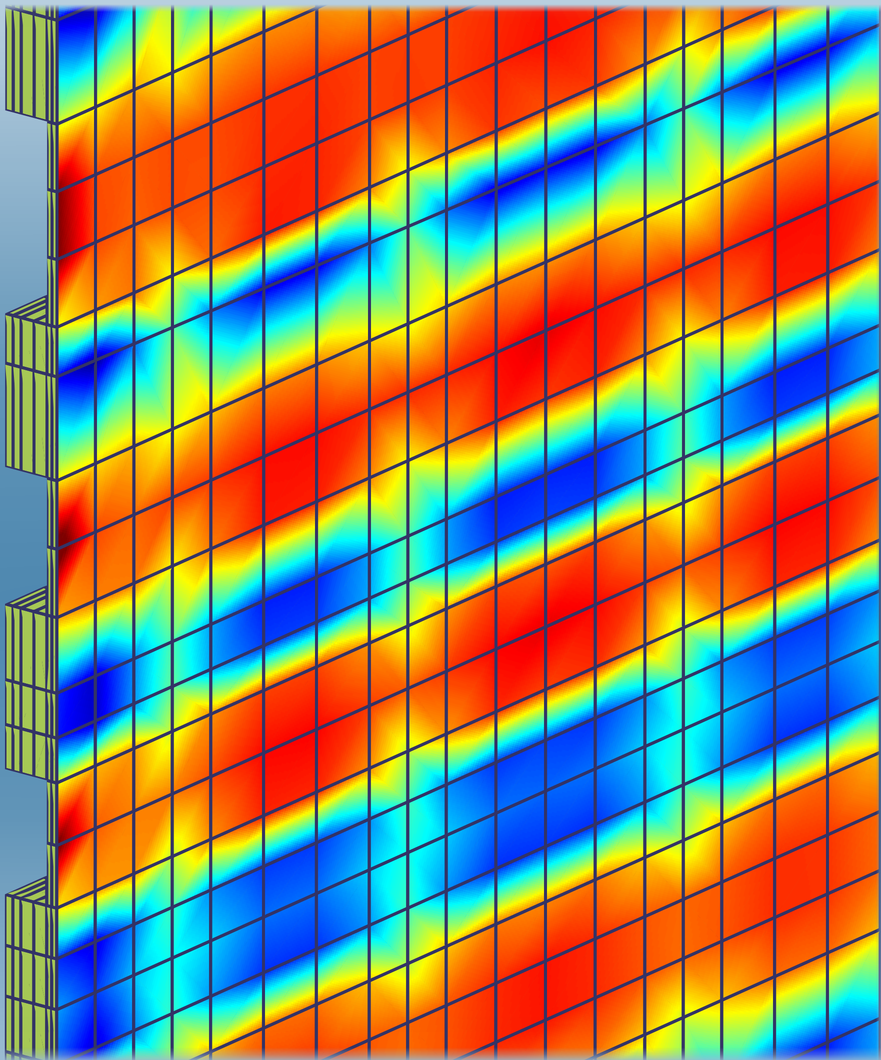
ECCOMAS
European Community on
Computational Methods in
Applied Sciences

ECCOMAS Thematic Conference

CompWood 2023

September 5-8, 2023 | Dresden | Germany

Computational Methods in Wood Mechanics



TECHNISCHE UNIVERSITÄT DRESDEN

Institute for **Structural Analysis**

https://compwood2023.cimne.com

Computational Methods in Wood Mechanics

CompWood 2023

Dresden, Germany
5 - 8 September 2023

A publication of:
International Center for Numerical Methods in Engineering (CIMNE)
Barcelona, Spain

ISBN: 978-84-123222-7-9

Printed by: Artes Gráficas Torres S.L., Huelva 9, 08940 Cornellà de Llobregat, Spain

TABLE OF CONTENTS

PREFACE

Dear participants of CompWood 2023,

it is our great pleasure to cordially welcome you at the Technische Universität Dresden, on the oc-casion of the third edition of the ECCOMAS Thematic Conference on Computational Methods in Wood Mechanics – from Material Properties to Timber Structures (CompWood 2023).

Dresden is one of the greenest cities in Europe, situated in the Elbe Valley in a hilly landscape lined with vineyards. 62 % of the city's area is green and wooded. Parks and green spaces can be found throughout the place, and on the outskirts, there is also a large contiguous forest area, the Dres-dner Heide. Saxon Switzerland, a characteristic landscape including a national park and large forest stands, is also not far from Dresden. The importance of wood has always been high in Saxony - both in traditional areas such as carving, historical architecture and local and international fine arts, as well as in modern construction. As a science location, Dresden also contributes to advancing scien-tific research on wood and timber.

One of the most urgent challenges of our time is climate change and the fight against its origins. An important contribution is to make the building industry more sustainable. By this, wood as a natural, biodegradable, renewable and CO2-absorbing raw material has increasing importance and is a promising candidate as building material of the future. The exceptional properties of wood can be exploited even better in new wood and timber-based products, like cross-laminated timber, com-posites or densified wood. This should build upon a strong scientific base. Currently, many fields of research are being explored. The data acquisition regarding tomography and physical properties as well as the description of material behaviour are important to understand the structural behaviour and to reach the ambitious climate goals, further accompanied by scientific approaches on safety assessment and optimisation.

The objective of the CompWood 2023 ECCOMAS thematic conference is to facilitate the progress in wood mechanics by bringing together scientists focusing on the micro- up to the structural scale. We would like to provide a platform for the dissemination of new methods and technologies. The goal is to present and discuss results of recent research activities, to exchange knowledge, and to discuss new paths for future research in order to extend our knowledge base. Computational methods, often in combination with experimental investigations, substantially contribute to ex-plore the anisotropic, hygroscopic, and time dependent properties of wood and to exploit them in engineered wood-based products and structural applications, not limited to the built environment. We are glad that we could attract a broad interest with 58 expected presentations, including nu-merical, experimental, theoretical as well as applied contributions. Five distinguished keynote lec-turers will span over the above-described conference topics and we are thankful to them for ac-cepting the invitation.

The conference is organised by the Institute for Structural Analysis at the TU Dresden. We would like to acknowledge the support of ECCOMAS for providing the possibility to organise the CompWood conference under their auspices. Many thanks also go to the Scientific Advisory Com-mittee for helping advertising the conference. The financial support by LuxScan Technologies from the Weinig Group is gratefully acknowledged.

Finally, we would like to thank you for your contribution to the success of this conference. We hope you find the presentations and the discussions interesting and stimulating, to have a wonderful time in Dresden and that you will leave the city with a lot of great impressions and new ideas for your research. Enjoy your stay and welcome to the TU Dresden!

Michael Kaliske
Chairman of the 3rd CompWood ECCOMAS thematic conference

CONFERENCE SPONSOR

LUXSCAN TECHNOLOGIES S.à.r.l.

12 Rue de l'industrie

L-3895 Foetz

Luxembourg

www.weinig.com

INVITED SPEAKERS

Advanced concepts for modeling failure and transport processes in wood and wood-based products
Prof. J. Eberhardsteiner
Institute for Mechanics of Materials and Structures,
Vienna University of Technology,
Vienna, Austria

Enhancing mechanical properties of wood by thermo hydro mechanical treatments
Prof. Dr. A. Kutnar
InnoRenew CoE Research Institute,
University of Primorska,
Koper, Slovenia

Effective nonlinear FE-modelling of progressive failures of (3D) timber structures jointed with multiple-fastener connections
Prof. Dr. S. Ormarsson
Department of Building Technology,
Linnaeus University
Växjö, Sweden

Influence of morphology on effective hygro-elastic properties of wood
Prof. A. S. J. Suiker
Institute for Applied Mechanics and Design,
Eindhoven University of Technology,
Eindhoven, Netherlands

Beyond wood - structural and functional diversity in lignified tissues
Prof. C. Neinhuis
Chair of Botany,
Technische Universität Dresden,
Dresden, Germany

ORGANISATION

Technische Universität Dresden (TU Dresden)

Institute for Structural Analysis

CONFERENCE ORGANISERS

Chair of the conference

Michael Kaliske
Technische Universität Dresden, Germany

Local Organising Team

Niklas Schietzold
Technische Universität Dresden, Germany

Daniel Konopka
Technische Universität Dresden, Germany

Josef Stöcklein
Technische Universität Dresden, Germany

Robert Fleischhauer
Technische Universität Dresden, Germany

SCIENTIFIC COMMITTEE

- S. Aicher (Germany)
- H.J. Blass (Germany)
- R. Brandner (Austria)
- I. Burgert (Switzerland)
- J.M.C. Ballarín (Spain)
- W.S. Chang (UK)
- P.L. Clouston (USA)
- T. Descamps (Belgium)
- M. Fragiacomo (Italy)
- A. Frangi (Switzerland)
- S. Franke (Switzerland)
- J. Füssl (Austria)
- K. Gamstedt (Sweden)
- J. Gril (France)
- P. Haller (Germany)
- D. Sandberg (Sweden)
- M. Hughes (Finland)
- J. Köhler (Norway)
- P. Kuklik (Czech Republic)
- E.N. Landis (USA)
- M. Lukacevic (Austria)
- U. Müller (Austria)
- L. Muszinski (USA)
- P. Niemz (Switzerland)
- S. Ormarsson (Sweden)
- G. Pot (France)
- G. Schickhofer (Austria)
- E.I. Saavedra Flores (Chile)
- S. Svensson (Sweden)
- J. Xavier (Portugal)

CONFERENCE SECRETARIAT

CIMNE Congress Bureau

Campus Nord UPC
Building C1 - Office C4
C/ Gran Capità, S/N 08034 Barcelona, Spain
Tel.: +34 93 405 4696

Conference Secretariat: CompWood_sec@cimne.upc.edu

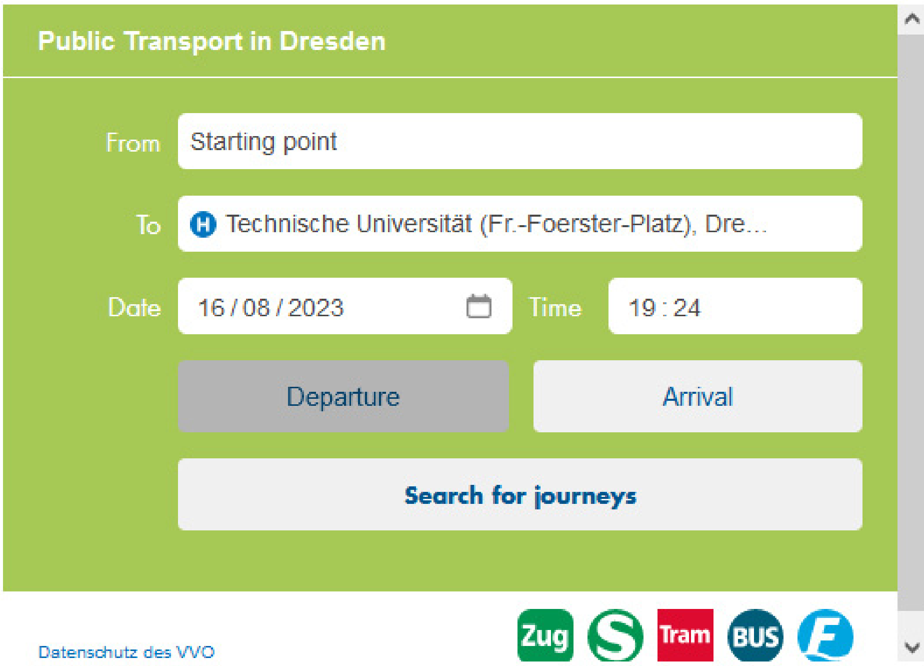
CONFERENCE VENUE

The conference will take place at the main campus of Technische Universität Dresden, at "Chemie Gebäude". The campus is located in the south of Dresden, close to the city center. It can easily be reached from Dresden Hauptbahnhof (main station) by public transport. Dresden Hauptbahnhof has direct train connection to Dresden International Airport in the north of Dresden

Chemie Gebäude Campus

How to get to the TU Dresden

The conference rooms are located in the building CHE as indicated in the map. The address is Bergstraße 66. Please check also https://navigator.tu-dresden.de/karten/dresden/geb/che/?language=en



Ticket for Local Public Transport

All participants will receive a ticket for local public transport.

Your name tag in combination with this ticket (VVO GmbH) will enable you to travel on all trams, busses and suburban trains within Dresden (tariff zone 10) whole day.

Please take your ticket with you whenever using public transport! Information on routes, timetables and the route network in Dresden can be found on the DVB AG website at https://www.dvb.de/en-gb/ or with the help of the DVB AG app (https://www.dvb.de/de-de/fahrplan/dvb-mobil/).

Car: Take the motorway A4, at interchange Dresden-West change to the A17 to Praha. Exit at Dresden-Südvorstadt. Follow the road into town for around 2.5 km up to the campus of the Dresden University of Technology (Bergstrasse). The lecture hall center is on the left side.

Unfortunately, no parking sites are available on the TU-Campus. We recommend the use of the ticket for the local transport, which enables you to travel on all busses and trams within Dresden.

Train From the Dresden Main Station take the bus no. 66 (towards Coschütz / Mockritz). Get off after two stops at the station “Technische Universität” (Fritz-Förster-Platz).

Plane From the airport Dresden-Klotzsche take the city-railway (S-Bahn S2) to the Dresden Main Station (Dresden-Hauptbahnhof).

From the Dresden Main Station take the bus no. 66 (towards Coschütz / Mockritz). Get off after two stops at the station “Technische Universität” (Fritz-Förster-Platz).

Catering and Lunch

Coffee, tea, soft drinks, biscuits and finger food will be served in the foyer or courtyard of the "Chemie Gebäude" during the coffee breaks. For the welcome reception on Tuesday, also wine and beer is served. Lunch will be held in the refectory "Alte Mensa". All participants will receive coupons for this at registration. Those who have registered as students need to show their student ID for lunch.

Conference Dinner

The conference dinner will take place on Thursday, September 7, in one of the oldest ballrooms of the region, the Ballhaus Watzke. With its historic atmosphere and charming ambience, it offers the perfect setting for an inspirating get-together. Ballhaus Watzke is known for its excellent cuisine, serving regional specialties and seasonal dishes. Participants can look forward to a culinary journey where both meat lovers and vegetarians will get their money's worth. It is located right next to the river Elbe with a far view to the Dresden old town.

Please use the following address:

Ball- & Brauhaus Watzke

Kötzschenbroder Str. 1

01139 Dresden

Germany

SUMMARY

PLENARY LECTURES

CONFERENCE TOPICS

CONTENTS

PLENARY LECTURES

CONFERENCE TOPICS

Application/Engineering

Composites

Connections

Cross-Laminated Timber

Cultural Heritage

Densification

Fracture

Microscale and Homogenisation

Moisture Influence and Nonlinearity

Physical Properties

System Safety and Optimisation

Tomography

PLENARY LECTURES

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Advanced concepts for modelling failure and transport processes in wood and wood-based products

J. Füssl*, M. Lukacevic*, F. Brandstätter*, C. Vida*, S. Pech*, M. Autengruber* and J. Eberhardsteiner*

* Institute for Mechanics of Materials and Structures
Faculty of Civil and Environmental Engineering, TU Wien
Karlsplatz 13/202, 1040 Vienna, Austria
josef.eberhardsteiner@tuwien.ac.at, www.tuwien.at/cee/imws/simulation

ABSTRACT

The field of engineered timber construction has seen a significant upsurge in recent years. This surge is attributed to increased focus on sustainability and ecology, improved quality and availability of innovative timber products, and the reliable integration of these products into complex structural frameworks. Despite this growth, assessing and modelling the mechanical performance of timber constructions pose challenges due to the variability of construction elements, connection materials, and specialised components. This has been pre-dominantly addressed through experimental determination of mechanical properties, which proves time-consuming and offers limited scalability.

A potential solution lies in experimental programs with numerical simulations, which can generate abundant mechanical data about a tested component. Not restricted by measurement methods used in experiments, numerical models provide detailed insights into deformation, strain, and stress states. Given a trustworthy numerical model, extensive parameter studies can be conducted to generate a comprehensive database for further development of guidelines and standards. Furthermore, for large components like glued laminated timber beams or cross-laminated timber panels, numerical simulations are much more cost-effective than equivalent experimental tests.

However, the benefits of numerical simulations hinge on the creation of models that realistically depict the mechanical behaviour of complex timber components. Challenges include the need for reliable material parameters, the variability of naturally grown wood, and the modelling of the material's orthotropic behaviour. Also, material nonlinearities, like quasi-brittle failure mechanisms, need to be considered, necessitating suitable numerical methods and adequate input material parameters. Notably, validating simulation tools based on selected experiments is essential to assess prediction quality and increase confidence in simulation results.

Although a general simulation tool capable of addressing all these challenges does not currently exist, scientific activity in this domain is increasing with promising developments worldwide. This presentation aims to illustrate the potential future of numerical simulation tools in selected areas of relevance for timber construction: the numerical modelling of moisture transport processes in wood and quasi-brittle failure mechanisms in timber components. The presentation introduces a model that can describe moisture transport processes under and over the fibre saturation point of wood [1, 2]. An engineering approach to determining moisture gradients in cross-sections of wood, depending on the relative humidity of the environment, is presented, along with an extension of this simulation concept to predict moisture-induced cracking [3]. Additionally, a model predicting

the bending strengths of glued laminated timber beams is discussed [4], highlighting its use in investigating the controversial size effect in glued laminated timber beams [5]. Finally, a numerical concept, the phase-field method [6], is introduced. This method could, for the first time, be capable of describing complex failure mechanisms in wood in a physically based and stable manner [7]. The presentation concludes with representative examples where numerical simulations could be applied.

REFERENCES

[1] Autengruber, M.; Lukacevic, M.; Füssl, J. (2020). Finite-element-based moisture transport model for wood including free water above the fiber saturation point. International Journal of Heat and Mass Transfer 161, 120228 (2020) https://doi.org/10.1016/j.ijheatmasstransfer.2020.120228

[2] Autengruber, M.; Lukacevic, M.; Eberhardsteiner, J.; Füssl, J. (2022). Computergestützte Modellierung von Feuchtetransportprozessen in Holzwerkstoffen. Bautechnik 99(10), 781–788. https://doi.org/10.1002/bate.202200045

[3] Brandstätter, F.; Autengruber, M.; Lukacevic, M.; Füssl, J. Prediction of moisture-induced cracks in wooden cross sections using finite element simulations. Wood Science and Technology 57, 671–701 (2023). https://doi.org/10.1007/s00226-023-01469-3

[4] Vida, C.; Lukacevic, M.; Eberhardsteiner J.; Füssl, J. Modeling approach to estimate the bending strength and failure mechanisms of glued laminated timber beams 255, 113862 (2022) https://doi.org/10.1016/j.engstruct.2022.113862

[5] Vida, C.; Lukacevic, M.; Hochreiner, G.; Füssl, J. Size effect on bending strength of glued laminated timber predicted by a numerical simulation concept including discrete cracking. Materials & Design 225, 111550 (2023). https://doi.org/10.1016/j.matdes.2022.111550

[6] Pech, S.; Lukacevic, M.; Füssl, J. A hybrid multi-phase field model to describe cohesive failure in orthotropic materials, assessed by modeling failure mechanisms in wood. Engineering Fracture Mechanics 271, 108591 (2022) https://doi.org/10.1016/j.engfracmech.2022.108591

[7] Pech, S.; Lukacevic, M.; Füssl, J. Validation of a hybrid multi-phase field model for fracture of wood. Engineering Fracture Mechanics 275, 108819 (2022). https://doi.org/10.1016/j.engfracmech.2022.108819

Beyond wood - structural and functional diversity in lignified tissues

Christoph Neinhuis

TU Dresden
Faculty for Biology
christoph-neinhuis@tu-dresden.de

ABSTRACT

Wood, i.e., secondary xylem derived from a bifacial cambium is widespread among plants. However, various types of lignified cells and tissues can be found and are often connected to specific functions, three examples of which will be presented.

Flagellaria is a climbing monocot with a unique stem anatomy and biomechanical properties that attaches to the surrounding vegetation via leaf tendrils. Biomechanical methods such as three-point bending and torsion tests were used together with anatomical studies on tissue development, modification and distribution. Mechanical properties were modulated via tissue differentiation processes mainly affecting the cortex of the stem. Although F. indica lacks secondary cambial growth, the climbing habit is facilitated by a complex interaction of tissue maturation and attachment.

Apple (Malus) fruit peduncles are highly modified stems that connect growing fruits securely to the branch while the weight, i.e., static and dynamic loads increase. We studied the tissue formation and modification during fruit development in peduncles, in which fibers contribute mainly to tensile strength and overall axial rigidity of the peduncles while sclereids effectively increase bending stiffness.

Some Martyniaceae produce lignified capsules with hook-shaped extensions that attach to feet of large mammals. The arrangement of fibers in the fruit wall is unique among plants that we studied anatomically and mechanically under different load conditions. At the cell wall level, both a large microfibril angle and greater strain rates resulted in moderate Young's moduli of 4-9 GPa, and high tolerance against large deformations under various load conditions. Longitudinally arranged fiber bundles contribute to a great tensile strength. At the tissue level, transversely oriented fibers absorb radial stresses upon bending and stabilize longitudinal bundles against buckling. While the increased flexibility allows for proper attachment of fruits during dynamical locomotion, the high strength and stability prevent a abrupt failure due to heavy loads exerted by the animal.

REFERENCES

[1] Hesse, L., et al. (2016). "Biomechanics and functional morphology of a climbing monocot." Annals of Botany Plants **8**. DOI: 10.1093/aobpla/plw005
[2] Horbens, M., Feldner, A., Hofer, M., Neinhuis, C. (2014). "Ontogenetic tissue modification in Malus fruit peduncles: the role of sclereids." Annals of Botany **113**(1): 105-118. DOI: 10.1093/aob/mct262
[3] Horbens, M., Gao, J., Neinhuis, C. (2014). "Cell differentiation and tissue formation in the unique fruits of devil's Claws (Martyniaceae)." American Journal of Botany **101**(6): 914-924. DOI: 10.3732/ajb.1400006
[4] Horbens, M., M., Eder, M., Neinhuis, C. (2015). "A materials perspective of Martyniaceae fruits: Exploring structural and micromechanical properties." Acta Biomaterialia **28**: 13-22. DOI: 10.1016/j.actbio.2015.10.002

Effective nonlinear FE-modelling of progressive failures of (3D) timber structures jointed with multiple-fastener connections

Sigurdur Ormarsson*, Le Kuai†

*Building technology, Linnaeus University, sigurdur.ormarsson@lnu.se
†Building technology, Linnaeus University, le.kuai@lnu.se

ABSTRACT

Slotted-in steel plate connections in glulam structures are often critical elements in the design, especially if they are exposed to significant in-plane moment action during varying environmental conditions. In design of optimized multiple fastener connections, correct calculations of fastener forces and their directions during progressive plasticization of the dowel groups are difficult to perform manually. The overall aim of this work is to develop an effective and flexible finite element model to simulate deformations and stresses in glulam structures jointed with mechanical dowel-type connections. The model is a simple (parameterized) 3D-model using effective structural elements for the wood and the steel plate members and non-linear connector elements for the mechanical connections. The connector properties and failure modes are mainly based on the European Yield Model (EYM) by [1]. In this specific study, the model was used to simulate global bending deformations of several glulam beams jointed with slotted-in steel plate connections. Detailed connection behaviours were also computed in terms of slip deformations, load carrying capacities, force distribution within the dowel group and the failure modes of the fasteners, see Figure 1. The proposed model was experimentally verified using results obtained from a joint project with the Material Testing Institute (MPA) at University of Stuttgart. Since the model operates in a 3D-space, it has a potential to be further developed concerning model adaptivity in complex 3D-structures, brittle connection failures, moisture related stresses and rope effect caused by large rotation of the fasteners.

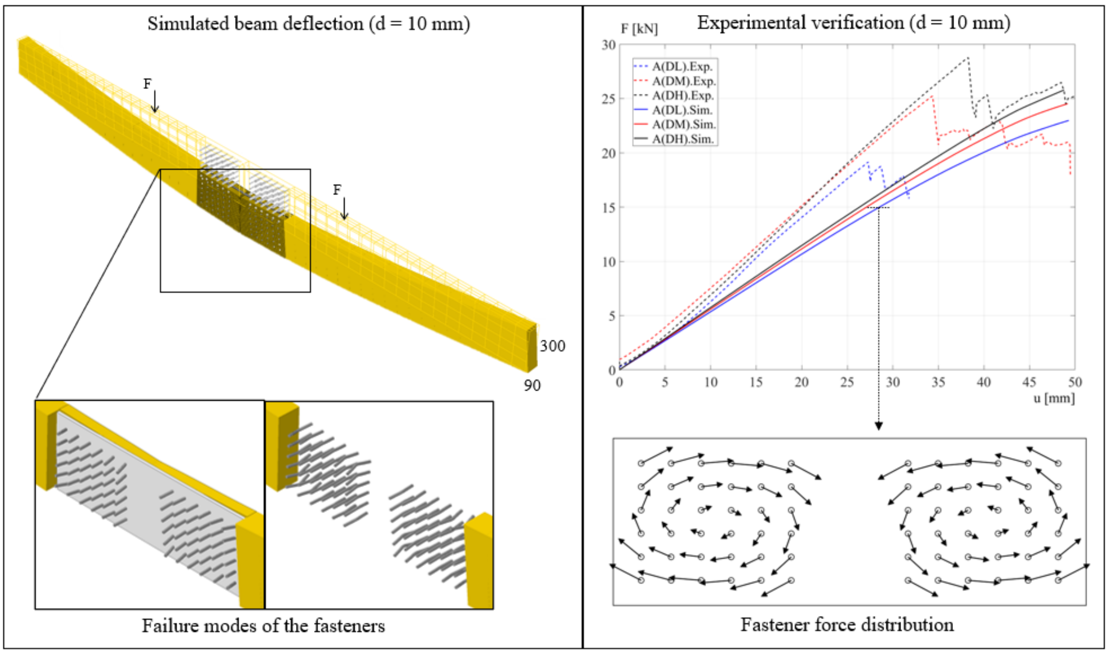


Figure 1: Typical numerical results from the developed glulam model.

REFERENCES

[1] K. W. Johansen, "Theory of timber connections," Int Assoc Bridge Struct Eng, vol. 9, pp. 249–262, 1949, doi: 10.5169/seals-9703.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Enhancing Mechanical Properties of Wood by Thermo Hydro Mechanical Treatments

Andreja Kutnar*

* University of Primorska
Titov trg 4, 6000 Koper, Slovenia
InnoRenew CoE
Livade 6a, 6310 Izola, Slovenia
andreja.kutnar@upr.si; andreja.kutnar@innorenew.eu
https://innorenew.eu/

ABSTRACT

With the climate change challenges the world is facing, also wood processing has been putting more focus on wood modification treatments with lower environmental impacts. It is not only about modifying the wood into very durable wood with long service life, but also about the environmental impacts of the processing and end of life of modified wood, its reuse and recycling. In this presentation the work that has been done in the past fifteen years, with the focus on the thermo hydro mechanical (THM) treatments, will be discussed. Furthermore, the need for future research in the field will be presented.

In a THM process, the thermo hydro (TH) process is combined with external forces to shape the wood. The force may be applied to the wood in the longitudinal direction, in the transverse directions, or in combination of both. In the longitudinal direction, the force may be tensile or compressive; in the transverse directions, the force usually is compressive. The purpose may either be to join pieces of wood, to compress the cell structure to increase the bulk density, or to shape the wood material in its cross-section or into a 3D-form.

In general it is possible to densify any wood species by the THM treatment. The degree of densification is however depended on the initial density of the species. Furthermore, the orientation of the wood to be densified influences the densification. The densification is easier on diffuse porous hardwoods than on softwoods. Densification of softwoods is best in the radial direction, while for hardwoods with large aggregated rays in the tangential direction. The densification pattern and resulting density profile depends on the morphology of the wood and plasticization of the material at the time of compression.

Wood densification is performed on the wood that has been soften prior mechanical compression by heat, steam, or chemicals. However, the mechanical compression can be applied also on wood without pre-treatment or softening. There have been many examples of wood compression techniques up through the last century. The methods have varied from mechanical to hydrostatic compression with added steam and/or heat. However, the methods have only proved limited commercial success. Examples of typical THM products are:

- high-density and thermally modified veneer panels without adhesive,
- welded wood dowels in cross-laminated timber,
- surface-densified flooring,
- bulk-densified wood component for electrical installations or wear-resistance mechanical transmissions, and
- different type of shaped wood mainly for interior use.

Influence of morphology on effective hygro-elastic properties of oak wood

M.A. Livani*, A.S.J. Suiker*, A. Crivellaro†, E. Bosco*

* Eindhoven University of Technology
Eindhoven, The Netherlands
A.S.J. Suiker@tue.nl

† University of Suceava
Suceava, Romania

ABSTRACT

A multi-scale framework is presented for the prediction of the macroscopic hygro-elastic properties of oak wood. The distinctive features of the current multi-scale approach are that: i) four different scales of observation are considered, which enables the inclusion of heterogeneous effects from the nano-, micro-, and meso-scales in the effective constitutive behaviour of oak at the macro-scale, ii) the model relies on three-dimensional material descriptions at each considered length scale, and iii) a moisture-dependent constitutive assumption is adopted at the nano-scale, which allows for recovering the moisture dependency of the material response at higher scales of observation. In the modelling approach, oak wood is considered homogeneous at the macro-scale. The meso-scale description considers the cellular structure of individual growth rings with three different densities. At the micro-scale, the heterogeneous nature of cell walls is described by the characteristics of the primary and secondary cell wall layers. Finally, the nano-scale response is determined by cellulose micro-fibrils embedded in a matrix of hemicellulose and lignin. The oak properties at the four length scales are connected via a three-level homogenization procedure, whereby, depending on the geometry of the fine-scale configuration, an asymptotic homogenization procedure or Voigt averaging procedure is applied at each level to determine the effective hygro-elastic properties at the coarse scale. In addition, the moisture adsorption isotherms at each scale are constructed from a volume-weighted averaging of the moisture adsorption characteristics at the scale below. The computational results demonstrate that the macro-scale moisture-dependent, hygro-elastic behaviour of oak wood is predicted realistically, thereby revealing the influence of the material density, the micro-fibril orientation, and the hygro-elastic properties from the underlying scales. The computed macro-scale properties of oak are in good agreement with experimental data reported in the literature.

CONFERENCE TOPICS

APPLICATION/ENGINEERING

Discussion on the consistency of design concepts in EC5
Data fitting or mechanical background

Georg Hochreiner*

* TU Wien, Institute for Mechanics of Materials and Structures
Karlsplatz 13, 1040 Wien
georg.hochreiner@tuwien.ac.at, www.imws.tuwien.ac.at

ABSTRACT

Motivation

Current standardization efforts are also focused on ***revising EC5***, which is scheduled by CEN at approximately 15-year intervals. The significant increase in volume and pages does not correspond to a growth in engineering competence or more efficient constructions. Mechanical transparency and a flexible range of applications are still lacking. Usually, each simplification of design equations leads to a loss of performance and competitiveness.

Contrary to historically developed solutions, the advancement of ***digitalization through BIM*** necessitates design concepts based solely on geometry, mechanical characterization and arbitrary loading scenarios, potentially excluding hand calculations.

Additionally, recent developments in ***AI-based tools*** may tempt professionals to reduce personal training and skill development. This negative perspective aligns with the current EC5, which encourages use by untrained engineers or carpenters.

Methodology of design concepts

Both the current and future EC5 contain a mix of design methods characterized by two typologies:

- Many design equations are derived from ***data fitting*** to experimental or even numerical data. FEM is considered suitable for the scientific community but not for practical use by engineers. The application of these formulas is possible even without understanding the corresponding failure mechanisms and does not require skills in structural modelling. Often, the formulations conflict with structural modelling and FEM due to the lack of transparency in material characteristics and system effects. This issue complicates training as well, as ex-plaining a "black box" is challenging. The strict limitations on applicability conflict with the diverse demands from building practice and do not provide a foundation for parameter studies or strategic development of material models or design concepts.
- Only a small set of design situations reflects the **application of engineering methods** closely connected to the principles of force equilibrium and displacement compatibility. Generally, the verification procedure consists of two steps: The calculation of internal forces or stress components by hand or FEM is followed by applying failure characteristics for decision-making concerning optional reinforcements. This loop may be repeated if the structural system requires modifications due to features like plasticity or crack formation. Structural modelling skills are essential in this case. Without limitations on specific configurations, this method has proven to be a powerful foundation for developing material models or design concepts, meeting demands from building practice, architecture, and environmental conditions. This approach is independent of realization type, whether through design tables, hand calculations or general-purpose structural engineering software.

Concepts and results from hand calculation must also be ***reproduceable by adequate structural modelling***. Otherwise, it will be impossible to overcome limitations in EC5 and expand to domains beyond personal experience without losses on safety and performance.

Case Study - Multiple Methods for the Same Mechanical Background

Three groups of design situations within EC5 illustrate this unfortunate situation:

- The four issues of ***compression at an angle to the grain*** according to Hankinson, design of ***tapered*** or ***curved beams***, and ***round holes in beams*** share the same mechanical characterization: The calculation method is based on linear elasticity. There is evidence of stress components in the local fibre coordinate system being triggered by arbitrary types of loading. The applicability of simple failure criteria aligns with multi-surface failure criteria and the design concept focuses on the level of stress or strength parameters. However, the present version and draft for revision of EC5 still contain the mix of different approaches, motivated solely by user-friendliness and ease of use. Regrettably, only the concept for curved beams adheres to adequate engineering methods.
- The same situation applies to the package consisting of design regulations for ***notches***, ***rectangular holes in beams***, ***loading of sub-cross sections parallel to the fibre*** and ***handling of cracks*** due to shrinkage. These issues are also linked by the same mechanical characterization: The evidence of peak stress or singularities could be addressed using fracture mechanics in terms of crack energy consumption. In this case, the design concept should shift towards load amplification factors. Again, only the concept for notched beams is based on a simplified and inflexible version of fracture mechanics with transformation of the results to the grade of utilization on stress component level.
- The numerous analytical ***formulas according to Johansen*** with expansion to multi-layer materials and independent intermediate layers are based on principles of limit analysis and have been fitted to experiments. However, the demand for consistent slip-curves, including shear load and corresponding relative displacements, could easily be addressed by a single type of numerical structural modelling with an unlimited scope of application.

Discussion and Benefit

The ***ever-growing volumes of standards*** show, that expectations for streamlined codes without excessive complexity respective boring textbook stuff have not yet been addressed. Interoperability of design standards for different materials, in terms of terminology and methods, is necessary for optimizing and creating hybrid systems. A minimum level of structural modelling should be established without losing design-sensitive information, including corresponding material characterization but not methods for the realization of the verification process itself. Additionally, material characterization must be independent of the depth of structural modelling and not limited to beam theory, as is the case within EC5.

The motivation for a modern reorganization of design standards could be enhanced by the ***availability of tools*** that support digital design processes. The assessment of wall elements with openings - similar to wall-like beams - and floor elements with arbitrary geometric configurations has been the first area of application for FEM and has been proven for decades. These issues are no longer exclusive to scientific software and are now ***affordable for smaller engineering firms***.

A rigorous shift from numerous specialized solutions to just ***a few powerful methods*** would strongly indicate, that the overall demand for increased efficiency has been recognized within design standards.

Conclusion

The development of ***FE-guidelines*** for the verification of members and systems made of steel and timber is a step in the right direction, given the fact that current design standards still largely represent building practices from decades ago. Therefore, the design process should and must be based on ***engineering skills*** and not be accessible to untrained users. Otherwise, EC5 will not be able to fulfil expectations regarding efficient and more economical consumption of building materials.

Modelling Failure of Timber Frame Walls Subjected to Combined Shear and In-Plane Bending Loads

D. Byloos*, T. Engelen*†, B. Vandoren*

*Hasselt University
Martelarenlaan 42, 3500 Hasselt
dries.byloos@uhasselt.be
tine.engelen@uhasselt.be
bram.vandoren@uhasselt.be

† EnergyVille, imec, imo-imomec
Thor Park 8320, 3600 Genk

ABSTRACT

Timber frame construction is becoming a more commonly used manner of building low to mid-rise multi-storey buildings in Europe. With this shift towards timber, it becomes increasingly important to understand the different mechanical behaviours of these structures such as the racking resistance (the resistance of the structure against horizontal loads such as the wind load) or the in-plane bending of timber frame walls. Today, several numerical models focus on modelling the racking resistance. Vessby et al. [1] implemented elasto-plastic connectors to simulate the mechanical behaviour of the sheathing-to-framing connections, while Källsner and Girhammar [2] used plastic models to simulate the shear behaviour. Another approach to modelling the racking resistance is seen in [3], where Vogrinec et al. proposed a method in which the stiffness of the sheathing and connectors is combined into a virtual diagonal element.

Despite the advances in the development of such numerical models, there is still a gap in knowledge regarding the in-plane bending behaviour of timber frame walls. In the literature, no simulations which try to characterise this behaviour are performed. However, in-plane bending is very important when looked at in the context of robustness, in particular for mid- to high-rise timber buildings where there is a chance of a possible removal or partial functionality loss of underlaying components, as shown in figure 1. In such a case, the timber frame wall above the removed wall will be loaded in bending and possibly in shear.

