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RESEARCH ARTICLE

Design Provisions for An Easy Intervention in the Future Life of a Structure. The Case of the Post- Byzantine Timber-roofed Basilicas of Troodos Area in Cyprus

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Abstract:

Background:

This article deals with the timber- roofed basilicas of Troodos which were built from the mid-15th to the late-19th century AD. The most impressive constructional feature of these basilicas is the existence of two constructionally distinctive, but cooperating, parts of the roof. The basilicas' construction system is mainly characterized by the ability to confront successfully the dynamic loads of an earthquake.

Objective:

This study investigates design provisions that can make easier any future intervention and retrofitting.

Methods

It is suggested that the design concept of these basilicas incorporated, among other objectives, a remarkable provision for an easy repair intervention and retrofitting, at a later stage during their life.

The timber- roofed basilicas of Troodos demonstrate a cleverly designed structure, where the co-operation between the roof and masonry plays an important role in their anti-seismic design.

Results and Conclusion:

The timber-roofed basilicas of Troodos present a remarkable design provision that made intervention an easy task, at any stage of their future life. This particular design concept seems to be valuable even today and can be easily adopted when designing modern contemporary structures with a long-term life objective.

Keywords: Timber-roof, Cyprus, Anti-seismic design, Intervention, Retrofitting, Troodos area.

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1. INTRODUCTION

The island of Cyprus presents a distinctive type of basilicas with a wooden roof, which were built from the mid 15th to the late 19th century AD. According to researchers, this type seems to be unique in the European and Mediterranean area and probably worldwide too. There are more than 130 churches of this type, all of them located within the boundaries of the Troodos Mountain Area, which is the highest of the two mountain regions in Cyprus. As far as typology is concerned, 75% of the churches are single-aisled (Fig. **1**), and another 20% are three-aisled (Fig. **2**). There are also six cases of two-aisled churches (5%), all of them being the result of an extension of a single-aisled church.

The steep inclination of the roof was morphologically associated with the western Middle Age European roofs and was attributed to the influence of the Franks, who ruled the island from 1191 until 1480 AD [1, 2]. On the other hand, recent findings of a thorough constructional analysis strongly suggest that this particular roof type has similar characteristics with the so-called "eastern-type" construction systems [3 - 6].

The "eastern-type" construction systems are mainly characterized by their ability to confront successfully the dynamic loads of an earthquake, a frequent phenomenon around the

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East-Mediterranean basin. Compared to the “western-type” constructional systems, they present, under dynamic loads, a hyper-static behaviour, equal distribution of loads throughout the whole structure, a slightly flexible stiffness (in order to absorb large amounts of energy during an earthquake) and a “box-like” behaviour (Fig. **3**) [7 - 10]

Fig. (1). The single-aisled basilica of Saints Sergios and Vachos, at Kalopanayiotis village. East façade (Photo M.Pelekanos) [4].

Fig. (2). View of the three- aisled basilica of Panayia, at Kourdali village from the North- East (Photo M.Pelekanos). [3].

