ECCOMAS
European Community on
Computational Methods in
Applied Sciences

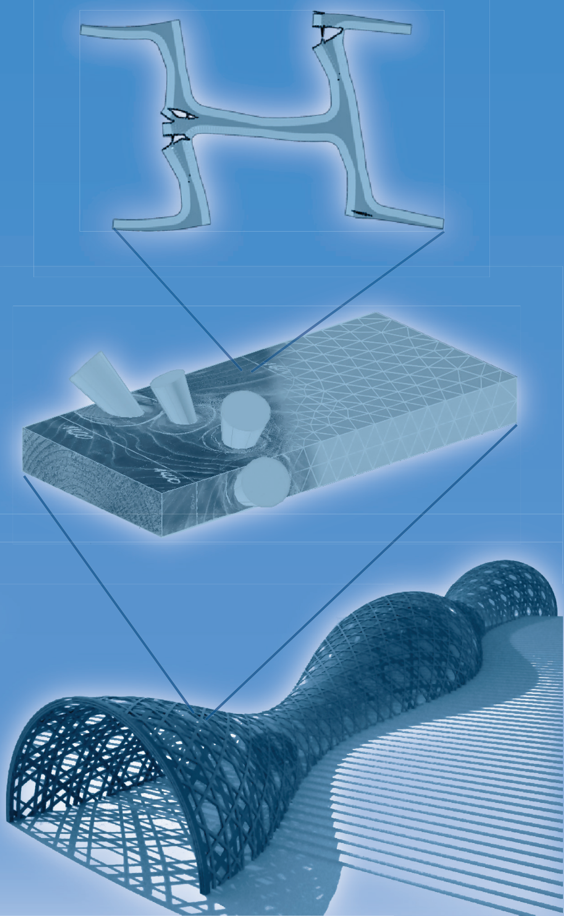
ECCOMAS
Thematic Conference

CompWood 2017

June 7-9, 2017 | Vienna | Austria

Computational Methods in Wood Mechanics – from Material Properties to Timber Structures

Programme & Book of Abstracts



http://compwood.conf.tuwien.ac.at

www.tuverlag.at
ISBN 978-3-903024-49-6
ISBN 978-3-903024-49-6
TU Verlag
an der Technischen Universität Wien

Programme & Book of Abstracts

CompWood 2017

ECCOMAS Thematic Conference on Computational Methods in Wood Mechanics – from Material Properties to Timber Structures

June 7-9, 2017
Vienna, Austria

http://compwood.conf.tuwien.ac.at

Table of Contents

Foreword	3
Conference Organisation	4
Conference Venue	4
Way to Conference Venue	5
Social Programme	5
Tourist Information	6
Scientific Programme	7
Abstracts	19
Author Index	95

Editors:
Josef Füssl
Thomas K. Bader
Josef Eberhardsteiner

Dear participants of CompWood 2017,

It is our great pleasure to cordially welcome you at the Vienna University of Technology (TU Wien), the oldest of its type in Central Europe, situated in the heart of one of the culturally richest and most livable cities in the world; on the occasion of the ECCOMAS Thematic Conference on Computational Methods in Wood Mechanics – from Material Properties to Timber Structures (CompWood 2017).

Increased research activities in the field of wood mechanics have, during the last decades, advanced our understanding of the inherent material properties of wood and wood-based products as a consequence of its unique microstructure, elementary components, and their interaction. At the same time, the use of timber in engineering applications has steadily increased over the last years and new engineered wood-based products have revolutionized wood building technology. Wood is, mainly due to its natural, biodegradable, renewable, and carbon dioxide storing characteristics, an attractive building material for creating a global, sustainable built environment in the future. In order to succeed in this challenge, however, high quality wood-based products with well-defined material properties and reliable design methods are required. This should build upon a strong scientific knowledge base in the field of wood mechanics and computational methods are expected to play a key role, considering that we are living in the era of digitalization. Moreover, the increasing competition for this raw material will require innovative methods to ensure efficient utilization of this natural resource.

The objective of the CompWood 2017 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 want to contribute 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 novel future research in order to extend our knowledge base. Computational methods, often in combination with experimental investigations, substantially contribute to explore 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. This is why we aim to bridge length scales; and we are glad that we could attract a strong interest with 69 expected presentations, including numerical, experimental, theoretical as well as applied contributions. Five distinguished keynote lecturers will span over the above described conference topics and we are thankful to them for accepting the invitation.

The conference is jointly organized by the TU Wien and the Linnaeus University, but would not have been possible without the great efforts of Martina PÖLL, the Secretary General of the conference. We would like to acknowledge the support of ECCOMAS for providing the possibility to organize the CompWood conference under their auspices, and even accepting our proposal for a second edition of the conference in Växjö, Sweden, 2019. Many thanks also go to the Scientific Advisory Committee for helping advertising the conference. The financial support by the City of Vienna and proHolz Austria 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, that you have a wonderful time in Vienna 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 TU Wien!

Josef Füssl, Thomas K. Bader, Josef Eberhardsteiner
Chairmen

Conference Organisation

Organising Institutions

Vienna University of Technology (TU Wien)
Institute for Mechanics of Materials and Structures
Linnaeus University, Sweden
Department of Building Technology

Chairmen

Josef FÜSSL (TU Wien)
Thomas K. BADER (Linnaeus University)
Josef EBERHARDSTEINER (TU Wien)

Secretary General

Martina PÖLL (TU Wien)

Scientific Advisory Committee

Hans Joachim BLASS (Germany)
Ingo BURGERT (Switzerland)
José Manuel CABRERO BALLARÍN (Spain)
Wen-Shao CHANG (UK)
Thierry DESCAMPS (Belgium)
Marco FIORAVANTI (Italy)
Massimo FRAGIACOMO (Italy)
Kristofer GAMSTEDT (Sweden)
Joseph GRIL (France)
Peer HALLER (Germany)
Mark HUGHES (Finland)
Michael KALISKE (Germany)
Markus LUKACEVIC (Austria)
Ulrich MÜLLER (Austria)
Peter NIEMZ (Switzerland)
Anders OLSSON (Sweden)
Sigurdur ORMARSSON (Sweden)
Erick SAAVEDRA (Chile)
Gerhard SCHICKHOFER (Austria)
Erik SERRANO (Sweden)
Luca UZIELLI (Italy)
Jan-Willem VAN DE KUILEN (Germany, Netherlands)

The Conference Venue

The conference venue is Vienna University of Technology (TU Wien), Main Building, Karlsplatz 13, 1040 Vienna. All scientific events will take place in the Main Building.

Main Building, TU Wien


Cupola Hall

Heurigenrestaurant "10er Marie"

Your Way to the Conference Venue

The conference venue can be easily reached by public means of transport (underground: U1, U2, U4; tramways: D, J, 1, 2, 62, 65; buses: 4A, 59A):

From the Airport

- **by taxi** € 40.00

  The ride takes approximately 20 minutes.

- **by bus** € 8.00 (one way), € 13.00 (return ticket)

  Buses run at intervals of 20 min. in front of the arrivals' area of the airport: the ride to Schwedenplatz/Morzinplatz (connections to U1, U4) takes approx. 20 minutes.

- **by CAT (City Airport Train)** € 12.00 (one way), € 21.00 (return ticket) (reduced fares available if ticket is paid online in advance)

  Trains run at intervals of 30 min. (xx:05 and xx:35); the non-stop ride to the City Air Terminal (Landstraße) (connections to U3, U4) takes approx. 16 minutes.

- **by train („Schnellbahn")** € 4.40 (one way)

  Trains also run at intervals of 30 min.; the ride to the City Air Terminal (Landstraße) (connections to U3, U4) takes approx. 25 minutes.

From Railway Station "Wien Meidling / Philadelphiabrücke"

- Take underground U6 (direction Floridsdorf) to Längenfeldgasse. There switch to underground U4 (direction Heiligenstadt) to Karlsplatz.

From Railway Station "Wien Westbahnhof"

- Take underground U3 (direction Simmering) to Stephansplatz. There switch to underground U1 (direction Reumannplatz) to Karlsplatz.

From Railway Station "Wien Hauptbahnhof"

- Take underground U1 (direction Leopoldau) to Karlsplatz.

By Car

- The conference venue is near the main transit route through Vienna. However, parking in the central areas of Vienna is limited to 1½ – 2 hours, and a parking voucher (available at tabacconists (‚Trafik')) is required.

Social Programme

Banquet: Thursday, June 8, 2017, 20:00
The banquet, given by the Mayor of the City of Vienna for all registered participants and accompanying persons, will take place at the Heurigenrestaurant 10er Marie.

Busses for all participants will leave at 19:00 next to the conference venue. Please see the map on the cover page for details.

Tourist Information

Currency
The official currency in Austria is the Euro. 1 Euro = 100 Cents. The symbol for the Euro is €.

Foreign Exchange, Banks & Credit Cards
Money can be changed at the airport, at banks, exchange bureaus, and larger hotels. For a cash advance, credit cards can be used at cash dispensers ("Bankomat") which are available all over the city.

Important Telephone Numbers

Emergency Number	112	Police	133	Medical Service	141
Fire Brigade	122	Ambulance	144		

Pharmacy
The nearest pharmacy is located on Wiedner Hauptstraße 14 (open: Mon-Fri 8:00-18:00, Sat 8:00-12:00). The same opening times apply to most pharmacies in Vienna. A 24-hour pharmacy standby service is available throughout the city. Details of the nearest open pharmacy are posted at every pharmacy. For telephone information call +43 1 1455.

Prices and Tips
Menu prices usually include service and taxes. In restaurants, a tip of approximately 5-10 % is expected.

Shopping
Typical shopping hours are Monday to Friday 9:00 - 18:00 and Saturday 10:00 - 13:00 (17:00). Apart from some tobacconists and small supermarkets at petrol stations and at the main railway stations, shops are closed on Sundays. Luxury shops with an elegant clientele can be found in the pedestrian zone of the Graben and of Kärntnerstraße (underground lines U1 and U3 / station Stephansplatz). Street entertainers and outdoor cafés contribute to the special atmosphere of this area. A well known shopping area is Mariahilferstraße (underground line U3 / station Neubaugasse).

Taxi
The main taxi companies in Vienna can be reached on: +43 1 31300 or +43 1 40100 or +43 1 60160.

Transportation
The best way to discover Vienna is by public transport. The transport system is based on a dense network of trams, buses, subways, and trains. The following tickets are available:

- Single-ride ticket: € 2.20 (at vending machines), € 2.20 (in trams only)
- 24-hour (multiple-ride) ticket: € 7.60
- 48-hour (multiple-ride) ticket: € 13.30
- 72-hour (multiple-ride) ticket: € 16.50
- Week card (multiple-ride ticket): € 16.20 (valid from Monday to Monday)

Tickets are available at Vienna Transport sales counters and at tobacconists. Apart from the Vienna Card, tickets can also be obtained from vending machines at the underground stations.

- Vienna Card: € 13.90 (24-hour (multiple-ride), € 21.90 (48-hour (multiple-ride), or € 24.90 (72-hour (multiple-ride) ticket, reduced rates for guided tours, at restaurants, ...)

Voltage
Voltage: 230 Volts. Plugs are Continental-style two-pin. A plug adaptor should be taken along if incompatible electronic gadgets are used.

Scientific Programme

Information for Lecturers

- Please check the time and lecture room of your presentation in the daily programme and on the info boards as there might have been changes.
- Technical staff is assigned to each lecture room for help with technical equipment.
- Each lecture room is equipped with a notebook (Windows 7, Microsoft Office 2013, Acrobat Reader) and a video projector. You are asked to upload your presentation on this notebook as soon as possible, but at the very latest in the break before the session.
- Please be present at least 10 minutes prior to the start of your session and let the chairperson know you are there.
- Please make sure to stay in your session from the beginning on in order to ensure smooth changes between the individual presentations.
- The time allotted for the presentations is 20 min. (incl. discussion) for all presentations. The chairpersons are requested to stop presentations after the allotted time has passed.

Information for Chairpersons

- Please check the time and lecture room of the session you are chairing in the daily programme and on the info boards as there might have been changes.
- All lecturers of your session are requested to approach you in the lecture room at least 10 minutes before the start of the session. This allows you to identify lecturers who have not arrived yet.
- Technical staff is assigned to each lecture room for help with technical equipment. They are responsible for the technical equipment in the lecture room and are ready to help you in any other aspect.
- You are kindly asked to switch between presentations by simply announcing the name of the next presenter and the title of the presentation. Due to the tight schedule, there will not be sufficient time for introducing individual lecturers in a more detailed manner.
- Please do your best to strictly limit the duration of each presentation and discussion to the allotted time.
- If a lecturer is missing, please stick to the original programme, i.e., extend the discussion time of the preceding presentation or allow a break for the duration of the missing lecture(s). This enables participants to listen to chosen individual lectures according to the announced sequence.

Keynote Lectures

Wednesday, June 7, 2017

09:20 KL I **Massimo Fragiacomo** *(University of L'Aquila, Italy):*
A framework for seismic analysis of timber structure

09:50 KL II **Hans Joachim Blaß** *(Karlsruhe Institute of Technology, Germany)*:
State-of-the-art and challenges in engineered timber connections

Thursday, June 8, 2017

09:00 KL III **Michael Kaliske** *(Technical University of Dresden, Germany):*
Multiphysical simulations of wood and wooden structures

Friday, June 9, 2017

09:00 KL IV **Joseph Gril** *(University of Montpellier 2, France):*
Modelling the time-dependent behaviour of wood

14:30 KL V **Kristofer Gamstedt** *(Uppsala University, Sweden):*
Development of a support structure for the wooden shipwreck Vasa

Wednesday, June 7, 2017, 09:00 - 14:00

09:00 - 09:20

Opening session — **Cupola Hall**

J. Füssl (Conference Chairman)

09:20 - 10:20

Cupola Hall

Keynote lectures
Chair: Josef Eberhardsteiner

09:20 KL I **M. Fragiacomo, G. Rinaldin, C. Bedon, M. Izzi:** A framework for seismic analysis of timber structures

09:50 KL II **H. J. Blaß**: State-of-the-art and challenges in engineered timber connections

10:20 - 10:50
Coffee Break

Cupola Hall

Session I — **Cupola Hall**

Brittle failure in wood products and connections
Chair: Erik Serrano

10:50 I:1 **J. L. A. Vessby, S. Florisson, T. Sisay Habite:** Numerical simulation of moisture driven fracture in mechanical timber connection using XFEM

11:10 I:2 **C. Avez, B. Roensmaens, M. Verbist, J.M.G. Branco, T. Descamps:** A cohesive zone model to study timber-to-steel-plates bonded joints

11:30 I:3 **K. Ostapska-Luczkowska, K. A. Malo:** Numerical simulation of timber shear experimental test with cohesive zone fracture model

11:50 I:4 **M. Lukacevic, J. Füssl, J. Eberhardsteiner:** A microstructure-based multisurface failure criterion for the description of brittle and ductile failure mechanisms of wood

12:10 I:5 **A. d. M. Wahrhaftig:** Experimental exploratory study of failure modes in models of wooden rectangular beams

12:30 I:6 **S. O. Marthin, E. K. Gamstedt:** On the hierarchical structure of wood and its mechanisms providing high tensile strength

12:50 - 14:00
Lunch Break

Festive Hall

Wednesday, June 7, 2017, 14:00 - 16:30

Session II — **Cupola Hall**

Identification of mechanical properties & advanced grading
Chair: Kristofer Gamstedt

14:00	II:1	**A. Olsson, M. Hu:** Timber models and prediction of stiffness and strength
14:20	II:2	**Y. Faydi, L. Brancheriau, G. Pot, R. Collet:** Prediction of oak wood mechanical properties based on vibratory tests
14:40	II:3	**F. García Fernández, P. de Palacios, A. García-Iruela, L. García Esteban, B. González Rodrigo:** Predicting particleboard modulus of rupture through artificial neural networks using production parameters
15:00	II:4	**H. Petersson, B. Källsner, J. Vessby:** In-plane buckling analysis of transversely loaded timber beams
15:20	II:5	**T.-Y. Kuo, W.-C. Wang:** Experimental and numerical investigation of grain orientation of timber with knot by using digital image analysis
15:40	II:6	**G. Kandler, M. Lukacevic, J. Füssl**: Experimental and numerical investigations on the mechanical behavior of glued laminated timber

Session III — **Boeckl Hall**

Timber connections
Chair: Jose Manuel Cabrero

14:00	III:1	**M. Verbist, J. M. G. Branco, T. Descamps:** Hammock shape shear stress distribution in the single step joint
14:20	III:2	**F. W. Panella, A. Pantaleo:** Numerical simulation and experimental validation of fatigue behavior of wood-glass fiber composite T joint
14:40	III:3	**A. Pantaleo, D. Ferri:** Numerical 3D finite element modelling and experimental validation for dowel type vs tenon-mortise type wooden joints for window frames
15:00	III:4	**A. Livingstone, P. Patlakas, S. Smith, R. Hairstans:** Automated code compliance checking to EC5 in BIM for structural timber connections
15:20	III:5	**P. Sejkot, S. Ormarsson, J. Vessby:** Numerical and experimental study of punched metal plate connections to obtain spring stiffness needed for 3D buckling analysis of long-span timber trusses
15:40	III:6	**E. Nathan, T. Tsalkatidis**: Numerical analysis of the withdrawal capacity of large steel dowels in cross-laminated timber panels

16:00 - 16:30
Coffee Break

Cupola Hall

Wednesday, June 7, 2017, 16:30 - 18:30

Session IV **Cupola Hall**

Cross-laminated timber

Chair: Henrik Danielsson

16:30	IV:1	**L. Franzoni, A. Lebée, F. Lyon, G. Foret:** Closed-form homogenization of CLT panels with periodic gaps
16:50	IV:2	**E. I. Saavedra Flores, J. C. Pina, C. F. Guzmán, P. González, S. Yáñez:** Multi-scale modelling strategies for cross-laminated timber structures
17:10	IV:3	**B. González Rodrigo, A. Fraile de Lerma, J. C. Mosquera Feijoo:** Modeling of the seismic behavior of structures of cross-laminated timber panels
17:30	IV:4	**T. Furtmüller, B. Giger, C. Adam:** A mechanical material model for cross-laminated timber obtained by numerical homogenization
17:50	IV:5	**K. Saavedra, E. I. Saavedra Flores, J. Hinojosa:** On the multiscale simulation of buckling and delamination in cross-laminated timber structures

Session V **Boeckl Hall**

Modelling viscous effects in wood

Chair: Joseph Gril

16:30	V:1	**S. Huč, T. Hozjan, S. Svensson:** Influence of misalignment between direction of observation and wood material orthotropy on viscoelastic strain measurements
16:50	V:2	**J. C. Pina, E. I. Saavedra Flores, C. F. Guzmán, S. Yanez:** A multi-scale model for the creep behaviour of wood
17:10	V:3	**M. Capron, S. Bardet, K.C. Sujan, M. Matsuo, H. Yamamoto:** One-dimension visco-elastic modelling of wood in the process of formation to clarify the hygrothermal recovery behavior of tension wood
17:30	V:4	**B. Homerin, M. Rhême:** Finite element modelling (FEM) of the viscoelastic behavior of a wooden spring system
17:50	V:5	**S. E. Hamdi, R. Moutou Pitti, O. Saifouni:** Moisture driven failure monitoring in wood material: numerical analysis based on viscoelastic crack growth approach
18:10	V:6	**S. Huč, S. Svensson**: Coupled two-dimensional modelling of long-term behavior of wood subjected to mechanical stress and varying climatic conditions

