ASSESSING HISTORIC TIMBER ROOF STRUCTURES
Methodology and Case Studies from a Belgian Viewpoint

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The load bearing capacity of timber roof structures is looked at based on visual inspection, on site material investigation and structural analysis. This article focuses on the extent in which current European standards and guidelines are useful in the assessment of the actual safety, reflecting experience from several case studies. Attention goes to the applicability of standards for safety assessment of historical structures, limitations of numerical tools in the structural analysis, the impact of lack of knowledge, material data, geometry and other information. The Overall impressions reflect the findings from case studies treated in Romania, namely: the choir of the evangelical church at Drăuşeni, the house nr. 22 at Piaţa Mică at Sibiu and others located in Belgium, such as the Saint-Jacobs church at Leuven.

1. Introduction

Safety is a key issue in the preservation of our built, cultural heritage. Both ISCARSAH Recommendations (ISCARSAH, 2005) and ISO13822 cover the assessment of existing structures. The ISCARSAH recommendations are set align with ISO13822. Vice versa, a Historical Structure Annex to the standard ISO 13822 is in preparation to provide additional considerations towards its application for historical structures. The annex covers the special characteristics of historical structures, including elements related to structural analysis and target reliability level. Further activities within this field are developed by Workgroup 20 “Wood and wood based materials” of the Technical Committee UNI/NORMAL in Italy. In 2004 it has developed two standards which embrace the problems of diagnosis through visual inspection and of the intervention criteria on ancient timber structures to be restored (UNI 11119, 2004; UNI 111138, 2004). Rilem TC 215 AST “In situ assessment of structural timber” brings together leading scientists and practitioners in the field of in-situ evaluation of physical and mechanical properties of existing structural timber elements (Kasal, 2008a).

All standards refer to a sequence within the preservation process, often referred to as: anamnesis and analysis, diagnosis, therapy, control and prognosis. In all comparable flow charts, it is in the detailed analysis phase that the reliability question is put forward. Is there a need for intervention, is the actual reliability sufficient? From practice, both in Belgium and abroad, it is clear that for historical timber structures this assessment is not straight forward and requires a lot of expertise in different engineering areas.

In the subsequent sections, attention goes to the overall sequence within the assessment framework from the perspective of historical timber structures and the experience gained in case studies treated recently:

- Belgium: Churches at Leuven: Saint-Jacobs (Schueremans et al., 2007), 17th century abbey barn “Tiendenschuur” at Herckenrode (Brosens et al., 2005), abbey barn and farm wing at Park Abbey at Heverlee (Ignoul et al., 2005);
- Romania [Magnus, 2008]: Church of Drăuşeni, Roof structure of a dwelling (block B) at the Piaţa Mică nr.22 at Sibiu (Magnus, 2008).

Fig.1. Romanian case studies - Church of Drăuşeni and roof structure of a dwelling (block B) at the Piaţa Mică nr. 22 at Sibiu

For specific information related to these case studies, the reader is referred to the references indicated. This text summarizes overall findings and mainly focuses on the Romanian case studies.

2. Anamnesis

Historical research reveals a lot of information related to the construction (technology), the conception and the significance of the building, the techniques and the skills used, the subsequent changes in both the structure and its environment and any events that may have caused damage, notification of malfunctioning, repairs, materials used and others.

(Visual) inspection of the structure is carried out to obtain an initial understanding and to give an appropriate direction to subsequent investigation. The main goal is to identify decay and damage, to retrieve whether the phenomena have stabilized or not and to determine whether or not urgent measures have to be taken because of possible immediate risks. Up till now, it can be seen as the most powerful non-destructive technique. A proper documentation, including graphs, drawings, photographs, is crucial to be useful afterwards within the structural analysis. As an example, Figure 2a reports a cross-section of the main truss (MT) and Figure 2b the comprehensive representation of the onsite inspection of the gothic timber structure of the Church of Drăuşeni, built at the end of the 13th century in a village in the actual county of Braşov in Romania.

Field research and *laboratory testing* are carried out to gain information about geometry, mechanical, structural and chemical material characteristics, stresses and deformation and discontinuities within the structure. A list of possible on site techniques is given in Table 1 (Magnus, 2008; Kasal 2008b).