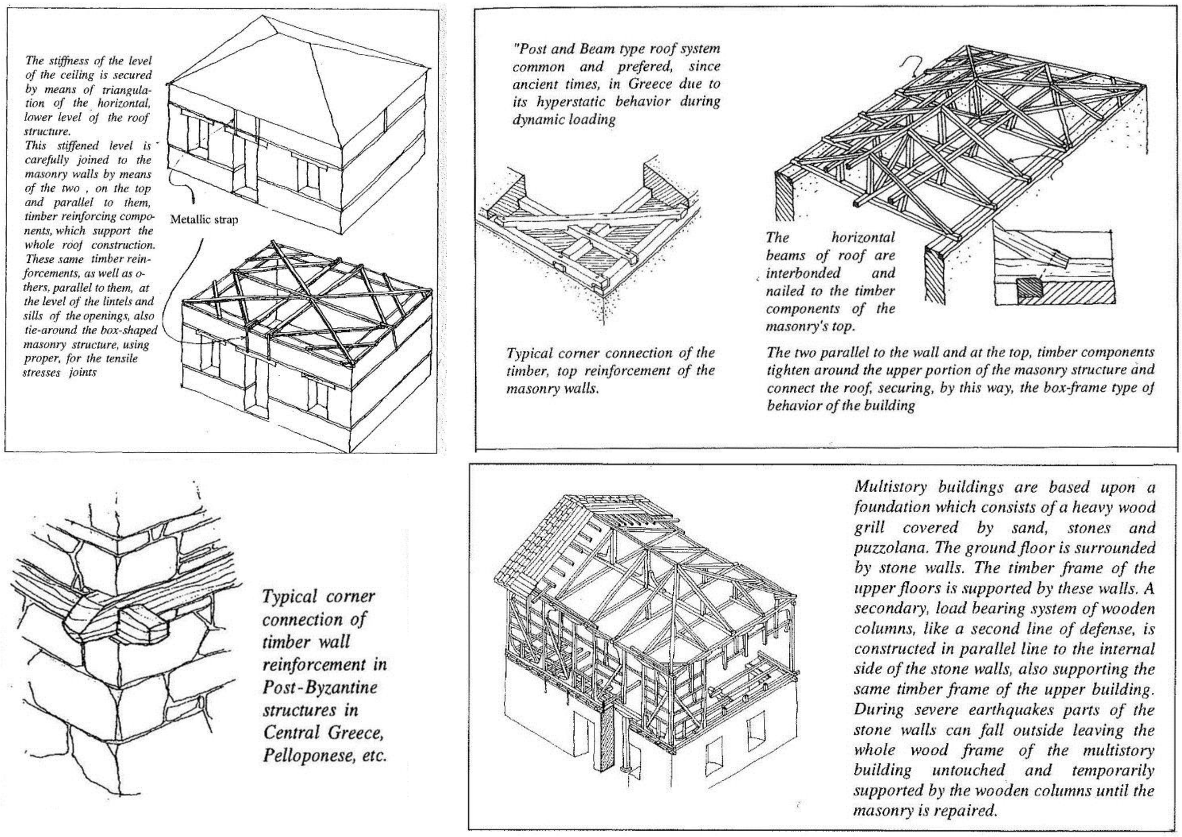

Fig. (3). Typical constructional systems of roof structures in Greece (Touliatos P., 2001, "The box–framed entity and function of the structures: The importance of wood's role." [7].

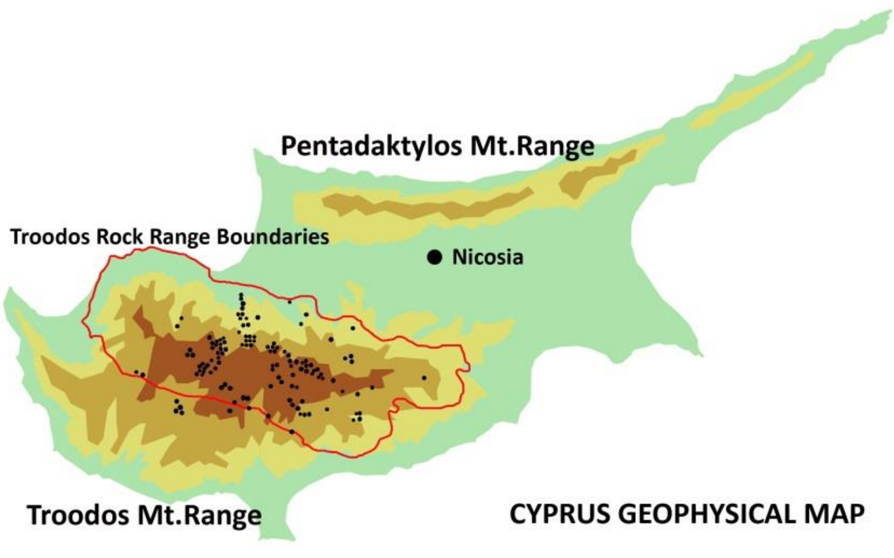

Fig. (4). Geophysical map of Cyprus, showing the boundaries of the Troodos volcanic rock zone and the location of the timber-roofed basilicas (M. Pelekanos) [13].

As mentioned above, the timber-roofed basilicas of Troodos present many similarities, as an anti-seismic constructional system, with other historical structures in the East-Mediterranean basin. On the other hand, an observer also detects many differences, in terms of their general appearance and geometrical form. For example, all Troodos' basilicas, within their horizontal base, achieve the desired stiffness by forming a rectangular- shaped structure of interlocking wooden members. No triangles are formed and the structure is not dense, as seen in other examples (Fig. **3**), leaving, in this way, the desired unobstructed view to the ceiling.

It is obvious that, because of their function as a church, the builders tried to eliminate as many horizontal wooden supports as possible within the interior space. On the other hand, they had to construct an anti-seismic structure, so they had to invent other construction methods. The Troodos basilicas' roofs achieved their horizontal stiffness by using semi-rigid joints in all connections, between the tie-beams and the linear "box-like" composite beams along the long walls. As far as their stiffness along the main axis was concerned, all basilicas used the two wooden boards' planes as diaphragms. In other cases, around the East-Mediterranean basin, this aim was achieved by adding purlins, or forming triangular shapes, along the long axis (Fig. **3**, images above right and below right). It is remarkable that these local constructional systems have been achieved to share all these common anti-seismic design principles without adopting a common form.

There are many theories and suggestions about the primary aim of this particular roof structure. Some of these opinions indicate, as an important factor that determines the steep inclination of the roof, the need to protect the churches from the heavy rain and snow in the Troodos Mountains [11]. However, this suggestion is not sufficient to explain (a) the fact that these basilicas can be found at an altitude as low as 200 meters above the sea level, and (b) the fact that at "Pentadaktylos", the second mountain range of Cyprus, not a single church of this type is found, although a great part of this range is higher than many areas of Troodos [12]. Of course, climate played a certain role in taking the primary design decisions, but it is suggested that it was not the dominant one.

A detailed study of the geological map of Cyprus reveals that there is a factor which is even more important (Fig. **4**). Most of the 130 churches are situated within the boundaries of the Troodos volcanic rock zone and only five, of all, were constructed outside, but very close to its southern boundary, almost three centuries after the first appearance of the type. Within this zone, the builders could find easily the three major and essential building materials. The first was the extremely hard local Troodos stone, which could not be shaped for use in arches and domes and was more suitable to use in simple vertical masonry. The second was the plentiful timber from the local pine forests that was used for the roof construction and the third was the volcanic red soil, used for the roof flat tiles. It is suggested that the immediate availability of these local materials, played a significant role in the evolution of this construction type.