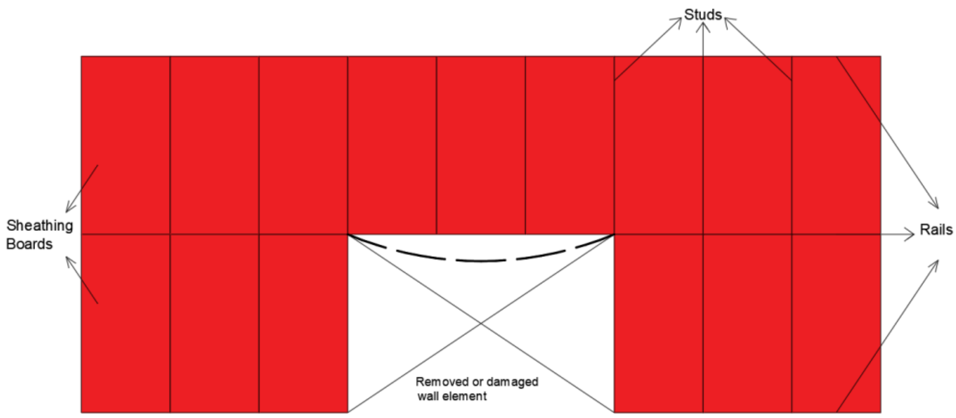
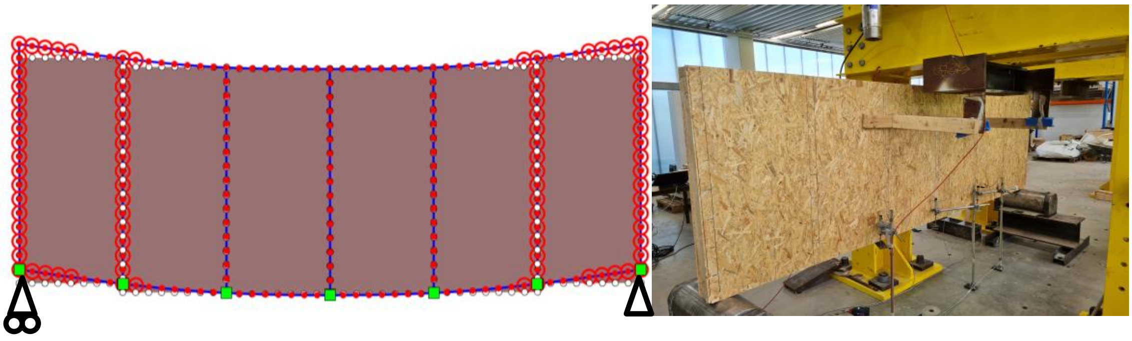


Figure 1: In-plane bending occurring in a timber frame wall due to damage to the supporting underlying wall

In this contribution, a finite element model is developed which makes it possible to simulate the horizontal loading onto a timber frame wall and which can also perform a numerical analysis on the in-plane bending. The model is verified through comparing the results from the numerical simulations with four-point bending experiments performed at the structural laboratory of the Construction Engineering Research Group (CERG) at Hasselt University.

Figure 2a shows the result of an in-plane bending simulation, where the red circles around the red dots represent the connections which failed. Figure 2b is a picture of the performed experiments.



(a) (b)

Figure 2: 4-point bending test (a) Simulation in the self-developed numerical model (b) Experiment conducted in the laboratory

One of the key elements in such a finite element model is the constitutive behaviour of the sheathing-to-framing connectors. In the proposed model, this behaviour is modelled using orthotropic spring elements which use two multilinear damage laws [4], one law for the shear behaviour perpendicular to the grain of the timber frame components (studs and rails), and one law for the shear behaviour parallel to the grain of the timber frame components. Both laws are calibrated using connection tests which are performed according to NBN-EN-1380 [5]. Figure 3 shows a representation of the results gathered from the first bending simulations compared to experimental results.

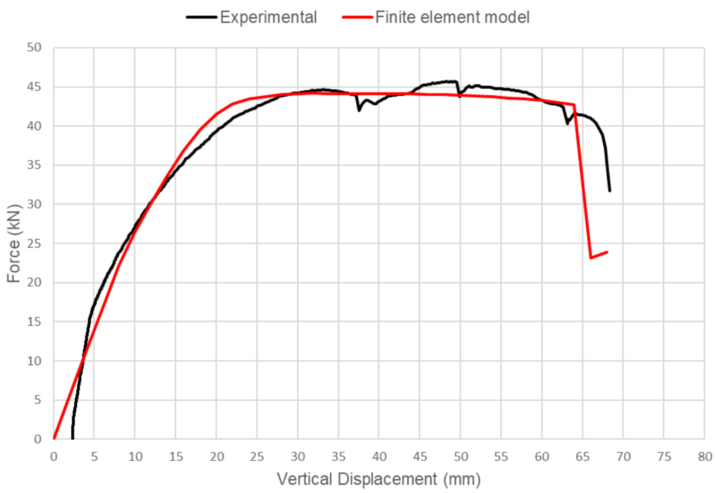


Figure 3: Comparison between experimental and numerical results from in-plane bending simulation

REFERENCES

[1] Kuai, L., Ormarsson, S., & Vessby, J. (2023). Nonlinear FE-analysis and testing of light-frame timeber shear walls subjected to cyclic loading. *Construction and Building Materials*, *362*.
[2] Källsner, B., & Girhammar, U. A. (2009). Plastic models for analysis of fully anchored light-frame timber shear walls. *Engineering Structures*, *31*(9), 2171–2181.
[3] Vogrinec, K., Premrov, M., & Kozem Šilih, E. (2016). Simplified modelling of timber-framed walls under lateral loads. *Engineering Structures*, *111*, 275–284.
[4] de Borst, R., A. Crisfield, M., J.C.Remmers, J., & V.Verhoorsel, C. (n.d.). Non-linear Finite Element Analysis of Solids and Structures. In *Non-linear Finite Element Analysis of Solids and Structures* (Second, pp. 170–219).
[5] Bureau of Normalization. (2009). *NBN-EN-1380: Test methods – Load bearing nails, screws, dowels and bolts.*

ON THE REINFORCEMENT OF TIMBER FRAMES WITH SUPERELASTIC TENSEGRITY

Baidehi Das[1,2], Julia de Castro Motta[2], Ada Amendola[2], Fernando Fraternali[2*]

[1]Department of Civil Engineering and Architecture
University of Catania, Italy
(baidehi.das@phd.unict.it)

[2]Department of Civil Engineering
University of Salerno, Fisciano (SA), Italy
(jdecastromotta@unisa.it, adaamendola1@unisa.it, f.fraternali@unisa.it)

ABSTRACT

We study the mechanical response of tensegrity bracing systems to be used for the reinforcement of timber frames with energy dissipation capacity. This technology consists of lightweight and high-strength systems with re-centering capabilities formed by pretensioned tensile elements and a variety of tensegrity systems (). The investigated braces incorporate superelastic cables or bars and timber struts. They can be designed making use of parametric algorithms and fractal geometry concepts. When designing the analyzed brace units with a tapered profile, which is also convenient to architecturally conceal the structure, it is shown that it is possible to optimize its performance in terms of buckling load, displacement magnification in the transverse direction and energy dissipation. The employment of the tensegrity braces for the reinforcement of timber frames is diffusely examined. The presented results highlight the enhanced properties of such structures in terms of ductility factor and energy dissipation capacity, as compared to more conventional bracing systems.

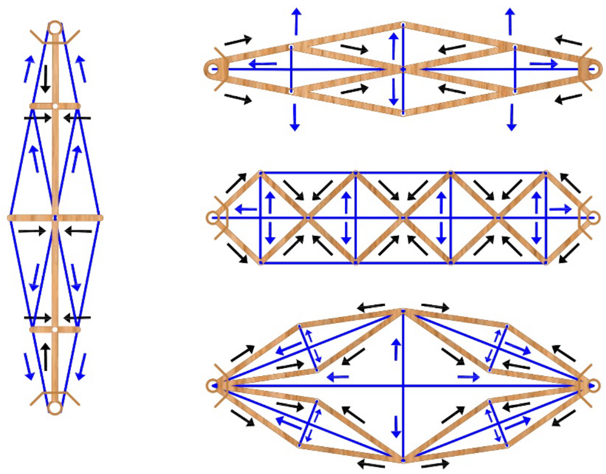


Fig. 1. Internally prestressed braces with superelastic cables or bars and timber struts.

KEYWORDS*: Seismic design, Bracing systems, Tensegrity structures, Superelastic response, Energy dissipation Recentering*

REFERENCES

[1] Santos, F., Benzoni, G., Fraternali, F. 2019. Seismic performance of superelastic tensegrity braces. Ingegneria Sismica – International Journal of Earthquake Engineering, 36(3), 20-37.

[2] Fraternali, F., Santos, F. 2019. Mechanical modeling of superelastic tensegrity braces for earthquake-proof structures. Extreme Mech Lett, 33, 100578.

[3] Santos, F., Caroço, C., Amendola, A., Miniaci, M., Fraternali, F. 2022. 3D tensegrity braces with superelastic response for seismic control. Int J Multiscale Comput Eng, 20(5), 53-64.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Revisiting Bending Induced Stresses in Inhomogeneous Timber Beams

D. Hoffmeyer* and A.R. Damanpack†

* Department of Technology and Innovation
University of Southern Denmark
Campusvej 55, DK-5230 Odense, Denmark
daho@iti.sdu.dk

† Department of Mechanical and Electrical Engineering
University of Southern Denmark
Campusvej 55, DK-5230 Odense, Denmark

ABSTRACT

Calculation tools for structural design of timber elements ought to be either as simple or as comprehensible as possible to minimize the chance of producing errors or to minimize the amount of time spent during the design phase of a structural component. At the same time they should be accurate enough to predict a stress state close to reality, though within the paradigm of the associated statistical uncertainties. Timber beams loaded in bending and shear are commonly designed according to Bernoulli beam theory, most often assuming an isotropic and homogeneous material for which e.g. Navier's and Grashof's formulas are appropriate [1]. These formulas for determining stresses are, however, not theoretically sufficient when analysing a solid beam cross-section with a cylindrically orthotropic material with (at least) radially varying material parameters. The theoretically 'correct' approach is rarely mentioned in standard text books, [1], but has been considered in e.g. [2], though without indicating obvious and modern solution strategies, e.g. finite elements. This contribution revisits the classical elasticity theoretical problem of determining stresses in a cantilever-type beam structure with linearly varying bending moments and constant shear force distributions.

A cantilever beam with concentrated transverse forces at the free end is considered. The material is cylindrically orthotropic and allows for radially varying elastic properties, though with constant Poisson's ratios. A displacement field is constructed based on superposition of displacements of a centre line along the beam length - corresponding to classical Bernoulli beam theory - and some unknown functions taking axial warping and in-plane distortion into account,

$$u_\alpha(x, y, z) = \bar{u}_{\alpha,\text{Bernoulli}} + f_\alpha(z)\psi_\alpha(x, y) \tag{1}$$

where $\alpha = x, y$ denotes the cross-sectional coordinates and z the longitudinal coordinate. The function $f_\alpha(z)$ accounts for axial variation of the in-plane functions. The constitutive model is based on the compliance matrix in the local cylindrical coordinate system where each material parameter is a function of location. The corresponding stiffness matrix is then transformed to a global Cartesian reference coordinate system by a suitable transformation,

$$\mathbf{C}(x, y) = \mathbf{T}^T\mathbf{C}_\ell(r)\mathbf{T} \tag{2}$$

With the strains derived from the displacement field in (1) and the stiffness matrix in (2) the stresses can be set up. The associated equilibrium equations for the stress state

then takes a simple form due to the assumptions of the cantilever structure. A standard Galerkin approach is used to set up a governing equation based on the equilibrium equations and the external loads, all multiplied with suitable test functions. An advantage of this method is the need only to integrate over the cross-sectional area - and it is thus possible to determine the 3D stress state by a 2D analysis of the cross-section. The unknown in-plane functions ψ_α are determined based on a discretized structures and solved by finite elements. The governing equation amounts to an algebraic system of the form

$$\mathbf{Kd} = \mathbf{F} \tag{3}$$

where the 'displacement' components in $\mathbf{d}$ allows for direct calculation of all six stress components. Especially, the in-plane stresses do not vanish due to the nature of the material.

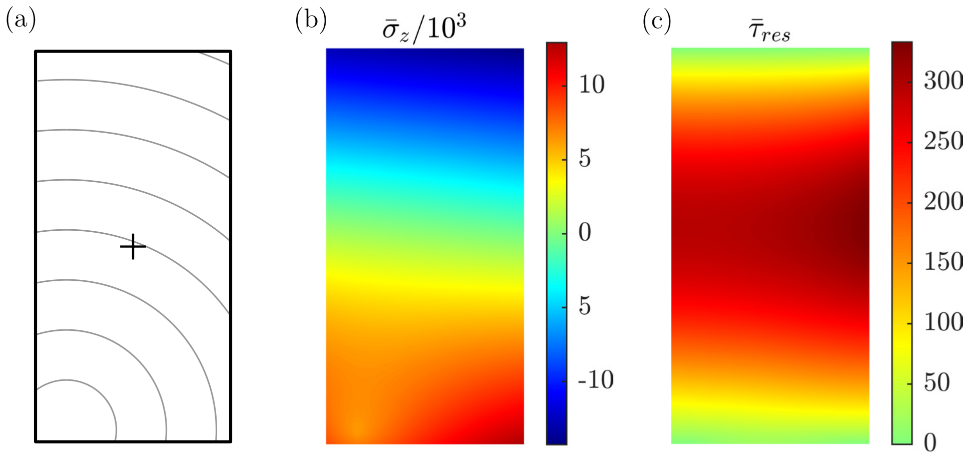


Figure 1: 100 × 50 mm cross-section with distribution of annual rings (a), normal stresses from a bending moment of 1 Nm (b) and resulting shear stresses (c) from a shear force of 1 N. Stresses in [Pa].

A beam cross-section of sawn timber may be seen in the above figure (left), with the given explicit distribution of the annual rings. When loaded in bending in one direction the normalized longitudinal stresses σ_z and $\tau_{res} = \sqrt{\tau_{yz}^2 + \tau_{xz}^2}$ are seen in the figure (middle) and (right) respectively. The radially varying material parameters are obtained from [3]. The distributions have some similarity with predictions from Navier's and Grashof's formulas although noticeably different. Preliminary analyses reveal that the relative deviations to the maximum stresses from Navier's and Grashof's formulas can be insignificant, but can also range up to more than 15 % and 10 % respectively, depending on the cut-out from the tree trunk. Accordingly ordinary beam theory should be applied carefully, especially when designing timber beams based on stresses determined from tools derived for beams with isotropic and homogeneous materials.

REFERENCES

[1] Porteous, J. & Kermani, A., *Structural Timber Design to Eurocode 5*, 2nd. edition, Wiley-Blackwell, 2013.

[2] Lekhnitskii, S. G., *Theory of Elasticity of an Anisotropic Body*, Mir Publishers, translated from the 1977 Russian edition, 1981.

[3] Ormarsson, S. &, Cown, D., Moisture-Related Distortion of Timber Boards of Radiata Pine: Comparison with Norway Spruce, *Wood and Fibre Science*, vol. 37, no. 3, pp. 424-436, 2005.

SUBSTRUCTURE MODELLING OF FULL SIZE TIMBER MODULES

Rajan Maharjan*, Johan Vessby*

* Building technology, Karlstad University
rajan.maharjan@kau.se, johan.vessby@kau.se

ABSTRACT

From an environmental sustainability point of view, modern construction practices increasingly favor carbon neutral buildings including those made from timber. Prefabricated timber modules have become popular due to their efficient in-house production followed by systematic and rapid on-site installation. Construction companies often use these lightweight modules for residential buildings up to six story when feasible. While several studies are available that simulate stiffness and strength of shear walls, a major component of the module responsible for transferring shear load and acting as a load bearing wall for vertical loads, e.g [1] and [2] for the EC5 design principles, relatively little work has been done to analyze the structural performance of entire modules. This is likely due to limited time span the construction type has been common practice, practical challenges associated with experimental tests and numerically demanding simulations of large structures. However, there are some exceptions, e.g [3].

This study introduces the concept of “super elements”, which are developed by condensing the internal degrees of freedom (DOF:s) of a whole timber module to specified parts of its boundary. The aim of this study is to reduce the number of DOF:s by using substructuring so that an entire structure can be analyzed while subjected to external loading. Substructuring is a method of dividing a whole model into user defined parts (super elements) and coupling these together to create a global model [4]. The internal DOF:s of the super elements are “condensed” using static condensation, and the super elements are then connected to the rest of the model along selected restrained DOF:s [5]. Figure 1(a) shows an example of a building with timber modules, while Figure 1(b) illustrates parts of a full-size timber module. Figure 1(c) represents a super element of the module. A simple, linear FE super element is developed for analyzing a part of a whole timber structure and it is coupled to the rest of the structure only at designated pre-selected nodes. The model is then used to analyze the response during various load cases applied to the whole structure.

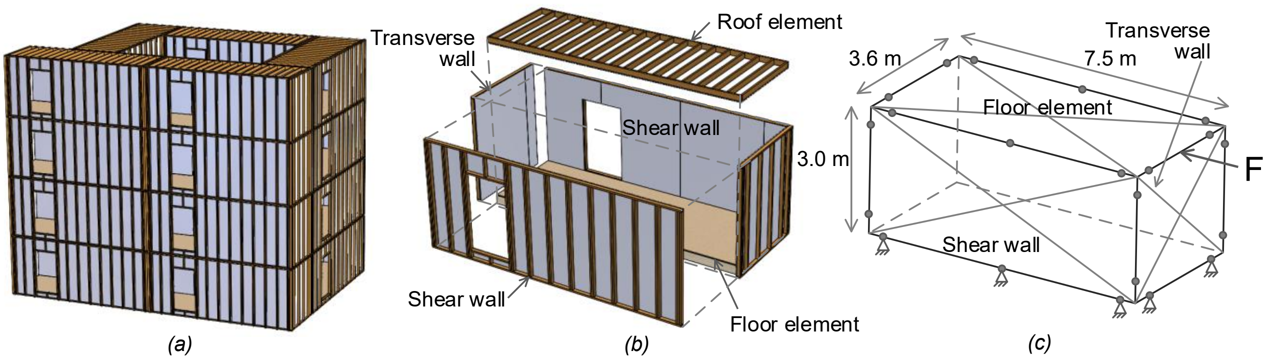


Figure 1: (a) An example of a modular timber building, (b) parts of a timber module and (c) sub structuring the module with parts connected together at pre-selected nodes.

REFERENCES

[1] Kuai L., Ormarsson S., Vessby J., Maharjan R., A numerical and experimental investigation of non-linear deformation behaviours in light-frame timber walls, Eng. Struct. 252, 2022, 113599.

[2] EN-1995-1-1, Eurocode 5: Design of Timber Structures-Part 1-1: General-Common Rules and Rules for Buildings, Brussels, 2004.

[3] Ormarsson S., Vessby J., Johansson M., Design of innovative modular-based timber structure based on advanced modeling and full-scale tests, World Conference on Timber Engineering 2021, WCTE 2021.

[4] Flodén O., Persson K., Sandberg G., Reduction methods for the dynamic analysis of substructure models of lightweight building structures, Computers & Structures, Volume 138, 2014, Pages 49-61.

[5] Dassault-Systèmes, Simulia user assistance 2020: Abaqus/CAE user’s guide: Vèlizy-Villacoublay, France, 2020

COMPOSITES

Braided veneer composites – investigation on the infiltration behaviour and the resulting mechanical properties

Yuanxi Liu*, Alexander Liebsch*, Carolin Siegel†, Anton Gelencsér*, Simon Kunze*, Robert Kupfer*, Chrisitan Korn†, Maik Gude* and André Wagenführ†

* Technische Universität Dresden, Institute of Lightweight Engineering and Polymer Technology, Holbeinstr. 3, 01307 Dresden, Germany
alexander.liebsch@tu-dresden.de

† Technische Universität Dresden, Institute of Natural Materials Technology, Marschnerstr. 39, 01307 Dresden, Germany
christian.korn@tu-dresden.de

ABSTRACT

With its distinctive anisotropy and high specific stiffness, wood as a renewable raw material offers high potential and applicability for resource-efficient lightweight design. However, wood as construction timber can only be used to a limited extent to produce geometrically complex structures. Alternatively, it can be used as fibre reinforcement for wood-polymer-composites (WPC) to realize geometrically complex structures, but only with a limited load bearing capacity [1-4]. Processing the wood into continuous veneers stripes and processing them into preforms with a defined fibre orientation using braiding technology is an efficient approach to overcome this limitations.

In a previous work the development of a process chain for braiding veneer, starting with the production of continuous veneer stripes and ending with the braiding of the veneers (s. Figure 1) was shown. By infiltrating the preforms with bio-based thermosets load adapted hollow profiles with varying cross sections can be produced [1]. That work focussed on the realization of the process chain and the mechanical properties of resulting veneer composite were not investigated.

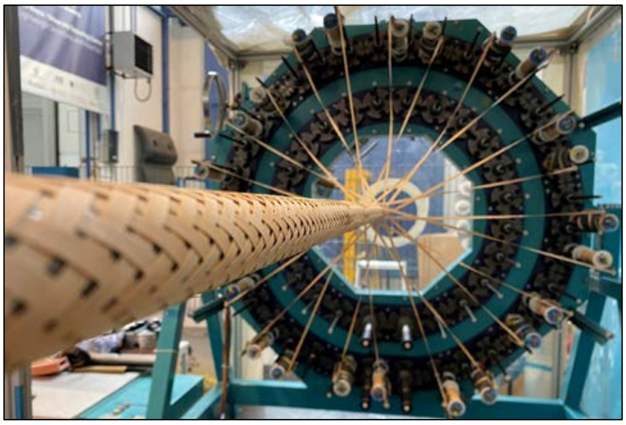


Figure 1: Braiding of veneer tapes.

The objective of this study is to characterize the mechanical properties of veneer composites. In the first part of the paper, the infiltration behaviour of veneer braids is evaluated. The objective is to maximize the veneer content in the composite in order to achieve a high degree of lightweight design. For this purpose, a specific infiltration strategy was developed and the influence of the process parameters on the veneer content was elaborated. As can be seen in Figure 2, the veneer content can be increased by an adapted infiltration strategy.

Figure 2: Braided veneer composites with different veneer content.

The second part of the investigation focusses on the characterisation of the mechanical properties. Initially, the mechanical properties, including modulus and ultimate strength, of the raw material, i.e. the veneer (copper beech) and the bio-based epoxy (SUPER SAP EP 305 from Entropy Resins), used in the composites are characterised. Next, flat specimens of veneer composite with different impregnation states are prepared and their resulting mechanical properties are tested experimentally. In addition the mechanical behaviour of the veneer composites is simulated using representative volume elements (RVE). Initially, the geometry of the veneer braid must be captured and replicated in a numerical model. This requires the preparation of micrographs of the laminate, from which the fiber volume content, characteristic fiber path and cross-section are extracted and employed as input data for the RVE. The mechanical properties of the veneer and the epoxy are used to calibrate the mechanical behavior of the RVE, enabling investigation of the laminate's internal behavior at a mesoscopic scale. Figure 3 illustrates the process.

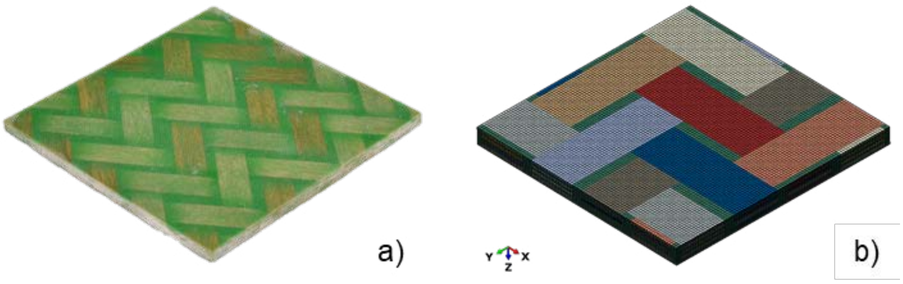


Figure 3: Numerical modelling of braided veneer composites: a) test specimen, b) representative volume element.

REFERENCES

[1] S. Eckardt et al. “Herstellung und Verarbeitung von kontinuierlichen Furnierbändern zu geflochtenen Hohlprofilen”. In *Tagungsband des 20. Holztechnischen Kolloquiums, Dresden*, Band 33, (pp. 113-122) 2022

[2] Mattern, Y., Strobel, P., “Freiform-Holzprofil und dessen Herstellung”. Patent EP3446843A1, 2018.

[3] Beck, C., Taranczewski, R. “Einrichtung zur Herstellung eines aus mehreren Lagen von Blättern aus Holz als Furniere bestehenden Rohres und damit hergestelltes Rohr”. Patent DE102013208166A1, 2013.

[4] A. Göbert et al “3DWoodWind: robotic winding processes for material-efficient lightweight veneer components”. Construction Robotics 6, pp 39-55, 2022.

Load sharing in Timber-Concrete-Composite Ceilings – Form Experiment to FE-Analysis

Hubertus Kieslich *, Klaus Holschemacher *, Michael Kaliske †

* Structural Concrete Institute, Leipzig University of Applied Sciences
POB 301166, 04251 Leipzig
hubertus.kieslich@htwk-leipzig.de, https://ifb.htwk-leipzig.de

† Institute for Structural Analysis, Technische Universität Dresden
Technische Universität Dresden, Institut für Statik und Dynamik der Tragwerke,
01062 Dresden
michael.kaliske@tu-dresden.de, https://tu-dresden.de/bu/bauingenieurwesen/sdt

ABSTRACT

Timber-concrete composite (TCC) structure consists of timber beams (or layer) and a concrete topping, joined together using special shear connectors. Despite the fact that TCC-slab-type structures are well known and commonly used for many years, some questions are not fully understood yet. Among them is the load sharing perpendicular to the timber beam axis, if the loads are not distributed uniformly on the whole floor (compare Fig. 1). In case of such loads the bearing capacity of the TCC structure is increased due to the lateral load sharing, depending on e.g. the proportions of the slab (span, interjoist), the properties of the concrete layer, and level of connection.

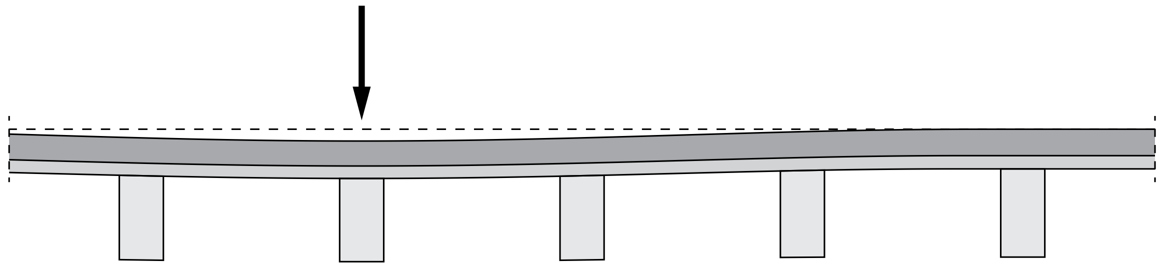


Fig. 1: Principle of lateral load sharing in TCC-structure [1]

In this context, an intensive research project combining experimental and numerical investigations was realized at the Structural Concrete Institute of HTWK Leipzig/Germany. The experimental program focused TCC-specimen (consisting of three timber beams) where single loads were applied to one, central beam of the slab-type specimen. The experimental investigations presented contain short-time full-scale bending tests of 7 TCC and one pure timber beam ceiling (compare Fig. 2 top, left). For all tests the specimen were loaded up to the failure of the slabs. Based on the experimental results, a Finite-Element study was performed, where the influence of various parameters, like span of the slab, joist spacing, dimensions of beams, load level as well as type and position of load, on the transversal load sharing were investigated to provide distribution factors for different load cases. The FE-model used was validated on basis of experimental investigations. They included push-out testing (to determine the connection properties), material tests of timber and concrete, as well as short-time full-scale bending tests. Due to the investigation of load-level and concrete cracking on load sharing the advanced tool for nonlinear analysis ATENA was used (Fig. 2 top, right). In this paper 24 FE-models of TCC slabs with different geometrical dimensions are presented to consider the influence of geometrical parameters on the lateral load distribution. The span of the beams was changed between 3 and 6 m, the timber beam distance between 0.7 and 1.0 m. The cluster of parameters included in the investigations was chosen in accordance to common dimensions of existing timber beam ceilings.

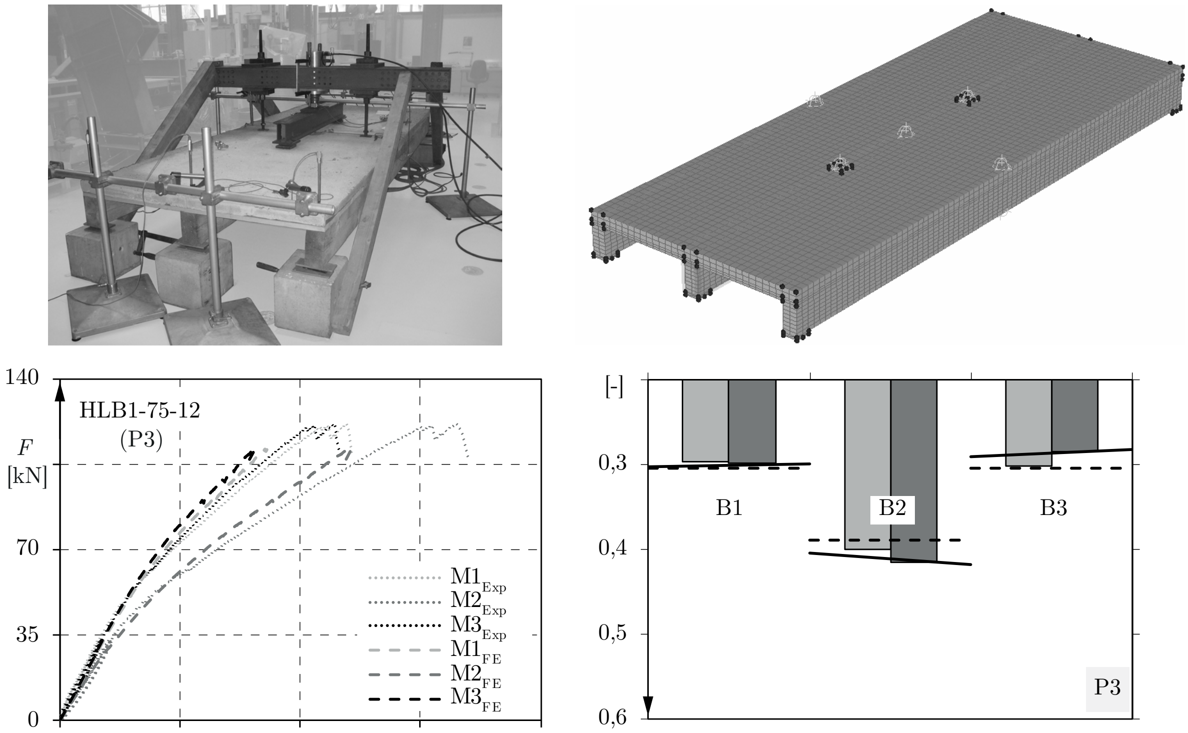


Fig. 2: Experimental short-time full-scale bending tests (top, left), FE-model (top, right), comparison of load-deflection-curves of experiment and FE-model (bottom, left), comparison of distribution factors for the experiments, the FE-model and numerical approximation in SLS and ULS (bottom right) [1]

Different ceilings where calculated at several load levels to obtain the deflection including possible non-linear or plastic deformations. The parametric study includes slab systems consisting of 3, 5 and 7 parallel beam structures. The deflection of each single beam was recorded and lateral distributions factors were derived (deflection of considered beam divided by the sum of deflections of all beams). They are main result of the investigations providing information about the transversal share of loads from the beam directly located under a concentrated load to adjacent beams. This proposal enables an easy and sufficient design of TCC slabs exposed to heavy single loads.

The authors gratefully acknowledge the financial support provided by European Social Fund (ESF) and Free State of Saxony (100088538).

REFERENCES

[1] Kieslich, H.: *Zum Quertragverhalten von Holz-Beton-Verbunddecken*. PhD-thesis (in German) Dresden (not published yet)

[2] Kieslich, H.; Holschemacher, K.: Transversal load sharing in timber-concrete floors – experimental and numerical investigations. In: J. Eberhardsteiner; W. Winter; A. Fadai; M. Pöll: *Proceedings of the World Conference on Timber Engineering (WCTE 2016)*, Vienna, Austria, 2016, p. 2355–2364

[3] Kieslich, H.; Holschemacher, K.: Load-sharing effects in TCC-constructions – experiments. In: J. Jasieńko; T. Nowak: *Proceedings of the 3nd International Conference on Structural Health Assessment of Timber Structures (SHATIS'15)*, Wroclaw, Poland, 2015. p. 1009–1019

[4] Kieslich, H.; Holschemacher, K.: Load-sharing effects in TCC-constructions – FE-analysis. In: J. Jasieńko; T. Nowak: *Proceedings of the 3nd International Conference on Structural Health Assessment of Timber Structures (SHATIS'15)*, Wroclaw, Poland, 2015. p. 1020–1026

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Modeling and simulation of the bending of prestrained composite plates

Klaus Böhnlein[1], Stefan Neukamm[2], Oliver Sander[3]

[1] Technische Universität Dresden, Faculty of Mathematics, 01062 Dresden, Germany,
klaus.boehlein@tu-dresden.de

[2] Technische Universität Dresden, Faculty of Mathematics, 01062 Dresden, Germany,
stefan.neukamm@tu-dresden.de

[3] Technische Universität Dresden, Faculty of Mathematics, 01062 Dresden, Germany,
oliver.sander@tu-dresden.de

ABSTRACT

The presence of prestrain has an enormous effect on the mechanical behaviour of thin plates and is exploited in the design of shape-shifting films or self-forming wood structures. In our work we investigate nonlinearly elastic composite plates with periodic microstructure and prestrain in the bending regime. We are particularly interested in predicting the equilibrium shape of such plates based on the configuration of the composite on small length scales. In [1] we present a new approach that combines mathematical homogenisation and dimension-reduction with numerical methods. Our starting point is a three-dimensional, nonlinear elasticity model for a periodic composite occupying a domain with small thickness. The model resolves the micropscopic details of the material heterogeneity and the prestrain. By means of simultaneous dimension reduction and homogenisation, we rigorously derive (as a Γ-limit for vanishing thickness and period) an effective, two-dimensional non-linear bending model that allows for large bending deformations and that features an emergent spontaneous curvature term. The effective properties of the plate model (bending stiffness and spontaneous curvature) are characterised by a set of corrector problems, which can be considered as a tailor-made RVE. The theory applies to composites with arbitrary geometry and possibly anisotropic elastic properties.

We then numerically investigate the equilibrium shapes predicted by our two-dimensional model for composites with different geometries, e.g., bilayers with fibre-reinforced layers or composites with prestrained inclusions. In the special case of a globally periodic composite, the associated problem reduces to an algebraic, non-convex (but finite dimensional) minimisation problem. In the general case, particularly, in the presence of boundary conditions or for graded microstructures, we appeal to a minimising movement scheme to numerically approximate critical points of our plate model.

REFERENCES

[1] Böhnlein, K., Neukamm, S., Padilla-Garza, D., & Sander, O. A homogenized bending theory for prestrained plates. *Journal of Nonlinear Science, 33(1), 1-90, 2023.*

Multiscale micromechanics stiffness modeling of plant fiber-reinforced composites

Markus Königsberger*, Markus Lukacevic* and Josef Füssl*

* TU Wien, Institute for Mechanics of Materials and Structures
Karlsplatz 13/202, A-1040 Vienna
markus.koenigsberger@tuwien.ac.at, markus.lukacevic@tuwien.ac.at, josef.fuessl@tuwien.ac.at

ABSTRACT

Plant fibers are a very promising alternative to synthetic fibers for reinforcing composites. These green biocomposites benefit from the extraordinarily high mechanical properties of the basic building block of all plants: the crystalline cellulose with a tensile strength of more than 2 GPa [3] and a longitudinal stiffness of roughly 200 GPa [4]. This study aims at predicting the elastic stiffness of biocomposites by means of upscaling the properties of crystalline cellulose to the macroscopic scale.

To achieve this goal, the hierarchical microstructure of biocomposites is resolved across several length scales [5, 6], with crystalline and amorphous cellulose at the nanoscale, which, intermixed with the other basic material constituents such as lignin and hemicellulose, form the cell wall, and eventually, the technical plant fibers, see Fig. 1. The fibers are finally embedded in a matrix material, whereby the matrix-fiber bond is modeled by means of spring-type interfaces. Eshelby-based homogenization theory is used to upscale the stiffness of cellulose and lignin, accessible from atomistic modeling [4] or small-scale testing, to the macroscale. Limiting to slightly-weakened interfaces with small interface compliances, the Eshelby problem (developed for perfectly bonded interfaces) can be enriched [1], and the corresponding concentration tensors are used in this work.

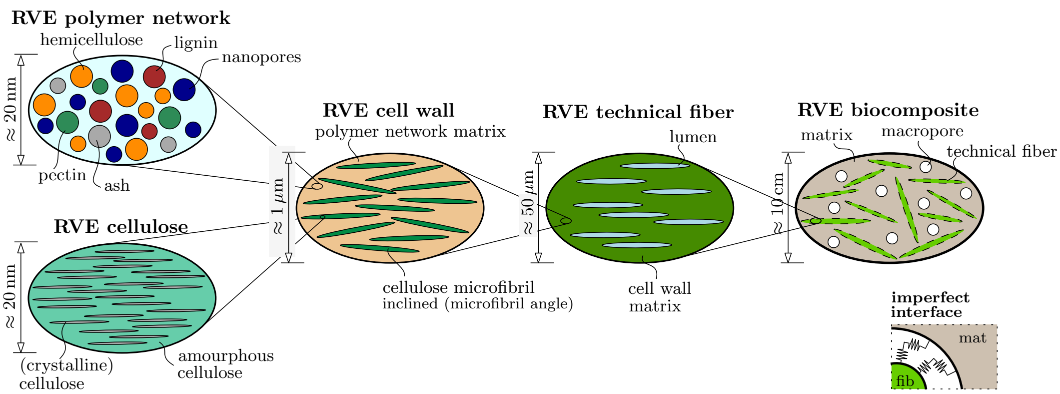


Figure 1: Multiscale hierarchical representation of biocomposites after [5, 6].

The resulting homogenized stiffness at the scale of the technical fiber and of the biocomposite is compared to experimental stiffness data, obtained from tensile test results, see e.g. [2]. Therefore the model is specified for the experiment, i.e. fiber and matrix are chosen accordingly, the actual volume fractions are considered, and the fiber aspect ratio (ratio of fiber length to fiber diameter) as well as the fiber orientation distributions are estimated based on the production technology and microscopic images (for instance aligned with a single 1D axis, isotropic along a 2D plane, isotropic in 3D space, or any other distribution mathematically described by von Mises or von Mises-Fisher distribution functions). The resulting comparison of model and experiments, see Fig. 2, demonstrates the suitability of the homogenization approach and the hierarchical structure of plant fibers. Given the analytical nature of the model, quantitative sensitivity studies are performed in due time. This shows that several biocomposites that are tested in the literature seem to suffer from weakly bonded interfaces and thus, cannot exploit the full stiffness of the plant fibers. Future work will focus on the integration of this analytical model into a numerical finite element model to model the typically rather nonlinear stress-strain response of biocomposites.

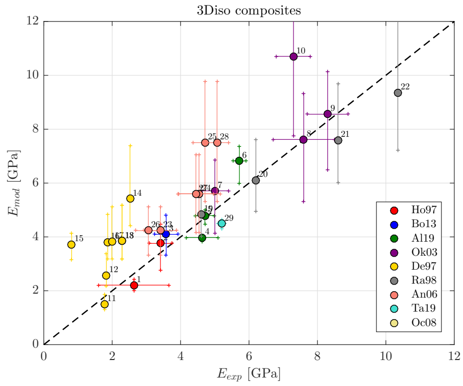


Figure 2: Model validation based on experimental data on biocomposites with random fiber orientation: experimentally measured (abscissa) vs. model-predicted elastic modulus (ordinate)

REFERENCES

[1] Dinzart, F.; Sabar, H. New micromechanical modeling of the elastic behavior of composite materials with ellipsoidal reinforcements and imperfect interfaces. *Int. J. Solids Struct.*, 108:254–262, 2017.