Thursday, June 8, 2017, 09:00 - 14:00

Cupola Hall

Keynote lecture
Chair: Josef Füssl

09:00 KL III **M. Kaliske:** Multiphysical simulations of wood and wooden structures

Session VI Cupola Hall

Modelling moisture in wood I
Chair: Josef Füssl

09:30 VI:1 **R. Fleischhauer, J. U. Hartig, P. Haller, M. Kaliske:** Modelling and experimental investigations of densification of wood for forming processes

09:50 VI:2 **S. Florisson, S. Ormarsson:** The effect of surface emission, diffusion and initial moisture profiles on stress development in timber boards

10:10 VI:3 **S. Fortino, P. Hradil, A. Pousette:** A numerical approach to study the effects of coatings on the moisture gradients and moisture induced stresses in glulam beams of timber bridges

10:30 - 11:00 Coffee Break

Cupola Hall

Session VII Cupola Hall

Modelling moisture in wood II
Chair: Sigurdur Ormarsson

11:00 VII:1 **C. F. Pambou Nziengui, R. Moutou Pitti, E. Fournely, J. Gril:** Impact of moisture content changes on the mechanical behavior of Pseudotsuga Menziesii

11:20 VII:2 **C. Zhang, D. Derome, J. Carmeliet:** Multiscale modeling of hygromechanical behavior of wood cell wall S2 layer

11:40 VII:3 **D. Konopka, M. Kaliske:** Multi-Fickian hygro-mechanical investigation of wooden cultural heritage

12:00 VII:4 **M. Schiere, S. Franke, B. Franke, A. Müller:** Numerical sensitivity study of moisture induced stress levels in glulam cross sections

12:20 VII:5 **K. Schulgasser:** Why tangential shrinkage of wood is greater than radial shrinkage

12:40 VII:6 **M. Autengruber, M. Lukacevic, J. Eberhardsteiner, J. Füssl:** A numerical simulation tool for coupled heat and mass transfer in wood

13:00 - 14:00 Lunch Break

Festive Hall

Thursday, June 8, 2017, 14:00 - 16:10

Session VIII — **Cupola Hall**

Composite and reinforced structural elements

Chair: Massimo Fragiacomo

14:00	VIII:1	**J. Pyykkö, S. Svensson:** Evaluation of computational models for timber-concrete composite beams
14:20	VIII:2	**A. Kovačič, B. Šubic, G. Fajdiga:** Computer modelling of hybrid wooden beams for window frames
14:40	VIII:3	**M. Frese:** Computational examination of the effect of beech LVL reinforcing modules on the bending stress of glulam beams with shear failure
15:00	VIII:4	**M. Riegler, S. Dworak, U. Müller:** Introducing a virtual technological model for the formation of wood-based composites
15:20	VIII:5	**M. Schneider, J. Mareš, S. Gigli:** The influence of damaged zones in wood columns on its load bearing capacity

Session IX — **Boeckl Hall**

Vasa ship and wooden structures

Chair: Erick Saavedra Flores

14:00	IX:1	**R. Afshar, N. Alavyoon, A. Ahlgren, N. van Dijk, A. Vorobyev, K. Gamstedt:** A full-scale finite-element model of the Vasa ship
14:20	IX:2	**N. van Dijk, A. Ahlgren, A. Vorobyev, R. Afshar, K. Gamstedt:** Risk assessment for buckling of the original foremast of the Vasa ship
14:40	IX:3	**A. Vorobyev, F. Garnier, N. van Dijk, R. Afshar, O. Hagman, K. Gamstedt:** Evaluation of displacements of a wooden hull section of the Vasa ship by means of 3D laser scanning
15:00	IX:4	**F. Frontini, J. H. Siem:** Modelling of a historic timber roof using the finite element method
15:20	IX:5	**G. Rinaldin, M. Fragiacomo, C. Amadio:** Accuracy of N2 inelastic spectra for timber structures

15:40 - 16:10
Coffee Break

Cupola Hall

Thursday, June 8, 2017, 16:10 - 18:10

Session X | **Cupola Hall**

Mechanical behaviour of joints and connections
Chair: Hans Joachim Blaß

16:10	X:1	**M. Dorn, K. De Borst:** Realistic modelling of the interface between wood and dowel in connections
16:30	X:2	**B. Iraola, J. M. Cabrero:** Strategies to model wood behavior and progressive failure
16:50	X:3	**T. K. Bader, J. Vessby:** Modeling displacement path dependence in nailed sheathing-to-framing connections
17:10	X:4	**N. Couvreur, D. Laplume, T. Descamps, B. Roensmaens:** Use of an optimization procedure for the ULS design of bolted glulam timber joints
17:30	X:5	**F. Nouri, H. R. Valipour:** Finite element modelling of steel-timber composite beam-to-column joints
17:50	X:6	**M. Yurrita, J. M. Cabrero:** New concepts for the development of a formula for the embedment strength of timber

Session XI | **Boeckl Hall**

Simulations
Chair: Markus Lukacevic

16:10	XI:1	**A. Khaloian Sarnaghi, J.-W. van de Kuilen:** Combined CFD and solid FEM numerical modelling of imperfections in wooden materials
16:30	XI:2	**Y.-H. Yeh, Y.-S. Tsai, M.-F. Hsu:** Life cycle assessment of high-rise residential timber building located in urban context
16:50	XI:3	**Z. Chen, F. Pled, L. Chevalier, H. Makhlouf, E. Launay:** Identification of the mechanical properties of particle boards and stochastic simulation of the behavior of furniture
17:10	XI:4	**T. Yojo, C. O. Souza, M. J. A. C. Miranda, S. Brazolin:** Wood cell elastic model for stress and deformation analysis - implementation

20:00 - 23:30
Conference Banquet

Heuriger „10er Marie“
(see details on page 5)

Friday, June 9, 2017, 09:00 - 13:30

Cupola Hall

Keynote lecture
Chair: Thomas K. Bader

09:00 KL IV **J. Gril:** Modelling the time-dependent behaviour of wood

Session XII Cupola Hall

Applications
Chair: Anders Olsson

09:30 XII:1 **S. Ormarsson, M. Johansson:** Numerical simulations of structural behaviour of volume modules used for construction of multifamily timber houses

09:50 XII:2 **K. Persson, O. Flodén:** Effect of variations in material properties on low-frequency vibrations in wood structures

10:10 XII:3 **U. Müller, G. Singer, S. Kirschbichler, W. Leitgeb, T. Jost:** The road from creating a material model to a structural component of wood for automotive applications

10:30 - 11:00
Coffee Break

Cupola Hall

Session XIII Cupola Hall

Multiscale considerations
Chair: Michael Kaliske

11:00 XIII:1 **A. M. Rindler, C. Hansmann, U. Müller, J. Konnerth:** Mechanical contribution of the adhesive layer to the dimensional stability of multi-layered wood based panels

11:20 XIII:2 **C. F. Guzmán, E. I. Saavedra Flores, J. C. Pina, S. Yáñez:** Finite element approach to simulate cellulose molecules

11:40 XIII:3 **F. K. Wittel, D. Mora, S. O. Olaniran, M. Rüggeberg:** Micro-mechanical multi-scale models for spruce with generic modifications

12:00 XIII:3 **P. M. J. S. Godinho, M. Jajcinovic, T. K. Bader, W. J. Fischer, U. Hirn, W. Bauer, C. Hellmich:** A continuum micromechanics approach to the strength of planar fiber networks: paper material applications

12:20 XIII:5 **M. Li, J. Füssl, M. Lukacevic, J. Eberhardsteiner:** Numerical limit analysis approaches for strength predictions of cross-laminated timber plates

12:40 - 13:30
Lunch Break

Cupola Hall

Friday, June 9, 2017, 13:30 - 15:10

Session XIV — **Cupola Hall**

Modelling of wood products
Chair: Thomas K. Bader

13:30 XIV:1 **H. Danielsson, E. Serrano:** Experimental and numerical investigations of the stiffness of in-plane loaded CLT beam elements

13:50 XIV:2 **J. U. Hartig, S. Facchini, P. Haller:** Experimental and numerical investigations on a glass fiber reinforced molded wooden tube made of beech exposed to lateral vehicle impact

14:10 XIV:3 **G. Balduzzi, G. Kandler, J. Füssl:** Estimation of the bending stiffness of GLT beams: a novel procedure based on enhanced analysis of the boards' stiffness and first order beam models

Cupola Hall

Keynote lecture
Chair: Thomas K. Bader

14:30 KL V **K. Gamstedt, R. Afshar, N. P. van Dijk, A. Vorobyev:** Development of a support structure for the wooden shipwreck Vasa

Closing Session — **Cupola Hall**

15:00 **T.K. Bader** (Conference Chairman)

Abstracts

KL I

A Framework for Seismic Analysis of Timber Structures

M. Fragiacomo[†], G. Rinaldin[†*], C. Bedon[‡], M. Izzi[‡]

[†] Dept. of Civil, Construction-Architectural & Environmental Engineering, University of L'Aquila, massimo.fragiacomo@univaq.it
[†*] Department of Architecture, Design and Urban Planning, University of Sassari, grinaldin@uniss.it
[‡]Department of Engineering and Architecture, University of Trieste, Piazzale Europa 1, 34127 Trieste, Italy, bedon@dicar.units.it & izzimatteo@gmail.com

The simulation capabilities of a specifically developed phenomenological model for timber structures are described and presented through some representative case studies. This component model has been developed based on the behaviour of a single nail embedded in wood, considering the compressive behaviour of the wood and plasticization of the nail. As a result, the behaviour in cyclic conditions due to seismic actions, was modelled through a slip-type piecewise hysteretic relationship (Figure 1a), and some desirable features such as stiffness and strength degradation were included. Most of the connections employed in timber structures use nails or screws, allowing the application of the proposed framework to various types of subassemblies and to full-scale structures. In particular, this framework has been used to simulate various timber building typologies, such as light-frame, cross-laminated (Figure 1b), log-house (Figure 1c) and moment-resisting frame structures, at different levels, from the single nail (Figure 1d) to the whole joint behaviour. Hence, a discussion on the results from non-linear static and dynamic analyses is provided, contributing to the improvement of the numerical methods adopted in literature until now.

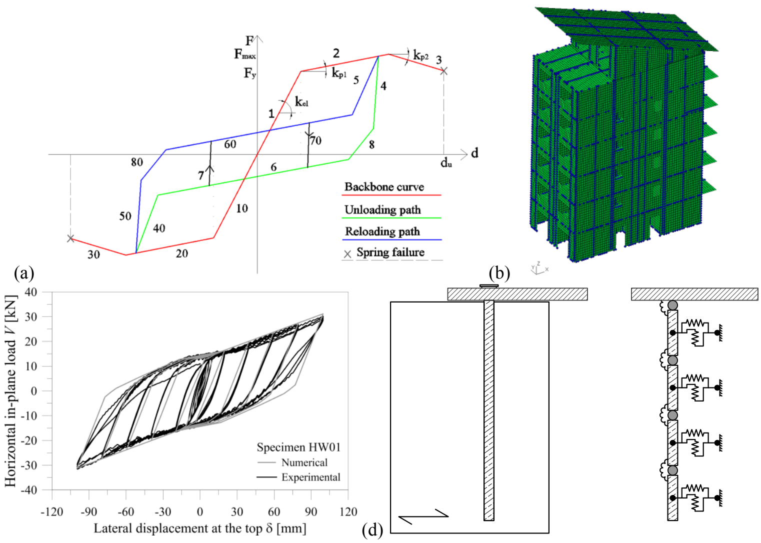


Figure 1: Shear hysteretic law from [1] (a), 3D view of numerical model of a 7-storey CLT buildings from [2] (b), numerical-experimental comparison in terms of base shear vs. top displacement for a Blockhaus wall from [3] (c), schematics of a steel-to-timber joint from [4] (d).

References

[1] Rinaldin G., Amadio C., Fragiacomo M. (2013) A Component approach for the hysteretic behaviour of connections in cross-laminated wooden structures, Earthquake Engineering and Structural Dynamics, 42:2023-2042. DOI: 10.1002/eqe.2310.

[2] Rinaldin G., Fragiacomo M. Non-linear simulation of shaking-table tests on 3- and 7-storey X-Lam timber buildings. Engineering Structures, 113 (2016) 133-148, DOI: 10.1016/j.engstruct.2016.01.055.

[3] Bedon C., Rinaldin G., Fragiacomo M. Non-linear modelling of the in-plane seismic behaviour of timber Blockhaus log-walls. Engineering Structures, 2015, 91, pp. 112-124.

[4] Izzi M., Rinaldin G., Polastri A, Fragiacomo M. Numerical modelling of timber joints with dowel-type fasteners. European Journal of Wood and Wood Products, 2017, under review.

KL II

State-of-the-art and challenges in engineered timber connections

Hans Joachim Blaß

Karlsruhe Institute of Technology (KIT), blass@kit.edu

Since more than half a century, the design of laterally loaded dowel-type fasteners in timber connections is based on the yield model first published by Johansen [1]. He only considered timber-to-timber connections, disregarded normal forces in the fasteners and took into account only the elastic fastener bending capacity. Meyer [2] extended Johansen's model by taking into account the plastic fastener bending capacity as well as the rope effect, the latter caused by tensile forces in nails after the inclination of the fastener axis due to e.g. the formation of plastic hinges. Later developments exploit the high axial capacity of fully threaded screws by an inclined arrangement in timber-to-timber or steel-to-timber connections. While a failure of the fastener itself is extremely rare in softwood timber-to-timber connections with laterally loaded dowels, bolts or smooth nails studied by Johansen or Meyer, the following parameters tend to significantly increase normal or shear forces in fasteners:

- Steel-to-timber instead of timber-to-timber connections. Here, the maximum fastener shear force is located in the shear plane at the same position as the maximum bending moment in failure modes including plastic hinges.
- Improved anchorage of the fastener in timber members e.g. through continuous threads for screws. The fastener normal force and – in steel-to-timber connections – the shear force reduce the plastic fastener bending moment capacity.
- Higher timber densities – e.g. in hardwoods – increase the load-carrying capacity of the connection and thereby the fastener normal and shear forces.
- Inclined fastener arrangement by reducing the angle between fastener axis and shear plane leads to significant decrease in fastener lateral loads and significant increase of fastener normal forces.

While the design of connections with inclined fasteners considers fastener tensile failure, the interaction of fastener bending moment, shear and normal force in laterally loaded fasteners is generally not yet taken into account. The influence of the moment, normal and shear force interaction is shown for relevant cases and a simplified method is discussed to take interaction into account.

In timber structures high load-carrying capacity and stiffness of mechanical connections is generally desirable, since connections mostly are weaker than the members to be connected. Therefore, it is mainly the capacity's lower 5 percentile which is used in design. In structures designed to resist earthquakes however, mechanical timber connections are used as dissipative areas. Here, it has to be ensured that the dissipative connection reaches its plastic capacity before the connected members or other non-dissipative connections fail. Examples for dissipative connections in CLT buildings are joints in shear walls while joints between floor elements typically should be as strong and stiff as possible and energy dissipation is not required there. Figure 1 shows examples of both non-dissipative and dissipative CLT edge connections.

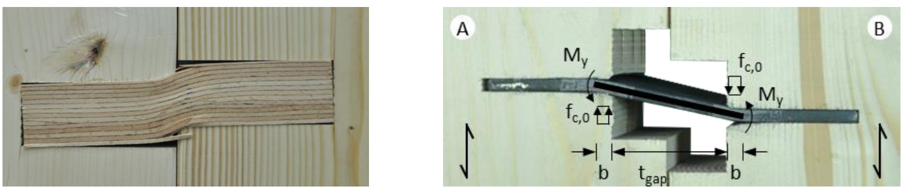


Figure 1: High capacity non-dissipative connection for floor diaphragms (left) and dissipative connection with steel plate bridging deliberate gap (right)

The connection in Figure 1 (left) with shear keys made of Beech LVL is able to achieve the shear capacity of the adjacent CLT members. The gap in the connection in Figure 1 (right) using steel plates as fasteners minimizes the plastic embedding deformation in the CLT member and maximizes the energy dissipation contribution of the steel plate. Thereby the typical pinching of hysteresis loops as well as the impairment of strength during repeated loading in timber connections with laterally loaded dowel-type fasteners is basically avoided and the behaviour during earthquakes remarkably improved. The connection behaviour of different connections is outlined and possible applications are shown.

References

[1] Johansen, K. W., Forsøg med traeforbindelser. Medd. 10, Lab. for Bygningsstatik Danm. Tekn. Højskole, Kopenhagen (1941).

[2] Meyer, A.: Die Tragfähigkeit von Nagelverbindungen bei statischer Belastung. Holz als Roh-und Werkstoff (1957) 15: 96. doi:10.1007/BF02609174

KL III

Multiphysical simulations of wood and wooden structures

M. Kaliske

Institute for Structural Analysis, Technische Universität Dresden, 01062 Dresden, Germany,
michael.kaliske@tu-dresden.de

Over the last decade, intensive experimental research has been conducted and a number of models to describe the physical characteristics of wood have been developed. This contribution gives insight into developments of material and finite element models and the application to describe the load bearing behavior of wooden structures.

The starting point of the load bearing analysis is the macroscopical wooden object of interest. In general, it is a complex, three-dimensional structure, often consisting of several components of different wood species, quality or material direction. The material is characterized by an orthotropic, elastic constitutive model considering the fiber directions. Ductile and brittle failure are described by multi-surface plasticity and cohesive interface formulations, respectively. Even at normal European climate, the moisture dependency of the material is an important aspect in the constitutive characterization. The mechanical performance is strongly dependent on the material's moisture content. Beside the moisture-influenced material properties, hygro-expansion, i.e. swelling and shrinking, will result in constraints and internal stresses, when ambient climate changes over time. Thus, to describe the moisture distribution within a structure versus time, reliable, transient moisture transport models have been developed and implemented. Multi-FICKian diffusion is accounted for leading to higher accuracy in the moisture profile and, thus, stress determination, in comparison to single-FICKian models.

Furthermore, the modeling of moisture- and time-dependent visco-elasto-plastic behavior ("creep") under long-term loading conditions is presented. New macroscopical approaches, considering creep failure, modified hygro-expansion and mechano-sorptive effects have been introduced.

Especially for the long-term behavior, the multi-physical processes in wood are not known in detail. Limited experimental investigations and sometimes contradicting results lead to an uncomplete, uncertain knowledge of material characteristics. However, the natural variation of wood properties is very large, too. In many cases, the characteristics of a structural member are not available and experimental tests not feasible. Fuzzy analyses provide the means to define realistic result intervals, even for usually small data-sets of experimental investigations for the determination of constitutive parameters. Next to these material inhomogeneities, structural inhomogeneities, like branches, knots or resin pockets may influence the mechanical performance on the macro-scale.

For the majority of applications, these models are accurate enough. In case of production of innovative wood products by densification and thermo-hygro-mechanical wood forming processes, another recent research field is devoted to the simulation at large strains.

The mentioned aspects of modeling wood and wooden structures have been investigated and applied to different structures. Simulated examples of face staggered joints with material inhomogeneities up to complex musical instruments at hygro-mechanical loading illustrate the nonlinear, multiphysical complexity and the opportunities of computational engineering techniques in wooden structural analysis.