The bearing walls of these basilicas are constructed of the volcanic stone of Troodos. The long walls, to the north and south, which bear the load of the roof, are usually short, about 2.5- 3.0 m (Fig. **5**). The west wall rises to a pointed triangular shape, up to 6 meters in single-aisled and almost 8 meters in three-aisled basilicas. To the east, there is the apse of the sanctuary, which sometimes is clearly visible from the exterior as a half of a cylinder with half of a dome on top, and in other cases, it is fully inscribed in the general rectangular shape of the church.

The openings are few, usually a main door to the west and another one, or in some cases two, on the long walls, a narrow window high up on the west wall and a small slot-opening over the apse of the sanctuary (Figs. **6** and **7**). The interior surface of the masonry is coated with plaster and, in many cases, it is decorated with high- quality frescoes (Fig. **8**). The foundations of the bearing walls are usually very shallow, and in some cases, where there is an inclined terrain, they are founded at different levels (Fig. **9**).

Fig. (5). Church of Panayia at Moutoullas village. Detail of the connection between the timber roof and the south wall (Photo M. Pelekanos).

Fig. (6). Church of Ayioi Andronikos and Athanasia at Kalopanayiotis village. West Entrance (Photo M. Pelekanos).

Fig. (7). Church of Panayia at Moutoullas village. The west entrance, now leading to the Narthex which was built at a later stage (Photo M. Pelekanos).

Fig. (8). Church of Ayios Ioannis Prodromos at Askas village. Frescoes on the interior arcade (Photo M. Pelekanos).

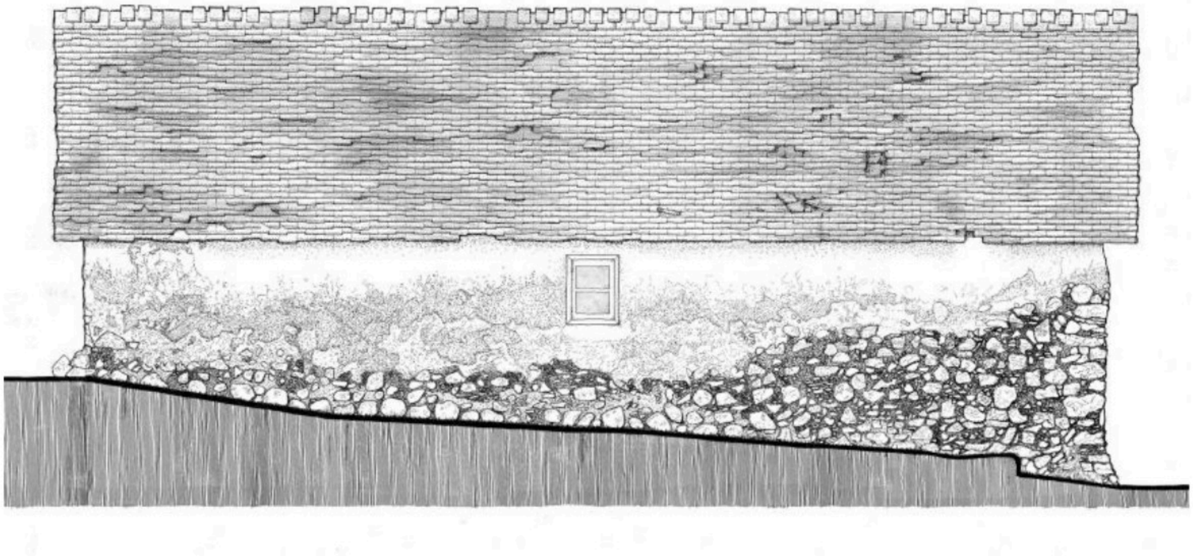

Fig. (9). Church of Ayioi Sergios and Vachos at Kalopanayiotis village. South elevation showing the inclination of the surrounding terrain [4].

2. THE CONSTRUCTION OF THE ROOF

The Troodos basilicas differ strongly from other church types in Cyprus, not only morphologically, but also due to the uniqueness of their construction system. The most impressive constructional feature of these structures is the existence of two distinctive, but cooperating, parts of the timber roof. The so-called inner roof, a triangular prism with great stiffness, distributes its static loads on the southern and northern walls. The outer roof, which carries the heavy flat tiles, is actually suspended from the inner roof, and it overhangs the two long walls, to protect their vulnerable upper part from the rainwater. In many churches, the roof covers totally the area of the sanctuary apse to the east, while to the west, the timber roof overhangs usually by 40 to 50 cm (Figs. **10-13**) [13].

The construction of the inner roof starts by placing two wall-plates along the north and south walls (Fig. **10**) (1). On these wall-plates, and at distances of around 2 meters, tie-beams with specially shaped edges (4) are connected. Between tie beams, planks in an upright position (2) are placed to keep the right distances, to fill the gap in-between and to lock the wooden members at right angles. Two square-shaped members (3) complete the composite “box-like” beams on the long walls, locking within their structure the edges of the transverse tie-beams (Fig. **14**).

Then, a series of rafters (Fig. **11**) (5) are placed every 30-40 cm, and are connected to the ridge-purlin, called “Carina” (6), at the top of the Inner Roof. At these roofs, the ridge-purlin is not a major bearing element, as in western-type roofs, as it functions more as a connector than as a beam (Fig. **15**). Several auxiliary planks (7, 9) are placed in order to close firmly the gaps of the interior cover. A small triangular-shaped wooden section (8) is slightly penetrating the upper surface of the rafters, in order to connect them firmly to the coming wooden boards, forming a slightly flexible diaphragm (Fig. **12**) (10).