[2] Bourmaud, A.; Ausias, G.; Lebrun, G.; Tachon, M.-L.; Baley, C. Observation of the structure of a composite polypropylene/flax and damage mechanisms under stress. *Industrial Crops and Products* 43, 225-236, 2013.

[3] Saito, T.; Kuramae, H.; Wohlert, J.; Berglund, L. A.; Isogai, A. An ultrastrong nanofibrillar biomaterial: The strength of single cellulose nanofibrils revealed via sonication-induced fragmentation, *Biomacromolecules* 415 14 (1) (2013) 248–253

[4] Dri, F. L.; Shang, S. L.; Hector, L. G.; Saxe, P.; Liu, Z. K.; Moon, R. J.; Zavattieri, P. D. Anisotropy and temperature dependence of structural, thermodynamic, and elastic properties of crystalline cellulose Iβ: A first-principles investigation, *Model. Simul. Mater. Sci. Eng.* 22 (8) (2014).

[5] Königsberger, M.; Lukacevic, M.; Füssl, J. Multiscale micromechanics modeling of plant fibers: upscaling of stiffness and elastic limits from cellulose nanofibrils to technical fibers. *Materials and Structures*, 56(13), 2023.

[6] Königsberger, M.; Senk, V.; Lukacevic, M.; Wimmer, M.; Füssl, J. Multiscale micromechanics stiffness upscaling of biocpomposites In: *Prepared for sumbisstion to Composites Part B* 2023.

Numerical modeling of plant fiber-reinforced composites: Combining main failure mechanisms for accurate macroscopic strength predictions

Valentin Senk*, Markus Königsberger*, Markus Lukacevic* and Josef Füssl*

* TU Wien, Institute for Mechanics of Materials and Structures
Karlsplatz 13/202, A-1040 Vienna
valentin.senk@tuwien.ac.at, markus.koenigsberger@tuwien.ac.at,
markus.lukacevic@tuwien.ac.at, josef.fuessl@tuwien.ac.at

ABSTRACT

Biocomposites, composed of natural fibers and a biodegradable polymer matrix, have gained attention in recent years due to their potential of being more sustainable and environmentally friendly than traditional composite materials [1]. While several experiments confirm the promising mechanical properties of such biocomposites [1, 2], there is a lack of sophisticated models to accurately predict the mechanical behavior of these types of materials under different loading conditions. Only a few studies have attempted to combine both the complex fiber-matrix morphology and the highly non-linear material behavior in a single unified model [3, 4].

In this study, a numerical model is developed that describes the complex interactions between cellulose fibers and matrix in biocomposites, accounting for all major failure mechanisms. In more detail, our model considers matrix softening, fiber breakage, and fiber-matrix debonding as the primary drivers for macroscopic composite failure. To implement these mechanisms, we employed a non-linear plasticity law with isotropic hardening and softening, XFEM, and cohesive zone models in an FE-Model of a unit cell (with periodic boundary conditions) containing parallel fibers (one in the center, one on the four edges), see Fig. 1.

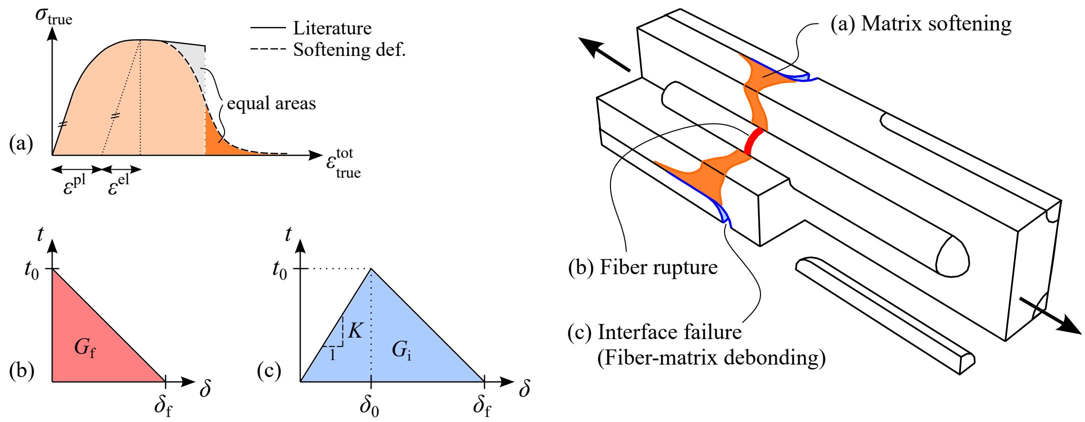


Figure 1: Main failure mechanisms depicted schematically for uniaxially loaded unit cell containing two parallel fibers and their description with constitutive laws: (a) Matrix softening with a von Mises plasticity definition with isotropic hardening and softening, (b) fiber rupture with XFEM and a traction separation law and (c) interface failure respectively fiber-matrix debonding with cohesive surfaces and a traction separation law.

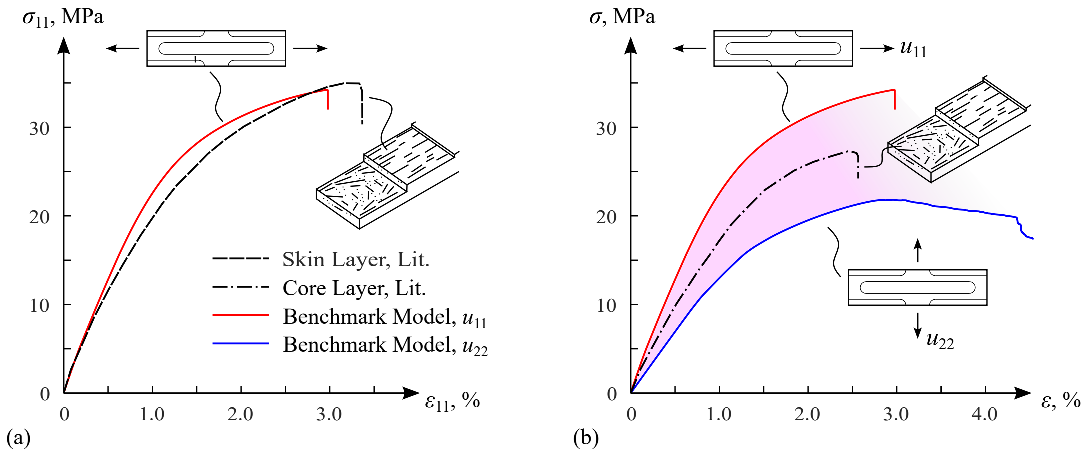


Figure 2: Comparison of the benchmark model to literature results on short-fiber-reinforced composites [2]. (a) Uniaxial tensile tests on a composite with aligned fibers and (b) Uniaxial tensile test on composites with randomly oriented fiber, where model predictions (for parallel fibers loaded in longitudinal and transversal direction) bound the experimental data.

The model is validated using experimental data from the literature [2], see Fig. 2 for an example. It accurately predicts tensile and compressive properties of short- and long-fiber-reinforced composites. The unit cell approach allows for additional sensitivity studies, which provide quantitative insights, for instance, into the softening effect related to a reduced interfacial shear strength or the strengthening effect related to longer fibers. Future research will focus on lignin-based biocomposites and, moreover, on a link between an analytical [5] and a numerical modeling approach, to achieve a comprehensive mechanical prediction model for complex biocomposite materials.

REFERENCES

[1] Pickering, K.L.; Aruan Efendy, M.G.; Le, T.M. A review of recent developments in natural fibre composites and their mechanical performance. In: *Composites Part A: Applied Science and Manufacturing*, 83, 98-112, 2016.

[2] Bourmaud, A.; Ausias, G.; Lebrun, G.; Tachon, M.-L.; Baley, C. Observation of the structure of a composite polypropylene/flax and damage mechanisms under stress. In: *Industrial Crops and Products* 43, 225-236, 2013.

[3] Sliseris, J.; Yan, L.; Kasal, B. Numerical modelling of flax short fibre reinforced and flax fibre fabric reinforced polymer composites. In: *Composites Part B: Engineering*, 89, 143-154, 2016.

[4] Castricum, B.A.; Fagerström, M.; Ekh, M.; Larsson F.; Mirkhalaf, S.M. A computationally efficient coupled multi-scale model for short fiber reinforced composites. In: *Composites Part A: Applied Science and Manufacturing*, 163, 107233, 2022.

[5] Königsberger, M.; Lukacevic, M.; Füssl, J. Multiscale micromechanics modeling of plant fibers: upscaling of stiffness and elastic limits from cellulose nanofibrils to technical fibers. In: *Materials and Structures*, 56(13), 2023.

Numerical Modelling of the In-plane Stiffness and Connection Behaviour of Composite Timber-Glass Wall Elements

Tine Engelen†*, Dries Byloos†, Bram Vandoren†

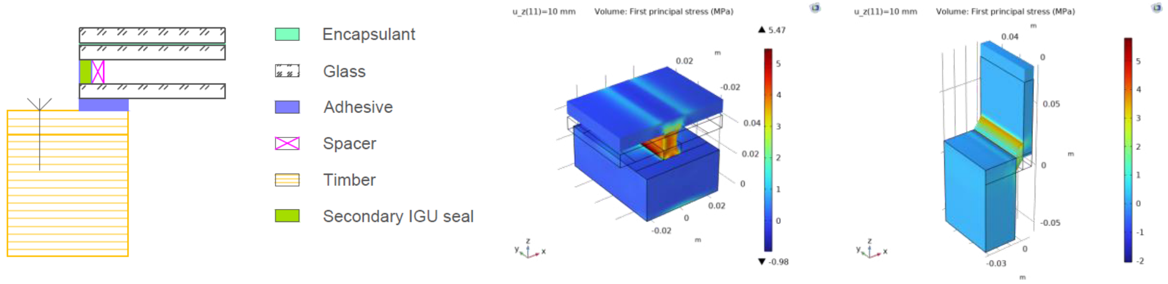
†Hasselt University
Martelarenlaan 42, 3500 Hasselt
tine.engelen@uhasselt.be
dries.byloos@uhasselt.be
bram.vandoren@uhasselt.be

*EnergyVille, imec, imo-imomec
Thor Park 8320, 3600 Genk

ABSTRACT

Because of their lightweight nature, the horizontal stability of timber structures is an important design criterion. This becomes even more important in building designs with open floor spaces and thus fewer internal walls: such free plan designs are key towards more flexible, modular, and adaptable buildings, i.e., buildings with a longer life span. Because of the absence of inner structural walls, which normally ensure the horizontal stability (the so-called racking resistance), the horizontal load-bearing capacity of the façade becomes very important. These façades, especially curtain wall type façades, often have large surfaces of glass windows. However, in the current calculation methods and building practice, windows are not contributing to the structural racking resistance. Therefore, in this contribution, a structural connection is developed to exploit the in-plane stiffness of the glass panel and, consequently, increase the horizontal stability of the underlying timber structure. As a result, a combination of loads on the structural connections is generated because of wind, shear, and thermal loads. For that reason, an in-depth study is performed to understand the stresses and strains in the structure. This way, a suitable design can be made to obtain a reliable system with the necessary structural rigidity. In this work, the behaviour of timber-glass wall elements is explored numerically, focusing on the connection behaviour.

The structural connection between the timber frame and the glass panel is made with a circumferentially applied adhesive, as shown in figure 1a and figure 2a. A numerical model is made in COMSOL Multiphysics® to study the bonded joints' behaviour. Existing research recognises an accurate material model's critical role in the connection behaviour [1], [2]. However, few have validated the material models of hyperelastic materials, such as the employed adhesives, with realistic experimental tests. Therefore, a small-scale, detailed model of the timber-glass connection is made and validated with experimental tests.

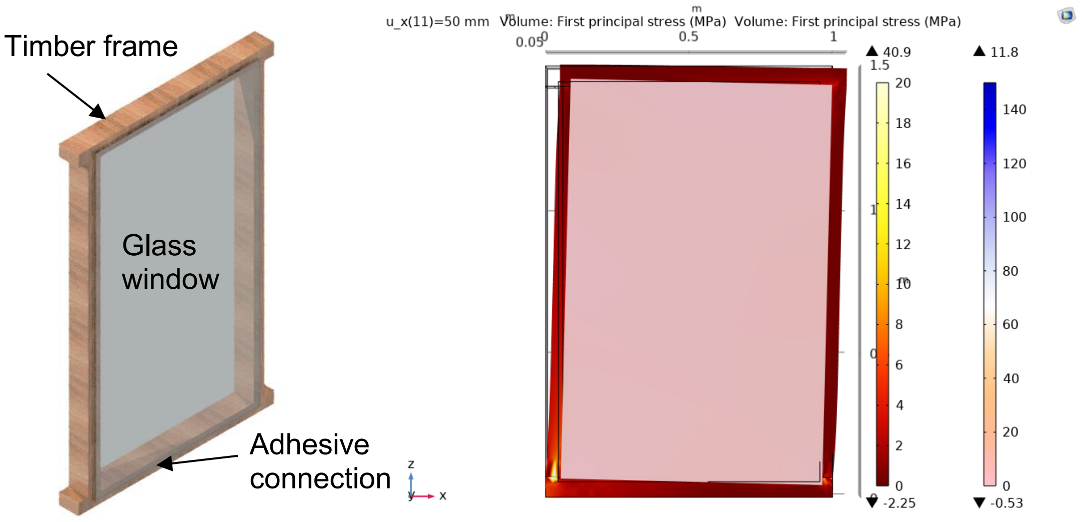


a) b) c)

Figure 1: a) Timber-glass connection design; b) tensile test specimen; c) shear test specimen

Studies have shown that the mechanical adhesive behaviour depends on the dimensions of the bond line and the loading state [3], [4]. Therefore, different hyperelastic material models which describe the highly non-linear material behaviour are implemented. Additionally, the combination of tensile and shear stresses in the adhesive is considered. Therefore, an appropriate limit state based on an elliptic function is used [5]. Tensile and shear tests will be performed on bonded timber-glass specimens with different adhesives, including silicone, polyurethane, and epoxy. Figures 1b and 1c show the numerical analysis of the specimen for the experimental tests.

After analysing the connections in detail, a full-size model of a timber-glass wall element is made, as shown in figure 2. The load-bearing timber frame, the adhesive bond, and the glass windows are modelled. The validated connection model is implemented into this full-size model. With this model, the impact of various design parameters such as the glass width, glass height and adhesive bond dimensions on the in-plane stiffness of the system is evaluated.



a) b)

Figure 2 a) Full-size timber-glass composite system; b) full-size numerical model

REFERENCES

[1] Ber, B., Premrov, M., & Štrukelj, A. (2016). Finite element analysis of timber-glass walls. *Glass Structures and Engineering*, 1(1), 19–37. https://doi.org/10.1007/s40940-016-0015-4

[2] Piculin, S., Nicklisch, F., & Brank, B. (2016). Numerical and experimental tests on adhesive bond behaviour in timber-glass walls. *International Journal of Adhesion and Adhesives*, 70, 204–217. https://doi.org/10.1016/j.ijadhadh.2016.06.012

[3] Machalická, K., & Eliášová, M. (2017). Adhesive joints in glass structures: effects of various materials in the connection, thickness of the adhesive layer, and ageing. *International Journal of Adhesion and Adhesives*, 72, 10–22. https://doi.org/10.1016/j.ijadhadh.2016.09.007

[4] Bues, M., Schuler, C., Albiez, M., Ummenhofer, T., Fricke, H., & Vallée, T. (2019). Load bearing and failure behaviour of adhesively bonded glass-metal joints in façade structures. *Journal of Adhesion*, 95(5–7), 653–674. https://doi.org/10.1080/00218464.2019.1570158

[5] Bues, M., Schuler, C., Albiez, M., Ummenhofer, T., Fricke, H., & Vallée, T. (2019). Load bearing and failure behaviour of adhesively bonded glass-metal joints in façade structures. In *Journal of Adhesion* (Vol. 95, Issues 5–7, pp. 653–674). Taylor and Francis Inc. https://doi.org/10.1080/00218464.2019.1570158

Shear connection of cross laminated timber wall elements using timber-concrete composites and carbon reinforced concrete

Birgit Beckmann*, Kristina Farwig*, Manfred Curbach*

* Institute of Concrete Structures, Technische Universität Dresden
Helmholtzstraße 10, 01069 Dresden, Germany
Birgit.Beckmann@tu-dresden.de; Kristina.Farwig@tu-dresden.de; Manfred.Curbach@tu-dresden.de; www.massivbau.tu-dresden.de

ABSTRACT

The investigation of shear connections for cross laminated timber (CLT) wall elements is presented in this work. Timber-concrete composite (TCC) is used to develop a joint construction for CLT wall elements. Shear failure is decisive for design even though the timber has actually considerably higher resistance. The consideration of shear connections can be found in e. g. [1] and [2]. While TCC has been mainly used for ceilings subjected to bending load on one hand and CLT wall elements are conventionally connected using screws or pins in combination with butt deck strips on the other hand, a connecting joint construction for CLT wall elements using TCC is investigated in this work. Prefabricated timber elements can be connected on-site in a tongue and groove system by filling the groove with fine-grained concrete of high strength. Different additional internal connectors have been investigated, as shown in Fig. 1. Notches and steel connectors such as screws and perforated plates have been used (see [[3]]) as well as new connection types like glued-in textiles, which are presented here. Textiles made of alkali-resistant (AR) glass and textiles made of carbon are used. Textile reinforced concrete (TRC) and herein especially carbon reinforced concrete (CRC) has become an important field of concrete research (see e. g. [4]-[7]). In this work, a combination of TRC and TCC is used to connect CLT wall elements. The TRC joints had glued-in textile grids at an angle of 45 degree. To investigate the load-bearing behaviour of the joints, experimental investigations were carried out. Compression-shear tests were done for varying joint construction types. As a reference series, pure fine-grained concrete is used, i.e. without additional connectors and using adhesion only. The results of the compression-shear-tests are shown in Fig. 2, where the joints with textile reinforced concrete are compared to the ones without internal connectors. The load-bearing capacity of the joints with textiles glued in the wood and embedded in the concrete matrix is higher than the of the joints without textile connectors. Comparing the TRC joints among each other, the joints with carbon textiles show a higher load-bearing capacity than the AR-glass textiles. The results of the tests show that high shear strengths can be achieved with the designed tongue and groove joint in comparison to usual connection methods of CLT walls.

Keywords: timber-concrete composite (TCC), prefabricated elements, cross laminated timber (CLT), shear joint, connectors, textile reinforced concrete (TRC), carbon reinforced concrete (CRC)

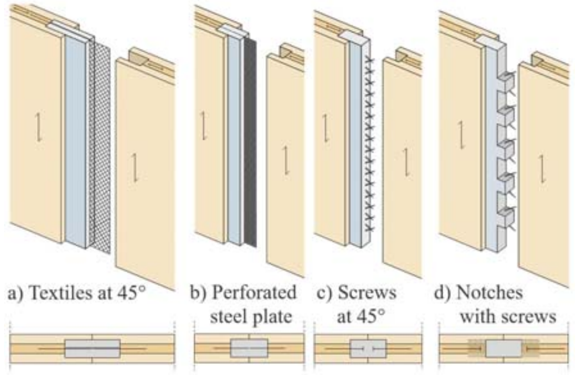


Fig. 1: Shear connection versions for cross laminated timber (Graphic: K. Farwig)

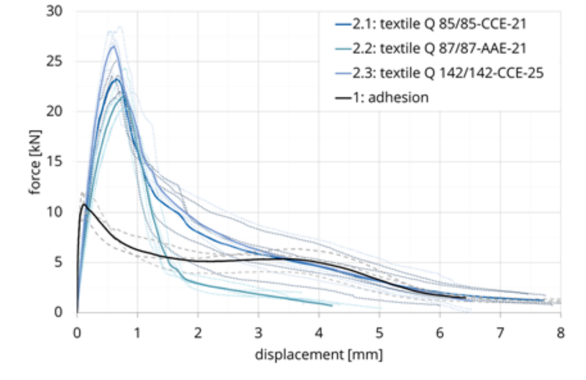


Fig. 2: Results of compression-shear-tests: adhesion and TRC (graphic: B. Beckmann)

REFERENCES

[1] Schickhofer G., Bogensperger T., and Moosbrugger T. (eds.) “BSPhandbuch – Holz-Massivbauweise in Brettsperrholz”. Publisher of the Technical University Graz, Graz, 2010, p. 384

[2] Brandner, R.; Bogensperger, T.; Schickhofer, G. “In plane Shear Strength of CLT: Test Configuration, Quantification and influencing Parameters”. Conference Paper, January 2013. Graz University of Technology, Institute of Timber Engineering and Wood Technology

[3] Farwig, K.; Curbach, M.: Grouting concrete for shear connection in butt joints of prefabricated cross laminated timber wall elements. In: Stokkeland, S.; Braarud, H. C. (eds.): Proceedings for the 6th fib International Congress 2022. Oslo, Norway: Novus Press, Olso, Norway, 2022, p. 1037-1046

[4] Beckmann, B.; Bielak, J. Bosbach, S.; Scheerer, S.; Schmidt, Chr.; Hegger, J.; Curbach, M.: Collaborative research on carbon reinforced concrete structures in the CRC/TRR 280 project. Civil Engineering Design 3 (2021) 3, S. 99-109 - DOI: 10.1002/cend.202100017

[5] Batarlar, B, Hering, M, Bracklow, F, Kühn, T, Beckmann, B, Curbach, M. Experimental investigation on reinforced concrete slabs strengthened with carbon textiles under repeated impact loads. Structural Concrete. 2021; 22: 120– 131. https://doi.org/10.1002/suco.201900319

[6] Zdanowicz, K, Gebauer, D, Koschemann, M, Speck, K, Steinbock, O, Beckmann, B, et al. Distributed fiber optic sensors for measuring strains of concrete, steel, and textile reinforcement: Possible fields of application. Structural Concrete. 2022; 23: 3367– 3382. https://doi.org/10.1002/suco.202100689

[7] Wagner, J.; Curbach, M.: Experimental characterization of bond fatigue of carbon reinforced concrete. civil engineering design 2 (2020) 5-6, p. 169-176 - DOI: 10.1002/cend.202000019

VENEER LAMINATES FOR TUBULAR STRUCTURES IN A TRIPOD – TESTING FOR DESIGN AND DAMAGE MODELLING APPROACHES

E. Kunze*, K. Tittmann*, Y. Mattern†, M. Gude*

*Technische Universität Dresden, Institute of Lightweight Engineering and Polymer Technology
Holbeinstraße 3, D-01307 Dresden, Germany
karsten.tittmann@tu-dresden.de and http://tu-dresden.de/mw/ilk

†Lignoa Leichtbau GmbH
Entenseestraße 31, 90607 Rückersdorf
kontakt@lignoa.de and https://lignoa.de/

ABSTRACT

Wood is characterized by excellent vibration damping, low material density and electromagnetic compatibility. Veneers laminates have a particularly high potential in this respect, as the combination of individually oriented veneer layers allows the properties of the laminate to be adjusted to the specific application requirements. Portable camera tripods require good vibration damping to avoid blurry images, as well as light weight and small pack size. In this project, veneer tube structures were developed to reduce the weight and pack size of an existing wooden camera tripod while improving the damping characteristics.

Experimental characterization of stiffness and strength parameters for different species of wood with focus on the effect of fiber orientation on the mechanical properties were carried out [1]. Particular attention was paid to the damping characteristics, which were determined by Dynamic Mechanical Analysis (DMA) in a 3-point bending setup (variation of wood species, fiber orientation, temperature, excitation frequency, see Figure 1). The characteristic values obtained from mechanical testing were used to numerically design the stiffness and strength behavior of the tripod tube structures. The stiffness and strength requirements were validated experimentally. Vibration measurements on the assembled tripod demonstrated a significantly improved damping behavior.

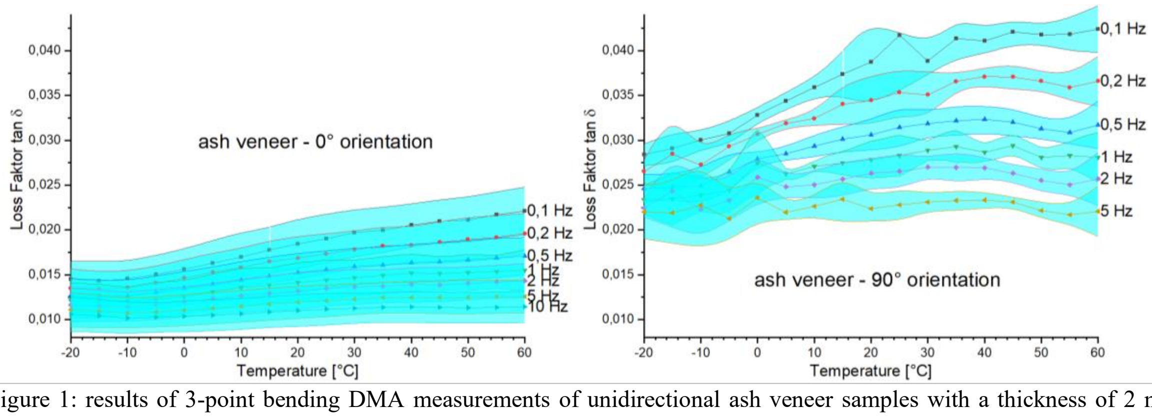


Figure 1: results of 3-point bending DMA measurements of unidirectional ash veneer samples with a thickness of 2 mm (length: 50 mm, width 10 mm) -temperature and frequency dependent material damping for loading in (0°) and perpendicular (90°) to fiber orientation

The calculation approaches used here for modelling damage initiation (adapted failure criterion for fiber reinforced polymers based on Cuntze [2]) shall be transferred to similar veneered structures with a more complex loading situation in future. A special focus will be on fatigue damage behavior under cyclic loading. For this purpose, existing models developed for fiber composites [e.g. 3] will be briefly presented along with a discussion of their transferability to veneer laminates

REFERENCES

[1] Weißenborn, O.; Geller, S.; Mattern, Y.; Strobel, P.; Gude, M., For the production and design of novel lightweight structures with tailor-made properties based on veneer lumber. In *Holztechnologie* 2020,61 (2): 50-54

[2] Cuntze, R.G., Efficient 3D and 2D failure conditions for UD laminae and their application within the verification of the laminate design. In *Composites Science and Technology*, 2006, 66:1081-1096

[3] Wacker, J.-D., Tittmann, K.; Koch, I.; Laveuve, D.; Gude, M., Fatigue life analysis of carbon fiber reinforced polymer (CFRP) components in hybrid adhesive joints. In: *Materialwiss. Werkstofftech*. 2021, 52:1230–1247

COMPOSITES

FINITE ELEMENT MODELING OF STEEL-WOOD FASTENER CONNECTION IN PRODUCT DEVELOPMENT: 3RD ECCOMAS THEMATIC CONFERENCE & ON COMPUTATIONAL METHODS IN WOOD MECHANICS
CompWOOD 2023

Frank Ding

Simpson Strong-Tie Company, Inc.
5956 W Las Positas Blvd. Pleasanton, CA 94588, USA
fding@strongtie.com

ABSTRACT

Fastenings are critical for the building structural integrity in the event of earthquakes or high winds. A member connection's performance is governed by how fasteners and metal connectors perform, as well as member itself. Nails/screws are the most common type of mechanical fasteners used to secure metal connectors to wood members in wood-frame construction. Nails/screws resist either lateral or withdrawal forces or a combination of the two. It is very critical to be able to simulate the behaviour of nails/screws under combined lateral and withdrawal loads to aid connector design. For timber connectors, the connection assembly is usually loaded to failure in order to identify ultimate load capacity. Highly nonlinear material behaviour with progressive damage and failure must be considered for the realistic simulation of connection performance.

In this presentation, we will discuss nonlinear finite element modelling of the nailed/screwed joint between a steel side member and a wood member using Abaqus mesh-independent fasteners. Additionally, we will discuss the use of physical tests to calibrate the model in order to accurately represent the highly nonlinear response, such as plastic yielding, large deformation plasticity, material damage, and failure.

In addition, the topic of Abaqus/Explicit procedure powered by High Performance Computing (HPC) will be covered because it is essential for efficient modelling and simulation productivity when dealing with highly nonlinear and complex production models.

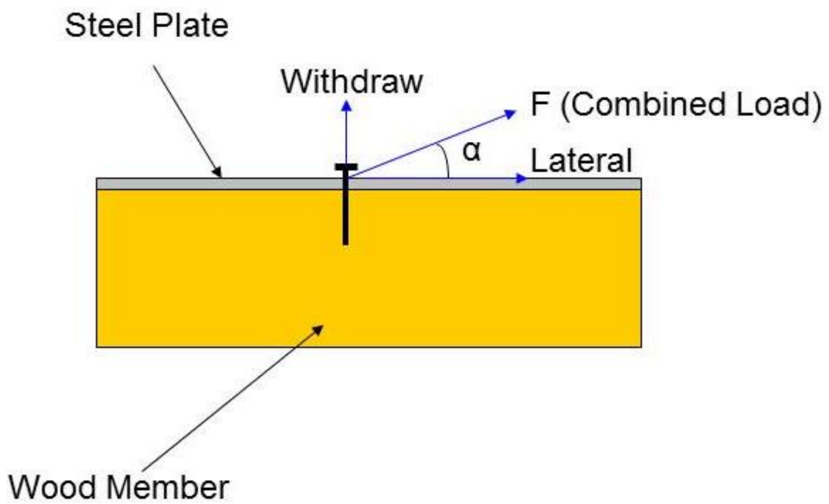


Figure 1: Single nailed joint test sketch.

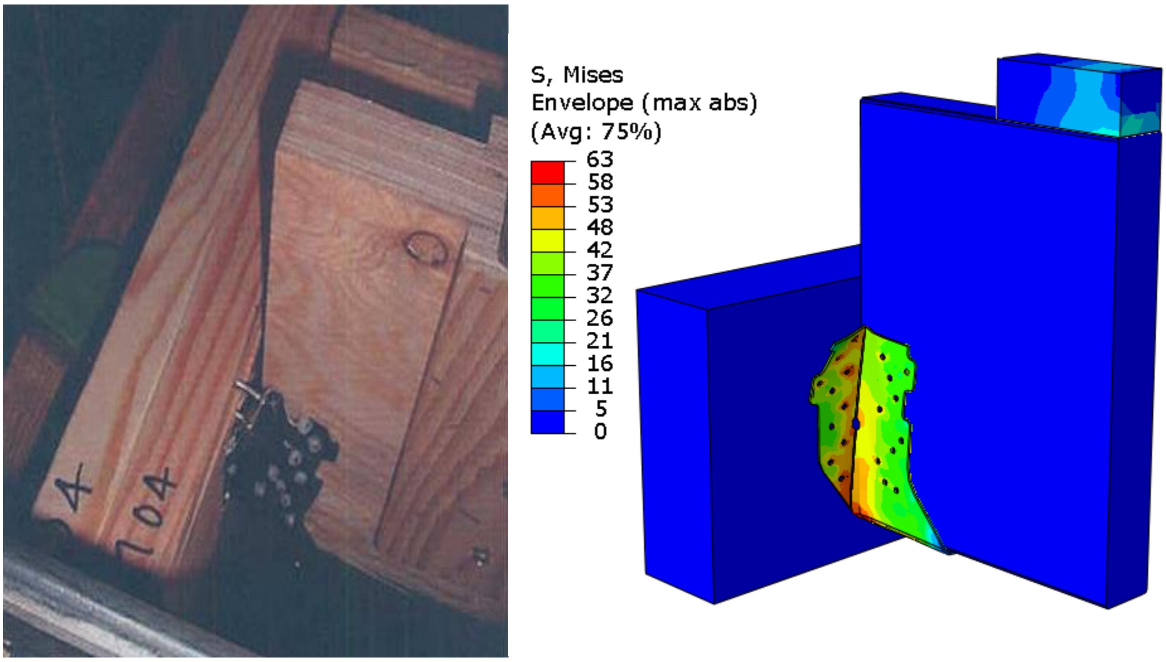


Figure 2: Face-mount truss hanger downward load a) Test, b) 3D Abaqus modeling

REFERENCES

[1] Chui, Y.H. and Ni, C. Load-embedment response of timber to reversed cyclic load. Wood and Fiber Science. Vol. 29 (2): (pp.148-160) 1997

[2] Weyer, S., and H. Hooputra, BMW Group, and Zhou, F., ABAQUS Deutschland GmbH. "Modelling of Self-Piercing Rivets Using Fasteners in Crash Analysis," Abaqus Users' Conference, Boston. (2006)

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Finite–Element Modelling of the Nail–Driving Process into Spruce Wood

Diah P. Rahmi*, Robert Fleischhauer*, and Michael Kaliske*

* Institute for Structural Analysis
Technische Universität Dresden
Georg-Schumann-Str. 7, 01187 Dresden
michael.kaliske@tu-dresden.de

ABSTRACT

Historically, wood is one of the most widely used construction materials. However, the variation of its properties due to the complex microstructure, see [1,8], is one of the main drawbacks of wood. Besides the material properties of a solid wood element, the strength and stability of a connection between wooden elements are essential in evaluating the overall structure quality. Wood in particular accepts a wide variety of fasteners, for example, nails, spikes, screws, and bolts. Among all fasteners, the nail is one of the most commonly used and is available in different types and sizes. The nail is designed to resist withdrawal under tension, lateral shear, or both loads combined. However, the design of nails is mostly based on the empirical method. The further development resulted in the theoretical method for designing the lateral resistance while the withdrawal resistance remains the same, i.e., see [2]. As for the nail–driving process in wood, the influence of driving direction and the effect of friction on the nail resistance and fracture phenomena in wood can be investigated further. While most researchers focus on experimental investigation, see [3,4,5], more attention could be given to computational modeling, as it might result in a lower industrial development cost. Furthermore, a more apparent description of how the geometry and the nail–driving process affect the resistance of a nail could also be achieved.

One of the main goals of the contribution at hand is to produce a numerical tool to model the nailing process. In general, simulating the nail–driving process involves modeling the nail, the specimen, and the frictional contact between both structures. In this contribution, the contact problem will be specified between rigid and deformable bodies. Therefore, in the current case, the nail will be modeled as the rigid body, and the specimen is defined as the deformable body. The contact problem is solved using the displacement–driven approach proposed in [6], where the implementation of the contact solution is restricted to a quasi-static analysis, and fracturing of the wood in the vicinity of the nail is not considered in the analysis.

There are two types of specimens used in the simulation. The first is made of polyurethane (PUR), modeled as an inelastic isotropic material using von Mises plasticity. The second specimen is spruce wood, modeled as a nonlinear inelastic anisotropic material using a constitutive model presented in [7]. Up to this point, only the mechanical part of the constitutive model is adopted. Prior to the contact simulation, the parameters of this material model are identified to fit the spruce wood behavior and validated using experimental data of spruce wood under tensile and compressive loading, applied in both parallel and perpendicular to the grain direction, see [8]. The PUR and spruce wood models used in the simulation are formulated with respect to finite deformations.

The implementation of the material model and contact solution in the numerical approach

are verified by a convergence study. The coefficient of friction between the spruce wood and the nail is taken from an experimental investigation. Moreover, due to the restriction of the contact solution in the quasi–static problem, the nail–driving force obtained from the numerical analysis is compared to the experimental result of pushing a nail into PUR and spruce wood. This experiment is carried out to eliminate the dynamic effects due to short-term impact loads of nailing. The comparison is shown to verify the practicality and the capability of the developed numerical tool in modeling the nail–driving process.

REFERENCES

[1] Gibson, L. J.; Ashby, M. F. *Cellular solids: structure and properties.* Press Syndicate of the University of Cambridge, Cambridge, UK. 1997.

[2] Soltis, Lawrence A. Fastenings. *Wood handbook: Wood as an engineering material.* General Technical Report FPL, GTR–113, Madison, WI: USDA Forest Service, Forest Products Laboratory, 1999; 7.1–7.28.

[3] Noguchi, M.; Sugihara, H. Studies on Static Withdrawal Resistance of Nail : Effect of Driving Method and Time after Driving. *Wood Research : Kyoto University Wood Research Institute Report* 1961; 25: 1–13

[4] Aytekin, A. Determination of screw and nail withdrawal resistance of some important wood species. *International Journal of Molecular Science* 2008; 9: 626–637.

[5] Takanashi, R.; Sawata, K.; Sasaki, Y.; Koizumi, A. Withdrawal strength of nailed joints with decay degradation of wood and nail corrosion. *Journal of Wood Science* 2017; 63: 192–198.

[6] Rahmi, D. P.; Fleischhauer, R; Kaliske, M. A displacement-driven approach to frictional contact mechanics. *International Journal for Numerical Methods in Engineering* 2023. (submitted for publication)

[7] Fleischhauer, R; Kaliske, M. Hygro– and thermo–mechanical modeling of wood at large deformations: Application to densification and forming of wooden structures. *Advances in Mechanics of Materials and Structural Analysis: In Honor of Reinhold Kienzler* 2018: 59–97.

[8] Jenkel, C.; Leichsenring, F.; Graf, W.; Kaliske, M. Stochastic modelling of uncertainty in timber engineering. *Engineering Structures* 2015; 99: 296–310.

Numerical Analyses of Timber Beams with Perpendicular-to-grain Reinforcement at the Support

Erik Serrano*

* Division of Structural Mechanics, Lund University
P.O. Box 118, SE 221 00 Lund, Sweden
erik.serrano@construction.lth.se

ABSTRACT

By the use of e.g. bonded-in dowels, or self-tapping screws, efficient reinforcement at supports for compression perpendicular to the grain can be achieved. Examples of previous studies on the topic includes the work of Bejtka [1], Bejtka and Blaß [2] and the overview by Dietsch and Brandner [3].

One challenge in developing design equations for reinforced supports relates to the influence of the distance between the reinforcing rods, and how many (or few) rods need to be inserted in order to efficiently distribute the support force into the timber volume.

The work presented involves non-linear finite element analyses taking into account the plastic behaviour of the wood. A plasticity model as described by Serrano in [4] and adopted in the work of Akter [5] was used in a series of parameter studies to investigate the influence of the rod (screw or dowel) placement on the force distribution between rods and within the wood volume close to the support. The analyses are based on the use of material data as found in the literature, and model calibration was also done using results from literature.

The presentation includes a discussion of the modelling approaches employed, the main results from the analyses and possible implications as regards design recommendations.

