PORTUGUESE "PALLADIANA" TRUSS ROOFS: CONSTRUCTIVE AND STRUCTURAL CHARATERISTICS

João S. Martins[1]*, António S. Gago[1] and Pedro Lopes[2]

1: Departamento de Engenharia Civil, Arquitectura e Georecursos
Instituto Superior Técnico - Universidade de Lisboa
Av. Rovisco Pais, 1, 1049-001 Lisboa, Portugal
e-mail: joao.sarrazola@ist.utl.pt, antonio.gago@tecnico.ulisboa.pt
web: https://fenix.tecnico.ulisboa.pt/investigacao/icist

2: Academia Militar - Portuguese Military Academy
Rua Gomes Freire, 1169-203 Lisboa, Portugal
e-mail: lopes557@hotmail.com web: www.academiamilitar.pt/

Keywords: Construction, History, Roofs, Palladianas, Wood structures

Abstract *Rafter roofs, either gabled or hipped, were the traditional way to cover buildings in Portugal until the second half of the sixteenth century. Foreign architects and engineers, who designed in the late sixteenth century some Portuguese large buildings, inspired local designers and new types of roof structures, allowing covering large spans, were adopted at the beginning of the seventeenth century. In what concerns roof structures, São Roque Church, in Lisbon, built in 1584, was one of the cases that greatly influenced the Portuguese civil engineering. The main nave of São Roque Church is 17 meters wide and the traditional roof structures were not able to overcome such span. For that, the Italian architect Fillipo Terzi based his design in a roofing structure widely used in Italy, the "Palladiana" truss roof, but until then, unknown in Portugal. This "innovation" had become known by the Portuguese architects, engineers and building masters and in eighteenth century it was used when large spans were required. From the survey carried out, apparently, only three roofs built with this type of trusses remain nowadays in the Lisbon area: the one already mentioned in São Roque Church, another one in the Cathedral of Santarém, built around 1700, and another structure in the Asilo de Inválidos Militares, in Runa, Torres Vedras, built on the early years of the nineteenth century. This paper aims to describe the constructive details of the Portuguese "Palladiana" roof trusses, the differences between the three case studies, as well as, their structural behaviour. The goal is to understand this type of structures (constructive details, connections and structural behaviour) contributing, with knowledge, to their preservation.*

1. INTRODUCTION

In Portugal, the most common type of roof structures was based on rafters. That system was used to build both gabled and hipped roofs (Figure 1) from the fourteenth century to the nineteenth century [1], and was, probably, introduced on the Iberian Peninsula during the Visigoth domination (centuries V to VIII). Since that period, the medieval rafter systems replaced, gradually, the typical Roman roofs structures, built with trusses, purlins and rafters.

Figure 1. Traditional Portuguese rafter roofs, gabled and hipped.

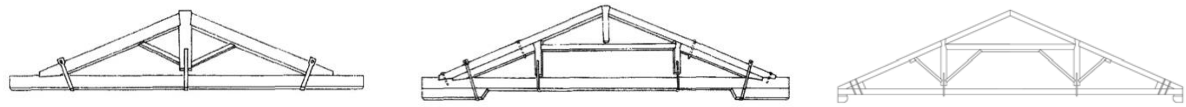
In sixteenth century, the design and erection of São Roque Church, in Lisbon, changed the paradigm of the roof structures in Portugal. For that Church it was proposed a main nave with a free spam of 17 meters and the traditional rafter roofs could not be used for such a wide church. A new solution had to be found, and the Italian architect Fillipo Terzi design a roof structure based on the single composite *Palladiana* (queen post) truss with struts. This innovation, according to an eighteenth century writer, had become very common in Portugal after the construction of São Roque Church, which was finish in 1584.

The present paper aims to describe the constructive details of the Palladiana trusses and to understand the structural behaviour of those structures, which allowed its use for long spans. Three case studies were used to support the present study: the São Roque Church, in Lisbon, the Santarém, Cathedral, built around 1700, and the Asilo de Inválidos Militares, in Runa, Torres Vedras, built on the early years of the nineteenth century. The differences between them, in what concerns dimensions, joint and other details are presented aiming to contribute to the preservation of those structures, as well as, any other that may still exist, but have not been referenced yet.

