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Carving joints for wood constructions. Calculation models

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Abstract

Romania is the only country in the world that has a large patrimony of wooden churches. These churches are historic monuments. Over the years, these buildings have been subjected to many actions that led to a degradation of structural elements and also to the degradation of joints between structural elements. Carving joints are predominant for this type of buildings. For the rehabilitation of this type of joints it is necessary to restore them and implicitly to know their behaviour and failure modes.

The article presents the evaluation of wood carving joints with simple threshold using analytical calculation and numerical modelling.

Keywords: carving joints, rehabilitation, analytical calculation, finite element.

1. INTRODUCTION

The wood is used from ancient times to the construction of bridges, houses, churches and many other applications in civil, industrial and agricultural structures. Wood can be easily used for resistance structures of tall buildings, over 7 or 8 floors, even 10 floors (ex. Residential building in Melbourne, Australia). In the future, large projects with buildings made of wood with 18 levels in hybrid system will be implemented.

In Romania an important activity is the restoration of numerous churches and residential buildings declared historical monuments, where wood is used as building material for the resistance structure. In Maramures County there are 93 wooden churches declared historic monuments. Eight of them were chosen to be part of UNESCO World Heritage, [5]. Some of these are: church "Sfantul Nicolae" from Budesti-Josani (year of construction: 1643), Figure 1, [6], church "Cuvioasa Parascheva" from Desesti (year of construction: 1717), Figure 2, [7], church "Sfanta Maria" from Ieud-Deal (year of construction: 1364), Figure 3, [8], church "Cuvioasa Parascheva" from Poienile Iezei (year of construction: 1602), Figure 4, [9].

Figure 1. Church "Sfantul Nicolae" from Budesti-Josani

Figure 2. Church "Cuvioasa Parascheva" from Desesti

Figure 3. Church "Sfanta Maria" from Ieud-Deal

Figure 4. Church "Cuvioasa Parascheva" from Poienile Iezei

Wooden buildings declared historical monuments can be made entirely of the wood elements (columns, beams, rafters, ridge, props etc.) or with only the roof structure made of the wood. These constructions are characterized by wooden joints technique, and by achieving shingled roof, ornamental motifs visible on the surface portals and frames made by chiselling or notching, Figure 5.

Figure 5. Wooden parts of church monuments

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Wooden churches represent the spiritual roots of Romania. Preserving them requires, in most cases, trans-disciplinary knowledge that combines tradition expressed by sustainability, and a combination of advanced methods of calculation.

2. CARVING JOINTS TO WOOD CONSTRUCTIONS

2.1. Wood as a building material

Due to its properties as a building material and the possibilities of supplying and ease of processing, wood was in the past, the most utilized building material. Due to its multiple technical and constructive advantages, the wood is, and it has been, one of the traditional construction materials. The constructions of wooden structural frame are based on an advanced design technique which gives them certain advantages in terms of structural strength, human comfort and energy savings. Wood is durable over time with exceptional strength, and this is shown by the buildings from around the world, [10]. The main qualities of wood as a building material are:

- Low characteristic density, 3.6 times less than steel.
- Quite high mechanical resistance in tensile and compression, parallel to the fibers (grains), and for transverse loads which produce bending.
- Coefficient of thermal expansion along the fibers is very small and, consequently, wooden structures do not require expansion joints.
- Dry wood has a low thermal conductivity coefficient, [1].

2.2. Wood carving joints

The elements of a wood structure, (pillars, beams, rafters, props etc.) are connected together to form the structural frame. The joints may be of the following types: wood carving joints, joints with metal connectors, mechanically dowelled fasteners joints, or joints with adhesives. One type of joint, commonly used in old buildings, is the wood carving joint. Wood carving joints are found in most roof structures of the buildings made in 16-19 centuries. Over the years these buildings were subjected to numerous actions: service loads, wind, snow, earthquake, and they produced damages to structural elements and also degradation of the joints between structural elements. In many cases, it is necessary to strengthen the structure. Rehabilitation of wooden buildings declared as monuments must keep the same architecture and technology of execution so that significant values for history and culture of national civilization should not be altered. In strengthening of wooden constructions special problems occur in achieving specific traditional joints–carving, which are no longer found in modern manufacturing technologies, and thus, in the technical regulations calculus. Restoring this type of connections require a deep analysis for sizing and load bearing capacities. Therefore it is actual

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the understanding and knowledge of these specific types of joints for old wooden buildings. Wood carving joints are the joints where the stress is directly transmitted from one element to another, without the use of intermediate connectors. The metal devices used in these joints (bolts, clamps, yokes etc.) play only a secondary role, preventing relative movement of the connected elements under the action of unforeseen loads calculations, either during installation or during operation.

