata, Dragano, Komilio, Aghios Petros, Vassiliki and Porto Katsiki beach. Thanks to the early morning hour that the mainshock occurred, slope failures did not cause any deaths. (Fig. 4).
- Lifeline failures were rather limited, with the most serious one being the breakage of the main sewage

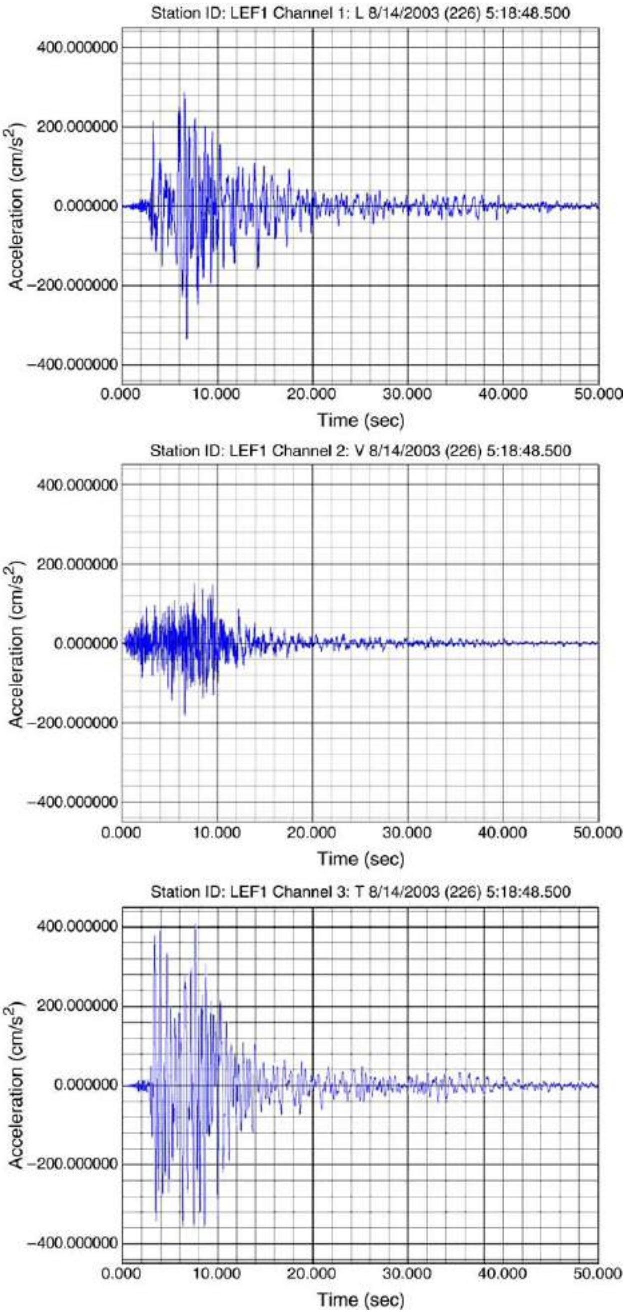

Fig. 2. The Lefkada mainshock of August 15, 2003. Recordings at Lefkada hospital (station LEF1).

pipeline in the town of Lefkada. It is interesting to note that the failure occurred at a transition zone from soft to stiffer soils, a situation known from past earthquakes to be more prone to damage, due to difference in the stress conditions on the pipeline in each soil type during the shaking.

- Ground settlement in some buildings along the waterfront in the town of Lefkada. Due to the more or less uniform settlement under each building, any damage caused to their load-bearing structural systems should be rather attributed to the shaking than the ground settlement. In a certain case of two adjacent buildings, the different degree of settlement resulted in a differential height difference of approximately 5 cm between them, as could be macroscopically established by a common pipeline system that broke. (Fig. 5).

Fig. 3. Ground settlement and lateral spreading of poorly compacted fills behind the seawall in Vassiliki village caused cracking of concrete pavement.

Fig. 4. Road connecting villages of Tsoukalades and Kathisma cut off by landslides (courtesy: A. Anastasiadis, Dpt. of Soil Dynamics, ITSAK).

A preliminary assessment of the geotechnical aspects of the earthquake can be found in Gazetas [5].

4. Seismic response of structures

4.1. Description of building types in Lefkada island

Buildings in Lefkada island can be classified in five categories, according to their load-bearing system (Table 1).

The town of Lefkada consists of the historic centre district (mainly with older, traditional buildings and soft soil conditions), surrounded by the more recent Bei and Neapoli districts, with typically modern R/C buildings

Table 1
Building types in the island of Lefkada

Category	Description	Remarks
A	One- or two-storey stone masonry buildings	Buildings more than 50 years old, with load-bearing system of stone masonry. Sometimes they incorporate empirical lateral load-bearing systems, which are in general insufficient.
B	One- to three-storey traditional wood buildings	Met mainly in the town of Lefkada. Load-bearing system by wood frames, sometimes with clay bricks as infill.
C	Buildings of special typology with dual structural system	A traditional structural typology met mainly in the old town district of Lefkada. Main load-bearing system of stone masonry on ground floor level, complemented by a secondary (redundant) wood structural frame. Structural system of wood frames used in upper floor(s).
D	Modern R/C buildings with one to five storeys	The majority of houses, office and hotel buildings, up to five storeys high (in the town of Lefkada). Load-bearing system with cast-in-place reinforced concrete. Walls with hollow bricks used as infill.
E	Middle-age and later-era monuments	Buildings of architectural heritage, with no special seismic provisions. Mostly churches and some castles along the entrance from the mainland to the island.

Fig. 5. Ground settlement resulted in 5 cm height difference between adjacent buildings in Lefkada waterfront, as witnessed by broken pipelines (photo taken after repair).

on better quality, stiffer soils. The whole town has an estimated number of 2100 buildings. An in situ survey of a representative sample of the building stock (approximately 10% of the total stock) yielded the following distribution of building categories: 6% masonry buildings (categories A and E), 15% wood buildings (category B), 34% buildings with dual structural system (category C), while the remaining 45% of the building stock consists of R/C buildings (category D). For the whole building stock of the island, the only relevant data available are some preliminary results from the 2001 National Census, but with a building categorization based rather on the construction material than on the structural type. According to preliminary data from the Greek National Statistical Service site (http://www.statistics.gr), out of 15,683 buildings on the island, 38.87% are made of concrete, 1.04% of steel, 4.51% of wood, 14.46% of bricks, 39.46% of stone masonry and 1.66% of other materials. It should be noted that any effort to find a one-to-one correspondence with the structural types of Table 1 will most certainly introduce inherent uncertainties (e.g., it is not certain if, during the census, the buildings of category C were classified as masonry, as seems most probable, or if some were classified as wood buildings).

(a) Masonry buildings

Buildings in category A are generally one- or two-storey old houses, many of them over 50 years old, with load-bearing masonry walls made of stone or brick, weak lime (and rarely cement or clay) mortar, and usually, but not always, without any seismic provisions such as horizontal concrete or wooden tie-belts. Floors are typically wooden, consisting of beams uniformly distributed and covered by wooden planking. The roofs in such buildings consist of wooden trusses covered by wooden planking and tiles.

