ANALELE UNIVERSITĂȚII
"EFTIMIE MURGU" REȘIȚA
ANUL XX, NR. 3, 2013, ISSN 1453 - 7397

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Issues Regarding the Mechanical Behavior of the Romanesque Roof Structure - Lutheran Church of Sebeș

In Transylvania only a few historical roof structures with romanesque character are still preserved, most of them with several structural degradations. The comprehension of mechanical behaviour of these structures makes it easy the work of monuments specialist in terms of diagnosis and structural prediction. In this paper is analyzed the roof structure placed over the main nave of Lutheran Church of Sebeș (Alba county- Romania), pursuing the influence of his constitutive elements regarding the structural stability at dead loads and non-gravity loads.

Keywords*: historic monuments, historic roof structure, roof structures with a romanesque character, mechanical behavior*

1. Introduction

A representative monument of religious architecture in Transylvania, the Lutheran Church of Sebes has a complex structure, whose construction, started in the first half of the thirteenth century, was completed around the year 1460 to 1470. The type of the main body of the building is basillical, with a central nave higher than the flanking aisles. On the easterly direction, the central nave is continued by a gothic chancel from fourteenth century.[1],[2] This one impresses with its planar dimensions and with the height that exceeds that of the main nave. In the western parte of main nave, the building is completed with a main tower flanked by two small towers. The roof structure placed over the main nave is the subject of this paper.

2. Structural design of the roof structure

Over the main nave there is a roof structure with romanesque character, made up from identically main trusses, relatively closed placed one to each other, without longitudinal bracing frames.

Figure 1. The roof structure with romanesque character-Lutheran Church of Sebes

Each truss is made up of a triangular frame consisting of tie beam and two common rafters, inside which are orderly placed several pieces of wood: collar beam, rafter braces and angle braces.

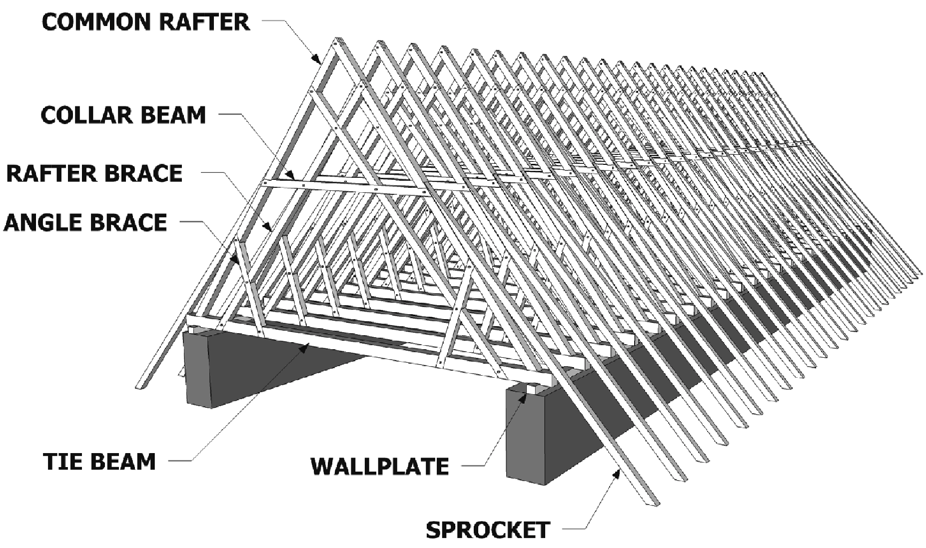


Figure 2. Elements of the roof structure

Outside of the triangular frame are placed the sprockets, which are extended over the flanking aisles. The loads taken by trusses are transmitted to the supporting load-bearing walls through the simple wall-plates.

2.1. The geometry of roof structure

The roof structure covers an area with a length of 23.58 (m) and a width of 7.81 (m), having a height (from the bottom of the tie beam) of 5.65 (m). The distance between the trusses are not equal, being in the range of 0.67 ÷ 1.17 (m). The distance between wall plates is 7.97 (m), and its slope is 53 °.

Table 1.

