THESIS (PhD) BOOKLET

University of Sopron

Faculty of Wood Engineering and Creative Industries

Cziráki József Doctoral School of Wood Sciences and Technologies

Head of institution: Prof. Dr. Róbert Németh

PhD. program: F3 Timber Structures

Program Leader: Prof. Dr. Ferenc Divós

Field of science: Materials Science and Technologies

DEVELOPMENT OF A NOVEL FINITE ELEMENT MODEL AND MATERIAL DEGRADATION MODEL FOR SPRUCE TIMBER SPECIMENS

by Tamás Király

Supervisors: Dr. Zsolt Karácsonyi

Dr. Rudolf Polgár

Sopron

2023

Introduction

Wood is one of our most natural and human-friendly building materials and has played a significant role as a structural element both in the past and in the present. As a result of its increasing usage, wood is being used in many new areas where it was not previously considered. For this reason, the material properties of wood are being re-examined again to improve the design of the constructions.

An important prerequisite for the optimal use of wood as a structural building material is the determination of the strength properties of wood components using a method, that is as economical as possible. Since the development of computer science at the end of the 20th century, the computational power and usability of numerical methods have increased dramatically, making complex finite element simulations increasingly popular. Nowadays, numerous finite element models have been developed to describe wood materials. Therefore, wood as a material has been studied in a wide range of anatomical scales, trying to represent it with abstractions as accurate and realistic as possible.

In most cases, researchers assume a homogeneous bulk when the wood is investigated by the finite element method. Recently there are some research results, that consider a two-phase wood model by taking into account the annual rings. However, the challenge lies in creating the two-phase finite element model of the bulk material and determining the material properties of the earlywood and latewood.

Objectives

The goal of my research is to develop a finite element modeling technique that can be used to investigate the Norway spruce (*picea abies*) clearwood specimens individually. To develop an appropriate methodology, my research includes a review of the recent literature. In order to gain a better understanding of the behavior of timber specimens under load, it was also necessary to conduct experiments, the results of which were used to validate the methodology developed.

A further goal of my research is the development and parameterization of a finite element fracture mechanics model for Norway spruce specimens, as well as the comparison of its results with measurement data. Therefore, it was also necessary to determine the material properties for the simulations. By applying the modeling technique to individual specimens, the result of the measurements can be predicted by simulation. Examples of such results are the deflection by a predefined loading, the ultimate load and the path of the propagating crack under overload.

Material

In my research I examine Norway spruce at the meso scale by digitalizing the annual ring pattern of specimens to obtain conclusions about their load-bearing capacity and deformation shape. The failure mechanisms and the fracture of the specimens are therefore also investigated.

Initially, the aim was to reconstruct the experiments by using the photos of end-grains and creating unique finite element models of timber specimens. As for any other modeling approach, one of the major challenge lies in the determination of the necessary mechanical properties. As the model performance and prediction capacity is highly dependent on these properties. In my research, not only a finite element modeling method was developed, but also a method for determining the

material properties of the earlywood and latewood was proposed. For modeling individual specimens using the finite element method, a photoanalytical processing tool was developed that recognizes the specimen in the photo and the pattern of annual rings within it. This tool is needed to create a finite element model with the introduced approximation methods and distinguishing between earlywood and latewood in the bulk.

Subsequently, the finite element models were further developed, and I also propose a fracture model for Norway spruce based on the recent literature and the experiment results, which was adapted from the topic of fiber reinforced materials. To perform the simulations, the damage model was coded for the finite element solver ABAQUS. In my research, XFEM with linear elastic fracture mechanics (LEFM) is used to describe the crack initiation and propagation in case of brittle fracture.

Summary of results

The product of my research is a finite element modeling technique that allows to determine the load carrying capacity of a given clearwood Norway spruce specimen with a good approximation before measurements are performed, and a finite element damage model that allows to calculate the crack propagation in the timber specimen during overloading by numerical simulation.

In the first stage of my research, two theses have been introduced, with the help of which, the measurement results in the linear-elastic range can be reproduced by finite element simulation. With the developed photoanalytical processing tool it was possible to create the simplified finite element models of the clear wood Norway spruce specimens based on photos of the end-grain. Then, the orthotropic material properties of the earlywood and the latewood were determined based on the proposed thesis.

In the second stage of my research, XFEM with linear elastic fracture mechanics is used to describe the crack initiation and propagation in case of brittle fracture. To describe the failure mechanisms of the Norway spruce clear wood specimens, six damage initiation criteria are used. A normal vector to the crack surface is calculated for each damage mode, taking into account the orientation of the maximum and minimum principal stresses. A user-defined damage initiation criterion was implemented in FORTRAN for the finite element solver ABAQUS.

In addition, based on the experiment results the correlation between latewood ratio, ultimate force, ultimate elongation/deflection, calculated moduli, annual ring orientation and diameter of the annual ring at the edge-notch were obtained.

Doctoral Thesis

1. Thesis

For class A (highest quality class) or class B wood it can be assumed, that proportion of earlywood and latewood in the end cross-section of the analyzed timber beam nearly equals in all cross-sections along its longitudinal axis.

For the development of the finite element model of timber beams, their unique annual ring pattern is considered. The HSV color spectrum of picture of the end-grain pattern is analyzed in combination with the Canny edge detection technique using a proprietary photo analytical tool in order to separate the earlywood and latewood phases in the bulk.

