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Education in Assessment and Retrofitting of Historical Timber Structures: Integration of Teaching and Practice

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Abstract. The paper deals with the specific approach to teach the subject of assessment and retrofitting of historical timber structures to students of various colleges in an integrated and multidisciplinary course. Timber structures belong to the oldest structures in the world and because of their specific susceptibility to ageing, often require a profound analysis with respect to their current state and functionality. Especially in Europe, city centres are full of historical buildings that present an important cultural heritage, and as a consequence have a protected status. This status entails that these structures need to be assessed, maintained and monitored carefully, to keep the state of these structures at a level that they can perform. These tasks are often complicated and require interdisciplinary work. In education, this interdisciplinarity is often difficult to incorporate in the curriculum, as various expertises needed for cultural heritage assessment are separately and often fragmentary present at various colleges or faculties of universities, if present at all. Also, different teaching approaches may hinder course development. This paper deals with educational activities that have been developed and experienced at TU Munich and TU Delft, along with the cooperation with the University of Zagreb, dealing with the most important aspects of the assessment and analysis of historical timber structures.

Keywords: Cultural heritage · Assessment · Timber structures · Curriculum development · Case studies

1 Introduction

The general public awareness of the value of cultural heritage is ever increasing, resulting in expanding activities in research, publishing and standardisation, conservation programs, international networking of interested institutions, and establishment of legislative and financial bases for policymakers. There is, however, an evident need to offer or expand systematic education in the multidisciplinary field of conservation of the built heritage, which is emphasised here in the case of historical timber structures. Timber

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structures often go back centuries and form part of the cultural heritage worldwide. In Europe alone timber can be found in myriad structures, reaching back 500 years or more. The Roman foundation systems are still reflected in the technology of the present society, for instance, in vertical pile foundations in Amsterdam, Hamburg or Venice, to name just a few European historical sites. Most of those foundations are still fully functional, but careful assessment and monitoring are needed to verify their structural performance [1, 2]. Above ground, wood cultural heritage is much more accessible or visible to the public, and ancient buildings in Greece [3], or stave churches in Norway [4] are just a few examples of very old structures present in Europe. In contrast, comparable cultural heritage is found in many areas in Asia. The present status of conservation programs calls for the integration of practice and specific education. This was recently demonstrated in the examples of the major inspections of two large church roofs, from which specific aspects will be presented: the Zagreb cathedral in Croatia, which was hit by a major earthquake in 2020, or the St Bavo church in Haarlem in the Netherlands on the occasion of its 500th anniversary in 2020, with its 47 m high, 8-level structured timber tower (Fig. 1).

With respect to the preservation of this cultural heritage for future generations, good educational programs that comprehensively cover various aspects are essential. However, creating such a program is challenging, as universities are generally structured in a way that the required interdisciplinarity is difficult to realise. Each required discipline has developed into highly specialised areas over the last decades, and consequently, not all required knowledge is readily available and accessible. Experts may work in different departments and universities, in heritage institutions or be self-employed. In the following, various aspects of such a comprehensive teaching program are addressed based on criteria related to teachers and students, heritage requirements and methodologies for the assessment of existing structures.

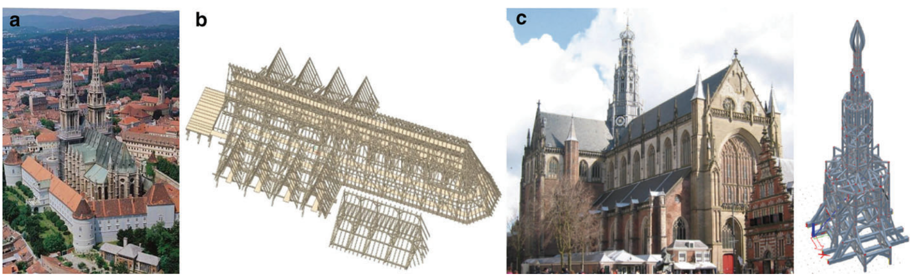

Fig. 1. a) Aerial view of the cathedral of Zagreb, Croatia, b) Rendering of the timber roof structure, c) St. Bavo church Haarlem, the Netherlands, d) Rendering of the 47m wooden bell tower.

2 Lecturing Challenges in Timber Heritage Structures

2.1 Overview of Lecturing Goals, Competencies and Prerequisites

Timber cultural heritage assessment covers a wide variety of topics that are preferably taught in a dedicated teaching program, or in a program that offers sufficient flexibility for both teachers and students, to set out out a course to become an expert after graduating. Starting from the beginning of a comprehensive assessment of a historic structure, the following professions involved can be identified: heritage experts (historian, archeologist), architects, structural engineers, wood technologists, material scientists, NDT-specialists, restoration experts, safety and fire experts. Often these experts must be in close contact with each other, but also with the cultural heritage and building authorities. As the inter- and multidisciplinarity is high, the following course attainments were formulated with the goal of creating of a dedicated course in assessment and retrofitting of timber structures. This serves as a backbone and guidance for a lecture series dealing with Assessment and Retrofitting of Existing Timber Structures (ARETS).

