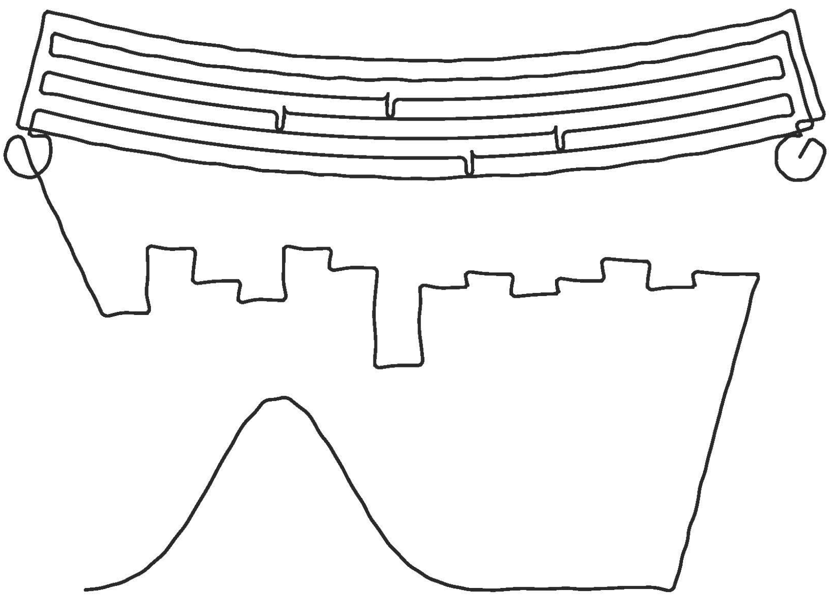
Universität Stuttgart

Cristóbal Tapia Camú

Variation of mechanical properties in oak boards and its effect on glued laminated timber

Application to a stochastic finite element glulam strength model



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Vorgelegt von
Cristóbal Tapia Camú
aus Berlin

Hauptberichter: Prof. Dr.-Ing. Harald Garrecht

Mitberichter: Prof. Dr. Frank Lam

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Contents

Zusammenfassung

Der nachwachsende Rohstoff Holz und hieraus hergestellte holzbasierte Bauprodukte (HBP) werden weithin als tragende Säule des nachhaltigen Bauens anerkannt. Aufgrund einer stark wachsenden Nachfrage und der mechanischen Vorteile gewinnt die bisher im Vergleich zu Nadelhölzern weniger genutzte Ressource *Laubholz* für HBPs zunehmend an Bedeutung. Gegenstand der durchgeführten Untersuchungen ist die Spezies Weißeiche (Quercus robur, Q. petraea), die nach der Buche (Fagus sylvatica) den zweitgrößten Laubholzbestand in Europa darstellt. Diese Arbeit adressiert die Erfordernis eines verbesserten Verständnisses und einer besseren Modellierung der Variabilität von Steifigkeit und Festigkeit entlang und zwischen Brettern sowie die daraus resultierenden Auswirkungen auf den Größeneffekt von Eichen-Brettschichtholz (BSH).

Für die Untersuchungen zur Variation der mechanischen Eigenschaften entlang der Hauptachse der Bretter wurde ein Satz von 53 Eichen-Brettern (Quercus robur) verwendet. Bei jedem Brett wurde die Position und Geometrie der Äste detailliert erfasst; diese Informationen wurden sodann zur digitalen Rekonstruktion der Äste verwendet. Die Elastizitätsmodul (E-Modul) parallel zur Faser wurde bei Zugbeanspruchung an 15 aneinander anschließenden 100 mm langen Brettsegmenten gemessen. Die Bretter wurden bis zum Zugversagen geprüft Die Bruchstücke wurden sodann, wenn möglich, in weiteren Zugprüfungen getestet. Auf diese Weise wurden mehrere Zugfestigkeitswerte pro Brett ermittelt.

