Behaviour of Traditional Portuguese Timber Roof Structures

Jorge Branco
PhD Student
University of Minho
Guimarães, Portugal

Paulo Cruz
Associate Professor
University of Minho
Guimarães, Portugal

Maurizio Piazza
Professor
University of Trento
Trento, Italy

Humberto Varum
Assistant Professor
University of Aveiro
Aveiro, Portugal

Summary

The aim of this paper is to present the results of a structural analysis of common trusses traditionally used in roof construction in Portugal. The study includes the results of a preliminary survey intending to assess the geometry, materials and on site pathologies, as well as a two-dimensional linear elastic static and dynamic analysis. The trusses behaviour under symmetric and non-symmetric loads, the king post/tie-beam connection, the stiffness of the joints and the incorrect positioning of the purlins, were some of the structural aspects that have been investigated.

1. Introduction

Traditional building construction in Portugal (from the 18th, 19th to early 20th centuries) adopted timber roof and floor structures and in some cases also timber reinforced masonry walls. A significant number of these buildings are still in use, despite some major modifications. Even when the use of concrete became generalised, timber structures kept an important use in roof construction. The common Portuguese timber roof structures are formed by trusses with an average span of 6 m, mostly following a king-post configuration. This kind of truss is characterized for having a horizontal member (tie beam), two principal rafters connected to the tie beam inclined to form the roof, a vertical member at the middle (king post) and two inclined struts, connecting the king post to each principal rafter. Figure 1 shows the geometric configuration and organization of the different members of a typical Portuguese king post truss.

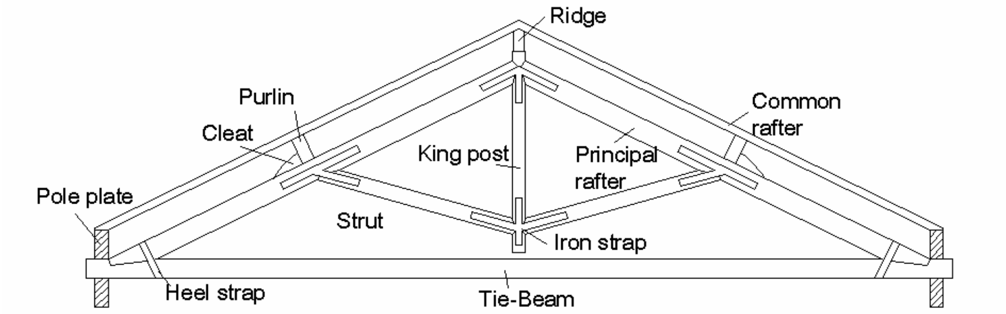


Fig 1 Portuguese king post truss configuration

Joints between members are made by notches, in some cases presenting tenon and mortise, which can be single or double. Forces are directly transferred by compression and/or friction. To improve the contact between the connected members, joints are usually strengthened with metal elements. The use of those elements, besides intended to counteract out-of-plane actions, aimed to ensure safety under reversal loads. Usually, stirrups, binding strip and bolts were used. The wood species more frequently utilised are: Maritime Pine (*Pinus pinaster*, Ait.), Eucalyptus (*Eucalyptus globules*, Labill.) and Chestnut (*Castanea sativa*, Mill.). The use of Chestnut is most common in monumental buildings. As this species shows a high natural durability, it is normal present in the oldest constructions. In recent years, the use of Eucalyptus increases significantly, because its low cost. The Maritime Pine, as the most spread species in Portugal, was always present in Portuguese construction.
In the design of new structures or assessment of existing ones, it is common to model trusses considering each member with perfect hinges at both ends. However, these joints offer a significant moment resistance and may be better classified as semi-rigid connections. This capability is especially important under non-symmetric loads as those induced by snow, wind and especially earthquakes. In rehabilitation works, the lack of practical but realistic models for the joints

generally leads to very conservative retrofits and upgrades in order to satisfy the safety and serviceability requirements present in recent Codes and Recommendations. Moreover, the misunderstanding of the global behaviour of traditional roof trusses can result in unacceptable stress distribution in the members as a result of inappropriate joints strengthening (in terms of stiffness and/or strength).
The main scope of this paper is to analyse the structural behaviour of the common trusses used in traditional Portuguese roof structures. The study [1] includes a two-dimensional linear elastic analysis of a plane truss representative of the traditional structures under static and dynamic loading. The trusses behaviour under symmetric and non-symmetric loads, the connection between the king post and the tie-beam, the stiffness of the joints and the incorrect positioning of the purlins are some of the structural aspects analysed.