Element name	**Lenght (m)**	**Cross section (cm)**	**Slope**
Common rafter	6,81	16 x 15	53°
Tie-beam	8,76	22 x 18	0°
Collar beam	4,07	14 x 14	0°
Rafter brace	6,38	15 x 13	50°
Angle brace	2,11	11 x11	73°
Sprocket		14 x 14	48°
Wall-plate	23,58	14 x 17	0°

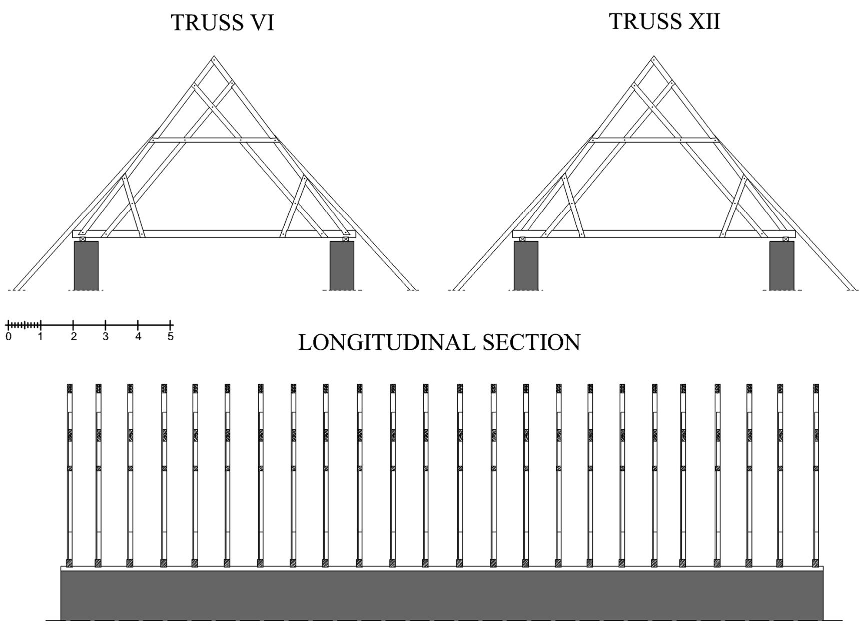


Figure 3. Roof structure drawings

2.2. Roof structure carpenter's joints

The type and the workmanship of joints affect the structural behavior of the trusses the roof structure. In this roof structure there are the following kinds of carpenter's joints:

- Joints for the lengthening of the wall-plate
- Half lap joints reinforced by oak peg – between common rafters and tie-beam
- Dovetail half lap joints reinforced by oak peg – between common rafters and rafter braces, common rafters and angle braces, common rafters and collar beam, tie-beams and angle braces, and between tie-beam and rafter braces
- Mortice and tenon joints – between common rafters and tie-beams
- Mortice and tenon joints reinforced by oak peg – between common rafters and tie-beams, between common rafters
- Notched joints – between tie-beams and wall plate
- Notched joints reinforced by oak peg – between angle braces and rafter braces, rafter braces and collar beam, and between rafter braces

Figure 4. Carpenter's joints

2.3. Material used

Following the researches, three types of wood have been identified in the roof structure:

- The oak wood (Quercus sp) – in the wall plates
- The pine wood (Abies Alba Mill) and the Spruce wood (Picea Abies Karst) in the other elements[3]

The wood was processed primarly by hewing with an axe. There are few elements processed by saw, inserted following the subsequent interventions.

3. Dating of the roof structure

This roof structure is not original, some reused elements being identified in the current structure. Other assumptions that support this theory are related to the geometrical non-conformities encountered at notched joints, the typology of carpenter's joints between common rafters and tie-beams, but also by an inscription engraved on the truss VI - northern rafter brace indicating 1671.