2. PALLADIANAS

The *Palladiana* truss, although was already used before the Italian architect Andrea Palladio (1508-1580), got its name due to the extensively use of that roof structures by Andrea Palladio. The name *Palladianas* was adopted to differentiate these type trusses from the king post trusses with struts (Figure 2.a)). The main characteristic of the *Palladianas* trusses, sometimes called *Queen Post* trusses, are: two rafters, connected at their bases to a tie beam; a collar beam at approximate two thirds of the height of the truss; and two queen posts. Another particular characteristic of these trusses is the under-rafter, connecting the tie beam to the queen post. Sometimes they also have a king post (Figure 2.b)).

According to the studies carried out by Valerianni [2], this kind of trusses was used for spans until 14 meters. For wider spans another type was used: the *double palladiana*, were two trusses are assembled very close to each other. Valerianni also mentions [2] that, according to authors from the seventeenth and nineteenth century, the slope of those structures should be from 19º to 23º.



a) b) c)

Figure 2. Traditional Italian trusses: a) Truss with king post and struts [2]; b) Simple *Palladiana* [2] c) Composite *Palladiana* [4].

According to Tampone [3], additional elements, such as struts and king posts, began to be used after the renaissance, on the seventeenth century. The composite *Palladiana*, with four struts, which was used in São Roque Church, is one of those cases, and can be seen as an evolution of the traditional *Palladiana* [4].

3. PORTUGUESE PALLADIAN ROOFS

From the survey carried out by the authors, apparently, only three roofs built with this type of trusses remain nowadays in Portugal: the one already mentioned, in the São Roque, Church (Figure 3.a), in Lisbon, another in the Santarém Cathedral (Figure 3.b), built around 1700, and another structure in the Asilo de Inválidos Militares - Runa Military Asylum (Figure 3.c), in Runa, Torres Vedras, built on the early years of the nineteenth century.

a) b) c)

Figure 3. a) São Roque; b) Santarém; c) Runa.

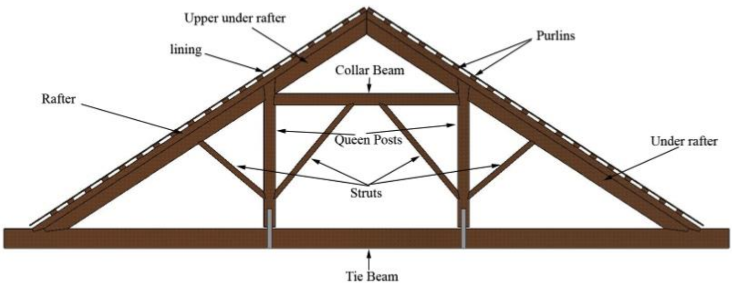
3.1. Church of São Roque, in Lisbon

São Roque church was the first case in Portugal where *Palladiana* trusses were used in a roof structure. In this case, twelve *Palladiana* composite trusses, spaced by 3.60 meters, were designed to cover a span of more than 17 meters.

Although an Italian inspiration is indisputable, a few differences from the typical

Palladiana trusses can be easily noticed. First, the slope angle, which is of 33º, is different from the angles (19º to 23º according to Fontana in 1694, cited by Valeriani [2]) of the Italian trusses. Furthermore, in São Roque Church was used an upper under-rafter, apparently not used in Italy. The introduction of struts in the São Roque Church trusses appears to be an innovation, since it was not used in the sixteenth century *Palladiana* trusses. Finally, the use of single *Palladianas* in such a wide span, might also be an innovation, since in Italy, at least in Rome [2], *double Palladianas* were used for spans larger than 14 meters.

The São Roque Church roof structure is composed by twelve trusses, separated between them by, approximately, 3.60 meters. The trusses are 20 metres wide, with an approximate height of 6.80 meters (Figure 4 and Figure 5) and are connected between them by 38 purlins. The dimensions of the structural elements can be seen in the table showed in (Figure 4).



Structural Elements	Width b [m]	Height h [m]
Tie-beam	0.35	0.44
Queen-post	0.40	0.35
Rafter	0.35	0.20
Under-rafter	0.35	0.35
Upper under-rafter	0.35	0.35
Collar-Beam	0.35	0.35
Strut	0.15	0.30
Purlins	0.11	0.17

Figure 4. São Roque Church: truss with the terminology used on the present paper and sections of its elements.