3. MODELS FOR EVALUATING BEARING CAPACITY OF CARVING JOINTS WITH SIMPLE THRESHOLD AND ORTHOGONAL CUTTING

3.1 Description of the connection type

Simple threshold joints (Figure 6) are used in timber constructions, especially for joints of timber framed roof structures. In order to achieve an acceptable behaviour in service, for carving joints with simple threshold and orthogonal cutting, certain conditions are imposed, namely:

- If the cutting is made at end nodes, in order not to weaken the piece, the depth of the cut - h_c, should not exceed one third of the height - h of the element (for rectangular cross-section of wood elements) or one third of the diameter - d, (for round cross-section of wood elements);
- If the cutting is made at intermediate nodes, in order not to weaken piece, depth of cut - h_c, should not exceed one quarter of the height - h, of cutting element (for rectangular cross-section of wood elements) or one quarter of the diameter - d, (for round cross-section of wood elements);
- In all cases, h_c, must be at least 2 cm for rectangular cross-sections and 3 cm for round cross-sections;
- To avoid the cracking development due to shrinkage, the length of the shear plane, L_f, must be greater than twice the height - h, of the element and at least equal to ten times the depth of the cut - h_c;
- For a better connection, the elements (during assembly, transportation and installation) are connected together by a bolt that also acts as a safety element.
- To create a bearing surface for the washer bolt tight, in order not to make another cut in the beam, under the beam is installed an additional support which increases the load capacity of joints, [2].

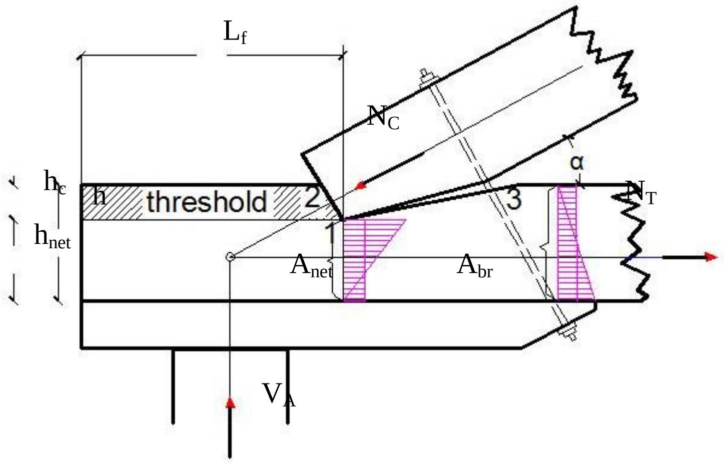

Figure 6. Carving joints with simple threshold and orthogonal cutting. Diagrams of normal stress distribution.

In Figure 6 it is seen how the crushing of the contact surfaces of the two elements takes place under the same angle (combination of equal resistance) and the axial force N_c of the compressed top beam (top chord of wooden truss) is taken both by surface 1-2 and by 1-3 also.

Figure 7 shows that the flow lines of stresses are developed in a single direction (linear stress development).

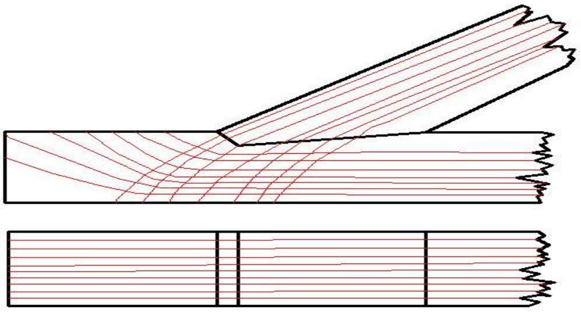

Figure 7. Isostatic flow stress lines for carving joints with simple threshold and orthogonal cutting

This represents an advantage compared to other types of connections where the flow lines of stresses are developed in two directions (plan stress development as in lateral carving joints or joints with spigots).

3.2 Analytical models to assess the load carrying capacity of carving joints with simple threshold and orthogonal cutting with limit states method

Carving joints with simple threshold and orthogonal cutting may lose load carrying capacity when one of the following limit states occurs:

1. Compression to an angle of the threshold
2. Development of slipping plan due to the shear stresses in the threshold
3. Failure of the bottom chord due to tensile stresses

Load carrying capacity of the joint is analytically determined according to European standard EN 1995-1 / 2004, [4].