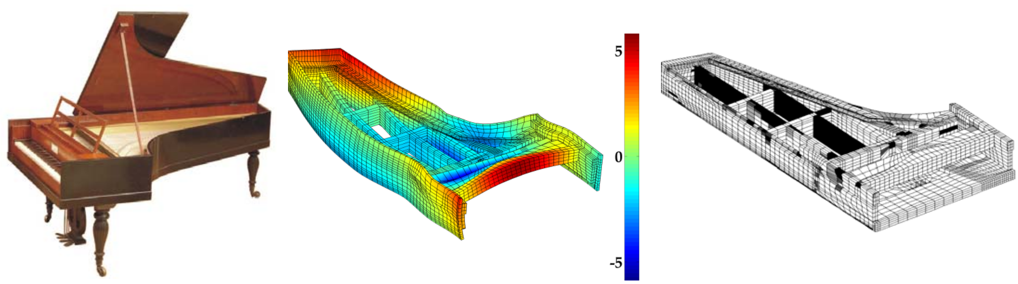


Figure 1: Pianoforte at hygro-mechanical load; moisture induced stresses and deformations dominate (center: vertical displacement in [mm]), hygro-expansion leads to irreversible deformations (right: plasticized elements in black).

Modelling the time-dependent behaviour of wood

Joseph Gril[†]

[†] LMGC, CNRS, Univ. Montpellier, France, joseph.gril@cnrs.fr

This presentation will be dedicated to the memory of David Hunt (1930-2016), who made very significant contributions to the understanding of time-dependent phenomena in wood.

As a hygroscopic polymer wood displays a viscoelastic behaviour strongly influenced by temperature and humidity. The time-dependency of its response to a mechanical loading results from the delayed movements of molecular components under stress, as much as from the kinetics of the sorption process or any other chemical reaction modifying the molecular structure. Mechanosorption is a typical example of such complex interaction. It refers to the phenomena observed when wood is subjected simultaneously to mechanical loading and sorption resulting from changing hygrothermal conditions. The difference between the observed response and that expected from viscoelastic data at constant moisture content (m.c.) (e.g., creep or relaxation) is defined as the mechanosorptive response – although the evaluation of that "expected" response is not straightforward*. Mechanosorption has been commonly modelled as a time-independent process, only governed by variations of the moisture content. This hypothesis is not easily verified due to the time-dependency of the sorption process, and it seems to be in contradiction with observations that it triggers viscoelastic processes. The large dominance of mechanosortive over constant-humidity creep is another belief that needs to be put in perspective: it depends on the reference being the dry or wet state [1].

Based on the work of Ranta-Maunus in the 70ties m.s. was initially modelled using viscous-like elements where time is replaced by m.c., distinguishing desorption (-), adsorption (+) and 'adsorption above highest level reached since loading' (++). Hunt in the 80ties introduced the m.s. 'trajectories' where the creep compliance is plotted against m.c., and the concept of 'creep limit' reached after repeated humidity cycles under load (Fig. 1a-d). He proposed that the creep limit is approached both in sorption and desorption, and explained the apparent recovery during adsorption as moisture expansion modified by strain [2]. This led to rheological models based on combinations of "m.s. dashpots" and springs, commonly used in numerical developments, with viscoelastic components modelled separately. It was also assumed by Matar [3], as a conservative hypothesis, when he derived equations of the long-term creep of softwood as a function of wood quality, in view of improved evaluation of Kdef factor in Eurocode5 (Fig. 1e).

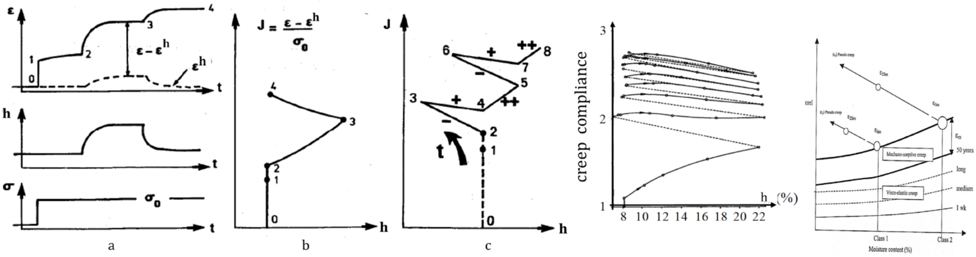


Fig. 1: Construction of mechano-sorptive trajectories: (a) Humidity cycle under constant load; (b) Corresponding trajectory; (c) Representation of Ranta-Maunus model; (d) effect of repeated cycles under load according to Hunt (1992), showing the apparent creep/recovery at the creep limit explained by a modified hygroscopic expansion; (e) Creep prediction combining creep at given m.c., m.s. creep and pseudo-creep/recovery according to Matar (2003).

* "Hygro-locks" is a convenient way to evaluate the "expected viscolelastic response" needed to define, by difference, the m.s. contribution. A hygrolock spring extends when loaded under wetting and does not under drying, and can be combined with dashpots to fit any viscoelastic spectra obtained at different m.c. levels [4]. An equivalent formulation was proposed by Colmars [5] to avoid excessive memory storage in long-term simulations.

References

[1] C. Montéro, J. Gril, C. Legeas, D.G. Hunt, B. Clair: Influence of hygromechanical history on the longitudinal mechanosorptive creep of wood. *Holzforschung* 66(6) (2012), 757-764.

[2] D.G. Hunt: Present knowledge of mechano-sorptive creep of wood, Creep in Timber Constructions (a state of the art report), Rilem Technical Committee, 112,. 1992, pp. 75-104.

[3] A Matar: The mechano sorptive creep of softwood in bending, PhD South Bank U. London, sup. D. Hunt, 2003.

[4] F. Dubois, J.M. Husson, N. Sauvat: Modeling of the viscoelastic mechano-sorptive behavior in wood. *Mechanics of Time-Dependent Materials*, 16(4) (2012), 439-46.

[5] J. Colmars, F. Dubois, J. Gril: One-dimensional discrete formulation of a hygrolock model for wood hygromechanics, *Mechanics of Time-Dependent Materials* 18(1) (2014), 309−328.

KL V

Development of a support structure for the wooden shipwreck Vasa

E. K. Gamstedt, R. Afshar, N. P. van Dijk and A. Vorobyev

Division of Applied Mechanics Division, Department of Engineering Sciences, Uppsala University, Uppsala, Sweden

Three other papers presented at this conference, with van Dijk, Afshar and Vorobyev, respectively, as main authors, deal with structural integrity of the museum ship Vasa. The present paper attempts to put these subtasks into context, with the ultimate goal to provide a numerical model of the ship to be used to assess improved potential support structures. This research project started 4 years ago, and was initiated by the Vasa museum, where conservators and technical personnel had over the years observed increasing creep deformation and degradation of the aging wood. Previous research projects on the Vasa have largely been focused on the chemical degradation of the oak wood to provide understanding of the degradation mechanisms and possible remedies to mitigate the chemical decay, i.e. a bottom-up approach. Since material re-conservation for improved structural stability is cumbersome for large components, a top-down structural engineering project was launched, with the ultimate aim to help designing an improved support structure. The present support structure in the form of cradles was designed based on experience rather than engineering calculations, starting after the shipwreck was salvaged and treated in the 1960s.

First the stress-strain properties were characterized in cubic specimens to save the precious archeological material [1], where the barreling effects were considered [2]. To account for the variability in density, microfibrillar angle, polyethylene glycol (PEG) and moisture content, a micromechanical homogenization scheme has been developed, which can be compared with results from nanoidentation [3]. PEG and moisture are known to have a profound effect on the mechanical behaviour of wood [4]. In addition to material properties, the effects of joint compliance will also affect the deformation of the ship structure. Since mechanical testing inside the ship is not possible, the joint behaviour was characterized in a replica of a hull section of the ship (see Figure 1). Simulation results of stresses and deformations in the ship are shown in Figures 2 and 3. This would allow quantitative comparison of different potential support solutions. Also creep properties of the archaeological wood are being characterized, so that the model can be extended to predictions of future deformation. Geodetic measurements could then be used for validation [5]. The approach undertaken in this project could hopefully be useful in design strategies of improved support for other aging and deforming wood structures in cultural heritage.

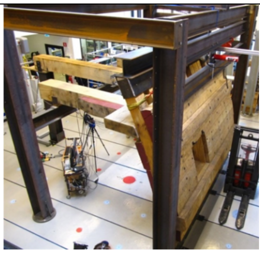


Figure 1 Structural testing of joint compliance in a full-scale replica of a wall section.

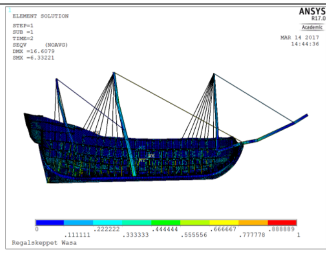


Figure 2 Illustration of FE simulation results showing a longitudinal section of the ship model and corresponding effective stresses in the timber members.

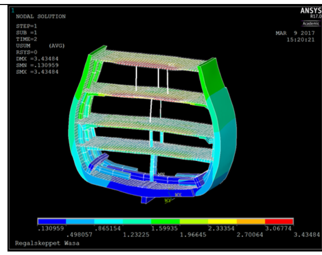


Figure 3 Illustration of FE simulation results showing the displacements in a transverse cross-section of the ship.

References

[1] Vorobyev, A., Arnould, O., Laux, D., Longo, R., van Dijk, N.P. and Gamstedt, E.K., "Characterisation of cubic oak specimens from the Vasa ship and recent wood by means of quasi-static loading and resonance ultrasound spectroscopy", *Holzforschung*, **70** (2015), 457-465.

[2] Vorobyev, A., Bjurhager, I., van Dijk, N.P. and Gamstedt, E.K., "Effects of barrelling during axial compressive tests of cubic samples with isotropic, transversely isotropic and orthotropic elastic properties", *Composites Science and Technology*, **137** (2016), 1-8.

[3] Wagner, L., Almkvist, G., Bader, T.K., Bjurhager, I., Rautkari, L. and Gamstedt E.K., "Influence of chemical degradation and polyethylene glycol on moisture-dependent cell wall properties of archaeological wooden objects: a case study of the Vasa shipwreck", *Wood Science and Technology*, **50** (2016), 1103-1123.

[4] Vorobyev, A., Almkvist, G., van Dijk, N.P. and Gamstedt, E.K., "Effects of density, polyethylene glycol treatment and moisture content on stiffness properties of waterlogged archaeological wood", accepted in *Holzforschung*, 2017.

[5] van Dijk, N., Gamstedt, E.K. and Bjurhager, I., "Deformation analysis of wooden structures of cultural heritage: Translation of geodetic measurements into average strain fields", *Journal of Cultural Heritage*, **17** (2016), 102-113.

I: 1

Numerical simulation of moisture driven fracture in mechanical timber connection using XFEM

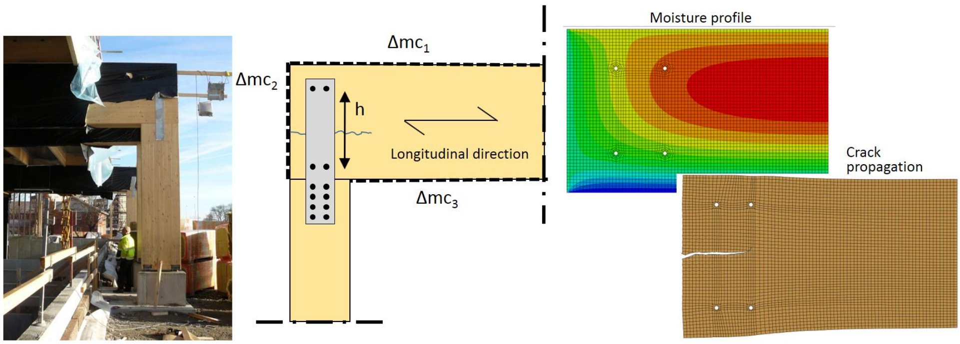
Johan Vessby†*, Sara Florisson† and T. Sisay†

†Department of Building Technology, Linnaeus University, johan.vessby@lnu.se

Structural timber and glulam elements are an appealing alternative when it comes to choosing between structural elements as load bearing parts in e.g. halls, arenas and residential buildings. The wooden material is relatively strong in respect to its weight and its stiffness is sufficient enough to allow its use in a wide range of applications. However, there are also challenges associated with handling the material, one of which is the dimensional instability associated with moisture changes. The effect of climate variations on moisture induced deformations, stresses and failure in timber structures has already been addressed by several researchers, see e.g. [1] and [2]. A numerical model developed in the finite element package Abaqus is proposed herein to simulate crack propagation caused by variation in climate.

In mechanical connections moisture induced strains in combination with boundary conditions that introduces constraints can lead to crack development and in turn weakening of wooden structures. Previous application of fracture mechanics typically focused on crack development caused by pure mechanical loading, see e.g. [3] for methods summarized and typical applications. Within the scope of the current work a numerical model is presented to simulate moisture driven crack growth within the beam/column dowel group connection shown in Figure 1.

The model consists of two dimensional hygro-mechanical plane stress and XFEM analysis coupled to a nonlinear transient moisture flow analysis. A visualization of the considered problem is given in Figure 1. This figure shows a beam to column connection, which is exposed to natural climate variation (*a*). A schematic description of the problem is shown in Figure 1 (*b*). Figure 1 (*c*) shows simulated moisture content gradient and significant cracked beam because of the deformation constraints imposed by the dowels.



(a) (b) (c)

Figure 1: (a) Example of exposed timber beam (b) simplified model of the exposed beam (c) example of crack growth using extended finite element method.

The transient non-linear moisture flow was modelled using Fick's law of orthotropic diffusion, using different diffusion coefficient in the two main directions, the length direction of the beam (assumed *parallel* to the fibers) and the direction *perpendicular* to that. The moisture transport in parallel direction was taken to be dominant. The shrinkage coefficients experience different values in perpendicular and parallel direction, α_{perp} and α_{par}, respectively. For the fracture model, the critical energy release rate, G_{IC}, is set to 300 J/m^2, the strength in the perpendicular direction, $f_{t,perp}$, to 2.5 MPa and the stiffness perpendicular and parallel to the length directions of the fibres are E_{perp}= 500 MPa and E_{par}= 10 000 MPa respectively.

References

[1] Sigurdur Ormarsson S., Gíslason Ó. V., Moisture-induced stresses in glulam frames *European Journal of Wood and Wood Products*, 74: 307–318, 2016.

[2] Saft S., Kaliske M., Numerical simulation of the ductile failure of mechanically and moisture loaded wooden structures *Computers and Structures*, 89: 2460–2470, 2011.

[3] Serrano, E. (2016). Rational modelling and design in timber engineering applications using fracture mechanics. In 2016 World Conference on Timber Engineering.

I:2

A Cohesive Zone Model to study timber-to-steel-plates bonded joints

C. Avez[†], B. Roensmaens[†], M. Verbist [‡*], Jorge Branco[‡] and T. Descamps[†]

[†]University of Mons, coralie.avez@umons.ac.be, bertrand.roensmaens@umons.ac.be, thierry.descamps@umons.ac.be
[‡]University of Minho, verbist.maxime@hotmail.com, jbranco@civil.uminho.pt

When designing a wood structure, the capacity of a connection is almost always lower than that of the members it's linking. Moreover, as minimum distances between connectors or edge distances must be respected, connections can be large and space-consuming. Connections are thus often regarded as the weakest part of a timber structure, and also the most expensive. Hence, finding new connectors and improving existing ones are important issues in the wood construction.

Glued connections can constitute an efficient alternative to classical connectors since they exhibit a high strength and stiffness. Moreover, as they are embedded in timber, they are fire-protected. The main drawback of those connections is the lack of design tools and guidelines.

This paper outlines the development of a finite element model to predict the strength of a glued connection made of steel plates set parallel to the grain in the central layer of a CLT panel, using a two component epoxy, and tested in tension. The timber slot in which the steel plate is inserted is wider than the steel plate thickness, thus producing a 2 millimeter-thick bondline. Apart from its mechanical advantages, this connection is also easy to implement on-site due to its geometry.

However, one drawback of this connection lies in the fact that, if the solid steel plate is not textured, the connection may fail at the interface between the steel and the glue, due to poor adhesion between those materials. Although proper surface preparation - mainly degreasing the steel prior to gluing – can guarantee the process of adhesion between the steel and the adhesive, on-site conditions are not conducive to good surface preparation and gluing process. Hence, ensuring mechanical interlock is the best way of preventing adhesion failure to occur. To highlight the effect of the surface texture, three types of steel plates exhibiting different levels of surface texturing have been tested. The influence of the surface texture of the steel plates on the strength and failure mode of the connection is discussed.

Among the different existing ways of modelling the adhesive thanks to Finite elements [1], cohesive zone models are chosen. Cohesive-zone model enables modelling the linear elastic response of the joint, the initiation of the damage (fracture criterion) and the damage evolution. The damage is defined using simulation tools already implemented in the software used (commercial package Abaqus). The pros and cons of using this modelling technique are discussed in regards with others FE modelling techniques. The model is fed by experimental results conducted on bulk samples of glue, as proposed by other authors [1], [2]. Properties experimentally cost- and/or time-demanding to obtain were calibrated and validated on full-scale specimens made of steel plates glued in CLT. Using cohesive damage modelling, the FE model correctly replicates the strength and failure mode of the three variations of the glued-in solid steel plate connection tested.

[1] L. F. M. da Silva and R. D. S. G. Campilho, *Advances in numerical modeling of adhesive joints*. 2012.

[2] A. M. G. Pinto, A. G. Magalhães, R. D. S. G. Campilho, M. F. S. F. de Moura, and A. P. M. Baptista, "Single-Lap Joints of Similar and Dissimilar Adherends Bonded with an Acrylic Adhesive," *J. Adhes.*, vol. 85, no. 6, pp. 351–376, 2009.

I:3

Numerical simulation of timber shear experimental test with cohesive zone fracture model

Katarzyna Ostapska-Luczkowska[†*], **Kjell A. Malo**[‡]

[†]Norwegian University of Technology, katarzyna.ostapska-luczkowska@ntnu.no
[‡]Norwegian University of Technology, kjell.malo@ntnu.no

A new specimen developed for shear modulus and shear strength identification [1] in wood is investigated. The experimental data obtained for tested specimens are analyzed numerically with the nonlinear fracture modeled with cohesive elements, see [3]. The pith location influence on the shear strength and fracture surface is investigated.

The fracture model is utilized to identify modes of failure other than pure shear mode in the direction parallel to wood grain. The presence of the opening mode caused by tension and bending in the specimen affects the estimation of shear properties. Numerical simulation of the full behavior in elastic and non-elastic stage allows for calculation of corrected pure shear properties. Moreover, the mixed LR-LT shear mode failure is analyzed based on the shape of the failure surface for each specimen.

Specimens tested experimentally have varied dimensions of width, height and shear zone length in between cuts, as can be seen in Figure 1. The desired crack location is indicated by the red color line in the figure below.

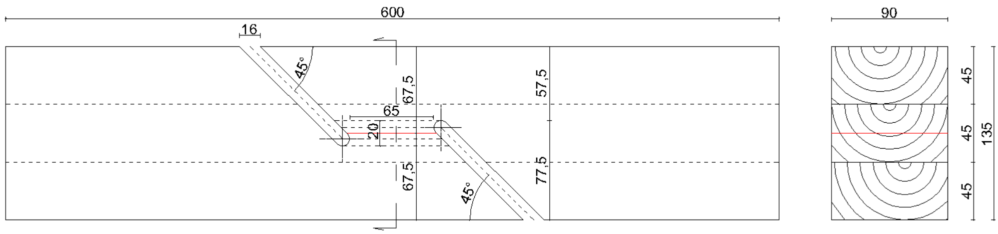


Figure 1: Example of shear specimen plan view and cross-section. Red line indicates expected fracture surface location.