Course attainments for ARETS:

- Understanding fundamental (chemical, physical, mechanical) properties of wood and engineered wood materials and their behaviour in structural applications under a variety of complex loading conditions and environments.
- Analyse, model, predict and explain the behaviour of wood and wood-based materials at multiple scales.
- Have state-of-art knowledge of the technologies available to assess the quality of wood and wood-based materials in existing structures.
- Describe, analyse, test, model and predict the effects of degradation of materials on their properties and address this in design applications.
- Understand and develop experimental and modelling techniques to assess and monitor the health of materials, degradation processes and evaluate their consequences for the structural behaviour and service life, and develop repair and maintenance strategies.
- Understand the possibilities and limitations of innovative and conventional construction materials and be able to use them optimally in structures that require retrofitting and/or repair.
- Address aspects of repair and retrofitting activities in timber structures, with special attention to the value and role of monuments and cultural heritage in society.

This course attainment list is used as the basis for a comprehensive set of lectures, covering the tasks that are required for a complete analysis of a structure. As the course topics are very diverse and in line with the interdisciplinary nature of the work. Consequently, implementing such a course in a curriculum remains challenging, as both students and teachers have their own individual backgrounds, often related to only a couple of topics. Especially when students with different Bachelor backgrounds enroll in a course for existing timber structures, course prerequisites might be needed. Over the years, a number of knowledge gaps have been identified. Students with a background in forestry and/or wood technology will have difficulties with the structural assessment tasks, whereas students with a civil engineering background will face difficulties with wood material science topics as most civil engineering curricula have core programs for steel and concrete structures, but not for wood science and technology or timber structures. Similar observations can be made with respect to the teaching staff, that ideally would consist of at least four different disciplines: covering cultural heritage, wood science/technology, timber structures, structural modelling and a NDT. Support from licensed building practitioners in carpentry is especially helpful when original wood working and carpentry is part of the investigation. The following points of attention for ARETS have been identified over the years:

- Civil engineering students have had less training in wood and timber structures in their early years of study. The focus in the early years is often related to structural design in concrete and steel and more generic, with a clear focus on new structures.
- Knowledge about wood and timber is less developed, while at the same time it is a highly complex material from a mechanical-physical viewpoint. It is highly anisotropic.
- Wood is biologically degradable and consequently may show more severe and more variable levels of decay. Identifying risks in a structure requires not only knowledge about wood, but also about building physics and combinations of building materials, p.e. wood-stone interfaces.
- Wood naturally shows a large scatter in quality and consequently mechanical properties. Structural sawn wood sizes have changed over time and are different nowadays as compared to historical applications. This has consequences at the mechanical-physical properties level.
- Old wood and recent wood may be regarded as two different materials, inasmuch as historic wood has never been disinfected by kiln drying, was applied with more varieties in structure and quality (sapwood, juvenile wood, grain deviations), and may be technically impaired by the history of dynamic loadings, creep, moisture gradients and biological infestations. Students should be aware of such aberrations, even when coming from the colleges where modern wood structural applications are studied.
- Differences between timber grading and in-situ grading need to be addressed, as neither civil engineering students nor forestry/wood science students have been trained in that respect.
- In-situ measurement techniques may have to be adjusted for timber, as they have often been developed for concrete, steel, or forestry related fields, or even beyond that. Applying them on (existing) timber structures may call for adaptations in the form of additional research and test runs. Additional work may be required if a known application has been verified for a single wood species only.
- Original documentation related to the structure is not always present so students have to learn to back-engineer the structure as well as the materials´ origins, but also understand the often complex carpentry joints.
- Cultural heritage may restrict certain types of interventions, so heritage status and rules must be carefully studied and followed.
- Language and nomenclature varies between professions, regions and countries.