Auf der Grundlage der E-Modul-Ergebnisse wurde ein autoregressives Model erster Ordnung [AR(1)] für die Simulation lokaler E-Modul-Profile entlang eines Brettes entwickelt. Das Model berücksichtigt die Nicht-Stationarität der E-Modul-Profile mittels einer zweistufigen Methode. Zunächst wird ein Gaußscher AR-Prozess durchgeführt, der dann in einer normalisierten E-Modul-Verteilung abgebildet wird. In einem zweiten Schritt wird das Ergebnis so skaliert, dass es einem vorgegebenen globalen E-Modul entspricht. Die Zugfestigkeitswerte wurden

mittels Ereigniszeitanalyse (*Survival Analysis*) analysiert, wobei unterschiedliche parametrische und regressive statistische Modelle angepasst wurden. Die modellierten Zugfestigkeiten wurden sodann mittels eines Kreuz-Korrelationskoeffizienten mit den lokalen E-Modul-Werten gekoppelt, womit ein modifiziertes Vektor-Autoregressives Model (VAR) für den lokalen E-Modul und die Zugfestigkeit erhalten wurde. Nummerische Simulationen mit den angepassten Zugfestigkeitsmodellen ergaben einen vergleichsweise hohen Größen-, d.h. Längeneffekt, der durch einen Größenexponenten von rd. 0.23 für das 5%-Quantil charakterisiert wird.

Es wurde ein stochastisches Finite-Element-Model zur Analyse von BSH-Trägern entwickelt. Das Model berücksichtigt die mittels eines VAR-Models generierte lokale Variation der mechanischen Eigenschaften entlang jeder einzelnen Lamelle sowie die stochastische Verteilung der Keilzinkenverbindungen aneinander anschließende Bretter. Zur Berücksichtigung der Schädigungsentwicklung in den Holz- und Keilzinkenelementen, wurde ein einfacher Energie-basierter bruchmechanischer Ansatz verwendet. Das Model wurde an Versuchen mit Eichen-BSH-Trägern mit drei unterschiedlichen Querschnittsgrößen, die an der MPA Universität Stuttgart durchgeführt wurden, kalibriert. Nachfolgend wurde das Modell auf einen zweiten bei FCBA, Frankreich, geprüften Datensatz von Eichen-BSH angewandt. Die durch das Model vorhergesagten Ergebnisse stimmen gut mit den Experimenten überein. Insbesondere wird hierbei der Größeneffekt der Trägerhöhe richtig dargestellt. Der Einfluss der Materialmodelle für Holz und Keilzinkungen wurde parametrisch untersucht. Es wurde gezeigt, dass die untere Verteilungsregion der lokalen Zugfestigkeitsverteilung die Biegefestigkeitsverteilung des BSH am meisten beeinflusst. Dies ist vorteilhaft, da die untere Verteilungsregion mittels Ereigniszeitanalyse vergleichsweise präzise abgeschätzt werden kann, während die obere Verteilungsregion weitere Annahmen erfordert.

Der Autor hofft, dass die vorliegende Arbeit dazu beiträgt, die Diskussion zur Modellierung von tragenden Bauprodukten aus Laubholz zu befördern.

Abstract

Scope

The renewable material wood and hereof derived structural engineered wood products (EWPs) is widely acknowledged as being the major pillar of sustainable building construction. Due to the strongly increasing demand and technical assets the wood resource *hardwoods*, previously less used as compared to softwoods, is gaining a high momentum for EWPs. Here, the species white oak (Quercus robur, petraea) representing beside beech (Fagus sylvatica) the largest hardwood stocks in Europe is investigated. This work addresses the need of improved understanding and modeling of the variability of stiffness and strength along and between boards and the resulting impact on the size-effect of glued laminated timber (GLT) made of oak.