The inner roof is then completed by nailing wooden boards (10) along the rafters. A special purlin (11) is nailed temporarily to the rafters, through the gap between the boards, and is supported by a series of inclined strut-supports (12). Each support’s specially-shaped lower edge is founded in a notch on every tie-beam. In this way, the heavy load of the outer roof will be distributed mainly on the strong (14 X 14 cm) transverse tie-beams.

After the completion of the inner roof, the outer roof is ready to be literally suspended from it, using the special purlin (11). External rafters (Fig. **13**) (13) are placed every 35 to 50 cm and overhang the walls by 50 to 60 cm. On top of the rafters, small purlins (14) are nailed approximately every 10 cm, to hold the flat roof tiles. Every single tile covers the lower ones by 65%, and all the joints are crossed, achieving in this way a full waterproofing of the roof. The covering is completed by placing a series of angle- shaped tiles over the top edge of the roof.

3. THE CO-OPERATION BETWEEN THE TIMBER ROOF AND MASONRY

As mentioned before, the load of the roof is totally carried, through the two composite beams, on the southern and northern walls. In relation to the maximum compressive strength of such stone walls, the static load from the roof is relatively small. Because of the seismicity of the island, the main issue is to analyze the way, in which the entire structure behaves when the dynamic load of an earthquake is applied.

It is well known that unreinforced masonry cannot resist significant dynamic loads perpendicular to their plane. In terms of vulnerability, in all basilicas, the long walls present the lower values (due to their short height, the heavy load and their direct horizontal connection to the roof). The wall to the East presents significant resistance to out of plane loads, due to the hemi-cylindrical shape of the apse.

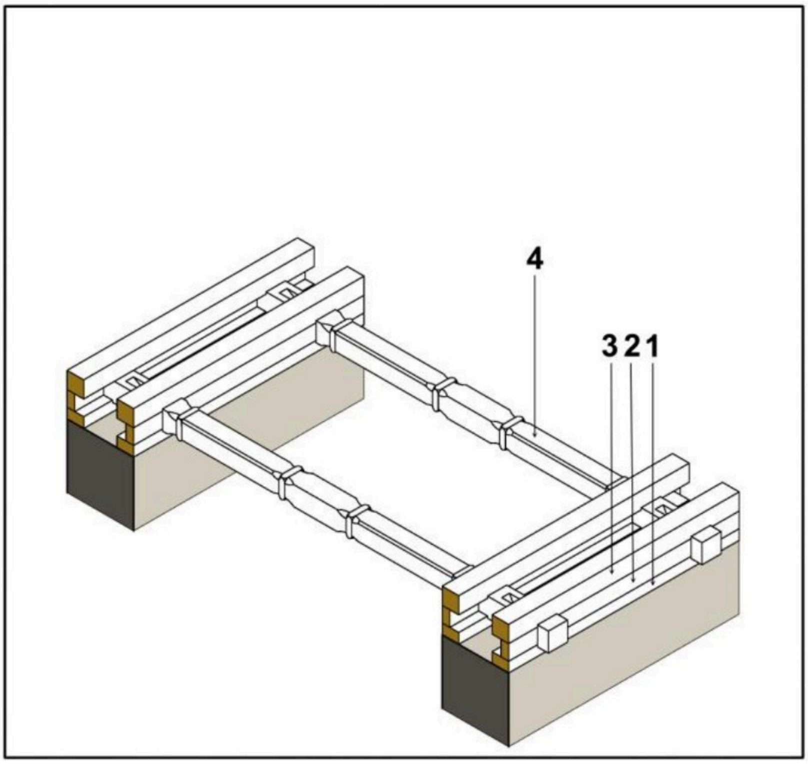

Fig. (10). Wall-plates are placed along the north and south walls (1). On these, and at distances of around 2 meters, tie-beams with specially shaped edges (4) are connected. Between tie beams, planks in an upright position (2) are locked. Two square-shaped members (3) complete the composite "box-like" beams on the long walls, locking within their structure the edges of the transverse tie-beams (M. Pelekanos) [13].

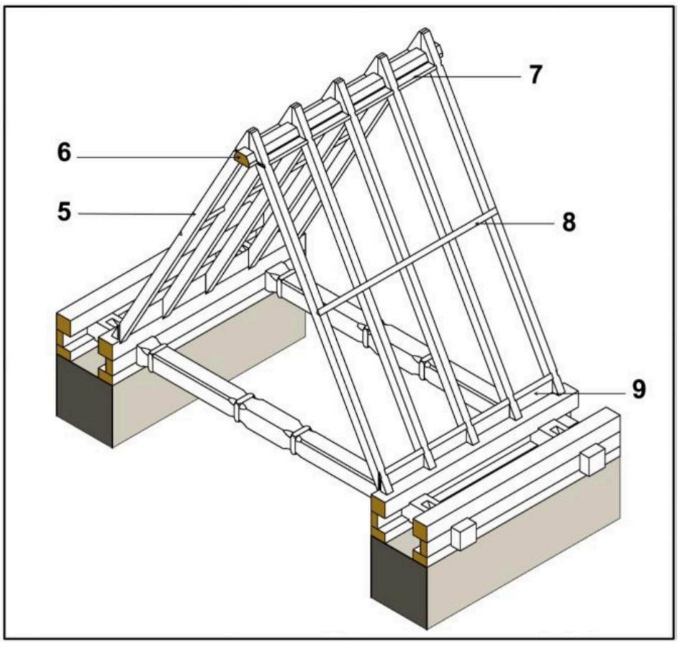

Fig. (11). Rafters (5) are placed every 30-40 cm and are connected to the ridge-purlin, called "Carina" (6), at the top of the Inner Roof. Planks (7, 9) are placed in order to close firmly the gaps of the interior cover. A small triangular-shaped wooden section (8) is penetrating the upper surface of the rafters, in order to connect them firmly to the coming wooden boards. (M. Pelekanos). [13].