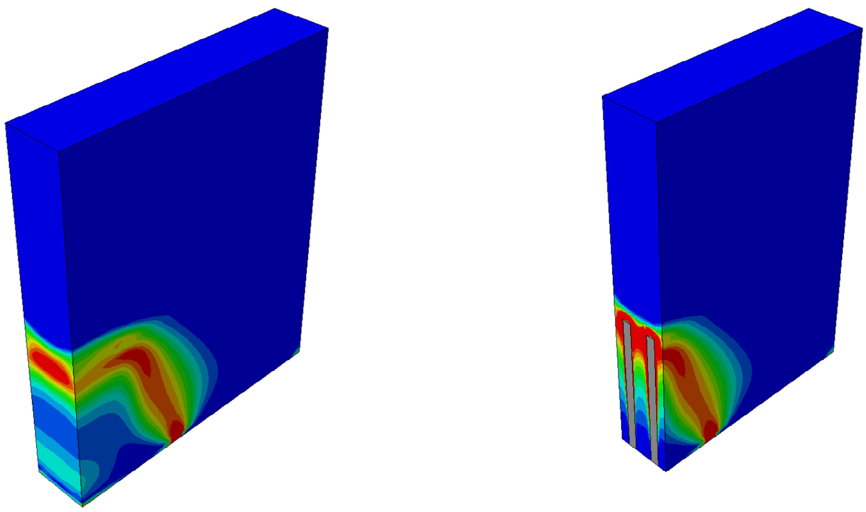


Figure 1: Finite element model of beam reinforced at the support. Left: Contour of plastic strain energy density at the support. Right: Cut through the model showing two reinforcing rods.

REFERENCES

[1] Bejtka, I.; Verstärkung von Bauteilen aus Holz mit Vollgewindeschrauben, PhD-thesis, KIT Scientific Publishing, Karlsruhe, 2006.

[2] Bejtka, I.; Blaß, H.J.; Self-tapping screws as reinforcements in beam supports, CIB-W18/39-7-2, Proceedings of the international council for research and innovation in building and construction, Working commission W18 – timber structures, Meeting 39, Florence, Italy, 2006.

[3] Dietsch, P.; Brandner, R.;Self-tapping screws and threaded rods as reinforcement for structural timber elements – A state-of-the-art report. *Construction and Building Materials 97, pp. 78–89, 2015.*

[4] Serrano, E.; Notes on a plasticity model for wood in compression, Report TVSM-7167, Division of Structural Mechanics, Lund University, 2020.

[5] Akter, S.T.; Experimental characterization and numerical modeling of compression perpendicular to the grain in wood and cross-laminated timber; PhD-thesis; Department of Building Technology, Linnaeus University, Växjö, Sweden, 2022.

NUMERICAL MODELLING OF THE LOAD-DEFORMATION BEHAVIOUR OF CONNECTIONS WITH INCLINED SCREWS

Dorotea Caprio*, Robert Jockwer†

* MSc.
Department of Architecture and Civil Engineering (ACE)
Chalmers University of Technology
Sven Hultins gata 6
412 96 Göteborg, Sweden
dorotea.caprio@chalmers.se
† Assoc. Prof.
robert.jockwer@chalmers.se

ABSTRACT

High-performance state-of-the-art connections in modern timber structures are made with self-tapping screws [1] due to their ease of use, wide range of application, and the possibility to reach a high degree of utilization of the timber cross-section. These connections show a distinct non-linear load-deformation behaviour [2] and allow for precise optimisation with regard to strength, stiffness, and ductility.

In this contribution we present results from a project carried out at Chalmers University of Technology. Numerical models for the description of the load-deformation behaviour of connections with screws have been developed.

The models are based on beam-on-nonlinear-elastic foundation models considering the elastoplastic behaviour of the fastener and its nonlinear elastic embedment in the wood as described in [3][4]. The most relevant parameters in these models are the configuration of the connection (i.e. screw to load application angle), the properties of the screw (i.e. diameter, steel yield and tensile strength), and the properties of the timber (i.e. grain direction). The interaction between screw and timber is considered by the withdrawal and embedment parameters, which in turn are also dependent on the timber density, screw geometry, and loading direction. The model parameters are calibrated based on tests on specimens with different screw to grain and screw to load direction.

From parametric input parameters, the non-linear load-deformation behaviour of the connections is determined in order to evaluate the behaviour of entire structural systems. The load-deformation curves are described by parametric curves.

REFERENCES

[1] Ringhofer A (2017) Axially loaded self-tapping screws in solid timber and laminated timber products. PhD Thesis, TU Graz. ISBN: 978-3-85125-556-0

[2] Jockwer R, Steiger R, Frangi A (2014) Fully Threaded Self-tapping Screws Subjected to Combined Axial and Lateral Loading with Different Load to Grain Angles. In: Aicher S, Reinhardt H-W, Garrecht H (eds) Materials and Joints in Timber Structures. Springer Netherlands, pp 265–272

[3] Lemaître R, Bocquet J-F, Schweigler M, Bader TK (2019) Beam-on-Foundation Modelling as an Alternative Design Method for Timber Joints with Dowel-Type Fasteners – Part 2: Modelling Techniques for Multiple Fastener Joint or Connection. In: Proc. of the INTER Meeting 6/Paper 52-7-9. Tacoma, USA

[4] De Santis Y, and Fragiacomo M. (2021) Timber-to-Timber and Steel-to-Timber Screw Connections: Derivation of the Slip Modulus via Beam on Elastic Foundation Model. Engineering Structures 244 (2021): 112798. https://doi.org/10.1016/j.engstruct.2021.112798.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Push-out Testing of Screws for Timber-Concrete Composites: Evaluating Experimental Performance

Sergio J. Yanez*†, Eduardo Pérez* and Juan Carlos Pina*

* University of Santiago of Chile (USACH), Faculty of Engineering, Civil Engineering Department, Chile
sergio.yanez.c@usach.cl; eduardo.perez@usach.cl; juan.carlos.pina@usach.cl

† Corresponding author

ABSTRACT

Composite concrete-wood systems or TCC (Timber Concrete Composite) are challenging to analyze due to their highly variable behavior that depends on the connection characteristics. The estimation of the load-slip curve is essential to accurately predict the overall structural performance since slip at the connection interface is almost inevitable. Design codes do not specifically consider the composite concrete-timber behavior, and different expressions have been adopted to estimate the stiffness resistance of the connection. Therefore, it is crucial to analyze different connectors' performance, particularly when designing composite structures using local materials or when design codes do not cover specific connection features. This work presents a parametric mechanical characterization of typical timber to concrete connections using push-out tests. The study aimed to investigate the mechanical response at the interface of the system by testing different types of connectors in various arrangements and numbers. The slip force curve was obtained by applying continuous loading until failure, and recommendations on constructive care are provided. The experiments used radiata pine wood of dimensions 5 x 5 inches, G30 concrete, and 6 mm lag screws with the number of connectors varying from 1 to 4. Three different arrangements were analyzed, including screws placed at 90° with threads embedded in the timber element, screws placed at 90° with 1 cm of threads embedded in the concrete, and lag screw at 45°. The group effect and screw inclination were studied, and a comparison with international standards was performed. The specimens with four connectors spaced 10 cm apart did not show significant variation in resistance based on linear extrapolation from single screw resistance. Inclined screws showed an increase in resistance and rigidity due to induced tensile stress. The estimation of the slip modulus showed differences up to 150% when compared to the formulation of Eurocode 5. In summary, this research provides valuable insights into the mechanical behavior of timber to concrete connections using push-out tests. The results highlight the importance of analyzing different connector types, arrangements, and numbers to accurately predict the overall structural performance.

REFERENCES

[1] Ceccotti, A., Composite concrete-timber structures. In: *Progress in structural engineering and materials*, pp. 264-275, 2002.

[2] Rodrigues, J., Dias, A. and Providência, P., Timber-concrete composite bridges: State-of-the-art review. In: *Mathematics and Sustainability*, pp. 6630-6649, 2013.

CROSS-LAMINATED TIMBER

COMPUTATIONAL MODELLING OF CROSS-LAMINATED TIMBER BUILDINGS AND THEIR CONNECTIONS SUBJECTED TO EARTHQUAKE LOADS

Erick I Saavedra Flores[1], Rodrigo Tapia[1], Sebastián Torres-Olivares[1], Yasmín Delgado González[1], Juan C. Pina[1], Carlos F. Guzmán[1], Sergio J. Yanez[1],

[1] Departamento de Ingeniería en Obras Civiles, Universidad de Santiago de Chile, erick.saavedra@usach.cl

Cross-laminated timber (CLT) is a relatively new construction building system based on structural panels made of several layers of boards stacked crosswise and glued together on their faces [1]. As CLT panels are light-weight structural elements with high stiffness and strength to bending, compression and shear, they are an economically competitive building system when compared to traditional options and therefore, are a suitable candidate for some applications which currently use concrete, masonry and steel. Given the numerous advantages of building with timber, an increasing number of multi-story CLT buildings is sprouting around the world.

In this work we investigate the nonlinear computational modelling and collapse of CLT buildings by means of a multi-scale modelling strategy. In order to determine the mechanical properties of CLT, a computational homogenisation scheme based on the volume averaging of the stress and strain fields over a representative volume element (RVE) of material is adopted. CLT floors and walls are modelled with mechanical properties obtained by the present multi-scale approach. Metallic connectors are modelled with their hysteretic non-linear behaviour, including damage. The behaviour of each connector is defined along three orthogonal axes. The building chosen for this investigation includes angle brackets, hold-downs, shear connectors and panel-to-panel screws. Some of our numerical predictions are compared with experimental results and are validated successfully. This is part of an ongoing research.

References

[1] E.I. Saavedra Flores, R.M. Ajaj, I. Dayyani and Y. Chandra: Multi-scale model updating for the mechanical properties of cross-laminated timber. Computers and Structures, 177 (2016), 83-90.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

FE-modeling of long-term creep behavior in CLT-beams loaded in bending

Le Kuai*, Johan Vessby†, Sigurdur Ormarsson*†

* Building technology, Linnaeus University and Building technology, Karlstad University, le.kuai@lnu.se

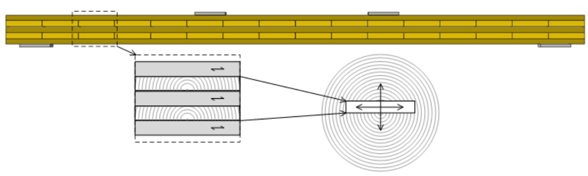
† Building technology, Karlstad University, johan.vessby@kau.se

*† Building technology, Linnaeus University, sigurdur.ormarsson@lnu.se

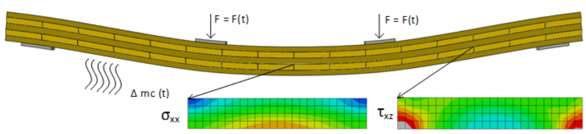
ABSTRACT

Cross laminated timber (CLT) panels have gained wide spread acceptance as load-bearing elements in tall timber buildings and modular structures with large openings. They are used for both in-plane and out-of-plane load-bearing purposes, with the latter causing bending of the panel. While there are various methods available for short-term bending analysis by hand, the gamma method is the most commonly used. However, for the long-term behaviour analy-sis there are considerably fewer methods available. Some relevant experimental works have been reported in [1 - 5], where some of them include rheological models and suggested val-ues for kdef. Despite these works, there is a need for flexible numerical models that can sim-ulate the long-term behaviour of CLT under simultaneous mechanical and environmental load cases. Such work has previously been performed for timber beams with different cross-sections [6].

In this study, a finite element model is developed for a CLT beam subjected to long-term bending, accounting for moisture-related deformations and creep effects. The model is pa-rameterized with respect to geometrical parameters (such as the number of layers and cross-sectional dimensions of the wood lamellas) as well as material parameters and material orien-tations. The simulation results clearly indicate that the bending deforma-tion of the beam is significantly influenced by the large rolling shear strains in the cross layers.



(a)



(b)

Figure 1: *a) Geometry, loads and boundary conditions of a CLT beam b) Simulated deformation and local stress varia-tion in the CLT beam.*

REFERENCES

[1] Akter, S. T., Binder, E., & Bader, T. K. (2022). Moisture and short-term time-dependent behavior of Norway spruce clear wood under compression perpendicu-lar to the grain and rolling shear. Wood Material Science & Engineering, 1-14.

[2] Binder, E., Derkowski, W., & Bader, T. K. (2022). Development of creep deformations during service life: A comparison of clt and tcc floor constructions. Buil-dings, 12(2), 239.

[3] Gräfe, M., Dietsch, P., & Winter, S. (2018). CLT under in-plane loads: Investigation on stress distribution and creep. In International Network on Timber Engineering Research INTER, Meeting 5 (pp. INTER-51).

[4] Jöbstl, R. A., & Schickhofer, G. (2007). Comparative examination of creep of GLT and CLT slabs in bending. In CIB W18 (pp. 1-15).

[5] Ormarsson, S., & Dahlblom, O. (2013). Finite element modelling of moisture related and visco-elastic deformations in inhomogeneous timber beams. Engi-neering structures, 49, 182-189.

[6] Unterwieser, H., & Schickhofer, G. (2013, May). Characteristic values and test configu-rations of CLT with focus on selected properties. In Report, Focus Solid Timber Solu-tions–European Conference on Cross Laminated Timber (CLT), COST Action FP1004, Graz (pp. 53-73).

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Influence of global failure criterion definition on bending strength and failure mechanisms of glued laminated timber beams

Christoffer Vida*, Markus Lukacevic*, Georg Hochreiner* and Josef Füssl*

* Institute for Mechanics of Materials and Structures, TU Wien
Karlsplatz 13/202, A-1040 Vienna
christoffer.vida@tuwien.ac.at, markus.lukacevic@tuwien.ac.at
georg.hochreiner@tuwien.ac.at, josef.fuessl@tuwien.ac.at

ABSTRACT

The efficient use of wood-based products, e.g., glued laminated timber (GLT), requires a sound understanding of their mechanical behavior to formulate holistic design concepts. Numerical simulations can contribute to achieving this by covering a large sample size and realizing large beam configurations, which would involve tremendous effort in experimental testing. Nowadays, the dimensions of manufactured GLT beams cover a wide range, reaching a depth of up to about 3 m. The versatile application of such beams needs to be adequately reflected in the design process. However, the influence of large beam dimensions on the bending strength, also called size effect, presented in the literature [1, 2, 3] is a matter of debate among experts. Numerical simulation results might heavily depend on the modeling strategy and their implemented local failure mechanisms. Thus, in this contribution, we focus on the influence of selected global failure criteria on the predicted size effect and the progress of failure mechanisms at the load-bearing capacity.

We developed an advanced finite element modeling approach [4] that covers discrete cracking and plastic deformations to simulate the entire load–displacement path of GLT beams subjected to four-point bending tests. In an extensive parameter study [3], we investigated the size effect and found that the characteristic bending strength decreased with increasing beam size. We analyzed different global failure criteria definitions to investigate their influence on the size effect, e.g., a load drop of 3 %, a system stiffness decrease of 1 %, and the first vertical crack initiation in the outermost tensile lamination. The predicted size effect was heavily influenced by the applied global failure criteria (Fig. 1). The criterion using the first vertical crack initiation led to a more significant bending strength decrease than the load drop criterion. This agrees with the results presented by Frese and Blaß [1]. The stiffness reduction criterion showed basically a constant bending strength, which coincides with the results presented by Fink et al. [2].

The implemented local failure mechanisms governed the structural behavior during the loading process. The formation of vertical cracks was implemented within the laminations by the extended finite element method (XFEM). Horizontal cracks could occur between the lamination by employing cohesive failure surfaces. Together, the two directions of cracking enabled the formation of continuous crack patterns over multiple laminations, where a horizontal crack could join vertical cracks in adjacent laminations with a horizontal offset. Plastic deformations were considered in the upper beam half, in the zone of compressive stresses, using the multisurface failure criterion [5, 6]. At the point of global failure, we found that the number of laminations damaged by cracking increases with beam size. The relative ratio of damaged laminations to the total number of laminations stayed constant for the large beam sizes.

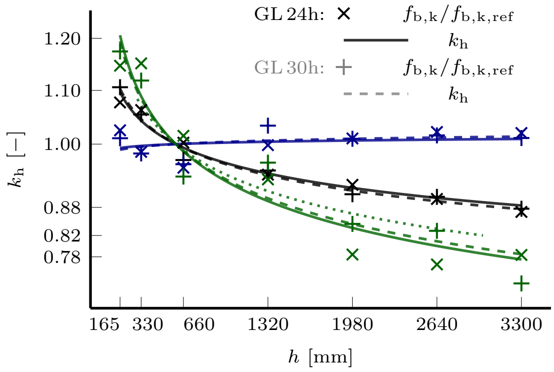


Figure 1: The obtained size effect, commonly expressed by the factor k_h, based on the three different global failure criteria: (i) the load drop criterion in black, (ii) the system stiffness reduction criterion in blue, and (iii) the first vertical crack initiation in the outermost tensile lamination criterion in green compared to (iv) the proposed result by [1] with the dotted line in green.

In conclusion, the applied global failure criterion influenced the predicted size effect of GLT beams. With increasing beam size, the number of damaged laminations increased up to the point of global failure. Although the modeling strategy heavily influences the obtained load-bearing capacities, the presented advanced simulation concept seems to be a promising way to achieve reasonable predictions. Further experimental test series on GLT beams with different dimensions would allow simulation concepts to be validated and their informative value to be strengthened. Large parameter studies of different kinds, which can be performed efficiently with simulations, would gain value and could be used as a basis for standardization.

References

[1] Frese, M.; Blaß, H. J. Numerical description of size and load configuration effects in glulam structures. In: *Proceedings of the 12th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP12)*, pp. 1–8, 2015.

[2] Fink, G.; Frangi, A.; Kohler, J. Probabilistic approach for modelling the load-bearing capacity of glued laminated timber. *Engineering Structures*, 100:751–762, 2015.

[3] Vida, C.; Lukacevic, M.; Hochreiner, G.; Füssl, J. Size effect on bending strength of glued laminated timber predicted by a numerical simulation concept including discrete cracking. *Materials & Design*, 225:111550, 2023.

[4] Vida, C.; Lukacevic, M.; Hochreiner, G.; Füssl, J. Modeling approach to estimate the bending strength and failure mechanisms of glued laminated timber beams. *Engineering Structures*, 255:113862, 2022.

[5] Lukacevic, M.; Lederer, W.; Füssl, J. A microstructure-based multisurface failure criterion for the description of brittle and ductile failure mechanisms of clear-wood. *Engineering Fracture Mechanics*, 176:83–99, 2017.

[6] Pech, S.; Lukacevic, M.; Füssl, J. A robust multisurface return-mapping algorithm and its implementation in Abaqus. *Finite Elements in Analysis and Design*, 190:103531, 2021.

NUMERICAL AND EXPERIMENTAL EVALUATION OF THE STRUCTURAL PERFORMANCE OF CROSS LAMINATED TIMBER WITH AIR GAPS

Robert Jockwer*, Yutaka Goto†

* Assoc. Prof.
Department of Architecture and Civil Engineering (ACE)
Chalmers University of Technology
Sven Hultins gata 6
412 96 Göteborg, Sweden
robert.jockwer@chalmers.se

† Dr. sc.
Department of Architecture and Civil Engineering (ACE)
Chalmers University of Technology
Sven Hultins gata 6
412 96 Göteborg, Sweden
yutaka@chalmers.se

ABSTRACT

Cross laminated timber (CLT) has been a major contributor of the expansion of the technical possibilities especially in structural capacity. While CLT has advantages, the practical production of CLT often consumes much more high-quality raw materials compared to the actual amount that is in many cases necessary for providing sufficient structural capacity.

In the project *Next Generation CLT* (Project Number 2020-01784 funded by FORMAS, the Swedish research council for sustainable development) performed at Chalmers University of Technology we aim to develop an optimized layup of a CLT-like wood-based panel with air gaps between single boards for loadbearing structures of buildings. Its novelty is characterized by the optimized composition and amount of the timber used for a panel in terms of structural capacity, hygrothermal performance (no decay/mould risk) and environmental impact. The specific objective of the present study is to (1) design basic configurations of wall panel with air gaps for laboratory tests, and (2) analyse the basic performance in a small scale.

The gaps in the cross-layers reduce not only the effective rolling shear strength but also the composite action of the panel. For a first quantification of these effects, shear tests according to EN 16351 [1] have been performed on three- and five-layer CLT configurations. It was particularly focussed on the determination of the impact of gap configuration on the strain distribution in the panel, which was analysed by digital image correlation. The Figure (left) shows an example of the shear strain measurements in the tests.

A considerable stress concentration effect at the corner of longitudinal and cross-layers with increasing gap length was observed in the tests. The failure of the panels was initiated due to shear and tension perpendicular to grain stresses at these points. The optimisation of the performance and strength of the panel needs to consider these aspects.

In a next step the different configurations were modelled in Abaqus in order to determine the stress distribution in the specimens and to predict the failure initiation and strength. The specimens follow those proposed in EN 16351 for rolling shear tests and were modelled as a 3D deformable solid extrusion in Abaqus. The material was modelled as an elastic orthotropic material. The material properties were chosen as the average material properties of the graded raw material and analysed using static analysis.

For the results of the finite element modelling, the shear stress distribution in the LR- and RT-

plane, as well as the normal stress distribution in the RR-direction, were analysed more in detail. It was focussed particularly on the stress distribution and concentrations at the transitions of the gaps and cross-layers. Utilization ratios were calculated from the shear and perpendicular to the grain stresses in order to identify the effect of the gap configuration on the failure load.

In the contribution the impact of the air gap layout, configuration, material reduction, and gap width on the stress distribution and utilisation rate will be compared in more detail. The small-scale tests are compared with results on full size panel tests in bending that are currently carried out at Chalmers University of Technology [3]. The composite action and CLT panel performance in different applications is analysed.

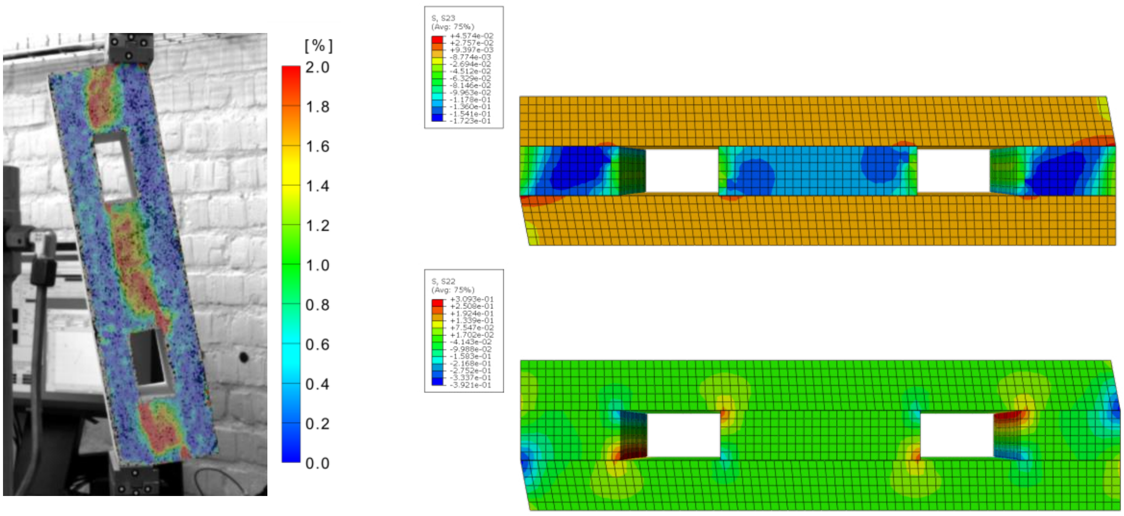


FIGURE: Shear stress distribution in a 3-layer CLT specimen and shear and perpendicular to grain stress distributions from FE models [2]

REFERENCES

[1] EN 16351:2015 Timber Structures - Cross Laminated Timber - Requirements. Brussels, Belgium: European Committee for Standardization CEN.

[2] Moberg A., and Xiao L., (2022), Next Generation CLT - Material optimisation of CLT with regard to structural performance by the introduction of air gaps in the cross-layers, Master's thesis, Chalmers University of Technology, Gothenburg, Sweden.

[3] Kurzawinska H., and Tahmasebi M., (2023), Performance optimization of CLT (NextGenCLT), Master's thesis, Chalmers University of Technology, Gothenburg, Sweden.

Numerical and Experimental Study of Flexural Properties of Cross-Laminated Timber (CLT) from Oil Palm Wood (*Elaeis guineensis* JACQ.)

Martin Hackel*

* OWL University of Applied Sciences and Arts
Campusallee 12, D-32657 Lemgo
martin.hackel@th-owl.de

Oil palms (*Elaeis guineensis* JACQ.) are a versatile raw material producing crop for palm and palm kernel oil, for the food, chemical and pharmaceutical industries as well as the energy sector. As a result, the global oil palm cultivation area spans over 28.9 million hectares, mostly in Southeast Asia [1]. The clearing of plantation areas after the end of the economic lifespan (25 – 30 years) results in up to 180 million m³ of usable oil palm wood per year [2, 3]. Possible substitution potentials of the material are unrecognised and not utilised, partially due to limited knowledge about the material properties. Glued building products like GLT and CLT have been identified as a possible field for substitution approaches [3]. The use in multi-storey constructions as well as relatively large material consumption for CLT offer approaches for the use of oil palm wood.

The anatomical structure of oil palm wood as a monocotyledon differs greatly from the structure of common wood species used in the construction sector (dicotyledons). Monocotyledons do not show secondary thickness growth and therefore no annual rings. Characteristics typical of dicotyledons such as knots and wood rays are not present. On a macroscopic level oil palm wood is more homogeneous than common wood species. The tissue of the oil palm is composed of high-density vascular bundles and low-density parenchymatous ground tissue. The vascular bundles run mostly parallel, but slightly helical to the mantle surface of the trunk. Deviations occur in the area of the leaf bases [4]. The material is comparable to long-fibre reinforced composites. The area percentage of the vascular bundles varies with the position in the trunk and shows correlations with structurally important material properties (e.g. density) [5]. The density shows comparable behaviour and is exponentially decreasing from the outside to the inside and from the bottom to the top of the trunk [6] and varies between 170 and 790 kg/m³ [2]. The elastomechanical properties of oil palm wood show strong, mainly power law correlation with the density [5]. Oil palm wood is assumed to be orthotopic with negligible differences between radial and tangential direction [2].

The correlations between elastomechanical properties and density [5] and the density gradients within the trunks [6] require the ripping of the material to lamellas with smallest cross-sections of 60 mm x 20 mm (resulting in reduced density gradients). A subsequent grading according to the density [7] into four density classes (< 250 kg/m³; 250 - 349 kg/m³; 350 - 425 kg/m³; > 425 kg/m³) is necessary. Five-layer test specimens are produced to investigate the flexural properties. According to [8] and [9], the dimensions of the test specimens are 3200 mm x 600 mm x 100 mm. Edge glueing of the lamellas is not carried out. The test specimen layups vary based on the density classes. The influence of different layups is investigated. Four-point bending test are performed in accordance to [8] and [9]. Flexural strength and local and global moduli of elasticity are used to validate the modelling.

The modelling of the test specimens serves to test in principle the applicability of the finite element method for modelling cross laminated timber from oil palm wood. The modelling of the bending tests is carried out using the software package RFEM 6.02 (Dlubal Software GmbH). Two-dimensional plane elements and alternatively three-dimensional volume elements are used in the modelling. The influence of the representation of the specimen width and resulting inhomogeneity in the respective layers is to be investigated. The representation of the test specimens within the software is carried out in the form of assembled individual components, which correspond to the lamellas of the comparative test specimens of the laboratory tests. The elastomechanical properties required for the modelling are assigned according to the lamella density. To determine the corresponding properties, correlations between the density and the respective properties are used, e. g. according to [7], [10] and [11]. A solid bond is assumed between the faces of the individual lamellae. On the edge, a bond is implemented using friction coefficients in accordance to the laboratory tests.

The implementation and comparison of the results of the modelling and laboratory tests are part of an ongoing research project. Final results are not yet available at the time of the writing of this abstract. The results of these investigations are to be used in the further course of the project to optimise the modelling as well as for computer-aided optimisation of the cross laminated timber structure.

REFERENCES

[1] Food and Agriculture Organization of the United Nations. Crops and livestock products. In *https://www.fao.org/faostat/en/#data/QCL* 2023.

[2] Lim, S. C., Khoo, K. C. Characteristics of oil palm trunk and its potential utilization. In *Malaysian Forest* (49) (pp. 3–22) 1986.

[3] Fruehwald, A., Fruehwald-Koenig, K. The Use of Oil Palm Trunks for Wood Products. In *By-Products of Palm Trees and Their Applications* (pp. 69–80) 2019

[4] Tomlinson, P. B., Horn, J. W. & Fisher, J. B. *The anatomy of palms: Arecaceae - Palmae*. Oxford University Press, 2011

[5] Fruehwald-Koenig, K., Heister, L. Macro- and Micromechanical Behavior of Oil Palm Wood (Elaeis guineensis JACQ.): Tensile, Compression and Bending Properties. In *Submitted publication* 2023.

[6] Koelli, N. *Density and Moisture Distribution in Oil Palm Trunks from Peninsular Malaysia*. Bachelor-Thesis, University of Hamburg, 2016

[7] Fruehwald-Koenig, K. Properties and Grading of Oil Palm Lumber. In *Proceedings: 21st International Nondestructive Testing and Evaluation of Wood Symposium* (pp. 204–212) 2019

[8] CEN European Committee for Standardization. *EN 408+A1:2012-07: Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties* 2012.

[9] CEN European Committee for Standardization. *EN 16351:2021-03: Timber structures - Cross laminated timber – Requirements* 2021

[10] Fruehwald-Koenig, K., Faust, B. & Hackel, M. Elastic Constants and Shear Strength of Oil Palm Wood (*Elaeis guineensis* JACQ.). In *Publication in preparation* 2023

[11] Fruehwald-Koenig, K., Heister, L. Compression and Tensile Properties of Oil Palm Wood (*Elaeis guineensis* JACQ.) in Construction Size. In *Construction and Building Materials (submitted)* 2023

CULTURAL HERITAGE

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Experimental-numerical study on the sensitivity of historical art objects to different museum climate conditions

Rianne A. Luimes*†, Paul H.J.C van Duin*, Jan Dorscheid*, Lisette Vos*, Akke S.J. Suiker†, Emanuela Bosco† and Katrien Keune*

* Rijksmuseum Amsterdam
Department of Conservation and Science, Hobbemastraat 22, 1071 ZC Amsterdam, The Netherlands
r.luimes@rijksmuseum.nl, p.van.duin@rijksmuseum.nl, j.dorscheid@rijksmuseum.nl, l.vos@rijksmuseum.nl, k.keune@rijksmuseum.nl

† Eindhoven University of Technology
Department of the Built Environment, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
r.a.luimes@tue.nl, a.s.j.suiker@tue.nl, e.bosco@tue.nl

ABSTRACT

Sustainability is high on the agenda of the Rijksmuseum Amsterdam, because of the goal to become one of the most sustainable museums in the world. Conservators and scientists have been closely working together to explore sustainable specifications for indoor climate conditions that can be safely exposed to susceptible art objects [1, 2, 3]. Recently, a research project has been initiated to investigate the structural behaviour of oak wood panels in historical cabinets and paintings exposed to different climate conditions by means of in-situ monitoring and numerical modelling. The main purpose of this project is to determine whether a safe relaxation of the Rijksmuseum climate specifications is possible, such that the energy consumption of the climate installations can be reduced and the Rijksmuseum can achieve its climate goals.

The art objects of interest are two cabinets attributed to Jan van Mekeren and two panel paintings from the first half of the seventeenth century, as shown in Figure 1, of which either is part of the collections of the Rijksmuseum and Castle Amerongen. The objects have comparable characteristics, in terms of the date of construction, the composition of the structure, the materials used, and their historical value. Conversely, the temperature and relative humidity conditions to which the objects are exposed to are completely different. The objects part of the Rijksmuseum collection are displayed/stored in a strict, highly controlled climate, while the objects part of the Castle Amerongen collection are displayed in a fluctuating, moderately controlled climate. The cabinets and paintings therefore provide an excellent case study to compare the effects of strict and fluctuating climate conditions on the structural response of comparable, susceptible art objects.

The experimental part of the research project includes the in-situ monitoring of the structural response of the cabinets and paintings. Over a full calendar year, i.e., all four seasons, the structural response of and the climate conditions to which the objects are exposed to are measured. For this purpose, the inside of the right side panel and the bottom of the drawer of the cabinets and the back side of the substrate of the paintings are equipped with various sensors. Displacements and strains are recorded by attaching LVDTs (linear variable displacement transducers) and strain gauges to the objects. In addition, the temperature and the relative humidity are recorded by placing climate sensors inside and

(a) Cabinet (b) Panel painting

Figure 1: Art objects included in the experimental campaign. (a) Cabinet, Jan van Mekeren. Oak veneered with various wood species. Amsterdam, circa 1695-1710. Castle Amerongen, Amerongen. (b) Agatha Geelvinck (1617-38). First spouse of Frederik Dircksz Alewijn, Dirck Dircksz. van Santvoort, 1637-1640. Oil paint on oak panel. Rijksmuseum, Amsterdam SK-A-1318.

on top of the cabinets, and behind and in front of the panel paintings. All measured data are logged on regular time intervals and transferred daily to a network server via a data connection. By comparing the measured structural response of the objects under the strict Rijksmuseum climate and the fluctuating climate at Castle Amerongen, the effects of different climate conditions on the objects can be better understood.

The numerical part of the research project is dedicated to the simulation of the structural behaviour of the objects under various climate fluctuations. For this purpose, a previously developed thermo-hygro-mechanical model for wood is applied, which accounts for moisture hysteresis and aging effects [3]. The model is first used to predict the stress and strain fields developing in the objects under the climate fluctuations measured in the in-situ experiments, thereby providing detailed insight in the structural behaviour of the art objects. Subsequently, a parameter variation study is carried out to determine the outer limits of indoor climate specifications that can be safely applied to the art objects. By using the insights obtained from the in-situ experiments and numerical simulations, the effects of different climate conditions on susceptible cabinets and paintings can be better understood. This allows to draw conclusions on a possible relaxation of the indoor museum climate specifications, which in turn helps the Rijksmuseum and other museums to fulfil their sustainability goals and achieving a more sustainable climate policy.

REFERENCES

[1] Luimes, R.A., Suiker, A.S.J., Verhoosel, C.V., Jorissen, A.J.M. and Schellen, H.L. Fracture behaviour of historic and new oak wood. *Wood Science and Technology*, 52, pp. 1243-1269, 2018.

[2] Luimes, R.A., Suiker, A.S.J., Jorissen, A.J.M., van Duin, P.H.J.C. and Schellen, H.L. Hygro-mechanical response of oak cabinet door panels under relative humidity fluctuations. *Heritage Science*, 6(72), pp. 1-23, 2018.

[3] Luimes, R.A. and Suiker, A.S.J. Numerical modelling of climate-induced fracture and deformation in wood: Application to historical museum objects. *International Journal of Solids and Structures*, 210-211 pp. 237-254, 2021.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Hygro-Mechanical Long-term Analysis of Wood at Structural Scale

Josef Stöcklein*† and Michael Kaliske*

* Institute for Structural Analysis, TU Dresden
01062 Dresden
tu-dresden.de/bu/bauingenieurwesen/sdt

†josef.stoecklein@tu-dresden.de

ABSTRACT

The hygro-mechanical response of wooden structures to mechanical and climatic loads is complex and not sufficiently investigated. Large effort is needed for experiments and modelling of the material behaviour. While mechanical and moisture transport phenomena are well known, respectively, the coupling is still a wide field of research. Especially, the mechanical long-term response to mechanical and moisture loads, the mechanosorption, is being investigated. The aim is both, to understand the mechanisms of mechanosorption and to find simple models to describe the behaviour, which are applicable for simulations at structural scale.

Within this contribution, experiments are presented investigating the coupled hygro-mechanical material behaviour of wood [1]. Creep experiments at constant and oscillating climate have been carried out as well as constrained swelling and shrinkage experiments. Mechano-sorption models are discussed and adapted. The resulting model is capable to simulate viscous and mechanosorptive strain as well as moisture induced stresses.

The model is then applied to wooden cultural heritage objects on structural scale using a Finite Element framework [2]. Long-term analyses are carried out and validated by experiments in a climate chamber and in natural climate. By this, the effect of viscous creep and mechanosorption on wooden panel paintings is investigated and the capability of the modelling for long-term simulations at any mechanical and climatic load is demonstrated.

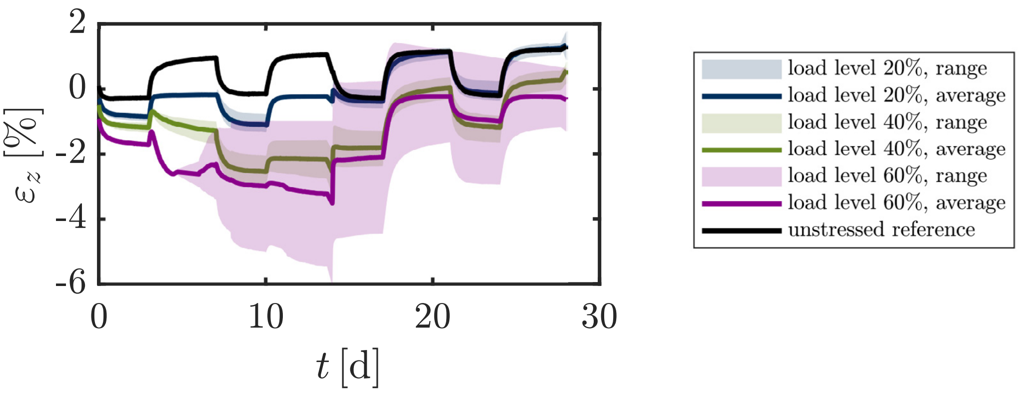


Figure 1: Creep strain of a compression test at changing relative humidity and four different stress levels.

REFERENCES

[1] Stöcklein, J.; Grajcarek, G.; Kaliske, M. Validation and parameter identification of material modelling for short- and long-term behaviour of pine, spruce and limewood for cultural objects – an experimental-virtual lab. *Wood Science and Technology*, in preparation.

[2] Stöcklein, J.; Grajcarek, G.; Kaliske, M. Time-dependent hygromechanical comparison of historical panel paintings in experimental-virtual lab. *Journal of Cultural Heritage*. in preparation.