(b) Wood buildings

Category B buildings are made of wood frames with diagonal wood braces. In some cases, wood frames are filled with clay bricks or covered by planks. This type of buildings exhibited a very satisfactory seismic behaviour, without any damage to the load-bearing wood frames.

(c) Buildings with dual masonry and wood frames system

Category C buildings are mostly two-storey (and in some cases three-storey) ones. As mentioned above, their special characteristic is the dual load carrying system used on ground floor level to handle seismic actions. The main load-carrying system consists of stone masonry walls, while the redundant (secondary) load-carrying system consists of wood frames at the inner perimeter of the masonry walls. In case the masonry walls fail due seismic actions (e.g., heavy

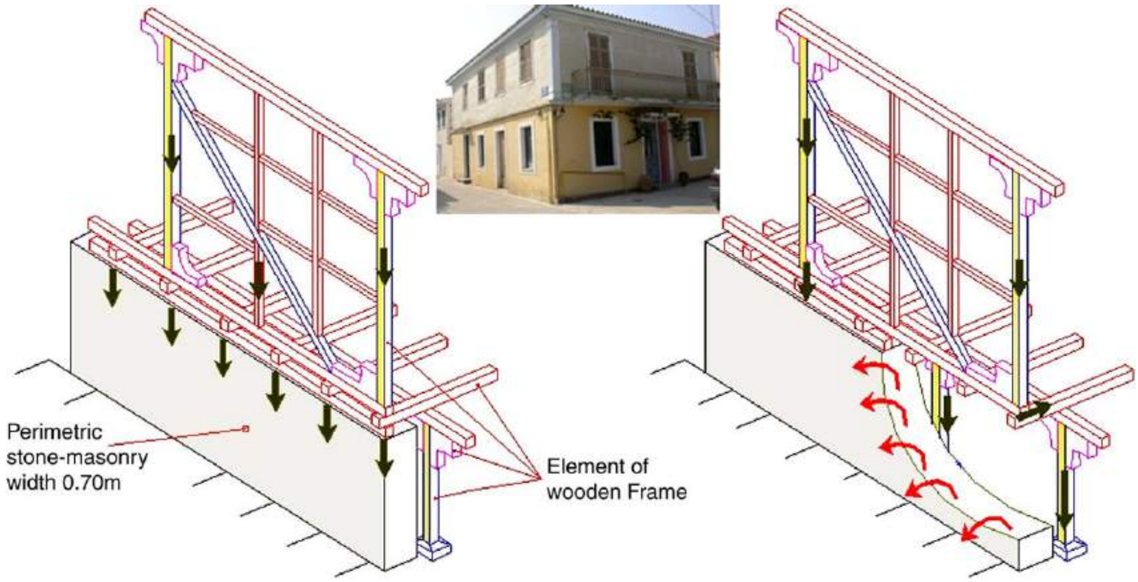

Fig. 6. Traditional dual system building (inset photo) and mechanism of activation of secondary wood frame in case of failure of masonry load-bearing wall.

cracking and/or partial collapse leading to reduced load-bearing capacity), the wood frames are activated in order to carry the upper floors' loads (Fig. 6). On upper floors the load-bearing system consists of wood frames with diagonal trusses and brick infills. The dual bearing system, combined with the relatively low mass of the upper storeys, exhibits a remarkably reduced vulnerability to earthquake actions. Due to poor soil conditions (and a high water table level), the masonry walls are typically founded on extended footings made up of horizontally placed tree trunks. An analytical investigation of the seismic behaviour of such structures is presented later in the paper.

(d) Reinforced concrete buildings

As already mentioned, reinforced concrete (category D) buildings comprise the majority of the building stock in the more recent Bei and Neapoli districts. They are generally one- to five-storey buildings, constructed during the last decades. In many (especially those designed according to the 1984 seismic code and thereafter), shear walls are used to resist seismic actions. In this category of buildings, an important characteristic, playing a key role in their response to earthquakes, is the type of the ground storey. The General Greek Building Code (not the code for the seismic design) permits buildings to have an open ground storey ("pilotis", to be used as car parking, playground or flowerbed space), without counting it in the maximum permitted total floor area. This became very popular, but created a "soft" first storey, due to the drastic reduction of brick infills in comparison to the storeys above. A similar, but not as severe, problem is created with ground storeys used as shops, due to the elimination of several infill walls for creating large front windows and large continuous interior spaces. In the island of Lefkada, an area with the highest seismicity in Greece, although use of pilotis is not uncommon (at least for the more recent buildings), in most cases care has been taken to mitigate their undesirable consequences through extensive use of shear walls and design of regular space frames with small to medium spans. Also, the quality of workmanship (for both load-bearing and nonstructural components) is in general higher than the one met in other regions of Greece. Carefully constructed infill walls and extensive use of horizontal R/C belts (up to two along the wall's height) is a common practice. Various types of foundations are met, ranging from spread footings to mat foundations. In the town of Lefkada, due to rather poor soil conditions, proper measures are usually taken for the foundations, such as the use of concrete piles. An analytical investigation of the dynamic behaviour of a representative R/C building is presented later in the paper.

(e) Middle-age and later-era monuments

The fifth category of buildings, (category E), includes middle-age and later-era monuments. Their seismic resistance system, if any, was formed empirically by experienced local technicians. Structures of this category in the island of Lefkada are mainly churches and some castles.

4.2. Strong ground motion compared to seismic code provisions

The first Greek Seismic Code (AK) was issued in 1959, and was revised in 1984. A major new revision took place in 1992 (EAK1992), and upgraded versions were published in 2000 and 2003. Until 1992, design was based on maximum allowable stresses, and thereafter on ultimate strength. In all codes, the area of Ionian islands (where Lefkada belongs) was characterized as one with the higher seismicity in Greece.

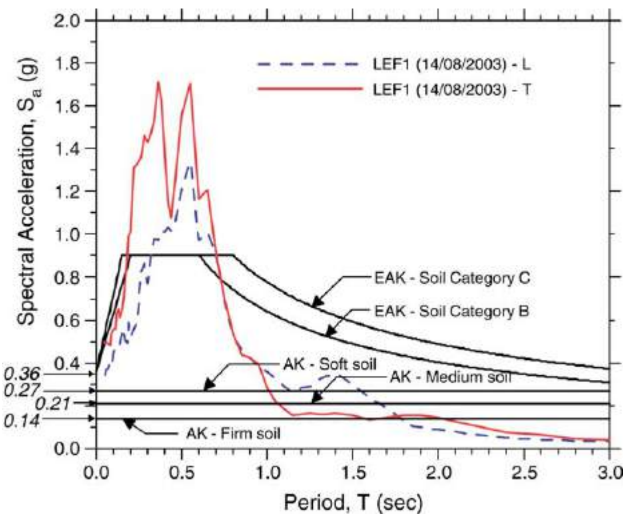

Fig. 7. Response spectra of horizontal components of Lefkada mainshock (5% damping) compared with elastic design spectra of the Greek Seismic Code (EAK2000) and the pre-1992 code (AK) provisions.

