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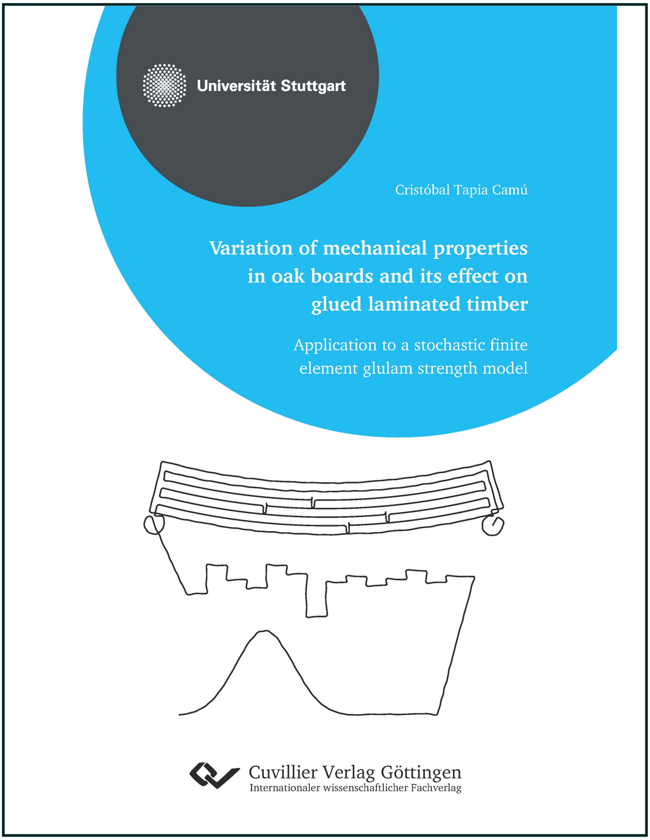
Variation of mechanical properties in oak boards and its effect on glued laminated timber

Application to a stochastic finite element glulam strength model



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 silvicular 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.

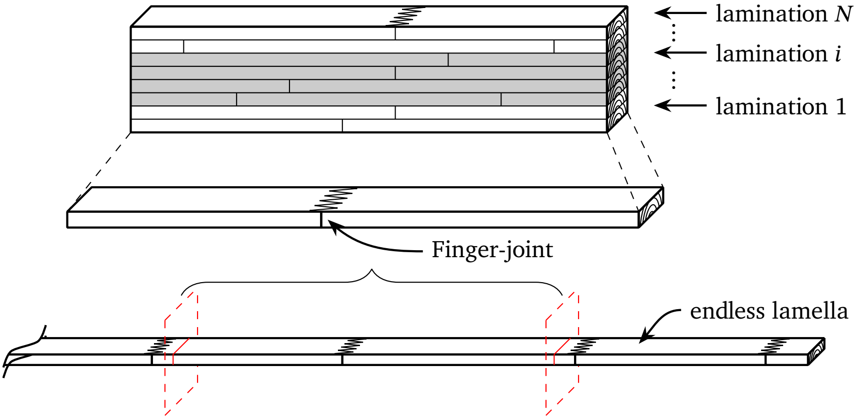


Figure 1.1. Description of the engineered timber product glued laminated timber

Compared to solid timber, the build-up of GLT allows for higher flexibility in terms of possible geometries and maximum spans, the latter being commonly limited to about 25 m due to transportation constraints. A further advantage is commonly referred to as *homogenization* of the material, which is associated with a reduction in the variability of the mechanical properties; e.g. low stiffness of one board is compensated by possible higher stiffness of adjacent laminations, thus the variation of stiffness at the beam level is reduced. A further relevant concept is known as the *lamination effect*. This corresponds to the positive mechanical effect obtained from vertically stacking lamellas, and originates mainly from two aspects: (i) the restraining of lateral deformations of individual laminations (see Fig. 1.2) due to local defects—thus preventing what would otherwise mean a reduction of tensile resistance (Foschi and Barrett, 1980)—and (ii) the redundant nature of a parallel system, where local failures in one lamination can be compensated to some degree by the adjacent laminations. The direct consequence of the lamination effect is the fact, that the observed bending strength of GLT beams is higher than that of the individual laminations.

