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TRADITIONAL BUILDING CRITERIA IN THE LEFKADA ISLAND: PECULIARITIES OF THE FOUNDATION SYSTEM

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Abstract. *The traditional construction technique in use in the town of Lefkada, Greece, has attracted scientific interest since the end of the nineteenth century, when British engineers were called to draw up a report of the damage caused by the earthquake that had occurred in the Ionian Islands in 1825. The British government, which at that time exerted power over the area, in recognition of the effectiveness proven by the structural system adopted in the town traditional buildings, ordered to apply the same concept both for restoration and for new construction, in accordance with the rules specified in a Code of Construction (1827). Inside the Mediterranean area, the Ionian Islands are exposed to specially high seismic hazard, so that the effectiveness of the Lefkada building technique has been observed and studied thoroughly; recently, after the earthquake occurred in 2003, detailed analyses of the above ground structure and of the relative design details have been published [5,1,4]. However, the knowledge of the underlying foundation system has been lacking so far. The interest in this problem comes from the softness of the ground which is typical of the area where the Lefkada town was erected: the Venetians created the town ex novo, moving the inhabitants from the Castro of Santa Maura to a marshy coastal area, which had been reclaimed. The problem of the foundation settlement, therefore, has always had to be considered in the design phase. On the basis of on-going studies, in this paper it is shown that the Lefkada building tradition peculiarities are present not only in the above ground structure, but in the foundation system as well. Two alternative solutions in use for the foundation structure are described, together with the construction technique and the employed materials. In the paper it is also highlighted that the adoption of effective building criteria, able to oppose adverse environmental conditions coming from both earthquakes and poor soil conditions, was based exclusively on the use of locally available resources and on the local building tradition.*

1 INTRODUCTION

Lefkada belongs to a group of seven islands, the Ionian Islands, located in the middle of the Mediterranean sea. Despite a picturesque look, it is characterized by hard soil conditions, with the western coast almost inaccessible due to unstable slope conditions, with a mountainous backcountry not suitable for agriculture, and a marshy eastern coast, exposed in the past to attacks, being separated from the mainland only by an isthmus. Moreover, due to the local geo-seismological condition, the Ionian Islands are exposed to high seismic hazard, one of the worst conditions in Europe.

Due to the permanent need of facing critical environmental conditions, the building tradition has developed very efficient structural solutions. While in the backcountry squat buildings are in use, interconnected in structural aggregates, along the coast, and mainly in the town of Lefkada, a specific system was developed; from the point of view of the construction materials, it is a mixed solution, based on the use of wood, which is largely available along the coast. For this system, many claim the authorship in the relevant bibliography; the origin, indeed, is strictly connected to specially demanding local conditions, related to both the seismic hazard and the limited bearing capacity of local soil .

In this context, the building tradition developed a construction model which, through experience, was progressively improved on the basis of empirical data. In this model, special interest is related not only to the uprising structure, but to the particular foundation system as well, to which this study is specifically devoted.

2 TRADITIONAL ARCHITECTURAL SOLUTIONS IN LEFKADA

2.1 The 1825 seismic event

In 1825, in the month of January, a strong earthquake hit the island of Lefkada, followed by a sequence of aftershocks for over twelve days; this event has been classified as one of the worst in the recent history of the island, due to the simultaneous action of both the earthquake and the tsunami which hit the town of Lefkada.

Apart from the collapse of infrastructures, the destruction of both shops and harbours caused problems to the economic recovery. Under the British domination, a few documents were developed, now available in the archive of the Lefkada administrative offices, which provide a classification of the damage state as it was surveyed in both the town and the rest of the island. On the basis of this work, an official document was published, specifying Rules for the construction of new buildings; this was done on behalf of Senator Sidney G. Osborne and published in the Island Gazette n. 496 on June 30th, 1827 in Corfu. In the document, provisions were given about several aspects: construction materials, criteria to have vertical straight walls, thickness of the wall section at the ground level, maximum height, minimum distance between buildings (in order to prevent hammering and for fire safety as well). The text was articulated in 15 sections and specified procedures to be followed both in the case of repair works and of new construction as well. The document, indeed, imposed to follow the traditional construction technique, thus preserving it; thanks to it, we can have a clear understanding of the effectiveness of the traditional technique in use in the town, which can be observed still now; at he same time, we can also know the different construction techniques over the island, related to different soil typologies and economic conditions.