For Lefkada, the base shear seismic design coefficient, according to the 1959 Greek Seismic Code was $\varepsilon = 0.08$, 0.12 and 0.16, for firm, medium and soft soils, respectively. This coefficient was constant, independent of the building's period and applied uniformly to all buildings. Since the 1959 Code was based on the allowable-stress design method, the coefficient is modified to correspond to ultimate strength design, leading to values of $\varepsilon' = 0.14$, 0.21 and 0.27 [6].

For the seismic zone in which Lefkada belongs, with the highest seismic hazard, seismic codes from 1992 and onwards, establish a ground acceleration coefficient of $\alpha = 0.36$ and typical design spectra (with a spectral magnification factor $\beta_o = 2.5$). In Fig. 7, the response spectra of the two horizontal components of the Lefkada mainshock (for 5% damping) are compared with the elastic design spectra of the Greek Seismic Code (EAK2000) provisions (for soil types B-medium and C-soft). In the same figure, the pre-1992 provisions (AK) are also plotted.

In Greece, limit-state design was introduced in the codes in 1992, and a reduction ('behaviour') factor q is applied to the seismic actions in order to take into account the elastoplastic behaviour of the structure during the design earthquake. According to the post-1992 Greek Seismic Codes, the maximum allowable behaviour factor is $q = 3.5$ for reinforced concrete frames (with or without shear walls), $q = 1.5$ for masonry and $q = 2$ for wood frames. Before 1992, design in Greece was based on the maximum allowable stress concept, i.e., essentially elastic design was used. It is obvious that low-rise buildings with relatively small mass and fundamental period ($T < 0.15$–0.20 s), which comprise the majority of the building stock in Lefkada, were not heavily stressed, due to the particular shape of the response spectrum of the mainshock. The ductility demands imposed by this particular earthquake on buildings in this specific range were not too high (i.e., for $0 < T < 0.20$ s ductility demands D are in the range of $1.6 < D < 2.25$), thus explaining the limited damage observed. Higher buildings were in general built according to modern code provisions, thus possessing higher resistance to seismic actions. Moreover, it is noted that existing buildings possess a substantial amount of strength reserves (depending mainly on their redundancy and on the overstrength of individual structural members), as well as possible additional energy dissipation mechanisms, which contribute to a significant increase of their behaviour factor. Experience gathered from this and previous seismic events suggests that seismic protection of Greek urban areas relies also on several alternative factors (such as regular configuration of the structural system, extensive use of shear walls, properly built infill walls with horizontal R/C belts, high quality in materials and workmanship, etc.) [7].

4.3. *Distribution of damage in the meisoseismal area*

Most damage from the August 14, 2003 mainshock occurred in the island of Lefkada. Also less severe damages were reported in the nearby regions of Thesprotia and Aitoloakarnania in the mainland, as well as in the island of Cephalonia.

As established through in situ inspections in the island of Lefkada, serious structural damage to buildings was rather limited, given the intensity and proximity of the main event. In Fig. 8 damage distribution in various parts of the island is shown. Damage pies in the figure show the percentage of unharmed buildings (dark parts) vs. buildings that presented some form of damage (light parts). The percentage of harmed buildings varies from 1% to 29%. As can be seen from the figure, most damages (15% to 25% harmed buildings) were observed in communities on the western part of the island, in a NE/SW direction parallel to the seismic fault that caused the mainshock (see Section 2). Assuming a more or less equal vulnerability of low-rise buildings throughout the island, directivity of the seismic motion seems to have played an important role in the damage distribution. Extended damage was especially reported in the villages of Lazarata, Asprogerakata, Kavalos and the surrounding area, most probably due to the soil conditions and the basin morphology of the region that amplified the shaking. Some deviations from the general damage trend (as in the older villages of Poros and Marantoxori, in the southeastern part of the island, with a high damage percentage or in the more recent villages of Kathisma and Kalamitsi on the west coast with relatively few damages) can be attributed to building stocks with different than usual vulnerability levels: in recently created communities, buildings conform to the more strict provisions of modern seismic codes, while in old villages, most of the buildings were built with no seismic provisions.

The area with the higher number of damaged buildings was the town of Lefkada, in the northeastern part of

Fig. 8. Damage distribution of buildings in Lefkada island. The dark green portion of damage pies corresponds to unharmed, light yellow to buildings presenting some form of damage.

the island, where the majority of the building stock is found. Despite the intensity of the event, and the proximity of the town to the epicentral area (∼12 km), only one, poorly designed R/C building collapsed. Most damages were concentrated in the old town district, while minor damages were reported to the more modern Neapoli and Bei districts. The intensity for the main event in the old, historic district of Lefkada was estimated between VII and VIII of the modified Mercalli scale, with no apparent differentiations throughout the district. A two-level inspection of 3165 buildings, all over the island of Lefkada, resulted in 1544 "green", 1495 "yellow" and 126 "red". These results confirmed the evaluations of the macroseismic intensity. The classification, referred to degree of damage ("red", "yellow", "green") is briefly described as follows:

"Green": Original seismic capacity has not been decreased, the buildings are immediately usable and entry is unlimited.

"Yellow": Buildings in this category have decreased seismic capacity and should be repaired. Usage is not permitted on a continuous base.

"Red": Buildings in this category are unsafe and entry is prohibited. Decision for demolition will be made on the basis of more thorough inspection.

4.4. Observed damage to buildings

As mentioned previously, the main event produced one of the strongest motions recorded in Greece. In the town of Lefkada, at approximately 12 km from the epicentre, the recorded seismic motion had peak ground accelerations of $0.42g$ and $0.33g$ in the horizontal directions and a bracketed duration of 18 s [1]. Despite its severity, damage to buildings (and especially the most modern R/C ones) was rather moderate, for reasons that are presented later. Of course, the seismic vulnerability of a building depends to a great degree on its structural system. A notably common — albeit nonstructural — damage, met in all types of buildings with tiled roofs, was the detachment of a large percentage of tiles. A more detailed description of damage observed for each of the structural typologies met in the island of Lefkada (see Section 4.1) is presented below.

4.4.1. Observed damage to buildings according to their structural system

(a) Masonry buildings

Traditional stone masonry buildings (category A, see Section 4.1) have usually one or two storeys; they constitute a small percentage of the building stock in the island, and are mainly met in the villages. Damage (cracking or partial collapse of masonry walls) to such buildings was observed mainly in villages in the western part of the island. Failures are to be attributed mainly to insufficient or nonexistent seismic resistance measures (almost all of them were not built according to any seismic code), as well as to their already poor condition (old age, inadequate maintenance) even before the main event.

(b) Wood buildings

These constitute a small percentage of the building stock, and are mainly met in the town of Lefkada. The wood frames that comprise the load-bearing system have diagonal trusses to carry transverse loads. Due to their relatively small mass and the flexibility of the wood frames, they presented almost no structural damage.