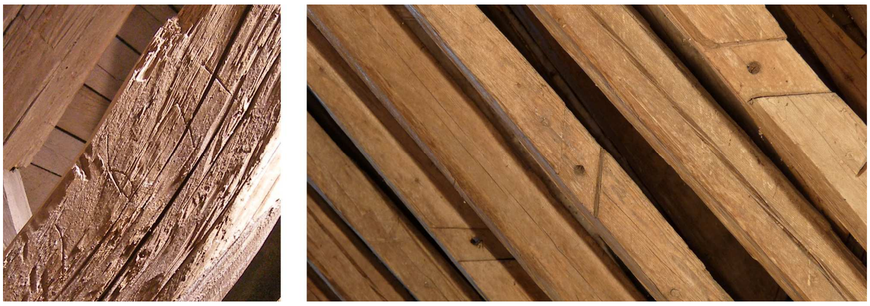


Figure 5. (left)The inscription engraved on the farm VI, (right) Re-used elements

Dendrochronological analysis carried out in the year 2012 has revealed the existence of elements dating from the years 1370 to 1392 at trusses VII and VIII, but also the elements dating from the first half of the seventeenth century.[3]

4. Mechanical behavior of roof structure

A series of computational tests at dead loads and non-gravity actions were performed in order to identify the mechanical behavior of the roof structure. Two load cases are considered:

- load case 1 (LC1) - dead loads in combination with snow loads
- load case 2 (LC2) - dead loads in combination with wind loads

The static analysis was done through AXIS VM structural analysis software based on the finite element method, using the planar model represented by the truss. The planar model was discretized into linear elements connected at their nodes by hinges. The dimensions of elements were obtained based on precise roof survey performed in-situ. The material was modeled as being linear elastic and ortotropic. The connection between trusses and supporting load-bearing walls was considered by simple support. The loadings were established in compliance with Eurocode 1 and Eurocode 5.

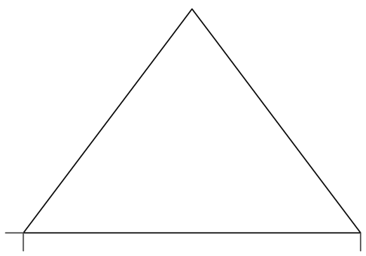
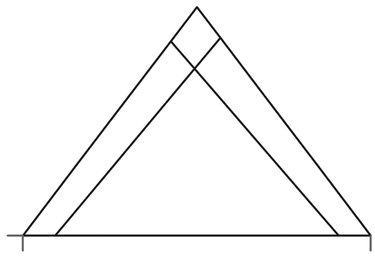
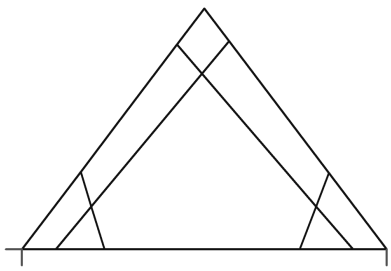
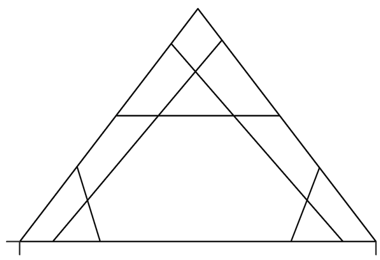
Structurally, this roof structure represents a spatial system made up of planar sub-units, interconnected by the elements supporting the covering. Due to the lack of separate system for providing structural stabilization in the longitudinal direction, this roof structure has a low spatial stiffness.

On the longitudinal direction the roof structure is reinforced through the elements supporting the covering which creates together with the covering a stiff plane. The presence of masonery gables at the ends of the roof structure, the covering system fixed in the masonery gables, the placement of first and last truss at a short distance from the masonery gables, all of these provide an additional stiffness.

On the crosswise direction, the stability of roof structure is provided by trusses and their structural design.