From the general list of the buildings which suffered damage, which is then confirmed by a detailed list, it comes out that stone was the prevailing construction material in the island villages; timber was not limited to floor slabs and roof structures only in a limited number of cases in the south of the island, in the Vassiliki province.

It has to be underlined that the town of Lefkada, which developed mainly after the arrival of the Venetians, is the only urban centre in the island presenting problematic soil conditions, whereas villages in the backcountry usually rise on a compact limestone soil.

2.2 Urban structure and construction characteristics of Lefkada historical centre

The historical centre of the town of Lefkada was planned so as to allow the drainage and natural flow of rain water to the sea and to take advantage of a frequent wind condition, blowing from N-NW, which helps reducing humidity. Lefkada centre has preserved its original structure, dating back to the 18th century, and is made of independent adjacent units.

With reference to studies developed at the National technical University of Athens [5, 1, 4], it is possible to briefly summarize the main characteristics of a typical building. This normally has one single floor, with a maximum of three; the ground floor presents a stone masonry structure, while the upper levels present a frame structure, based on the mixed use of timber and brick elements. All the floor slabs are timber structures and the roof is covered by tiles. Openings are arranged symmetrically in plan and, in order to protect timber structures at upper levels from humidity, the outer façade was covered with wood boards.

The ground floor has a maximum height of 3 m, and is made of stone masonry walls with thickness in the range 60 – 100 cm, with the external leaf composed by roughly shaped elements, whereas well shaped elements are used in the corners; stones on the internal leaf are plastered. The space included between the external leaves is filled with mortar and small pieces of stone and brick.

In parallel to the masonry structure, a second structure is realized, consisting in timber columns with a centre to centre distance of 2 – 3 m. The slab timber beams provide connection of these columns to the masonry walls.

Due to the high deformability, this secondary timber structural system at the first floor does not contribute to the seismic resistance; however, due to the strong connection to the slab, it plays a fundamental role in case of partial or total collapse of the masonry walls, providing support to vertical loads. It is therefore a passive protection system, which is activated in case of damage to masonry, the primary resistance system; in addition, it would allow masonry repair without interfering with the rest of the building.

Timber floors play a double role, resisting to both vertical loads coming from upper levels and to those directly acting on them; such loads are transferred not only to the perimeter walls, but to the secondary timber structure as well. All the connections among timber elements are extremely accurate and well detailed.

Considering that economic resources have always been very limited in Lefkada, it can be assumed that the secondary system was conceived also to the purpose of increasing the structure seismic performance in the sense of allowing an easier and cheaper repair of the damaged building.

This system requires, for maximum effectiveness, that the columns rest on a stable supporting surface, not allowing for differential settlements; it is also required that masonry at the ground level is compact and well connected to the foundation walls.

2.3 Some remarks after the 2003 earthquake event

Following the earthquake of August 14th, 2003[1] a damage report was prepared [3], based on the inspection of 3165 dwellings. In the report, damage is classified according to the different structural typologies: A – traditional masonry buildings, B – traditional buildings with the special secondary system for vertical loads, C – reinforced concrete buildings, – D monumental buildings dating back to the Middle Ages or earlier.

