Extended Abstract

Behavioral Study of *Palladian* Roof Trusses

Case studies of the S. Roque's Church, Santarém's Cathedral and Military Asylum of Runa

Pedro Filipe Garcia Lopes

Military Academy & Instituto Superior Técnico, Universidade de Lisboa

October 2014

Abstract

Nowadays there are innumerable traditional trusses, built since the 16th century that have lasted until today. They can be found in the roofs of buildings which have a great historical and cultural value. One of these kinds of trusses, is called *palladian* truss, thought and built in Italy in the 15th century, which rapidly spread throughout Europe by the hand of architects and carpenters, including Portugal. The present study aims to study the structural behavior of this type of truss using the Eurocode 5, part 1-1, so that it can be possible to functionally characterize its elements. The study is based in three case studies of this type of truss. They were made in different centuries and have different characteristics which enable us to point out their most important elements and their function, thus opening the horizon to future interventions of rehabilitation and reinforcement of this kind of structure.

Keywords: Timber Structures, Timber roofs, Eurocode 5, *Palladian* Trusses

1. Introduction

Early in mankind's history has timber played an important role in man's evolution. It served as a hunting tool, allowing him to overcome obstacles thus providing him with mobility and the power to discover new locations. Timber provided man shelter in huts, which became known as the first roof structures. Early timber was used as a structural element and hence the need for the understanding of its physical characteristics and mechanical properties for the correct conception and construction of safe and long lasting structures. Nowadays the design of these structures is made according to the Eurocode 5, combined with the EN338[1] and EN1912[2] standards tracking timber from its origin until its final destination in buildings, making it a material susceptible of being structurally characterized.

---

[1] Strenght classes

[2] Establishes the correlation between strength classes and the assignment of visual grades and species

In this work the study of timber roofs will be developed, more accurately the study of *palladian* trusses. This kind of structure arrives in Portugal from Italy in the 15th century and appears due to the need to build roofs with increasingly bigger spans and to add loads along the slope. This kind of roof with specific elements and geometry appears in some Portuguese roofs, hence the need to undertake a survey of its structural behavior, which may enable the recovery and rehabilitation of some of them, knowing in advance the functions of each of the its constituent elements.

In order to characterize the behavior of these elements, we will follow the EC5 part 1-1: *General – Common rules and rules for buildings,* we will make a bidimensional analysis of the structure, analyzing in three case studies this type of roof: the S. Roque's Church in Lisbon, Santarém's Cathedral and the building of the Military Asylum of Runa. Timber has characteristics that make it a very advantageous material at the structural level and even though its use has decayed with the introduction of concrete and steel, the cultural heritage it gave us is huge, what makes it a material under constant study but with few qualified technicians, who haven´t been able to increase its usage in structures.

Allied to the timber's strength and unique characteristics of an organic material, which is easily obtained, is the low environmental impact, low energy cost and low levels of pollution. These factors may become decisive when you think of timber nowadays, since its study becomes indispensable not only for the rehabilitation of old structures, but also to introduce it in new buildings.

2. Timber's historical evolution as a structural material

Timber as it is stated in the dictionary is an organic material, compact and hard, formed by the tissue of woody plants, resistant and light what makes it a propitious material to use in construction. This is a fibrous structured material, formed by fibers which are one direction orientated and that means that it also has different properties depending on the direction which is being studied. The directions of the grain are: direction of the grain or longitudinal, perpendicular to the grain or transversal and radial direction. Timber is classified by the former characteristic, as an anisotropic and heterogeneous material, which enables it to have such a particular behavior. In addition to these properties, it has other physical properties, such as the water content and hygroscopicity[3]; bulk density, retractility, and the reaction and resistance to fire. As for the mechanical properties, the tensile and compression strength, the bending strength, the cut, stiffness, fatigue and creep strength (Negrão & Faria, 2009) should be highlighted. These properties are influenced by the botanical species, the location within the wood, the humidity, the density and the defects that it has.

---

[3] Material with the ability to absorb water from the air (contraction), and release water by evaporation (retracts) according to the temperature changes and the partial pressure of the water vapor of the surrounding environment, achieving thus a hygroscopic balance with it.