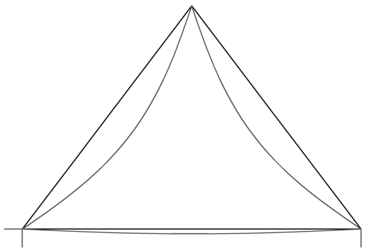
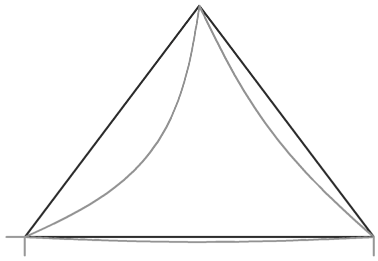
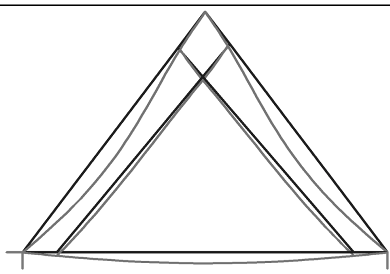
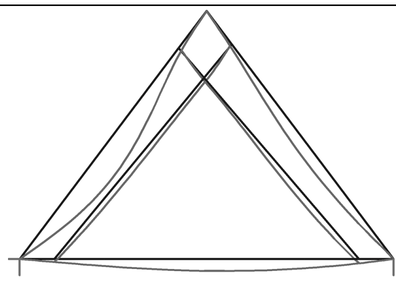
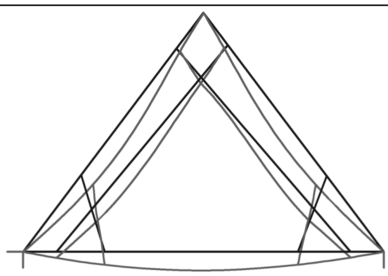
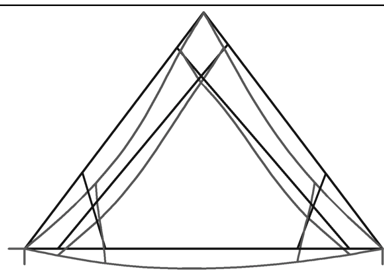
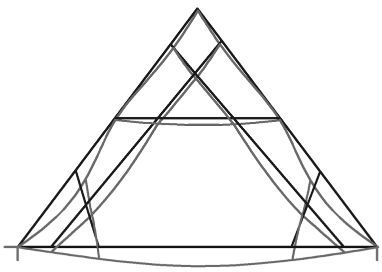
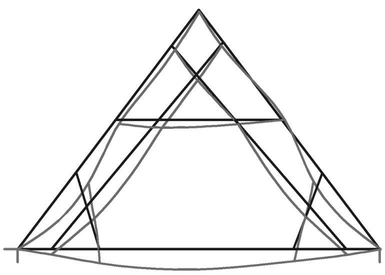
Structural analysis of the truss was performed on four models representing the stages of truss assambling. (view Table 2)

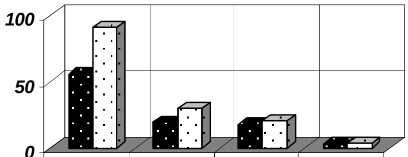
Table 2

Undeformed models	
Model I	Model II
	
Model III	Model IV
	

The first model is the simplest one, being made only by common rafters and tie-beam. The second model has in adition rafter braces. The third model has in adition to previous model angle braces. The latest model is completed by collar-beam and this one represents the final configuration of truss.

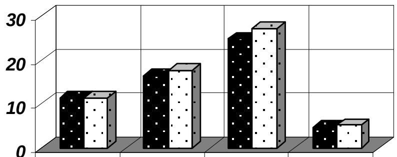
Table 3.

	LC1-Dead loads and Snow loads Deformations of truss members	LC2-Dead loads and Wind Loads Deformations of truss members
Model I		
Model II		
Model III		
Model IV		



	Model I	Model II	Model III	Model IV
■ Dead loads and Snow loads	55,652	19,187	17,715	2,859
□ Dead loads and Wind loads	90,992	29,756	20,493	3,469

Figure 6. Maximum deformations of common rafters (mm)



	Model I	Model II	Model III	Model IV
■ Dead loads and Snow loads	11,339	16,438	24,876	4,762
□ Dead loads and Wind loads	11,339	17,669	27,119	5,111