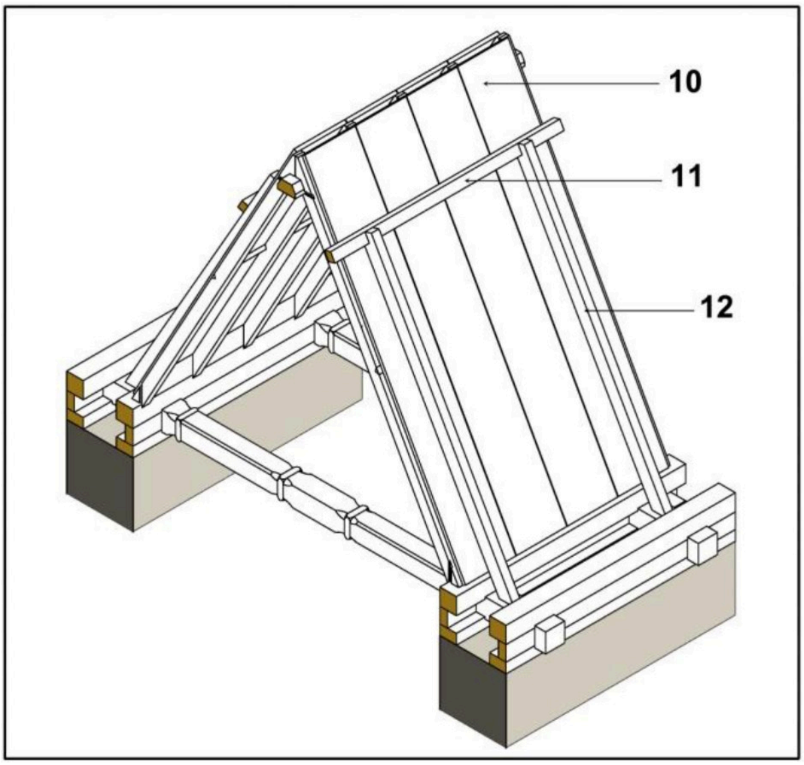

Fig. (12). The Inner Roof is completed by nailing wooden boards (10) along the rafters. A special purlin (11) is fixed to the rafters, and is supported by a series of inclined strut-supports (12). Each support's lower edge is founded in a notch on every tie-beam. In this way, the heavy load of the coming Outer Roof is distributed mainly on the strong (14 X 14 cm) transverse tie-beams. (M. Pelekanos). [13].

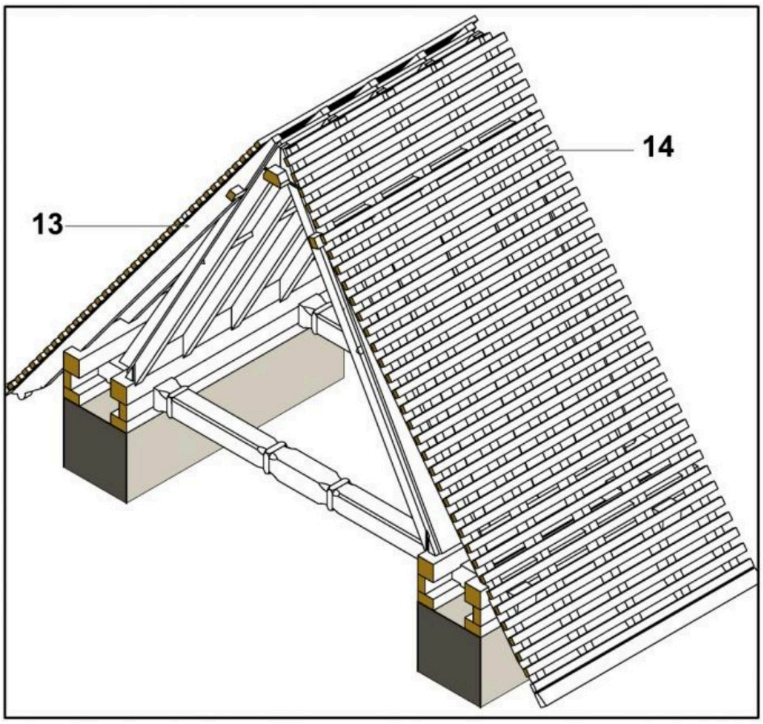

Fig. (13). The Outer Roof uses the special purlin (11) in order to be suspended from the Inner Roof. External rafters (13) are placed every 35 to 50 cm and overhang the walls by 50 to 60 cm. On top of them, small purlins (14) are nailed approximately every 10 cm, to hold the coming flat roof tiles. The covering is completed by placing a series of angle- shaped tiles over the top edge of the roof. (M. Pelekanos). [13].