CompWOOD 2023

On the effect of moisture exchange in panel paintings

P. Foti[1], A. Califano[2], C. Bertolin[1], C. Gao[*], F. Berto[1,3]

1: Norwegian University of Science and Technology (NTNU), Department of mechanical and Industrial Engineering, Richard Birkelands vei 2B, 7034 Trondheim, Norway
pietro.foti@ntnu.no
chiara.bertolin@ntnu.no
chao.gao@ntnu.no
filippo.berto@ntnu.no

2: University of Salerno, Department of Industrial Engineering, Via Giovanni Paolo II132, 84084, Fisciano, Italy
amcalifano@unisa.it

3: Sapienza University of Rome, Department of Chemical, Material and Environmental Engineering (DICMA), Piazzale Aldo Moro 5, 00185 Rome, Italy
filippo.berto@uniroma1.it

[*] Corresponding Author: Chao Gao
Richard Birkelands vei 2B, 7034 Trondheim, Norway
chao.gao@ntnu.no

ABSTRACT

An hygrothermal-mechanical-coupled model has been developed to assess the safety conditions of panel paintings subjected to a change in environmental conditions (change of relative humidity (RH) at constant temperature (T)). A similarity with a thermal problem has been established and exploited.

The materials parameters have been defined for the model considering as driving potential the RH (%); indeed, any other existing driving potential would have discontinuities between the different layers constituted by wood, gesso and tempera, complicating the model. For example, the moisture content (MC) can also be considered as driving potential; however, it varies abruptly from layer to layer, while the RH, varies continuously between each layer. The needed parameters for the model have been taken from literature [1–3] and expressed consistently with RH as driving potential.

Considering the well know equation (see [4]) that, at a specific T, relates the MC (%) with the RH (%) through the GAB coefficients (V, c and k), it is possible to derive useful expressions for modelling the RH change phenomenon. Then, the dimensional change parameter can be obtained as well. However, in this contribution, these expressions have been used only for the wood layer, while, due to lack of GAB coefficients for gesso and tempera, a constant hygrometric dimensional change coefficient has been used for them (*i.e.,* linear dimensional change within a 5-15% MC range).

Therefore, our modelling approach to simulate the hygrothermal-mechanical response of the panel painting can investigate the environmental effect together with its coupled temporal evolution—particularly, a time-dependent behaviour of panel painting as a function of external mass transfer parameter, geometrical parameters or boundary conditions.

Figure 1 presents the results of this preliminary study in which the wood and gesso layers in the panel painting have a thickness of 40 mm and 2 mm, respectively. Different boundary conditions have been considered: i) no moisture exchange through the gesso layer; ii) moisture exchange through the gesso layer assuming the same external mass coefficient used for the wood layer bottom surface. It is worth highlighting that moisture flux has been allowed in the model only along the y direction in Figure 1. The conditions of the panel painting, both in terms of RH% and stress along the x direction, refer to 6 hours (figure 1a, 1b, 1c and 1d,) and 10 days (figure 1e, 1f, 1g and 1h) after the abrupt change occurred. If moisture exchange is prevented in the gesso surface in direct contact with the environment and the panel painting is left in the new RH conditions long enough for the painting to reach the final stable RH conditions, it could be inferred that an high thickness ratio between the wood and the gesso layers would result in a final deformed shape for the whole component

mainly controlled by the wood layer, with the gesso being in a compression state (see figure 1 f)) at least until when its moisture content is not significantly changing due to the moisture exchange allowed through the wood-gesso interface. However, the final stable state may also result in a tension state depending on the geometrical conditions of the whole component and on the mismatch between gesso and wood coefficients of moisture expansion. Even if the compression state of gesso may be thought as desirable, the interface between the two layers may be subjected to high shear stresses, possibly leading to the layers delamination. On the contrary, a low thickness ratio between the wood and the gesso layers would result in the gesso layer being affected by change in its MC in a shorter time; besides, in this case, the painting deformed shape and stress field highly depends on both the difference in the coefficients of moisture expansion and the thicknesses ratio.
However, a condition of no moisture exchange through the gesso layer cannot be assumed to be realistic for panel paintings. Figures 1c and 1g report the expected RH % trends in the component after 6 hours and 10 days, respectively, assuming moisture exchange also through the gesso layer. In such a case the gesso layer is experiencing variations in its MC since the change in the environmental conditions resulting in shrinkage and tension stresses, as it can be seen from Figures 1d. This stress condition is induced because, being the gesso surface in direct contact with the environment and having a low thickness with respect to the wood layer, it will reach the final RH conditions in a shorter time with respect to the wood layer (see Figure 1g in which the gesso is already almost at the final 10% RH condition while the core of the wood is still at the initial RH conditions). The tension stress conditions are due to the wood being still at its original dimension while the gesso being already at its final shorter dimensions. Of course, this also induces shear stresses at the interface of the wood and gesso layer and, therefore, delamination should not be excluded as well.

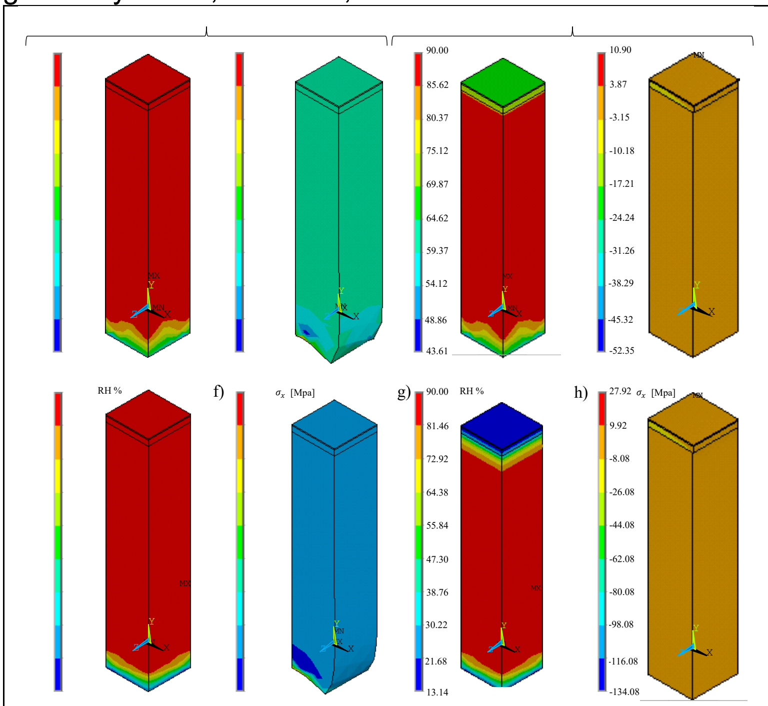


Figure 1: RH % contour plot due to an abrupt change in the environmental conditions from 90 to 10% RH for a panel painting with: a) no moisture exchange through gesso layer after 6 hours; c) moisture exchange through gesso layer after 6 hours; e) no moisture exchange through gesso layer after 10 days; g) moisture exchange through gesso layer after 10 days. σ_x stress induced by an abrupt change in the environmental conditions from 90 to 10% RH for a panel painting with: b) no moisture exchange through gesso layer after 6 hours; d) moisture exchange through gesso layer after 6 hours; f) no moisture exchange through gesso layer after 10 days; h) moisture exchange through gesso layer after 10 days.

REFERENCES

[1] Soboń M, Bratasz Ł. A method for risk of fracture analysis in massive wooden cultural heritage objects due to dynamic environmental variations. Eur J Wood Wood Prod 2022;80:1201–13. https://doi.org/10.1007/s00107-022-01841-3.

[2] Time B. Hygroscopic moisture transport in wood. Norwegian University of Science and Technology Trondheim; 1998.

[3] Morais JL, Xavier JC, Dourado NM, Lousada JL. Mechanical behaviour of wood in the orthotropic directions. SharePDF Net-Free Download PDF File (Online) Http//Sharepdf Net/View/87548/Mechanical-Behaviourof-Wood-in-the-Orthotropic-Directions (Accessed Sept 24, 2013) 2001.

[4] Bertolin C, de Ferri L, Strojecki M. Application of the Guggenheim, Anderson, de Boer equation to study the impact of sealing treatments on pine wood sorption characteristics. Mater Des Process Commun 2021;3:1–12. https://doi.org/10.1002/mdp2.189.

DENSIFICATION

3rd ECCOMAS Thematic conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

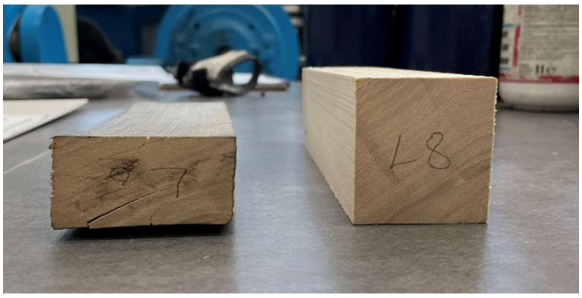
A ROAD TOWARDS A SUSTAINABLE THERMO-HYGRO-MECHANICAL WOOD DENSIFICATION PROCESS

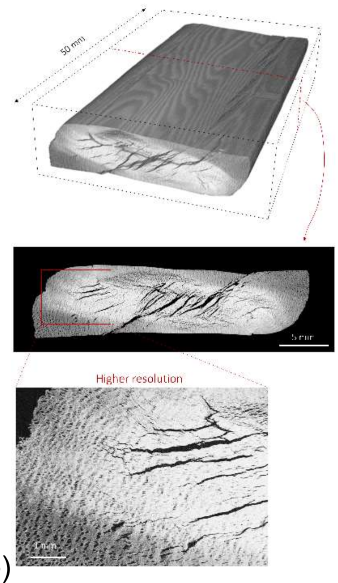
Marie-Stéphane Colla*, Sophie Ryelandt*, Thomas Pardoen*

* Université catholique de Louvain
Institute of Mechanics, Materials and Civil Engineering
Place Sainte Barbe 2, L5.02.02
1348 Louvain-la-Neuve
Belgium
marie-stephane.colla@uclouvain.be
sophie.ryelandt@uclouvain.be
thomas.pardoen@uclouvain.be
https://uclouvain.be/en/research-institutes/immc

ABSTRACT

Due to climate change, the Belgian forests are under pressure and their health is becoming a major concern. For the moment, the forest parcels contain mostly a unique wood species presenting high density suitable for structural applications. However, it has been proven that the presence of a multitude of wood species, including fast growing species with lower density will strengthen forests health and ensure their sustainable exploitation. In this context, the wood industry is searching a way to add value to such low density wood, that is most often not exploited. One possible approach is to densify the wood using thermo-hygro-mechanical processes, Fig 1.


(a)



(b)

Figure 1 - Thermo-hygro-mechanically densified wood: (a) after densification process, (b) analysis of damage inside the specimen by X-ray tomography.

In this research, design of experiment has been used to identify the most promising densification parameters for poplar wood by uniaxial compression. The relationship between the densification process and the mechanical properties, including Young's modulus, hardness, and fracture toughness, of densified wood is investigated through quasi-static mechanical tests, microhardness mapping, microstructural characterization and X-ray tomography. The optimization of the densification process is studied in combination with continuum constitutive models to understand the effects of gradients during the process and their implication on the visco-elasto-plastic behaviour of wood.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Investigations on the thermo-mechanical behaviour of densified veneer wood for cryogenic applications

Jens U. Hartig*, Martin F. Eichenauer*, Jörg Wehsener* and Peer Haller*

* Affiliation
Technische Universität Dresden, School of Civil and Environmental Engineering, Faculty of Civil Engineering, Institute of Steel and Timber Construction, Chair of Timber Engineering and Construction Design, 01062 Dresden, Germany
E-mail: jens.hartig@tu-dresden.de, martin.eichenauer@tu-dresden.de, joerg.wehsener@tu-dresden.de, peer.haller@tu-dresden.de

ABSTRACT

In the course of a less CO2 intensive energy production, liquid energy sources like liquid natural gas (LNG) or liquid hydrogen gain increasing importance. A crucial point for using these energy sources is storage and transportation. Both have to be accomplished with low heat input to avoid e.g. gas boil-off and finally loss. Thus, these liquid energy sources are usually stored and transported in containers and lines packed into thermal insulation. However, common insulation materials like technical foams usually have insufficient mechanical properties and are not applicable for supporting constructions.

An increasingly used material for supporting constructions of low-temperature, liquefied energy sources is densified veneer wood (DVW). DVW is often produced of veneers of beech (*Fagus sylvatica* L.), which are impregnated with a phenol resin and additionally densified transverse to the grain. General properties of DVW are presented e.g. in [1]. There are several applications for DVW with this regard like supporting blocks for tanks in transport ships [2, 3] or spacers for tube-in-tube transportation lines. For a reliable structural verification of the support structure, the knowledge of the thermal and mechanical properties is important. The temperature range for LNG applications is between -161°C on the side of the tank and about 20°C on the side exposed to ambient conditions. The temperature gradient results in imposed deformations. Restrained imposed deformations result in imposed stresses. Imposed tensile stresses might exceed the tensile strength of the wood, which results in the development of cracks. This is associated with the impairment or even the loss of the thermal insulation function. This results into two negative effects: the heat input to the tank, increasing the temperature of the liquefied gas and the cooling of the hull plating made of steel. The latter might result in the embrittlement of the steel and a higher proneness for failure.

Literature shows limited studies into the mechanical behaviour of wood or wood materials at very low (cryogenic) temperatures. In the review paper of [4], a significant influence of the temperature on the mechanical properties of wood is demonstrated. The diagrams in [4] show that, in general, the values of the mechanical properties increase with decreasing temperature. However, moisture has a significant influence on the low temperature behaviour of wood. High moisture contents may result in structural damage due to the volume increase of the water during icing and reduced mechanical properties. A thorough literature review on the influence of moisture and temperature down to cryogenic values is given in [5]. In [5], also selected mechanical properties of beech (*Fagus orientalis*

Lipsky) at room temperature and at -196°C were determined, which confirmed the statements above. In [2] mechanical tests on DVW at room temperature and at -163°C were performed.

In this paper, experimental investigations on the mechanical properties and the heat storage capacity of wood are presented. The compression behaviour parallel and transverse to the lamination direction was determined at five temperature levels: +60°C, +20°C, -40°C, -78°C (with dry ice) and -196°C with (liquid nitrogen). The heat storage capacity was determined with differential scanning calorimetry (DSC) in a range of -160°C and +60°C. The interlaminar shear strength was determined at ambient temperature. Moreover, a technique for hygro-thermal moulding of DVW to circular shapes is presented in order to produce supports for circular tanks and tubes with low cut-off.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support from German Federal Ministry of Economic Affairs and Energy for the project "Development of thermo-hygro-mechanical processes for bend forming of densified veener wood to technical profiles" (grant numbers ZF4453301WZ7 and ZF4453302WZ9). The authors also thank the project partner Deutsche Holzveredelung Schmeing GmbH & Co. KG, Kirchhundem for collaboration and Dr. Christiane Kothe (TU Dresden, Institute of Building Construction) for performing the DSC measurements.

REFERENCES

[1] Ehlbeck, J.; Hättich, R.: Physikalische, insbesondere mechanische Eigenschaften von Kunstharz-Preßholz. *Holz als Roh- und Werkstoff* 44(12):449-452, 1986.

[2] Kim, J.-H., Ryu, D.-M., Park, S.-B., Noh, B.-J., Lee, J.-M.: A study of feasibility of using compressed wood for LNG cargo containment system. *Journal of the Korean Society of Marine Engineering* 40(4):307-313, 2016.

[3] Ehrich, K.: *Entwicklung eines Faser-Kunststoff-Verbund-Werkstoffs als Auflager für ein LNG-Tanksystem.* Dissertation, Universität Rostock, Rostock, Germany, 2017.

[4] Gerhards, C.C.: Effect of moisture content and temperature on the mechanical properties of wood: an analysis of immediate effects. *Wood and Fiber Science* 14(1):4-36, 1982.

[5] Özkan, O.: Effects of cryogenic temperature on some mechanical properties of beech (Fagus orientalis Lipsky) wood. *European Journal of Wood and Wood Products.* 79(2):417-421, 2021.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Morphogenetic Vectors in the Densification of Cellular Scaffolds

Alessia Ferrara*, Sophie Marie Koch† and Falk K. Wittel*†

* ETH Zürich, Institute for Building Materials
HIF, Laura-Hezner-Weg 7, 8093 Zürich, Switzerland
aferrara@student.ethz.ch

† sokoch@ethz.ch
*† fwittel@ethz.ch

ABSTRACT

The densification or compaction of cellular tissue is a practicable solution to extend the use of wood far beyond its native mechanical limitations of application. Examples range back centuries from shuttles in weaving looms to ship building, weaponry, bearings and supports to aircraft propellers or tonewood - all making use of increased density, stiffness, strength, wear resistance, or related properties. Compaction of wood is mainly achieved in radial or transverse direction by simultaneously applying pressure and heat beyond the glass transition temperature of lignin, to allow for non-destructive folding of the cellular scaffold. Recently, research on delignified softwood, resulting in cellulose scaffolds opened for chemical modification, fostered new possibilities for wood applications - also in combination with densification processes [1]. The other way around, it also opened up new technological perspectives to manipulate folding patterns during densification, and consequently the performance of the densified wood components, which are the core motivation for this numerical work.

Starting from real tissue sections of spruce wood, we study the evolution of the morphology of cellular folding patterns in computer simulations. It is our aim to numerically find control parameters for different densification protocols, namely quasi-static densification, quasi-static densification with superimposed transverse oscillatory excitation, vacuum densification, as well as shrinkage-induced self-densification. For this purpose, we apply explicit Finite Element Method (FEM) simulations with the ABAQUS software on cellular models, whose constitutive properties are calculated on the fly via a hierarchical multi-scale approach. Our work shows, that the chosen technological path for densification itself is of great importance for tailoring the resulting material behavior.

REFERENCES

[1] Keplinger, T., Wittel, F. K., Rüggeberg, M., Burgert, I., Wood Derived Cellulose Scaffolds—Processing and Mechanics. Adv. Mater. 2021, 33, 2001375. https://doi.org/10.1002/adma.202001375

PREDICTION OF THE THERMO-MECHANICAL PROPERTIES OF RADIATA PINE WOOD THROUGH AN ASYMPTOTIC HOMOGENISATION APPROACH

Carlos A. Rojas Vega*, Emanuela Bosco‡, Erick I. Saavedra Flores†, Carlos F. Guzmán†, Sergio J. Yanez†, Juan C. Pina†

* Department of Mechanical Engineering, Eindhoven University of Technology
Eindhoven 5600 MB, The Netherlands
c.a.rojas.vega@tue.nl & https://research.tue.nl/en/persons/carlos-rojas-vega

‡ Department of the Built Environment, Eindhoven University of Technology
Eindhoven 5600 MB, The Netherlands
e.bosco@tue-nl & https://www.tue.nl/en/research/researchers/emanuela-bosco/

† University of Santiago of Chile (USACH), Civil Engineering Department
Estación Central, Santiago, Chile
erick.saavedra@usach.cl & https://obrasciviles.usach.cl/academicos/erick-saavedra-flores/
cf.guzman@usach.cl & https://obrasciviles.usach.cl/academicos/carlos-felipe-guzman/
sergio.yanez.c@usach.cl & https://obrasciviles.usach.cl/academicos/juan-carlos-pina/
juan.carlos.pina@usach.cl & https://obrasciviles.usach.cl/academicos/ sergio-yanez-cart/

ABSTRACT

One of the main challenges faced by engineers during the design of timber buildings is the knowledge of wood's thermo-mechanical properties. Although, for several European and North American species these properties are frequently characterized and available, this is not necessary the case for wood grown elsewhere. Besides, wood's properties are highly dependent on the tree growth process, that varies based on the specie and location among other factors. Then, the direct use of properties available for example in European Standards is not always reliable. To circumvent this issue, in this work a multiscale modelling strategy based on asymptotic homogenisation is presented [1]. This approach enables incorporate the influence of wood's complex microstructure and large morphological variations present at the microstructural level, that lead to a wide scatter of the macroscopic properties. The model is based on the hierarchical nature of wood and incorporates the three material scales generally identified in softwoods i.e., the microfibril scale, the wood cell scale, and the growth ring scale. The effective thermomechanical macroscopic properties are estimated by sequentially applying the homogenisation procedure from the microfibril scale all the way up to the macroscopic scale. The model is used to investigate the thermo-mechanical response of radiata pine grown in Chile. To determine values of the microstructural parameters that generate macroscopic properties consistent with those observed experimentally, a parameter identification strategy was used. The latter considers four elements: an existing experimental database on timber boards density and bending tests, the multiscale model, a timber board bending test finite element model and a genetic algorithm for the optimization procedure. With the resulting microstructural parameters, the model is then used to estimate the effective elastic, thermal, and thermo-mechanical properties of radiata pine wood.

REFERENCES

[1] Rojas Vega, C., Pina, J.C., Bosco, E., Saavedra Flores, E.I., Guzmán, C.F. and Yanez, S.J., Thermo-mechanical analysis of wood through an asymptotic homogenisation approach. *Construction and Building Materials*, 125617, 2022.

FRACTURE

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

A brief overview on the development of research in the area of physical mechanical properties from solid wood and wood based materials

Peter Niemz*†

* ETH Zürich, Institute for Building Materials
Laura-Hezner-Weg 7, CH-8093 Zürich
niemzp@retired.ethz.ch

† Luleå University of Technology
Forskargatan 1, 931 87 S-Skellefteå, Sweden
peter.niemz@ltu.se

ABSTRACT

Wood science covers in particular the areas of the formation and composition as well as the chemical, biological and physical-mechanical properties of wood. First comprehensive studies have already been published in the last century. Detailed knowledge of wood is required for the processing of wood, the production of wood-based materials, and the utilization of wood and wood-based materials as buildings and various other products such as furniture. This review gives a brief overview on the physical-mechanical properties of wood and wood-based materials. These fundamentals are also essential for understanding technological processes and product development and especially also for the modeling. For modelling we need a lot of datas. In this aerea we have a lot of open questions.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

A Coupled Hygro-mechanical Phase-field Approach to Simulate Moisture-induced Fracture of Wood

Dennie Supriatna, Johannes Storm, Daniel Konopka and Michael Kaliske

Institute for Structural Analysis, Technische Universität Dresden
01062 Dresden, Germany
{dennie.supriatna, johannes.storm, daniel.konopka, michael.kaliske}@tu-dresden.de,
tu-dresden.de/isd

ABSTRACT

The three-dimensional simulation of anisotropic failure in wood, especially brittle fracture behaviour at tensile of shear load is very challenging. Several methods have been developed within the framework of the Finite Element Method (FEM) with different accuracy and computational costs. Whereas approaches like cohesive elements or so-called Extended Finite Element Method (XFEM) describe discrete cracks between or inside solid elements, phase-field is an energetic formulation that introduces further degrees of freedom to the damaged material phase.

This study presents a novel anisotropic multi-physically coupled phase-field approach and a numerical investigation of wood's brittle behaviour while considering water transport and modelling of moisture-induced cracking [3]. In addition to the mode-dependent feature of fracture resistance, which requires accurate crack kinematics and is developed in [2], a realistic multi-Fickean diffusion model, consisting of two phases, bound water and water vapour concentration, is adopted and developed to account for discontinuities such as crack. To derive water transport phenomena in the presence of the crack, the discontinuous Reynold's transport theorem is employed. Using this theorem, a hygro-mechanical Representative Crack Element based on [1] is developed to describe water transport and hygro-mechanical coupling for the fully-damaged state of the material. A continuous crack representation, i.e., an anisotropic phase-field approach accounting for mixed fracture mode is developed further to take hygro-mechanical coupling and water transport into account.

The example in Figure 1 shows the crack propagation induced by constrained shrinkage within a drying process at a plate with a single notch. The crack is initiated at the notch due to the tensile stress concentration and propagates along the wood fibre direction for this benchmark at 45° measured with respect to the e_1-axis. Moreover, the developed crack influences the diffusion behaviour by stopping the bound water transport, whereas the water vapour can pass the crack.

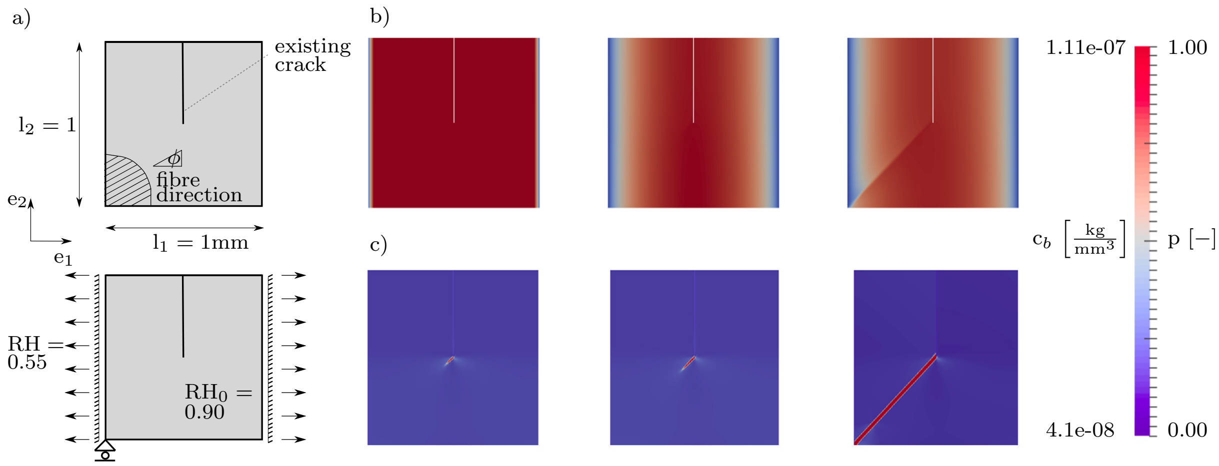


Figure 1: Single notch structure at drying process, a) geometry and mechanical and hygric boundary conditions, and characteristic results at selected states of b) bound water concentration c_b and c) crack propagation with phase-field parameter p.

REFERENCES

[1] Storm, J.; Yin, B.; Kaliske, M. The concept of Representative Crack Elements (RCE) for phase-field fracture: transient thermo-mechanics. *Computational Mechanics*, 399, pp. 1165–1176, 2022.

[2] Supriatna, D.; Yin, B.; Konopka, D.; Kaliske, M. An anisotropic phase-field approach accounting for mixed fracture modes in wood structures within the Representative Crack Element framework. *Engineering Fracture Mechanics*, 269, p. 108514, 2022.

[3] Supriatna, D.; Storm, J.; Konopka, D.; Yin, B.; Kaliske, M. Phase-field modelling of moisture-induced fracture of wood, in preparation.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

An anisotropic eigenfracture approach accounting for mixed mode fracture in wood structures within the Representative Crack Element framework

Marcel May*†, Daniel Konopka* and Michael Kaliske*

*Institute for Structural Analysis, TU Dresden
01062 Dresden
tu-dresden.de/bu/bauingenieurwesen/sdt
†marcel.may@tu-dresden.de

ABSTRACT

The FE-analysis of anisotropic fracture mechanical phenomena in wood remains a formidable task, particularly when dealing with intricate loading scenarios and mode-specific behavior. To enable simulation of fracture without a priori knowledge of the crack path, energetically motivated approaches are particularly appropriate. This work presents the promising eigenfracture method (EFM), which has shown good numerical performance and has not yet been applied to anisotropic materials such as wood [1]. A method is introduced to incorporate three-dimensional directional dependence of both elasticity and fracture evolution into EFM. Moreover, the model is constructed using the conceptual framework of the Representative Crack Element (RCE) approach, which permits accurate modeling of physical crack deformations, including opening, closing, shearing, and mixed mode deformations. The governing equations are systematically derived and implemented into the FE framework. In representative numerical examples, advantages are demonstrated over the well-known phase-field method (PFM). We provide a realistic ratio of the energy release rates parallel to and perpendicular to the fiber direction in order to achieve correct crack patterns, see Fig. 1. The computational effort is reduced, as the unknown variable required for determining the crack kinematics is already solved at material level, a feature that also enables parallelization.

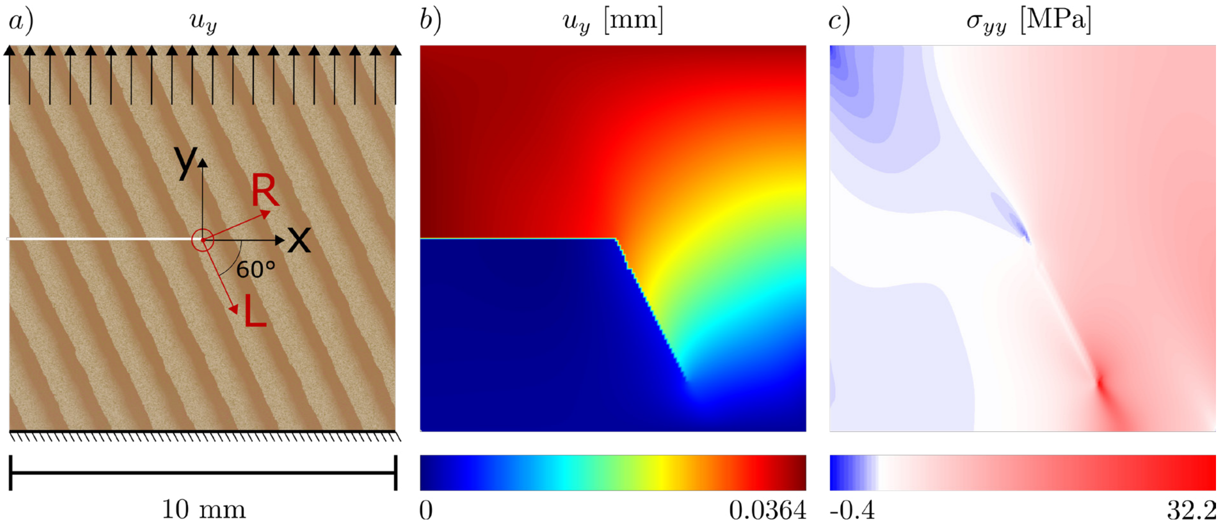


Figure 1: Quadratic Single Edged Notch Plate (t= 5 mm) with a) DIRICHLET boundary condition u_y and fibre direction (L=Longitudinal; R=Radial), b) resulting displacements u_y and c) stresses σ_{yy}.

REFERENCES

[1] May, M.; Konopka, D.; Kaliske, M. An anisotropic eigenfracture approach accounting for mixed mode fracture in wood structures within the Representative Crack Element framework. *Engineering Fracture Mechanics*, in preparation.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Phase field method-based modeling of fracture in wood

Sebastian Pech*, Markus Lukacevic* and Josef Füssl*

*TU Wien, Institute for Mechanics of Materials and Structures
Karlsplatz 13/202, A-1040 Vienna
sebastian.pech@tuwien.ac.at, markus.lukacevic@tuwien.ac.at, josef.fuessl@tuwien.ac.at

ABSTRACT

Wood, as a naturally grown material, exhibits an inhomogeneous material structure as well as a quite complex material behavior. For these reasons, the mechanical modeling of fracture processes in wood is a challenging task and requires a careful selection of numerical methods. To be competitive in high-performance fields of civil engineering, where traditionally concrete or steel was used, accurate failure simulation of wood is necessary. Promising approaches like limit analysis or the extended finite element method (XFEM) in combination with microstructure materials models deliver good but not yet satisfying results. Particularly the latter approach, including XFEM, has severe difficulties with crack paths in regions with complex morphology, mainly around knots. Therefore, in this work, the focus is laid on the recently emerging and very popular phase field method [1, 2, 6]. Especially geometric compatibility issues that limit the use of XFEM can be avoided, as the crack is not discretely modeled but smeared over multiple elements. This allows the formation of complex crack patterns, defined by the underlying differential equations and boundary conditions but not restricted by the mesh geometry. Additionally, through recent developments, the phase field method can be adapted to model cohesive behavior [3], multiple different damage mechanisms [7], proper crack driving forces in orthotropic materials [5] and the influence of the microstructure on the macroscopic crack orientation [4]. In this work, we combined and further enhanced those extensions to model wood fracture. The hybrid phase field model for orthotropic materials with favorable fracture planes and multiple failure mechanisms is presented in [9]. The model was validated in [8] on different test setups and showed a good agreement with experimental results.

The simulation of knot groups for predicting the tensile and bending strength of wooden boards is of great interest for using wood more efficiently. Due to the nature of the phase field method, it is easily applicable to three-dimensional problems, which allows the simulation of such knot groups, considering the strongly varying fiber orientations.

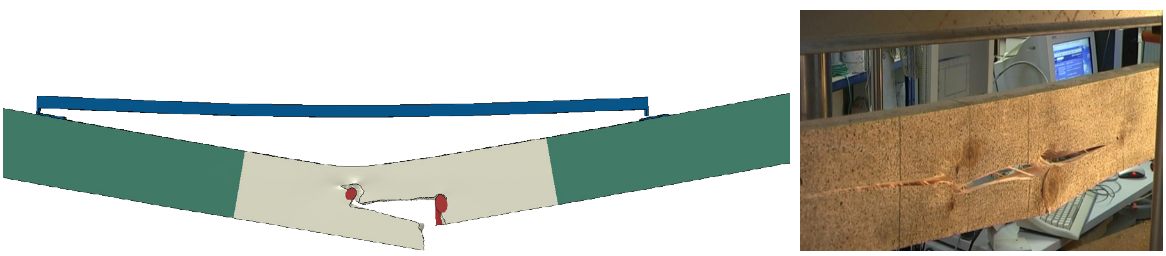


Figure 1: Crack pattern in a knot group in a four-point bending test.

Using the phase field method and computing the spatially varying fiber courses in a wooden board, it was possible to predict a crack path very similar to the experimentally observed (see Figure 1). The crack initiated in both cases at the lower knot. Subsequently, it propagated upwards and around the knot. At this point, in the model, only the horizontal crack along the fiber direction to the left emerged. Due to differences in the knot reconstruction, the influence of the knot or knot group in the upper left region is different in the model and leads to a different crack path. Nevertheless, important parts of the crack pattern for predicting the bending strength of the board are captured by the model. Compared to XFEM the simulation is much more robust and the complex crack topology could be modeled. Future research focuses on properly tuning the phase field model to predict experimental results of a wide range of different knot groups. Subsequently, the tuned model will be used to derive a metamodel, bypassing the computationally intensive phase field simulation and thus allowing the application of the model in larger scale simulations.

REFERENCES

[1] Francfort, G. A.; Marigo, J.-J. Revisiting Brittle Fracture as an Energy Minimization Problem. *J. Mech. Phys. Solids* 1998, 46 (8), 1319–1342.

[2] Bourdin, B.; Francfort, G. A.; Marigo, J.-J. Numerical Experiments in Revisited Brittle Fracture. *J. Mech. Phys. Solids* 2000, 48 (4), 797–826.

[3] Wu, J.-Y. A Unified Phase-Field Theory for the Mechanics of Damage and Quasi-Brittle Failure. *J. Mech. Phys. Solids* 2017, 103, 72–99.

[4] Teichtmeister, S.; Kienle, D.; Aldakheel, F.; Keip, M.-A. Phase Field Modeling of Fracture in Anisotropic Brittle Solids. *Int. J. Non Linear Mech.* 2017, 97, 1–21.

[5] Steinke, C.; Kaliske, M. A Phase-Field Crack Model Based on Directional Stress Decomposition. *Comput. Mech.* 2018, 1019–1046.

[6] Bourdin, B.; Francfort, G. A.; Marigo, J.-J. The Variational Approach to Fracture; *Springer-Verlag GmbH*, 2008.

[7] Bleyer, J.; Alessi, R. Phase-Field Modeling of Anisotropic Brittle Fracture Including Several Damage Mechanisms. *Comput. Methods Appl. Mech. Eng.* 2018, 336, 213–236.

[8] Pech, S.; Lukacevic, M.; Füssl, J. Validation of a Hybrid Multi-Phase Field Model for Fracture of Wood. *Eng. Frac. Mech.* 2022, 275, 108819.

[9] Pech, S.; Lukacevic, M.; Füssl, J. A Hybrid Multi-Phase Field Model to Describe Cohesive Failure in Orthotropic Materials, Assessed by Modeling Failure Mechanisms in Wood. *Eng. Frac. Mech.* 2022, 271, 108591.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Prediction of moisture gradients and related crack depths in wooden cross sections subjected to indoor climate conditions using a finite-element-based simulation approach

Florian Brandstätter*, Maximilian Autengruber*, Markus Lukacevic* and Josef Füssl*

* TU Wien, Institute for Mechanics of Materials and Structures
Karlsplatz 13, 1040 Vienna, Austria
www.imws.tuwien.ac.at

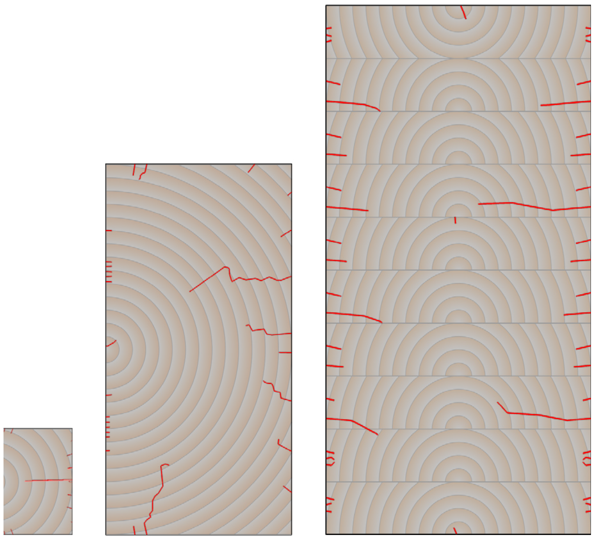
florian.brandstaetter@tuwien.ac.at; maximilian.autengruber@tuwien.ac.at; markus.lukacevic@tuwien.ac.at; josef.fuessl@tuwien.ac.at

ABSTRACT

Moisture significantly affects wood. Not only material parameters, such as density, strength and stiffness, depend on the moisture content (MC) but also changes in MC cause swelling and shrinking, as wood absorbs and desorbs moisture out of the air. Depending on the surrounding climate conditions, considerable differences in MC in the wood component can occur, resulting in large moisture gradients. Due to wood's orthotropic material behavior, swelling and shrinkage strains are constrained, leading to moisture-induced stresses, which can result in crack initiation and propagation.

About 50 % of the damages in large-span timber structures are related to high and low MC as well as MC changes, where almost half of the found damages were cracks [1]. However, little is known about the correlation between moisture gradients and specific damage characteristics, like crack depths. Based on finite element simulations, the crack depth development of two solid timber (ST) and one glued laminated timber (GLT) cross section over time for various relative humidity (RH) reductions and four initial MCs are investigated. To this end, moisture fields are determined based on a multi-Fickian transport model [2-7] in a first step. Subsequently, the moisture fields are used as loadings for linear elastic stress simulations, where an extended finite element approach enables the simulation of discrete cracking with a multisurface failure criterion [8] defining the failure behavior. Based on the simulation results (see Figure 1), correlations between moisture gradients and maximum crack depths in indoor climate conditions are derived, allowing the prediction of maximum crack depths.