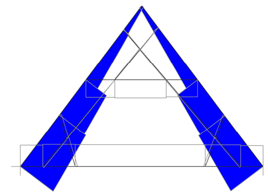
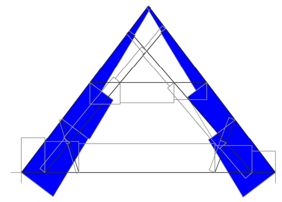
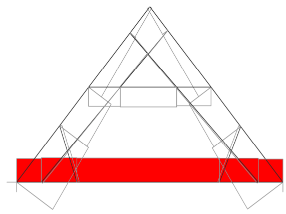
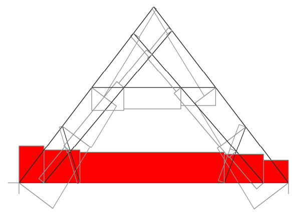
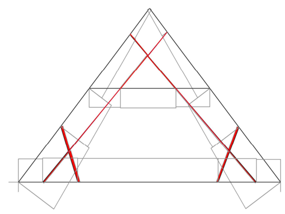
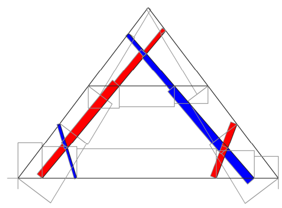
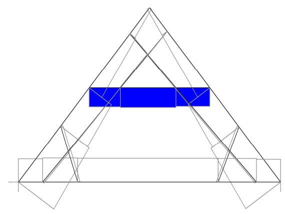
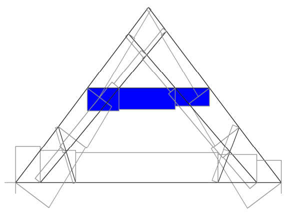
Figure 7. Maximum deformations of tie-beams (mm)

Under the action of forces in crosswise direction, the common rafters have tendency to bend, the elements placed adjacent to them exerting a less or higher influence in reduction of bending.

As can be seen in Figure 6 and 7, the maximum deformation in common rafters and tie-beams are coming from non-gravity actions, of short duration. At both load cases the highest deformations of common rafters occur on the first model. The lowest deformations in common rafters occur on the last model (Model IV).

By succesive insertion of truss elements can be observed a significant decrease in common rafters bending. Thus, in the load case 1(LC1) the deformations of the rafters are reduced by 68% through the using of rafter braces, by 77% when the angle braces are inserted and by 96% in the case of the last model, with collar beam inserted. In the load case 2 (LC2) the rafter braces reduce the common rafters deflections by 65%. Deformations are 68% reduced by using of angle braces and 95% in the model with collar-beam. Regarding the tie-beam, its deformations grow successively with the insertion of rafter braces and angle braces. When the collar beam is used – connected to the common rafters and rafter braces the deflection of tie-beam decreases by 81% compared with the highest value recorded at Model III.

Table 4.

Axial forces in truss members of Model IV		
COMPRESSION TENSION	LC1 Dead loads and Snow loads	LC2 Dead loads and Wind Loads
Common Rafters		
Tie-beam		
Rafter Braces and Angle Braces		
Collar beam		

By analyzing the above diagrams can be observed the following issues:

- In the case of dead loads, the collar beams have a more important role than the rafter braces in stabilizing of trusses. Even in the absence of rafter braces and angle braces, the collar beams provides a reduction in bending rafters by 90% compared to the Model I. The rafter braces, being in tension, ensure the stabilization of collar beams and tie-beams. The role of angle braces in reducing of common rafters bending is insignificant compared with collar beam.

- In the case of non-gravity actions, the rafter braces have a significant role in stabilizing of trusses. In the final configuration of the truss, the use of collar beam provides, in turn, a significant decrease in deformation. Usually, in the case of non-gravity actions, the interposition of collar beams between the rafters leads to an almost equally deformation of the common rafters towards the action direction. At this roof structure, following the connection between collar beam and rater braces, the common rafters deformation is greatly reduced. Angle braces have a more important role in stiffening of common rafters - tie-beam connection, than in reducing of bending.

5. Conclusion

The lowest deformation in trusses at crosswise actions are owed by the elements intuitively placed by carpenters in frame and which creates a stiff network. Without the use of these elements, the stability of triangular frame made by tie beam and two common rafters is much diminished. By using of combination of collar beams, rafter braces and angle braces, is provided an effective solution in terms of structural stability.

ACKNOWLEDGMENT: This paper was supported by the project "Improvement of the doctoral studies quality in engineering science for development of the knowledge based society-QDOC" contract no. POSDRU/107/1.5/S/78534, project co-funded by the European Social Fund through the Sectorial Operational Program Human Resources 2007-2013

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