Cohesive elements applied in the simulation of the crack progress are inserted in the predicted crack zone. The initial elastic compliance for the intrinsic bi-linear traction-separation law (TSL), crack initiation criteria and evolution law are specified both in the normal and in the respective shear direction. The initial elastic slope of TSL is assumed high enough as not to cause the artificial compliance in the whole model at the elastic stage. Crack initiation criteria are strength based and evolution law is energy based with the mixed mode rule assumed as quadratic traction-separation criterion.

The total fracture energy is the sum of single mode fracture energies:

$$G_T = G_n + G_s + G_t \tag{1}$$

Where G_n is normal mode fracture energy and G_s and G_t are first and second shear direction respectively. The experimental data collected for different specimen dimensions are presented in the Table 1.

Table 1 : Shear modulus and shear strength mean values obtained from experiments in [1].

Height of specimen [mm]	Width of specimen [mm]	Length of the shear zone [mm]	G_{mean} [MPa]	$f_{v,mean}$ [MPa]
600/640	135	65	1084,15	4,44
600/790	225	115	1061,52	4,88
600/800/940	315	165	1062,57	4,83
600/1050	200	165	1242,4	4,03

References

[1] L. Sigbjørnsen: Shear Properties of Nordic Glulam CE L40c. Master's Thesis, NTNU, Department of Structural Engineering, 2012. http://hdl.handle.net/11250/237143
[2] I. Smith, E. Landis, M. Gong: Fracture and Fatigue in Wood. John Wiley Sons, (2003).
[3] S. Vasic, I. Smith, E. Landis: Finite element techniques and models for wood fracture mechanics. *Wood Science and Technology*, 39 (2005), 3-17.

I:4

A microstructure-based multisurface failure criterion for the description of brittle and ductile failure mechanisms of wood

Markus Lukacevic[†*], **Josef Füssl**[†], **and Josef Eberhardsteiner**[†]

[†]Vienna University of Technology, markus.lukacevic@tuwien.ac.at

As a natural composite, the failure behavior of wood highly depends on structural features on several lower length scales. Thus, an approach for the prediction of failure mechanisms of wood has been proposed, leading to a better description of mechanical processes in wood and, thus, to an improved performance of wood-based products in service.

In the last step of our damage concept for wood [1], previously proposed failure criteria [2] were applied to finite element unit cells at the annual ring scale. Extensive parameter studies on load combinations allowed the identification and classification of the main failure mechanisms at the clear-wood level. Based on these findings, a single multisurface failure criterion was formulated, which is able to represent brittle and ductile failure mechanisms. Figure 1 shows the 3D representation of the new failure criterion, where red surfaces indicate crack initiation (surfaces 1 to 3 and 7) and blue ones plastic failure surfaces (surfaces 4 to 6 and 8). Furthermore, to enable the simultaneous simulation of plastic failure and crack initiation, an algorithm for multisurface failure criteria was presented.

In addition to the previous validation of failure mechanisms and crack patterns at the annual ring scale [2], comparisons of the new multisurface failure criterion to an extensive set of experiments of clear-wood spruce samples in the LR-plane showed that both ductile and brittle failure mechanisms can be predicted very well. Furthermore, the application of the model to a dowel-type timber connection confirmed the tool's capability to represent both plastic failure and the development of cracks at the same time, even in confined regions.

By implementing this new failure criterion into previous developments of a numerical simulation tool for wooden boards [3-6], which enables the mathematical description of fiber deviations in the vicinity of virtually reconstructed knots, realistic simulations of complex failure mechanisms of not only single wooden boards and their use in timber connections but also of more complex wood-based products, like Glulam and CLT elements, are rendered possible. Furthermore, the simulation tool is used in the development of new wood composites, by making the material wood more predictable and, thus, more interesting for engineering applications.

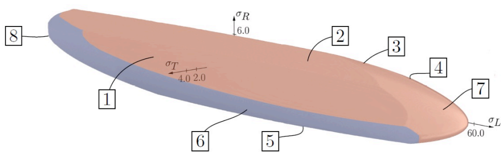


Figure 1: 3D representation of the failure surfaces in the σ_L-σ_R-σ_T stress space with the shear stresses being equal to zero.

References

[1] M. Lukacevic, W. Lederer, J. Füssl: A microstructure-based multisurface failure criterion for the description of brittle and ductile failure mechanisms of clear-wood. *Engineering Fracture Mechanics*, DOI: 10.1016/j.engfracmech.2017.02.020

[2] M. Lukacevic, J. Füssl, R. Lampert: Failure mechanisms of clear wood identified at wood cell level by an approach based on the extended finite element method. *Engineering Fracture Mechanics*, 144:158–175, 2015

[3] C. Hackspiel, K. de Borst, M. Lukacevic: A numerical simulation tool for wood grading model development. Wood science and technology, 48(3), 633-649, 2014.

[4] M. Lukacevic and J. Füssl: Numerical simulation tool for wooden boards with a physically based approach to identify structural failure. *European Journal of Wood and Wood Products*, 72(4):497–508, 2014.

[5] M. Lukacevic, J. Füssl, M. Griessner, J. Eberhardsteiner: Performance assessment of a numerical simulation tool for wooden boards with knots by means of full-field deformation measurements. *Strain*, 50(4):301–317, 2014.

[6] M. Lukacevic, J. Füssl: Application of a multisurface discrete crack model for clear wood taking into account the inherent microstructural characteristics of wood cells. *Holzforschung*, 70(9):845–853, 2016.

Experimental exploratory study of failure modes in models of wooden rectangular beams

Alexandre de Macêdo Wahrhaftig

Federal University of Bahia (UFBA), Polytechnic School, Department of Construction and Structures (DCE)
Rua Aristides Novís, Nº 02, 5º andar, Federação, Salvador – BA, Brazil, CEP: 40210-910
alixa@ufba.br

According to the study of mechanical properties, wood is an elastic or elastoplastic material that presents different structural behaviour when tensioned or compressed. From the viewpoint of elasticity, wood is considered anisotropic, or rather it is a material with elastic properties that vary with the direction considered, unlike an isotropic material, in which they remain constant.

During tree growth, the internal structure of the solid material consisting of the wood becomes highly oriented and therefore anisotropic. On a macroscopic level, the arrangement of the timber structure results in length and diametric growth processes. The structure of the timber is therefore usually referred to two privileged axes related to these directions: the longitudinal direction (L) along the fibre and the radial direction (R) relative to the annual growth rings. A third direction (T) is tangential to the annual growth rings. The three orthogonal planes (RT, RL, and LT) formed by these directions are then three planes of symmetry of the internal structure of the wood. The anisotropy of the wood also stems from its cell structure, which is mostly composed of fibrous material and will have an impact on the apparent mechanical properties of the wood.

To study the failure modes of wooden parts and to observe their anisotropy in this process, we performed a series of exploratory tests on models of beams, taking into account the different positions of fibres and growth rings and the different relationships between height and length. The pieces were made of dicotyledonous wood that was first class and free of defects with a moisture content of about 15%, making a total of nine samples in three groups. Failure by shearing and normal stresses was observed and was well characterized in terms of records left in the samples, as exemplified in Figure 1. In addition, when describing the failure modes, the results are discussed with the presentation of images and graphics for each case.

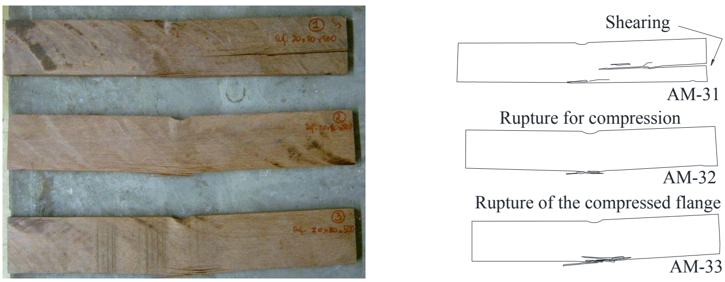


Figure 1: Example of a result found in the experimental exploratory investigation

References

[1] Konopka, D., Gebhardt, C., & Kaliske, M., Numerical modelling of wooden structures. *Journal of Cultural Heritage*, (2016). doi:10.1016/j.culher.2015.09.008.

[2] Pitti, R. M., Dubois, F., & Pop, O., Sur une éprouvette assurant la stabilité de la propagation de fissure en mode mixte dans le matériau bois. *Comptes Rendus Mécanique*, (2008) 336, pp. 744–749. doi:10.1016/j.crme.2008.07.004.

[3] Lukacevic, M. & Fussl, J., Numerical simulation tool for wooden boards with a physically based approach to identify structural failure. *Eur. J. Wood Prod.* (2014) 72, pp. 497–508. doi:10.1007/s00107-014-0803-y.

[4] Zhu, J., Nakano, T., Tokumoto, M., & Takeda, T., Variation of tensile strength with annual rings for lumber from the Japanese larch. *Wood Sci.*, (2000) 46, p. 284. doi:10.1007/BF00766218.

[5] Yates, J.K. & Lockley, E.E., Documenting and analysing construction failure. *Journal of Construction and Engineering Management*. (2002). doi:10.1061/(ASCE)0733-9364(2002)128:1(8).

I:6

On the hierarchical structure of wood and its mechanisms providing high tensile strength

Otte Marthin†*, and Kristofer Gamstedt‡

†Applied Mechanics, Uppsala University, Sweden, email: otte.marthin@angstrom.uu.se
‡Applied Mechanics, Uppsala University, Sweden, email: kristofer.gamstedt@angstrom.uu.se

Wood materials show a remarkable strength and damage tolerance compared with manmade materials, especially if one considers the relatively simple building blocks and low density of wood. A particular feature of wood, which is also the case of many other load-carrying biological materials, is the hierarchical structure [1]. In the case of wood, the cellulose chains are bonded together into elementary microfibrils, which are bonded into microfibrils, which form the cell-wall of the tracheids, which are layered into annual rings, forming the stem of the tree. Similar hierarchical features can be found in tendons, bone, muscles, as well as in manmade ropes, all of which have a very high macroscopic tensile strength, considering their constituent materials. In tensile rupture of these materials, there are simultaneous fracture processes accumulating on multiple length scales. The fracture surface area is typically immense, as is the amount of dissipated energy [2]. A literature survey has been carried out, to relate estimates of the tensile strength of the fibers on each length scale to the shear strength of the stress-transferring matrix between fibers at the same scale. A suitable relationship between the two values triggers a balance between fiber rupture and crack deflection, which can increase the fracture toughness and damage tolerance, at several length scales. A review of these mechanisms will be presented.

Numerical studies with input parameters from wood materials have been initiated to simulate the damage accumulation leading to final failure, in an attempt to show how strength can be improved by a hierarchical design. How some of these aspects may be transferred to toughening of engineered composites will also be discussed.

References

[1] P. Fratzl, R. Weinkamer: Nature's hierarchical materials. *Progress in Materials Science*, 52 (2007), 1263-1334

[2] E. Much, M. E. Launey, D. H. Alsem, E. Saiz, A. P. Tomsia, R. O. Ritchie: *Science*, 322 (2008), 1516-1520 Science. 2008;322(5907):1516-20.

Timber models and prediction of stiffness and strength

Anders Olsson†*, Min Hu†

†Linnaeus University, 351 95 Växjö, Sweden, anders.olsson@lnu.se

Machine strength grading of timber has been performed since about fifty years, first using flatwise bending machines and later using dynamic excitation of axial resonance frequencies in combination with weighing. Using these methods coefficients of determination, between indicating properties (IP) and bending or tension strength, of about $0.50 < R^2 < 0.55$ are reached for Norway spruce. Today, the most accurate methods available on the market comprise X-ray or tracheid effect scanning in combination with dynamic excitation. Application of such methods give coefficients of determination to bending strength of about $0.64 < R^2 < 0.69$. The purpose of this presentation is to discuss hypotheses and strategies to be able to reach future improvements in machine strength grading in the future.

Computational mechanics can be used for assessment of stiffness and strength of almost any structure, if the material and geometrical properties of it are known in sufficient detail. Thus, the challenge in strength grading of timber is to establish sufficiently accurate mechanical models of individual boards. The use of such models in machine strength grading require (a) that the models can be established on the basis of data that can be sampled by machines in production speed at sawmills and (b) that the necessary calculations can be performed in this high speed too. During development, however, it is reasonable to focus on the ability of a timber model to capture, in sufficient detail, the mechanical properties of each physical board.

Researchers have often assumed that a single weak zone somewhere along the board, caused by a single big knot or a group of knots, determines the bending strength of the board. In accordance with this assumption Olsson et al. [1] presented a model by which a critical local edgewise bending stiffness is calculated, on the basis of a combination of dynamic axial modulus of elasticity (MOE) and high resolution fiber orientation data of the wood surfaces. Furthermore, they also showed [2] that the application of such local stiffness as IP to bending strength gives among the most accurate prediction of bending strength of Norway spruce timber that has been reported for large timber samples (more than 900 pieces). Also other strength grading methods that are available on the market and able to give accurate predictions of bending strength, e.g. strength grading machines that utilize information from X-ray scanning, are based on assessment of single, local, weak zones in combination with dynamic axial MOE.

A novel hypothesis, according to which global buckling in the edgewise direction may be involved when boards loaded in edgewise bending reach their ultimate load, has been presented by Petersson et al. [3]. If such buckling occurs, global measures of stiffness, and several different weak zones within a board, rather than a single weak zone, should be decisive for the ultimate load capacity. It has also been shown [4] that very accurate prediction of bending strength can be achieved on the basis of a global board stiffness measure in combination with another global measure, namely a measure of the overall inhomogeneity of the board. The latter measure is obtained by utilizing a set of resonance frequencies corresponding to edgewise bending modes of boards. The investigation, [4], however, only comprised a small timber sample of 105 boards.

The aim of this presentation is to discuss and tentatively assess the quite different views and explanations regarding bending strength of timber discussed. For this purpose, an extensive database of experimental data is available. Moreover, work aiming at the establishment of finite element (FE) models that are able to accurately capture both local and global stiffness of boards will be presented. Such models are needed for development and assessment of different types of new or improved strength grading methods. For the purpose of verification of the ability of FE models to capture stiffness on local levels, and for assessment of suitable measures of local stiffness, digital image correlation giving strain fields over two wide surfaces of boards subjected to bending are used.

References

[1] A. Olsson, J. Oscarsson, M. Johansson and B. Källsner. Prediction of timber bending strength and in-member cross-sectional stiffness variation on basis of local wood fibre orientation. *European Journal of Wood and Wood Products,* 71 (2013), 319-333.

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

[3] H. Petersson, B. Källsner, S. Ormarsson: Strength grading of structural timber based on buckling analysis and scanning techniques. *World Conference on Timber Engineering*, August 22-25, 2016, Vienna.

[4] A. Olsson, J. Oscarsson, E. Serrano, B. Källsner M. Johansson, B. Enquist: Prediction of timber bending strength on basis of bending stiffness and material homogeneity assessed from dynamic excitation. *Wood Science and Technology, 46 (2012), 667-683.*

II:2

Prediction of oak wood mechanical properties based on vibratory tests

Y.FAYDI[1], L.BRANCHERIAU[2], G.POT[1], R. COLLET[1]

[1] LaBoMaP , Arts et Metiers, HESAM, COMUE BFC, 71250 Cluny
[2] CIRAD - Département PERSYST, UPR 114 "Biomasse, bois, énergie, bio-produits"
TA B114/16 73 Rue Jean François Breton 34398 Montpellier Cedex 5

Visual grading of timber downgrades wood mechanical properties comparing to machine grading [1]. The most widely recognized grading machines are based on resonance frequency measured from vibratory tests. The prediction of the modulus of elasticity (MOE) can be accurately determined with these vibratory methods [2]. However it is more difficult to predict the modulus of rupture (MOR) especially in the case of low correlation between MOE and MOR. Indeed, this work concerns low grades of French oak for which the coefficient of determination between MOE and MOR equals 0.4.

The present paper presents a deeper exploitation of output parameters of vibratory tests in the aim of a better prediction of the MOR. To achieve that, two statistical methods are introduced.

The first one is Partial Least Squares (PLS) for which each amplitude of the spectrum is considered as a predictive variable. The same method has been used before for larch species [3] but in this latter work the predictions of MOE and MOR depended on board's section and percussion impact. In the present study, these effects have been removed thanks to a normalization of the signal.

The second method relies on global output parameters of vibratory tests (Young modulus, shear modulus, density..etc) totaling 31 parameters. A stepwise regression is applied to reveal the most correlated parameters to observations (MOE or MOR).

For a set of 150 oak boards with different sections, the efficiency of models is evaluated through the coefficient of determination between the predictive values and values obtained thanks to four points bending tests (MOE and MOR). To estimate the stability of models, a cross validation technique is used and consists in partitioning the original sample into a calibrating set to set the model, and a validating set to evaluate it. At the end, the root mean square of cross validation (RMSECV) is calculated. Table 1 shows a comparison of the two proposed methods and the usual one.

	MOE		MOR	
Variable or method of prediction	**R^2**	**RMSECV (MPa)**	**R^2**	**RMSECV (MPa)**
Acoustic compression MOE from first Eigen frequency	0,76	1109	0,27	19,3
PLS based on full vibrational spectrum	0,64	1553	0,63	17,3
Stepwise regression based on Eigen frequencies	0,86	883	0,46	17,2

Table 1 : Main results of MOE and MOR prediction

Stepwise technique significantly improves the prediction of MOE and reduces the error of prediction comparing to a compression vibratory test based only on the first Eigen frequency. PLS allow to enhance the coefficient of determination of the MOR from 0.27 to 0.63. However, it is difficult to make a difference between PLS and stepwise methods because their RMSECV are close: both are reduced by 2 MPa compared to a usual vibratory test based only on the first Eigen frequency. These results are being confirmed by a large experimental campaign including 450 boards of French oak. They show that a deeper exploitation of vibratory signals can lead to a better wood grading.

Acknowledgement

This study is sponsored by regional council of Bourgogne Franche-Comté and Carnot ARTS institute.

References

[1] R.Collet, L.Bleron, J. Croisel, JD. Lanvin : The processing of small low-grade French oaks into solid cross laminated panels, International Scientific Conference on Hardwood Processing (2011).

[2] H. Baillères, G.Boughton L.Brancheriau: Strength and stiffness assessment technologies for improving grading effectiveness of radiata pine wood. BioResources 7(2012), pp.1264–1282.

[3] L.Brancheriau, H.Baillères: Use of the Partial Least Squares Method with Acoustic Vibration Spectra as a New Grading Technique for Structural Timber. Holzforschung 57(2003), pp. 644–652.

Predicting particleboard modulus of rupture through artificial neural networks using production parameters

García Fernández F.[†*], de Palacios P.[†], García-Iruela A.[†], García Esteban L.[†] and González Rodrigo B.[‡]

[†1]Dpto. de Sistemas y Recursos Naturales. Universidad Politécnica de Madrid, francisco.garcia@upm.es, paloma.depalacios@upm.es, a.garciai@alumnos.upm.es, luis.garcia@upm.es
[‡]Dpto. Ingeniería Civil: Construcción, Infraestructuras y Transportes. Universidad Politécnica de Madrid, beatriz.gonzalez.rodrigo@upm.es

According to the latest FAO[1] data, global particleboard production is estimated at 100 million cubic metres, generating a market of $15.1 \cdot 10^3$ million dollars.

One of the most important properties of particleboard for its structural use is modulus of rupture (MOR). However, the test for this property lacks the immediacy necessary for real-time application to production line control. To reduce the delay in obtaining results, which affects the entire industry[2], it would be beneficial to have modelling tools to enable determination of mechanical properties using parameters taken directly from the production line. In relation to this, the use of artificial neural networks (ANN) has grown in recent years in various fields of science and technology. The nature of ANNs as universal function approximators[3] makes them powerful modelling tools, particularly when it is important to obtain a high degree of reliability rather than determining the relations between the variables involved[4].