(c) Buildings with dual masonry and wood frames system

Traditional buildings with a dual structural system (category C, see Section 4.1), behaved in a rather satisfactory way, given the intensity of the main event. In some cases partial collapse of the masonry walls took place (Fig. 9(a)), but the structural stability of the building was ensured by the activation of the secondary (redundant) wood frame on the ground floor level. In the upper floors, the load-bearing wood frames suffered no damage, but cracking to

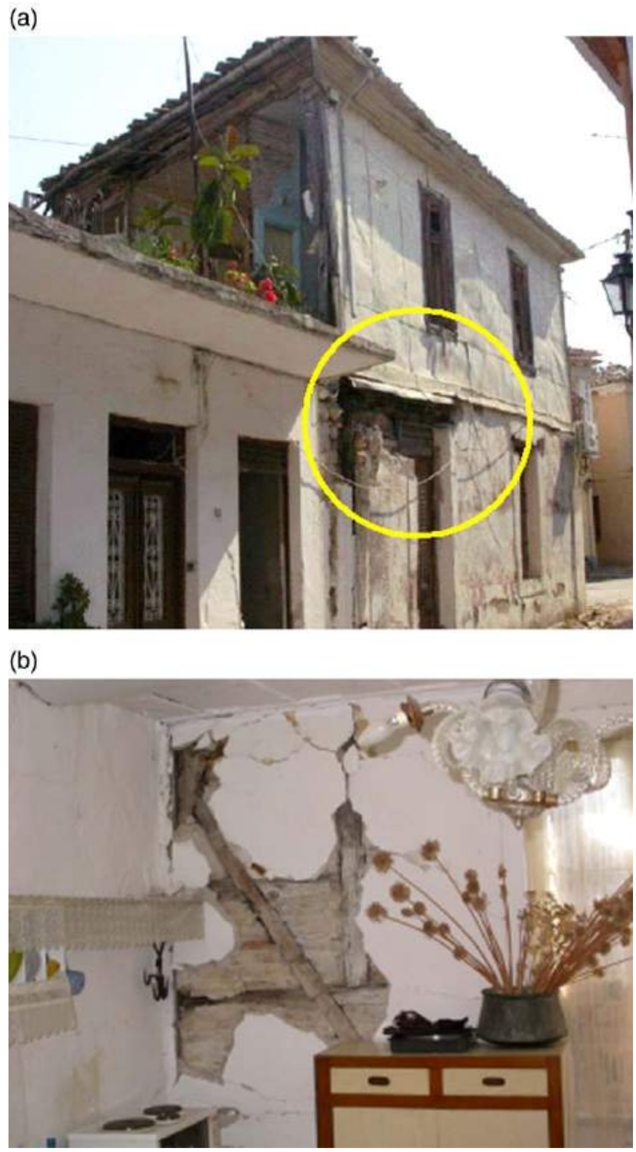

Fig. 9. Traditional dual system building in Lefkada town. (a) Local failure of stone masonry wall over door opening. Vertical loads from upper floor carried by activation of redundant wood frame on the ground floor. (b) Typical observed damage of brick infills at midheight of upper floor.

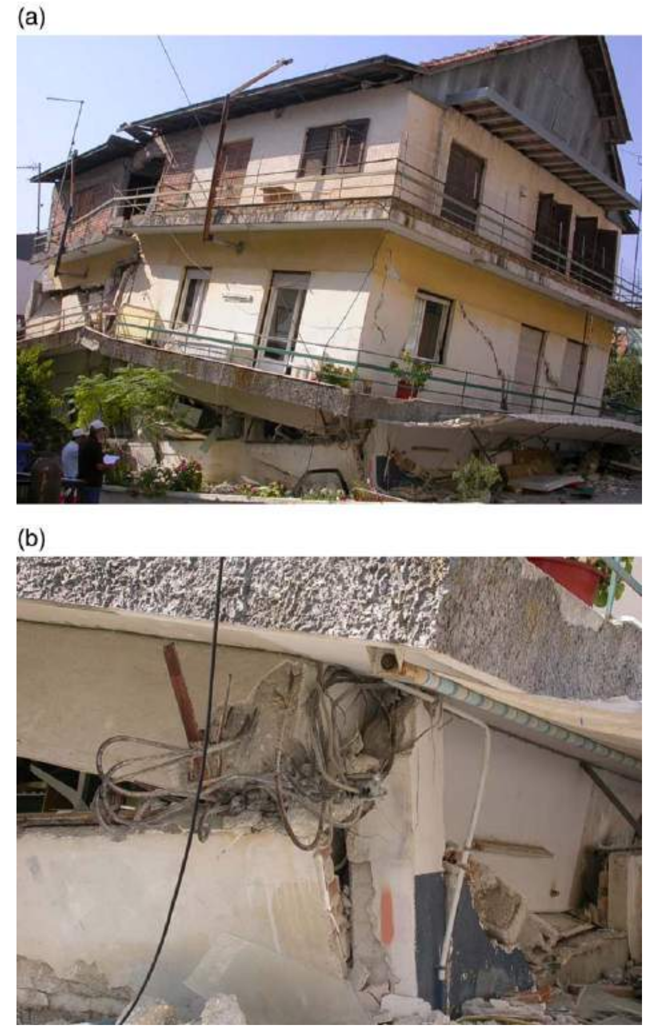

Fig. 10. (a) Collapse of poorly designed R/C building in the town of Lefkada; (b) detail of corner column, with lack of stirrups.

the brick infills was observed (Fig. 9(b)). These cracks were difficult to be noticed from outside, since the external walls at the upper storeys are typically clad with zinc sheets (for rain protection). Damage could thus be observed only on the interior faces of the walls, which are usually plastered with lime. Due to the use of the extended wood footings described in Section 4.1, and the relatively small mass of these buildings, no foundation settlings were observed, despite the poor soil conditions at the old town district of the town of Lefkada, where the majority of such type of buildings is found. Severe or total damage observed to a limited number of buildings of this type can be attributed to old age and poor maintenance, with the earthquake aggravating their already poor condition.

(d) Reinforced concrete buildings

It should be noted that the majority of the majority of R/C (category D, see Section 4.1) buildings (and especially the post-1985 ones) behaved in a satisfactory way. They responded essentially within the elastic range during the mainshock, presenting no or minimal damage to their load-bearing system. Nevertheless, several local damages were observed to structural and nonstructural elements. Only one collapse of a three-storey building occurred in the Neapolis district of the town of Lefkada (Fig. 10). The ground floor failed totally, while the remaining two retained a structural stability enough to spare the lives of the inhabitants. The building was poorly designed with inadequate stirrups at the columns while each storey was constructed in different years (1969, 1975 and 1980) and a wooden penthouse added sometime later. Apart from the obvious poor quality of the workmanship, on the ground floor thick brick infill walls were constructed at its backside while large openings existed at the façade, thus leading to torsional effects. Additionally, due to the openings, short columns were unintentionally

Fig. 11. Shear failure of ground floor column of R/C building (town of Lefkada). The non-existence of infill walls at the façade of the ground floor storey led to torsional phenomena.

Fig. 12. Short column failure in R/C building (built in 1983).

Fig. 13. Detachment of infill wall built out of the plane of the R/C structural frame. Architectural detail presenting a potential hazard in case of shaking.

created in the façade. The collapse can thus be attributed to the overall poor seismic resistance of the building than the intensity of the seismic motion. In fact, the collapse took place in an area where damage to other R/C buildings was limited, and soil conditions were better than in other town districts.