In addition, the influence of the initial MC on crack depth development is investigated, illustrating the importance of the initial MC for the design timber structures. Furthermore, the effect of cross section size on crack depth evolution is analyzed. It is revealed that more significant moisture gradients occur in larger cross sections, and therefore, cracks are initiated earlier, and cracking tends to last longer. Finally, the influence of reducing RH linearly over time on crack growth is studied, showing that maximum crack depths in small cross sections can be reduced significantly while larger cross sections are less affected.



(a) ST 6 × 8 (b) ST 14 × 28 (c) GLT 20 × 40

Figure 1: Examples of the cross section dependent crack patterns at the end of the simulation for two solid timber (ST) and one glued laminated timber (GLT) cross sections. In addition, the pith location and the annual rings of the cross sections are illustrated.

REFERENCES

[1] Dietsch, P.; Gamper, A.; Merk, M.; Winter, S. Monitoring building climate and timber moisture gradient in large-span timber structures. Journal of Civil Structural Health Monitoring 5(2):153–165, 2015.

[2] Eitelberger, J.; Hofstetter, K.; Dvinskikh, S. A multi-scale approach for simulation of transient moisture transport processes in wood below the fiber saturation point. Composites Science and Technology 71(15): 1727–1738, 2011.

[3] Fortino, S:; Genoese, A.; Genoese, A.; Numerical modelling of the hygro-thermal response of timber bridges during their service life: A monitoring case-study. Construction and Building Materials 47:1225–1234, 2013.

[4] Fortino, S.; Hradil, P.; Genoese, A. Numerical hygro-thermal analysis of coated wooden bridge members exposed to northern european climates. Construction and Building Materials 208:492–505, 2019.

[5] Frandsen, H.L.; Damkilde, L.; Svensson, S. A revised multi-fickian moisture transport model to describe non-fickian effects in wood. Holzforschung 61:563–572, 2007.

[6] Konopka, D.; Kaliske, M. Transient multi-fickian hygro-mechanical analysis of wood. Computers & Structures 197:12–27, 2018.

[7] Krabbenhøft, K.; Damkilde, L. A model for non-fickian moisture transfer in wood. Materials and Structures 37(9):615–622, 2004.

[8] Lukacevic, M.; Lederer, W.; Füssl, J. A microstructure-based multisurface failure criterion for the description of brittle and ductile failure mechanisms of clear-wood. Engineering Fracture Mechanics 176:83–99, 2017.

MICROSCALE AND HOMOGENISATION

3[rd] ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

A multi-physics finite strain model for the coupled hygro-viscoelastic behavior of the wood cell wall

Raúl Lazo-Molina and Carlos Felipe Guzmán

University of Santiago of Chile (USACH), Civil Engineering Department
cf.guzman@usach.cl
https://linktr.ee/cf.guzman

ABSTRACT

This work presents a multi-physics numerical model for the S2 layer of the wood cell wall, which is treated as a nanocomposite matrix-fiber material, formulated within the large deformations regime. The matrix is considered as a polymeric gel composed of hemicellulose, lignin, and water molecules that is reinforced with cellulose fibrils, as shown in Figure 1. The model accounts for the hygro-expansion and mechano-sorptive effects, which are the result of the volumetric expansion due to the diffusion of water molecules through the amorphous polymeric network, and the coupling of moisture content with the viscoelasticity caused by mechanical stresses, respectively. The mechanical contribution of the cellulose fibrils is also included, accounting for the elastic behavior of the crystallized cellulose and the viscoelastic behavior of the amorphous cellulose. The model is based on a generalized Maxwell rheological model where the swelling phenomenon is coupled with viscoelastic dashpot elements. The change in material stiffness due to moisture, and the diffusion restriction imposed by the cellulose fibrils, are also considered. The model is numerically implemented using FEniCS, a free software that allows to solve variational problems through the finite element method by means of symbolic programming.

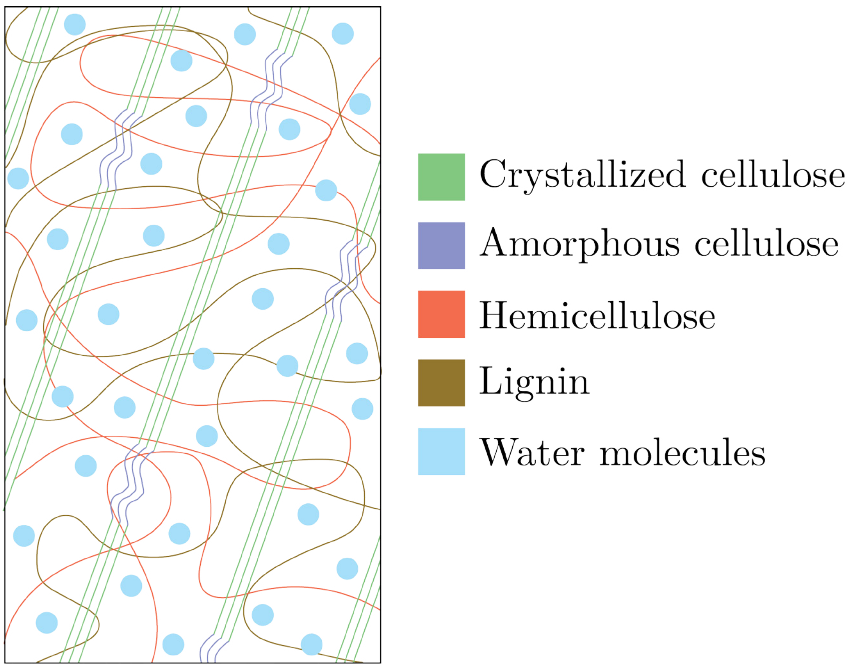


Figure 1: Wood cell wall composite.

Characterization of mechanical properties of five hot-pressed lignins extracted from different feedstocks by micromechanics-guided nanoindentation

Michael SCHWAIGHOFER*, Luis ZELAYA-LAINEZ*, Markus KÖNIGSBERGER*, Markus LUKACEVIC*, Sebastián SERNA-LOAIZA†, Michael HARASEK†, Anton FRIEDL†, Olaf LAHAYNE*, Valentin SENK*, Josef Füssl*

* TU Wien
Karlsplatz 13/202 1040 Vienna, Austria
E-mail: michael.schwaighofer@tuwien.ac.at
URL: https://www.imws.tuwien.ac.at/home/

† TU Wien
Getreidemarkt 9/166, 1060 Vienna, Austria
URL: https://www.tuwien.at/tch/icebe

ABSTRACT

Lignin is a major component of wood and the second most common organic natural material on the planet [1]. The increasing need for renewable and sustainable materials is the motivation to find new ways to use technical lignins, e.g., as a matrix in bio-composites. However, to model such bio-composites, it is essential to reliably identify the mechanical properties of lignin [2], which are so far not well known. Furthermore, technical lignins extracted from lignocellulosic materials show chemical differences in composition, size, cross-linking, and functional groups due to differences in raw material and isolation methods (pulping process and further isolation and purification methods) [3]. Therefore, five hot-pressed lignins, obtained with different extraction processes from different feedstocks, are tested with microscopy-aided grid nanoindentation.

Five technical lignins extracted from hardwood (HW), softwood (SW), and grass (G) using enzyme hydrolysis (E), organosolv (OS), and kraft pulping (K) were pressed into discs at 90 °C under a pressure of 108 MPa. The lignin discs were embedded into a 2-component resin and attached to a microscope slide. The surfaces of the samples were smoothed by means of a rotating diamond head attached to an ultra-milling-sectioning system. Displacement-controlled grid nanoindentation tests were performed on the specimens with a diamond Berkovic tip and maximum indentation depths ranging from 150 nm to 1200 nm. The indentation modulus is evaluated with the Oliver-Pharr [4] method from the measured force-

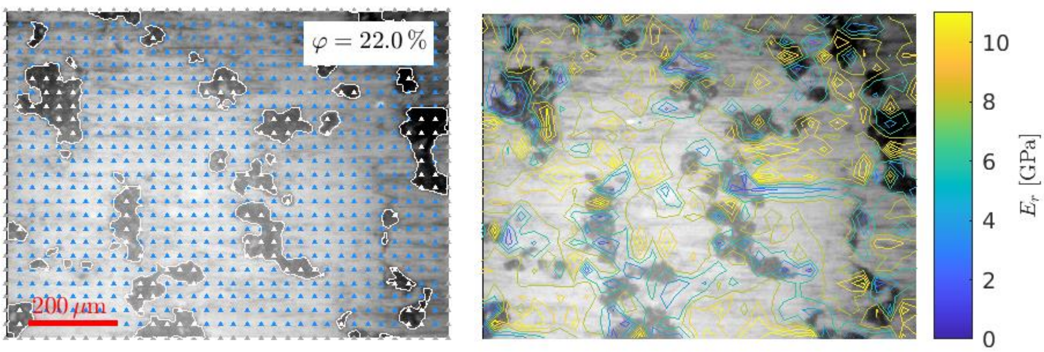


Figure 1: Light microscopy image of the probed area of OS-HW: left figure including the identified pores (dark gray áreas with white borders) and a map of the indents in the pores (white triangles) as well as the indents used for evaluation (blue triangles); right figure including a contour map of the indentation modulus [5]

displacement curve.

Hot-pressing introduced a porous microstructure into the lignin specimens. Therefore, we mapped the indents onto the light microscopy image of the indented area, see Fig.1. This allowed us to exclude the indents in the pores and correlate the indentation properties with the minimum distance of the indents to the closest surface pore. The correlation revealed that the indents "feel" the pores, i.e., a lignin-pore composite is tested rather than the sought pure lignin. Further statistical evaluation of the nanoindentation results at indentation depths ranging from 150 nm to 1200 nm allowed for retrieving reliable mechanical properties of the porous lignin, free of indentation size effects.

The obtained mechanical properties strongly correlate with the porosity of the lignin specimens, see Fig.2 for the indentation modulus E^r. This relationship can be described very well with the Mori-Tanaka homogenization scheme in the framework of continuum micromechanics. With the micromechanics fit, we back-calculated the stiffness of "solid" lignin free of any pore influence, resulting in a Young's modulus of 7.1 GPa [5]. The excellent fit between the micromechanics model and the measured indentation modulus confirms that the solid lignin's indentation modulus is similar for all five lignins and independent of the extraction process and feedstock.

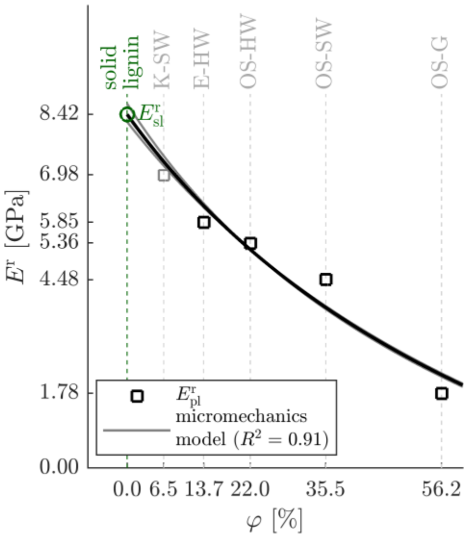


Figure 2: Porosity-dependent indentation moduli of porous and solid lignin: nanoindentation-derived average size independent moduli (square points) compared to best-fit Mori-Tanaka homogenization, which predicts, at zero porosity the indentation modulus of solid lignin [5]

REFERENCES

[1] Windeisen E. and Wegener G. *Lignin as Building Unit for Polymers*. In *Polymer Science: A Comprehensive Reference*; Elsevier, 2012.

[2] Königsberger, M., Lukacevic, M. & Füssl, J. Multiscale micromechanics modeling of plant fibers: upscaling of stiffness and elastic limits from cellulose nanofibrils to technical fibers. *Mater Struct* 56, 13 (2023). https://doi.org/10.1617/s11527-022-02097-2

[3] Gosselink R. J., Snijder M. H., Kranenbarg A., Keijsers E. R., De Jong E., and Stigsson L. L. Characterisation and application of NovaFiber lignin. *Ind Crop Prod*, 2004, 20(2), 191–203

[4] Oliver W. and Pharr G. An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments. *J Mater Res*, 1992, 7(6), 1564-1583

[5] Schwaighofer, M., Zelaya-Lainez, L., Königsberger, M., Lukacevic, M., Serna-Loaiza, S., Harasek, M., Lahayne, O., Senk, V., and Füssl, J. Characterization of mechanical properties of five hot-pressed lignins extracted from different feedstocks by microscopy-aided nanoindentation. *Materials & Design*, (2023) https://doi.org/10.1016/j.matdes.2023.111765

CHARACTERIZING THE INTERACTION BETWEEN PAPER FIBERS BASED ON EXPERIMENTAL AND NUMERICAL TESTS

Greta Kloppenburg*, Caterina Czibula†, Elisabeth Walther*, Johannes Neumann*, Ulrich Hirn†, Jaan-Willem Simon*

* Civil Engineering Mechanics,
University of Wuppertal, Germany
kloppenburg/ewalther/joneumann/jaan.simon@uni-wuppertal.de

† Institute of Bioproducts and Paper Technology,
TU Graz, Austria
caterina.czibula/ulrich.hirn@tugraz.at

ABSTRACT

In recent decades, there has been a remarkable increase in the demand for renewable and recyclable materials. One of these materials having a small ecological impact is paper or paperboard. In order to expand its range of applications, it is essential to understand the microstructural mechanisms responsible for the structural properties of paper. A powerful tool for investigating these microstructural characteristics are numerical fiber network models. Therefore, the long-term goal is to improve existing realistic microstructural network models of paper and paperboard [2], including plasticity and damage. In this work, paper fiber bonding behavior is examined utilizing real and virtual experiments since suitable parameters for microscale models cannot be obtained from macroscale experiments. At the macroscale, it is difficult to impossible to separate the different mechanisms like single fiber elasticity, plasticity and damage from network effects. Hence, we strive to determine (i) contact stresses between individual fibers by numerical models and (ii) parameters for a cohesive contact formulation.

While cellulose fibers obtained from wood are the base material for virtually all types of paper, different manufacturing processes and compositions lead to drastic differences in paper quality and mechanical properties. Individual fibers hold together without glue or adhesive, but through intermolecular and mechanical bonding mechanisms [1]. Together, they form a network that has remarkable strength, which can be observed in the various applications of paper and paperboard. The properties of this network depend, on the one hand, on the fibers themselves and, on the other hand, on the bonding between fibers.

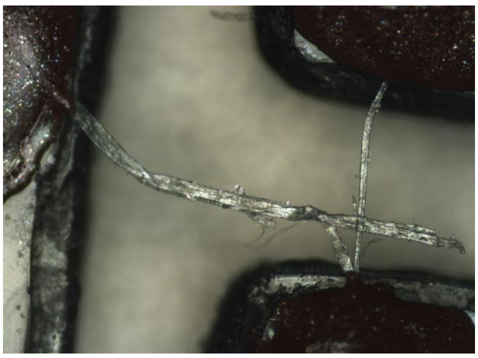


Figure 1 Experimental setup: Fiber cross fixed onto sample holder using nail polish. The horizontal fiber is fixed on the loaded end, and the cross fiber is glued on both ends.

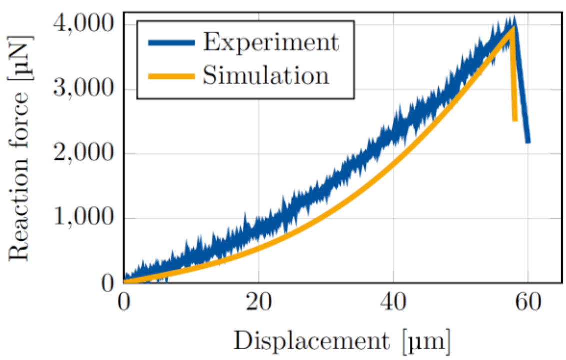


Figure 2 Force-displacement curve of one experimental and numerical fiber cross test

To analyze the fiber-fiber interaction independent of other network characteristics, we prepared artificial fiber crosses based on the papermaking process from a suspension of water and fibers without adhesives, ensuring realistic bonding properties. These fiber bonds contained only two fibers per sample. One fiber was glued to a specimen holder at both ends. The other fiber, which was glued only at the loaded end, was pulled on in fiber direction using a Dynamic Mechanical Analysis instrument, see Figure 1. An example of the recorded reaction force vs. displacement is depicted in Figure 2.

This motion introduced a shear load into the bond, which is also known as mode II loading. Mode I (normal) and mode II (shear) experiments are well established in the field of fiber-reinforced plastics to characterize the contact behavior between components, as intended in this work.

Due to the small dimensions of the fibers, it is not possible to determine contact surface forces between the fibers in experiments. The use of numerical models can overcome this issue. It is also possible to determine contact forces and to analyze influences of different geometric or material properties on the bonding behavior. Therefore, the experimental results were transferred into numerical finite element models. The modeled fiber crosses had the same geometry as the fibers in the experiments, and the contact areas were also the same.

The interaction between the fibers was prescribed by a mixed-mode cohesive contact formulation, which described the damage propagation between the surfaces with a traction-separation law considering both, mode I and mode II loadings, within the contact area. This was necessary because even when a shear load was applied externally, some small rotations of the fixed fiber introduced normal forces within the bond. In the simulation, the experimental displacements were applied and the separation points were targeted (see Figure 2). In consequence, the cohesive contact parameters could be determined. These were contact stiffness, damage onset traction, and fracture energy in both normal and shear directions, as well as the B-K parameter [3], which influences the mode mix. As a result, a series of contact parameter sets could be identified from several fiber cross tests.

This work improves the understanding about microstructural mechanisms of paper, as fiber-fiber interaction is decisive for the behavior of an entire fiber network. Moreover, providing realistic contact parameters helps to increase the representativeness of numerical paper fiber network models. This makes it an even more valuable tool for finding the optimal paper composition and to describe the overall structural behavior of paper.

REFERENCES

[1] Hirn, U., Schennach, R. Comprehensive analysis of individual pulp fiber bonds quantifies the mechanisms of fiber bonding in paper. *Scientific Reports* 5, 10503, 2015

[2] Li, Y., Yu, Z., Reese, S., Simon, J.-W. Evaluation of the out-of-plane response of fiber networks with a representative volume element model. *Tappi Journal* 17, pp. 329-339, 2018

[3] Benzeggagh, M. L., Kenane, M. Measurement of Mixed-Mode Delamination Fracture Toughness of Unidirectional Glass/Epoxy Composites with Mixed-Mode Bending Apparatus. *Composites Science and Technology* 56, pp. 439–449, 1996

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Rheological Study of Wood at Tissue Scale

Alessia Ferrara* and Falk K. Wittel*†

* ETH Zürich, Dep. of Civil, Env. and Geomatic Eng.
HIF E 27, Laura-Hezner-Weg 7, 8093 Zürich, Switzerland
aferrara@student.ethz.ch

*† fwittel@ethz.ch

ABSTRACT

Wood's sophisticated hierarchical structure results in a complicated behavior with strongly oriented properties in its three anatomical directions. This makes a full understanding of the long-term hygro-mechanical behavior still difficult and challenging. The hierarchical structure plays a fundamental role in the macroscopic behavior originating from the features characterizing the lower scale. We focus on the tissue scale to understand the relation between the bulk wood and the constituents' organization of the cell wall. For this purpose, we propose an advanced cellular model that reproduces the rheological behavior of wood tissue and, concurrently, present results of an experimental campaign conducted on tissue samples of Norway spruce (*Picea abies*).

We implement a 3D Finite Element model that comprises the orthotropic hygro-elastic and visco-elastic deformations as additive components of the total strain. The fibers' arrangement is approximated as a honeycomb with hexagonal cells of varying morphology, depending on the position inside a growth ring. A rheological model for the macroscopic continuum is adapted to the multi-layered cell wall scale within the framework of linear viscoelasticity. The material properties set for each composite layer concur to define the properties of the cell wall and, in turn, the tissue overall behavior. We investigate the influence of microstructural variations on the resulting wood performance through several numerical simulations under different combinations of mechanical and hygral load.

Our experimental campaign includes tensile and shear creep experiments at constant moisture content at different loading degrees and levels of relative humidity. Thin sections are taken at different positions and orientations, i.e. earlywood and latewood, as well as alternating growth ring tissues. The results of the experimental campaign are confronted with the simulation results to complement the understanding of the role of different tissue types in the macro-scale rheological behavior of wood.

REFERENCES

[1] D. F. Mora Mendez et al. "Mechanical behavior of chemically modified Norway spruce: a generic hierarchical model for wood modifications". Wood Science and Technology 53.2 (2019), 447–467.

[2] K. Persson. "Micromechanical modelling of wood and fibre properties", PhD Thesis, Lund University (2000).

MOISTURE INFLUENCE AND NONLINEARITY

A Fiber Bundle Model for Wood Mechanosorption

Júlio O. Amando de Barros* and Falk K. Wittel†

* ETH Zürich, Institute for Building Materials
HIF E 27, Laura-Hezner-Weg 7, 8093 Zürich, Switzerland
jortiz@ethz.ch

† fwittel@ethz.ch

ABSTRACT

The long-term mechanical response of wood under moisture and load variations, the so-called mechanosorption, is a difficult, yet not fully understood deformation mechanism. The combination of sparse experimental data and of purely empirical models results in a diffuse phenomenological understanding, even though the topic is of increasing interest due to the technological progress in timber engineering. We propose a physical, anatomical-motivated model that can successfully reproduce the mechanosorptive data of wood on different scales.

We formulate a Fiber Bundle Model (FBM), that is based on the FBM with stick-slip dynamics developed by Halász and Kun (2009). We propose a number of changes and extensions to the model, such as varying slip thresholds, moisture-dependent compliance, and hygro-expansion. When a fiber slips, we make global and local adaptations. While the load of the slipping fiber is globally redistributed, we give the possibility for a local reduction of slip thresholds of the nearest next neighboring fibers. This extension is motivated by an interpretation of inter-fiber stress transfer as the collaborative effort of hydrogen bonds that will reform after a slip but not as perfect as in the initial configuration. To recover frozen strains, reverse slips are introduced.

We explore the parameter space of our model and the effect of fundamental assumptions on the resulting system response for a given moisture and load history. We give reasonable assumptions for the parameter ranges and demonstrate that our model simulations can reproduce all observed phenomena of hygro-mechanic interactions of wood. However, the choice of parameters depends on the interpretation of the model with respect to scale, whether one considers macroscopic or single fiber tests or even isolated S2 cell way layer behavior. We believe, that our model can foster new ideas and contribute to discussions on the phenomena of mechanosorption in wood, considering its hierarchical nature.

REFERENCES

[1] Halász, Z.; Kun, F.: Fiber bundle model with stick-slip dynamics,. In: *Physical Review E 80* 027102, 2009.

CONSTITUTIVE UPDATE TO PREDICT THE NON-LINEAR BEHAVIOR OF WOOD, BASED ON A CONNECTION BETWEEN THE JACOBIAN EXPLICIT AND THE DEFORMATION GRADIENT

Roberto Quinteros-Mayne*, Ignacio de Arteaga Jorda*†, José Manuel Cabrero*•

* Universidad de Navarra, Departament of Building Construction, Services and Structures, 31009 Pamplona
Roberto.quinteros@pucv.cl ,† Iarteaga@unav.es, •Jcabrero@unav.es

ABSTRACT

Wood, as a natural growth material, is characterized by exhibiting a heterogeneous and highly anisotropic structure, making its study difficult [1-4]. Given such complexity in its geometric domain, its mechanical response is strongly non-linear, which makes necessary advanced numerical tools to predict its mechanical behavior under different load conditions [5]. To date, many constitutive models with different scale lengths have been developed to generate responses, and with them predict the non-linear behavior of wood [6-10]. Nevertheless, the application of the nonlinear framework is limited due to its high computational costs and numerical difficulties [11].

This study presents a constitutive model that predicts the nonlinear behavior of wood with a low computational cost and reduced numerical difficulty through an updated algorithm based on the Jacobian plastic multiplier, the relative Green-Lagrange strain and the deformation gradient [12,13]. To that end, an explicit integration expression is derived from the plastic multiplier and the consistent tangent operator, making both variables dependent on the stress state, normal vector and interal parameters from the previous step [14-16]. In this way, the reference configuration frame is obtained indirectly from the Jacobian and the plastic multiplier, as well as the deformation gradient.

A yield surface of general orthotropic plasticity with strain hardening is used, incorporating plastic flow through the Tsai-Hill yield function [17,19], valid for compression boundary conditions such as tension.

The connection between the Jacobian and the deformation gradient allows for a reduction in the calculation time, given that the elasticity range, like the plasticity range, depends on the proposed integration scheme which does not require iterative processes when the analysis is quasi-static. In the case of a dynamic analysis, very large steps can be used without loss of convergence in the Newthon-Raphson process.

The financial support provided by the Spanish Ministerio de Ciencia e Innovación and FondoEuropeo de Desarrollo Regional under contract PID2020-118569GB-C21 MINECO/FEDER UE is gratefully acknowledged.

REFERENCES

[1] Voichita Bucur, Patrick N.J. Rasolofosaon, Dynamic elastic anisotropy and nonlinearity in wood and rock, Ultrasonics, Volume 36, Issue 7, 1998,Pages 813-824, ISSN 0041-624X, https://doi.org/10.1016/S0041-624X(98)00004-3.

[2] Kirsten M.Ø. Jensen, Esther Rani Aluri, Enrique Sanchez Perez, Gavin B.M. Vaughan, Marco Di Michel, Eleanor J. Schofield, Simon J.L. Billinge, Serena A. Cussen, Location and characterization of heterogeneous phases within Mary Rose wood, Matter, 2021, ISSN 2590-2385, https://doi.org/10.1016/j.matt.2021.09.026.

[3] Stefan Holmberg, Kent Persson, Hans Petersson, Nonlinear mechanical behaviour and analysis of wood and fibre materials, Computers & Structures, Volume 72, Issues 4–5,

1999, Pages 459-480, ISSN 0045-7949, https://doi.org/10.1016/S0045-7949(98)00331-9.

[4] Jan Niklas Fuhg, Christoph Böhm, Nikolaos Bouklas, Amelie Fau, Peter Wriggers, Michele Marino, Model-data-driven constitutive responses: Application to a multiscale computational framework, International Journal of Engineering Science, Volume 167, 2021, 103522, ISSN 0020-7225, https://doi.org/10.1016/j.ijengsci.2021.103522.

[5] Füssl, J., Li, M., Lukacevic, M., Eberhardsteiner, J., & Martin, C. M. (2017). Comparison of unit cell-based computational methods for predicting the strength of wood. Engineering Structures, 141, 427-443, https://doi.org/10.1016/j.engstruct.2017.03.005

[6] B. Iraola, J.M. Cabrero, An algorithm to model wood accounting for different tension and compression elastic and failure behaviors, Engineering Structures, Volume 117, 2016, Pages 332-343, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2016.03.021.

[7] M. Gharib, A. Hassanieh, H. Valipour, M.A. Bradford, Three-dimensional constitutive modelling of arbitrarily orientated timber based on continuum damage mechanics, Finite Elements in Analysis and Design, Volume 135, 2017, Pages 79-90, ISSN 0168-874X, https://doi.org/10.1016/j.finel.2017.07.008.

[8] E. Benvenuti, N. Orlando, C. Gebhardt, M. Kaliske, An orthotropic multi-surface damage-plasticity FE-formulation for wood: Part I – Constitutive model, Computers & Structures, Volume 240, 2020, 106350, ISSN 0045-7949, https://doi.org/10.1016/j.compstruc.2020.106350

[9] Henrik Danielsson, Per Johan Gustafsson, A three-dimensional plasticity model for perpendicular to grain cohesive fracture in wood, Engineering Fracture Mechanics, Volume 98, 2013, Pages 137-152, ISSN 0013-7944, https://doi.org/10.1016/j.engfracmech.2012.12.008.

[10] Guindos, P., Guaita, M. Un modelo tridimensional de material de madera para simular el comportamiento de la madera con cualquier tipo de nudo a macroescala. Wood Sci Technol 47, 585–599 (2013), https://doi.org/10.1007/s00226-012-0517-4

[11] Fuhg, J. N., Böhm, C., Bouklas, N., Fau, A., Wriggers, P., & Marino, M. (2021). Model-data-driven constitutive responses: application to a multiscale computational framework. International Journal of Engineering Science, 167, 103522, https://doi.org/10.1016/j.ijengsci.2021.103522.

[12] Areias, P., Jorge, R. N., de Sá, J. C., Rabczuk, T., & Reinoso, J. (2018). General constitutive updating for finite strain formulations based on assumed strains and the Jacobian. Finite Elements in Analysis and Design, 143, 32-45, https://doi.org/10.1016/j.finel.2018.01.006.

[13] Tomaš, I., Cisilino, A. P., & Frontini, P. M. (2015). Una implementación implícita del modelo viscoplástico de Arruda-Boyce. Revista Internacional de Métodos Numéricos para Cálculo y Diseño en Ingeniería, 31(3), 171-181, https://doi.org/10.1016/j.rimni.2014.06.001.

[14] Simo, J. C., & Hughes, T. J. (2006). Computational inelasticity (Vol. 7). Springer Science & Business Media.

[15] de Souza Neto, E. A., Peric, D., & Owen, D. R. (2011). Computational methods for plasticity: theory and applications. John Wiley & Sons.

[16] Dunne, F., & Petrinic, N. (2005). Introduction to computational plasticity. OUP Oxford.

[17] Sirumbal-Zapata, L. F., Málaga-Chuquitaype, C., & Elghazouli, A. Y. (2018). A three-dimensional plasticity-damage constitutive model for timber under cyclic loads. Computers & Structures, 195, 47-63, https://doi.org/10.1016/j.compstruc.2017.09.010.

[18] Oudjene, M., & Khelifa, M. (2009). Elasto-plastic constitutive law for wood behaviour under compressive loadings. Construction and Building Materials, 23(11), 3359-3366, https://doi.org/ 10.1016/j.conbuildmat.2009.06.034

[19] Khelifa, M., Oudjene, M., & Khennane, A. (2007). Fracture in sheet metal forming: Effect of ductile damage evolution. Computers & Structures, 85(3-4), 205-212, https://doi.org/ 10.1016/j.compstruc.2006.08.053

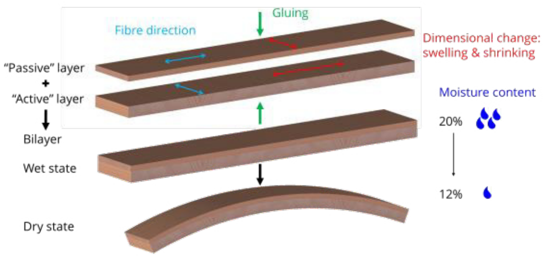
Wood actuation: A smart way of utilizing dimensional instability

Markus Rüggeberg*

*TU Dresden, Institute of Forest Utilization and Forest Technique
Pienner Str. 19, 01737 Tharandt, Germany
Markus.rueggeberg@tu-dresden.de

ABSTRACT

The swelling and shrinking of wood is commonly regarded as a challenge and limiting factor in the utilization of wood. However, it can also be seen as a material inherent capacity for generating movements when used in a smart way. By manufacturing wooden bilayers with differential fiber orientation in the two layers (Fig. 1a), one obtains humidity driven actuators as well as curved elements by an innovative self-forming process rather than with heavy machinery and large external forces.

a) 

b) 
c) 

Fig.1(a) Manufacturing of wood bilayers (graphic courtesy of P. Grönquist; b) The Urbach Tower, which consists of self-formed wood bilayer elements; c) self-formed chair conisting of two bilayer elements (b & c: ©Institute of Computational Design and Construction, University of Stuttgart)

We could demonstrate that the swelling and shrinking of wood can be transformed into shape changes of wood bilayers [1]. The nature and magnitude of shape changes can be predicted and programmed into the material by controlling fibre orientation, geometrical parameters and moisture content [1-3]. However, the inherent inhomogeneity of wood, the variability of material properties, and the complex behaviour limits the precision of the simulations for predicting the shape change. Interestingly, the prediction works much better for beech than for spruce. Upscaling to meter scale has successfully been proven by the manufacturing of self-formed curved cross-laminated timber for the Urbach Tower (Fig. 1b) [4]. Next to computational possibilities and challenges, I will present further applications such as autonomous shading systems [5], self-forming furniture (Fig. 1c) and self-forming wood pipes.

REFERENCES

[1] Rüggeberg, M.; Burgert, I. (2015): Bio-Inspired Wooden Actuators for Large Scale Applications. Plos One 10 (4).

[2] Grönquist, P.; Wood, D.; Hassani, M M.; Wittel, F. K.; Menges, A.; Rüggeberg, M. (2019): Analysis of hygroscopic self-shaping wood at large scale for curved mass timber structures. Sci Adv 5 (9), eaax1311.

[3] Hassani, M. M.; Wittel, F. K.; Hering, S.; Herrmann, H. J. (2015): Rheological model for wood. Computer Methods in Applied Mechanics and Engineering 283, S. 1032–1060.

[4] Wood, D.; Grönquist, P.; Bechert, S.; Aldinger, L.; Riggenbach, D.; Lehmann, K. et al. (2020): From Machine Control to Material Programming: Self-shaping wood manufacturing of a high performance curved CLT structure – Urbach Tower. In: Jane Burry, Jenny Sabin, Bob Sheil und Marilena Skavara (Hg.): Fabricate 2020. Making resilient architecture. London: UCL Press, S. 50–57. Roe, R. Deforest, S. Jamshidi, *Mathematics and Sustainability.* Texts for Quantitative Critical Thinking. Springer, Cham, 2018

[5] Vailati, C.; Bachtiar, E. V.; Hass, P.; Burgert, I.; Rüggeberg, M. (2018): An autonomous shading system based on coupled bilayer elements. Energy and Buildings 158, S. 1013–1022.

PHYSICAL PROPERTIES

Advanced numerical method for the modelling of beech lamellas based on local material properties

Franziska Seeber*, Ani Khaloian Sarnaghi*, Jan-Willem van de Kuilen*†

* Technical University of Munich, School of Engineering and Design,
Winzererstraße 45, 80797 Munich, Germany.

† Delft University of Technology, Faculty of Civil Engineering and Geosciences
Delft, Netherlands.

ABSTRACT

The computational accuracy of wood highly depends on the accuracy of the developed model, inter alia due to its anisotropy and heterogeneity. Since the share of European beech (*Fagus sylvatica* F.) in central European forests increased in the last decades, research interests on this specific wood species increased consequently [1]. Material properties of this species are varying locally and do scatter more than those of softwood species as e.g. spruce. Therefore, by refinement of the models on one side and considering the computational efficiency on the other, the prediction of strength can be enhanced and might build a step towards the development of high strength timber products.

This research focuses on numerical simulations, considering the local scatter of material properties by using the physically measured local fiber directions on the surface of boards. By means of numerical simulations, a model has been introduced for virtual strength prediction, where local material properties were integrated from the laser-scan data [2]. This model is further extended here to consider local fiber directions, pith location, and a variable knot stiffness. As a benchmark case, validations tests for 1) sufficiently covering various heterogeneities and 2) scattering material properties of European Beech have been performed under bending, where the displacements have been measured by means of Digital Image Correlation (DIC). In this way, the numerical models have been validated not only within the elastic range, but also in the nonlinear ductile range, as well as its damage initiation criteria. The numerical analysis of the damaging behaviour of the quasi-brittle material under tension provides a deeper insight for strength prediction, besides describing the scatter of the material within statistical evaluation. Therefore, the presented approach may provide a detailed model for prediction of strength and may initiate a step towards numerical damage and failure analysis for engineering wood products.

Corresponding author: Franziska Seeber, seeber@hfm.tum.de

REFERENCES

[1] Rais, A., Bacher, M., Khaloian-Sarnaghi, A., Zeilhofer, M., Kovryga, A., Fontanini, F., Hilmers, T., Westermayr, M., Jacobs, M., Pretzsch, H., van de Kuilen, J.W., Local 2D fibre orientation for tensile strength prediction of European beech timber. In *Contruction and Building Materials*, Vol. 279, 2021.

[2] Seeber, F., Khaloian-Sarnaghi, A., Rais, A., & van de Kuilen, J.W. A numerical strength prediction approach for wood using element-wise local fiber directions form laser scanning. In *Materials & Design,* 2023.

Comparison of timber local moduli of elasticity under axial and bending loading, obtained by classical beam theory and finite element modelling

G. Pot*, R. Duriot†, S. Girardon*, J. Viguier*, L. Denaud*

* Arts et Métiers Institute of Technology, LaBoMaP, UBFC, HESAM
F-71250 Cluny, France
guillaume.pot@ensam.eu, stephane.girardon@ensam.eu, joffrey.viguier@ensam.eu, louis.denaud@ensam.eu

† Université de Lorraine, LERMAB
F-88000 Epinal, France

ABSTRACT

Timber mechanical properties assessment relies on grading methods that use non-destructive measurements in input. Fibre orientation is such an input that can be obtained by existing sawn timber industrial scanners. Several models exist in the literature to use fibre orientation data as an indicating property of timber mechanical properties. Jehl *et al.* [1,2] and Olsson *et al.* [3] proposed to use the of fibre orientation in analytical models based on classical beam theory (BT), which was used for modelling both bending and tension loading of sawn boards [4-5]. Finite element (FE) models based on fibre orientation data were developed later [6,7]. In particular, Lukacevic *et al.* [7] used the grain-flow analogy of Foley's work [8] to obtain the fibre orientation around knots.

3D FE modelling is expected to be more representative of the mechanical behaviour of timber, in particular in knotty areas with large fibre deviations, because it allows considering the complexity of the phenomena happening in such a heterogeneous area. However, analytical models still are useful since they can be computed in a very short amount of time, which is interesting in the context of wood quality assessment by machines at industrial speeds. Thus, it is useful to understand the reasons for the differences in stiffness between FE and BT mechanical modelling, which is the objective of this work.

For this purpose, artificial beams were modelled for various knot positions in the longitudinal-tangential plane, by considering the surrounding fibre deviations obtained with the grain-flow analogy method (see example Fig. 1). BT and FE models were built from it, and their deformations under 4-point bending and tensile loading were obtained. The local modulus of elasticity as defined in EN 408 standard [9] was determined for both modelling methods.

Thanks to this approach, it is shown that BT modelling, even by taking into account the heterogeneity of local modulus in beam longitudinal direction, does not truly represent the actual deformations that can be depicted with FE modelling. It results in significant differences in the assessment of the local modulus of elasticity between the two modelling methods. In addition, the results show how axial and bending local moduli of elasticity of timber can be different depending on the knot position across the board. These results can help for the improvement of the indicating properties used for timber strength grading.