These mathematical models have been successfully applied to obtain the mechanical properties of wood-based products using more easily-measured properties[5] or manufacturing parameters[6]. In this study, an ANN was developed to model particleboard MOR using manufacturing parameters, obtaining sufficient reliability[5] for application in the factory.

To do this, 300 particleboard panels were used, obtaining the MOR of panels straight off the production line and relating it to the production parameters of temperature of strands and resin, moisture content of the mat, adhesive percentages, percentage and type of additives, conveyor speed and press temperature. To develop the neural network, the same methodology described by the authors in earlier research studies was followed[5]. The results obtained for the artificial neural network are shown in the following table (table 1).

Table 1. Result of the artificial neural network design and testing process

Property	Phase	Structure	Equation	R	p-value	Signif. diff.
MOR	Training	[8 7 2 1]	$Y=0.74 \cdot X+3.3$	0.87	0.36	No
	Validation		$Y=0.66 \cdot X+4.2$	0.79	0.27	No
	Testing		$Y=0.49 \cdot X+6.2$	0.72	0.10	No

As the correlation coefficient was higher than 0.70 and there were no significant differences between the real and the simulated values for the testing set, the network obtained can be accepted for determining MOR using the manufacturing parameters[5] and, therefore, for application in production line control in the factory.

This study is part of the Research Project AGL2013-43510-R of the 2013-2016 National Plan for Scientific and Technical Research and Innovation of the Ministry of Economy and Competitiveness of the Government of Spain.

References

[1] Food and Agriculture Organization of the United Nations (FAO): *ForesSTAT* (2010). http://faostat.fao.org/site/626/DesktopDefault.aspx?PageID=626#ancor [accessed 16 June 2016].
[2] D.F. Cook, C.T. Ragsdale, R.L. Major. Combining a neural network with a genetic algorithm for process parameter optimization. *Engineering applications of artificial intelligence* 13 (2000), 391-396.
[3] K. Hornik, M. Stinchcombe, H. White: Multilayer feedforward networks are universal approximators. *Neural Networks* 2 (1989), 359-366.
[4] R.D. De Veaux, J. Schumi, J. Schweisberg, L.H. Ungar: Prediction intervals for neural networks via nonlinear regression. *Technometrics* 40(4) (1998), 273-282.
[5] F. García Fernández, P. de Palacios, L.G. Esteban, A. García-Iruela, B. González Rodrigo, E. Menasalvas: Prediction of MOR and MOE of structural plywood board using an artificial neural network and comparison with a multivariate regression model. *Composites: Part B,* 43 (2012), 3528-3533.
[6] D.F. Cook, C.C. Chiu: Predicting the internal bond strength of particleboard, utilizing a radial basis function neural network. *Engineering applications of artificial intelligence* 10 (1997),171-177.

II:4

In-plane buckling analysis of transversely loaded timber beams

Hans Petersson[†*], Bo Källsner[†], and Johan Vessby[†]

Linnæus University, hans.petersson@lnu.se, bo.kallsner@lnu.se and johan.vessby@lnu.se

Finite element modelling is applied in the buckling analysis and obtained results are compared with experimental results from timber boards tested in accordance to the European standard EN 408. Some of the results obtained were presented in [1] and further findings and conclusions about the modelling will be presented. Only in-plane buckling analysis will be treated and the influence of combined axial and transverse loading on bending strength will be discussed. The results obtained appear promising in providing reasonably accurate predictions of structural strength.

The loadbearing capacity of transversely loaded timber beams are in timber engineering today determined by use of a strength criterion, where the so called bending strength f_m is considered as a characteristic material value representative for the material wood. However, an in-plane transversely loaded beam can, when the beam part in tension reloads, buckle in a similar way as the buckling of a compressed column. This phenomenon of reloading of the tensioned part is in most cases the reason why a slender or intermediately long timber beam fails due buckling when it is transversely loaded.

In an in-plane beam analysis usually a reference axis x is introduced related to the gravity centre of the entire cross section. The displacements of this axis (axial u, transversal w and rotational r) express the displacements all over the beam volume if plane sections are assumed to remain plane. To model the new buckling phenomenon two separate reference axes are introduced: one for Part 1 in compression and one for Part 2 in tension. In the beam analysis six displacement variables are used of which two can be eliminated. This will make it possible to take into account that the displacement variables according to ordinary beam theory are included (3 variables), that the connection area between Part 1 and Part 2 coincides (2 variables) and that one additional variable of importance can be included.

How the material stiffness parameters are varying in wood is strongly dependent on tree growth. The property variation in the radial direction from pith to bark is of great importance. The problem of finding the main principal material directions and the characterization of the material stiffness properties with respect to the radial distance from pith were treated in [2]. Such an approach might be applied in a more accurate analysis where it is too imprecise to use the same constant value E for the axial and bending stiffnesses and a single constant value for the shear modulus G.

If the longitudinal E-modulus approximately is considered as constant (either $E=E_{global}$ or $E=E_{local}$) the bending stiffness is $Ebh^3/12$ and the axial stiffness is Ebh. Then the failure load for a beam loaded in four point bending can be expressed by a critical bending moment M_{cr} or alternatively by a formal bending strength as $f_m = 6\, M_{cr}/b\,h^2$. In [1] a relation between the bending strength f_m and the longitudinal elasticity modulus E was given as $f_m = 0.0040\, E$. This relation was obtained from in-plane buckling analysis using the assumptions of a constant E -value and a shear modulus of $E/16$. The numerical results were compared with experimental results presented in [3], where the specimens were tested according to EN 408. The ratio between the mean values of f_m and E from eight test series was in an astonishing good agreement with the computed results. Over five hundred tested boards with different cross sectional dimensions were studied.

References

[1] H. Petersson, B. Källsner and S. Ormarsson: Strength grading of structural timber based on buckling analysis and scanning techniques, WCTE 2016 World Conference on Timber Engineering, August 22-25, 2016, Vienna, Austria.

[2] H. Petersson: Use of optical and laser scanning techniques as tools for obtaining improved FE-input data for strength and shape stability analysis of wood and timber, European Conference on Computational Mechanics, Paris, 2010.

[3] A. Olsson, B. Källsner, J. Oscarsson and B. Enquist: A new paradigm in strength grading of structural timber (in Swedish). Linnaeus University, Faculty of Technology, Report No 29, 2014.

Experimental and Numerical Investigation of Grain Orientation of Timber with Knot by Using Digital Image Analysis

Tzu-Yu Kuo†* and Wei-Chung Wang‡

† Department of Power Mechanical Engineering, National Tsing Hua University, Taiwan, Republic of China, asmit.com@msa.hinet.net

‡ Department of Power Mechanical Engineering, National Tsing Hua University, Taiwan, Republic of China, wcwang@pme.nthu.edu.tw

Wood is a kind of orthotropic composite material found in natural. The mechanical behavior of wood depends on the grain orientation [1], percentage of latewood [2], and distribution of knot [3, 4], etc. One specimen shown in Fig. 1 was adopted to analyze the mechanical properties. The digital image processing technique was applied to determine the grain orientation. Figures 1(a) and 1(c) were used to find the grain orientations. Figure 1(c) was used to determine the size and position of knot. Figure 1(b) was used to calculate the proportion of latewood. Based on the obtained grain orientation and knot information, finite element method (FEM) was employed to calculate the strain distribution of the test specimen. The three-dimensional digital image correlation (3D-DIC) method was used to analyze the surface deformation of the specimen under four-point bending.

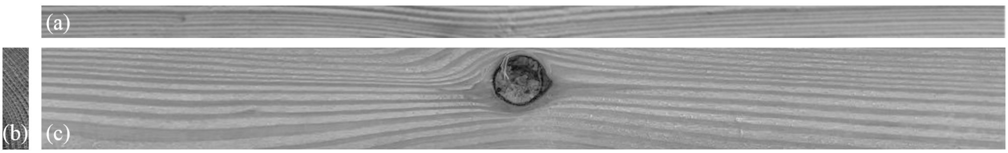


Figure 1: The images of the specimen surfaces (a) longitudinal-radial, (b) radial-tangential and (c) longitudinal-tangential.

Japanese cedar (Cryptomeria japonica), produced in Hsinchu County of northern Taiwan, was used as the specimen material in this study. Before experiment, the specimen was placed at 25°C and controlled at 60% relative humidity for more than one week. The digital image processing software of MATLAB was applied to determine the grain orientation and knot position by the surface image of wood specimen. During the process of determining grain orientation and knot, the image had to be filtered because of too much unnecessary information such as noise. The first step of image processing was to change color image to gray level image. Second, linear filter was used to smooth images. Third, histogram equalization was conducted to enhance the contrast and to make edge lines of grain clearer. And then, edge detection method was employed to find the grain edge. Finally, the least squares method was applied to measure the angle of grain orientation. To verify the results of the angle of grain orientation, the MATLAB results were substituted into FEM software, ANSYS, to simulate strain behaviors of wood plates under four-point bending. During the experiment, the DIC software, VIC-3D, was used to analyze the surface deformation.

In this paper, digital image processing technique was adopted to measure wood grain orientation and knot by the surface image of the wood specimen. The angles of grain orientation thus obtained were substituted into the FEM software, ANSYS, to simulate strain behaviors of wood plates under four-point bending. Based on the 3D-DIC results, the findings show that the variation of grain orientation and knot would affect the stiffness of the wood plates. Moreover, with the use of the effective stiffness, the tendency of the 3D-DIC results can be correctly calculated from the ANSYS results. Therefore, the proposed method presented in this paper has great potential to predict the reliability and safety of wood constructions.

References

[1] T. Y. Kuo and W. C. Wang: Experimental and numerical investigation of effects of fiber orientation of wood stiffness. *5th International Symposium on Experimental Mechanics (5-ISEM'2015) and 9th Symposium on Optics in Industry (9-SOI)*, Guanajuato, Mexico, August 17-21, 2015.

[2] T. Y. Kuo and W. C. Wang: Determination of effective modulus of elasticity of wood from proportion of latewood. *2016 World Conference on Timber Engineering (WCTE 2016)*, Vienna, Austria, August 22-25, 2016.

[3] A. Briggert, M. Hu, A. Olsson and J. Oscarsson: Evaluation of three dimensional fiber orientation in Norway spruce using a laboratory laser scanner. *2016 World Conference on Timber Engineering (WCTE 2016)*, Vienna, Austria, August 22-25, 2016.

[4] G. Kandler, M. Lukacevic, J. Füssl: From the knot morphology of individual timber boards to the mechanical properties of glued laminated timber. *2016 World Conference on Timber Engineering (WCTE 2016)*, Vienna, Austria, August 22-25, 2016.

II:6

Experimental and numerical investigations on the mechanical behavior of glued laminated timber

Georg Kandler†*, Markus Lukacevic† and Josef Füssl†

†Vienna University of Technology, TU Wien, georg.kandler@tuwien.ac.at

Timber is a naturally grown material and each timber board exhibits a unique knot pattern and spatial fluctuation of mechanical properties. Within glued laminated timber (GLT) the variations in the effective mechanical properties are reduced due to homogenization effects. However, particularly in regards of structural failure mechanisms, the wooden board morphology still has significant impact. An automated knot reconstruction algorithm is used for obtaining the knot morphology of a sample of 50 GLT beams. Considering the knot morphology, within this study the experimentally observed mechanical behaviour of these beams is evaluated and interpreted.

The 3D knot morphology is reconstructed from fibre angle measurements on the surface of each board and an estimate of the pith location. The resulting fibre angle measurements are used to determine knot areas on all wooden surfaces. In addition to these automatically obtained knot areas, the pith location is recorded manually. The binary field indicating knot intersection areas on the surfaces combined with the pith location allows the reconstruction of each knot by means of a rotationally symmetric 3D cone [1].

Once the knot geometries are reconstructed within each board, effective mechanical properties for knot groups can be computed from suitable indicating properties. The obtained 3D data for all knots is further used to determine a 3D fibre angle distribution within the volume of the board, based on the so-called grain-flow analogy [2]. Subsequently, through a 3D finite element analysis, a spatial distribution of mechanical properties within each timber board is obtained. As result, a stiffness or strength profile for each timber board was generated, which can then be used for further analysis.

With the stiffness and strength properties of each timber board at hand, 50 GLT beam specimens could be virtually reconstructed with high accuracy, cf. Figure 1. Subsequently, the morphological and mechanical parameters of individual knot groups are compared to the actual failure mechanisms that occurred during experimental testing of the specimens. This yields new possibilities for assessment and interpretation of different indicating properties.

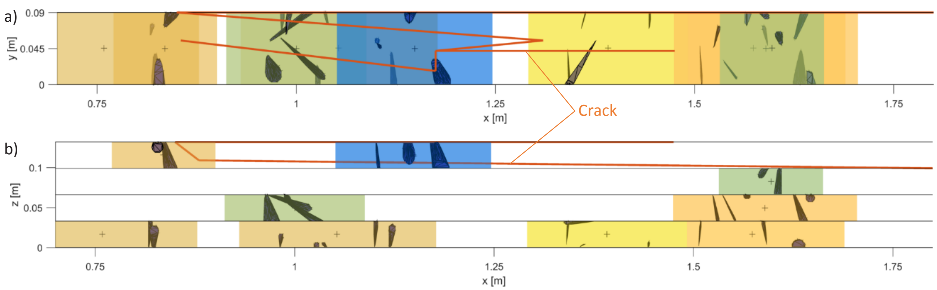


Figure 1: (a) Top and (b) side view of reconstructed knot groups and the experimentally observed crack of a 4-lamella specimen under bending load

In conclusion, starting at clearwood properties and measurements of fibre angles on the surface of a timber board, realistic distributions of mechanical properties within each wooden board are determined numerically. Based on knowledge of single timber board properties, the mechanical behaviour of glued laminated timber beams can be interpreted in new ways. Subsequently, this may lead to more advanced models for deterministic and probabilistic analysis of GLT beams.

References

[1] G. Kandler, M. Lukacevic & J. Füssl: An algorithm for the geometric reconstruction of knots within timber boards based on fibre angle measurements. *Construction and Building Materials*, 2016, 124, 945-960.

[2] C. Foley: A three-dimensional paradigm of fiber orientation in timber. *Wood Science and Technology*, 2001, 35(5), 453-465.

[3] Kandler, G., Füssl, J., Serrano, E. & Eberhardsteiner, J.: Effective stiffness prediction of GLT beams based on stiffness distributions of individual lamellas. *Wood Science and Technology*, 2015, 49(6), 1101–1121.

Hammock Shape Shear Stress Distribution in the Single Step Joint

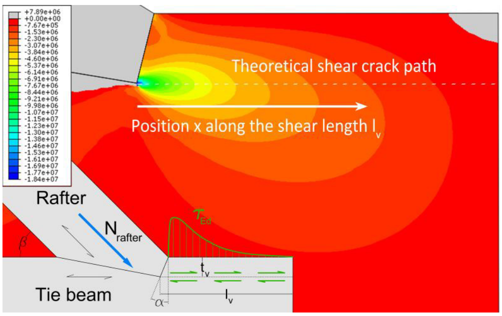
Maxime Verbist[†*], **Jorge M. Branco**[†], **Thierry Descamps**[‡]

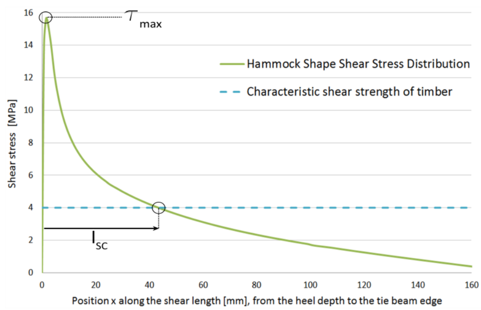
[†* †] ISISE, University of Minho, DECivil, Campus de Azurém, 4800-058, Guimarães, Portugal,
[†*] verbist.maxime@hotmail.com, [†] jbranco@civil.uminho.pt
[‡] University of Mons, DSM, Mons, Rue du Joncquois 53, 7000, Belgium, Thierry.DESCAMPS@umons.ac.be

Being subject to the horizontal thrust from the rafter inside the timber carpentry, the Single Step Joint (SSJ) may be structurally damaged by the shear crack at the heel depth in the tie beam. In order to prevent this failure mode, the equation below (1) must be checked from the review of Verbist et al. [1].

$$N_{rafter} \leq k_{v,red} \cdot f_{v,k} \cdot \frac{b\,.\ \min(l_v,\ 8.t_v)}{\cos\beta} \qquad (1)$$

The reducer coefficient ($k_{v,red}$) of the timber characteristic shear strength ($f_{v,k}$) takes into account the non-uniform shear stress distribution, called Hammock Shape Shear Stress Distribution (HSSSD), at the heel depth (t_v) along the shear length (l_v) parallel to the grain in the tie beam, as shown in Figure 1. By performing FEM on ABAQUS software, the present research aims at defining the general pattern of the HSSSD, and which SSJ geometrical parameters significantly influence the heterogeneous shear stress distribution (thus, the emergence conditions of the shear crack) in the tie beam. Through modeling several SSJ geometrical configurations, both parameters of the HSSSD illustrated in Figure 2 have then been assessed: the maximal shear stress τ_{max}, and the shear concentration length l_{SC} (along which the shear stress is superior to the characteristic shear strength of timber). A parallel numerical assessment on the HSSSD has also been performed in the Double Step Joint with the same purposes.





Figures 1 and 2 : Shear stress distribution along the grain in the tie beam (left). Pattern and parameters of the HSSSD (right).

The numerical assessment has shown that the HSSSD significantly varies according to the geometrical proportion l_v/t_v between the shear length and the heel depth (as Aira et al. [2] noticed it for the Notched Joint), to the inclination angle α of the front-notch contact surface, to the rafter skew angle β, and to the friction forces at the bottom-notch contact surface (as Villar et al. [3] observed it for the Single Step Joint). While the last two quoted variables can be taken into account in the design equation (1), the reducer coefficient $k_{v,red}$ only depends on both α and l_v/t_v parameters. By comparing with the experimental results from the SSJ geometrical configurations tested [1], the numerical assessment on the HSSSD can determine the values of the reducer coefficient $k_{v,red}$ as shown in Table 1.

Table 1 : Value of the reducer coefficient $k_{v,red}$ for one SSJ geometrical configuration tested.

SSJ Geometrical Configuration	l_{SC} [mm]	l_{SC}/l_v [%]	τ_{max} [MPa]	N_{rafter} [kN]	$k_{v,red}$
GCPTB_30_tv30_lv240	39.2	16.3	20.6	70	0.75

References

[1] Verbist, M., Branco, J.M., Poletti, E., Descamps, T., Lourenço, P. (2016). Single Step Joint : overview of European standardized approaches and experimentations. CINPAR 2016 – XII International Conference on Structural Repair and Rehabilitation. Porto, Portugal – 26-29 October, 2016.

[2] Aira, J.R., Descamps, T., Van Parys, L., Léoskool, L. (2015). Study of stress distribution and stress concentration factor in notched wood pieces with cohesive surfaces. European Journal of Wood and Wood Products – Volume 73, Issue 3, pp 325-334 – May 2015.

[3] Villar, J.R., Guaita, M., Vidal, P., Arriaga, F. (2007). Analysis of the Stress State at the Cogging Joint in Timber Structures. Biosystems Engineering – Volume 96, Issue 1, pp 79-90 – January 2007.