Also, in several waterfront buildings in the town of Lefkada. a more or less uniform foundation settlement was observed. Since no differential settlements were involved, any local damages to structural or nonstructural elements should be rather attributed to the shaking itself.

Among the most typical local failures observed in R/C buildings are the following:

– Severe damage to poorly designed columns and walls in buildings with soft storey at ground level.
– Damage to vertical structural elements at ground floor level due to non-symmetrical distribution of infill walls.
– Shear and/or flexure failure of poorly designed columns. (Fig. 11).
– Shear failure of short columns that were originally not designed to act as such (e.g., non-continuous infill walls on either side due to openings) (Fig. 12).
– Shear failure of R/C shear walls due to inadequate web reinforcement.
– Flexural cracking at R/C beam ends. It should be noted, however, that this type of failure has a beneficial contribution to the overall building stability, since formation of plastic hinges at columns is avoided.
– Cracking of infill walls (diagonal shear cracks, detachment of the wall from the surrounding frames, out-of-plane collapses) (Fig. 13).
– A systematic oxidation of the steel reinforcement was observed at the base of the ground floor columns, due to the high underground water level. In some cases, the

Fig. 14. Cracking of masonry walls of Agios Minas church (town of Lefkada).

oxidation was very severe, a serious vulnerability factor for the structural safety.

(e) Middle-age and later-era monuments

Among middle-age and later-era monuments (category E), churches suffered the most serious and extensive damage. More than 40 churches all over the island (with the majority in the town of Lefkada) were put out of service until restoration measures were taken. Churches in Lefkada are typically built with stone masonry walls, have a rectangular floor plan and a wooden roof. Serious damage was observed at the perimeter walls as well as at the corners of adjoining walls (Fig. 14). No collapse of bell towers was reported, but one should notice that most towers were of recent build (with R/C or steel elements), since the original ones had been destroyed in past earthquakes. It should also be noted that several churches had been already restored after suffering damage during an earlier $M = 6.5$ earthquake in 1948. The middle-age castle of Agia Mavra, at the entrance of the town of Lefkada from the mainland, suffered no damage to its exterior walls. In its interior, partial collapse of some building ruins as well as some permanent displacements of some stone parapets and decorative elements was observed.

4.4.2. Factors affecting damage to buildings

As mentioned earlier, damage from this strong event in Lefkada was not as severe as one might have expected in view of the intensity of the mainshock and the fact that pre-1985 buildings were built according to the outdated 1959 seismic code. The majority of the building stock in Lefkada behaved in a nearly elastic manner (especially R/C buildings and, to a great extent, traditional dual system buildings), since they did not present serious damage to their load-bearing systems. This should be attributed to several factors, the most important of which are:

(1) Due to the particular shape of the response spectrum of the mainshock, buildings with relatively small fundamental period ($T < 0.15$–0.20 s), which constitutes the majority of the building stock in Lefkada, were not heavily stressed. Higher buildings were in general built according to modern (post-1985) code provisions, thus possessing higher ductility levels and resistance to seismic actions.

(2) The substantial strength reserves possessed by buildings, due mainly to their redundancy, the infill walls and the overstrength of individual structural members.

(3) The existence of additional energy dissipation mechanisms (e.g., those provided by the cracking of the infill walls). The beneficiary effect of the usually good quality of workmanship met in many of the buildings towards their seismic behaviour is also not to be neglected. This fact probably stems from the long-lasting experience of the local constructors with strong earthquakes.

(4) The earthquake motion was most probably not as intense throughout the city as the record obtained at the hospital building would indicate. Large motion variations are typically observed at small epicentral distances (also the case here) and become even greater due to variations in local soil conditions. The fact that practically no damage was observed in sections of town, where the quality of construction was statistically no different from that in the damaged areas, is a strong indication of this effect. Site response analyses that were recently performed at ITSAK for different locations in the town of Lefkada also support this conclusion (A. Anastasiadis, personal communication [8]).

4.5. Analytic investigation of seismic response of different building types

In order to gain insight into the seismic behaviour of the building stock, a dynamic analysis of two buildings with different structural types was performed. The first one is a representative traditional dual system (category C) building, while the second is an R/C (category D) building, both with dimensions and structural details typical of the ones found in Lefkada. These two structural types comprise almost 80% of the building stock in the town of Lefkada. Since this investigation is intended to serve as a general evaluation of the overall dynamic behaviour of the examined structural type and the various factors that affect it, and not as a detailed investigation of some specific damage observed, linear elastic analyses were performed. This approach is further justified by the fact that the majority of the building stock in Lefkada behaved in a nearly elastic manner, since they did not present serious damage to their load-bearing systems. Damage observed to masonry buildings (categories A and E, see Section 4.4.1) was to be expected, given the

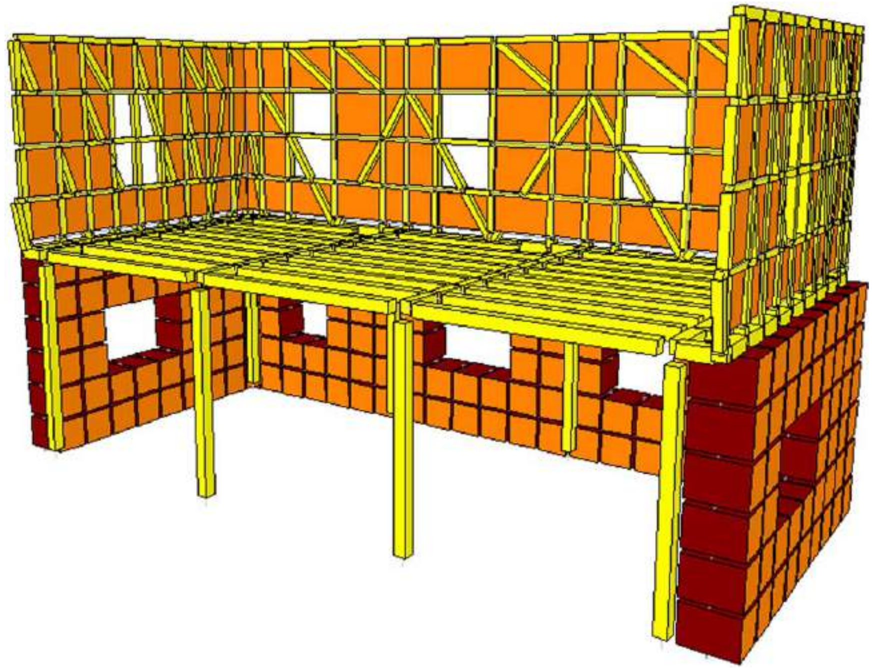

Fig. 15. Section of Finite Element model of traditional dual system structural building (façade elements not shown).

lack of seismic protection measures and poor condition in the majority of such buildings. On the other hand, damage to wood (category B buildings) was minimal (Section 4.4.1). Thus the analytical investigation was focused on the more interesting cases of buildings of categories C and D, which in general performed better than anticipated, given the proximity and intensity of the mainshock.