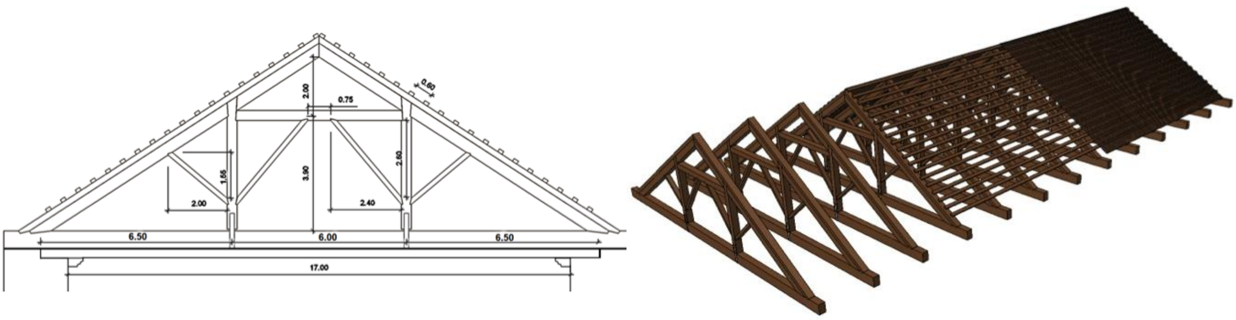


Figure 5. São Roque Church: dimensions of the truss and 3D model of the roof.

To build this roof, the wood had to be imported [5] since there was no available wood in Portugal. Each tie-beam is made from just one piece of wood, 22 meters long, and in the Portuguese forests it was not possible to find trees of this size. Despite the absence of written documentation about the kind of wood used in the execution of trusses, visual analyses indicate that the species is, probably, Larch (*Larix deciduas*).

To connect the upper under-rafter and the collar-beam to the queen posts, a kind of *mortise and tenon joint* was used, ensuring that the connection does not move. Between the queen post and the under rafter, apparently, no such joint exists, so the top of the under-rafter appears to be only resting on a cut done on the collar-beam (Figure 6 and Figure 7).

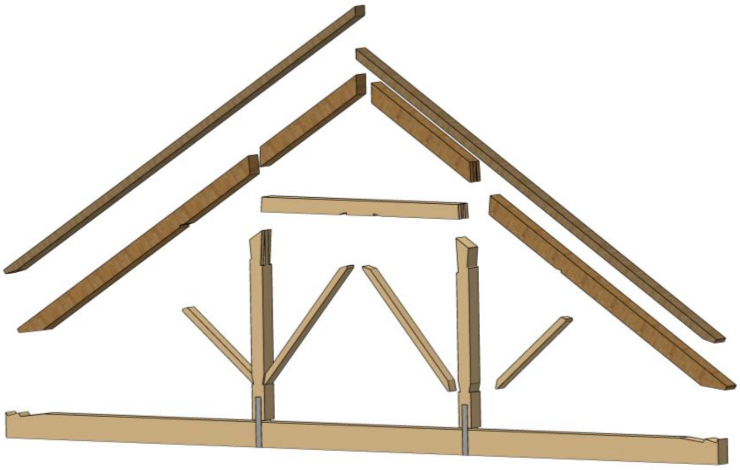


Figure 6. São Roque Church: Exploded view of the truss.

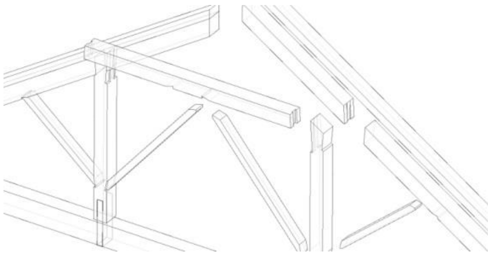
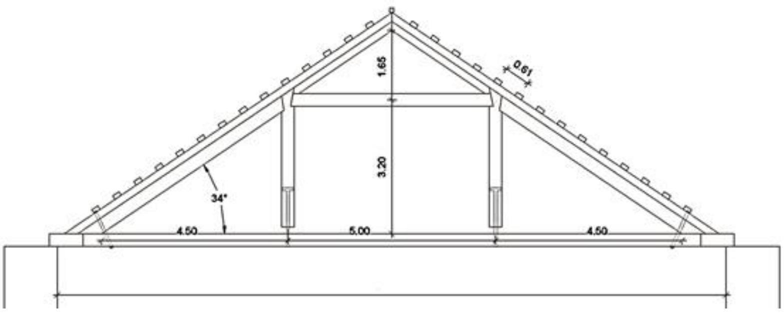


Figure 7. São Roque Church, connection details.