III:2

Numerical simulation and experimental validation of fatigue behavior of wood-glass fiber composite T joint

W.F. Panella[1], A.M. Pantaleo[2,*]

[1]Università del Salento, Dipartimento di Ingegneria dell'Innovazione, francesco.panella@unisalento.it
[2] Università degli studi di Bari Aldo Moro, Dipartimento di scenze agro-ambientali, antonio.pantaleo@uniba.it

Several aspects of marine wood composite T-joints have been investigated in literature in the last decades, addressing in particular the influence of both joint geometry, including fillet radius and overlaminate thickness [1], and of the glue bonding on the strain distribution [2]. The joint geometry and the delamination of curved surfaces are recognized as main factors influencing the joint strength. Other researches [3-5] focus on modelling and testing glass fibre reinforced T-joints subjected to disbonds at various interfaces, using FEM and the virtual crack closure technique (VCCT), while fatigue behaviour of the T-joints has been studied by other researches [6], showing that fatigue strength generally increases both with fillet radius, and with an increase in the number of plies in the overlaminate. Failure occurs through a delamination in the boundary angle and a typical disbond of the inside fillet takes place, leading to an internal crack propagation. However, the sequence of final failure events could not be easily discerned, and a more detailed analysis for determination of critical stress regions in T-joint is necessary.
In this paper, a numerical FE model is developed with ANSYS and validated by experimental tests to identify possible damage locations and fatigue breakage in different wood-glass fiber composite T-joints for marine applications. Both static and fatigue tests in three-point bending configuration have been performed, as reported in Fig 2, while the wood composite T joint schematic is reported in Fig 1. It consists of horizontal and vertical wooden panels joined by a laminate reinforcement. The junction between the two panels is made by laminating reinforced strips of glass woven on both sides, in order to form a double angle connection. The orizontal panel is laminated with external reinforce (representing the null shell), the vertical panel is a simple wood not reinforced (rappresenting the boat ribs).

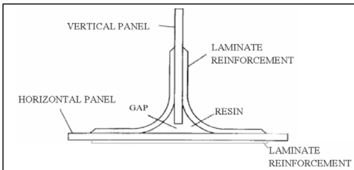


Fig 1. Typical T-joint.

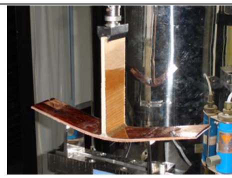


Fig 2 Experimental test set up

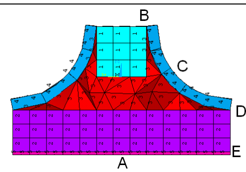


Fig 3. Failure points - FEM modeling

The numerical model of the T-joint has been successfully validated by experimental static test, and the stress analysis allowed identifying the regions most susceptible to damage, which are the curved regions of the overlaminate. The fatigue analysis identified the critical zone of the joint to be the area near the fillet radius on the horizontal panel. In particular there are two critical zone near fillet radius: on the superior laminate of reinforcement and in the inferior laminate of reinforcement. This approach could be useful when designing joint geometries, selecting composite materials for reinforcement, and predicting the performance and fatigue behaviour in real applications.

References

[1] Phillips HJ, Shenoi RA. Damage tolerance of laminated tee joints in FRP structures. Composites Part A 1998;29(4):465–78.
[2] Dharmawan F, Thomson RS, Henry Li, Herszberg I, Gellert E. Geometry and damage effects in a composite marine T-joint. Composite Structures 66 (2004) 181–187.
[3] Herszberg I., LI H.C.H., Dharmawan F., Mouritz A.P., Nguyen M., Bayandor J. Damage assessment and monitoring of composite ship joints. Composite Structures 67 (2005) 205–216.
[4] LI H.C.H., Herszberg I., Davis C.E., Mouritz A.P., Galea S.C. Health monitoring of marine composite structural joints using fibre optic sensors. Composite Structures 75 (2006) 321–327.
[5] LI H.C.H., Dharmawan F., Herszberg I., John S. Fracture behaviour of composite maritime T-joints. Composite Structures 75 (2006) 339–350.
[6] Read P.J.C.L., Shenoi R.A. Fatigue behaviour of single skin FRP tee joints. International Journal of Fatigue 21 (1999) 281–296.

Numerical 3D finite element modelling and experimental validation for dowel type vs tenon-mortise type wooden joints for window frames

A.M. Pantaleo[1,*], D. Ferri[2]

[1] Università degli studi di Bari Aldo Moro, Dipartimento di scenze agro-ambientali, antonio.pantaleo@uniba.it
2. structural engineer in Bari, ferri.domenico@gmail.com

Wood is enjoying increasing popularity in the building sector. In order to fully exploit the potential of this material, particularly in two and three-dimensional structures, improved knowledge of the mechanical behaviour of the material and more complex constitutive models are required. The mechanical performances of timber joints are particularly important for the design of wood structures. In general, joints are one of the weakest points in timber structures. In particular, in the case of glulam profiles for window frames, dowel-type joints are often used to achieve higher stiffness of the profile that reach the strength levels of mortise-tenon joints. In this paper, a finite element model for a dowel-type glulam joints is proposed to investigate the mechanical performances of various typologies of joints for wooden profiles. The numerical prediction of the proposed finite element method is compared to experimental results of mechanical testing. Moreover, failure mechanisms are assessed, in order to predict the strength of such joints.
The rationale of the research relies on the potential damages (i.e. breaking of the frame) that can be caused by poor quality of 90° joints, due to a number of factors such as joint geometry, gluing processes, typology of adhesives. The most widespread options for 90° joints for wooden window frame manufacturing are the dowel type and the tenon-mortise type. Both technologies present specific manufacturing requirements, production costs and times, and typical strength and structural behaviour. However, there is scarce scientific literature on accurate modelling and comparison of these typologies of joint. In particular, FEM has been applied to wooden joints and structures in recent years [1-3], but there is a limited number of studies on 3D modelling techniques and their specific applications on different geometries and typologies of 90° joints. The proposed 3D FEM is validated by experimental tests on 90° joints of Red Oak (*Quercus Rubra*) glued laminated wood for window profiles taken from a manufacturing production line. The test results show that the 90° tenon-mortise corner joints have higher strength that dowel type, and the accuracy of the FE model is acceptable in the proposed range of admissible deformations. The proposed approach can be applied when evaluating the suitability of a given typology of corner joint for specific window frame geometries, windowpane weight and external loads. The joint geometry and test set up are reported in Fig 1-3.

Fig 1. Tenon-mortise corner joint.

Fig 2 Dowel corner joint

Fig 3. Experimental test set up

References

[1] 1. Pantaleo A, Ferri D, Pellerano A, (2013) Wooden window frames with structural sealants: manufacturing improvements and experimental validation of a finite element model, Journal of adhesion science and technology http://dx.doi.org/10.1080/01694243.2013.827093
[2] Resch E, Kaliske M. Three-dimensional numerical analyses of load-bearing behavior and failure of multiple double-shear dowel-type connections in timber engineering. Comput. Struct. 2010;88:165–177.
[3] Xu BH, Taazount M, Bouchaïr A, Racher P. Numerical 3D finite element modelling and experimental tests for dowel-type timber joints. Constr. Build Mater. 2009;23:3043–3052.

III:4

Automated code compliance checking to EC5 in BIM for structural timber connections

Andrew Livingstone[†*], Panagiotis Patlakas[‡], Sean Smith[†], Robert Hairstans[†]

[†]Edinburgh Napier University, A.Livingstone@napier.ac.uk
[‡]Birmingham City University, Panagiotis.Patlakas@bcu.ac.uk

The authors have introduced in previous work a novel method for automating timber connections to the Eurocode 5 (EC5) within a Building Information Modelling (BIM) platform at a proof-of-concept stage [1, 2]. This approach combines the mathematical process of Multi-Dimensional Data Fitting (MDDF) with BIM to provide the end user with Automated Code Compliance (ACC). In the present paper, this methodology is extended to create reliable predictive models of the behaviour of metal dowel type timber connections under lateral loading. The work presented here highlights the applicability of the method in the design of standard timber connections, thus enabling the development of ACC tools within standard BIM software platforms. The application of the MDDF methodology in structural timber design problems has previously undergone proof-of-concept validation and verification [1].

MDDF refers to the multidimensional data fitting of a dataset with an arbitrary number of dimensions. MDDF has not previously found wide application within the structural timber field. By utilising MDDF, extremely large datasets derived from existing EC5 calculations can be simplified into a single algebraic expression that can be integrated into a "smart" BIM component and thus allow the development of ACC processes.

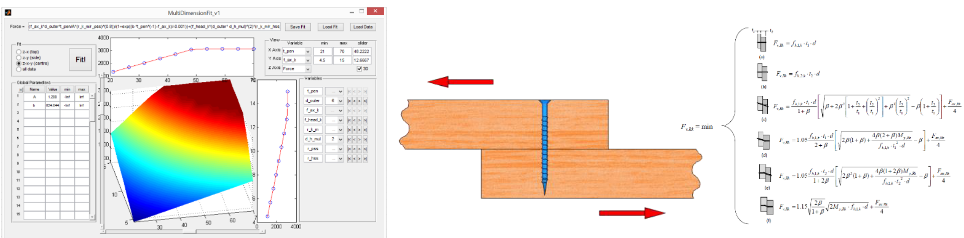


Figure 1(a) fitting software user interface; (b) timber connection studied (c) single shear – failure modes

In order to achieve these objectives a large dataset is created containing a^n points in the data set, where: n = number of variables; a = increments per variable. The authors have previously developed a graphical user interface (Figure 1(a)) for the visualisation of data and the data fitting process [1]. The user inputs a fitting equation into the software and the software then attempts to fit that equation to the data by computational iteration, varying the inputted parameters accordingly in each iteration.

The initial proof of concept was looking at the axial load-carrying capacity of fasteners used in secondary (i.e. non-structural) applications such as cladding. In this paper, we have chosen to study the lateral load-carrying capacity of metal dowel-type fasteners (Figure 1(b)). The prescribed EC5 calculation method relies on an improved version of Johansen's equations (Figure 1(c)), which present significant obstacles for optimised programming into a native BIM environment. The MDDF approach creates a mathematical model which can be validated by comparing against the results of calculated EC5 equations.

Once the process described above has been completed, the resulting equations are programmed into a BIM platform. In this paper, the output of the MDDF is programmed into a structural detail modelled in Autodesk Revit©, using the software's native Application Programming Interface (API). This implementation allows the user to have ACC of the structural design parameters, revolving around the multidimensional problem that has been presented above.

The methods previously demonstrated by the authors for creating "smart" BIM components for structural timber calculations have been utilized for the lateral load carrying capacity of metal dowel type fasteners. This extension of the technique proves that it can be used to enable ACC for more complex real-world applications beyond simple proof-of-principle examples. The results of this paper provide the framework for calculating all timber-to-timber metal dowel type connections. This simplifies the implementation of ACC for these timber connections within a BIM framework.

References

1. Livingstone, A., et al., Multi-Dimensional Data Fitting for the structural design of a simple timber connection. World Conference on Timber Engineering, 2016.

2. Patlakas, P., A. Livingstone, and R. Hairstans, A BIM Platform for Offsite Timber Construction, in eCAADe 2015. 2015. p. 597-604.

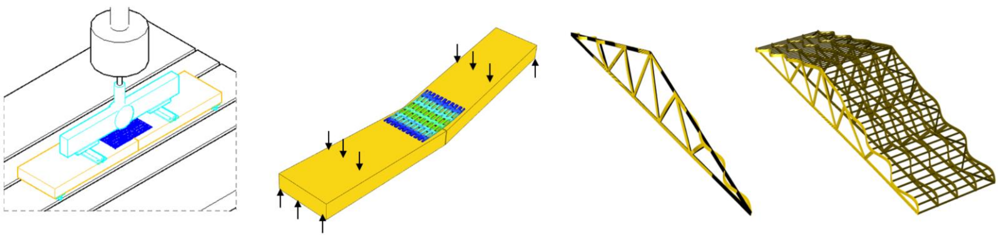
Numerical and experimental study of punched metal plate connections to obtain spring stiffness needed for 3D buckling analysis of long-span timber trusses

P. Sejkot†*, S. Ormarsson†, and J. Vessby†

†Department of Building Technology, Linnaeus University, Växjö, petr.sejkot@lnu.se

Instability failures of timber structures are reported relatively frequently although there are methods available how to prevent such failures. For trussed long-span timber roofs it is practically more difficult to prevent the out-of-plane deformations than for shorter trusses. To prevent lateral buckling failure of the entire roof structure, the trusses are joined together with a semi-rigid bracing system of wood. It comprises of several slender timber battens oriented perpendicular to the trusses connected to a (relatively slender) bracing truss/trusses positioned in the roof plane between the top chords of the timber trusses. Both the long-span timber trusses and the bracing trusses are manufactured using punched metal plate fasteners while the battens normally are fastened to the trusses by means of nails. The influence of the stiffness in the lateral bracing system on the out-of-plane truss stability was studied in [1]. However, simplified connection model based on insufficient experimental data for out-of-plane stiffness (shear and rotational stiffness) of punched metal plate connections was used as input for the 3D buckling analysis of the timber trusses.

Hence, a full-scale experimental setup to obtain all the six spring stiffness (1 axial shear slip between the metal plate and the wood member, 2 out-of-plane shear slip, 2 out-of-plane rotations and 1 twist rotation) needed for 3D simulation of the punched metal plate connections has been prepared. Figure 1 (*a*) shows an experimental setup for testing out-of-plane rotational stiffness of the punched metal plate connection. The surface strains of the punched metal plate fastener and the wood closely around will be measured using digital image correlation (Aramis system). The obtained experimental output will be used to calibrate the numerical (solid/shell) model of the experimental test sample shown in Figure 1 (*b*). This numerical model in turn is used to simulate all the six spring stiffness parameters needed for a 3D structural (beam/spring) model used to simulate global deformations and out-of-plane buckling behavior of the pitched long-span timber truss shown in Figure 1 (*c*). To study the influence of these connection spring parameters on buckling behavior of individual timber truss, a parameter study was performed. Figure 1 (*c*) shows the first buckling mode for a truss loaded with a symmetric vertical load on the top of the top chords. Finally, the structural truss model was used to simulate a full roof structure with a semi-rigid bracing system visualised in Figure 1 (*d*). For the individual truss simulation the lateral bracing system were modelled with lateral springs with stiffness k_s = 200 kN/m [1].



(*a*) (*b*) (*c*) (*d*)

Figure 1: (a) Experimental setup for testing out-of-plane bending of a punched metal plate connection, (b) Simulated deformations and stresses in the tested timber sample jointed with punched metal plate connection, (c) Simulated out-of-plane buckling mode of a single timber truss, (d) Simulated buckling modes of a trussed long-span timber roof with semi-rigid bracing system.

According to Eurocode 5, all pitched timber trusses are designed as an in-plane structure meaning that the bracing systems used are assumed to be capable to prevent the out-of-plane failure of the structure. In [1] numerical results show that this assumption needs to be further studied for long-span timber structures. The aim of this work is to get better understanding of out-of-plane stiffness and behavior of pitched long-span timber trusses used in roof structures with semi-rigid bracing systems of wood. This knowledge is needed to improve the design procedure of the whole structural roof system with respect to out-of-plane buckling failure.

References

[1] S. Ormarsson, J. Vessby, B. Källsner, I. Filchev: Numerical analysis of failure modes and force distribution in a pitched roof structure of wood. *WCTE 2016 e-book*, 2136-2144.

III:6

Numerical Analysis of the withdrawal capacity of large steel dowels in cross-laminated timber panels

Einar Nathan†, Themistoklis Tsalkatidis†*

† Faculty of Sciences and Technology, Division of Building and Architecture,
Norwegian University of Life Sciences, Ås, Norway
†einar.nathan@nmbu.no, †*themistoklis.tsalkatidis@nmbu.no

New construction materials and elements made of timber are used worldwide. One such material is cross-laminated timber (CLT) panel[1]. This new use of wood implies that we also need to investigate the connectivity between these timber elements. In particular, panel-to-panel connections require further research. Steel is often used in conjunction with CLT, whether as part of a hybrid system or in connections between the materials. Steel is often used both in connections [2] between CLT panels and as an extending ribbon that absorbs tensile forces. The combination of materials with different properties in joints or elements is a challenge for their design. Such a difference is the behavior of steel and wood in relation to humidity. The fact that the wood is very sensitive to humidity [3] has in many cases resulted in undesirable phenomena, when combined to steel. Timber expands and contracts in relation to its moisture content, this does not apply for steel. Therefore, there is a need to investigate CLT connections and especially focus on the interaction between steel and wood [4].

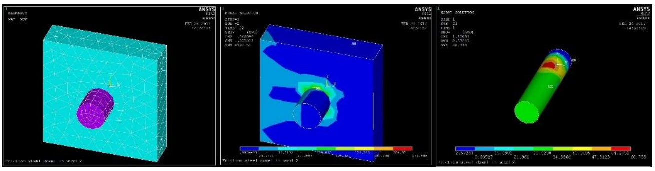


Figure 1: Numerical model under study

This paper examines the relation between CLT panel and large steel dowels. More specifically a finite element analysis of the increase in withdrawal capacity of large steel dowels in CLT panels due to reduction of moisture content in wood is examined. When timber dries out, it shrinks. This shrinkage varies in relation to the direction of the fibers in the wood. Steel, however, is not affected by moisture- related shrinkage. The withdrawal capacity of steel dowels as a result of the contraction of timber is the main parameter under study. Large dowels are placed in predrilled holes in CLT panels that are in humid conditions. Then the panels are left to dry. The desiccation of the timber implies that the timber contracts. This contraction generates compressive forces that act on the dowels. These pressure forces are applied on the dowels normal to their withdrawal direction. Therefore, the friction forces between the steel and timber increase, resulting in a significant increase of the withdrawal capacity of the dowels. The outcomes of the numerical analysis are presented and discussed.

References:

1. Brandner, R., et al., *Cross laminated timber (CLT): overview and development.* European Journal of Wood and Wood Products, 2016. **74**(3): p. 331-351.
2. Hassanieh, A., H.R. Valipour, and M.A. Bradford, *Load-slip behaviour of steel-cross laminated timber (CLT) composite connections.* Journal of Constructional Steel Research, 2016. **122**: p. 110-121.
3. McClung, R., et al., *Hygrothermal performance of cross-laminated timber wall assemblies with built-in moisture: field measurements and simulations.* Building and Environment, 2014. **71**: p. 95-110.
4. Izzi, M., et al., *Experimental investigations and design provisions of steel-to-timber joints with annular-ringed shank nails for Cross-Laminated Timber structures.* Construction and Building Materials, 2016. **122**: p. 446-457.

Closed-form homogenization of CLT panels with periodic gaps

L. Franzoni†,‡, A. Lebée†*, F. Lyon‡, G. Foret†

†Laboratoire Navier, Ecole des Ponts, 6/8 Av. Blaise Pascal, Champs-sur-Marne, France
arthur.lebee@enpc.fr , lorenzo.franzoni@enpc.fr
‡CSTB Marne la Vallée, 84 Av. Jean Jaurès, Champs-sur-Marne, France

Cross Laminated Timber (CLT) panels are nowadays widely used in timber engineering. Each layer of the crosswise lay-up is made of narrow lamellas. The recent standard requirements for CLT [1] allows lateral gaps between lamellas up to 6 mm (Fig. 1a). The presence of such gaps has been pointed out to modify the mechanical response under out-of-plane loads [2] and under in-plane shear [3]. Moreover, the gaps can be increased up to hundreds of millimeters and filled by insulating material, in order to obtain lightweight timber products (Fig. 1b) with an improved thermal and acoustical performance. The development of these innovative panels is still limited due to lack of simplified tools for predicting their mechanical behavior.