2.2 Lecture Contents for Assessment and Retrofitting of Existing Timber Structures – Courses

Given the list, it becomes clear that a lecture series about structural assessment of timber structures can be set-up in various ways, depending on how a university curriculum is built-up. A list of subjects is given in Table 1, covering the prime aspects from what a complete analysis of one of the structures of Fig. 1. Would comprise. For each of these subjects, the course content must be screened for complexity on the one hand and for applicability in practice on the other. For example, there is no need that the students learn all particularities of wood pathology. Instead, it suffices if they are able to distinguish between the white rot, brown rot and blue stain, know the essentials about xylofagous insects, etc. On the other hand, the basics about the wood species' natural durability (e.g. EN 350:2016) and hygrotechnical conditions that present the unavoidable risk of biological decay (wood moisture content above 21%) should be adopted by every student, regardless of his/her dominant curriculum. In addition, students should also be additionally directed to specific literature, should they wish to learn more, or encounter a need for such knowledge. The identified course content can be presented to students in various ways but there must be room for self-study and profundity. Here, a distinction is made in ´subject based courses´ and ´technology or transversal skills´ based teaching programs. In the first, the whole set is structured as a specific course, basically covering the aspects of a full assessment analysis, incl. Feedback reporting to the ´virtual customer´ having a cultural heritage structure to be assessed. This is how it would work in practice and how it is followed in Table 1. The other option relates more to the various ´science´ fields, requiring subject teachers to be trained in all aspects of technologies and materials. As examples: materials science (Subject 2,3,6,7), Inspection techniques (NDT, Subject 8) technologies applied to various relevant materials, or structural safety and engineering (Subjects 9–13) for all structural materials.

Table 1. Proposed core contents of a course for assesment and retrofitting of timber structures.

Subject		Content
1	Introduction existing and historical structures	Examples of building technologies, structures, historical and geographical context. Documentation
2	Wood properties	Mechanical and physical properties of relevant species
3	Wood identification	Determination of wood species, collection of basic material properties
4	Cultural heritage	Principles, Standards and Guidelines for assessment, ICOMOS guidelines, definitions, cultural heritage valuation
5	Inspection procedures	Levels of (visual) inspection and assessment, risk identification, protocols, reporting
6	Decay processes in wood	Influences of biological, physical, chemical and mechanical decay on properties

(*continued*)

Table 1. (*continued*)

Subject		Content
7	In-situ grading	Mapping of the components, visual assessment of wood quality, knots, cracks, connection types, moisture content
8	Inspection techniques	Terrestrial laser scanning, microdrilling, dynamic excitation (stress waves), X-ray, ultrasound, (stereo)photography,…
9	Structural safety	Estimate of historical loads, load cases, modelling and reliability for future use
10	Traditional timber joints	Type and quality (local deformations, cracks, alignment, gaps, load-slip behaviour, nomenclature,…)
11	Structural analysis	Structural calculation model, geometry, assignment of material and connection properties, load cases (earthquake, wind,…), sensitivity analysis
12	Repair	Repair methods (strengthening, stiffenings, fire safety, etc. (GIRs, steel, FRP)
13	Reinforcement of beams and floors, connections	Calculation and design of composite structures, p.e. strengthening
14	Case studies	Example cases of historical buildings
15	Field work	Field studies on existing structures related to the abovementioned topics

A brief overview of inspection objectives, evaluation and testing, repair and strengthening for civil engineering students can be found in STEP Lectures D3 and D4, from the STEP/Eurofortech programme [5, 6].

3 Example Cases

In this chapter, a couple of subjects will be highlighted and related to the complexities of teaching. An in-depth look will be given to grading aspects of wood, micro-drilling as one of the more widely applied inspection methods, laser-scanning, the complexity of carpentry joints and some considerations on the selection process of methods.

3.1 Grading of Timber and In-Situ Grading

Most structural engineers are trained using a strength class system. In Europe, strength classes are defined based on bendings strength and stiffness, as well as density and are defined in European standard EN 338 as C-, or D-class values for Coniferous and Deciduous species, respectively. However, strength class assignments are the result of grading operations on large quantities of material with visual grades from grading standards. These grading standards are based on trade ready material and have been developed only since around 1950. The difficulties associated with strength class assignments are addressed in [7], where it is also shown that the cross sectional sizes used for modern day strength class assignment are considerably smaller than those found in historical structures. In a structural assessment it is quite the opposite. In historical structures, a small number of structural elements is present, generally selected under the supervision of the head carpenter when the structure was built. When grading in-situ, pieces are not always accessible from 4 sides as required in strength grading, and drying cracks are often far beyond grade limits. An example of an oak beam with extreme knot sizes relative to the width on which the knot is visible, is given in Fig. 2, taken in the St. Bavo church (see Fig. 1). Generally, a defect ratio $b/W > 0.5$ would lead to a rejection. However, as this is only a secondary beam, loaded in compression, there is no need to intervene structurally. A further aspect with strength classes related assignments is related to the material density. Low grades of hardwoods such as oak, are graded on the basis of a low strength, caused by fibre deviations and large knots. This could lead to a strength class assignment as low as D18. However, the associated density should remain that of oak, around 700 kg/m^3. In structural analysis programs that have incorporated strength class tables, this might lead to a clear underestimation of the self-weight of the structure, that should anyway be modified as an upper boundary density value.