3.2. Cathedral of Santarém

Cathedral of Santarém was built in the end of the seventeenth century, being completed in 1711. Its roof structure is quite similar to the one built in São Roque Church, except for the struts that do not exist in the Santarém structure, probably due to its smaller span. The span of Santarém Cathedral in about 14 meters and the roof structure is made with 10 trusses, separated between them by 3 meters (Figure 8). As in São Roque Church, the slope angle of the roof is, around, 33º.



Structural Element	Width, b [m]	Height, h [m]
Tie-Beam	0.30	0.30
Queen Post	0.30	0.30
Rafter	0.30	0.18
Upper under-rafter	0.30	0.18
Under-rafter	0.30	0.30
Collar-beam	0.30	0.30
Purlins	0.18	0.15

Figure 8. Santarém Cathedral: dimensions of the truss and sections of its structural elements.

It must be mentioned that in Santarém, as it happened in São Roque Church, it was used an upper under-rafter, apparently not used in Italy (Figure 9). However, although being very similar to São Roque´s roofing structure, a big evolution regarding the joints (Figure 9) can be identified in Santarém roofing structure. The under rafters, the collar beam and the queen-posts, are, in this case, safely joined through a complex system of notches (without nails), not allowing any movements.

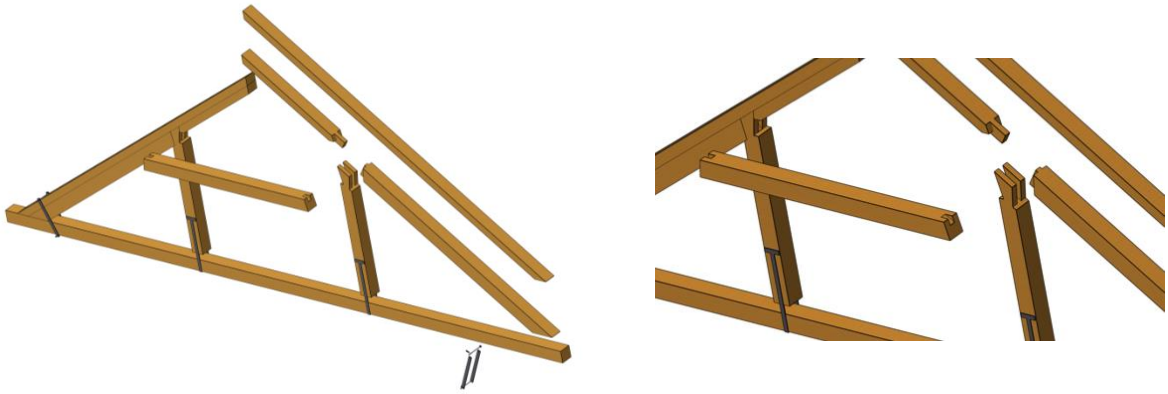
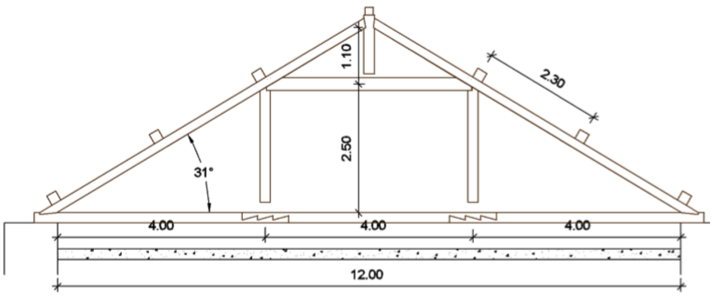


Figure 9. Santarém Cathedral: Exploded view of the truss and connection details.