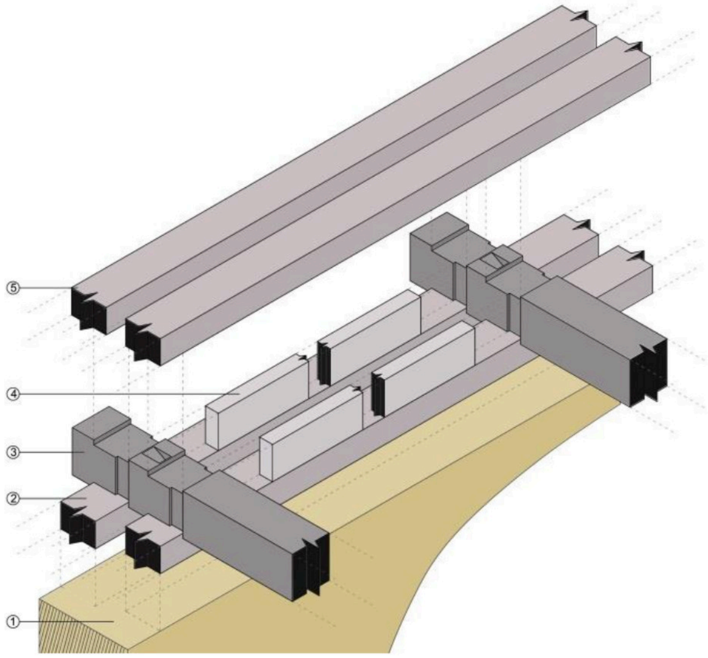

Fig. (14). Church of Ayia Marina at Filousa village (three-aisled, 17th cent.). Detail shows how the composite "box-like" beam is formed. The tie-beams are locked by three pairs of beams, without any nailing. The system stays firm due to (a) the special interconnection of all its parts and (b) the existence of the heavy loads of the Outer Roof [5].

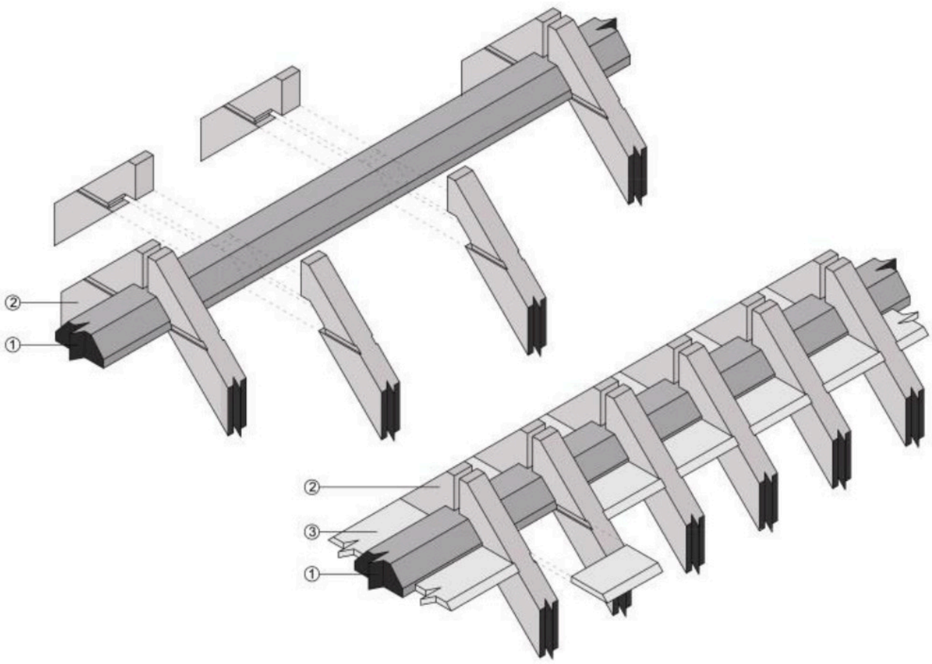

Fig. (15). Church of Ayia Marina at Filousa village (three-aisled, 17th cent.). Detail showing the construction of the highest part of the Inner Roof, where internal rafters are connected to the ridge-purlin while holding it. Planks are then placed horizontally between the rafters in order to close firmly the gaps of the interior cover [5].

It is clear that the highest value of vulnerability is presented by the western wall, because of its height, the absence of ribs, the weak connection to the roof and the lack of a significant static load over its top. To confront its vulnerability, the builders placed two tie-beams in contact with the western wall, on both the sides. Despite their certain awareness about the problems caused by the exposure of the external wooden tie-beam in severe weather conditions, the decision was considered critical, in order to achieve a full co-operation between the masonry and the wooden roof (Fig. **16**). Moreover, the pairs of tie-beams at the western and eastern end of the church form, along with the two composite beams on the long walls, a full timber circumferential binding. This structure has been well known, from the ancient and Byzantine times, as the “Imantosis” (from the Greek word “imantas” which means a “belt”).

Finally, the important role of these unique tie-beams, as far as the static load is concerned, can be clearly shown in cases, where a sudden failure of the exterior tie-beam leads to a significant crack on the masonry’s corner (church of St. Sergios and Vakhos, at Kalopanayiotis village) (Fig. **17**). As shown in the figure below, the tie-beam, exposed to severe weather conditions, has gradually decayed and finally cracked. Subsequently, the nearby masonry cracked, due to the lateral thrusts that were no longer counterbalanced by the broken tie-beam. It can also be noted that the highest point of the crack on the masonry presents the same width as the crack on the wooden beam. Probably due to an incorrect intervention in the past years, no internal tie-beam was placed in contact with the western wall, increasing in this way its vulnerability.