In what concerns the structural behavior of timber, when it is subject to tensile a fragile crack occurs where the behavior of the material is almost linear to the crack, figure 1 shows a generic element of timber subject to compression where the same doesn´t happen, since the compression is associated to the crushing of the fibers. In the graphic it is visible the elasticity area where the material reveals the elasticity behavior. In this area it starts out as a linearity in the timber behavior, where the load is directly proportional to the deformation. When the carrying load is increased we reach the limit of proportionality, from that on the deformation increases with the increase of the load, but not in a proportional way. If the load value continues to increase the timber will have a plastic behavior, until the maximum load capacity is reached, causing the material to reach the yielding point and therefore collapses.

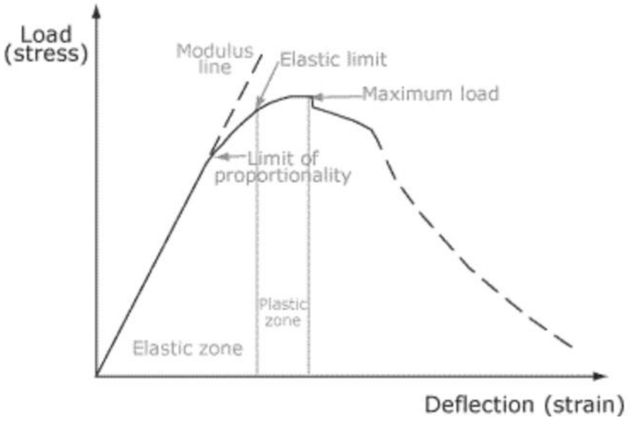


Figure 1 - Timber behavior and the relationship between load and displacement - Martins 2010

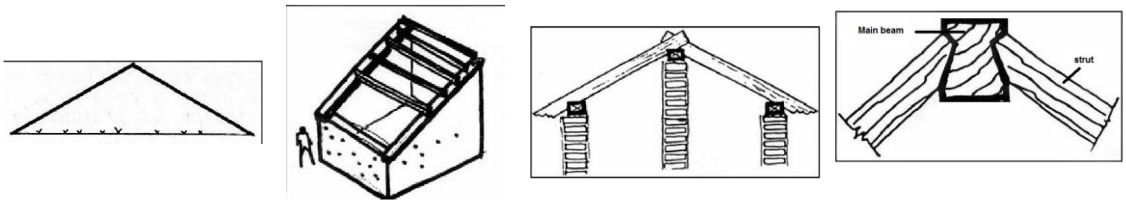
In the 9th and 10th chapter of Vitruvius's second Book - *De la madera y del Abeto superior y inferior* of his work De Architectura, we find references to timber, in it he recommends the selection and cut the timber in the beginning of autumn and the beginning of spring. This cut should be preceded of the seasoning of the timber through an incision which allows the sap to come out.

Due to its abundance in nature it was the first material used by man (Scala, 1895). Since the prehistory it was always been a guarantee of survival, enabling the construction of shelters and hunting tools. It was through the pole and log that it was possible to overcome spans, cover spaces that replaced the caves and provide man with more mobility. It was then that the first concept of beam appears, so simple as the trunk of a tree that was used to cross a brook (Mateus, 2007). It is with timber that the art of building houses appears and also the art of construction. In what concerns timber structures and in particularly timber roofs, timber was worked precisely by carpenter masters, whose art became professionally recognized by the romans through their drawings of bridges, roofs, lifting devices, centring amongst others.

2.1. Evolution of timber roofs

The timber trusses are elements that are considered fundamental in roofs for as nearly as two thousand years, since ancient Greece. It is not possible to describe exactly when the first truss appeared as a roofing structure, but the oldest in existence dates from the 6th century and appears in Saint Catherine's Monastery in Mount Sinai in Egypt, this is a simple timber truss (Cabo, 1996).

The initially built roof is called simple roof, (Osa, 2009), with only two sloping jack rafters and linked at the top (figure 2a), afterwards in Egypt in 3000 B.C. (Oliveira, 2009) the roofs with purlins appear; formed essentially by plam-tree trunks that connect both walls (figure 2b). Afterwards in buildings in Greece and Babylon appears the so called *Purlin and Rafter Roof* (Bluteau, 1712) (figure 2 c). In ancient Greek, already in the Classical period appears the a jack rafter truss and beam truss, also known as *"asnaria"* (Martins, Gago, Caldas, & Oliveira, 2013) in which the main wall is replaced by a top beam (figure 2d) which splices the two jack rafters, which makes it possible to increase the free span of the building to the double.



a) b) c) d)

Figure 2 - Evolution of timber roofs - adapted from Osa, 2009

In the Visigoth period appears in the Iberian Peninsula this kind of roof and it is characterized by the longitudinal locking which is insured by the lining, which means that there isn't a top beam, and the union of the *jack rafters* is made by a halving joint.