Experimental

A set of 53 oak boards (Quercus robur) was used to study the variation of mechanical properties along the board's main axis. For each board, detailed information regarding size and position of knots was obtained, which was then used to digitally reproduce the geometry of the knots. The modulus of elasticity (MOE) parallel to the fiber was measured in tension along each board in 15 consecutive segments of 100 mm in length. The boards were tested in tension until failure and the remnants were then tested in secondary tension tests, when possible. Thus, multiple values for tensile strength were obtained per board.

Based on the MOE results, a first order autoregressive [AR(1)] model for the simulation of local MOE profiles within board was developed. The model considers the non-stationarity of the MOE profiles by means of a two step method. Firstly, a Gaussian AR process is conducted and then mapped to the *normalized MOE* distribution. In a second step, the result in scaled to fit a specified global MOE value. The tensile strength data was analyzed by means of survival analysis, where different parametric and regression type statistical models were fitted. The tensile strength models were coupled to the localized MOE AR(1) model by means of a cross-correlation coefficient, thus obtaining a modified vector autoregressive (VAR) model for the local MOE and tensile strength along board. Numerical simulations with the fitted tensile strength models predicted a relatively high size effect, i.e. length effect, characterized by a size-effect exponent of around 0.23 at the 5 %-quantile level.

Stochastic FE model for GLT

A stochastic finite element model for the analysis of GLT beams was developed. The model considers the local variation of mechanical properties within each lamination, simulated by the derived VAR model, as well as the stochastic distribution of finger-joints connecting adjacent boards. A simple energy-based failure mechanism is considered for the evolution of tensile damage in wood and finger-joint elements. The model was calibrated with experiments of oak GLT beams of three different cross-sections tested at the MPA, University of Stuttgart, and then applied to simulate a second database of oak GLT beams tested at FCBA, France. The results obtained with the model are in good agreement with the experiments. In particular, the *size effect* of beam depth is correctly represented. The influence of the used material models for wood and finger-joints was analyzed parametrically. It is shown that the lower tail of the local tensile strength distribution, which can be estimated rather accurately by survival analysis dominates the GLT bending strength.This is fortunate, as the lower tails can be estimated by means of survival analysis in a rather accurate manner, while the upper tails require further assumptions.

Vision

The author hopes that the presented work contributes to stimulate the discussion on modelling of structural timber elements made of hardwoods.

Acknowledgements

This is the result of my research endeavors of the past years at the Division of Timber Constructions of the Materials Testing Institute, University of Stuttgart. Although the path leading to this point was not always smooth, it was certainly a very rewarding experience from both a technical and human perspectives. The first time I came to Stuttgart as a student in 2010 I was supposed to stay only for one semester—which I extended for another two—and I never thought that I would later come back and stay here for so long. I started working on the subject of this thesis in 2015 without knowing that it would eventually become my Ph.D. thesis, nor that I would enjoy so much working on it. This only shows how difficult it is to know the effects of our decisions and actions in the long term. Even more so in science! ('Will my research have any meaningful impact?' 'Am I in the right track to solve this problem?' …<*Insert your researcher existential doubt here*>.) It is easy to feel overwhelmed or constantly considering to change plans—do I even have a plan? I should say, in my defense, that I do have some vague ideas that help me point the general direction I want to follow, however, the main reason for having survived this long in the scientific world is most certainly owed to the people surrounding me. During my time working on this thesis I counted with the invaluable support of so many people that (maybe even unaware of it) helped me succeeding in this task. To all those people I am very grateful.

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Stuttgart, March 2022 Cristóbal Tapia Camú

“I do not know why a certain event occurs; I think that I cannot know it; so I do not try to know it and I talk about chance.”

— Lev Tolstoy, *War and peace*

Chapter 1

Introduction

1.1 European forests in the 21st century

Forests in Europe are currently in the midst of a significant change in their tree-species distribution (Cheaib et al., 2012; Delzon et al., 2013). The increase in global temperatures in the last century and the changes in local weather conditions deriving from it (e.g. rain patterns, drought periods and winds) have already started showing some effects (Lindbladh et al., 2000). The consequences that the current climate change will ultimately bring to the European forests are largely unknown; the amount of variables that play a relevant role is considerable (Lindner et al., 2014)—alone the prediction of future temperatures depends on highly sensible parameters like estimated greenhouse gases emissions. In spite of these uncertainties, enough scientific evidence points to major changes in the forest, characterized by steady geographical shifts, as well as expansions and contractions of the habitable regions of species (Meier et al., 2011). This dynamic changes the distribution of species in the forests, and consequently affects the silviculural activity in a direct manner.