4.5.1. Traditional dual system building

The interesting concept in these buildings is the existence of the redundant wood frame on the ground level, which is fully activated after possible local collapse of the main load-bearing system, which consists of exterior masonry walls of thickness of 0.50–0.70 m. As already mentioned before, the overall response of this type of buildings during the Lefkada earthquake was satisfactory, with no damage to the wood load-bearing frames which performed as planned in the few cases of masonry failures (Fig. 9(a)). The most common damage was the failure (out-of-plane dislocation and/or in-plane cracking) of the infill walls on the upper storeys. Buildings of this type constitute 34% of the building stock in the town of Lefkada and a significantly bigger percentage for the rest of the island. In the town of Lefkada, the majority of the buildings in the old historic center district belong to this structural type. Due to poor soil conditions and a high water table level, the masonry walls are typically founded on extended footings made up of horizontally placed tree trunks. The wood frames (with diagonal struts) on the upper floors are usually filled by raw clay bricks and are protected from rain by zinc sheets nailed on the exterior faces. Floors are typically wooden, and given the rather small plan dimensions of the buildings, they provide a rather satisfactory diaphragmatic in-plane behaviour. Roofs are also made of wood and covered by tiles.

For the analysis of a two-storey representative building the SAP2000 [9] structural analysis program was used. Shell elements were used for modeling the masonry walls of the ground floor and the infill walls of the upper floors, and frame elements for the wood frame (Fig. 15). For the mechanical properties of the materials involved, the following mean values were used for Young's modulus E, Poisson ratio υ and density ρ, based on existing literature and past experience of the research team:

- Wood $E = 9000\,000$ kN/m^2 $\upsilon = 0.30$ $\rho = 0.5$ t/m^3
- Stone masonry $E = 4325\,000$ kN/m^2 $\upsilon = 0.15$ $\rho = 2.7$ t/m^3
- Clay brick infill walls $E = 1708\,000$ kN/m^2 $\upsilon = 0.15$ $\rho = 2.1$ t/m^3

The more recent Greek Seismic Code (EAK2000) prescribes the same viscous damping ratio $\zeta = 5\%$ for both the wood frame and the masonry walls, so this value was used for the elastic analysis of the traditional building. In buildings of this type, the largest portion of their mass is distributed on the exterior walls. The ground floor storey has five to six times the mass of a typical upper storey. This mass distribution differs from that of an R/C building, where most of the mass is found on the floor slabs. Eigenvalue analysis yielded a fundamental period of around 0.02 s (around 0.03 s for three-storey buildings). As can be seen by the response spectrum of the mainshock (Fig. 7), in this period range there is almost no spectral amplification of the excitation.

Time history analyses were also performed, using the recordings of the mainshock in the town of Lefkada (station LEF1). Three different excitation directions (0°, 45° and 90°) were assumed, in order to get an envelope

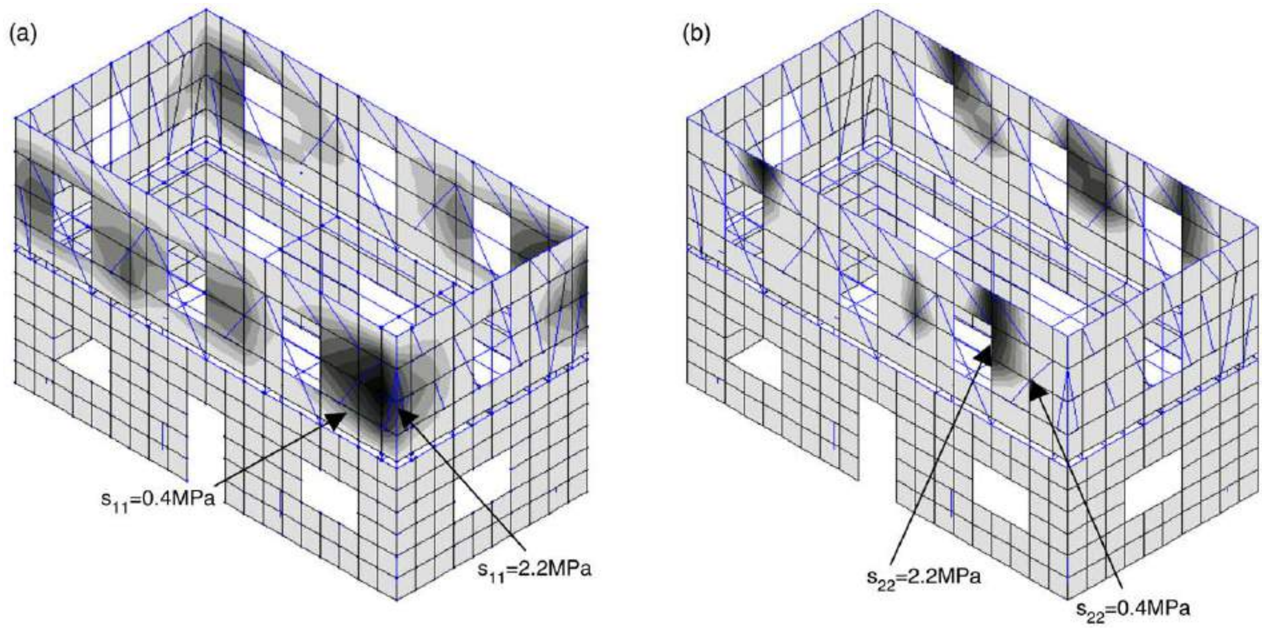

Fig. 16. Envelopes of tensile stresses in masonry elements from time-history analysis: (a) stresses s_{11}, (b) stresses s_{22}. Contours above typical tensile strength of masonry (>0.4 MPa) as well as at highest stress levels are denoted by arrows.

of the possible stress states of the building. In Fig. 16, the envelopes of the tensile stresses are presented, with contours indicating stress levels $s_{11}, s_{22} > 0.4$ MPa (typical tensile strength for Greek masonry). High tensile stress concentrations are observed in midheight of the infill walls of the upper floors, agreeing with in situ observations: typical failures observed in post-earthquake investigations involved the detachment of the infill walls from their surrounding frames, crackings and out-of-plane falls of the infill walls (Fig. 9(b)). The analyses also show a low stress concentration on the ground floor masonry, due to their big thickness, with an increase of tensile stresses around openings (and indeed, the relatively few damage cases observed for stone masonry involved local failures in these regions — see Fig. 9(a)). At the same time, wood frames remain in the elastic range, presenting no structural failure, a fact also confirmed from in situ investigations.

The analytical investigations agree with field observations of a satisfactory behaviour of buildings of this structural type during the Lefkada earthquake. It is a structural concept developed before 1800 A.D. by the local population, that has proven its merit in many instances of severe excitations in this earthquake-prone region: even in the case of very strong shaking, damage is usually limited to the masonry walls, while the redundant wood frame assures the life safety of the inhabitants and the rather easy repair to the original state.