The effectiveness of the building system which is here analyzed, type B, is documented as follows. "In this composite system, a wooden frame has special carved corners that strengthen beam-to-column joints, and wooden stiffening walls with x-braces. In the plane of these stiffening walls, various masonry materials may be added in order to increase the stiffeners and the energy absorbing capacity of the whole system. On the ground floor, the wooden frame comes in contact with the external masonry wall, with which it is well connected. The carved corners are also put in the lower part of the column, that is fixed to the foundation. In some cases, there was a partial collapse of masonry walls, 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 the brick infills was observed. These cracks were difficult to notice at first, since the external walls at the upper stories are typically clad with zinc sheets (for rain protection). Damage could be observed only on the interior faces of the walls, which are usually plastered with lime. Due to the use of extended wood footings or piles described above, and the small weight of these buildings, no foundation settling was observed, despite the poor soil conditions in the old district of the old town of Lefkada, where the majority of such building types are found. The severe or total damage to a limited number of buildings of this type can be attributed to old age and poor maintenance. "

The above remarks, which were formulated following a severe seismic event (7th to 8th grade of the Mercalli scale), prove not only the effectiveness of the construction technique, but the full cooperation between the uprising and underground systems as well.

3 THE LEFKADA FOUNDATION SYSTEM

Building in Lefkada requires to face two critical issues: frequent earthquakes and ground subsidence. The soil in the town of Lefkada is an alluvial deposit which, according to EC8, could be classified as a C class soil ("deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of metres": 180 < Vs30 < 360 m/s, 15 < NSPT < 50, 70 < Cu < 250 kPa").

The high level of soil deformability is a permanent condition for the urban area, and it might affect also the behaviour of the sophisticated structural system conceived to resist earthquakes. In the absence of a rigid base, indeed, the passive secondary system would not be effective due to the relative settlements which would take place during the structure life time and to the consequent modification in the stress distribution.

From the analysis of literature, it appears that the Lefkada foundation system has been studied to a limited extent; a global interpretation of the conceptual design, indeed, is still lacking. In Touliatos' description [4], foundations are a special system, resting over a timber grid at a depth of 60-100 cm; the interspaces between timber elements is covered with sand,

[1] On August 14th, 2003 a 6.4 Mw earthquake took place, with epicentre in the Ionian Sea, approximately 30 km N/E of the town of Lefkada. The recorded peak ground acceleration was 0.42 g)

stones and hydraulic mortar. Four years later, Triandafillos and Milton [6] provided a more detailed scheme of the foundation system which, in their assumption, would be constituted of polished stones, fine sand with pozzolan, and horizontally laying timber elements. In this view, the foundation system would not suffer from subsidence due to the proper use of such materials.

As anticipated by Touliatos [4], special interest comes from the foundation lower part, resting under the water table level. In [6] reference is made to the description provided by Papadatou- Ghiannopoulou [2], which is based on the assumption of a timber grid composed by three layers of parallel wooden beams at a distance of 45 cm, with length in the range 1 to 2 m, with a rectangular or circular cross section and an area of approximately 130 cm^2.

In the authors' opinion, such a construction technique had the purpose of keeping the foundation masonry walls above the water table (which in the town area was 0.5 – 1.0 m deep), thus reducing the possibility of relative settlements. It is also known that bark was removed from wood elements before use; also, they were kept about seven weeks in "marine mud", in order to make them resistant to the attack of micro-organisms and so protected from decomposition; finally, they were made waterproof with a tar and pitch cover.

Triandafillos and Milton [6], at the end of their dissertation, suggest interesting considerations about the real nature of this foundation system which, in their opinion, might have been conceived as a primitive version of a base isolation system. According to them, additional investigations should be taken on, in order to clarify the base isolation assumption and, moreover, the real composition of the system.

This last, indeed, is not yet known in detail; also, the real purpose of the timber grid has still to be interpreted. At present, the level of knowledge for the uprising structure appears to be very different from that available for the underground system. After compensating such difference, it will be possible to formulate assumptions on the real possibilities of foundations of this kind and of the whole system.