2. Truss geometry and loads adopted

The truss selected for the analysis, representative of the traditional Portuguese king post truss, is reported in Figure 1, and has a free span of 6.26 meters. The distance between centres of the trusses was set to 3.5 meters. The roofs are normally covered with ceramic tiles, present 30º slopes with rafters spaced 50 cm over the purlins and the ridge. Maritime Pine species was adopted for all timber elements.
Self-weight, live load and snow were considered according to the recommendations in the Portuguese structural code [2]. The snow loads represent a location in the north of Portugal (400 meters altitude). Wind was not considered in these analyses because depends on various parameters (as roof geometry, height and the exposition), but also because for this kind of timber roof structures the wind, normally, is not a conditioning design load. Seismic action was considered proportionally to the masses associated to the self-weight of the structural elements and to the quasi-permanent value of the live-loads. For the numerical analyses, the Finite Element Method (FEM) program SAP 2000 was used [3]. Figure 2 shows the geometry of the FE model and table 1 summarizes the concentrated loads considered for each loading case.

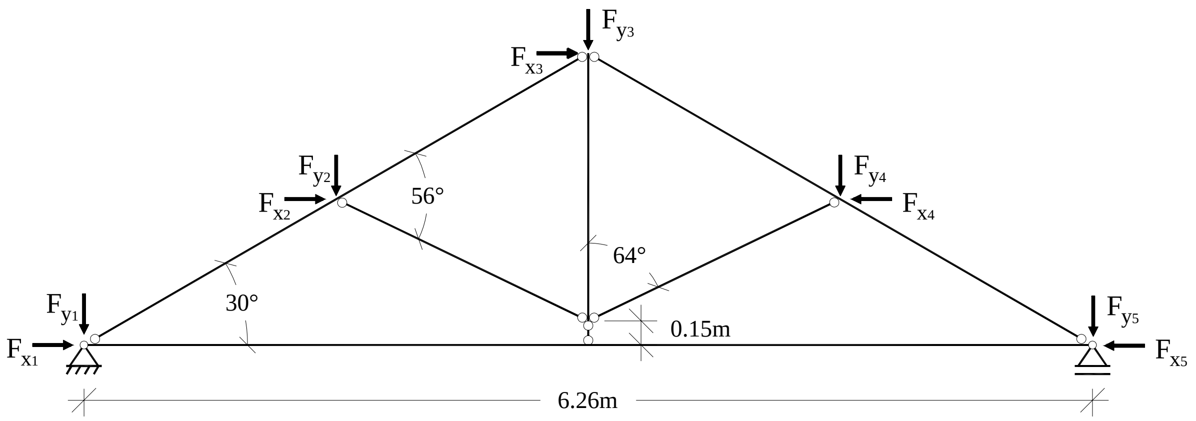


Fig 2 FEM model adopted for the king post roof truss with concentrated loads

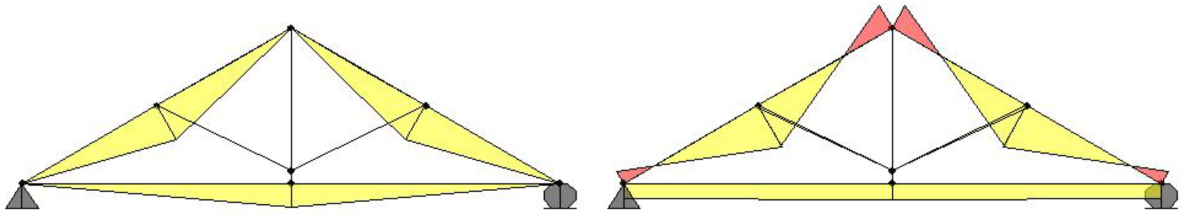
Table 1 Loads, in kN, for each loading case considered