3.2.1. Evaluation of load carrying capacity in compression

The strength condition is shown in equation 1:

$$N_s = N_c cos\alpha \leq m_c f_{c,\alpha,d} A_s \tag{1}$$

Where:

- N_s is the compression force acting to an angle;
- N_c is the compression force
- m_c is the factor for compression;
- A_s is the compression surface, calculated with the following relationship:

$$A_s = \frac{bh_c}{cos\alpha} \tag{2}$$

- $f_{c,\alpha,d}$ is the design resistance to compression to an angle α, determined according to the next relationship:

$$f_{c,\alpha,d} = \frac{C_{ri} Q_{ri}}{C_{ri} \sin + Q_{ri} \cos^2 \alpha} \tag{3}$$

$$C_{ri} = f_{c,0,d} m_{TC} = k_{\text{mod},c} \frac{f_{c,0,k}}{\gamma_M} m_{TC} \tag{4}$$

$$Q_{ri} = f_{c,90,d} m_{TC} = k_{\text{mod},c} \frac{f_{c,90,k}}{\gamma_M} m_{TC} \tag{5}$$

where:

C_{ri} is the design tensile stress along the grain

Q_{ri} is the design tensile stress perpendicular to the grain

m_{TC} is the factor for tension;

$k_{mod,c}$ is the modification factor for duration of load and moisture content

$f_{c,0,d}$ is the design compressive strength along the grain

$f_{c,90,d}$ is the design compressive strength perpendicular to the grain

$f_{c,0,k}$ is the characteristic compressive strength along the grain

$f_{c,90,k}$ is the characteristic compressive strength perpendicular to grain;
γ_M is the Partial factor for material properties, also accounting for model uncertainties and dimensional variations.

3.2.2. Evaluation of load carrying capacity in shear

The strength condition is shown in equation 6:

$$N_s \leq m_f f_{v,d} A_f \tag{6}$$

where:

- N_s is the compression force acting to an angle;
- m_f is the shear coefficient for working conditions;
- A_f is the shear surface, $A_f = bL_f$;
- $f_{v,d}$ is the design shear resistance.

The distribution of the shear stresses is shown in Figure 8.

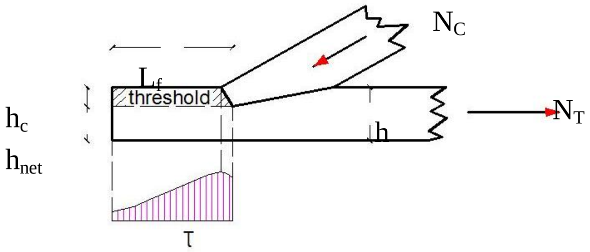

Figure 8. Diagrams of shear stresses in the shear plan

3.2.3. Evaluation of load carrying capacity in tension

- If the tensile force passes through the centroid of the net cross-section:

$$N_T \leq m_t f_{t,0,d} A_n \tag{7}$$

- If the tensile force doesn't pass through the centroid of the net cross-section:

$$\frac{N_T}{m_t A_n f_{t,0,d}} + \frac{N_T e_t}{m_m f_{m,d} W_n} \leq 1 \tag{8}$$

where:

- N_T is the tensile force;
- A_n is the net area;

- $f_{t,0,d}$ is the design tensile resistance;
- $f_{m,d}$ is the design bending resistance;
- m_t is the factor for tension;
- m_m is the factor for bending;
- W_n is the elastic section modulus.
- e_t is the offset distance of the load relative to the vertical portion of the element

3.3 Finite element numerical models for studying the behaviour of carving joints with simple threshold

The finite element analysis (FEA) has been made using the software program ANSYS-12. The models for the carving joint were developed in two situations:

- Case A: the two wooden bars of the carving joint have been defined as two distinct solid bodies, Figure 9;
- Case B: the two wooden bars of the carving joint have been defined as one solid body, Figure10.