By determining the surface ratio of earlywood and latewood, the thesis states that this value can be converted to a volume ratio. The density of the earlywood and latewood rings can be determined by measuring finite small specimens. If the

assumptions are good enough, the given formula should lead to the measured weight of the beam. This indicator is easy to determine and non-destructive.

The results of the compared measurements and finite element models based on the introduced thesis show good agreement within the linear elastic limit. For natural wood, EUROCODE 5 requires a safety factor of at least 1.3, which is very optimistic. For this reason, the values within the 30% margin of error can be considered good.

2. Thesis

The rule of mixtures combined with the correlation between the orthotropic material properties and density of earlywood and latewood lead to equations, which can be used to define the stiffness relations for the Norway spruce between earlywood and latewood.

Based on the conducted research the material properties of earlywood and latewood for Norway spruce are obtained. These values provide a good basis for further investigations. However, it should be noted, that depending on the origin of the wood material, a recalibration of the material values may be necessary. The equations established in this thesis allow the determination or calibration of the material values for the batch of Norway spruce used.

3. Thesis

With the presented failure criteria and failure stress values, it is possible to describe the damage process and the crack propagation of clearwood Norway spruce specimens in case of brittle failure.

Wood shows ductile behavior in compression and brittle behavior in tension and shear, where both failure modes can occur simultaneously. In cases, where wood mainly behaves like a brittle material, the linear elastic fracture mechanic principles based on the fracture toughness parameter K_{IC} are able to characterize the fracture process adequately. In these cases, the failure of spruce specimens can be described by six failure criteria. The damage initiation mechanisms are: tension and compression in the three main directions. Pure shear modes are not considered.

When at least one of the six failure criteria is met, the damage initiation is triggered. The criterion that reaches the critical value sooner is responsible for the failure.

Overall, it can be concluded that the quality of the results means that the 3rd thesis is plausible.

Publications related to the topic of the thesis:

Király T., Polgár R., Andor K. (2020): Modeling the early- and latewood annual rings as orthotropic material for FE calculation of Norway spruce timber beams using the rule of mixture. Abstract book for the 16th Miklós Iványi International PhD & DLA Symposium, Pollack Press, pp. 73-74, ISBN: 978-963-429-578-5

Király T. (2021): Macroscopic Material Degradation Model of Wood for XFEM using the Rule of Mixtures. Abstract book for the 17th Miklós Iványi International PhD & DLA Symposium, Pollack Press, pp. 147-148, ISBN: 978-963-429-811-3

Király T., Karácsonyi Zs., Polgár R., (2023): Modeling the earlywood and latewood annual rings of Norway spruce timber beams for finite element calculation. Wood Research 68 (1), pp. 28-43, DOI: 10.37763/wr.1336-4561/68.3.55857

Király T., Karácsonyi Zs. (2023): Fracture testing of edge-notched timber beams with different annual ring orientations. Wood Research, Vol. 68(3), pp. 558-571, DOI: 10.37763/wr.1336-4561/68.3.558571

Király T., Karácsonyi Zs., Polgár R. (2023): Macroscopic material degradation model of Norway spruce clear wood for XFEM. Results in Materials (*under publishing*)

Conference participations related to the topic of the thesis:

Király T. (2020): Modeling the early- and latewood annual rings as orthotropic material for FE calculation of Norway spruce timber beams using the rule of mixture. Pécs, PhD and DLA Symposium 2020, Conference presentation

Király T. (2021): Macroscopic Material Degradation Model of Wood for XFEM using the Rule of Mixtures. Pécs, PhD and DLA Symposium 2021, Conference presentation

Other publication activities:

Király T., Primusz P. (2020): A gumiabroncs és az útpályaszerkezet érintkezési kapcsolatának elemzése végeselem módszerrel [*Finite element analysis of the tyre-road structure contact using the finite element method*]. Útügyi lapok, Vol. 8 (14), DOI: 10.36246/UL.2020.2.04

Király T., Primusz P. (2021): Ikerabroncs-terhelés hatására ébredő igénybevételek meghatározása hajlékony útpályaszerkezetben [Determination of dual-tyre loading stresses in flexible pavement structures]. Soproni Egyetem Kiadó, pp. 402-409, ISBN: 9789633343739

Király T., Primusz P. (2022): Simulation of Static Tyre – Pavement interaction using two FE Models of Different Complexity. Applied Sciences – Basel, 12 (5) Paper 2388. p24, DOI: 10.3390/app12052388

Polgár R., Bálint B.E., Horváth A., Király T. (2023): Matematika tanár szakos hallgatók oktatási készségeinek hallgatóközpontú fejlesztése mikrotanítási környezetben [Developing student-centered teaching skills for mathematics teacher students in a microlearning environment]. Dimenziók, Matematikai Közlemények.

Other conference participation:

Király T. (2021): Aszfaltburkolatú útpályaszerkezetek elemzése végeselem-módszerrel [Finite element analysis of asphalt pavement structures]. HAPA XIV. Fiatal Mérnökök Fóruma, Conference presentation

Király T. (2022): Aszfaltburkolatú útpályaszerkezetek elemzése végeselem-módszerrel [Finite element analysis of asphalt pavement structures], HAPA XXII. Nemzetközi Aszfaltkonferencia, Conference presentation