



Influence of Geometric Ratios on the Structural Behaviour of Historic Timber Roof Structures

Alexandra I. Keller^(✉)  and Marius Mosoarca 

Department of Architecture, Faculty of Architecture and Urban Planning, Politehnica University
Timisoara, Timisoara, Romania
alexandra.keller@upt.ro

Abstract. Heritage buildings and historic structures are highly complex systems that have to be understood by performing multi-, inter-, and transdisciplinary studies. It is therefore important to understand how structural parts influence each other and how individual structural elements and their position affect the general behaviour of the whole system.

Recent studies concerning roof structures have highlighted that there is a close link between all structural elements, not only from a load-bearing point of view but also from a geometric point of view. Therefore, it was observed that the general shape of the roof and the position of the main structural elements were defined by complex geometric ratios.

Starting from this observation, the study is aimed at evaluating how important these geometric ratios are in the structural behaviour of historic timber roof structures from the 18th, 19th and 20th century from Timisoara. To evaluate their importance, numerical simulations were performed on the main frames of the selected case studies with original geometric ratios and altered ratios and their behaviour was compared in terms of displacements in key areas of the structure. The main scope of the study is therefore to highlight whether the presence of pure geometric ratios improves the structural behaviour of the considered roof structures or if these principles are only related to the general aesthetics of the roof structure.

Keywords: Roof structures · Geometric ratios · Interdisciplinary assessment · Timber structures

1 Introduction

Roofs are a valuable part of heritage buildings, on the one hand they have a fully functional role, meant to protect the building from various meteorological factors, but more than this, they complete their aesthetics, influencing their general appearance and their importance in the surrounding urban space [1–3].

Recent studies have shown that there is a close link between the geometry of a roof, its height and general shape, and different architectural styles, the relationship between the roof and the building experiencing a continuous change throughout history [4]. More than this, studies have also highlighted that the same geometric principles are

also influencing the general layout of historic roof structures, defining the position of the main structural elements and joints [5–10]. Despite the fact that principles and studies related to the protection of heritage buildings and historic timber structures encourage a multidisciplinary assessment [11, 12], and despite existing inter and transdisciplinary studies no connection between geometric principles and the structural behaviour of roof structures has been made until now.

Based on these observations, a study was conducted with the main aim of observing whether the use of geometric principles identified in historic timber roof structures in Timisoara is purely aesthetic and only related to the philosophies of the craft-guilds or if they also influence the behaviour of these structures. To understand this connection, linear numerical simulations were performed, and the link was assessed by comparing their deformation at selected points.

2 Analysed Roof Structures

For the study three different types of roof structures were considered (Fig. 1), which according to previous studies have shown different geometric principles and a predominant use of various ratios reaching from the golden ratio to dynamic and static ones. All these ratios define the general geometry of the roof, but also the position of all main structural elements with regard to each other (Fig. 2):

- The first roof structure, which was observed in the case of 18th century buildings, is a sophisticated purlin roof structure of central European influence. This type is transferring all the loads directly to the exterior walls since no additional posts were used. In order to connect the rafters in the central area a collar and straining beam were used, the first one connected to the rafters and the second one to the inner rafters of significant cross-section. From a geometric perspective, the roof structure comprises various ratios related to a square: 1: 1 and $\sqrt{2}$.
- The second roof structure is a type with inclined posts, which is rather peculiar in the city but comprises almost exclusively golden ratios Φ (1.618 ratios between all structural elements). This roof structure comprises no horizontal connection between the upper part of the posts or between the rafters, but a series of trimmers and passing braces which form a series of triangles in the wall area, therefore ensuring the load transfer from the roof to the exterior walls.
- The third roof structure is a typical queen post roof with an additional king post placed at the top due to the span width of the building. In this case, passing braces were also used, which connect all major structural elements. This structure presented according to the geometric analysis a great variety of dynamic ratios - 2, 3 and $\sqrt{5}$ accompanied by 1:1 ratio in the king-post area.