4. DESIGN PROVISIONS FOR AN EASY INTERVENTION AND RETROFITTING IN THE FUTURE

The design concept of the timber-roofed basilicas of Troodos incorporated, among other objectives, remarkable provisions for an easy repair intervention and retrofitting, at a later stage during their life. There are, at least, three such major provisions.

The first one is the builders’ decision to divide the timber roof into two distinct parts. It is obvious that the most vulnerable part would be the outer roof, as it is exposed directly to the weather conditions (Fig. **18**). Just a small leakage between the tiles would be enough to cause, in some years, the decay and destruction of the wooden part. The design concept to construct a constructionally distinct outer roof, gave to the builders’ descendants the way to intervene without destructing or dismantling the inner roof. One could easily de-assemble any part of the outer roof, repair the damaged part and re-assemble, without affecting the inner roof and the church’s function. In this case, there was no need for retrofitting as it was easy to replace any part by a similar one.

The second major provision was the cleverly- designed exposed tie-beams on the eastern and western walls. Their connection to the box-like composite beams of the northern and southern walls was such, that allowed their easy replacement without affecting the rest of the structure. The way the tie beam was interlocked with the composite beams allowed it to be easily “pulled out” in a horizontal movement and be replaced by an identical beam, “pushed back” into the slot in a reversed horizontal movement. Once again, there was no need for retrofitting, as it was easy to replace the damaged tie beam by a similar new one (Figs. **16** and **17**).

Finally, there was a third provision, even for a rare situation. When decay problems reached the inner roof, then the problems would become more complicated. Even in this case, the de-assembling of the damaged parts, would leave most of the remaining parts unaffected and re-usable, as no nails were used on the inner roof’s construction (except from the boards). In this case, again, the intervention would be just a parts’ replacement rather than a retrofit action.

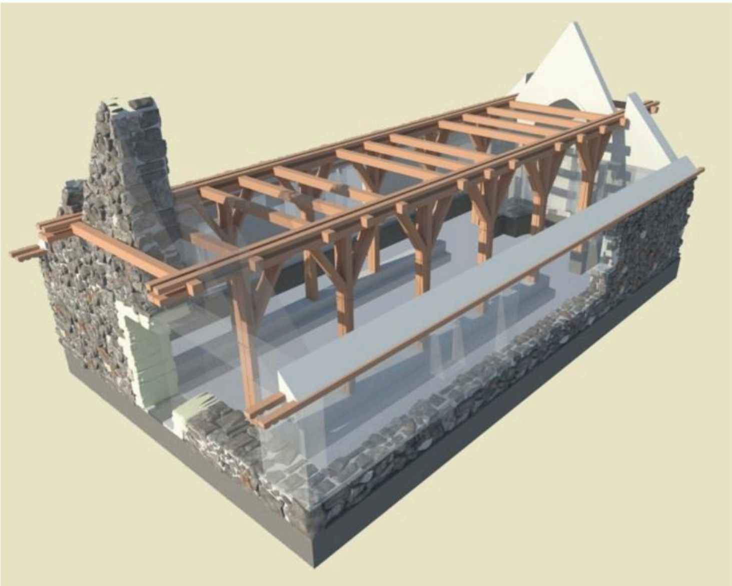

Fig. (16). Church of Panayia at Kourdali village (three- aisled, 16th century). Digital simulation showing the horizontal part of the Inner Roof, with the series of the tie-beams in the middle aisle. Two pairs of tie-beams are embracing the western and the eastern walls, in order to achieve the co-operation between the masonry and the roof. Furthermore, these two pairs, along with the two composite beams over the series of the wooden posts, are forming an “Imantosis”, a belting system, in order to achieve a “box-like” behaviour of the building during an earthquake [3].

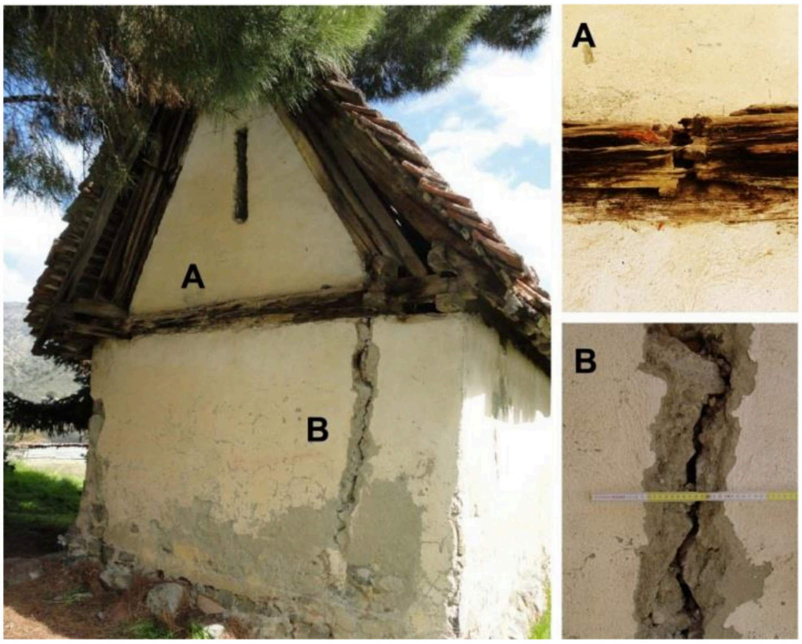

Fig. (17). Church of Ayioi Sergios and Vakhos at Kalopanayiotis (single- aisled, 18th century). The exposed tie-beam on the western wall was gradually decayed and finally cracked. Subsequently, the masonry nearby cracked, due to the lateral thrusts that were no longer counterbalanced by the destroyed tie-beam. Probably due to an incorrect intervention in the past years, no internal tie-beam was placed in contact with the western wall, increasing in this way its vulnerability [4].