The suppression of the central wall implies the introduction of axial forces on the jack rafters, and this is one of the reasons that led to the truss that solves the problem of the axial forces in the supports of the jack rafters, though the introduction of a binding element, thus avoiding the passage of horizontal forces to the walls, figure 3.

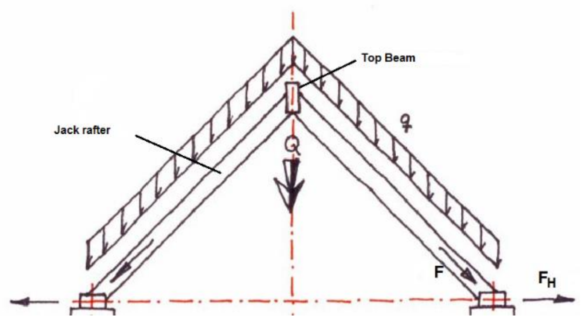


Figure 3 - Diagram of load and resulting forces - adapted from OSA 2009

Another problem is the bending of the jack rafters and the first way to solve this problem was to introduce an horizontal bar that connected the jack rafters, roughly in its half way. This element, which would be named straining beam works essentially at compression, allowing the bending stresses to diminish, reducing the effects of the roof load and the wind action; and originates the straining beam truss. Later, as a way to solve the force F_H, the concept of tie beam is used for the first time, as a piece that resists to tensile stresses, absorbing completely the resulting horizontal force.

The first timber trusses are born in the renaissance. Invented by the romans, they are self-supporting roofs of triangular section and with them appear the first treatises about timber structures, mostly about roofs. This took place mostly in Italy, were the majority of the treatises were based on the work of Vitruvius (Sánchez, 2006), written by authors such as Alberti, Serlio and Palladio.

2.1.1. *Palladian* Truss

Among the roof structures that were mentioned above, the *palladian* trusses, owe its name to Andrea Palladio, even though they existed before him, because he used them intensively in his works. These roofs are used throughout Europe until the modern age in the 18th century, when the metal connections and iron tie beams were introduced thus creating the *Polanceau* truss. The base structure of the *palladian* truss is shown in figure 4. In this kind of roof the knots are also an essential part, because they establish the connection of the elements by splicings or joints.

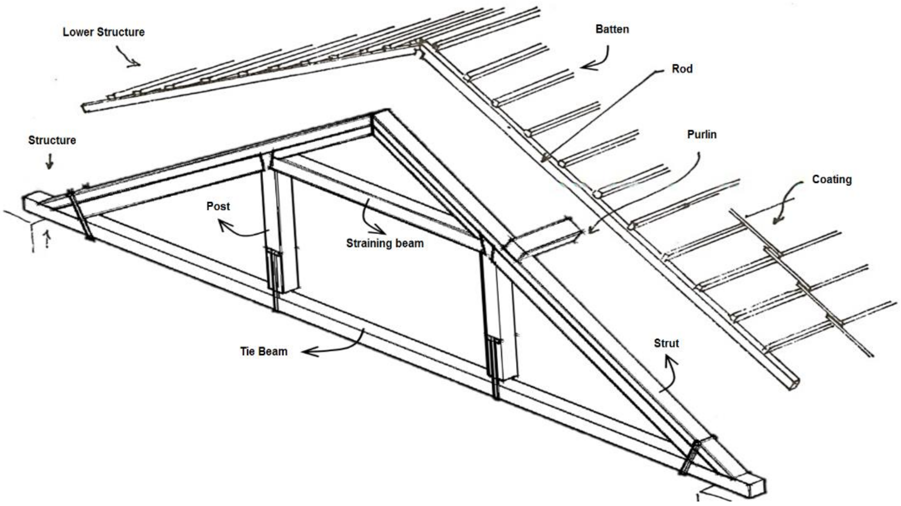


Figure 4 – Example of the *palladian* truss

Finally, the kind of truss depends on the kind of building, the span that needs to be overcome, the overloads, the admitted solicitations, the kinds of support and the nature of the buildings structure (Osa, 2009) and since timber is a highly strength and durable material it is an excellent solution to roof structures, since the trusses use the resistance ability of the woody materials mainly to tensile and bending strength (Cabo, 1996).