It is clear that several of these tests are rather intrusive or relatively expensive, and therefore are seldom applied. Besides visual inspection, mainly resistance drilling (Resistograph®) and core drilling (Zaphenschneider) are used frequently within research projects in Belgium, Figure 3.

Method	Information	ND/SD/D
Visual inspection	Geometry, rate of growth, natural and mechanical/structural defects, …	ND
Stress and acoustic waves	Dynamic modulus of elasticity, internal defects	ND
Electric resistivity	Moisture content measurement	ND
Radiography – X-ray	Visualization of internal elements (screws, connection pieces), knots, voids, structural defects…	ND
Infrared thermography	Imaging of local moisture concentration, internal knots and voids, structural defects, decayed wood…	ND
Species determination	Determination of specious	ND
dendrochronology	Determination of age	ND
Endoscopy - videoscopy	Internal inspection of knots and voids, structural effects, decay of wood	SD
Resistance drilling (Resistograph ®)	Density and defects	SD
Core drilling (Zaphenschneider)	Core diameter is limited: 5-10 mm Used for compressive, tensile strength and Young's modulus	SD
Pin penetration resistance	Density and surface damage	SD
Specimen extraction	Extraction of cores or prismatic specimens for laboratory tests	D
Full-member tests	Mechanical properties of full-members	D
Standard tests of mechanical properties	Bending tests, compressive or tensile tests until specimen failure to obtain experimental data on ultimate strength	D

Table 1 Classification of methods for in-situ timber evaluation (Kasal 2008b; Magnus, 2008)

3. Analysis

Within the structural analysis of the historic timber structure, a model is built, Figure 4. Of course at all time, the structural model is a compromise between a scheme close to reality, but too complex to calculate and a scheme, easy to calculate, but far away from reality. The better the model is in line with reality, the more reliable the diagnosis will be. Therefore, a step-by-step procedure within the modeling is used. Initially, with the information available from a visual inspection, a first structural model is made, often not accounting for detailed information on material degradation, missing structural elements, actual deformed shape of the structure. The outcome results of the structural model are compared with the deficiencies identified on site. This initial analysis is worth full since it better aligns additional research efforts.

The updated model therefore should ideally account for:

- overall geometry of the timber roof, cross-sections of the structural elements, nodal details, displacements, missing elements, structural interventions, alterations and weakening;
- actual material properties, taking into account the rate of decay (mechanical and physical-chemical-biological), instead of the material characteristics specified in the original design or provided by codes;
- the correct nature of connections and boundary conditions, including differential settlements of the supports;
- the uncertainty associated with the validity and accuracy of the models

In general, following remarks can be made:

- The structural analysis software used (Powerframe, Buildsoft nv) is mainly developed for the design of new timber structures, according to the limit states design principles, using partial safety factors;
- There is no software available that accounts for the time dependent (creep) behavior of timber. The general frame analysis software mainly used within practice does not account for the non-isotropic material characteristics of the timber.

Within the analysis different types of nodes are encountered. The outcome of the analysis results strongly depend on the nodal stiffness assumed and their actual restrained, Figure 5.

The connection between upper plate and collar beam plus queen post on the one hand and lower plate and queen post and tie beam on the other hand are modeled only to work in compression. Tensile forces are not transferred, Figure 6.

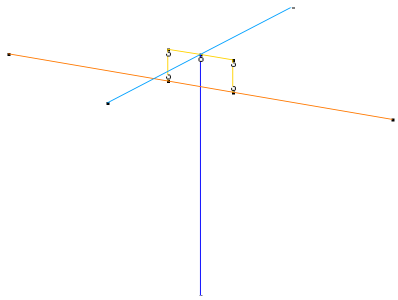
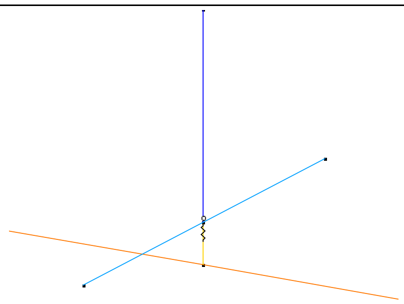
Joint	*Model*	*Example on site*
Connection between upper plate, collar beam and queen post		
Connection between lower plate, tie-beam and queen post		