3.3. Runa Military Asylum

Runa Military Asylum was built on the early years of the nineteenth century. Its roof structure is similar to the one built in Santarém Cathedral, with a smaller span, about 12 meters. The roof structure is made with trusses with a slope angle of 31º, separated between them by 3.5 meters (Figure 10).



Structural element	Width b [m]	Height h [m]
Tie-beam	0.20	0.20
Queen-post	0.20	0.20
King-post	0.20	0.15
Rafter	0.17	0.17
Collar-beam	0.15	0.25
Purlin	0.20	0.20
Common Rafter	0.10	0.10

Figure 10. Runa Military Asylum: dimensions of the truss and sections of its structural elements.

The roofing structure of Runa Military Asylum is the simplest of the three presented on this paper. However, is the most interesting case due to the fact the structure was built in modules (Figure 11), which means that a pre-fabricated scheme was used. It must be mentioned that prefabrication schemes were not a novelty in the Iberian carpentry at that time. Instead the prefabrication was used in Iberian Peninsula, at least, since the fifteenth century.

Unlike the previous cases, Runa structure has a king-post and no under-rafters were used. In this roof structure the tie-beam was made by three segments, connected by means of a joint able to support tensile axial stresses. The tie-beam was the first element put in place. After that, the rafters were lifted the queen posts joined to them and last element, the collar-beam, connected to the structure. In this structure the elements were connected by joints with a complex detailing which were, in this case, reinforced by metallic nails.

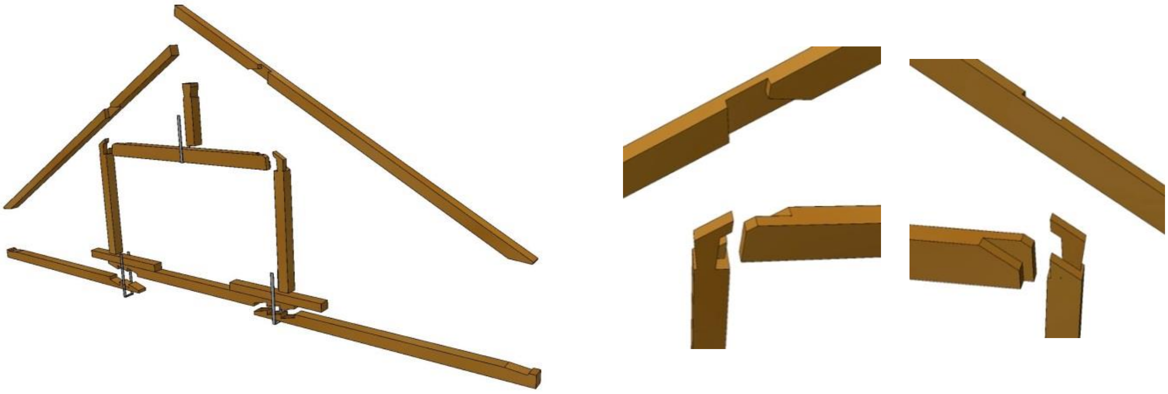


Figure 11. Runa Military Asylum: elements of the trusses and detail of the joints.

After the assembling, each truss was connected to the neighbours' trusses by purlins with a length equal to the distance between consecutive trusses (Figure 12).

Figure 12. Runa Military Asylum: 3D model with the assembling order.

4. STRUCTURAL ANALISIS

In the present study the structural behaviour of the previous three roof structures was modelled using 2D linear elastic finite element models (Figure 13). Dead loads were quantified considering typical values for materials self-weights (Table 1). Live loads and wind loads were computed considering the recommendations of Eurocode 1, parts 1.1 and 1.4 [6]. The seismic load was not considered at this stage of the study. The loads combinations were defined according to Eurocode 0 [7] and the partial safety factors, as well as, the safety assessment, were done following Eurocode 5 [8].

The structural safety assessment was performed considering the ultimate limit states of tension, compression, bending, shear, combined bending and axial tension, combined bending and axial compression and buckling. For the serviceability limit states the assessment was performed by comparing the instantaneous and final deformations against to the Eurocode 5 limits.