In the analysis of this problem, several hypotheses have been formulated (see fig. 1), mainly about the support condition for the ground floor and the secondary timber structure; questions have been posed also about the presence of a set back in the perimeter walls and about the construction materials. On the basis of their own field experience, the authors suggest a new interpretation for the foundation system (fig. 2), assuming that a couple of different solutions were systematically adopted, depending on the specific economic situation.

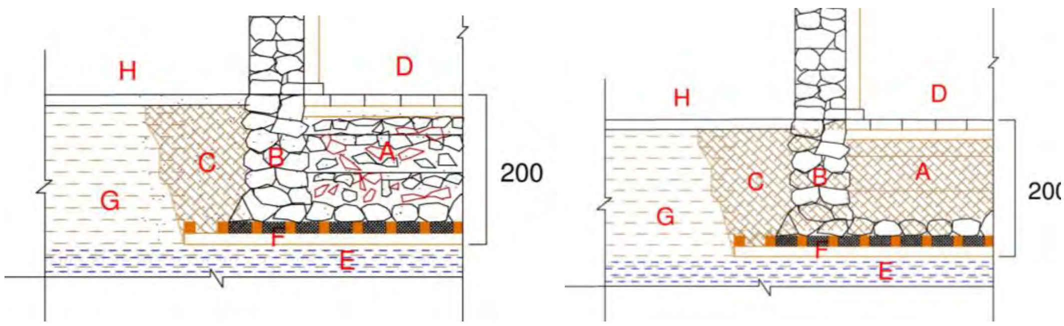


Figure 1. Initial assumptions on the foundation system.

According to collected witnesses, the foundation surface is always 80 – 100 cm deep in the soil, so that the structure may rest on the original clay soil, below the watery deposit of the reclaimed lake.

Considering that in the old building tradition a fast complete drainage of water was not possible, two different construction solutions were adopted depending on the availability of both time and economic resources.

In order to explain the reasons and the modalities of this foundation system, a clear understanding of the local soil condition is required. The foundation excavation was about 80 – 100 cm deep, in order to reach the original lagoon bottom. This is made of a clay material; specifically, a soft, compressible and waterproof quality of clay, not adequate for the structural loads and the needs of the town historical centre. Going deeper into the soil, a less compressible material is found; at a depth of 5 – 6 m the original bedrock is found (named "kastro"[2]) . In the past neither efficient digging machines nor drainage pumps were available; because of this, builders had to set the foundation lower surface relatively high in the ground, at a maximum depth of 150 cm. They were therefore forced to develop techniques which enabled the mortar to set in the presence of both water and air as well. From this need, two different solutions were generated: those who could allow themselves the use of pozzolan (called "Buzolana") or volcanic materials ("Tephra") realized foundation walls, resting directly on the ground, with stones and a hydraulic mortar; instead, those who could not afford those materials, made use of a timber grid, providing a flat surface for the erection of walls, avoiding the contact with water. The grid extended homogeneously under the entire house perimeter; in the case of a higher water table level, additional timber layers were inserted, normal to underlying ones.

From the analysis of data recorded during recent earthquakes, satisfactory results have been observed with both the construction techniques. In the first case, indeed, foundations result in a hard and monolithic structure, a "concrete box" directly connected to the ground floor; in the second case, a hard wall is present, resting on a grid filled with sand, rocks and hydraulic mortar, which plays the role of a stiff surface for an effective support to the upper structure.