3. Structural Security Assessment in Timber Roofs

Nowadays people use regulations and norms approved by the European Committee for standardization (CEN), which aims at ensuring that the structure project is standardized at the European level, through the enforcement of Eurocodes. In order to perform the structural security search on timber trusses the following regulations will be taken into account:

- EN 1990-1-1-2002, Eurocode 0 - Part 1-1 – Basis of structural design;
- EN 1991-1-2003, Eurocode 1 - Part 1-1 – General actions;

- EN 1991-1-4-2005, Eurocode 1 - Part 1-4 – General actions - wind actions;
- EN 1995-1-1-2004, Eurocode 5 - Part 1-1 –Design of timber structures, general-common rules and rules for buildings.

Briefly the structural searches, the ultimate limit states and the serviceability limit states, guarantee not only the structure's stability but also the limits and damage control, following the calculation methodology based on the data collected from the material and the quantification of the actions on the structure. With these we form combinations of actions to obtain the final forces on the elements, using a calculation model specific to each structure in analyses and using afterwards the automated calculation program SAP 2000®, that analyses and calculates the distribution of the forces made by elements through a linear analysis. We take into account a permanent duration class and a factor k_{mod} associated to 0.6, service class is 1, and the quantification of the permanent actions, G, overload Q_1 and wind action, Q_2 are made by the partial coefficients method, using load combinations.

Since the loads act on the structure always in the direction of the timber grain, we will only perform security searches in this direction, which include for the ultimate limit states the assessment of the tension [1], compression [2], bending [3], shear [4], combined bending and axial tension [5], combined bending and axial compression, [6] and buckling [6.1], and for the serviceability limit states the search of instantaneous deformation w_{inst} and final w_{fin}.

4. Case Studies

In order to be able to develop and analyze the evolution in the construction methods and the kind of behavior of the *palladian* roof trusses, we shall study three roofs with this typology but from different ages. The first built in the 16th century is the nave of S. Roque's Church in Lisbon (figure 5a), the *palladian* truss consists of struts and has an approximate span of 19 meters. The second case is the nave of the Santarém's Cathedral (figure 5b), built in the final of the 17th century, with a lesser span of about 16 meters and is classified as composed *palladian* truss. Finally, the case of the building of the Military Asylum in Runa (figure 5c) built between the late 18th and the beginning of the 19th century. In this case we have a simple *palladian* truss with a 12 meter span.

a) S. Roque's Church b) Santarém's Cathedral c) Military Asylum in Runa

Figure 5 – Case studies

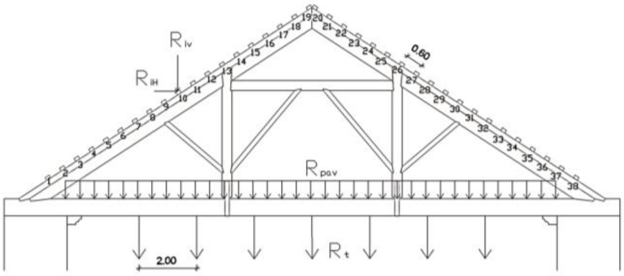
4.1. First Case study – S. Roque’s Church in Lisbon

The S. Roque Church’s roof, a composed *palladian* truss with diagonal struts is represented in figure 6 and its elements have the characteristics shown in figure 6. The timber used in the S. Roque’s roof comes from Eastern Europe. It can be concluded that it is made of “*riga*”, strenght class C30, from where the rest of the mechanical and stiffness properties were collected. The applied loads can be divided in purlin, floor and ceiling loads, according to figure 6b. This load values are shown in table 1.

Element	Width b [m]	x	Height h [m]
Tie beam	0.35	x	0.44
Post	0.40	x	0.35
Principal rafter	0.35	x	0.20
Upper Jack rafter	0.35	x	0.35
Lower Jack rafter	0.35	x	0.35
Straining beam	0.35	x	0.35
Strut	0.15	x	0.30

Angle
33º
Distance between trusses
3,6 m
Span
19 m

a) Characteristics of the S. Roque’s truss type



b) S. Roque’s Truss loads

Figure 6 - S. Roque’s Church truss type and geometry

Table 1 – Applied loads in S. Roque’s truss

Comb.	Purlin 1 to 6		Purlin 7 to 19		Purlin 20 to 25		Purlin 26 to 38		Ceiling	Floor
	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_t [kN]	R_{pav} [kN/m]
[1]	7.273	0.864	6.927	0.639	5.729	-0.138	5.862	-0.052	6.335	8.820
[2]	6.864	1.440	6.287	1.066	4.291	-0.230	4.513	-0.086	6.335	2.430
[3]	5.193	0.576	4.962	0.426	4.164	-0.092	4.252	-0.035	4.693	3.240
[4]	4.920	0.960	4.536	0.710	3.205	-0.154	3.353	-0.058	4.693	1.800

After introducing the loads in the model, the maximum forces of principal elements, for load combination 1, are withdrawn see table 2a and the resulting displacements for load combination 3, is shown in table 2b.