4.5.2. *Reinforced concrete building*

In order to evaluate the contribution of various factors that affected the dynamic response of R/C structures, a four-storey building with dimensions and structural details representative of those found in Lefkada was analyzed (Figs. 17 and 18). The structural frame consists of columns and shear walls in a rather dense layout (spans of about 3.5 to 4 m). Shear walls constitute a significant portion of the load-bearing system, as is rather typical in Lefkada buildings. The ⊓-shaped core is typically used to house the stairs and/or lift of the building. In the analyses, the role of two factors that were deemed most important was investigated, i.e., the role of infill walls and the compliance of the foundations. Given the long-lasting experience of the local population with strong earthquakes, infill walls are usually carefully constructed, with several horizontal R/C belts along their height, clearly affecting the response of the structure, although their role, according to the Greek Seismic Codes, is not taken into account during the design of a building. Also the foundation compliance, which is usually not taken into account in the design process, affected in a beneficial manner the overall building behaviour, as is suggested by the analytical investigation that follows.

For the analysis the SAP2000 [9] structural analysis program was used. Shell elements were used for modeling the shear walls, and beam elements for the rest of the structural frame. Infill walls were modeled by diagonal truss elements, according to well-established methods proposed in the literature [10]. For the simulation of the foundation compliance, vertical and horizontal springs were used at the foundation. Based on information of the soil profile in the old district of the town of Lefkada, a dynamic spring constant of $k_{sdv} = 2400$ kN/m^3 was estimated for the vertical springs and $k_{sdh} = 1600$ kN/m^3 for the horizontal ones.

Eigenvalue analysis yielded the two fundamental translational periods in the range of 0.20–0.25 s for the case of

Fig. 17. A typical R/C building in the town of Lefkada that responded elastically during the mainshock. The inset photo shows the interior of the ground floor. Note the small spans of the beams and the extensive use of shear walls.

the bare (no infill walls), clamped at the base building. Taking into account infill walls, the corresponding periods lay in the 0.16–0.19 s range. The role of the soft soil was more accentuated: fundamental periods lay in the 0.75–1.00 s range when springs were added to the original bare clamped structure.

Time history analyses performed, using the recordings of the mainshock (station LEF1), confirmed the importance of the above factors in the seismic response of the building. Considering the clamped structure and not taking into account infill walls, shear stress concentrations surpassing the code limits ($s_{12} > 1.9$ MPa) were observed at the ground floor level of the shear walls, and especially at the ⊓-shaped core (Fig. 19(a)). Tensile and compression stress fields were within the allowable limits, thus explaining the almost total absence of flexural type failures. Taking infill walls into account results in a decrease of the stress field level by about 15% on average. The compliance of the foundations plays a more important role, leading to a decrease of the stress field by 35% on average, combined with maximum vertical and horizontal displacements of the order of 4.5 and 3 cm respectively (Fig. 19(b)).

Since no damage was observed to buildings conforming to the Seismic Code provisions, the above analyses indicate that the compliance of the foundations and, secondarily, infill walls, might have played a significant role in mitigating the consequences of the severe Lefkada earthquake on R/C buildings. Of course, one should also not forget the existence of all other factors (attenuation of the seismic motion, overstrength and regular configuration of the structural system etc) that contribute to added safety margins of R/C buildings.

5. Emergency management

Emergency response to the disaster was underway immediately after the earthquake. Fortunately, the demands were less than those of previous similar intensity events, thanks to the fact that this $M = 6.2$ event did not cause life losses or heavy damage to structures. At the time of the main event, Lefkada Island had an estimated combined population of about 80,000 permanent residents and tourists. According to the 2001 National Census there are 22,506 permanent residents in the island. Despite the dense population, no deaths and about 45 injuries were reported.

The earthquake damaged mainly unreinforced masonry and poorly designed R/C structures as well as roads and marine structures, and caused limited damage to drinking and waste water systems as well as to the electrical power supply network. In fact, disruption of the traffic network on the western part of the island was the most serious infrastructure problem caused by the earthquake. Sixty-four civil engineers from the Greek Ministry for the Environment, Physical Planning and Public Works formed 32 inspection teams to proceed with visual assessments of buildings, providing the basis for determining which structures will require more thorough examination. The inspection was performed in two stages, a rapid one and a more detailed one, and was completed about 20 days after the mainshock for all the buildings of the island. Deviating from usually followed practices in previous Greek earthquakes, in the first level inspection, buildings were characterized simply as inhabitable or not inhabitable. It was only in the more detailed, second level inspection that the usual classification of the buildings in the known green/yellow/red categories (described in Section 4.3) was applied. The inspection procedure resulted in a more rapid first-level evaluation and its applicability to future events should not be ruled out.

6. Discussion and conclusions

The earthquake ($M = 6.2$) that struck the island of Lefkada on August 14, 2003 was one of the most intense ever recorded in Greece. The maximum horizontal peak ground acceleration was $a_g = 0.42g$, and the corresponding estimated bracketed duration was 18 s. Several conclusions can be drawn from the investigation of the earthquake and its effect on structures and infrastructure facilities:

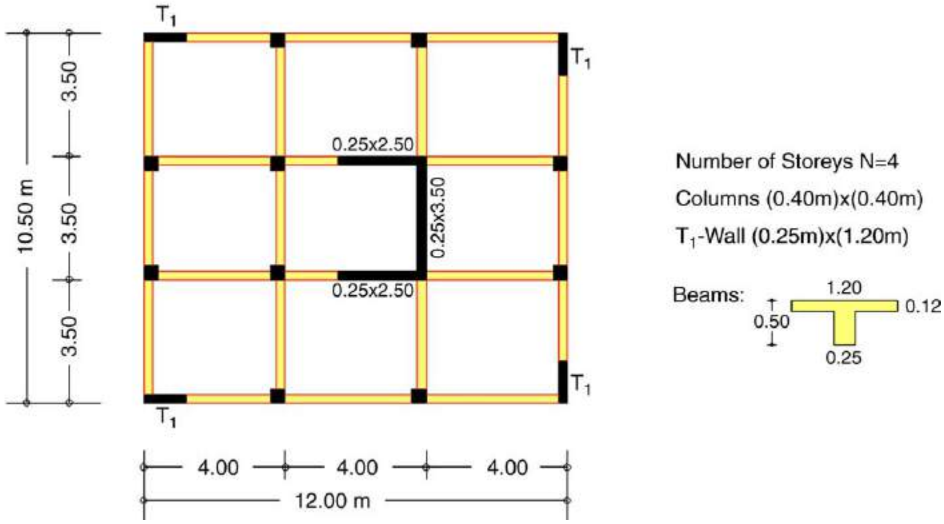

Fig. 18. Typical plan and formwork of representative R/C building.