A visual survey was enough to understand the nature of the wood in each case. The woods used in the trusses were the European Larch (Larix Deciduas) in São Roque Church, the Pitch Pine (*Pinus Rigida (caribaea)*) in Santarém Cathedral, and the Cedrus (maybe *Cupressus lusitánica*) in Runa Military Asylum. It was not possible to perform *in situ* or laboratory tests to characterize mechanically the wood. Instead, a bibliographic survey was performed and typical values of strength were found for the mentioned types of wood. For São Roque Church it was assumed for the trusses a wood strength class C30, for Santarém Cathedral, a wood strength class C24 and for Runa Military Asylum, a wood strength class C20/30.

Dead Loads		[kN/m^2]
Roof	Tiles, lining and common rafters	1.45
Floor	Wood planks	0.5
Ceiling	Wood lining	0.6

Table 1. Dead Loads – 2D Finite Element Model

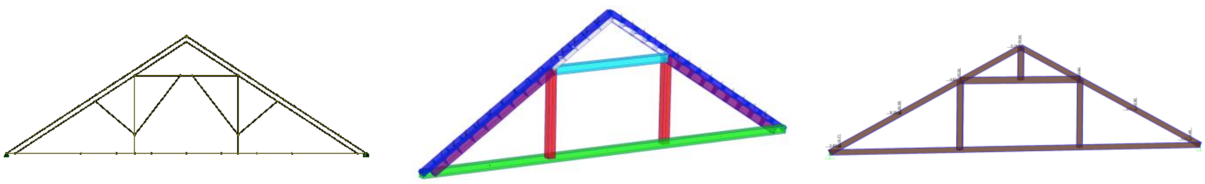


Figure 13. 2D elastic linear Finite element models – São Roque Church (left), Santarém Cathedral (center) and Runa Asylum (right).

From the finite element models it can bee understood that in *Palladiana* trusses the rafters and the collar-beam work in compression and the tie beam and the queen-posts in tension (Figure 14).

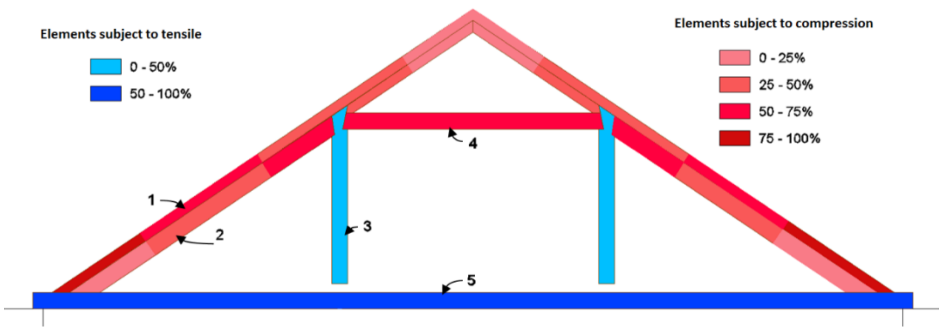


Figure 14. Palladian truss - Qualitative diagram of axial forces.

Considering the loads and the loads combinations established in Eurocodes 0 and 1, the forces, stresses and displacements obtain through the finite element models, the safety factors and the safety verifications required by Eurocode 5, it must be mentioned that in the cases of São Roque Church and Santarém Cathedral, the safety is satisfied in both limit states: ultimate and serviceability [9]. Although some inaccuracies could have been done in the quantification of the strength parameters, it is remarkable the fact that those ancient structures satisfied the exigent safety checks of Eurocode 5.

However, unlike previous cases, the truss roof of the Military Asylum Runa does not verify the safety in 3 of the 8 ultimate limit states required by Eurocode 5. Furthermore, in what concerns the serviceability limit states, Runa Military Asylum trusses do not satisfy the deformation limits in the rafters.

The difference between the previous cases is due to the section of the rafters. In São Roque Church and Santarém Cathedral an under-rafter was used in the trusses, which increased the rigidity and the strength of the rafters. In the case of Runa Military Asylum that extra element was not considered, which resulted in the non-fulfilment of the safety requirements.

5. CONCLUSIONS

Since the sixteenth century, after the construction of São Roque Church, in Lisbon, *Palladiana* trusses were commonly used in the roofs of Portuguese Churches and other large span buildings. Some innovations can be found in São Roque Church comparatively to the traditional (Italian) *Palladiana* trusses of sixteenth century, namely the introduction of struts, the use of single trusses for spans larger than 14 meters and the upper under-rafter element. Those innovations were replicated in the subsequent constructions (e.g. in Santarém Cathedral) and some other adaptations were tested successfully. The prefabrication of the structural elements is one of those novelties that were tested in some Portuguese roof structures (e.g. Runa Military Asylum).