Table 2 – Resulting forces and displacements in S. Roque’s truss elements

Element	M máx [kNm]	V máx [kN]	N máx [kN]	N in M Máx [kN]
Tie Beam	55.12	51.97	451.56	360.31
Principal rafter	6.52	5.17	-370.67	-
Lower Jack rafter	21.00	54.50	-276.51	-83.11

a) Internal forces related to ultimate limit states

	w_{fin} [m]
Tie beam	0.0137
Lower Jack rafter	0.0113

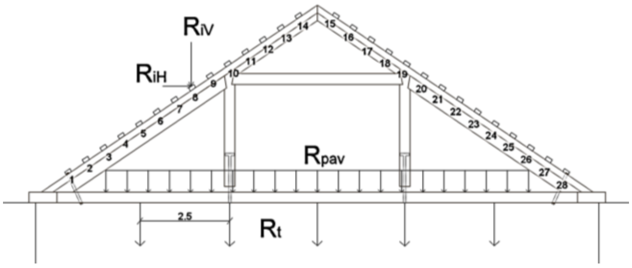
b) Final Element displacements

4.2. Second Case study – Santarém's Cathedral

The Santarém Cathedral's truss is similar to S. Roque's truss, the only difference is that it has no diagonal struts, since it also has a lesser span. The timber used in the roof of the Santarém's Cathedral, is made just as in S. Roque's Church, from pine, but in this case *pitch pine*, with a strength class of C24. The applied loads can be divided in purlin, floor and ceiling loads, according to figure 7b. This load values are shown in table 3.

Element	Width b [m]	x	Height h [m]
Tie beam	0.30	x	0.30
Post	0.30	x	0.30
Principal rafter	0.30	x	0.18
Upper Jack rafter	0.30	x	0.18
Lower Jack rafter	0.30	x	0.30
Straining beam	0.30	x	0.30
Strut	0.18	x	0.15

Angle
34º
Distance between trusses
3 m
Span
16 m



a) Characteristics of the Santarém Cathedral's truss type

b) Santarém Cathedral's Truss loads

Figure 7 – Santarém's Cathedral truss type and geometry

Table 3 - Applied loads in Santarém Cathedral's truss

Comb.	Purlin 1 to 6		Purlin 7 to 14		Purlin 15 to 19		Purlin 20 to 28		Ceiling	Floor
	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_t [kN]	R_{pav} [kN/m]
[1]	5.949	0.598	5.731	0.450	4.933	-0.088	5.021	-0.028	6.458	7.350
[2]	5.460	0.996	5.096	0.751	3.766	-0.146	3.914	-0.047	6.458	2.025
[3]	4.261	0.399	4.115	0.300	3.584	-0.058	3.643	-0.019	4.784	2.700
[4]	3.935	0.664	3.692	0.500	2.806	-0.097	2.904	-0.031	4.784	1.500

After introducing the loads in the model, the maximum forces of principal elements, for load combination 1, are withdrawn see table 4a and the resulting displacements for load combination 3, is shown in table 4b.

Table 4 - Resulting forces and displacements in Santarém Cathedral's truss elements

Element	M máx [kNm]	V máx [kN]	N máx [kN]	N in M Máx [kN]
Tie Beam	29.25	29.61	201.89	179.39
Principal rafter	3.63	8.67	-247.03	-
Lower Jack rafter	13.94	16.43	-214.26	19.17

a) Internal forces related to ultimate limit states

	w_{fin} [m]
Tie beam	0.0112
Lower Jack rafter	0.0098

b) Final Element displacements

4.3. Third Case study - The building of the Military Asylum of Runa

The roof structure can be classified as simple palladian truss, with an approximate span of 12 meters, where we can see the difference towards the rest of the case studies, since this truss is formed by the jack rafter along its slope. The timber used in the structure is cedar and since it isn't possible to find a strength classification in norm 338 for this type of timber, we shall follow an intermediate strength class, approximately C24. The applied loads can be divided in purlin, and floor loads, according to figure 8b. This load values are shown in table 5.