Fig. 1. Roof structures for the study - a) first roof structure; b) second roof structure; c) third roof structure [13]

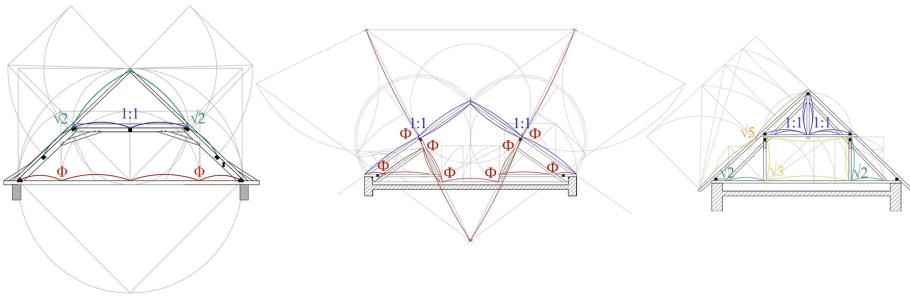


Fig. 2. Geometric analysis of selected roof structures [1]

3 Performed Numerical Analysis

In order to highlight the importance of the geometric ratios in the structural behaviour of the roofs, two different scenarios were taken into consideration (Fig. 3).

In the first scenario, numerical simulations were performed on the main frame of each of the roof structures, with the original layout by also respecting the cross sections of all the timber elements.

In the second scenario, numerical simulations were performed on an altered layout of the same main frame of each roof structure. For the alteration, to preserve the appearance of the roof from the outside, its general shape was kept as in the first scenario, leading to the same position of both rafters and tie-beam. Therefore, from the observations made during the geometric analysis, the element that influenced most of the ratios was identified as the intermediate purlins, placed close to the middle of the rafter. Therefore, their movement would change the position of the collar beam in the case of the first roof structure, the position of both the collar beam and posts in the case of the second, and the upper part of the inclined posts in the case of the third.

Since previous studies have shown that the middle of the twentieth century is leading to a change of the used ratios which are defining historic roof structures from highly complex ones to static ones (e.g. $1/2$, $1/3$, $3/4$ etc.), for the second scenario roof structures, these $1/3$ ratios were used to define the new position of the structural elements. Therefore, in the case of the first and third structure, the collar beam was moved in the upper third

of the rafters. In the case of the third roof structure, in order to preserve the presence of the inclined posts, their top mas moved toward the lower third of the rafters.

No changes were made to the cross sections of the timber elements.

All numerical simulations were performed using the SCIA Engineer finite element numerical simulation software by Nemetschek [14]. The structural elements were modelled as linear 1D members with respect to the geometry of the timber elements as obtained during the visual and geometric survey. Due to the main scope of the study, the decay and cross-sectional loss of the timber elements were not taken into consideration.

Despite the fact that the timber joints are highly complex, in order to understand the behaviour of the roof structures in both scenarios a more conservative approach was taken into consideration and all the joints were modelled and hinged. Since only one frame was modelled, in order to prevent out-of-plane displacements of the timber elements, the rotation of the joints was considered free only in the plane of the roof frame. The roof-to-wall connections were also considered hinged with the same conditions as in the case of the timber joints to permit the rotation of the whole structure.