Loading case	Fx_1	Fy_1	Fx_2	Fy_2	Fx_3	Fy_3	Fx_4	Fy_4	Fx_5	Fy_5
Self-weight	—	2.51	—	4.64	—	4.64	—	4.64	—	2.51
Live load	—	0.95	—	1.90	—	1.90	—	1.90	—	0.95
Snow	—	3.33	—	6.65	—	5.54	—	4.43	—	2.22
Mass Force 1	2.51	—	4.64	—	4.64	—	-4.64	—	-2.51	—
Mass Force 2	2.51	—	4.64	—	4.64	—	4.64	—	2.51	—
Mass Force 3	-2.51	—	-4.64	—	-4.64	—	-4.64	—	-2.51	—
Mass Force 4	—	-2.51	—	-4.64	—	-4.64	—	-4.64	—	-2.51
Mass Force 5	—	-2.51	—	-4.64	—	-4.64	—	4.64	—	2.51

3. Static behaviour

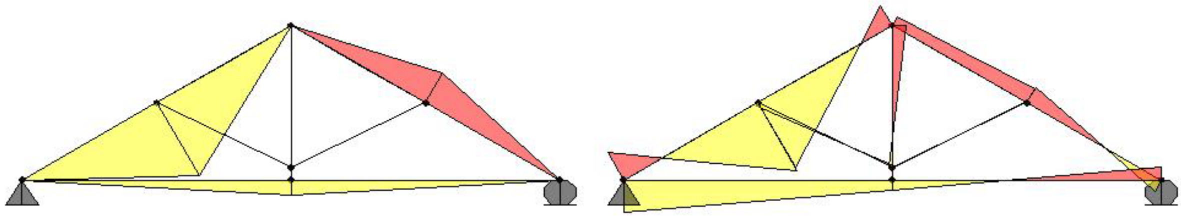
3.1 Influence of the joints stiffness

In practice, wood trusses are modelled considering perfect hinges at the ends of each element, however, common joints present significant stiffness [4]. Joint stiffness is directly dependent on the metal devices adopted in the timber connection. To study the influence of the joint stiffness in the global behaviour of the truss, two identical models in terms of geometry, materials and loads were considered. The models differ only in terms of joint stiffness: one with perfect hinges (Model A) and the other with rigid joints (Model B). Figures 3, 4 and 5 shows the bending moment diagrams obtained in both models for a symmetric load case (self-weight) and two non-symmetric load cases (snow and mass force 1).



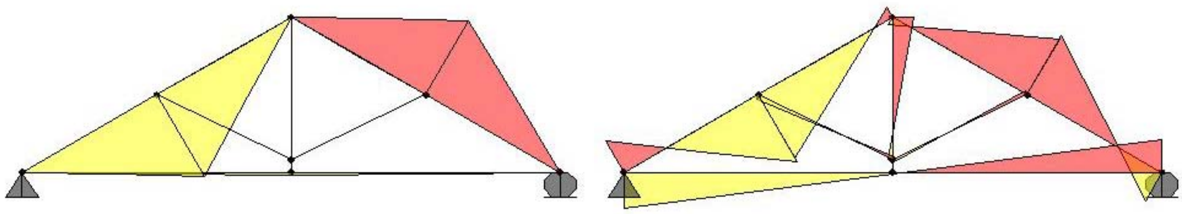
(a) Perfect hinges *(b) Rigid joints*

Fig 3 Bending moment diagrams for self-weight load case



(a) Perfect hinges *(b) Rigid joints*

Fig 4 Bending moment diagrams for snow load case



(a) Perfect hinges *(b) Rigid joints*

Fig 5 Bending moment diagrams for mass force 1 load case

Only for non-symmetric loads, the influence of the joint stiffness became relevant. In a plane structure, like the timber trusses under analysis, submitted to concentrated loads on the joints, without bending of the members, stress distribution in the structure results directly from its geometry.

3.2 Purlins eccentricity

One of the most frequent construction mistakes is related to the relative position of the purlins to the joints. When the purlins are put in place with an eccentricity relatively to the joints, important bending moments arise in some elements, which can compromise the global structural safety. To point out this effect, a new model was considered (Model C, with an eccentricity of 20 cm in the position of the purlins, with joints considered as perfect hinges).
Results in terms of maximum forces obtained in the Model A, with purlins correctly positioned over the joints, and in the Model C, purlins with eccentricity, are presented in Table 2.