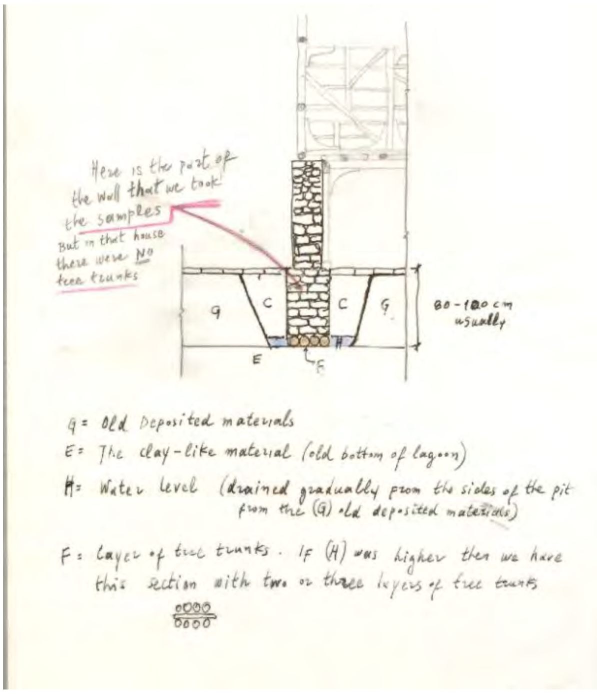


Figure 2. The foundation system according to K. Katopodis.

[2] A grey conglomerate, with sand and clay inclusions. Age: medium-superior Pliocene.

In the literature, wide consideration has been given to the “mixed” system, based on the use of a timber grid; for this reason, the analysis here presented has been addressed to the less known system, which still requires additional studies for a full understanding of both the material composition and the hydraulic properties.

About the local availability of construction materials, as it can be seen in the geological map[3] in fig. 3 (scale 1:100000), the Lefkada area is defined as an alluvial deposit, while the rest of the island is limestone, with the exception of small quantities of red earth (“*Erithroghi*”).