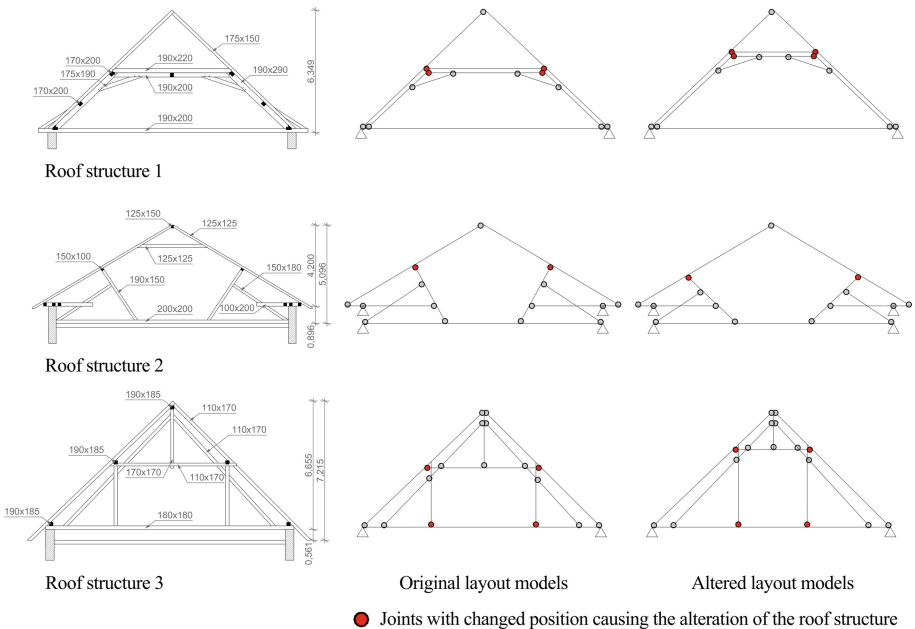


Fig. 3. Roof Structures Analysed – original and altered layouts used for the numerical simulations

3.1 Materials

Since the main objective of the study is to compare the effect of geometric ratios and their alteration on the structural behaviour of timber roofs, for this study a more conservative approach was considered suitable in terms of the mechanical properties. Therefore, a minimum strength class was considered for the structural elements in the numerical simulations, chosen according to EN338 [15] (Table 1).

Table 1. Mechanical properties of the used timber

Mechanical property	Abbreviation	Value
Self-weight		5.7 kN/m ³
Tensile strength	Ft,0,k	11.00 N/mm ²
Compressive strength	fc,0,k	18.00 N/mm ²
	fc,90,k	4.80 N/mm ²
Bending-strength	fm,k	18.00 N/mm ²
Shear-strength	fv,k	3.50 N/mm ²
Modulus of elasticity	E0.05	9500 N/mm ²
Mean modulus of elasticity	E0,mean	8000 N/mm ²
	E90,mean	630 N/mm ²
Shear-modulus	Gmean	590 N/mm ²

3.2 Loads

To better understand the effect of the considered geometric ratios on the behaviour of the three considered roof structures, in both the original state and for the altered layout, a load combination was considered in the numerical simulations which is the combination of the self-weight of the structures, the dead and live load, but also with the specific snow load of the region.

The self-weight of the timber structures was determined automatically by the SICA Engineer simulation software, based on the material density input. Additional dead-load was applied on the rafters, representing the finishing layers. Considering that the roofs are mainly used as storage attics, the live loads on the tie-beam were considered 1.50 kN/sqm, while on the exterior layer of the roof, on the rafters, a live load of 0.5 kN/sqm was applied.

The snow-load was calculated based on national code CR 1–1-3/2012 [16] considering the characteristic values of the location of the buildings to which they belong to in the city and the shape and slope of the roof. Despite the fact that the case study buildings are in similar contexts, the slope of the roofs are very different, reaching from 30° to 46° leading to snow loads of 0.68 kN/sqm in the case of the first roof structure, 1.17 kN/sqm in the case of the second and 0.55 kN/sqm in the case of the third.

4 Results

All three roof structures were evaluated by comparing the displacement of four key points placed along elements that do not suffer any changes from one scenario, to the other. Therefore, two points were considered in the middle of each rafter and two additional points at the base of the two posts in the case of the second and third roof structure and one along the tie beam in the case of the first one. The middle of the rafter was considered a valuable reference point, since it represents the original position of the intermediate purlins, the ones that were later on moved in the altered scenarios (Fig. 4).