Table 2 Maximum values of efforts, for each element, considering purlins with or without eccentricity relative to the joints

		Without eccentricity (Model A)			With eccentricity (Model C)		
	Element	Nsd (kN)	Vsd (kN)	Msd (kNm)	Nsd (kN)	Vsd (kN)	Msd (kNm)
Self weight.	Tie-beam	11.59	0.06	0.18	12.50	-0.06	0.19
	Rafter	-13.49	0.17	0.31	-15.53	-3.62	0.64
	Strut	-4.44	—	—	-4.72	—	—
	Post	3.75	—	—	3.98	—	—
Snow	Tie-beam	13.84	0.07	0.21	14.88	-0.07	0.23
	Rafter	-16.39	-0.68	1.24	-18.90	-4.72	1.67
	Strut	-5.31	—	—	-5.60	—	—
	Post	4.48	—	—	4.72	—	—
Mass force 1	Tie-beam	9.33	-0.02	0.06	9.33	-0.02	0.06
	Rafter	7.50	-1.22	2.20	9.79	1.41	2.27
	Strut	0.13	—	—	0.13	—	—
	Post	-0.15	—	—	-0.15	—	—

The eccentricity of the purlins modifies the stress distribution, but is more evident in the rafters. The bending moments for the self-weight load case increase 106% in the rafters, when the purlins eccentricity is introduced. For the snow and mass force 1 load cases, the bending moments on the rafter increase 35% and 3%, respectively, with the purlins eccentricity of 20 cm.

3.3 King post/tie-beam connection

A common uncertainty in the global structural behaviour definition of traditional Portuguese king post trusses is related to the connection between the king post and the tie-beam. Even if the ancient construction manuals suggest the disconnection between the post and the tie-beam, in practice, examples of misconceived connections can be found. In bibliography [5] and [6], it is recommended to suspend the tie-beam on the king post using an iron strap, only nailed to the king post (Figure 6). Therefore, the deformation of the tie-beam is reduced and the out- of-plane deformation of the truss is prevented. However, the use of this connection system is not universally founded. Examples (Figure 7) show that, in many cases, the king post is connected to the tie-beam, with nails or bolts, modifying the stiffness of the joint, without suspending the tie-beam.

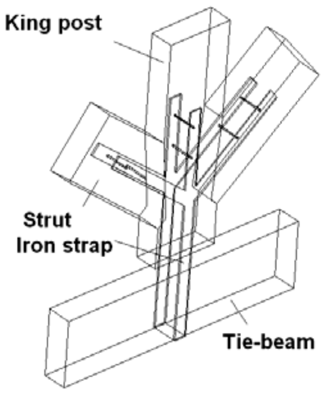
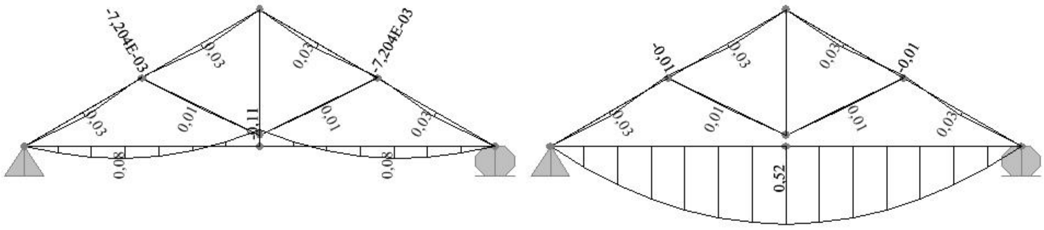


Fig 6 Ideal connection between the king post and the tie-beam [4]

Fig 7 Example of a misconceived connection between the king post and the tie-beam