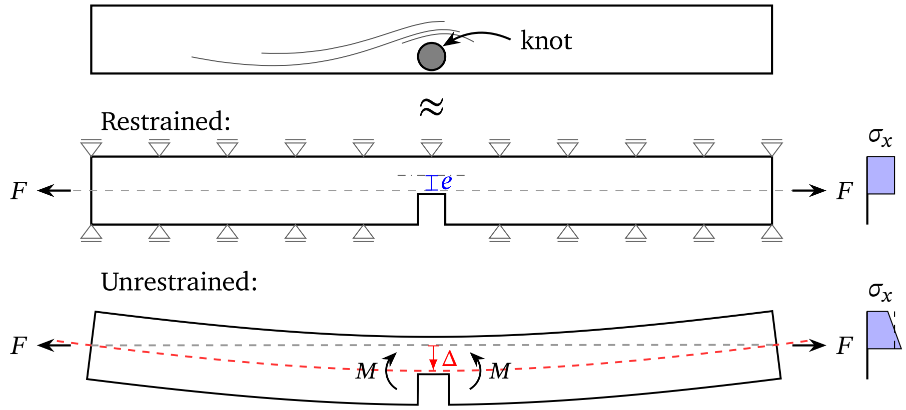


Figure 1.2. Lateral deformation of board in tension due to the presence of a knot on an edge (see also Foschi and Barrett (1980))

The degree of utilization of the material can be further increased by using so-called *composite build-ups*, characterized by the allocation of laminations of different strength grades—from the same species—throughout the cross-section. This is illustrated by the different colors of the laminations in Fig. 1.1. Specifically, boards of higher grades are placed in the outer zones (subjected to higher bending stresses), whilst lower grades can be used in the central part. The presence of lower grade boards in the central region of the cross-section has no negative impact in the shear resistance of the beam, as the shear strength remains practically the same for the different board grades. In this manner, an under-utilization of the higher quality material is reduced, and the usage of the material is optimized. The mechanical properties of such composite, as well as for homogeneous build-ups are specified in EN 14080 (2013).

1.3.1 Characterization of mechanical properties of glulam according to EN 14080

For the European market the build-up, strength features and minimum production specifications of GLT products is regulated by EN 14080 (2013). This standard defines minimum requirements on finger-joints and boards for the production of GLT with specific mechanical characteristics, defined as *GL* classes. GL classes are defined by their characteristic, i.e. 5 % quantile bending strength, $f_{m,g,k}$, meaning e.g. that a GLT beam of the class "GL24" presents a $f_{m,g,k}$ value of 24 N/mm^2. Homogeneous build-ups are marked by appending the letter "h" to the GLT class (e.g. GL24h), whilst composite build-ups, consisting of up to three lamination strength-grades, are denoted by the letter "c" (e.g. GL24c). The characteristic value attributed to each class is defined for a cross-sectional depth of 600 mm.

In order for the producer to declare the appropriate GL class, EN 14080 (2013) defines three possibilities:

1. The first option comprises the classification of the build-ups and their lamination properties according to tabulated values.
2. The second option is based on the use of a simulation-based, empirically adjusted equation relating the mechanical properties of finger-joints and boards to obtain the characteristic bending strength of the GLT.
3. The third alternative consists on the experimental determination of the GLT characteristic properties.