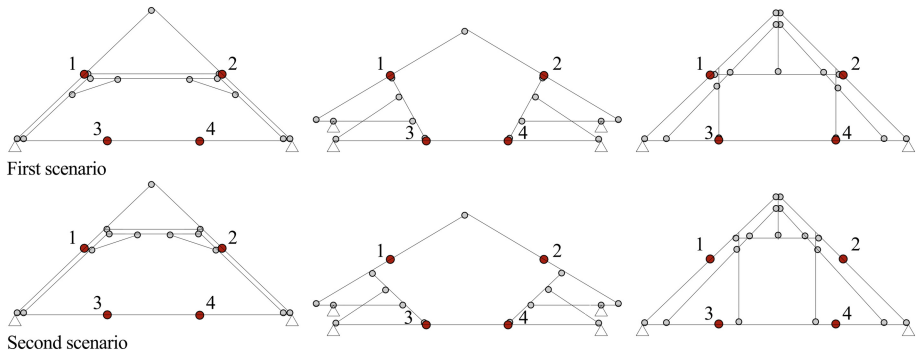


Fig. 4. Points where the displacement was evaluated and subsequently compared

Even from the first visual assessment of the deformed shape of the three roof structures, obtained by using the numerical simulation software, a completely different behaviour could be observed when altering the general position of the main structural elements (Fig. 5).

In the case of the first roof structure, an increase in the deformation of the rafters mainly in their lower third was observed, due to the new position of the collar and the straining beam. Only slight changes in the behaviour of the tie beam were observed. The second roof presented a rather peculiar behaviour, showing a reduction of the deformation in both the rafter and the tie beam area. Ultimately, the third presented a clear increase in the rafter deformation in its lower third, an increase of the tie beam close to the exterior support but a clear decrease of the vertical deformation between the two posts since they were placed closer together in the second scenario.

After this preliminary visual assessment, the horizontal and vertical displacements obtained from the four selected points were analysed and compared to properly understand the influence of valuable geometric ratios on the behaviour of the timber structure.

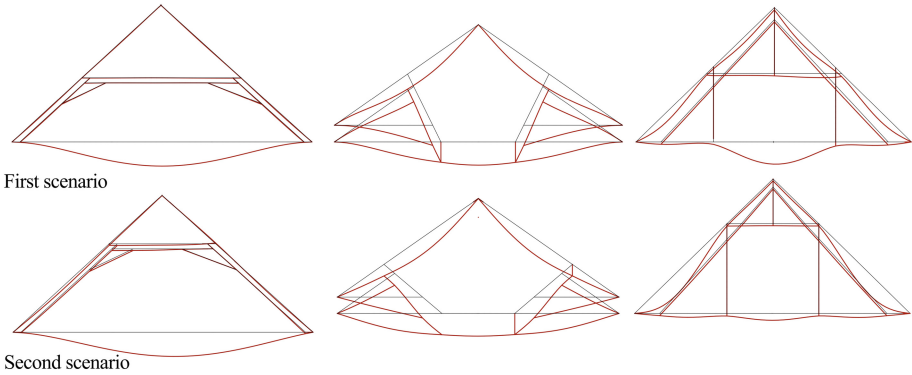


Fig. 5. Deformed roof structures in original (first scenario) and altered form (second scenario)

4.1 Roof Structure 1

In the case of the first case study, a clear increase in all the displacement was observed when changing the ratios off the roof structure (Table 2). When addressing the horizontal displacement of the four points under the applied loads, a significant increase was observed. The increase varies from about 60% up to 10 times in the case of the left rafter. This difference was caused mainly by the fact that the left counterbrace is slightly shorter and has a steeper angle than the right counterbrace. The same can also be said about the vertical displacements which present a 50% increase on the left side and a 70% increase on the right.

As expected by moving the collar and straining beam in the upper third of the roof structure, a higher deformation of the rafters was observed in their lower part since they are no longer supported by the horizontal beams, originally placed in the middle. This additional displacement also leading to an increase in the deformation of the tie beam which has no additional support due to the missing posts.

Table 2. Horizontal, vertical and total displacement results obtained for roof structure 1

Node	Original	Altered	Difference [%]	Original	Altered	Difference [%]
	U_{horiz} [mm]	U_{horiz} [mm]		U_{vert} [mm]	U_{vert} [mm]	
1	0.127	1.425	1022.05%	-0.913	-1.373	50.38%
2	-0.307	-2.511	717.92%	-1.406	-2.263	60.95%
3	0.003	0.005	66.67%	-98.453	-142.755	45.00%
4	-0.003	-0.025	733.33%	-99.18	-171.816	73.24%

4.2 Roof Structure 2

The second roof structure presents, due to its layout, a completely different behaviour from the other two case studies (Table 3). This is caused because the entire roof structure is composed of timber elements that intersect at different points leading to a series of overlapping triangles. The changes made to the position of the upper part of the post towards the lower third of the rafters actually improving the behaviour of the roof structure as a whole. A possible reason might be that by this movement the posts become almost perpendicular to the rafters and therefore ensure, together with all the other structural elements placed close to the building wall, a better load transfer towards the main load-bearing structure.