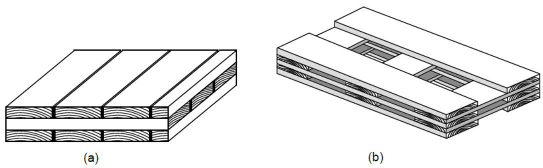


Figure 1: Standard CLT panel with lateral short gaps (a) and innovative product with wider gaps (b)

The elastic behavior of CLT panels with short and large gaps has been already studied by the authors [4] by means of a thick-plate homogenization scheme. The thick-plate behavior of the panel has been predicted imposing unit membrane, curvature and transverse shear strains to a periodic unit-cell. The strain energy stored in the unit-cell has been then calculated with FE simulations (Fig. 2a). In the present study, the unit-cell of CLT with gaps is modeled as a space frame of beams (Fig. 2b) in order to estimate the strain energy and the thick-plate behavior with a closed-form homogenization procedure. Indeed, the beam has only one coordinate and therefore beam equations can be integrated.

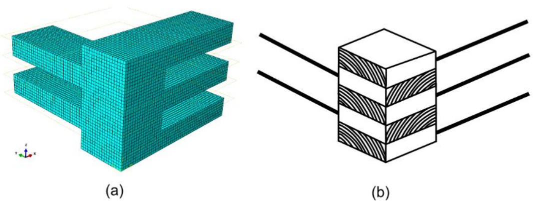


Figure 2: Unit-cell of a 5-ply CLT panel with gaps modelled with FE (a) and corresponding space frame of beams (b)

The obtained closed-form solutions can predict the bending, in-plane shear and shear force stiffnesses of CLT with gaps. Furthermore, closed-form expressions to estimate the longitudinal and rolling shear stress acting on CLT floors with gaps are derived. The comparison with the reference FE results [4] and existing closed-form approaches [5, 6] shows that the closed-form solutions suggested in this study can be used for practical design applications.

References

[1] EN 16351 (2016) Cross Laminated Timber: standard requirements. CEN: European Committee of Standardization
[2] Franzoni, L. Lebée, A. Lyon, F. Foret, G. (2016) Influence of orientation and number of layers on the elastic response and failure modes on CLT floors: modeling and parameter studies. *Eur. J. Wood. Wood. Prod.*
[3] Brandner, R. et al (2015) Shear properties of Cross Laminated Timber (CLT) under in-plane load: test configuration and experimental study. Proceedings of the 2nd INTER meeting, Sibenik (CRO)
[4] Franzoni, L. Lebée, A. Lyon, F. Foret, G. (2016) Elastic behavior of Cross Laminated Timber and regularly voided timber panels: thick-plate modeling and experimental validation (submitted)
[5] Moosbrugger, T. Bogensperger, T. Guggenberger, W. (2006) Cross Laminated Timber segments under uniform shear, with and without openings. Proceedings of the 9th WCTE meeting, Portland (USA)
[6] Kreuzinger, H (1999) Platten, Scheiben und Schalen. Ein Berechnungsmodell fur gangige Statikprogramme (in German). Bauen mit Holz 1:34-39

IV:2

Multi-scale modelling strategies for cross-laminated timber structures

E.I. Saavedra Flores[†*], J.C. Pina[†], C.F. Guzmán[†], P. González[†] and S. Yanez[†]

[†]Departamento de Ingeniería en Obras Civiles, Universidad de Santiago de Chile, Av. Ecuador 3659, Estación Central, Santiago, Chile
erick.saavedra@usach.cl, juan.carlos.pina@usach.cl, cf.guzman@usach.cl, paulina.gonzalez@usach.cl, sergio.yanez.c@usach.cl

Over the last two decades, cross-laminated timber (CLT) has been gaining popularity in residential applications, mainly in Europe and North America. CLT is a relatively new 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 [2].

In this work we review some recent applications of multi-scale modelling strategies adopted to capture the structural response of CLT. The material scales considered are the wood cell-wall at the order of few nanometers, the wood fibres with cross section dimensions of tens of micrometers, growth rings described by some few millimeters and the structural scale, at the order of meters. In order to couple these scales, 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. Periodic kinematical constraints are imposed on the RVE boundary domain. Here, the periodic repetition of the RVE generates the entire heterogeneous macro-continuum at each material scale. As we are interested in improving the predictions of our computational multi-scale simulations, we follow a Genetic Algorithm-based optimisation technique to calibrate the micro-mechanical parameters [1,3].

Experimental tests were conducted to measure the structural behaviour of CLT plates [1,4]. The experimental measurements were carried out in specimens made of radiata pine grown in Chile subject to bending, compression and in-plane shear loads. Our numerical predictions were compared with the experimental results and were validated successfully. Some of our main studies focused on the influence of the wood density on the sliding and rolling shear moduli and on the effective bending and shear stiffness in CLT plates.

Acknowledgements

E.I. Saavedra Flores acknowledges the financial support from the Chilean National Commission for Scientific and Technological Research (CONICYT), FONDECYT REGULAR research project No. 1160691.

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.
[2] M. Mohammad, S. Gagnon, B. K. Douglas, L. Podesto: Introduction to cross laminated timber, *Wood Design Focus* 22 (2) (2012) 3-12.
[3] R. Castro-Triguero, E. García-Macías, E.I. Saavedra Flores, M.I. Friswell and R. Gallego: Multi-scale model updating of a timber footbridge using experimental vibration data. Accepted for publication in *Engineering Computations*.
[4] E.I. Saavedra Flores, I. Dayyani, R.M. Ajaj, R. Castro-Triguero, F.A. DiazDelaO, R. Das, and P. González Soto: Analysis of cross-laminated timber by computational homogenisation and experimental validation. *Composite Structures*, 121 (2015), 386-394

Modeling of the seismic behavior of structures of cross-laminated timber panels

González Rodrigo, Beatriz[†], Fraile de Lerma, Alberto[†*],and Mosquera Feijoo, Juan Carlos[‡]
[†]Technical university of Madrid, beatriz.gonzalez.rodrigo@upm.es
[†*] Technical university of Madrid, alberto.fraile@upm.es
[‡] Technical university of Madrid, juancarlos.mosquera@upm.es

The construction system based on cross-laminated timber (CLT) panels is developing fast in recent years after its initial design in the 90s. The good behavior of the system to fire and seismic actions is facilitating its penetration in the building market for small and medium height buildings. CLT-based structural systems present good ductility and energy dissipation capacity. Energy dissipation is achieved through metal connections, as these elements work actively to provide strength, stiffness, stability and ductility.

The objective of this study is to validate a linear numerical model of a multi-storey structure built with CLT panels and metal connectors in the case of seismic actions. For this, panels are considered as an orthotropic panel material with properties equivalent to those of its layers properties. Additionally, shear connections (brackets) are simulated as the rigidity that they contribute to the system. Tension connectors are represented by the rotational stiffness created when the panel rotates with a connector on one end and wood being compressed in the other. The software use for numerical simulation was RFEM 5.06 [1]

The results of the simulation of a 3-storey structure tested at 1: 1 in the project SOFIE, allow concluding that the modeled rigidity is very close to real. However, the displacements obtained from Nocera Umbra, El Centro and Kobe seismic earthquake loads, scaled to peak ground acceleration of 0.15g, are close to those obtained in laboratory testing [2][3][4] (Figure 1). However, base shear show greater variation, reaching a maximum deviation of 60% with respect to the values obtained in the prototype tests. From the point of view of calculation this variation is always within safety values.

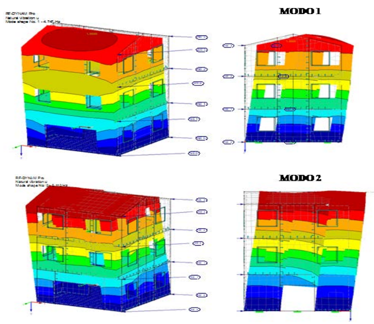


Figure 1: The first two modes of prototype vibration

It is concluded that the numerical method presented for linear dynamic analysis of CLT buildings is valid provided that the seismic loads keep the structure in the elastic range. Future research should aim at modeling the behavior outside the elastic range, and in particular, deeping knowledge about the hysteretic behavior of the connections.

References

[1] Dlubal Software GmbH, "Rfem 5.06-Software para calculo de elementos finitos y diseño de estructuras de madera." Alemania, 2016.
[2] A. Ceccotti, M. Follesa, M. P. Lauriola, and C. Sandhaas, "Sofie Project – Test Results on the Lateral Resistance of Cross-Laminated Wooden Panels," in *First European Conference on Earthquake Engineering and Seismology*, 2015, no. July, pp. 1–10.
[3] I. Gavric, "Seismic Behaviour of Cross-Laminated Timber Buildings," Universidad de Trieste, 2012.
[4] M. Follesa, I. P. Christovasilis, D. Vassallo, M. Fragiacomo, and A. Ceccotti, "Seismic design of multi-storey cross laminated timber buildings according to Eurocode 8," *Ingegneria Sismica*, no. 4. pp. 27–42, 2013.

IV:4

A mechanical material model for cross-laminated timber obtained by numerical homogenization

Thomas Furtmüller†*, Benjamin Giger† and Christoph Adam†

†Unit for Applied Mechanics, University of Innsbruck, Austria; thomas.furtmueller@uibk.ac.at

This contribution deals with the development of a material model for large-scale Finite Element (FE) analyses of point-supported cross-laminated timber (CLT) slabs.

In the first step, material properties of the constituents of the considered CLT elements are determined. Quasi-static three point bending tests are performed for three configurations of main fiber orientation (0°, 45° and 90° with respect to the load bearing direction). FE simulations of these tests are employed in an optimization procedure to derive both orthotropic elastic material parameters and parameters of Hill's yield function for the spruce wood boards. Parametric studies reveal significant material properties as well as parameters that cannot be identified satisfactorily by means of uniaxial bending tests.

In the second step, a numerical homogenization scheme is employed in order to derive the elastic stiffness matrix of a generalized shell section representing the CLT floor. To this end, a repeating unit cell is defined, where macroscopic homogeneous strains and curvatures can be implemented by means of nodal displacements and corresponding macroscopic shell normal forces and bending moments can be computed from the nodal reaction forces [1]. This unit cell is depicted in figure 1, together with typical deformation patterns due to pure twist and pure transversal shear.

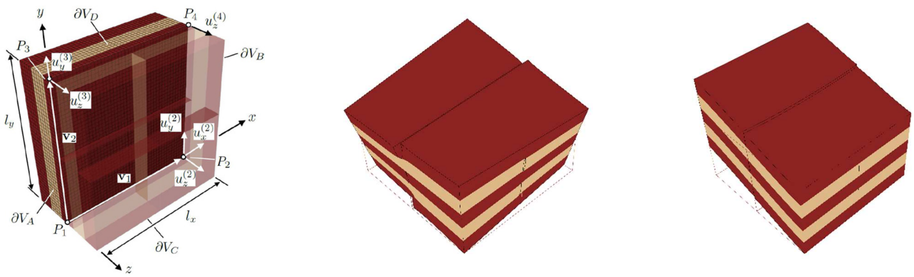


Figure 1: Repeating unit cell (left) and deformation due to pure twist (mid) and pure transversal shear (right)

To verify the homogenization procedure, modal analysis is conducted for a ficticious point-supported CLT slab with dimension of approximately 10x10 *m*. A computationally very expensive solid element model is compared to a shell model with generalized shell stiffness as computed by the homogenization scheme. The shell element model provides an excellent approximation of the resonant frequencies and the mode shapes, as can be seen in figure 2, requiring only a fraction of the computational expense of the solid element model.

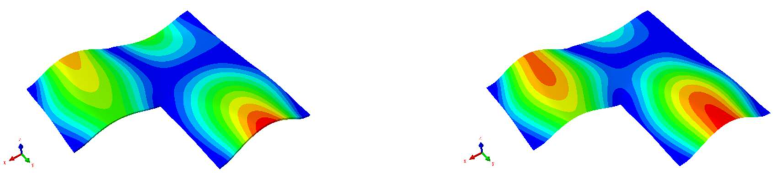


Figure 2: Second mode shape for the solid element model at $f = 7.36$ *Hz* (left) and for the shell element model at $f = 7.20$ *Hz* (right)

Homogenization is extended to inelastic deformation of the unit cell simulations. An approximate failure surface is derived and implemented as postprocessing variable. As a verification of the failure surface, an ultimate load analysis is performed for the solid element model. Plastic zones are in good agreement with the predictions obtained by the postprocessing variable in a corresponding shell element model.

References

[1] M. Mistler, A. Anthoine, C. Butenweg: In-plane and out-of-plane homogenisation of masonry, Computers and Structures 85 (2007) 1321-1330.

On the multiscale simulation of buckling and delamination in cross-laminated timber structures

Karin Saavedra†*, Erick I. Saavedra Flores‡, and Jorge Hinojosa†

†Dpto. Tecnologías Industriales, Universidad de Talca. Los Niches km1, Curicó, Chile,
{ksaavedra,jhinojosa}@talca.cl
‡ Dpto. Ingeniería en Obras Civiles, Universidad de Santiago de Chile. Av. Ecuador 3659, Santiago, Chile,
erick.saavedra@usach.cl

In this work, we present a multi-scale LaTIn-based Doman Decomposition Method (DDM) that have been recently improved for the simulation of slender structures in presence of nonlinearities such as delamination and buckling [1]. Here, a cohesive interface model is used to introduce delamination while unilateral contact is considered to avoid interpenetration. These two conditions are handled at the interfaces of the partitioned problem due to the mixed nature of the proposed DDM.

This strategy uses two scales to reach the solution iteratively: i) The microscale defines local problems on each subdomain and on each interface. ii) The macroscale defines a small number of degrees of freedom per interface, which are linked together by a homogenized behaviour and must verify the equilibrium of the whole structure. To improve the convergence rate and scalability, the parameters of the strategy – the search directions and the macroscopic space – are adopted following the recommendations proposed in [1].

The rolling shear failure in cross-laminated timber (CLT) panels has been already investigated in [2] by means of this strategy. Now, experimental tests have been conducted to measure buckling loads and delamination in CLT walls subjected to compressive loads. The experimental measurements were carried out according to the Chilean standard NCh 801 Of. 2003 [3]. Here, a progressive vertical displacement was applied at the top of the wall until reaching the critical load. Our numerical predictions were compared with the experimental results and were validated successfully. In particular, we studied the combined effects of buckling and delamination on CLT structures.

Acknowledgements

K. Saavedra acknowledges the financial support from the Chilean National Commission for Scientific and Technological Research (CONICYT), FONDECYT Initiation into research project No 11130623.
E.I. Saavedra Flores acknowledges the financial support from CONICYT, FONDECYT REGULAR research project No 1160691.

References

[1] K. Saavedra, O. Allix, P. Gosselet, J. Hinojosa, A. Viard, An enhanced nonlinear multi-scale strategy for the simulation of buckling and delamination on 3D composite plates. *Computer Methods in Applied Mechanics and Engineering*, In Press (2017).
[2] E.I. Saavedra Flores, K. Saavedra, J. Hinojosa, Y. Chandra, R. Das, Multi-scale modelling of rolling shear failure in cross-laminated timber structures by homogenisation and cohesive zone models. *International Journal of Solids and Structures*, 81 (2016), 219-232.
[3] INN – Instituto Nacional de Normalización, NCh 801. Of. 2003. Elementos de construcción – Paneles – Ensayo de carga compresión. Chile.

V:1

Influence of misalignment between direction of observation and wood material orthotropy on viscoelastic strain measurements

Sabina Huč[†‡*], Tomaž Hozjan[§], Staffan Svensson[†]

[†]University of Borås, Faculty of Textiles, Engineering and Business, SE-501 90 Borås, Sweden, sabina.huc@hb.se, staffan.svensson@hb.se
[‡]Division of Applied Mechanics, Ångström Laboratory, Uppsala University, SE-751 21 Uppsala, Sweden
[§]University of Ljubljana, Faculty of Civil and Geodetic Engineering, 1000 Ljubljana, Slovenia

It is expected for a solid material subjected to a tensile uniaxial load to stretch in the load direction and contract in transverse directions. For compressive uniaxial load it is expected that the material contracts in load direction and extends in transverse directions. Occasionally, wood material exposed to constant uniaxial load shows atypical creep behavior in transverse direction, such as positive transverse creep strain under longitudinal tensile load [1] and vice versa [2]. Experimental results [1] and [2] obtained independently imply the existence of a logical reason for such behavior. A possible explanation is sought in discrepancies in alignment of load directions and orthotropic material directions (longitudinal l, tangential t, and radial r). Here, the misalignment is studied on the experimental data by Schniewind and Barrett [1] by means of a 3D finite element analysis. The applied 3D model is an upgrade of a coupled 2D model for predicting viscoelastic creep of wood in two perpendicular directions simultaneously. Viscoelastic creep in shear is also accounted for. A detailed description of the rheological shear and 2D model's formulations, based on a Kelvin solid is presented in [3].

In the numerical analyses, orthotropic material directions are assumed to coincide with a local coordinate system (t, l, r), while a constant tensile load is prescribed in Y direction and the transverse strain $\varepsilon_{XX}(Y)$ is observed in X direction of a global coordinate system (X, Y, Z) (Figure 1a). Deviation of the orthogonal systems is varied by an angle α_X about the X-axis and an angle α_Z about the Z-axis for 3° up to 9°.

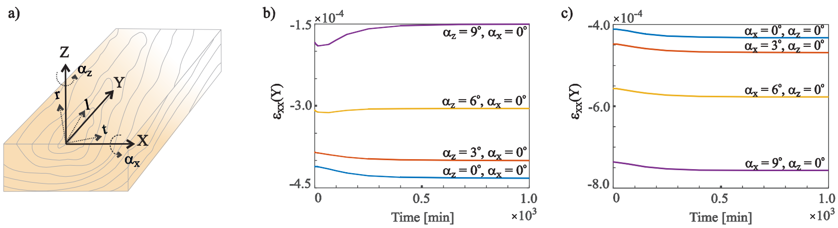


Figure 1: a) Deviation of the wood orthotropic directions (t, l, r) from the observed stress-strain directions (X, Y, Z), b) and c) viscoelastic strain development in X direction due to constant longitudinal tensile load in Y direction, $\varepsilon_{XX}(Y)$, for various combinations of rotation angles (α_X, α_Z)

Figure 1b shows that the unexpected behavior of $\varepsilon_{XX}(Y)$ in a positive direction is caused by the rotation α_Z, while the rotation α_X does not suggest that kind of behavior (Figure 1c). Magnitude of the rotation α_Z governs the emergence and the intensity of the unexpected creep behavior of wood (Figure 1b). Further analysis shows that the shape of the viscoelastic creep curves is greatly influenced by creep in shear. Application of the 3D rheological models of different complexities (described in [3]) confirms the atypical behavior of $\varepsilon_{XX}(Y)$ in general, although, the shape of the strain curves may not be identical due to the tuning of the material parameters. Similar analyses confirm the atypical negative creep strain in transverse directions due to the uniaxial compression load as reported in [2].

The performed analyses clearly show the influence of misalignment of the wood orthotropic directions and the observed stress-strain directions on the transverse strain distribution in uniaxial cases. Hence, this is one possible explanation for reported extraordinary behavior of wood, and calls for attention when unexpected strain distribution is monitored in future experiments.

References

[1] A.P. Schniewind, J.D. Barrett: Wood as a Linear Viscoelastic Material. *Wood Science and Technology*, 6 (1972), 43-57.
[2] T. Ożyhar, S. Hering, P. Niemz: Viscoelastic characterization of wood: Time dependence of the orthotropic compliance in tension and compression. *Journal of Rheology,* 57 (2013), 699-717.
[3] S. Huč, S. Svensson: Coupled two-dimensional modelling of viscoelastic creep of wood. *Wood Science and Technology*, (under review).