It is rather clear that the producers would strongly prefer either of the first two alternatives, as the realization of experimental tests is rather expensive. The equation mentioned in the second option relates the strength of both, finger-joints and boards with $f_{m,g,k}$ as

$$f_{m,g,k} = -2.2 + 2.5 \cdot f_{t,0,k}^{0.75} + 1.5 \cdot \left(\frac{f_{m,j,k}}{1.4} - f_{t,0,k} + 6 \right)^{0.65} \quad , \tag{1.1}$$

where $f_{t,0,k}$ and $f_{m,j,k}$ are the characteristic values for tensile strength of the boards and flat-wise bending strength of the finger-joints, respectively. In addition, the following restriction is specified for the finger-joints:

$$1.4 \cdot f_{t,0,k} \leq f_{m,j,k} \leq 1.4 \cdot f_{t,0,k} + 12 \quad . \tag{1.2}$$

Since the relation $f_{m,j,k} = f_{t,j,k} \cdot 1.4$ is implicitly assumed, the condition (1.2) means that the characteristic tensile strength of the finger-joint, $f_{t,j,k}$, must be higher than the characteristic tensile strength of the boards. In essence, the first alternative is nothing more than the application of Eq. (1.1) to a set of specific combinations of finger-joint and board strength values, and build-ups.

Although CE-marking of GLT beams according to EN 14081-1 (2016) is only possible for softwood GLT, the foreword of the standard mentions a *principle of applicability* to hardwood GLT, too. Regarding hardwood GLT, however, concerns on the validity of Eq. (1.1) have been raised, especially when considering the restriction of Eq. (1.2). This is owed to the empirical fact, that hardwoods, reaching in general much higher tensile strength values than the usual softwoods, often present problems at achieving the required (rather high) strength values for the finger-joints (Aicher and Stapf, 2014). As a consequence, for such cases, finger-joints represent the weakest region of the GLT, altering the statistical characteristics of the measured bending strength values. However, this does not mean that such GLT is not apt for structural use.

1.3.2 Towards standardization of hardwood GLT

Since the requirements specified in EN 14080 (2013) for softwoods cannot always be fulfilled by hardwoods (see above), alternative procedures have to be used to certify hardwood GLT. Currently the only available options consist in obtaining either a National Technical Approval or a European Technical Assessment (ETA) on the basis of a European Assessment Document (EAD)[1] (EU, 2014). Recently, a few producers have used these options to certify their production of GLT, e.g. for oak (Z-9.1-704, 2012; Z-9.1-821, 2013; ETA-13/0642, 2013) and chestnut (ETA-13/0646, 2013). However, the relative high costs associated with such a certification process, mainly due to a large number of required experimental full-scale tests, pose a clear barrier for many glulam producers. Engineered products from hardwoods, with all their structural advantages, can only become relevant if

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[1] Up to the year 2015, i.e. to the end of the European Building Products directive (EEC, 1988), the basis of an ETA, then called European Technical Approval, was the Common Understanding Approval Procedure (CUAP)

the proper regulations are adapted for their use, which points to the need for a standardization.

Therefore, the European Committee for Standardization has mandated the Technical Committee 124, Working Group 3, Task Force 1, with the development of a first standard for the regulation of the production of hardwood GLT. The idea is to create a document with provisions analogous to EN 14080 (2013) but considering the specifics of the different hardwood species and the limitations of the current adhesives. This is easier said than done, as the differences within hardwood species is known to be far larger than in softwood species. These differences span from the cellular level to the observed growth-bound defects, such as knots and fiber deviations, and have a direct influence in how the material behaves. Thus GLT made of hardwood might require slightly adapted models for each species. Although this is a difficult task, inspiration can be found in the process that lead to the standardization of softwood GLT.