ACKNOWLEDGEMENT

This study was funded by the region of Bourgogne Franche-Comté and the French National Research Agency (EffiQuAss project ANR-21-CE10-0002-01).

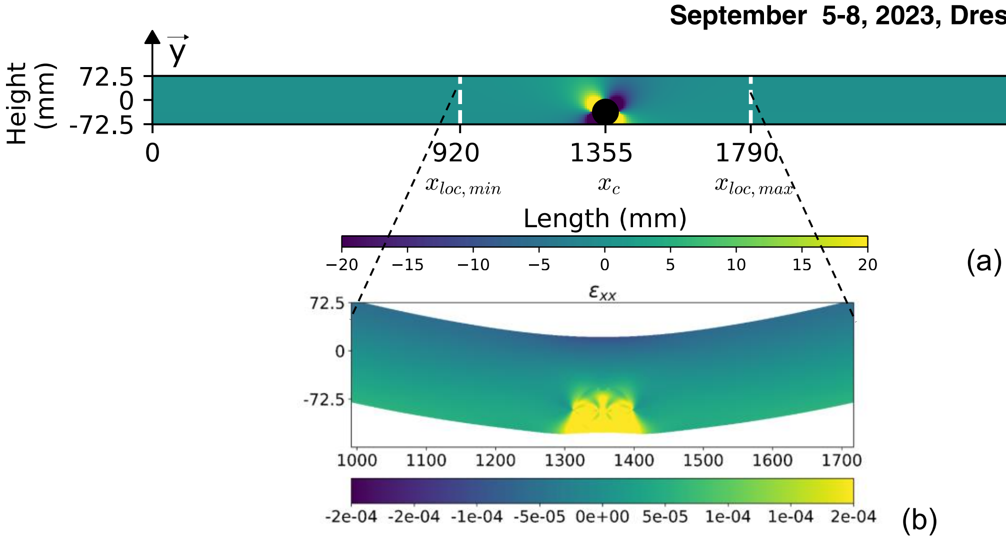


Figure1: Example of an artificial beam modelled with a knot positioned in the middle of it along the length, and at one-quarter of its height. (a) full beam with fibre angles; (b) longitudinal strains and deformation obtained by finite element modelling of 4-point bending in the area of determination of the local modulus of elasticity.

REFERENCES

[1] Jehl, A. Modélisation du comportement mécanique des bois de structures par densitométrie X et imagerie laser. PhD Thesis, ENSAM, 2012

[2] Jehl, A., Bleron, L., Meriaudeau, F., Collet, R. Contribution of slope of grain information in lumber strength grading. In: *17th international nondestructive testing and evaluation of wood symposium*. Sopron, Hungary, 2011

[3] Olsson, A., Oscarsson, J., Serrano, E., Källsner, B., Johansson, M. Prediction of timber bending strength and in-member cross-sectional stiffness variation on the basis of local wood fibre orientation. *European J of Wood and Wood Products* 71:319–333, 2013

[4] Olsson, A., Pot, G., Viguier, J., Faydi, Y., Oscarsson, J. Performance of strength grading methods based on fibre orientation and axial resonance frequency applied to Norway spruce (Picea abies L.), Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) and European oak (Quercus petraea (Matt.) Liebl./Quercus robur L.). *Annals of Forest Science* 75:102, 2018

[5] Briggert, A., Olsson, A., Oscarsson, J. Prediction of tensile strength of sawn timber: definitions and performance of indicating properties based on surface laser scanning and dynamic excitation. *Materials and Structures* 53:54, 2020.

[6] Lukacevic, M., Kandler, G., Hu, M., Olsson, A., Fïssl, J. A 3D model for knots and related fiber deviations in sawn timber for prediction of mechanical properties of boards. *Materials & Design* 166, 2019

[7] Hu, M., Olsson, A., Johansson, M., Oscarsson, J. Modelling local bending stiffness based on fibre orientation in sawn timber. *European J of Wood and Wood Products* 76:1605–1621, 2018

[8] Foley, C. Modeling the Effects of Knots in Structural Timber. PhD Thesis, División of the Structural Engineering, Lund University, 2003

[9] EN 408. Timber structures – Structural timber and glued laminated timber – Determination of some physical and mechanical properties, 2012

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Experimental Testing and Numerical Evaluation of the Strain-softening Behavior of Birch Using a Cross-validation Calibration Approach

Johannes Jonasson*†, Henrik Danielsson† and Erik Serrano†

† Division of Structural Mechanics, Lund University
Department of Construction Sciences, Faculty of Engineering, LTH, Box 118, 221 00 LUND, Sweden
johannes.jonasson@construction.lth.se, henrik.danielsson@construction.lth.se, erik.serrano@construction.lth.se

ABSTRACT

Softwood species are the most commonly used species in structural applications in northern Europe. However, in the last couple of years, utilization of hardwoods has gathered increased momentum, and different hardwood species, such as birch, have even been utilized in cross laminated timber and glued laminated timber [1]. In general hardwoods show an increase in strength and stiffness as compared to softwoods. However, the increase in fracture toughness is less pronounced, and, consequently, increased brittleness can be expected.

Many structural failures stem from introducing a new material, where the behavior is not completely understood or characterized [2]. Consequently, ahead of using a material with increased brittleness in structural applications, such as birch, understanding and characterizing the failure and/or fracture behavior is highly important. Research regarding mechanical behavior of birch has previously been carried out in e.g [3], where sawn birch timber boards were examined under compression loading, both parallel and perpendicular to the grain.

The aim of the present work is to characterize the fracture behavior of birch in tension perpendicular to grain. The experimental work to evaluate the fracture energy has been carried out according to the standardized Nordtest method [4], where a single edge notched beam (SENB) is loaded in three-point-bending. Softwood structural timber of class C24 was used as a reference.

In addition to the experimental investigations, numerical evaluations were carried out with several finite element models, both two- and three-dimensional, corresponding to the experimental set-up. Crack propagation was modeled along a predefined crack path where the strain-softening behavior was modeled by discrete nonlinear springs with intial length equal to zero, see Figure 1. Bi-linear, tri-linear and linear-exponential curves of the stress (σ) versus deformation (δ) response were used to model the strain-softening behavior. All types of stress-deformation curves were then evaluated and calibrated after the experimental results with a cross-validation calibration approach.

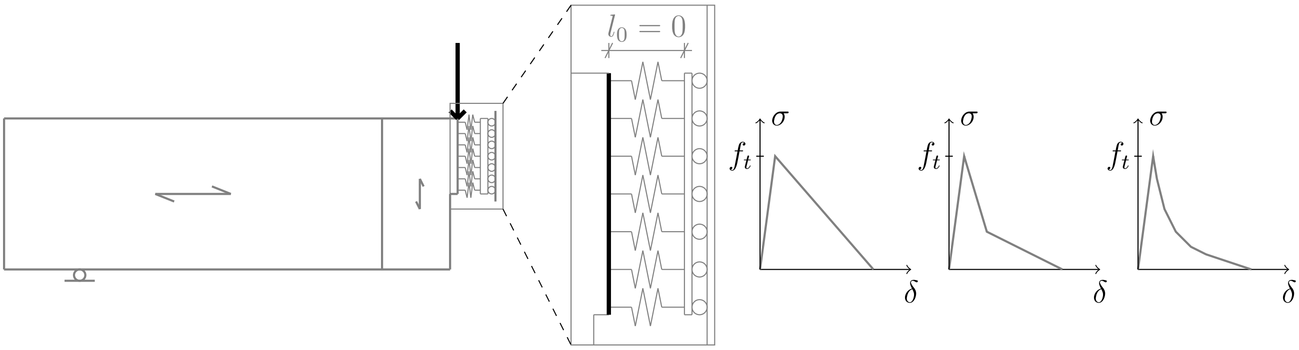


Figure 1: Calculation model of symmetric half of SENB specimen (left) and different stress (σ) vs deformation (δ) curves (right) used along the pre-defined crack path, marked by the black, thick line.

REFERENCES

[1] Jeitler, G.; Augustin, M.; Schickhofer, G. Mechanical properties of Glued Laminated Timber and Cross Laminated Timber produced with the wood species birch. In: *Proceedings of WCTE - 2016 World Conference on Timber Engineering.*

[2] Anderson, T.L. (2017). Fracture Mechanics: Fundamentals and Applications, Fourth Edition (4th ed.). CRC Press.

[3] Collins, S.; Fink, G. Mechanical behaviour of sawn timber of silver birch under compression loading. *Wood Material Science and Engineering*, 17:2, pp. 121-128, 2022.

[4] Nordtest: NT BUILD 422, Wood: Fracture energy in tension perpendicular to the grain. Espoo, Finland, 1993.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Towards a consistent benchmark dataset for the rheologic behavior of Norway spruce

Jonas M. Maas* and Falk K. Wittel†

* ETH Zürich, Institute for Building Materials
HIF E 27, Laura-Hezner-Weg 7, 8093 Zürich, Switzerland
jomaas@ethz.ch

† fwittel@ethz.ch

ABSTRACT

Even though sophisticated hygromechanical models of wood, like the one in Ref. [1], are able to describe the most important moisture-dependent rheological properties of spruce, beech, and ash from a computational point of view, their underlying material parameters deserve more attention. Typically, they are collected from different publications. This implies that experimental data originates from different trees, information on all orthotropic directions might be incomplete, only one loading direction might be considered, or climate dependencies might be missing. We lack data especially for plasticity, viscoelasticity, and mechanosorption under varying moisture for most species, particularly for shear. Scaling parameters between different directions, humidity, and species, based on questionable assumptions, is thus necessary, resulting in inconsistent data.

These inconsistencies decrease the quality of the model predictions, most notably for climate-related behavior. To improve the data on Norway spruce, we are developing a consistent material parameter set for benchmark purposes that will be made publicly available. For this, we determine from one spruce stem statistically sufficiently the elasticity, plasticity, hygroexpansion, viscoelasticity, and mechanosorption for compression, tension, and shear in all anatomical directions for different moisture contents. We measure viscoelasticity and mechanosorption with a self-constructed device that conducts climate-controlled creep tests of 3 compressive, 3 tensile, and 6 shear samples of thin macroscopic cross-sections simultaneously, resulting in one complete orthotropic data set per experimental run.

In this talk, we present the results of plasticity and viscoelasticity. We determine the compliances of a 3D orthotropic moisture-dependent viscoelastic Kelvin-Voigt model and the yield surfaces of a multidimensional multi-surface plasticity model. The material parameters are obtained by inverse FEM based on polynomial chaos expansion following Ref. [2]. To evaluate the improvement of modeling quality, we refine our model [1] with the obtained parameters and compare its response to with previous knowledge.

REFERENCES

[1] Hassani, M. M.; Wittel, F. K.; Hering, S.; Herrmann, H. J. Rheological model for wood. In: *Comp Meth Appl Mech Engn 283*, pp. 1032–1060, 2015.

[2] Müller, J.; Shoemaker, C. A. Influence of ensemble surrogate models and sampling strategy on the solution quality of algorithms for computationally expensive blackbox global optimization problems. *J Glob Optim 60*, pp. 123–144, 2014.

SYSTEM SAFETY AND OPTIMISATION

A FINITE ELEMENT APPROACH TO UNCERTAINTY QUANTIFICATION IN THE STRUCTURAL PERFORMANCE OF CROSS LAMINATED TIMBER

Fiona A. O'Donnell[†*], Sanjay R. Arwade[‡]

[†] Swarthmore College, Department of Engineering
500 College Ave, Swarthmore, PA, 19081
fodonne1@swarthmore.edu

[‡] University of Massachusetts Amherst, Department of Civil and Environmental Engineering
130 Natural Resources Road, Marston Hall, Amherst, MA, 01003
arwade@umass.edu

ABSTRACT

The growth of wood leads to heterogeneity in the material properties of dimension lumber and complex structural behavior. The spatial variation in material properties is due to both variation in clear wood at the material level and naturally occurring features, like knots, at the dimension lumber scale. Cross laminated timber (CLT) is a wood composite panel used in large-scale construction of floor, wall, and roof assemblies. CLT panels are prefabricated wood products composed of dimension lumber placed in alternating crosswise layers that are glued together at their surfaces with an adhesive under pressure. CLT's composite geometry leads to an averaging of the spatially varying mechanical properties among the constituent dimension lumber boards. As mass timber construction becomes an increasingly popular building material for mid- and large-scale construction projects, the influence of the material inhomogeneity on the effective mechanical properties of dimension lumber and resulting mass timber products needs to be characterized in detail.

There have been numerous advances in computational approaches to modeling the material heterogeneity of wood in recent years. Because knots and the resulting fiber deviations around knots are considered to be a primary cause of spatial variation in wood properties, knots and fiber deviations have been the focus of research efforts in this area. The most common approach was developed by Phillips et al, in which fiber deviation around knots is modeled based on the theory of laminar flow around an elliptical solid obstacle (Phillips et al, 1981). Foley expanded on this model by considering the addition of a dive angle (Foley, 2003). A number of authors have applied these theories in two-dimensional and three-dimensional FE models in which knots are modeled by circular, elliptical, cylindrical, or conical shapes (Kandler et al., 2016). An alternative approach to the flow grain analogy is the direct measurement of fiber orientation through laser scanning (Besseau et al, 2020) or X-ray scanning (Seeber et al, 2023).

The approaches found in literature are primarily deterministic calculations performed with finite elements methods. The development of probabilistic approaches to wood and mass timber are essential in increasing the reliability and competitiveness of wood and wood-based products in comparison to traditional building materials. While Monte Carlo simulations could be applied to introduce the probabilistic nature of the problem, finite element models that include complex fiber orientations require prohibitive computational effort. Thus, the objectives of this work are to:

- demonstrate a probabilistic approach for modeling the spatially varying material properties of dimension lumber that can be scaled to CLT geometry, and
- apply these models for uncertainty quantification of the structural performance of CLT under linear-elastic bending.

To achieve these objectives, previous research efforts will be leveraged, including the development of a simplified finite element model for the influence of knots on the effective properties of dimension lumber and the development of a probabilistic model for the distribution and geometry of knots in dimension lumber (O'Donnell, 2021). Three-dimensional finite element models will be developed in which CLT clear wood is modeled by a homogenous orthotropic constitutive law and knots are modeled by stiff inclusions under compressive loading and holes under tensile loading (Figure 1). The knot location and geometry in each board will be probabilistic. The model will be expanded to the CLT panel scale and subject to three-point bending. The midspan displacement and effective stiffness will be determined. Monte Carlo simulations will be applied to determine the mean, standard deviation, and coefficient of variation of both the panel stiffness and the midspan displacement response. The mean panel stiffness will be validated numerically, and the remaining results will be validated by comparison to the Variability Response Function approach to uncertainty quantification of CLT performance (O'Donnell et al, 2022).

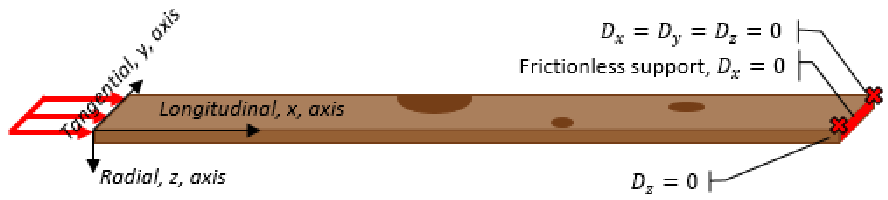


Figure 1. Schematic of finite element model for simplified knot geometry under tensile loading.

References

Besseau B, Pot G, Collet R, Viguier R. "Influence of Wood Anatomy on Fiber Orientation Measurement Obtained by Laser Scanning on Five European Species" (2020). *J. Wood Sci, 66 (74).* https://doi.org/10.1186/s10086-020-01922-y

Foley C. "Modeling the Effects of Knots in Structural Timber" (2003). *Lund Institute of Technology.*

Huber JA, Broman O, Ekevad M, Oja J, Hansson L. "A method for generating finite element models of wood boards from x-ray computed tomography scans" (2022). *Comput. Struct. 260 (106702),* https://doi.org/10.1016/j.compstruc.2021.106702

Kandler G, Lukacevic M, Füssl J. "An Algorithm for the Geometric Reconstruction of Knots within Timber Boards Based on Fibre Angle Measurements" (2016). *Construction and Building Materials, 124, 945-960.* https://doi.org/10.1016/j.conbuildmat.2016.08.001

Norimoto M, Yamada T. "The dielectric properties of wood: On the dielectric properties of the chemical constituents of wood and the dielectric anisotropy of wood"

O'Donnell FA, Arwade SR, Clouston PL. "Application of Variability Response Function to Cross Laminated Timber" (2022). *Probabilistic Engineering Mechanics.* *https://doi.org/10.1016/j.probengmech.2021.103177*

O'Donnell F. "Material Property Heterogeneity in Dimensional Lumber and its Relationship to Mass Timber Performance" (2021). *Doctoral Dissertations*. 2207. https://doi.org/10.7275/21482531.0

Phillips GE, Bodig J, Goodman JR. "Flow Grain Analogy" (1981). *Wood Sci, 14:55-64.*

Seeber A, Khaloian-Sargnaghi A, Rais A, van de Kuilen JW. "A numerical strength prediction approach for using wood element-wise local fiber directions from laser scanning" (2023). *Materials & Design Volume, 226, 111578.* https://doi.org/10.1016/j.matdes.2022.111578

Analysis of radial stress concentrations in curved glulam beams using Monte Carlo Simulations

Taoyi Yu*, Franziska Seeber*, Ani Khaloian*, Jan-Willem van de Kuilen*

* TUM School of Engineering and Design, Department of Materials Engineering, Professorship of Wood Technology, Technical University of Munich, Munich, Germany

ABSTRACT

Analyzing of stress concentration is important for structural analysis, as it may refer to the area where damage may be initialled. In glulam, stress concentration can be caused by material inhomogeneity, such as knots and finger-joints [1, 2]. When curved glulam beams are subjected to bending, tension perpendicular to grain is introduced. As the strength in this direction is relatively low, it becomes the key parameter that determines the load-carrying-capacity of a curved wooden beam.

In this work, a stress concentration phenomenon is found on the perpendicular to grain direction in curved glulam, which is caused by the anisotropy (cylindrical orthotropic as assumed here) of wood. Due to the variations of pith location from different layers, the strain perpendicular to grain varies in each layer, which results in the stress concentration.

In order to quantify such stress concentration effect on the strength of beams, a virtual cutting program combined with Monte Carlo analyses, which consider the uncertainty on the level of material directions of different board layers, is conducted. In this way, the annual-ring effect on stress concentration perpendicular to grain inside curved glulam beams is analyzed.

The developed virtual cutting program simulates the sawing process of boards and yields a reliable database of sawn boards, each with a characterised material direction with respect to the pith location. Lamellas are randomly selected from the database to constructed curved glulam beams in FE models for Monte Carlo Simulation. Parameters including lumber diameter distribution, taper function, orthotropic elastic properties are considered in this study for simulations of four common wood genera in Europe: Spruce, Pine, Larch, and Beech, (each genera contains one or more species and sets of material property values from different research works).

Based on the simulations, which adopt the material parameters of four wood genera, stresses perpendicular to grain may be up to 78% higher than what engineers usually estimate. This may be caused due to the reason that the difference of material parameters in radial and tangential directions are not considered in common engineering practices or in Eurocode 5. Such stress concentrations, which can trigger early damage of the structure, may indicate an underestimation of stresses perpendicular to grain in common practice.

REFERENCES

[1] G. Kandler, J. Füssl, A probabilistic approach for the linear behaviour of glued laminated timber, Engineering Structures 148 (2017) 673 – 685.

[2] A. Khaloian Sarnaghi, J. W. G. van de Kuilen, An advanced virtual grading method for wood based on surface information of knots, Wood Science and Technology 53 (3) (2019) 535 – 557. doi:10.1007/s00226-019-01089-w.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Multiscale Optimization with Orthotropic Material

Daniela Masarczyk*, Detlef Kuhl*

* Institute of Mechanics and Dynamics, University of Kassel
Mönchebergstr. 7, 34125 Kassel
masarczyk@uni-kassel.de, kuhl@uni-kassel.de

ABSTRACT

In the context of sustainable and resource efficient construction in civil engineering, the design of optimized structural elements represents a central challenge. Desired structural properties can be achieved or improved by geometrical adaptation of structural elements to the load. This design task is frequently supported by numerical optimization of their shape, their topology or both. Furthermore, the ongoing development of innovative wood-based materials allows optimization of their microstructure.

The optimal layout of a structure in terms of efficiency is characterized by preponderant load transfer by normal forces. Considering self-weight, which represents the predominant load case in many applications, the optimal shape of plane structures is thus given by the shape of a hanging membrane. This concept was put into practice by Heinz Isler in form finding of bending moment free shells. He investigated the hanging forms of textile materials of different designs and observed an impact of material design and thread direction on the hanging form of the fabric [1]. Modern textile wood composite materials offer the opportunity to transfer these findings to lightweight wood constructions. The material developed in the project TETHOK is characterized by a textile wooden material that is laminated into a polymer matrix [2]. Local adaptability of the weave of the wood textile to the load pattern offers the possibility to optimize the microstructure of the material.

The present study aims to investigate the impact of the microstructural composition of the material on the optimal shape of a structure for self-weight loading. This topic is treated using methods from computational mechanics and numerical optimization. Due to the focus on wood material, an orthotropic material model is considered. First part of this study aims to investigate the impact of the material model on the optimal shape. This task is treated using FEM and by comparison of results for different material models.

The second part treats numerical structural optimization aiming at the optimization of structural stiffness. The methods of optimization of shape and topology are combined to achieve structural optimization on multiple scales. In topology optimization, the available material is distributed within a predefined design domain; in shape optimization, that domain itself is optimized [3]. The material distribution problem is relaxed using the Solid Orthotropic Material with Penalization (SOMP) method which is based on the analogous method for isotropic material presented in [4]. The shape optimization problem is adressed by parametrization of the initially rectangular design domain. The impact of the optimized design domain on the resulting material distribution is investigated.

REFERENCES

[1] Ramm, E.; Schunck, E. Heinz Isler Schalen. Karl Krämer Verlag, 1986.

[2] Silbermann, S.; Heise, J.; Kohl, D.; Böhm, S.; Akbar, Z.; Eversmann, P.; Klussmann, H. Textile architecture for wood construction. In: *Research Culture in Architecture*, pp. 113-122, Birkhäuser, 2019.

[3] Bendsøe, M.P.; Sigmund, O. Topology Optimization: Theory, Methods and Applications, Springer, 2004.

[4] Bendsøe, M.P. Optimal shape design as a material distribution problem. In: *Structural Optimization*, 1(4), pp. 193-202, 1989.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Resampling from Polymorphic Uncertain Results in Numerical Timber Simulations

F. Niklas Schietzold, Wolfgang Graf and Michael Kaliske
Institute for Structural Analysis, Technische Universität Dresden
01062 Dresden, Germany
{niklas.schietzold, wolgang.graf, michael.kaliske}@tu-dresden.de, tu-dresden.de/isd

ABSTRACT

Inhomogeneities are inherent in wood material characteristics and in timber structures, necessitating realistic simulations that incorporate inhomogeneities by uncertainty models to assess structural reliability and safety. In an ideal scenario, comprehensive information about uncertain parameters, including arbitrarily extensive experimental data with perfect reproducibility, would be available. In such unobtainable conditions, engineers could model uncertainties of each system parameter using extensive knowledge, and their natural variation could be described using stochastic uncertainty models, The characteristic of this uncertainty, which is modeled based on ideally comprehensive knowledge is referred to as aleatoric uncertainty, see [2].

However, in reality, experimental setups are imperfect, reproducibility is only approximated, and cost constraints limit the number of available experiments. The resulting uncertainty stemming from this lack of knowledge is known as epistemic uncertainty characteristic, see [2]. Hence, epistemic uncertainty requires appropriate uncertainty models, such as intervals or fuzzy variables, in addition to aleatoric uncertainty models, such as stochastic variables.

In accordance with [1], the consideration of both, aleatoric and epistemic uncertainty in combined models, is the method of polymorphic uncertainty. A straightforward polymorphic uncertainty model is achived, if a parameter in structural analysis is considered uncertain and modeled by a probability distribution function based on limited experimental data. Due to the scarcity of data, a bandwidth of values is possible for the distribution's parameters. A polymorphic uncertainty model is directly achieved by incorporating this bandwidth through interval-valued modeling of the distribution's parameters, resulting in a “probability box” (p-box). If fuzzy variables are used for the parametrization of the distribution function, the more complex polymorphic uncertainty model of “fuzzy probability-based randomness” is deduced, see e.g. [1]. Several other combinations for polymorphic uncertainty models are documented.

Uncertainty quantification involves propagating uncertain inputs through a basic solution (structural analysis) to estimate uncertain outputs (uncertain structural responses). Polymorphic uncertainty quantification can be performed in a stacked analysis structure, where separate analysis steps account for the propagation of epistemic and aleatoric components of the polymorphic uncertainty model, see [1, 3]. The results of these analysis parts, as well as the polymorphic uncertain total output, are defined by information-reducing measures of the actual uncertain result quantities, see [3].

The fact that the complete actual uncertain quantities are not preserved for the uncertain output leads to challenges, if resampling is required from such uncertain results. Resampling

might be required, e.g. if complex structural analyses are subdivided into multiple simulation steps, where uncertain results of a simulation part are taken along as uncertain input quantities for another simulation part.

This contribution addresses the challenge of resampling from polymorphic uncertainty models reconstructed from information-reducing measures. The theoretical basis for polymorphic uncertainty modeling, quantification and information-reduction is outlined, highlighting the challenges and pitfalls involved in resampling from the reconstructed uncertain quantites. The developed novel methods for unbiased resampling are presented by numerical examples in timber structural safety assessment with complex numerical structural analyses of multiple simulation parts.

REFERENCES

[1] Graf, W.; Götz, M.; Kaliske, M. Analysis of dynamical processes under consideration of polymorphic uncertainty. *Structural Safety*, 52, pp. 294–201, 2015.

[2] Möller, B.; Beer, M. Engineering computation under uncertainty – capabilities of non-traditional models. *Computers and Structures*, 86, pp. 1024–1041, 2008.

[3] Schietzold, F. N.; Leichsenring, F.; Götz, M.; Graf, W.; Kaliske, M. Robustness versus Performance – Nested Inherence of Objectives in Optimization with Polymorphic Uncertain Parameters. *Advances in Engineering Software*, 156, p. 102932, 2021.

TOMOGRAPHY

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

3D fibre orientation reconstruction around a knot in Douglas fir

H. Penvern*, G. Pot*, J. Viguier*, R. Collet*, L. Demoulin *, B. Roux *,
A. Olsson†, M. Hu†

* Arts et Métiers Sciences et Technologies, LaBoMaP, BFC, HESAM
F-71250 Cluny, FRANCE
helene.de_sauvage@ensam.eu

† Department of Building Technology, Linnaeus University
351 95 Växjö, SWEDEN
anders.olsson@lnu.se, min.hu@lnu.se

ABSTRACT

The mechanical properties of structural timber largely depend on the occurrence of knots and on fibre deviation in the vicinity of knots. In recent strength grading machines, lasers and cameras are used to detect surface characteristics such as size and position of knots and local fibre orientation. Studies have shown how data from optical surface scanning can be used to model local wood properties and enable good prediction of boards' mechanical behaviour. Since laser scanning only gives reliable information about the fibre orientation in the plane of board surfaces, simple assumptions are usually made both regarding the out-of-plane fibre angle and the fibre orientation in the interior of boards [1,2], with no calculation of the actual 3D fibre direction. Lukacevic *et al.* [3] used a model based on the “grain-flow” analogy that was developed by Foley [4] to determine 3D fibre orientation around knots (being considered of conical shape), and compared strains on board surfaces determined from experiments and finite element simulations. The results indicated a potential for improved accuracy of strength grading methods utilizing information of 3D fibre orientation. However, Briggert *et al.* [5] showed that Foley’s model is dependent on information on the actual knots geometry to provide accurate results of growth layer geometry and fibre orientation.

The authors are unaware of studies utilizing Foley’s model on other species than Norway Spruce. The present work aims to develop a laboratory method, inspired by the work of Hu *et al.* [6], to evaluate growth layers geometry and fibre orientation inside a Douglas fir timber sample. The method presented in [6] was based on successive destructive planning in two different directions, revealing longitudinal-tangential (LT) and longitudinal-radial (LR) planes to reconstruct 3D fibre orientation supposing knot symmetry. Conversely, in the present work, growth layers and 3D fibre orientation were reconstructed based on scanning of LT planes only, utilizing the fact that fibres must be oriented in the plane of the respective growth layers.

A 310x210x50 mm^3 wood block containing a complete, isolated splay knot was cut from a Douglas fir slab. The block was first planed in the LR plane close to the knot centre. 600 dpi colour scans were performed on revealed LR planes, with an additional 2x2 mm² resolution laser dot scanning on the last. The block was then planed off 2 mm at a time in the other direction, revealing a series of LT planes from the pith to the bark (Fig. 1a.). After each planing, colour and laser dot scannings were made (Fig. 1b. & 1c.) such that a dataset of in-plane fibre angles and colour shades of surfaces throughout the sample was collected.

Using morphological filters on colour scans, we managed to binarize each growth layer and use them to reconstruct each of the wood block 3D growth layer boundary surfaces (Fig. 1d.). Then, with computation of local normal directions to growth surfaces and in-plane fibre directions of scanned surfaces, 3D fibre orientation of the whole sample was reconstructed. As a preliminary validation, Figure 1.e. illustrates the good agreement of the computed fibre orientation to the real one on the last LR plane. The study provides valuable data for Douglas fir knots and fibre deviation even though the method’s accuracy needs to be evaluated precisely.

Aknowledgement: This research was made possible thanks to financial support from the French national research agency through the EffiQuAss project (ANR-21- CE10-0002-01).

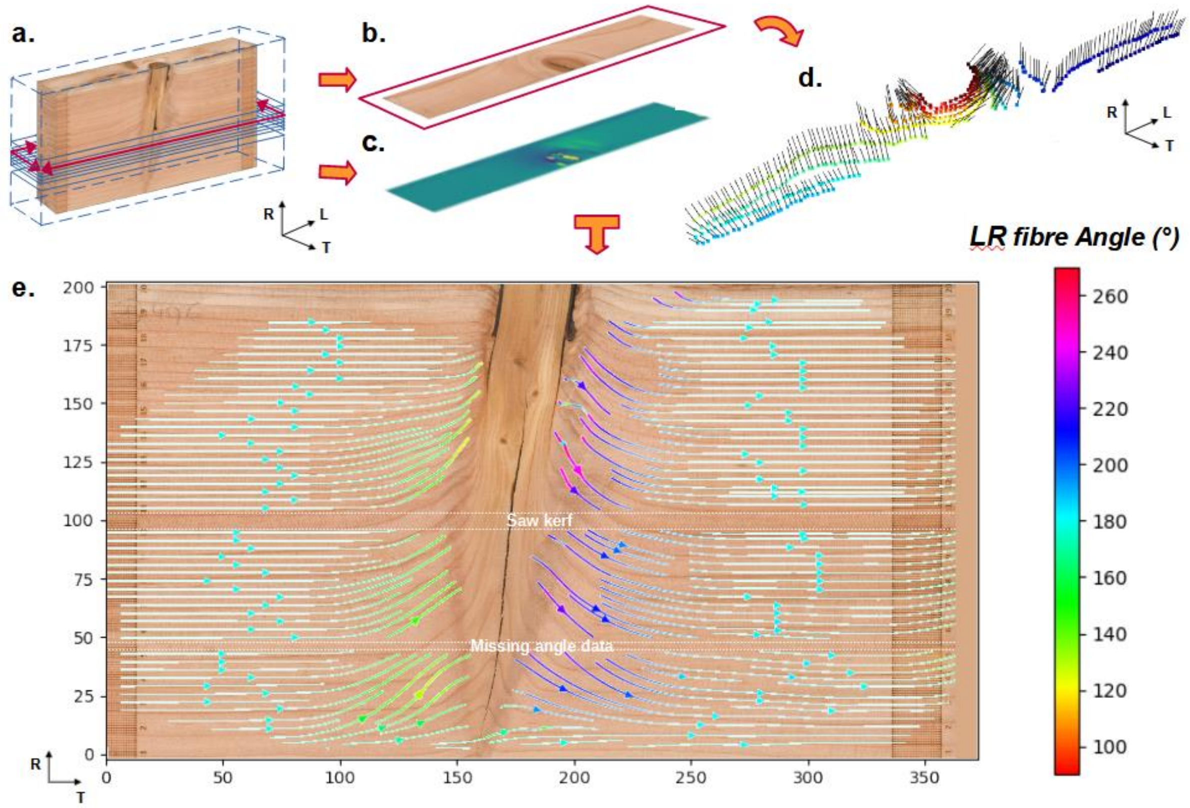


Figure 1. shows **a.** the original sample, which has been in cut into two halves on order to fasten the following successive **2-mm planing** with an industrial planing machine – **b. colour scanning** – **c. LT in-plane fibre angles** measurement with a laser point machine. After detecting growth-layer on the colour scans, **d.** a point cloud is made of the **boundary growth-ring surfaces, and normals** of these surfaces estimated. **e.** Streamplot showing the **resulting LR in-plane fibre orientation overlaid on the sample side colour scan**.

REFERENCES

[1] Rais, A. et al. Local 3D fibre orientation for tensile strength prediction of European beech timber. In : *Construction and Building Materials*, vol. 279 (3):122527, 2021.

[2] Olsson, A et al. Performance of strength grading methods based on fibre orientation and axial resonance frequency applied to Norway spruce, Douglas fir and European oak. In : *Annals of Forest Science*, vol.75 (4), pp.102, 2018.

[3] Lukacevic, M et al. A 3D model for knots and related fiber deviations in sawn timber for prediction of mechanical properties of boards. In: *Materials & Design*, vol.166, 2019.

[4] Foley, C.; Modeling the Effects of Knots in Structural Timber. In *Doctoral Thesis*. 10.13140/RG.2.2.30965.22243.

[5] Briggert, A. et al. Tracheid effect scanning and evaluation of in-plane and out-of-plane fiber direction in Norway spruce timber. In *Wood and Fiber Science*, vol. 50 *(4), 411–429, 2018.*

[6] Hu, M. et al. Growth layer and fibre orientation around knots in Norway spruce: a laboratory investigation. In : *Wood Science and Technology*, vol 52, pp. 7–27, 2018.

3rd ECCOMAS Thematic conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

APPLICATION OF DATA FROM X-RAY CT SCANNING AND OPTICAL SCANNING TO ADJUST MODEL PARAMETERS FOR GROWTH SURFACES GEOMETRY AND FIBRE DIRECTIONS IN NORWAY SPRUCE

M. Hu*, A. Olsson†

* Linnaeus University
Lückligs Plats 1, 351 95 Växjö, Sweden
Min.hu@lnu.se, Anders.olsson@lnu.se

ABSTRACT

Accurate assessment and grading of wood and sawn timber enable more optimized utilization of wood for diffrent applications. Important characteristics of the wood material include mechanical properties of clear wood and the occurance of natural defects such as knots and the related fiber disturbances which have significant negative effects on the strength of sawn timber. Therefore, knowledge of fiber directions close to knots is of great practical relevance. All wood fibers that are developed in the cambium of the tree at a certain point in time form together a thin growth surface, a part of an annual ring, around the tree trunk and the branches. The fibers are oriented in the plane of this thin surface. Foley [1] proposed mathematical models both for growth surface geometry and for fiber orientation in the vicinity of branches/knots, and these models produce plausible results i.e. apparently correct descriptions of the actual growth surface and fiber pattern close to knots, as shown in Figure 1a-d. However, Foley only used a limited set of experimental data to adjust model parameters and to verify modelled growth surface geometry and fibre orientation.

The objective of this research is to explore the potential use of X-ray computed tomography (CT) scanning and optical scanning to collect detailed experimental data of the 3D geometry of knots and growth surfaces in timber boards, and to develop a systematic method and procedure to adjust model parameters to give best fit between modelled and real growth surface geometry and fibre directions. CT scanning and laser scanning of a Norway spruce board, size 45 × 145 × 3600 mm^3, were performed and Foley's model was applied to a knot in the board. An industrial CT scanner (Micro Mito) was used to obtain stack images with 16-bit TIFF format stacked along the length direction of the board with a spatial resolution of 0.3 mm in all three orthogonal directions. Knots and growth surfaces were extracted using thresholding and labeling (Figure 1h and i). In-plane fiber angles on board surfaces were obtained using an optical scanner of make WoodEye. Model parameters were adjusted/optimized to fit experimental data. The procedure involved minimizing the sum of squared normal distances between modelled and experimentally obtained growth surfaces, and minimizing the sum of angle discrepancies for modelled and experimentally obtained fiber directions, respectively. The settings for model parameters were validated through visual comparison to experimental results. The results showed that the suggested methods provide the necessary data to enable adjustment and verification of the mathematical models. The experimental methods provided detailed data of the 3D geometry of growth surfaces and by adjusting the model parameters a more accurate representation of the actual growth surface geometry and fiber direction close to knots was obtained. A comparison between the modelled growth surface geometries and the experimental results showed partly good agreement but also significant discrepancies in areas very close to the knot (Figure 1f and g). Similarly, the modelled fiber direction were, over large areas, in good agreement with the experimentally obtained fiber directions in the investigated plane, but below the knot and very close to the knot significant discrepancies were identified, as can be seen in Figure 1e. The study showed a potential for using experimentally obtained data sets of the type described and to systematically and accurately determine values of model parameters. However, deepened and critical analysis of e.g. applied criteria and tresholds for knot segmentation remain, and data of more knots, growth surfaces and fibre orientation from diffrent boards needs to be collected and analysed to further develop and verify the procedures.