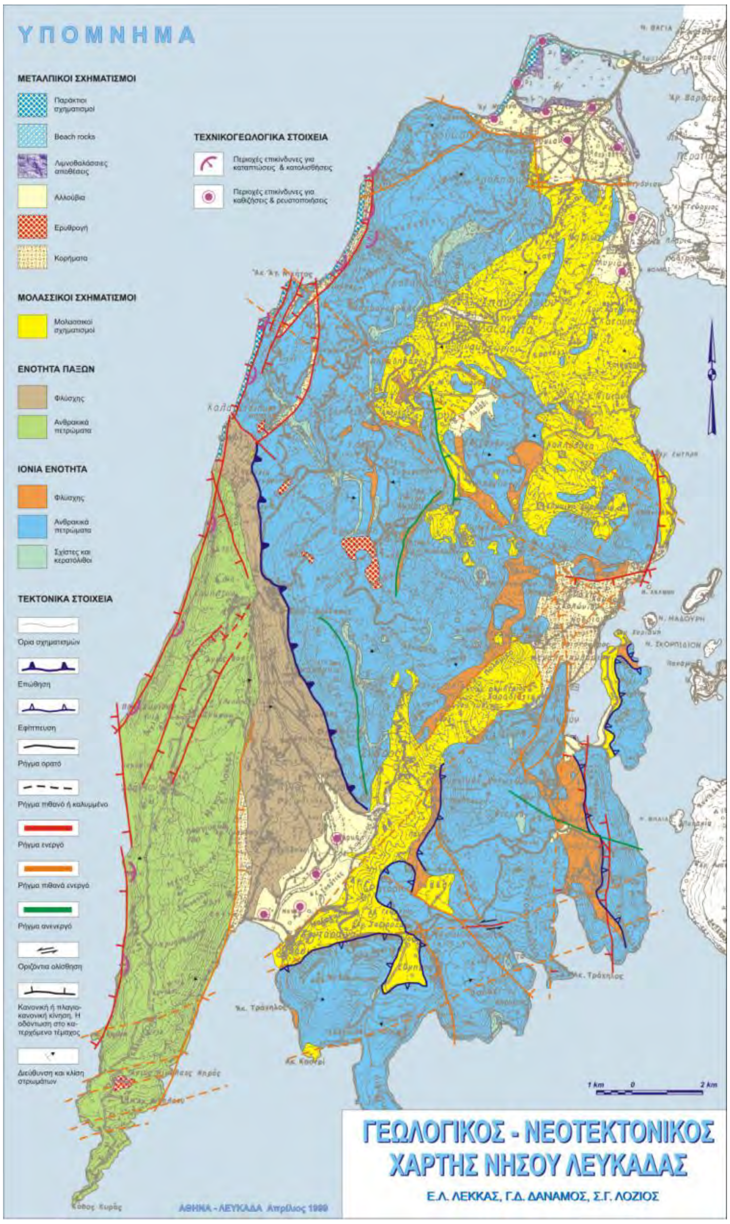


Figure 3. Geological map, 1:100000 (http://www.elekkas.gr/en/research/mapping.html)

[3] Prof. EFTHYMIS LEKKAS. Professor of Dynamic Tectonic Applied Geology, Faculty of Geology & Geoenvironment, National & Kapodistrian University of Athens, Vice-President of Earthquake Planning and Protection Organization,President of the Geological Society of Greece. http://www.elekkas.gr/en/research/mapping.html

In this study, the analysis of the foundation system of the first kind has taken advantage from the availability of a mortar specimen coming from a foundation structure; the specimen has been subjected to a petrographic analysis[4] in order to define the mortar composition (figg. 4, 5 and 6).

Analyses have shown that the specimen corresponds to a high quality mortar, specifically conceived for use in a non-aerial environment.

Materials suitable to provide hydraulic properties to mortar are present; also, it can be stated that they were correctly assembled in order to make the expected properties available. An example is given by the presence of volcanic stones in very thin grains, which convert the lime binder into a real binder with hydraulic properties.