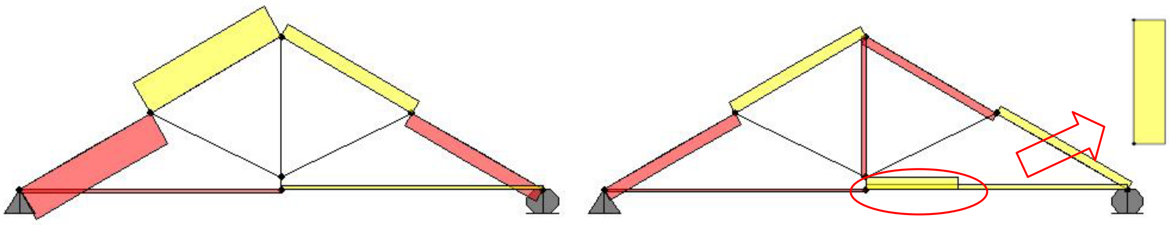
In order to highlight the influence of the connection between the king post and the tie-beam, two new models were analysed. First, a model without any connection between the king post and the tie-beam was considered (Model D), and compared to the similar model with the tie-beam suspended on the king post (Model A). The difference between both models is essentially in the tie-beam behaviour. When the tie-beam is suspended on the king post, the deformation due to its self-weight is reduced and consequently, a decrease of the bending moment in this element is achieved (Figure 8). It can be concluded that the use of the iron strap decrease the deformation induced by the self-weight and prevent the out-of-plane deformation of the structure.



(a) Tie-beam suspended on the king post *(b) Tie-beam disconnected from the king post*

Fig 8 Bending moment diagrams due to the self-weight, (kNm)

Subsequently, another model (Model E) was developed to evaluate the importance of the tie-beam/king post connection stiffness. This model differs from the Model A only in the stiffness of the tie-beam/king post connection. Also in this case, the stiffness connections alter significantly the stress distribution only for non-symmetric load cases. In this case, the distortion of the truss leads to important shear stresses in the king post. While, with an ideal connection, tie-beam suspended in the king post by a perfect hinge joint, the king post is only submitted to axial tension forces. Figures 9 shows the shear force distribution diagrams for the snow load case, for models A and E.



(a) Tie-beam suspended on the king post *(b) Tie-beam/king post with rigid connection*

Fig 9 Shear diagrams for the snow load case

4. Design

In this section is analysed the design stress variations, for each structure studied and for all the load cases considered in the analysis of the king post truss (see Table 1). In table 3 the main results are summarised, in terms of normal and shear stress, for each element and for each structural model.

Table 3 Maximum stress for each element and for all studied models

Model	Stress	Tie-beam	Rafter	Strut	King post
Reference (A)	σ (kPa)	2845.91	8180.82	2441.72	745.63
	τ (kPa)	30.43	176.59	9.61	—
Rigid joints (B)	σ (kPa)	4228.21	7298.16	4122.19	1827.78
	τ (kPa)	48.24	215.71	44.30	45.77
	Δσ (%)	48.6	-10.0	68.8	148.5
	Δτ (%)	58.5	22.2	361.0	—
Eccentric purlins (C)	σ (kPa)	3061.10	9190.83	2570.20	774.66
	τ (kPa)	31.62	1029.55	9.61	—
	Δσ (%)	7.6	13.3	5.3	5.3
	Δτ (%)	3.9	483.0	0.0	—
Tie-beam disconnected from the king post (D)	σ (kPa)	3228.10	8091.02	2442.50	724.55
	τ (kPa)	38.01	176.42	9.61	—
	Δσ (%)	13.4	-0.2	0.0	-1.5
	Δτ (%)	24.9	-0.1	0.0	—
Tie-beam/king post rigid connection (E)	σ (kPa)	3044.45	4246.10	2692.97	1535.83
	τ (kPa)	32.90	59.49	9.61	583.81
	Δσ (%)	7.0	-47.6	10.3	108.8
	Δτ (%)	8.1	-66.3	0.0	—

The traditional king post trusses behave essentially as plane structures whit normal stress in their elements. For the reference model, Model A, rafters are the members with higher stress (σ= 8.18 MPa). In the tie-beam and the struts, normal stresses of 2.8 MPa and 2.44 MPa were estimated, respectively, while for the king post normal stress is equal to 0.7 MPa. The shear stress (τ) is null in the king post, minor in the tie-beam and struts, and 0.2 MPa in the rafters.
Comparing the results, in terms of stress, for the reference model, Model A, with the other models under analysis, the following conclusions can be drawn.