Element	Width b [m]	x	Height h [m]
Tie beam	0.20	x	0.20
Post	0.20	x	0.20
Upper Post	0.20	x	0.15
Strut	0.17	x	0.17
Straining beam	0.15	x	0.25
Purlin	0.20	x	0.20

Angle
31º
Distance between trusses
3.5 m
Span

a) Characteristics of the Military Asylum of Runa's truss type b) Military Asylum of Runa's Truss loads

Figure 8 – Military Asylum of Runa's truss type and geometry

Table 5 - Applied loads in Military Asylum of Runa's truss

Comb.	Purlin 1		Purlin 2		Purlin 3		Purlin 4		Purlin 5		Purlin 6		Purlin 7		Floor
	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_V [kN]	R_H [kN]	R_{pav} [kN/m]
[1]	13.25	1.44	34.00	3.81	32.27	2.77	22.97	1.29	28.87	0.73	28.26	0.36	11.06	0.12	8.575
[2]	12.71	2.40	32.37	6.35	29.50	4.62	19.54	2.15	23.82	1.21	22.80	0.60	9.06	0.20	2.363
[3]	9.47	0.96	24.27	2.54	23.12	1.85	16.59	0.86	20.85	0.48	20.44	0.24	8.01	0.08	3.150
[4]	9.12	1.60	23.19	4.24	21.27	3.08	14.31	1.43	17.48	0.81	16.81	0.40	6.68	0.13	1.750

After introducing the loads in the model, the maximum forces of principal elements, for load combination 1, are withdrawn see table 6a and the resulting displacements for load combination 4, is shown in table 6b.

Table 6 - Resulting forces and displacements in the Military Asylum of Runa truss elements

Element	M máx [kNm]	V máx [kN]	N máx [kN]	N in M Máx [kN]
Tie Beam	19.84	23.65	183.44	183.44
Strut	32.90	22.99	-215.38	-209.41

a) Internal forces related to ultimate limit states

	w_{fin} [m]
Tie beam	0.0294
Strut	0.0635

b) Final Element displacements

5. Discussion and results analysis

The *palladian* truss, when built according to the old models of roman carpentry (which are the case in the S. Roque's Church and Santarém's Cathedral) usually include an element that is essential to the structural behavior of the truss: a principal rafter. Even though this is not one of the more used elements, it is the one that enables the standardization and degradation of the bending stresses, carrying the loads from the purlins to the jack rafter, allowing that the structure responds mainly to axial forces. In the cases where there isn´t a principal rafter (the case of

Military Asylum in Runa), the structure tends to be influenced by bending stresses, if the loads are introduced out of the knots. As for the deformations, these are controlled by adjacent elements of the structure, which is the case of the struts that bear the jack rafters, as well as the posts, which play a support role of the tie beam.

The first global result to draw from this kind of structures appears in figure 9 and represents a qualitative diagram of axial stresses in this kind of structure. We represent the solicitations with a color diagram in which the blue represents tensile stresses e in red the compression stresses. Within each one of these the intensity of the resulting stress corresponds to the maximum value, described by the intensity of the color.

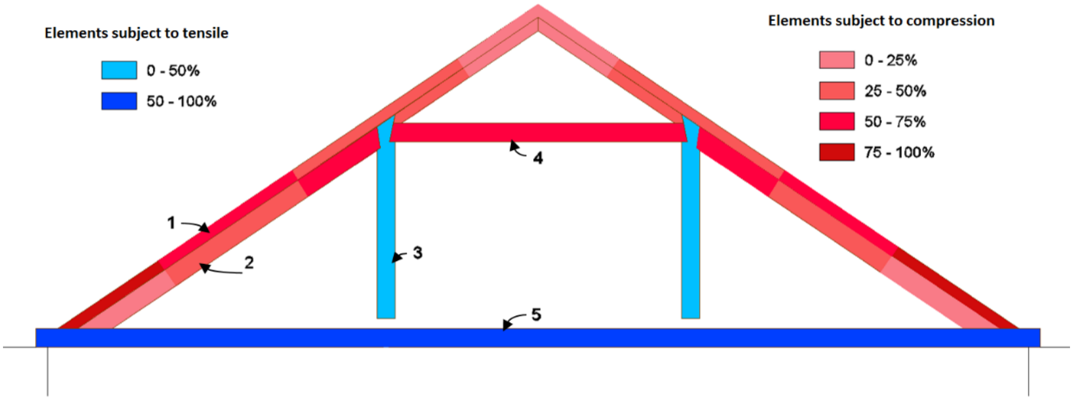


Figure 9 - Qualitative diagram of axial forces of the Palladian truss

In this global analysis we present in table 7 the main solicitation and the function of the elements that compose the *palladian* truss.