1.3.3 The example of softwoods: strength models

The research pathway that led to the empirical model between strength properties of boards and finger-joints, and the bending strength of the glulam beam defined in EN 14080 (2013) has a long trail that dates back to the early 1980's. The first reported glulam strength model that used computer simulations to consider the stochastic variability of the material was introduced by Foschi and Barrett (1980). This model divided each lamination into cells of a determined length and assigned a MOE and strength value to each of them, which were correlated to generate knot and density values by means of a function. Although the influence of finger-joints was not considered, the stochastic essence of the variation of mechanical properties along the boards defined the nature of the models to come. Of high relevance for the European standardization was the model presented by Ehlbeck et al. (1985), the so-called "Karlsruher Rechenmodel", based on an extensive study of the variation of the mechanical properties of boards and finger-joints of Norway spruce (*Picea abies*). There, several correlations between strength, modulus of elasticity (MOE) and grading criteria were established, allowing the simulations to better represent the distribution of properties in glulam beams. After a long period of calibration, the numerical model was finally implemented as Eq. (1.1), relating GLT bending strength with strength values of both, finger-joints and boards in Section 5.1.5 of EN 14080 (2013).

Further models have been developed since then, i.a. by Hernandez et al. (1992) and more recently by Fink (2014), both calibrated with softwood species. Blaß et al. (2005) presented the first adaptation of the "Karlsruher Rechenmodel" to a hardwood species (beech) and later applied it to a hardwood-softwood hybrid build-up (Blaß and Frese, 2006), manifesting the utility and versatility of a stochastic FE-based strength model. In all these models the correct characterization of the material properties of the boards and finger-joints plays an essential role to correctly simulate the behavior of the studied GLT material. Substantial research has been dedicated to this aspect, i.a. Showalter et al. (1987), Taylor and Bender (1991), Lam and Varoglu (1991a), Isaksson (1999), and Fink (2014), gathering large empirical databases and developing different methods to simulate the observed variation of properties within boards. The present work is inspired by these investigations and presents a new approach to analyzing and modelling the variation of properties within board, using oak as an example material. The simulated mechanical properties can then be applied to a softening-based glulam strength model in order to study the bending behavior of the simulated GLT.

1.4 Objectives

This thesis presents the implementation of a new glulam strength model for hardwoods. For this, experimental results on boards and finger-joints are described and analyzed in order to obtain correlations between different properties at a global level. A method to generate the needed properties considering the correlations between them and their statistical distributions is presented. Investigations on the variation of properties within single boards are analyzed as well, and a method to simulate the observed variation is developed.

A finite element model with fracture mechanics capabilities is implemented using the software Abaqus. The input data is generated using a combination of the global and local material models mentioned above. Characteristic bending strengths are obtained for different build-ups by the application of the Monte Carlo method, and the results are compared to experimental investigations, for which the distributions of material properties are known. Finally, the sensitivity of the model to different parameters is assessed by means of a parametric analysis.

To summarize, the objectives of this thesis are:

- Analyze the distribution of defects in oak boards,
- Analyze the variation of density, modulus of elasticity (MOE) and tensile strength within oak boards,
- Characterize the autocorrelation parameters of MOE along board,

- Characterize the variation of tensile strength within board and its dependence with localized MOE values,
- Develop a simulation model capable of generating MOE and tensile strength profiles, representing oak boards with specific characteristics, and
- Develop a finite element simulation model for the prediction of bending strength, considering softening behavior.

1.5 Scope

The present study investigates the mechanical properties of boards and glulam beams made of oak (*Quercus robur, Quercus petraea*). In this sense, the parameters obtained for the material model are limited to the studied species. However, the material and finite element models presented in this work should be generally applicable to other wood species—assuming that the required calibration has been performed.

1.6 Outline and overview

The structure of the thesis is designed to follow the development of the strength model in a logical manner. It starts with a review of the state of the art in Chapter 2, where previous glulam strength models are reviewed and the needed statistical background is presented. Chapter 3 introduces the materials used for both the glulam testings and the study on variation of properties along boards. The distribution of knots in boards is studied in Chapter 4. The variation of properties along boards is analyzed in Chapter 5. A model for the simulation of the properties along boards is presented in Chapter 6. The finite element model for the determination of bending strength is introduced in Chapter 7, where the different components and parameters are explained. The calibration of the model with the experimental data is done in Chapter 8, where also diverse parameters of the strength model are studied in order to observe the susceptibility of the model with regard to the parameters. Final conclusions and an outlook are presented in Chapter 9.