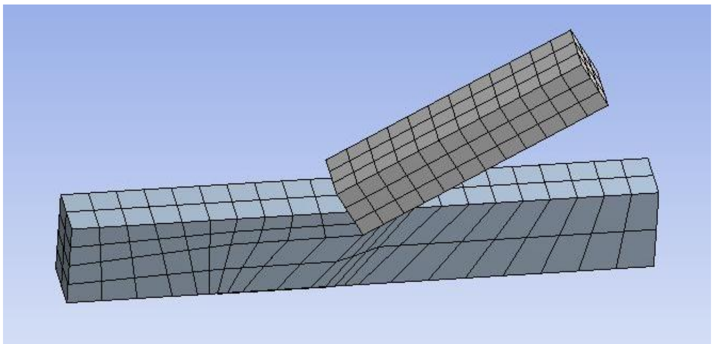

Figure 9. Case A, the two wooden bars of the carving joint with a contact area

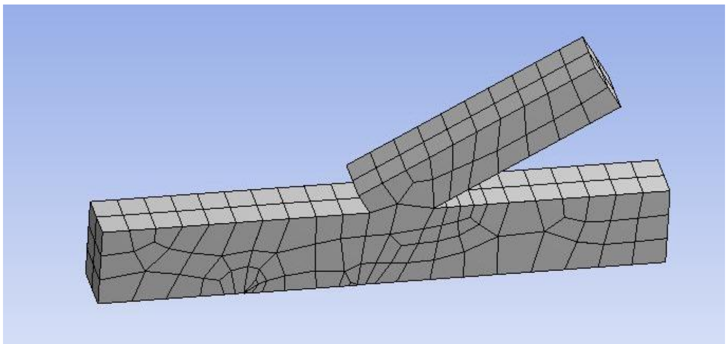

Figure 10. Case B, the two wooden bars of the carving joint defined as one solid body

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4. STUDY CASE FOR THE ASSESSMENT OF THE LOAD CARRYING CAPACITY OF CARVING JOINTS WITH SIMPLE THRESHOLD AND ORTHOGONAL CUTTING

The study case presents the assessment of the carrying capacity of a carving joint from a roof truss made of wood elements, with the geometric scheme presented in Figure 11, having the following data:

- The span of the truss: 10.50 meters
- The height of the truss: 3.00 meters
- The truss bay: 3.00 meters

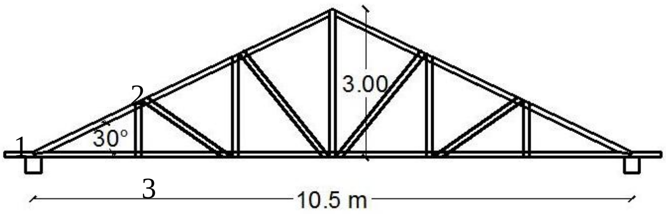

Figure 11. Geometric scheme of the wooden truss

The building is located in Iasi. According to the design code CR1-1-3-2012, “Snow action assessment for buildings”, [3], characteristic values of snow load on the ground is $s_k = 2.5$ kN/m2, [3].

The structure is subject to the following loads: the dead load (roofing self-weight, and the weight of insulation, bracing, roof deck, etc.) and the snow load. It's analysed the end joint where the connection is made by carving joints as shown in Figure 6.

The beams connected in the joint are defined: 1-2 for the upper beam (top chord) and 1-3 for the lower beam (bottom chord). First, an analytical study has been performed.

Table 1 shows the values of the internal forces and the normal stresses. These values were determined by analytical calculation, for the previously considered loading scenario.

Table 1. The internal forces and the normal stresses

Beam	Cross section (mm x mm)	Axial forces (N)	Normal stresses (MPa)	Compression stresses to an angle (MPa)
1-2	100x100	-94000	-9.4	-18.8
1-3	200x100	87000	11.6	

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The stresses obtained from analytical calculation are compared with the results provided by the finite element analysis performed with ANSYS-12 software. The results obtained for 3D models using the finite element analysis are presented in Figure 12 and Figure 13 for case A. For the analysis of case B the results are shown in Figure 14 and Figure 15.