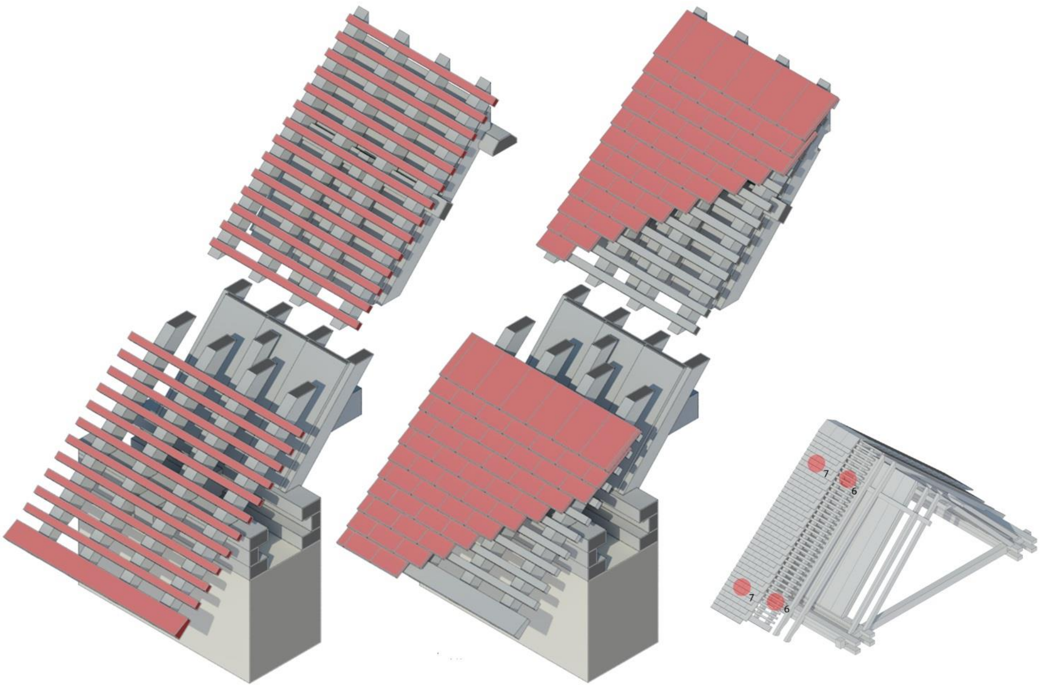

Fig.(18). Church of Panayia at Moutoullas village. 3D simulation showing the structure of the Outer Roof (with the exterior rafters, the purlins and the tiles) and its relation to the Inner Roof [6].

SUMMARY AND CONCLUSION

The wooden-roofed basilicas of the Troodos Mountain in Cyprus, built between the 15th and the 19th century, present a remarkable uniqueness, mainly because of their cleverly designed constructional system.

A thorough constructional analysis shows that most of the characteristics of this type of construction are similar to what is called an “eastern type” roof: the “box-like” behaviour of the entire structure in dynamic loads, the existence of a full circumferential binding (known as "Imantosis"), the uniform distribution of the loads throughout the whole structure, the relative flexibility of most of the connections and its hyper-static behaviour (*i.e.* alternative ways to distribute the loads when a failure occurs). All historical timber roof structures in the area of the Eastern Mediterranean Basin were constructed based on these principles, mainly to cope successfully with the frequent earthquake phenomenon.

The design of these basilicas fully adopt the principle of a uniform distribution of loads through multiple paths, and obtain their overall stiffness through numerous semi-flexible, or semi-rigid, joints. To achieve this goal, this unique roof structure was developed through the years into a particular and cleverly designed bearing system, retaining, on the other hand, a high level of simplicity in all construction details.

The design concept of the basilicas incorporated, among other objectives, a remarkable provision for an easy repair intervention and retrofitting, at a later stage during their life: (a) the easy de-assembling of the outer roof for retrofitting purposes, in order to keep the inner roof, and the interior of the church, untouched during the works, (b) the easy replacement of the important, but vulnerable, tie-beam on the exterior of the west façade and (c) the easy de-assembling and removal of almost any damaged part of the roof, that would leave most of the remaining parts unaffected and re-usable.

The timber-roofed basilicas of Troodos present, among other particular characteristics, a remarkable design provision that made intervention and retrofitting an easy task, at any stage of their future life. This unique design concept, which was invented and implemented in the past, seems to be valuable even in our days and can be easily adopted when designing contemporary modern structures with a long-term life objective.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

Not applicable.

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CONFLICT OF INTEREST

The author declares no conflict of interest, financial or otherwise.

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