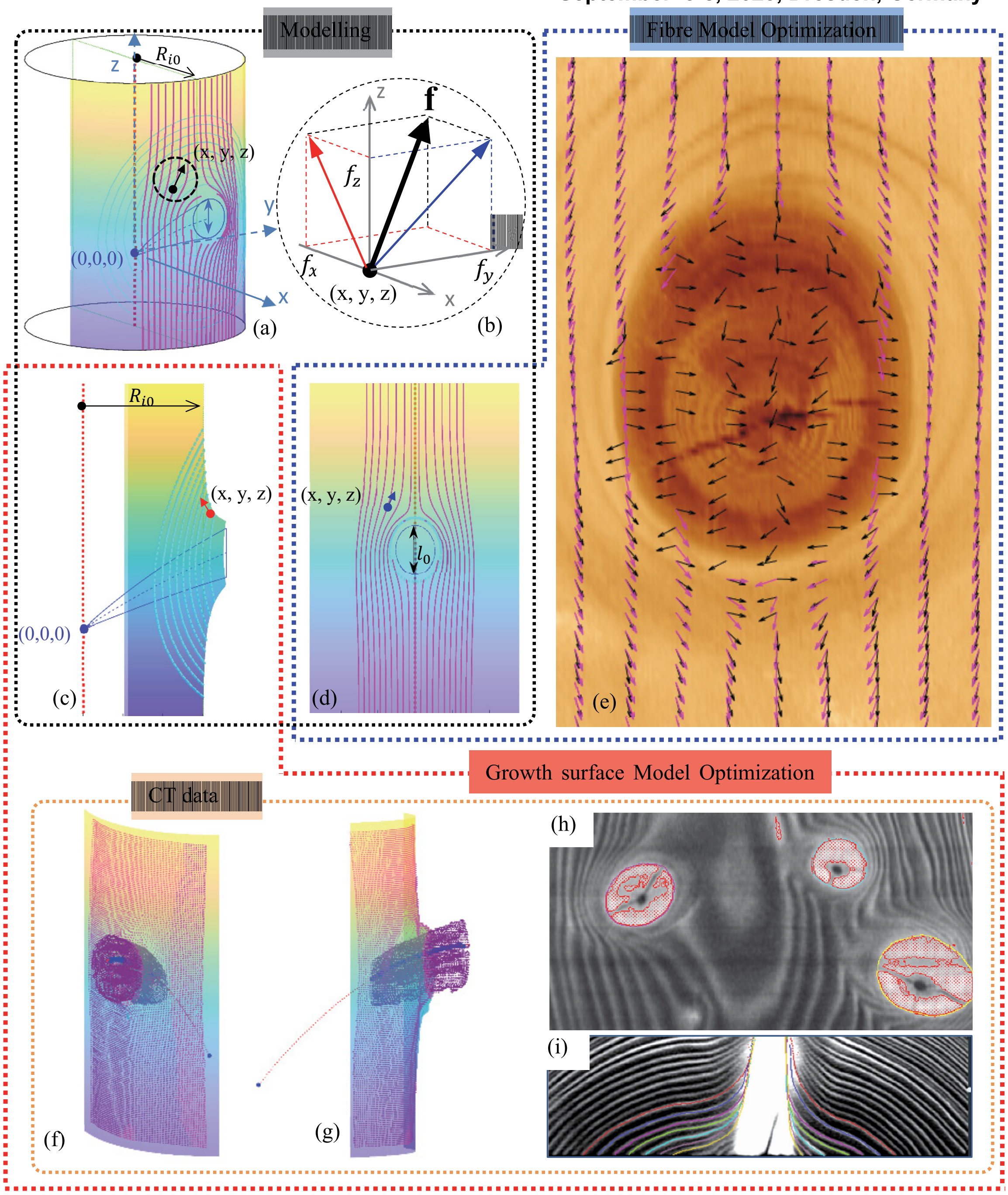


Figure 1. 3D models of growth surface and fibre direction are shown in (a)-(d). A direction of a wood fibre in 3D, represented by black arrow in (b) is determined by its projections onto two orthogonal planes. The projection onto the YZ plane shown in (b) and (d), is determined using Rankine Oval streamline functions. Combining the determined fibre projection with a mathematical model of the growth surface, the component f_x is determined. Experimental data of geometry of a knot and a growth surface shown in (f) and (g) were extracted from CT data. Fibre directions on board surfaces were collected using laser scanning and the results are indicated with black arrows in (e). The collected experimental data was used to determine values of model parameters giving results visualized in (a)-(d).

REFERENCES

[1] Foley C.: Modeling the Effects of Knots in Structural Timber. PhD thesis, Lund University, 2003.

[2] Hu M. et al.: Fibre directions at a branch-stem junction in Norway spruce: a microscale investigation using X-ray computed tomography. Wood Science and Technology, 56:147–169, 2022.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Developing an orthotropic linear-elastic model using the FE method and tomography

Tarik Chakkour and Patrick Perré

LGPM, CentraleSupélec, Université Paris-Saclay,
Centre Européen de Biotechnologie et de Bioéconomie (CEBB),
3 Rue des Rouges-Terres, 51110 Pomacle, France.
E-mail:: tarik.chakkour@centralesupelec.fr, patrick.perre@centralesupelec.fr

ABSTRACT

Wood is one of the natural materials characterized by strongly anisotropic properties, making its practice very direction dependent. Its particularity is that it is non-biodegradable, with the facility to be produced for human consumption. Wood is viewed as robust material utilized in the industrial framework, such as the building sector and timber engineering. Its internal structure permits it to be described locally as an orthotropic material. The wood fibers are composed of different layered structures. Each layer has properties of a transverse anisotropic material. These different layers contain some amounts of cellulose, hemicelluloses, and lignin. The orthotropic directions in the wood coordinate system are denoted by the letters **R**; **T** and **L** that design, respectively, the radial, tangential, and longitudinal directions in the wood material (see Fig. 1).

Over the past decade, the finite element method (FEM) has been extensively used to solve many engineering problems in diverse fields of applied science, particularly in structural mechanics and materials. This work is devoted to developing an orthotropic linear-elastic model successfully with the application of the finite element method (FEM). The wood species investigated in this study consist of two softwoods, poplar, and spruce. The choice of studying these wood sample species is motivated by porosity, anisotropy, and heterogeneity material. These wood samples are acquired by X-ray nano-tomograph to guarantee good resolution. To facilitate the post-processing, software, such as ImageJ, Avizo, and Python, is used to obtain a digital representation of the 3D morphology. The target is to extract morphological details. Then, each identified phase from this morphology is affected by the appropriate mechanical characteristics. This representation is the necessary input data for the finite element method (FEM) framework. The model is designed for any given material microstructure with managing its complex topology, but specifically for wood. This framework permits evaluating the nodal displacements, strain, and stress in the standard orthotropic directions. Further, this work aims to demonstrate the ability of a finite deformation approach for analyzing elastic orthotropic materials. The general-purpose FE tool is used for different categories of materials and their properties. The validation of this framework is based on an established strategy and organized into two steps. The first one consists in analyzing one bi-material without fiber. Next, the second one is to examine the same structure in three-dimensional space with making some orientations as illustrated in Fig. 1. This structure is modeled by the cubic box with equal side length, in which the material is assumed to be elastic, homogeneous, and determined by the mechanical properties.

The present contribution [2] is aimed at using PETSc library [3] considered popular and suitable for determining the solution of the elasticity system. This library illustrates

the solution in parallel by solving the global linear system. The originality of this work lies in taking full advantage of this library to perform the developed tool in time and computation. This study highlights the numerical mechanical tests that are conducted with compression and traction testing. These tests describe the deformation process by giving the graphical representation of the deformed mesh, as shown in Fig. 2. The homogenization strategy for wood species is used to perform the model framework. This homogenized elastic property is provided by computing the mean homogenized Young's moduli. Then, this study is achieved by showing numerical simulations, three-dimensional micromechanics analysis, and finite-element homogenization aspects. Finally, future work will carry out experimental tests using the universal testing machine.

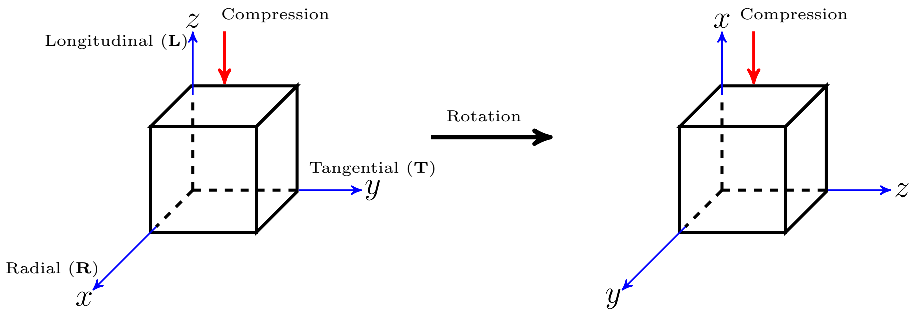
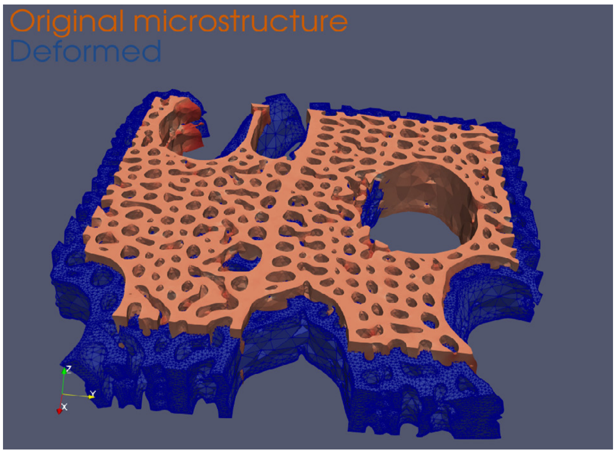
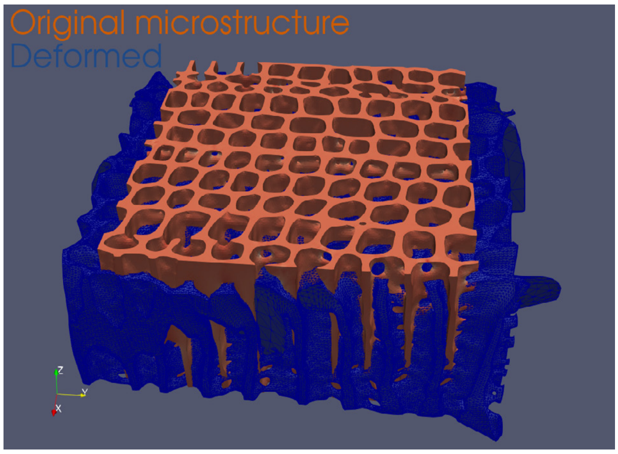


Figure 1: The rotated cubic microstructure from the reference coordinate system XYZ to the new coordinate system YZX.



(a) The poplar wood



(b) The spruce wood

Figure 2: The deformed microstructure for poplar and spruce wood specimens in longitudinal compression. The original microstructure is presented by the orange color, while the deformed one is presented in the mesh by the blue color.

REFERENCES

[1] Chakkour, T., Running Marching cubes algorithms mesh of 3D Finite Element over Abaqus solver, in review, 2023.

[2] Chakkour, T.; Perré, P., Using tomography and FE method to develop orthotropic linear-elastic model for wood applications, preprint, 2023.

[3] Balay, S.; Abhyankar. S et al, Petsc users manual, 2019.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Evaluation of Knots and Fibre Orientation by Gradient Analysis in X-ray Computed Tomography Images of Wood

Johannes A. J. Huber*, Linus Olofsson†

* Wood Science and Engineering, Luleå University of Technology
Forskargatan 1, 931 87, Skellefteå, Sweden
johannes.huber@ltu.se

† Wood Science and Engineering, Luleå University of Technology
Forskargatan 1, 931 87, Skellefteå, Sweden
linus.olofsson@ltu.se

ABSTRACT

The mechanical properties of wood are governed by growth-dependent structures on the micro- and macroscopic level, which are subject to natural variation. Numerical models of wood on a scale of individual pieces of sawn timber may need to account e.g. for the growth ring orientation or the presence of knots and their effects on the local material orientation, i.e. the variation of the fibre coordinate system (FCS). The FCS is composed of the mutually orthogonal longitudinal (l), radial (r) and tangential (t) directions. A growth surface represents a region of equal age, i.e. a former growth front of the tree, and at each point on a growth surface, the r direction consequently represents the surface normal. Growth surfaces surrounding a knot are usually approximated by analytical surfaces, onto which the l direction is modelled by hydrodynamic flow fields in lateral and by polynomials in the vertical direction, like in [1].

A data-driven method used for detecting the location of knots and eliciting the in-plane projection of the l direction on the surface of sawn timber is optical scanning combined with laser tracheid scanning [2]. A disadvantage of this method is that the internal structure of the scanned timber remains unknown and needs to be extrapolated, again based on assumptions of growth in wood. X-ray computed tomography (CT) of wood provides images of the internal density distribution from which features like the pith, the growth rings, knots and defects can be extracted by image analysis.

In a recent study [3], the local FCSs around knots were reconstructed by density gradient analysis in CT images, on which finite element models were based for predicting the bending behaviour of sawn timber. Growth surfaces in wood represent regions of nearly constant density and can therefore be analysed in CT images by gradient-based methods. The goal of the present study was therefore to study how the gradient of the density field derived from CT images of wood can be used to determine growth surfaces, the region of knots, the border between dead and live knot, and the locally varying FCSs.

The material studied was comprised of small log sections of Scots pine (*pinus sylvestris*) (approximate diameters of 50 mm - 300 mm and length 250 mm) containing knot whorls, which were dried to fibre saturation. CT scans were acquired at a voxel size of $0.5 \times 0.5 \times 0.5\,\text{mm}^3$ yielding a 3D image $J(x, y, z)$. After scanning, the sections were cut through the centrelines of the knots and manual measurements were conducted of the dead knot border, i.e. the position along the boundary of a knot after which a knot died off. At this

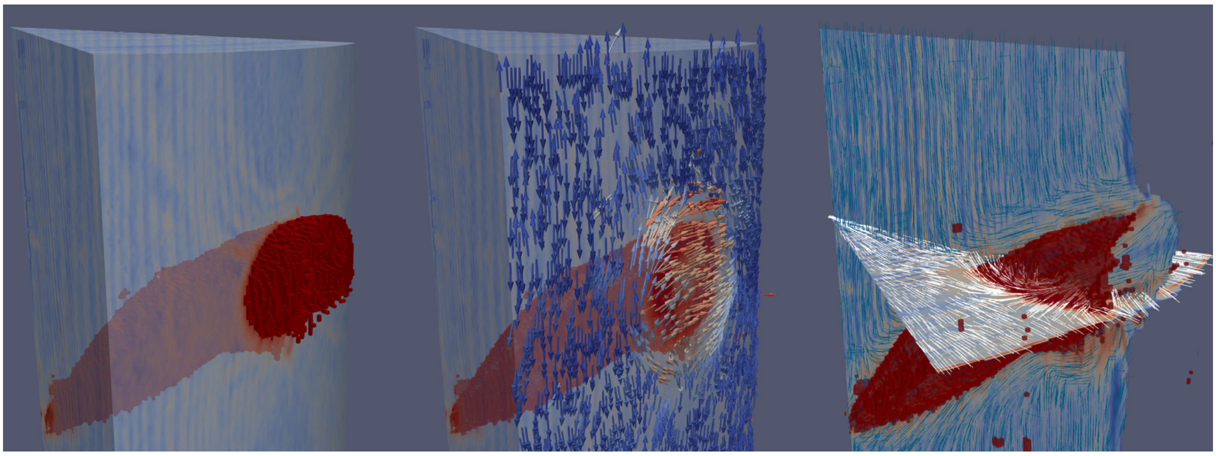


Figure 1: Gradient-based derivation of the l and r direction around a knot in a CT image

border, the diameter of the knot stops increasing and the surrounding fibres grow around the knot rather than merging with it. As the tree continues to grow, this will eventually lead to bark being encased around the knot inside the tree.

A purely data-driven analysis was performed based on the partial derivatives J_x, J_y, J_z, from which the gradient structure tensor (GST) was constructed, see equation 1.

$$\mathbf{GST}(J(x,y,z)) = w_\sigma * \begin{bmatrix} {J_x}^2 & J_xJ_y & J_xJ_z \\ & J_y^2 & J_yJ_z \\ \text{sym} & & J_z^2 \end{bmatrix} \tag{1}$$

where w_σ is a Gaussian convolutional kernel. The eigenvalues and eigenvectors of the GST were extracted for each voxel and the resulting vector field was used in the subsequent analyses. Equivalently, second order derivatives were studied to study curvature.

The results indicate that gradient-based analyses on CT images of wood can be used to approximate the locally varying FCSs around knots, see Figure 1 and that they may facilitate the determination of the region of dead and live knots.

REFERENCES

[1] Lukacevic, M.; Kandler, G.; Hu, M.; Olsson, A.; Füssl, J. A 3D model for knots and related fiber deviations in sawn timber for prediction of mechanical properties of boards. *Mater. Des.*, **166**: 107617, 2019.

[2] Olsson, A.; Oscarsson, J. Strength grading on the basis of high resolution laser scanning and dynamic excitation: a full scale investigation of performance. *Eur. J. Wood Wood Prod.*, **75**(1):17–31, 2017.

[3] Huber, J. A. J.; Broman, O.; Ekevad, M.; Oja, J.; Hansson, L. A method for generating finite element models of wood boards from X-ray computed tomography scans. *Computers & Structures*, **166**: 106702, 2022.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

Image-based Modelling of Wooden Structures for Structural Computation

Florian Spahn*, Kevin Moreno Gata†, Martin Trautz† and Sven Klinkel*

* Chair of Structural Analysis and Dynamics, RWTH Aachen University
Mies-van-der-Rohe-Str. 1, 52074 Aachen, Germany
spahn@lbb.rwth-aachen.de, www.lbb.rwth-aachen.de

† Chair of Structures and Structural Design, RWTH Aachen University
Schinkelstrasse 1, 52062 Aachen, Germany
morenogata@trako.arch.rwth-aachen.de, trako.arch.rwth-aachen.de

ABSTRACT

The contribution is concerned with a numerical analysis method for naturally grown timber elements. The proposed method employs an image-based modelling technique and isogeometric analysis.
Natural building materials such as tree trunks have been used in construction since time immemorial. Wood, in particular, is a natural and very strong building material that has been used for centuries. In accordance with its growth and due to its anisotropic structure, it is mainly processed as a longitudinally slender product. From an engineering point of view, traditional timber construction with linear elements connected by end joints is not an ideal solution in terms of load-bearing behaviour. In timber construction, joints are the weakest points of a structure.

Figure 1: Processing of scanned 3D mesh to NURBS model, with highlighted scaling line

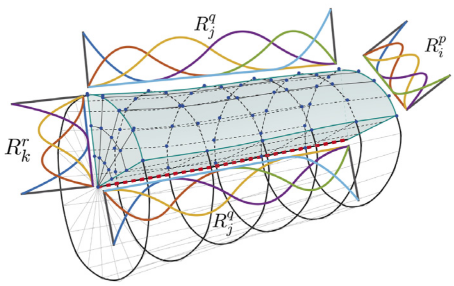


Figure 2: Section approximation of tree log, with NURBS basis functions in three corresponding directions

Placing joints in areas of minimum bending moment should result in more optimal static behaviour. An example of this is the Gerber joint used in traditional timber construction. This arrangement to offset the joints away from supports and knots, called 'off-knot construction', avoids the accumulation of material and mechanical fasteners and simplifies detailing [1].

In addition to the considerable productive and logistical efforts, the production of timber components in the form of beams and girders involves an additional wasteful effort. Motivated by these constraints and based on the principle of 'off-knot construction', integrated timber construction systems could be developed with minor adaptations that utilise curved and bifurcated elements within the natural (=raw, untreated) timber. These unprocessed, naturally grown components are irregularly shaped and difficult to fit into existing computational patterns.
To solve this problem, naturally grown timber components are 3D-scanned and processed in a CAD environment. The solid of the scanned timber structure is displayed as a 3D model in surface representation (cf. Figure 1 above). In an image-based workflow, the scan of the body is transformed into a NURBS model suitable for computer-based calculations (cf. Figure 1 below). In the Scaled Boundary Isogeometric Analysis (SBIGA) the exact representation of the boundary surface by NURBS is additionally used to approximate the solution. In this method, the surface is scaled into a single scaling centre. This scaling works semi-analytically in the case of a linear material description and with the help of a numerical approximation in the non-linear case [2]. For very slender structures, the method leads to extremely flat pyramidal substructures, resulting in numerical errors and an ill-conditioned stiffness matrix.
Therefore, a generalised SBIGA approach using a scaling line instead of a scaling centre is presented. This allows the analysis of slender objects without further partitioning of the structure, as it shares the naturally preferred directions of the corresponding material orientations. It also prevents the creation of obtuse-angled polyhedral elements (cf. Figure 2) and its resulting numerical discrepancies. Due to the conceptual modelling, the generalised method provides these results with significantly fewer equations required.

REFERENCES

[1] Moreno Gata, K.; Seiter, A.; Grizmann, D.; Trautz, M. Development of construction methods with naturally grown timber and bending-resistant joints. In: *Proceedings of WCTE 2023 World Conference on Timber Engineering*, Oslo, 2023.

[2] Chasapi, M.; Mester, L.; Simeon, B.; Klinkel S. Isogeometric analysis of 3D solids in boundary representation for problems in nonlinear solid mechanics and structural dynamics. In: *International Journal for Numerical Methods in Engineering*, 2021.

Acknowledgements Special gratitude for the financial support of the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation). Projekt-ID: 512769030

The TreeTrace Douglas database: quality assessment and traceability of Douglas fir

Fleur Longuetaud[1], Guillaume Pot[2] Frédéric Mothe[1], Alexis Barthelemy[1,3], Rémi Decelle[1,3], Florian Delconte[1,3], Xihe Ge[2],Grégoire Guillaume[2], Théo Mancini[2], Tojo Ravoajanahary[1], Jean-Claude Butaud[2], Robert Collet[2], Isabelle Debled-Rennesson[3], Bertrand Marcon[2], Phuc Ngo[3], Benjamin Roux[2], Joffrey Viguier[2]

[1] Université de Lorraine, AgroParisTech, INRAE, Silva
54000 Nancy, France
fleur.longuetaud@inrae.fr, frederic.mothe@inrae.fr, tojo.ravoajanahary@inrae.fr

[2] LABOMAP, Arts et Metiers Institute of Technology, Université Bourgogne Franche-Comté, HESAM Université
71250, Cluny, France
guillaume.pot@ensam.eu, xihe.ge@ens-paris-saclay.fr, theo@lesmancini.fr, jean-claude.butaud@ensam.eu, robert.collet@ensam.eu, bertrand.marcon@ensam.eu, benjamin.roux@ensam.eu, joffrey.viguier@ensam.eu

[3] Université de Lorraine, CNRS, LORIA
54000 Nancy, France
remi.decelle@loria.fr, florian.delconte@loria.fr, hoai-diem-phuc.ngo@loria.fr, isabelle.debled-rennesson@loria.fr

ABSTRACT

The objective of the present paper is to present an experimental dataset (downloadable at https:// doi. org/ 10. 15454/ YUNEGL) that can be of high value for the wood science community, and the first to be openly available to the best of author knowledge. The content of the database and detail about the data are presented in a datapaper [1].

The TreeTrace_Douglas database includes images and measurements at several stages of the processing of Douglas fir logs, from sawmill logyard to machine grading and destructive testing of boards, and is suitable for research on quality assessment and traceability. A total of 52 long logs, 156 short logs, 208 wood discs and 346 boards was analysed. The image data includes RGB images of log ends and board ends, RGB images and CT slices of strips, a set of images of the boards (RGB, laser and X-rays) obtained with an industrial scanner dedicated to board grading.The measurements include wood density, growth ring widths, pith and board location in the logs, heartwood and sapwood areas, mechanical properties of each board obtained by vibratory and static testing, and visual grading of the boards.

This database is suitable for working on the development of image processing algorithms to apply along the forest-wood chain: to trace the wood from the forest to the boards and to extract quality information at the different stages of the processing. A more traditional analysis of wood quality is also possible by relating the different variables (*e.g.*, wood density and ring width) to each other, to their position in the tree, and by relating the quality measured on the logs to the boards that are extracted from them. This dataset can also directly be used for the development of strength grading algorithms since it includes all the measurement made by current board scanners and vibration testing devices, plus

board traceability from the long log. Some examples of how the database can be used is described in the following part.

Pith detection algorithms has been developed [2] because they often serve as a basis for the detection of other characteristics and because pith position provides information on the severity of the eccentricity potentially related to the presence of compression wood for softwood species. The data can also be used to analyse some wood quality characteristics of Douglas fir and to estimate the amount of information that can be recovered from the analysis of log ends. For instance, a study is underway to analyse the relationship between tree growth and wood density at the ring level from the database. Indeed, an automatic detection of ring widths associated with a ring width – ring density model would provide relevant quality information. It would also be possible to link the properties of the logs (ring widths, wood density, juvenile wood area, heartwood and sapwood amounts, pith eccentricity) to the mechanical performances of the boards obtained from these logs. Another possible application is the development of strength grading algorithms such as that of [3] and [4] since the dataset includes the main measurements made by current industrial board grading machines. The location of the boards in the logs can also be used in the models like that of [5].

Acknowledgement

This research was made possible thanks to the financial support of the French National Research Agency (ANR) in the framework of the TreeTrace project, ANR-17-CE10-0016 and the EffiQuAss project ANR-21- CE10-0002-01

REFERENCES

[1] Longuetaud, Fleur, et al. Traceability and quality assessment of Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) logs: the TreeTrace Douglas database. In: *Annals of Forest Science*, 2022

[2] Decelle, Rémi and Ngo, Phuc and Debled-Rennesson, Isabelle and Mothe, Frédéric and Longuetaud, Fleur, A new algorithm to automatically detect the pith on rough log-end images. In: *21st International Nondestructive Testing and Evaluation (NDTE) of Wood Symposium*,Freiburg, Germany, 2019

[3] Olsson, Anders and Pot, Guillaume and Viguier, Joffrey and Faydi, Younes and Oscarsson, Jan, Performance of strength grading methods based on fibre orientation and axial resonance frequency applied to Norway spruce (Picea abies L.), Douglas fir (Pseudotsuga menziesii (Mirb.) Franco) and European oak (Quercus petraea (Matt.) Liebl./Quercus robur L.) In: *Annals of Forest Science*, 2018

[4] Rais, Andreas and Bacher, Martin and Khaloian-Sarnaghi, Ani and Zeilhofer, Monika and Kovryga, Andriy and Fontanini, Francesco and Hilmers, Torben and Westermayr, Maximilian and Jacobs, Martin and Pretzsch, Hans and van de Kuilen, Jan-Willem, Local 3D fibre orientation for tensile strength prediction of European beech timber. In: *Construction and Building Materials*, 2021

[5] Lukacevic, Markus and Kandler, Georg and Hu, Min and Olsson, Anders and Füssl, Josef, A 3D model for knots and related fiber deviations in sawn timber for prediction of mechanical properties of boards. In: *Materials and Design*, 2019

3rd ECCOMAS Thematic conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

X-RAY COMPUTED TOMOGRAPHY AIDED FINITE ELEMENT MODELLING TO ESTIMATE THE HYGROEXPANSION COEFFICIENTS OF NORWAY SPRUCE BRANCH WOOD

S. Florisson*, H. Lycksam†, F. Forsberg††, L. Hansson†††, E.K. Gamstedt††††

* Uppsala University
Department of Material Science and Engineering
Division of Applied Mechanics
Lägerhyddsvägen 1, SE-75 121, Uppsala, Sweden
sara.florisson@angstrom.uu.se, https://www.katalog.uu.se/profile/?id=N22-3

† Luleå University of Technology
Department of Engineering Sciences and Mathematics
Division of Fluid and Experimental Mechanics
E-building, University Campus, SE-97 187, Luleå, Sweden
henrik.lycksam@ltu.se, https://www.ltu.se/staff/h/henlyc-1.12819?l=en

†† Luleå University of Technology
Department of Engineering Sciences and Mathematics
Division of Fluid and Experimental Mechanics
E-building, University Campus, SE-97 187, Luleå, Sweden
fredrik.forsberg@ltu.se, https://www.ltu.se/staff/f/fred-1.9847

††† Norwegian University of Science and Technology
Department of Ocean Operations and Civil Engineering
Larsgårdsvegen 2, 6025, Ålesund, Norway
laha@ntnu.no, https://www.ntnu.edu/employees/laha

†††† Uppsala University
Department of Material Science and Engineering
Division of Applied Mechanics
Lägerhyddsvägen 1, SE-75 121, Uppsala, Sweden
kristofer.gamstedt@angstrom.uu.se, https://www.katalog.uu.se/profile/?id=N10-1856

ABSTRACT

To improve the sustainable character of wood, the forest product industry is looking for ways to use the entire tree in the manufacturing process of wood products. Such a zero-waste approach will lead to an increased usage of branches in the near future. In conifers, compression wood is formed as a reaction to gravistimulation or external forces such as wind. Consequently, Norway spruce branches have opposite wood (OW) at the upper side of the cross section and compression wood (CW) at the lower side [1]. OW and CW exhibit highly different mechanical properties, especially when exposed to moisture. This difference can have significant consequences when applying wood in applications such as timber structures, pulp and paper. Therefore, a need is seen for the proper identification of the hygroexpansion coefficients of both OW and CW, properties that have only been established on stem wood and largely at macroscopic material level.

Microscopic X-ray computed tomography (CT) aided finite element (FE) modelling is a non-destructive method to determine material properties on micro

material level [2]. This method is relatively new for wood, but has shown promising results when used to characterise elastic properties [3]. In this study, a CT aided FE model is presented to estimate the hygroexpansion coefficients of both OW and CW found in branches of Norway spruce. The study will adopt a methodology specially developed to automate the model development [3]. The methodology will assist in the design of an integrated process and help minimise human induced error. The tomographic data needed to build and calibrate the numerical model were obtained with a laboratory-based micro computed tomography scanner. The hygroexpansion of each specimen was studied with an *ex-situ post-mortem* scanning approach. State-of-the-art image-processing techniques were used to determine the four-dimensional (time + space) moisture content and strain information of the wood during wetting [4, 5]. By integrating the variability of material and specimen into the numerical model by using CT, a more naturalistic material behaviour was simulated and an improved assessment of the hygroexpansion coefficient could be obtained.

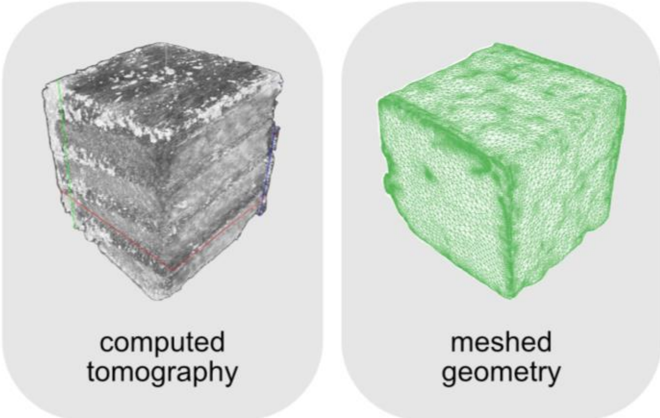


Figure 1: Volume rendering and meshed geometry from tomograms of a 2 mm cube of Norway spruce compression wood taken from branches.

REFERENCES

[1] T. E. Timell, *Compression wood in gymnosperms. Part I: Bibliography, historical background, determination, structure, chemistry, topochemistry, physical properties, origin, and formation of compression wood*. New York: Springer-Verlag Berlin Heidelberg New York Tokyo, 1985.

[2] J. H. Keyak, J. M. Meagher, H. B. Skinner, and C. D. Mote Jr., "Automated three-dimensional finite element modelling of bone: a new method," *Journal of Biomedical Engineering,* vol. 12, pp. 389-397, 1990

[3] S. Florisson, "A methodology for miscroscopic computed tomography aided finite element modelling of wood," in *Svenska Mekanikdagar*, Luleå University of Technology, Luleå, Sweden, 15-16 June 2022 2022: Luleå University of Technology.

[4] L. Hansson and E. Cherepanova, "Determination of wood moisture properties using a CT-scanner in a controlled low-temperature environment," *Wood Mater Sci Eng,* vol. 7, no. 2, pp. 87-92, 2012

[5] F. Forsberg, M. Sjödahl, R. Mooser, E. Hack, and P. Wyss, "Full three-dimensional strain measurements on wood exposed to three-point bending: Analysis by use of digital volume correlation applied to synchrotron radiation micro-computed tomography image data," *Strain,* vol. 46, pp. 47-60, 2010.

3rd ECCOMAS Thematic Conference on Computational Methods
in Wood Mechanics (CompWood 2023)
September 5-8, 2023, Dresden, Germany

X-ray computed tomography of paraffin phase change material embedded in hierarchical wood structures

Chutima Kongvarhodom*, Thanatporn Pongsiri*, Phakkhananan Pakawanit†,

Sutatch Ratanaphan††

*Department of Chemical Engineering, Faculty of Engineering,
King Mongkut's University of Technology Thonburi
126 Pracha Uthit Rd., Thung Khru, Bangkok 10140, Thailand
chutima.kon@kmutt.ac.th, thanatporn.pong@kmutt.ac.th

†Synchrotron Light Research Institute
111 University Avenue, Muang District, Nakhon Ratchasima 30000, Thailand
phakkhananan@slri.or.th

††Department of Tool and Materials Engineering, Faculty of Engineering,
King Mongkut's University of Technology Thonburi
126 Pracha Uthit Rd., Thung Khru, Bangkok 10140, Thailand
sutatch.rat@kmutt.ac.th

ABSTRACT

In recent years, the issue surrounding renewable energy sources has primarily revolved around the challenge of energy intermittency and its unpredictable nature. Therefore, energy storage technologies play a vital role in addressing the imbalance between energy supply and demand [1]. Phase change material (PCM) is one of the most efficient thermal energy storage materials. PCMs are normally impregnated into shape stabilization supports for energy storage applications [2], [3]. Wood becomes a promising material for a conduit for fluid flow and material storage due to its natural hierarchical structure and high porosity. However, the monitoring of PCMs impregnation in wood presents a challenge due to the structural complexity of wood. Synchrotron x-ray tomographic microscopy (SR-XTM) is a reliable and robust technique to observe the impregnation of PCMS in real geometries of wood. This work investigates the impregnation of paraffin mixed with emulsifier as a phase change material in rubberwood using a SR-XTM. Additionally, a numerical model solved by a finite element analysis with enthalpy-porosity method is conducted on the phase transition of paraffin in rubberwood to predict the time-dependent fractions of solid and liquid within rubberwood.

The microstructure of rubberwood is illustrated in Figure 1(a). The results of impregnating paraffin into unmodified rubberwood and delignified rubberwood by chemical treatment are illustrated in Figure 1(b) and Figure 1(c), respectively. As a result of the removal of hemicellulose and lignin, the impregnation ratio is higher in delignified rubberwood compared to unmodified rubberwood. This is due to the thinner cell walls or the enlargement of the wood cells. The impregnation ratios of unmodified rubberwood and delignified rubberwood are 26.84 ± 0.38% and 42.51 ± 0.81%, respectively.

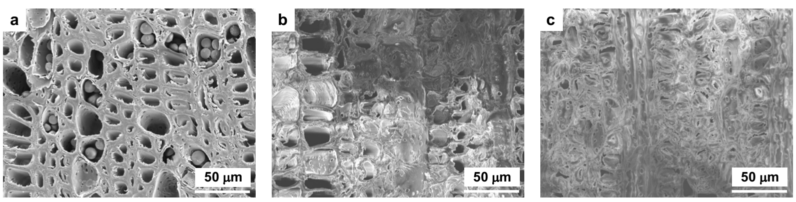


Figure 1 SEM images of unmodified rubberwood (a), unmodified rubberwood impregnated with paraffin (b), and delignified rubberwood impregnated with paraffin (c)

To examine the phase transition of paraffin impregnated in rubberwood, 2D simulations were conducted as shown in Figure 2. The rubberwood was initially exposed to a temperature of 70 °C. The results demonstrate that the liquid fraction of the paraffin increases over time as the temperature rises.

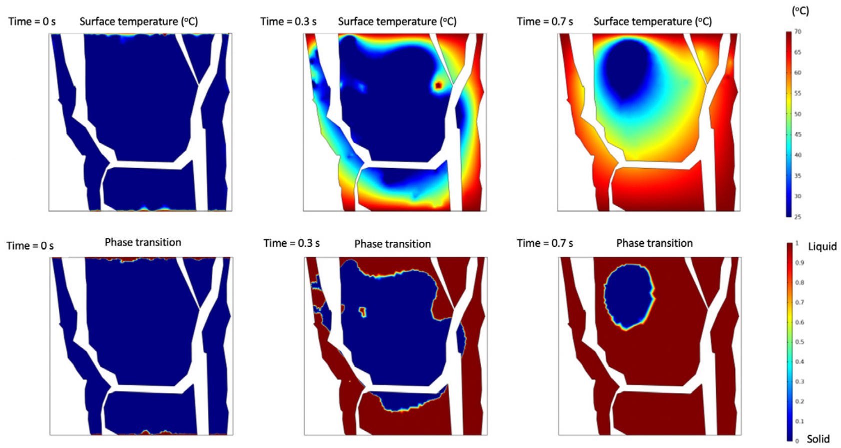


Figure 2: Temperature and phase transition of paraffin in 2D geometries of rubberwood obtained from a SR-XTM

Additionally, the impregnation of paraffin in rubberwood was investigated by a SR-XTM. As shown in Figure 3, paraffin was impregnated in both vessel and tracheid cells. However, the closed vessel cells act as a barrier of paraffin transport that would affect a reduction of impregnation.

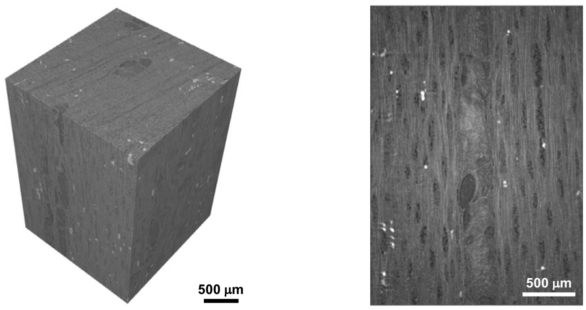


Figure 3: 3D and 2D views of delignified rubberwood impregnated with paraffin obtained from a SR-XTM

In conclusion, the impregnation of paraffin in rubberwoods, both unmodified and delignified, has been successfully demonstrated. The impregnation ratio was found to be higher in the delignified rubberwood due to the removal of hemicellulose and lignin. Simulations studying the phase transition of paraffin as a phase change material in rubberwood combined with the utilization of a SR-XTM have the potential to open new horizons for exploring a wide range of energy storage materials in woods.

REFERENCES

[1] Noël, J.; Kahwaji, S.; Desgrosseilliers, L.; Groulx, D.; White, M. Phase change materials. *Storing Energy*, pp. 249-272, 2016.

[2] Al-Shannaq, R.; Kurdi, J.; Al-Muhtaseb, S.; Farid, M. Innovative method of metal coating of microcapsules containing phase change materials. *Solar Energy*, Vol. 129, pp. 54-64, 2016.

[3] Xu, B.; Li, Z. Paraffin/diatomite composite phase change material incorporated cement-based composite for thermal energy storage. *Applied Energy*, Vol. 105, pp. 229-237, 2013

AUTHORS INDEX