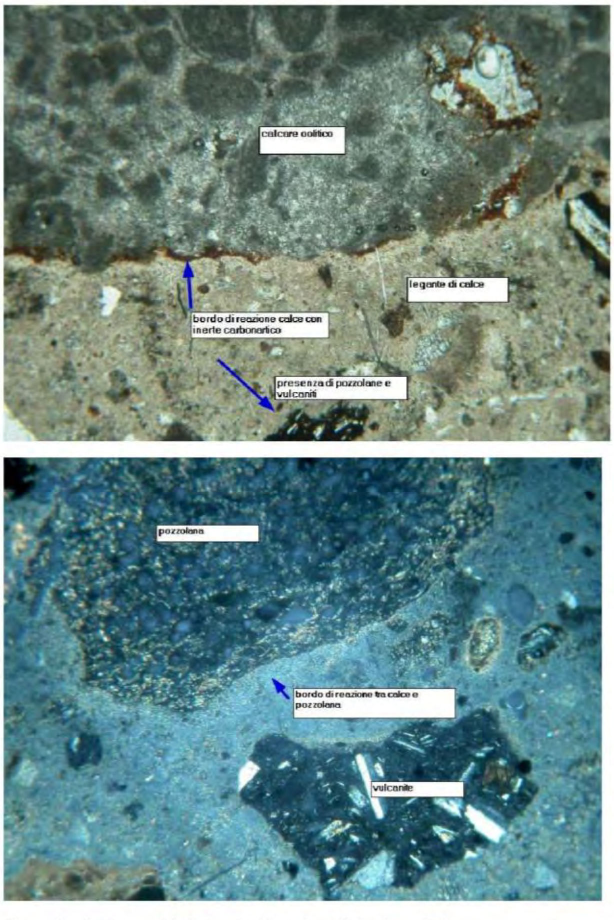


Figure 4. The mortar specimen as seen with the electron microscope

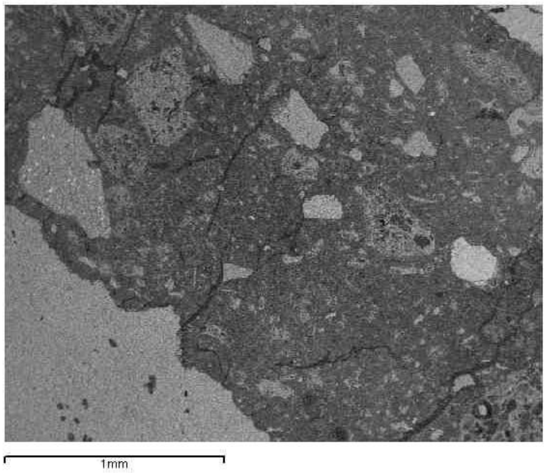
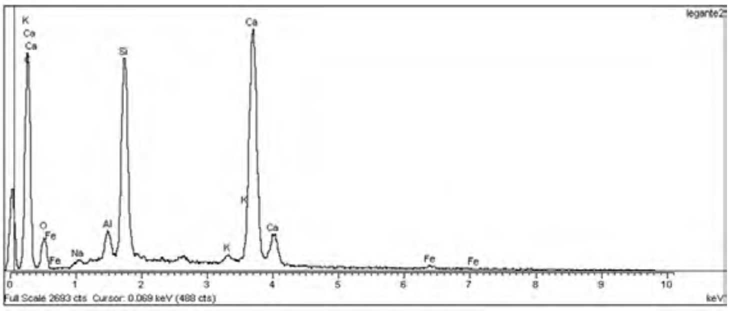


Figure 5. The mortar specimen as seen with the petrographic optical microscope.

[4] EDS01 and SS01 analyses have been performed by Dr G. Michiara (GEOFABER, Parma, Italy) by means of a petrographic optical microscope and of an electron microscope.



Element	App Conc.	Intensity Corrn.	Weight%	Weight% Sigma	Atomic%	Compd%	Formula	Number of ions
C K	139.56	0.7443	23.02	0.71	29.86	84.35	CO2	2.72
Na K	0.75	0.5389	0.17	0.03	0.12	0.23	Na2O	0.01
Al K	3.11	0.6971	0.55	0.03	0.32	1.04	Al2O3	0.03
Si K	20.45	0.8016	3.13	0.06	1.74	6.70	SiO2	0.16
K K	1.19	1.0330	0.14	0.02	0.06	0.17	K2O	0.01
Ca K	39.14	0.9162	5.24	0.10	2.04	7.34	CaO	0.19
Fe K	0.92	0.8620	0.13	0.03	0.04	0.17	FeO	0.00
O			67.61	0.72	65.84			6.00
Totals			100.00					
							Cation sum	3.11

Figure 6. Results from the EDS analysis of a portion of the binder. Silica peaks reveal the binder hydraulic properties.

4 CONCLUSIONS

The analyses performed within this study provide a contribution to a better knowledge of the foundation structures present in the Lefkada traditional buildings, which are characterized by a well known seismic protection system (Fig. 7). An explanation has been first given about the construction criteria; next, considerations have been proposed about the effectiveness of such a system, also in relation to the seismic behaviour.

In relation to this last issue and with special reference to critical areas, it should be considered that the building tradition, in the past, underwent constant modifications on the basis of empirical data coming from experience; this allowed a continuous improvement from the point of view of functionality, through an optimum use of both materials and expertise. In this spirit, the analyzed foundation system might be the result of an iterative process, in the search for an optimum response to both poor soil conditions and frequent earthquakes as well. The discussion on the seismic performance of this system needs, however, some care.

According to a specific interpretation, the foundation typology resting on a timber grid would benefit from the possibility of relative movements between the foundation structure and the surrounding soil. This assumption, however, can not hold, considering that both the solutions in use for the foundation system have provided good performance during earthquakes. The assumption is based on the consideration that the base isolation concept was known also in ancient times and was adopted, in some cases, in the surrounding area. The detailed description of the foundation system which has been here provided clearly shows that no sliding possibility is present over the timber elements because of the filling material inserted between adjacent elements.