Displacement analysis has shown an up to 6% decrease of the horizontal and vertical displacement of the middle point of both rafters and an up to 20% decrease of the vertical displacement in the lower part of the post. Since the structure is almost symmetric, no major differences were observed between its left- and right side behaviour under the considered loads.

Table 3. Horizontal, vertical and total displacement results obtained for roof structure 2

Node	Original	Altered	Difference [%]	Original	Altered	Difference [%]
	U _{horiz} [mm]	U _{horiz} [mm]		U _{vert} [mm]	U _{vert} [mm]	
1	28.164	26.399	-6.27%	-39.437	-37.278	-5.47%
2	-28.041	-26.277	-6.29%	-39.681	-37.515	-5.46%
3	0.074	0.086	16.22%	-53.297	-41.967	-21.26%
4	-0.075	-0.087	16.00%	-53.698	-42.312	-21.20%

4.3 Roof Structure 3

The third case study is also highlighting the importance of geometric ratios in the general behaviour of a historic timber roof structure (Table 4). As for the first case study, a 50-fold increase of the horizontal displacement of the rafter points was observed and a four-fold increase in the case of bottom part of the posts. Regarding the vertical displacement, an up to four times increase was observed for the middle point of the rafters and an up to 20% increase for the tie beam nodes. Similarly to the behaviour of the first analysed roof structure, by shifting the collar beam from the middle of the rafters towards their upper third, an increase in the deformation of the rafter was expected and obtained. Additionally, due to the general layout of the roof structure, since the queen posts are connected to the collar beam, by moving the beam the posts had also to be repositioned, leading to wider spans between the post and the exterior support of the structure, ultimately leading to the increase of the displacements in the tie beam area.

Table 4. Horizontal, vertical, and total displacement results obtained for roof structure 3

Node	Original	Altered	Difference [%]	Original	Altered	Difference [%]
	U _{horiz} [mm]	U _{horiz} [mm]		U _{vert} [mm]	U _{vert} [mm]	
1	0.067	3.782	5544.78%	-0.937	-4.916	424.65%
2	-0.718	-3.586	399.44%	-1.719	-4.66	171.09%
3	0.001	0.005	400.00%	-1.502	-1.816	20.91%
4	-0.001	-0.004	300.00%	-2.362	-2.655	12.40%

5 Conclusions

The study is approaching for the first time the link between geometric ratios, a feature which is highly relevant in defining the general layout of roof structures and the position of main structural elements, in all the periods studied in Timisoara and their structural behaviour. It is therefore highlighting that in the case of the considered roof structure types, these geometric ratios were in fact not only connected to the aesthetics of the structural system but are also influencing their structural behaviour. This observation is highly relevant for the general assessment of historic timber roof structures, highlighting that they are very complex systems and that no decision, structurally and aesthetically, was made without considering the other.

At the same time, the study also highlights that this connection is mainly relevant for roof structures containing a collar beam, where load transfer is highly influenced by its position. In the case of the roof structure with no collar beam, despite the fact that originally it presented the most valuable ratios, the geometry proved to not have the expected effect on its structural behaviour.

The results obtained are highly relevant for intervention works in heritage roof structures, with the main aim of reusing these spaces. Since the collar beams are in most cases placed at an inconvenient height, making the reuse of the attic space difficult, interventions strategies focus on moving the collar beam to a more suitable position which can have a negative impact on the future deformation of the structure and ultimately on the load transfer towards the main load bearing structure. It shows that restoration engineers should consider this feature when addressing this type of timber structure.

However, further studies are still necessary to completely understand the link between these complex ratios and the structural behaviour of other types of timber roof structure and a more comprehensive research is still necessary to understand these structures as a whole.

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