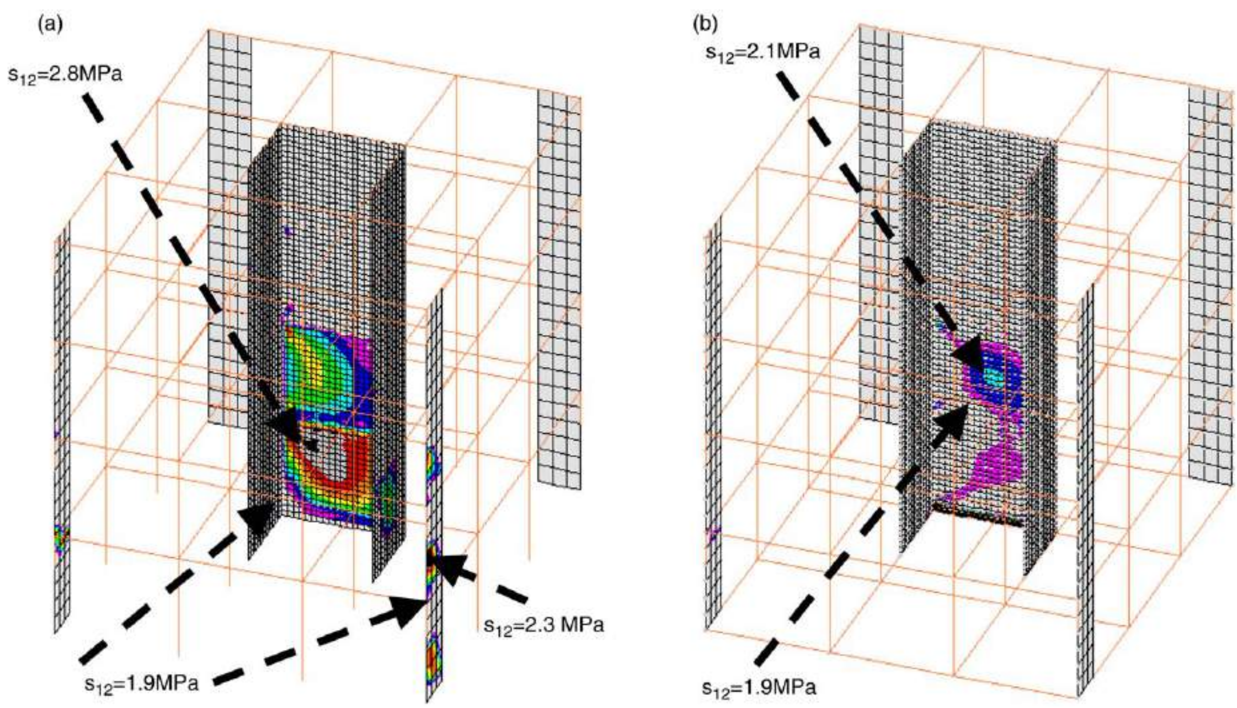

Fig. 19. Envelopes of shear stresses in shear walls from time-history analysis (without infill walls): (a) structure clamped at base, (b) structure on springs to model foundation compliance. Contours above allowable stress level (>1.8 MPa) as well as at highest stress levels are denoted by arrows.

- Due to either poor soil conditions or steep morphology of the island, the geotechnical failures observed exceeded those of most previous strong earthquakes in Greece. Phenomena of ground settlement, lateral spreading, liquefaction, landslides and rock falls were observed in several areas of the island, leading to damage of port and marine infrastructures and of a significant part of the road network in the western area of the island.
- Despite the strong shaking and, in some cases, the poor soil conditions (such as in the town of Lefkada), damage to buildings was rather limited. Due to the particular shape of the response spectrum, low-rise buildings with small (<0.20 s) fundamental period (which constitute the majority of the building stock) were not heavily stressed. Higher buildings were in general built according to modern seismic code provisions, thus possessing higher resistance to seismic actions.
- The area of Lefkada is one of the most earthquake-prone in Greece. Due to frequent shaking, the local population has a lasting awareness of earthquakes, and takes special care in the quality of workmanship in buildings. It is this experience, that led, even before 1800 A.D., to the

creation of traditional buildings in the area with a dual (masonry and wood frame) system to handle seismic actions. Even in modern, R/C buildings, the quality of workmanship is generally higher than that met in other Greek regions.

- The various failures observed in reinforced concrete buildings (collapse of one building, and local failures of the load-bearing systems in other cases), can be attributed rather to poor design and workmanship than excessive shaking. Local failures observed in traditional (masonry and dual system) buildings can be attributed to old age, poor condition and lack of adequate seismic resisting mechanisms. In many cases, failures were limited to nonstructural components, such as brick infill walls of R/C or wood load-bearing frames. Finally, several churches developed cracking in their load-bearing masonry walls, and were put out of service until restoration measures were taken.
- Analytical investigations of a traditional dual system building and a representative R/C building were performed. The analytical results agree with field inspections of damage, and also point out the significant role of the compliance of the foundations and the extensive use of infill walls in the mitigation of the consequences of the severe Lefkada earthquake on buildings. This earthquake, as well as previous ones, has demonstrated the importance of several alternative factors that contribute to increased safety margins of buildings. Among such factors, which usually are not taken into account in the design, one can mention the attenuation of the seismic motion, overstrength and proper configuration of the structural system, quality of workmanship, compliance of the foundations and soil-structure interaction phenomena in general, properly placed infill walls, etc.
- The emergency management of the event is deemed successful, especially since the earthquake took place in a densely populated region. A two-level inspection of the building stock was completed within 20 days of the main event, resulting in reduced damage to economic activities on the island.

Much has been learned from this and previous earthquakes, and significant progress has been made in Greece, especially during the last 20 years, in improving building codes and practices and in handling earthquake emergency situations.

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References

[1] Margaris B, Papaioannou C, Theodulidis N, Savvaidis A, Anastasiadis A, Klimis N et al. Preliminary observations on the August 14, 2003 Lefkada Island (Western Greece) earthquake. EERI special earthquake report, November 2003 (Joint report by Institute of Engineering Seismology and Earthquake Engineering, National Technical University of Athens & University of Athens).

[2] Karakostas VG, Papadimitriou EE, Papazaxos BC. Properties of the 2003 Lefkada, Ionian Islands, Greece, earthquake seismic sequence and seismicity triggering. Bulletin of the Seismological Society of America 2004;94(5):1976–81.

[3] Louvari E, Kiratzi AA, Papazaxos BC. The cephalonia transform fault and its extension to western Lefkada Island (Greece). Tectonophysics 1999;308:223–6.

[4] Dimitriou P, Theodulidis N, Margaris B, Papaioannou C, Savvaidis A, Anastasiadis A et al. The Lefkada earthquake ($M = 6.2$): strong ground motion–effect of the earthquake on the built and natural environment. Technical Chamber of Greece; 2004. p. 62 [in Greek].

[5] Gazetas G. Geotechnical aspects of the Ms 6.4 Lefkada island, Greece, 2003 earthquake: preliminary assessment. Proc. 5th international conference on case histories in geotechnical engineering. 2004.

[6] Anagnostopoulos SA, Rinaldis D, Lekidis VA, Margaris VN, Theodulidis N. The Kalamata, Greece earthquake of September 13, 1986. Earthquake Spectra 1987;3(2):365–402.

[7] Lekidis VA, Karakostas CZ, Dimitriu PP, Margaris BN, Kalogeras I, Theodulidis N. The Aigio (Greece) seismic sequence of June 1995: seismological, strong-motion data and effects of the earthquakes on structures. Journal of Earthquake Engineering 1999;3(3):349–80.

[8] Anastasiadis A. Dpt. of Soil Dynamics, ITSAK, 2004 [personal communication].

[9] Computers & Structures Inc. SAP2000—structural analysis program, ver. 8.2, Berkeley, CA, USA; 2003.

[10] Paulay T, Priestley MJN. Seismic design of reinforced concrete and masonry buildings. John Wiley & Sons Inc.; 1992.