Model (B), rigid joints

(1) Normal stress in the tie-beam increases 48.6 %, as a consequence of the higher bending moment (+202.7 %).
(2) In the king post surges shear stress.
(3) Struts suffer an increase of 68.5 % in the normal stress, and shear stresses become significant (44.30 kPa).

Model (C), eccentric purlins

(4) A significant increase of the shear stress in the rafters was verified (+483.5%). If a class service 3 is considered for the structure, this increase can compromise the structural safety (τ_{sd} = 1.03 MPa > f_{vd} = 1 MPa). **NOTE:** <u>According to the Portuguese NDA of Eurocode 5 [6], all elements in solid timber with a cross-section height larger than 100 mm shall be considered as belonging to class service 3</u>.

Model (D), tie-beam disconnected from the king post

(5) Removing the middle span support of the tie-beam, the normal stress on this element increases due to bending caused by its self-weight.

Model (E), tie-beam/king post rigid connection

(6) The stiffness change in the tie-beam/king post connection only causes significant stress variation in the king post. Consequently, for this element, the normal stress value is 1.54 MPa and the shear stress is 0.58 MPa, while for the reference model (Model A) those stresses are equal to 0.75 MPa and 0 MPa, respectively.

5. Dynamic behaviour

5.1 Natural frequencies and vibration modal shapes

For the study of the typical king post truss dynamic behaviour, it was calculated, for free vibration, the natural frequencies and the modal shapes. Table 4 summarizes the natural frequencies associated to the first six natural modal shapes, obtained for all models analysed.

Table 4 Natural frequencies for the analysed structures (Hz)

Mode	Model A *Reference*	Model B *Rigid joints*	Model C *Eccentric purlins*	Model D *Tie-beam/king post disconnected*	Model E *Tie-beam/king post rigid connection*
1st	6.37	7.68	6.26	6.37	16.85
2nd	17.03	17.13	16.71	11.17	23.50
3rd	39.97	40.06	39.39	17.13	39.98
4th	56.53	57.45	54.84	39.98	56.63
5th	88.60	88.72	89.73	57.10	90.16
6th	124.73	124.78	123.07	89.03	124.76

Analysing the first natural frequency obtained, no significant variations are observed in the first four models (A, B, C and D). For the model E, with the tie-beam/king post rigid connection a significant difference was found. The increase in the stiffness of the tie-beam/king post connection results in a stiffening of the truss itself, traduced by the increase of the first fundamental frequency (from 6.37 Hz to 16.85 Hz). This stiffness increase also influences the second natural frequency but with less importance, and does not affect the high order modes.
Disconnecting the tie-beam from the king post, model D, a new modal shape surges, with a frequency value of 11.17 Hz, corresponding to the local vibration of the tie-beam.

5.2 Time history analysis

The seismic response of common Portuguese king post truss was studied. The seismic response was computed for the ground acceleration time-history of a recent earthquake. The accelerogram adopted was recorded in the Duzce station, in Turkey, in 1999 during the Kocaeli Earthquake (Figure 10). The accelerogram has peak acceleration of 0.2g, which is close to the design acceleration range in Portugal [2].

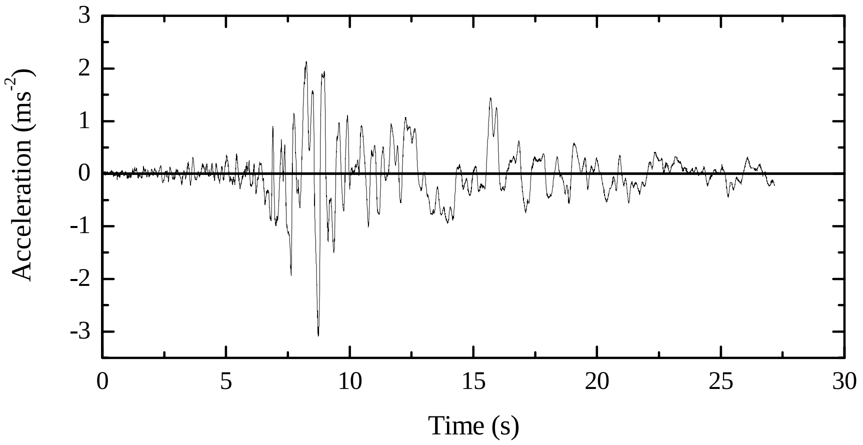


Fig 10 Accelerogram corresponding to the Kocaeli earthquake, Turkey (1999), Duzce station

The inertial forces were evaluated considering the masses associated with all gravity loads (self-weight of the structural and non-structural elements), and the live-loads with the respective reduction factors. It was considered in the analyses a damping ratio of 5%. In table 5 the maximum values of normal and shear stress are summarized, for each truss element and for each model.