Table 7 - Main functions of the composing elements of the palladian truss

	Element	Main Solicitation	Function
1	Principal Rafter	Compression	Receives the loads from the purlins degrades to the jack rafter, dissipate the bending moment on the structure;
2	Jack Rafter	Compression	Articulated between the tie beam; straining beam and the top of the truss, linked to square with the opposite jack rafter. It shows compression forces similar to the straining beam, degrading them to the principal rafter through the continuous connection between both of them;
3	Post	Tensile	Element that works in a tensile way just by serving as a support to the tie beam, diminishing its forces, as well as its deformation
4	Straining beam	Compression	Element that works at compression, preventing the bending of the jack rafter and also controls the deformation of this element
5	Tie Beam	Tensile/Bending	Receives the horizontal component of the compression forces of the jack rafter and principal rafter, preventing the truss from opening. It also works at bending, since it also carries the loads both from the roof and the roof floor.

5.1. Case studies Results' Analysis

After the security searches from the three case studies according to the EC5, we verify that the case study 1 and 2 have all the regulatory requirements to the ultimate limit states and serviceability limit states (see table 8 and 9), whereas in the Runa study, the same doesn't take place mainly due to the bending of the jack rafter.

Table 8 - Results of the ultimate and serviceability limit states assessments

ELU	Case Study 1 S. Roque's Church		Case Study 2 Santarém's Cathedral		Case Study 3 Military Asylum of Runa	
[1] Tensile	check		check		check	
[2] Compression	check		check		check	
[3] Bending	check		check		Doesn't check	
[4] Shear	check		check		Doesn't check	
[5] Bending and Tensile	check		check		Doesn't check	
[6] Bending and Compression	check		check		Doesn't check	
[6.1] Stability	check		check		Doesn't check	
ELS	Tie beam	Strut	Tie beam	Strut	Tie Beam	Strut
W_{inst_G}	check	check	check	check	check	Doesn't check
W_{inst_Q1}	check	check	-	-	-	-
W_{inst_Q2}	check	check	check	check	check	Doesn't check
W_{fin}	check	check	check	check	check	Doesn't check

These results confirm the importance of the principal rafter in this kind of structure, since it is the principal rafter that makes the distribution of the bending moments, making the structure act mostly on the axial forces.

5.2. Proposal for the reinforcement of the Military Asylum of Runa's truss

We present the proposal for the reinforcement of the truss of Runa, considering the security assessment according to the EC5. The reinforcement should maintain the characteristics of the truss as well as the kind of usage it has and shouldn't affect the large space of the roof. Since the main problem of the truss is caused by bending moments, mostly on the jack rafter, the solution can be found by introducing diagonal struts that support the load that come from the purlins 2 and 6. As the struts connect the post to the jack rafter, where the purlin lays and so that the post isn't subject to deformations due to the incoming load from the struts; the area between the posts is reinforced, underneath the structure of the roof floor, with an horizontal strut that has as a solely goal the absorption of the horizontal component of the inserted diagonal struts, figure 10.