It is believed that the proper interpretation of the real nature of this system should rather be based on different considerations. On the one side, the increase in the bearing capacity coming from the foundation depth should be considered; on the other one, the effect of the foundation mass on the global dynamic response of the building should be analyzed. Through this kind of considerations, it would probably be possible to reach a full understanding of the real effectiveness of the foundation system, together with a full appreciation of the anti-seismic conceptual design of the Lefkada traditional buildings.

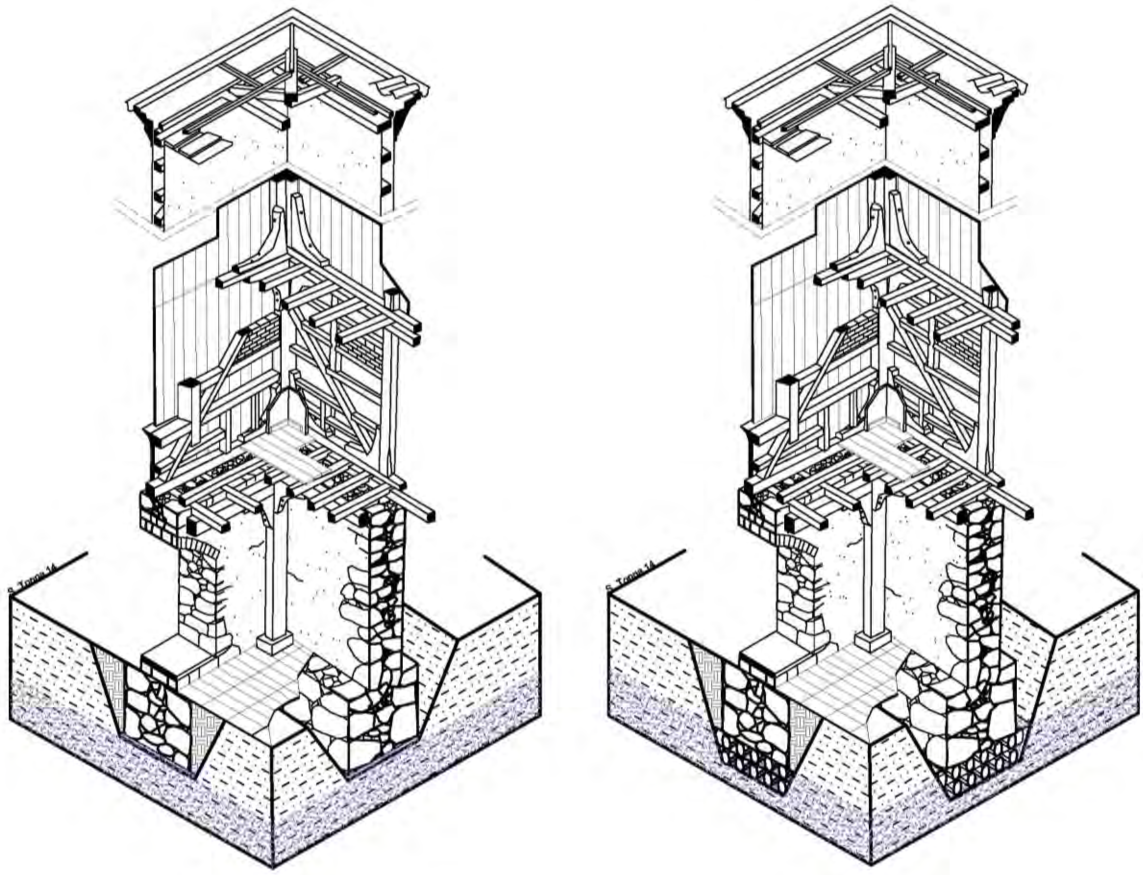


Figure 7. The foundation structures present in the Lefkada traditional buildings. On the left Foundation wall with pozzolana in the mortar, on the right with the timber grid.

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