Under the current and projected conditions, the habitable ranges of deciduous species (hardwoods) are expected to shift far northern with respect to their current boundaries. Field studies by Delzon et al. (2013) have confirmed a steady colonisation of Holm oak (*Quercus ilex*) northwards from its natural range in the last century, and simulations predict a probable ongoing of this development during this century (Cheaib et al., 2012). Meanwhile, coniferous species ranges will be confined to higher altitudes (Lexer et al., 2002) and latitudes (Delzon et al., 2013), where more suited climatic conditions are to be expected.

Although important, global warming is not the only driving force reshaping the forests. The silvicultural and forestry activity of the last century is largely accountable for the observed increase in disturbance impact in the European forests, mainly due to restructurations of the distribution of species (Seidl et al., 2011). The favoring of fast-growing species, e.g. Norway spruce (*Picea abies*) or Scots pine (*Pinus sylvestris*), which ensure small rotation periods, led to a displacement of native species from their natural environments and gave place to large monocultural forests all over Europe (Felton et al., 2010). This presents its own set of associated problems, e.g. an increased probability of large, concentrated die-backs of species due to a higher vulnerability to both biotic (pest outbreaks) and abiotic (winds, droughts) factors (Felton et al., 2010). The predicted climate change can only amplify these problems (see e.g. Lexer et al., 2002).

The understanding of the consequences of these two driving forces marked a turning point in the management of European forests regarding its economical, environmental and social uses (CEC, 2007). It became evident that forests need to adapt to the future climatic conditions, yet the natural process to achieve this—through natural dispersion of seeds—would not be enough to keep up with the predicted speed of climate changes (Meier et al., 2011; Delzon et al., 2013). Thus, the adaptation process needs to be assisted. Different guidelines exist to transit to more climate resilient forests in Europe (see e.g. LFBW, 2014). In general, mixed-species stands are now strongly encouraged, with the objective of reducing the vulnerability to diverse risks and promote biodiversity (CEC, 2007), while at the same time maintaining an economical competitiveness with respect to e.g. spruce monocultures (Agestam et al., 2006).

The interaction of climate change and these new forestry strategies will lead to a much higher share of hardwoods in the European growing stock, including oaks, beech and birch species, among others (Cheaib et al., 2012). In fact, in the last decades European forests have seen a steady increase in their share of deciduous species, which can be quantitatively observed i.a. in national forest inventories of different countries. For example, between the first and second German National Forest Inventory (1987–2002) Norway spruce has lost about 7 % of its total area to deciduous species in south-west Germany (Lindner et al., 2014). For the timber building industry, up until now clearly dominated by softwood species, this development presents many challenges and a need for adaption.

1.2 Hardwoods in the building industry

The described gradual transition to a higher proportion of deciduous species in the forests has motivated a small, yet steadily increasing proportion of the European timber industry to incorporate more hardwood products into their catalogs. This trend is further reinforced by additional factors, such as (i) the fact that often the mechanical properties of hardwoods are significantly superior to those from softwoods (Aicher and Stapf, 2014), and (ii) that from an aesthetical point of view many hardwoods are typically considered to be more visually appealing. In order to harvest the full potential of hardwoods, improvements at both technical and regulatory levels are required.