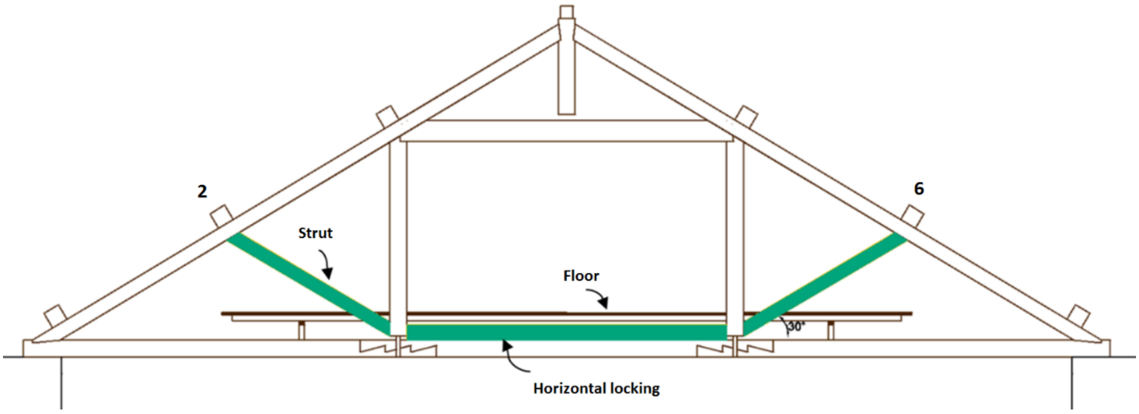


Figure 10 – Reinforcement solution for Military Asylum of Runa's truss

Through a simple pre-dimensioning, the sections (bxh) are introduced with 15x20 cm in the diagonal strut and horizontal strut. After the introduction of these elements all the security assessments are safeguarded.

6. Concluding Remarks

In the current work we set out to understand the evolution of timber as a structural material and how this material was applied in roofs, culminating on the study of the structural behavior of *palladian* trusses, brought to Portugal on the 15th century and which represent a huge legacy in the timber construction throughout Europe.

Timber is an excellent structural material, but has to be well characterized at the properties level so that we can make a correct structural analysis. It is through the EC5 that it is possible to perform the structural security searches on this kind of structures, according to the ultimate limit states and serviceability limit states. The present regulation helps to verify the security of the trusses, but also to define the criteria of the quantification of the actions and their characteristics, which enable us to reach the forces and displacements that act upon the truss.

These kind of structures appeared with the aim of supporting loads acting only on the connection points of the structure, making them act out mainly under axial forces. With the need to increase the roofs, the loads act out of the knot and that causes bending problems. Hence appear the composed *palladian* truss. Their behavior study is based on the analysis of three practical studies and it is concluded that there are indispensable elements to the proper functioning of this kind of truss, as for instance the principal rafter, but there are others, even though less important, that have a fundamental role in the control of displacements: post, struts, straining beam.

The present study can be used as a starting point to the development of the analysis, rehabilitation and structural reinforcement of this kind of structures, since there may be other cases in Portugal that are similar to the one in Runa that may need intervention.

References

Bluteau, R. (1712). *Vocabulário Portuguez e Latino*. Coimbra: Collegio das Artes da Companhia de Jesus.

Cabo, M. C. F. (1996). *De los orígenes y desarrollo de las armaduras de cubierta latinas*. Paper presented at the Primer Congreso Nacional de Historia de la Construcción, Madrid.

Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings (2006).

Martins, J. S. (2008). *Tectos Portugueses do séc. XV ao séc. XIX.* (Mestrado), Instituto Superior Técnico, Lisboa.

Martins, J. S., Gago, A. S., & Caldas, J. (2012). *Roof and Ceiling wood structures in Portuguese churches from the fifteenth to the seventeenth century: constructive characterization and comparison with the Spanish structures*. Paper presented at the 8th International Conference on Structural Analysis of Historical Constructions, Wroclaw, Polónia.

Martins, J. S., Gago, A. S., Caldas, J. V., & Oliveira, L. (2013). Telhados e Tectos de Asnaria, uma Constante na Construção Portuguesa do Gótico ao Barroco.

Mateus, T. (2007). *Bases para o dimensionamento de estruturas de madeira*. Lisboa: LNEC.

Negrão, J., & Faria, A. (2009). *Projeto de Estruturas de Madeira*. Porto: Publindústria, Edições Técnicas.

Oliveira, N. F. M. (2009). *Teoria e Prática de Técnicas de Construção e Conservação de Coberturas do séc. XVIII: Evolução Histórica, tratadísta do séc. XVIII, Diagnóstico de Anomalias e Restauro Estrutural.* (Mestrado), Unversidade de Trás-Os-Montes e Alto Douro, Vila Real.

Osa, G. G. L. d. l. (2009). *Origen Y Evolución De La Cercha.* (Master), Universidade Politécnica de Madrid.

Reis, A. C. d., Farinha, M. B., & Farinha, J. P. B. (2005). *Tabelas Técnicas*. Lisboa: Edições Técnicas E. T. L., L.da.

Sánchez, M. I. G. (2006). *Las Estructuras de Madera en los Tratados de Arquitectura* (S. L. Artes Gráficas Palermo Ed.). Madrid.

Scala, D. F. d. A. Y. (1895). Carpintería Antigua Y Moderna. In J. Roma (Ed.), (pp. 578). Barcelona.