Table 5 Maximum stress for each element and for the structures studied (seismic action)

Model	Stress	Tie-beam	Rafter	Strut	King post
Reference (A)	σ (kPa)	1250.63	1747.31	715.70	303.75
	τ (kPa)	16.88	91.19	7.03	0.00
Rigid joints (B)	σ (kPa)	1500.71	579.78	282.03	579.45
	τ (kPa)	23.10	73.47	17.34	12.10
	Δσ (%)	20.0	-66.8	-60.6	90.8
	Δτ (%)	36.9	-19.4	146.7	—
Eccentric purlins (C)	σ (kPa)	1240.11	5222.18	763.98	315.28
	τ (kPa)	17.05	436.79	7.03	0.00
	Δσ (%)	-0.8	198.9	6.7	3.8
	Δτ (%)	1.0	379.0	0.0	0.0
Tie-beam disconnected from the king post (D)	σ (kPa)	1657.00	5053.98	687.27	277.33
	τ (kPa)	28.21	160.82	7.03	0.00
	Δσ (%)	32.5	189.2	-4.0	-8.7
	Δτ (%)	67.2	76.4	0.0	0.0
Tie-beam/king post rigid connection (E)	σ (kPa)	1223.18	375.79	768.67	479.55
	τ (kPa)	17.90	24.89	7.03	124.09
	Δσ (%)	-2.2	-78.49	7.4	57.9
	Δτ (%)	6.1	-72.71	0.0	—

The king post truss elements are essentially subjected to normal stress. The rafters are the members with higher stresses. In the following, the main differences founded are discussed, in terms of stress distribution, for the different structural configurations analysed under the dynamic action. When the joints are modelled as rigid, the tie-beam shows an increase in the stress value (20% for the normal

stress and 36.9% for the shear stress), but the struts are the elements where the increase in terms of shear stress is more relevant (146.7%). The king post presents an increase on the normal stress of 90.8% and shear stress surges.
The eccentricity of the purlins essentially produces modifications in the rafter stresses. In these elements, the normal stress increases 198.9% and the shear stress increases 379.0%.
The disconnection of the tie-beam of the king post results in stress increase at the tie-beam and rafters. The more significant increase is found in terms of normal stress at the rafter (189.2%).
Providing a rigid connection between the tie-beam and the king post, the behaviour of the later is particularly affected. The normal stress increases of 57.9% and the shear stress presents a value of 0.12 MPa when, in the reference model (Model A), it was null.

6. Design recommendations

The typical Portuguese king post trusses show, essentially, normal stress in their elements caused by axial forces and bending moment induced by the self-weight and asymmetric loads (as the ones produced by snow and earthquakes). The elements with higher stress are the rafters, in terms of normal and shear stress. The tie-beam and struts have only significant normal stress and the king post only shows normal stress.
It was pointed out the variations in the truss behaviour that can be achieved as result of the model assumed in the design. Assessment of constructed trusses shows various differences on their structural model. Confusions in the definition of some connections and the consequences in the truss structural behaviour were highlighted. If construction recommendations are known, resulting of decades of experience, it is common to find examples where they were not taken into account. The application of concentrated loads out of the joints, for example originated by a wrong positioning of the purlins, can compromise the structural global safety. To analyse the behaviour and safety of these structures, it is important to use adequate models, considering the correct stiffness of the connections.
The tie-beam must be suspended to the king post. Iron strap shall be used, nailing it only in the king post, suspending the tie-beam with a connection without bending-stiffness. When the tie-beam/king post connection is rigid, the natural frequencies and modal shapes of the truss are clearly modified.

7. Acknowledgments

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