Consequently, the research output dealing with different aspects of the value chain of hardwoods has shown a steady increase in recent times. The topics are multiple and include e.g. in-depth studies of material availability, improved classification methods, determination of mechanical properties and development of engineered products such as glued laminated timber (GLT) and, to a minor degree, cross-laminated timber (CLT), too. In this context, the project "European hardwoods for the building sector" (EU Hardwoods, 2017)—where the origins of the present work can be found—was tasked with analyzing these topics in a holistic manner. The focus was then placed on a subset of the most relevant European hardwood species, consisting on beech (*F. sylvatica*), oak (*Q. robur, Q. petraea*), chestnut (*C. sativa*) and ash (*F. excelsior*). There, an assessment of the suitability of these species for structural applications in the form of engineered products was made.

The past decade has seen an increase in the efforts of bringing hardwood engineered structural timber products to the market. In Germany and Austria, special attention has been given to beech, being this the most abundant deciduous species in these countries, where both GLT and CLT have been an important research subject (see e.g. Frese, 2006a; Aicher et al., 2016; Ehrhart, 2020). For the case of oak wood, being the primary hardwood species in France and second most important in Germany, an increased interest has been observed, too (Aicher and Stapf, 2014; Faydi et al., 2017). Although oak was initially limited to GLT members with rather small cross-sections—mainly used as post and beam window façade elements—it quickly evolved to include larger cross-sections for structural applications (Aicher et al., 2014).

Further research has shown that an efficient way to incorporate hardwoods into structural elements is by means of so-called *hybrid elements*, where both softwoods and hardwoods—currently mostly beech—are used together, taking advantage of the superior mechanical properties of hardwoods where it is needed. For GLT beams this concept is applied by replacing the material of the outer laminations with hardwoods of high tensile strength (e.g. Blaß and Frese, 2006). In CLT plates, more interestingly, the middle cross-layers, where the failure mechanism is dominated by rolling shear, can be substituted by e.g. beech material that would normally be regarded of low quality, yet presents a much higher resistance to rolling shear (e.g. Aicher et al., 2016).

Although these concepts present a high relevance for the future of engineered timber elements, the landscape of hardwood products in the coming years will probably continue to be dominated by the more simple single-species products, especially in the form of glued laminated timber.

1.3 Glued laminated timber

Glued laminated timber (GLT) is currently one of the most used wood-derived engineered products in the world when considering beam-like applications. It is produced by connecting a series of boards lengthwise by means of finger-joints to form a so-called *endless lamella*. This lamella is cut at regular intervals, defined by the length of the beam to be produced. The obtained parts are stacked on top of each other, applying glue between each layer (see Fig. 1.1). A constant pressure is then applied normal to the wide lamella faces throughout the so-called *minimum pressing time*. This ensures a sufficient bond strength and enables a further curing of the adhesive without the need of additional pressure, including careful transportation.

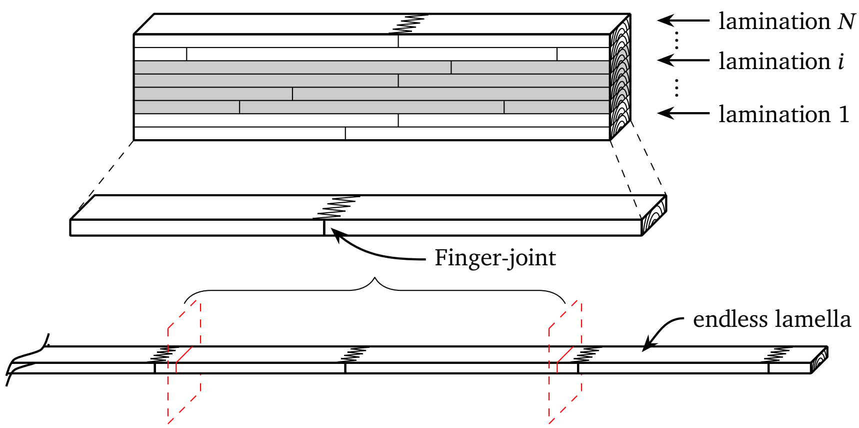

Figure 1.1. Description of the engineered timber product glued laminated timber