The detailing of joints has been developed since the first case, São Roque Church, and complex joinery systems, where the use of nails could be excused, were developed by the Portuguese carpenters.

It is supposed that some innovations have occurred, simultaneously, a bit throughout Europe, so it is not to exclude in the described developments influences from other European carpentry school. However, the authors did not find references to other contemporary European roof structure where the described elements and details have been used.

The structural safety of the three case studies, the roof trusses of São Roque Church, Santarém Cathedral and Runa Military Asylum, was studied by 2D finite elements models. The current standards, Eurocodes 0, 1 and 5, were followed in the loads computation and safety assessments. Although some inaccuracies could have been done in the quantification of the strength parameters, it is remarkable that São Roque Church and Santarém Cathedral structures satisfied the exigent safety checks of Eurocode 5.

However, the Runa Military Asylum, where the structure does not have the upper under-rafter, does not satisfy the safety checks. A reinforcement solution with the inclusion of struts and the reinforcement of the tie beam (Figure 15) it is one of the possibilities.

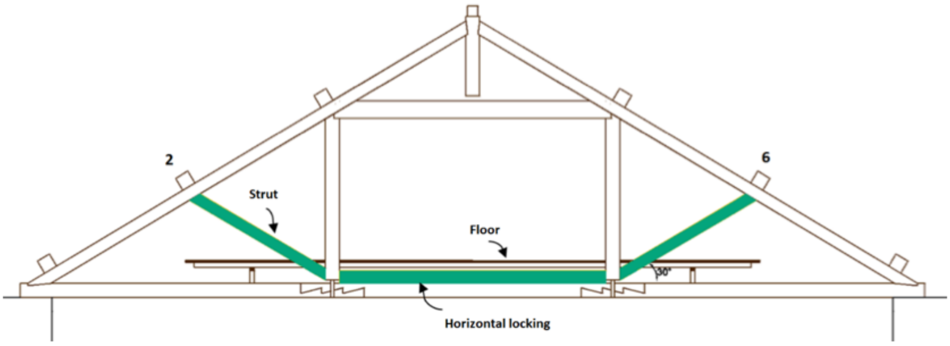


Figure 15. Runa Military Asylum Palladian truss - Strengthening Proposal.

REFERENCES

[1] J. Sarrazola Martins, A.Sousa Gago, J. Caldas, "Roof and Ceiling wood structures in Portuguese churches from the fifteenth to the seventeenth century: constructive characterization and comparison with the Spanish structures". In Proceedings of the 8th International Conference on Structural Analisys of Historical Constructions, SAHC2012. Wraclaw, Poland, 2012.

[2] S. Valeriani, "Historic carpentry in Rome", in Proceedings of the First International Congress on Construction History, Madrid, Spain, 20th-24th January, 2003.

[3] G. Tampone, "Coverings of the Italian Architectural Heritage", Online. 2005. Availble in WWW:<URL:http://www.european-wooden-religious-heritage.org/intermediate-meeting/collegio-ingegneri/coverings-italian-arch-heritage.asp>.

[4] G. Bettiol et al., "Structural analysis of the timber roofs of the “Arsenale” of Venice". In Proceedings of the 10th World Conference on Timber Engineering, Miyazaky, Japan, June 2-5, 2008.

[5] B. TELLES, "Chronica da Companhia de Iesu na prouincia de Portugal", ed. Paulo Craesbeeck, Lisbon, Portugal, 1644.

[6] EN 1991, Eurocode 1 - Actions on Structures.

[7] EN 1990, Eurocode 0 - Basis of structural design.

[8] EN 1995, Eurocode 5 - Design of timber structures - Part 1-1: General - Common rules and rules for buildings.

[9] P. Lopes, “Estudo Comportamental de Asnas de Cobertura Palladianas- Casos de Estudo da Igreja de S. Roque, Sé Catedral de Santarém e Asilo Militar de Runa”, IST, Lisbon, Portugal, 2014.