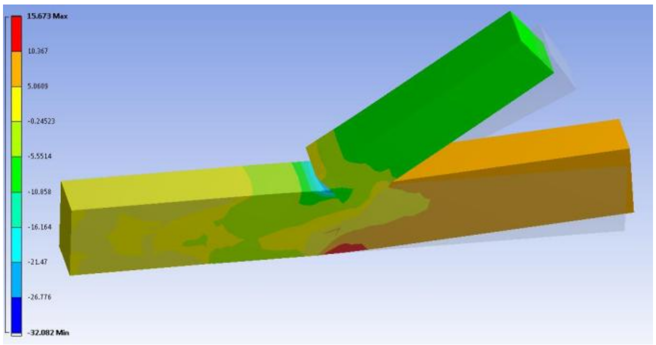

Figure 12. Normal stresses diagram for case A – FEA model

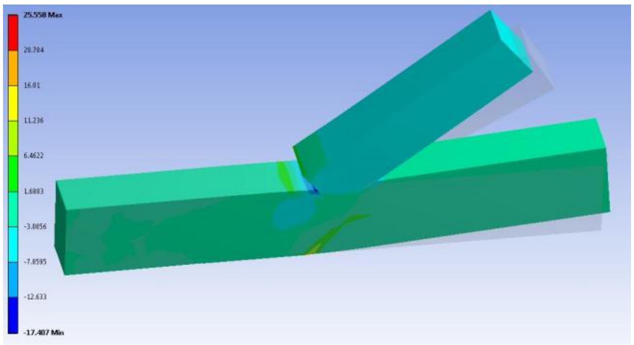

Figure 13. Shear stresses diagram for case A – FEA model

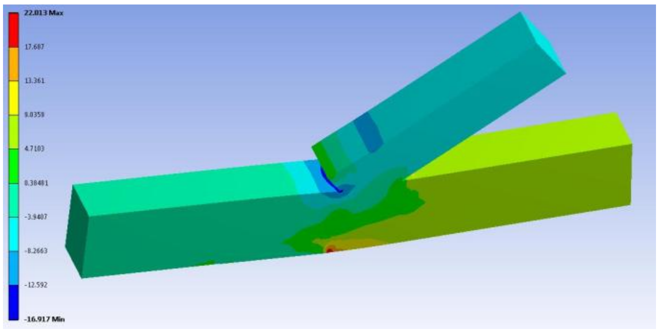

Figure 14. Normal stresses diagram for case B – FEA model

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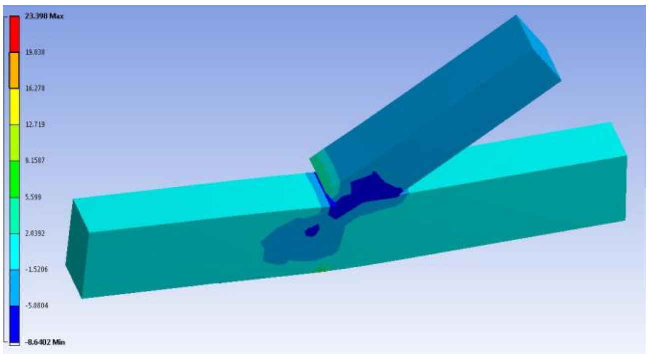

Figure 15. Shear stresses diagram for case B – FEA model

The resulted values from the finite element analyses, for the 3D models, are shown in Table 2.

Table2. Normal stresses and shear stresses for the modelled cases

Case	Maximum tensile stresses (MPa)	Maximum compression stresses (MPa)	Maximum shear stresses (MPa)
Case A	15.673	-32.082	25.558
Case B	22.013	-16.917	23.398

The results, obtained in FEM - case B, approached the analytical values, highlighting that the analytical model is based on the hypothesis of structural continuity between wood elements in carving joints.

In reality, the existence of imperfections in execution causes some gaps between the two wood elements, leading to the idea that FEM - case A is the model that could define the behaviour of the connection under loads, and also defines the development of stresses in the wood elements.

5. CONCLUSIONS

The carving joints are less used these days because they have disadvantages that influence choosing this type of joints. The joint technology reduces the section of elements, so it reduces the load carrying capacity of the element. The technology of fabrication is quite difficult, and it is time consuming and requires qualified workers.

Nowadays, there are many situations when the rehabilitation of joints is needed in buildings such as the historical monuments; therefore it is necessary, in order to strengthen them, to know how to evaluate rapidly the behaviour of structural elements and their joints for a correct sizing and for the strength checking.

The aim of the study was to present a comparative study case between the results of the analytical model and the finite element modelling cases for the evaluation of the carving joint with simple threshold. The comparative analysis of the obtained results highlights the following issues:

- The finite element modelling (FEM) of carving joints is possible.
- The fields of stresses obtained by FEM meet the isostatic flow lines of stresses for carving joints defined in classical theory for the assessment behaviour under loading conditions.
- Future research is required for refining the grid for FEA models and to validate the proper finite element model by experimental testing of the carving joints.

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