Table 2 Modeling of connection of collar beam or tie beam with queen post – only transfer of compressive forces - evangelical church at Drăuşeni

4. Diagnosis

Within the diagnosis phase, the structural integrity and its load-bearing capacity are assessed, often including engineering judgment. Since in general use is made from the limit states design concept including partial safety factors, the comparison of the design load effect (E_d) with the design resistance (R_d) does not reflect the critical failure/safety boundary. The outcome of the numerical analysis of this type of engineering software is therefore insufficient to state the actual remaining safety. On average when $E_d = R_d$, the failure probability (p_f) equals the target failure probability ($p_{f,T}$), which yields, in case of a new design with a service life of t_L=*50years*: $p_f=p_{f,T}=7.1\ 10^{-5}$.

The actual safety however could be retrieved when using a reliability based assessment framework, towards which there is clear tendency (Diamantidis, 2001; ISO 2394:1998). However, following requirements need to be fulfilled to enable a user-friendly applicability within practice (Schueremans et Verstrynge, 2008):

- accurate reliability algorithms in a user friendly environment and integration in between structural reliability software and appropriate structural analysis software;
- knowledge of random variables for the design variables (R: resistance, E: solicitations, a: geometry, θ: model uncertainty) and availability of materials models and related data. These are available for timber (JCSS, 2006);
- preset target failure probabilities ($p_{f,T}$) or corresponding target reliability values (β_T).

Although the numerical analyses performed for the case studies do not allow for a quantification of the actual failure probability according to statistical principals, they certainly point out on the major defects, shortcomings, misconception or deficiencies. In addition, the insight into the overall structural behavior is strongly enhanced. Both elements aid in an appropriate design of strengthening techniques. The main structural items revealed within the diagnosis phase of the Romanian case studies are summarized. Details are reported elsewhere (Magnus, 2008).

4.1. Choir of the evangelical church at Drăuşeni

Main conclusions related to structural behavior:

- Missing elements result in alterations of the force path followed to transfer the applied loading. The broken heel joints (rafter – tie beam) increases the stress level within the rafters and collar beam and intermediate connections;
- The lack of connection (in shear and tension) within the gothic hanging device and tie/collar beam alters the structural behavior significantly. This results in increased stress levels and deformations in the transversal directions and in lack of stiffness in longitudinal direction;
- With exception of the heel joints (rafter – tie beam) and the connection between the gothic hanging device and the tie beam/collar beam, the conception of the transversal trusses have proven to be adequate;
- The defense level almost acts as a mechanism, as it is composed of only rectangles with small counter braces. Within the numerical analysis, this results in large horizontal displacements. The visual inspection however does not indicate any malfunctioning.

4.2. House nr. 22 at Piaţa Mică at Sibiu

Main conclusions related to structural behavior:

- The main structural deficiency is the presumed misconception located at the western heel joint, Figure 7, where the support does not coincide with the heel joint rafter-tie beam, resulting in increased bending moments and displacements;
- In addition, the lack of waterproofing of the roof has led to deterioration of several connections. Again this results in increased stress levels within other structural components.

5. Interventions

Related to intervention techniques, the principle of minimum intervention applies. One however can clearly distinguish a different approach used within Western-European countries compared to Eastern-European or Scandinavian countries. Due to the lack of high strength class oak that often is used in historical timber roofs, timber replacements are often substituted with repair or strengthening using other materials, such as: epoxy (beam end epoxy-prosthesis, Fig. 8d), internal (repair of cracks) or external (increase of load-bearing capacity, Fig. 8c), strengthening of timber by means of glued steel or CFRP (Carbon Fiber Reinforced Plastics, Fig.8b), or additional steel elements (steel braces for wind stiffness, Fig. 8a) (Brosens et al., 2005; Ignoul et al., 2005) .

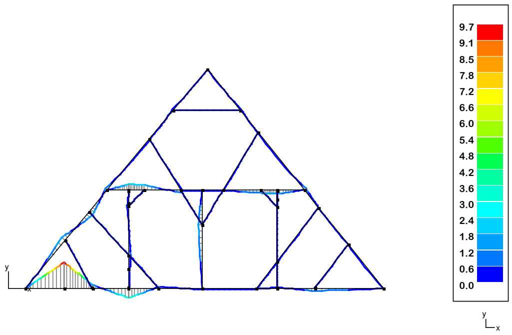


Fig. 2. Presumed design misconception located at the western heel joint and resulting bending moment due to vertical loading (dead weight)

The main concepts for structural interventions obtained from the diagnosis phase of the Romanian case studies are summarized. Details are reported elsewhere (Magnus, 2008).

5.1. Choir of the evangelical church at Drăuşeni

Main concepts for structural interventions proposed:

- The classical repair is required including: reconnecting joints, repair of heel joints (rafter-tie beam), replacement of missing elements;
- In the longitudinal direction the different main and secondary trusses are leaning over significantly. This leaning increases the stress level significantly. Relining these – which on itself will require the temporarily removal of the roof covering – will be insufficient. The longitudinal stiffness has to be regained. This is possible by means of an appropriate connection between the gothic hanging device and the tie/collar beam providing sufficient resistance in tension (and thus shear due to the present tab). As a result also the vertical stiffness within the main and secondary trusses is improved conceptually;
- The numerical analysis is not in line with the visual inspection related to the structural behavior of the defense level. Since additional braces to stiffen these rectangular frames would be a relatively intrusive intervention, and since the timber does not demonstrate any malfunctioning for a period of over more than 5 centuries, keeping the structure unaltered might be preferred.

5.2. House nr. 22 at Piaţa Mică at Sibiu

Main concepts for structural interventions proposed:

- Besides the classical repair as indicated for the former case study, main emphasis lies on the heel joint. A possible solution that preserves the heel joint is the insertion of a strut between the western rafter and the tie-beam in line with the western support. The efficiency of the intervention is supported by the numerical calculation, Figure 7b.

6. Preventive maintenance

Besides the interventions, preventive maintenance is of utmost importance. In the majority of cases, the overall conceptual design and execution of the timber structures is adequate. Neglect and small deficiencies led to severe decay on the long term. In this perspective, attention is to be paid at small but regular preventive maintenance preventing worse consequences such as:

- Regular cleaning of gutters;
- Intermediate repair of roof covering (replacement of tiles).

7. Conclusions

Within standards and ICOMOS (ISCARSAH) a framework is available for the assessment of existing structures. Within ISCARSAH an annex towards ISO 13822 is on the verge of being published, dealing with the specific case of assessment of historic structures, respecting their heritage value. Within ongoing research and restoration projects in Belgium, several timber structures are analyzed accounting for the outlined methodology, allowing for a critical appraisal of this type of standards.

At the same time, since these standards are general, they do not account for the specific complexity of timber in detail. From the case studies treated, it became clear that:

- Visual inspection is the main source of information in most case studies. Detailed information related to material properties is seldom available;
- Non-Destructive Testing is preferred but often provides only qualitative (or relative) information, not filling out the lack of quantitative information related to material properties;
- Within the structural analysis a step-by-step procedure starting with a simple model and extending the complexity of the model with the information gathered is preferable. It provides insight within the structural behavior and integrity;
- The actual safety of the structure is mainly dealt with similar to design based on the limit state format using partial safety factors although this procedure is made to cover up for the uncertainties at design stage. Reliability based assessment techniques calculating the failure probability, are hardly ever used.

Therefore, the main items that are envisaged for future research focus on filling out these shortcomings:

- correlation in between non-destructive testing and material strength classes;
- a database of structures and (non) destructive test results;
- impact of joint stiffness in the structural analysis results;
- use of reliability based assessment techniques for safety evaluation.

In addition, as also concluded from the most recent open panel discussion, chaired by the first author, at the SAHC-VI Structural Analysis of Historical Constructions Conference held at Bath (UK) July 2-4, 2008, there is a lack of conservation engineers having the expertise within the domain of structural analysis of historical constructions and related issues. At the civil engineering department, the restoration course is a non-compulsory course. On the contrary, basic statistics and probabilistic design are compulsory courses.

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