A multi-scale model for the creep behaviour of wood

Pina J.C.[†] [*], Saavedra Flores E.I.[†], C.F. Guzmán[†] and S. Yanez[†]

[†]Departamento de Ingeniería en Obras Civiles, Universidad de Santiago de Chile, Av. Ecuador 3659, Estación Central, Santiago, Chile
juan.carlos.pina@usach.cl, erick.saavedra@usach.cl, cf.guzman@usach.cl, sergio.yanez.c@usach.cl

Due to its complex microstructure, predicting the mechanical response of wood has always been a challenging task. In recent years the use of microstructural modelling and multi-scale methods has enabled to better understand, and consequently predict, the mechanical response of wood across different length scales [1, 2]. This approach has been used to estimate in a fairly successful way the behaviour of wood ranging from the linear to the non-linear regime. One of the major challenges that still remain open is the development of computational models that can accurately predict the time dependent creep response of wood materials. Although several references can be found in the literature investigating the creep behaviour of wood, most of these works try to understand the microstructural mechanisms that drive the creep based on experimental observations [3-5].

In this work we present a finite element-based multi-scale model developed to capture the creep behaviour of wood. At microscopic levels, several features of wood are taken into account, such as the volume fraction of hemicellulose, lignin and cellulose, their mechanical and physical properties, and microfibril angle; which are crucial to capture the inherent orthotropic nature of wood observed at the macroscopic level. To capture the creep related time dependent response a vico-elastic/visco-plastic constitutive model is adopted. The model is based on two parallel rheological models, a visco-plastic Prandtl model and and visco-elastic Maxwell model [2]. The mutli-scale approach used here makes possible to assess and understand the influence that the different microstructural features have on the macroscopic creep response of wood.

Experimental tests were conducted to measure the time dependent mechanical response of wood. The experimental measurements were carried out in specimens made of radiata pine grown in Chile subject to bending. Our numerical predictions were compared with the experimental results and were validated successfully.

Acknowledgements

E.I. Saavedra Flores acknowledges the financial support from the Chilean National Commission for Scientific and Technological Research (CONICYT), FONDECYT REGULAR research project No. 1160691.

References

[1] K. De Borst, C. Jenkel, C. Montero, J. Colmars, J. Gril, et al.: Mechanical characterization of wood: An integrative approach ranging from nanoscale to structure. *Computers and Structures*, 127 (2013), 53-67.
[2] E.I. Saavedra Flores, E.A. de Souza Neto, C. Pearce: A large strain computational multi-scale model for the dissipative behavior of wood cell-wall. *Computational Materials Science*, 50 (2011), 1202-1211.
[3] P.U.A. Grossman: Requirements for a model that exhibits mechano-sorptive behaviour. *Wood Science and Technology*, 10 (1976), 163-168.
[4] Z.P. Bazant: Constitutive equation of wood at variable humidity and temperature. *Wood Science and Technology*, 19 (1985), 159-177.
[5] D.G. Hunt: A unified approach to creep of wood. *Procedures of the Royal Society A*, 455 (1999), 4077-4095.

V:3

One-dimension visco-elastic modelling of wood in the process of formation to clarify the Hygrothermal Recovery behavior of tension wood

M. Capron[†‡*], S. Bardet[2], K.C. Sujan[†ˠ], M. Matsuo[†] and H. Yamamoto[†]

[†]Graduate School of Bio-agricultural Sciences, Nagoya University, marie.capron@esrf.fr
[2]Laboratoire de Mécanique et de Génie Civil (LMGC), Université Montpellier, sandrine.bardet@umontpellier.fr
[‡]ESRF – The European Synchrotron
[ˠ]Institute of Wood Technology, Akita Prefectural University, Graduate School of Bioresource Sciences

Wood production on stem by deposit of concentric layers on its periphery are going along with the setting up of growth stress. Growth stress has two origins: (1) loading due to weight of the structure is applied progressively when the tree is growing; (2) cell maturation, which happened at the end of the deposit of a new layer, causes an expansion, called maturation deformation, which can't happen freely due to the previous layer and lead to the creation of initial growth stress [1]. The growth stress can be released during cutting and also during hygrothermal treatment (HT), it can be called Hygrothermal Recovery (HTR) [2]. In this work, an one-dimension rheological modelling of wood in the process of formation is proposed to clarify the HTR behavior of Tension Wood (TW). This study focuses on the longitudinal dimensional changes. The rheological analogy is made of a series of four elements (Fig. 1): an elastic element represented by a spring of compliance S_0 which is equal to that of mature wood; a deformation mechanism, α, representing the expansion tendency during maturation; and two visco-elastic elements represented by a spring of compliance S_1 and S_2 in parallel with a dashpot also called Kelvin-Voigt model.

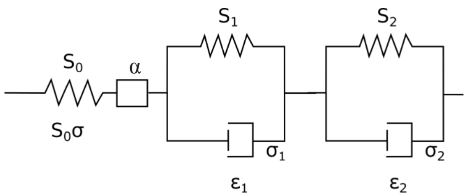


Figure 1: Rheological analogy representing the modelling using of 2 Kelvin-Voigt with α the maturation strain, S_0 the elastic or mature compliance and S_1 and S_2 the delayed compliance.

In order to find a coherent modelling parameters, a fitting with experimental data has been done using different samples from three species konara oak (*Quercus serrata* Murray), urihada maple trees (*Acer rufinerve* Siebold et Zucc.) [3] and keyaki (*Zelkova serrata* Makino). The modelling is able to fit the different parts of HTR for TW (Fig. 2).

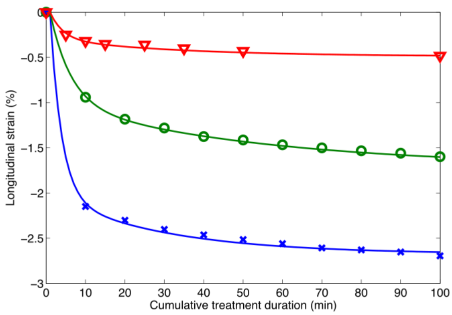


Figure 2: Longitudinal strain change as a function of cumulative treatment duration experimental data for *Urihada maple* (**o**), *Konara oak* (**x**) and *Keyaki* (▽) (TW) and their modelling using two visco-elastic elements (-).

References

[1] R.R. Archer: Growth Stresses and Strains in Trees. Springer Series in Wood Science – Hardcover, 1986.

[2] H. Kubler: Growth stresses in trees and related wood properties. *Forest Products Abstracts*, 10 (1987), 61-119.

[3] K.C. Sujan, H. Yamamoto, M. Matsuo, M. Yoshida, K. Naito, T. Shirai: Continuum contraction of tension wood fiber induced by repetitive hygrothermal treatment. *Wood Science and Technology*, 49 (2015),1157-1169.

V:4

Finite Element Modelling (FEM) of the viscoelastic behavior of a wooden spring system.

B. Homerin[†*] and M. Rhême[†]

[†]Bern University of Applied Sciences, Institute for Materials and Wood Technology, benoitjacques.homerin@bfh.ch

When applying appropriate cutting patterns, wood or wood-based materials have the potential to act as springs for many applications. As an example, this research aims at supporting the development of a wooden spring system as an alternative to the metallic coil springs widely used in the box springs of beds.

As a first step, an elastic FE three dimensional orthotropic model was developed and validated through experimental compression tests (Figure 1). Two wood species were considered: Norway Spruce (*Picea Abies*) and European Ash (*Fraxinus Excelsior*). The elastic properties of these species in the three anatomical directions were taken from the literature [1] [2]. The FE elastic model showed accurate results. The maximum discrepancy with the experimental results was found to be lower than 10% even when the geometrical parameters were changed.

In a second step, the model was further developed in order to predict the viscoelastic behavior of the spring system. That was achieved by using an Ansys User Programmable Feature developed in [3] which considers a 5-branches Generalized Maxwell Model (GMM) to simulate creep and stress relaxation. The viscoelastic properties in the three main directions are given in [3] for spruce, but they do not exist for ash. A characterization was therefore carried out using a micro-tensile device under constant humidity and temperature. The experimental creep curves in the three anatomical directions of the wood were fitted to the analytical GMM in order to determine the properties. After comparison of the viscoelastic models with experimental creep-recovery results, it was found that the viscoelastic model of ash underestimates the deformation over time by around 3%. Higher discrepancies were noticed for the spruce viscoelastic model. Although the simulated relative creep deformation is higher, the simulated absolute deformation is any time lower than the experimental deformation. By modifying the elastic moduli in the longitudinal direction (E_L), one is able to improve the model accuracy. The results of this research allow the development of wooden spring systems for a variety of different technical applications.

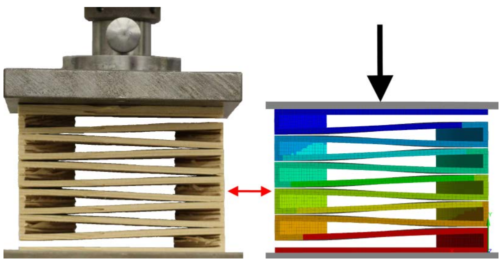


Figure 1: The wooden spring system and its orthotropic elastic FE model displayed in a compressed state.

References

[1] P. Navi, F. Heger: Comportement thermo-hydromécanique du bois: Applications technologiques et dans les structures. PPUR presses polytechniques, 2005.
[2] P. Niemz, S. Clauß, F. Michel, D. Haensch, A. Haensel: Physical and mechanical properties of common ash (fraxinus excelsior l.). *Wood Research*, 59 (2014), 671–682.
[3] J. Froidevaux: Wood and paint layers aging and risk analysis of ancient panel painting. PhD thesis, Université Montpellier II-Sciences et Techniques du Languedoc, 2012.

V:5

Moisture driven failure monitoring in wood material: numerical analysis based on viscoelastic crack growth approach

Hamdi S.E. [†]**, Moutou Pitti R.**[† ‡] **, Saifouni O.**[**]

[†]Université Clermont Auvergne, CNRS, Institut Pascal, F-63000 Clermont Ferrand, France
[‡] CENAREST, IRT, BP 14070, Libreville, Gabon
[**]DRIVE EA1859, Univ. Bourgogne Franche-Comté, F-58000 Nevers, France
[*]Rostand.moutou_pitti@uca.fr

Wood is considered as an orthotropic hydro-mechanical material whose mechanical behavior strongly depends on the moisture content and the temperature. Taking into account humidity and temperature variation, the mechanical behavior assessment becomes more complex due to the coupling effect between the mechanical stress and the hydric state (Thermo-Hydro-Mechanical behavior or THM) [1]. The viscoelastic behavior of wood under variable humidity, known as the mechanosorptive behavior, induces different responses in the drying and in the humidification phase. However, in presence of climatic variations, the long terms load and especially the crack initiations, the mechanical behavior of wooden structures is found highly modified. The effects of moisture changes on the propagation of cracks are not yet clearly identified. Therefore, it appears necessary to investigate the influence of the variable environment and crack growth process on the mechanical properties of wood structures.

This work completes the numerical results presented during the EUROMECH Colloquium 556 [2] about the effect of temperature variation on viscoelastic orthotropic material like wood. In this work, the temperature is supposed constant in order to investigate the effect of moisture content (MC) on fracture mechanics parameters. The new non-dependent integral A [3] is applied so as so to introducing the both opening and shear mode coupled with (MC) in crack growth process configuration. It is shown that for a stable crack propagation (the energy release rate G is a decreasing function of crack length), crack growth resistance is not constant, but changes with crack propagation (figure 1). The (MC) appears to be responsible for the changes, and leads to the formation of the so-called process zone [4]. The aim of this paper is to investigate the effect of temperature (T) and moisture content (MC) changes on wood fracture properties, focusing on crack driving forces, such as G or stress intensity factor (K). In the coming works, the effects of drying will be investigated in order to simulate the cracks observed experimentally during this phase.

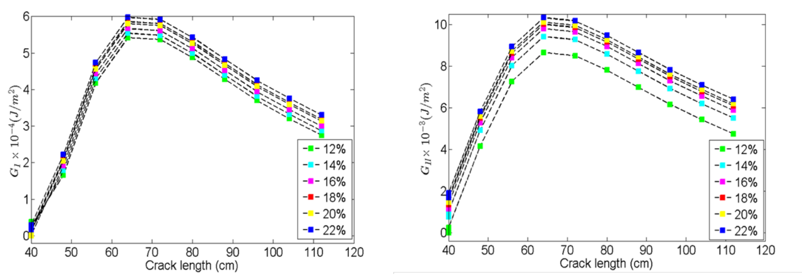


Figure 1: Effect of moisture content (MC) variation on G vs. crack length during heating process: ΔT = 10° C (a), ΔT = 30° C (b).

References

[1] R. Moutou Pitti, F. Dubois, C. Petit: Generalization of T and A integrals to time-dependent materials: analytical formulations. *International Journal of Fracture*, 161(2010), 187-198.
[2] R. Moutou Pitti, S.E. Eddine, F. Dubois: Fracture analysis in wood coupling viscoelastic behavior and temperature effects by non-dependent integrals. EUROMECH Colloquium 556. Theoretical, numerical and experimental analysis in wood mechanics. Dresden, 27-29 May, 2015.
[3] S.E. Hamdi, R. Moutou Pitti, F. Dubois: Impact of Hydro-Mechanical Loadings On Rupture Process *In Wood Material, Society for Experimental Mechanics*, 2016.
[4] H. Riahi, R. Moutou Pitti, F. Dubois, A. Chateauneuf: Mixed-mode fracture analysis combining mechanical, thermal and hydrological effects in an isotropic and orthotropic material by means of invariant integrals. *Theoretical and Applied Fracture Mechanics*, Part B 85 (2016), 424-434.

Acknowledgements

The authors wish to strongly acknowledge the National Agency of Research (ANR) for its financial support of this work through the project CLIMBOIS N◦ ANR-13-JS09-0003-01 labeled by ViaMeca.

V:6

Coupled two-dimensional modelling of long-term behavior of wood subjected to mechanical stress and varying climatic conditions

Sabina Huč[†‡*], Staffan Svensson[†]

[†]University of Borås, Faculty of Textiles, Engineering and Business, SE-501 90 Borås, Sweden, sabina.huc@hb.se, staffan.svensson@hb.se

[‡]Division of Applied Mechanics, Ångström Laboratory, Uppsala University, Box 534, SE-751 21 Uppsala, Sweden

Timber structures are exposed to various environmental conditions during their service life that induce creep deformation. Sustained load gives viscoelastic creep. Humidity variation causes moisture change and in turn shrinkage and swelling. Acting together load and moisture change cause mechano-sorptive creep of wood. Its orthotropic structure implies different, but coupled creep response in each material direction. A uniaxial excitation causes the response in transverse directions.

Mathematically, the long-term behavior of the material is described by an additive principle, where the total strain ε is a sum of the ε^{e} elastic strain, ε^{ve} viscoelastic strain, ε^{ms} mechano-sorptive strain, and ε^{s} strain due to shrinkage and swelling.

Combinations of spring and dashpot elements are suitable for describing creep of wood. A formulation of the coupled creep response in two dimensions is presented in [1]. Validation of the formulation for viscoelastic creep due to tensile load is presented in [2]. Similar approach can be applied for modelling mechano-sorptive creep, where the dashpot and spring combined as a Kelvin solid are considered

$$\begin{bmatrix} \sigma_{L} \\ \sigma_{T} \\ \sigma_{LT} \end{bmatrix} = \begin{bmatrix} Q_{LL}^{ms} & Q_{LT}^{ms} & 0 \\ Q_{TL}^{ms} & Q_{TT}^{ms} & 0 \\ 0 & 0 & Q_{LT}^{ms} \end{bmatrix} \begin{bmatrix} \varepsilon_{L}^{ms} \\ \varepsilon_{T}^{ms} \\ \varepsilon_{LT}^{ms} \end{bmatrix} + \begin{bmatrix} \eta_{LL}^{ms} & \eta_{LT}^{ms} & 0 \\ \eta_{TL}^{ms} & \eta_{TT}^{ms} & 0 \\ 0 & 0 & \eta_{LT}^{ms} \end{bmatrix} \begin{bmatrix} \dot{\varepsilon}_{L}^{ms} \\ \dot{\varepsilon}_{T}^{ms} \\ \dot{\varepsilon}_{LT}^{ms} \end{bmatrix}. \tag{1}$$

σ_{L} and σ_{T} are stresses in L and T directions, respectively; σ_{LT} is the shear stress, η are the material parameters of the dashpot, Q are the material parameters of the spring. ε^{ms} is dependent on change of moisture content u and its time derivative is determined as

$$\dot{\varepsilon}^{ms} = \frac{d\varepsilon^{ms}}{du}\left|\dot{u}\right|. \tag{2}$$

ε^{s} is defined as

$$\begin{bmatrix} \varepsilon_{L}^{s} & \varepsilon_{T}^{s} & \varepsilon_{LT}^{s} \end{bmatrix}^{T} = \begin{bmatrix} \alpha_{L} & \alpha_{T} & 0 \end{bmatrix}^{T} \left(u - u_{ref}\right) \tag{3}$$

where u_{ref} is a reference moisture content and α is a single valued parameter.

Prior to the stress-strain analysis, a moisture state in the material has to be determined. Variation of the moisture content in wood follows a variation of relative humidity in the surrounding air. This is modelled by a multi-Fickian moisture transport model [1] that describes the bound-water and water-vapor diffusion in wood. Both processes are coupled through sorption hysteresis, which defines the dependence of equilibrium moisture content in wood on the variation of relative humidity and its history. Calculated moisture content is used as an input to the mechanical analyses.

The moisture and the mechanical model are implemented in a finite element program. The obtained results of the coupled analyses allow observing temporal and spatial distribution of the moisture dependent strains and stresses in timber members. The coupled moisture and mechanical model present a complete two-dimensional mathematical description of the time-dependent behavior of wood subjected to a constant load and varying humidity.

References

[1] H.L. Frandsen: Selected Constitutive Models for Simulating the Hygromechanical Response of Wood. PhD Thesis, Aalborg University, Denmark, 2007.

[2] S. Huč, S. Svensson: Coupled two-dimensional modelling of viscoelastic creep of wood. *Wood Science and Technology*, (under review).

VI:1

Modelling and Experimental Investigations of Densification of Wood for Forming Processes

Robert Fleischhauer†, Jens U. Hartig*, Peer Haller* and Michael Kaliske†

†Institute for Structural Analysis, Technische Universität Dresden, 01062 Dresden, michael.kaliske@tu-dresden.de
*Institute of Steel and Timber Construction, Technische Universität Dresden, 01062 Dresden

The microstructure of wood is significantly influencing its structural behavior at different loading scenarios. Tracheids or fibers, which form the bulk material of the specific wood as well as rays, which consist of parenchyma cells and sap channels, which conduct fluids, are important parts of the microstructure. The mechanical behavior of wood possesses an inherent dependency on temperature and moisture. Its thermomechanical properties are in general characterized by anisotropic thermo-inelasticity, which depends strongly on moisture related transport and saturation phenomena.

Three sequential phases are taking place, when dry wood absorbs water from the surrounding environment. First, due to a chemical sorption moisture is bonded within the cell walls without any swelling process. Second, the moisture accumulates inside the pores of the microstructure. Third, with ongoing moisture absorption, a capillary condensation occurs until saturation is reached, see [1]. Capillary forces and diffusion are generating the moisture transport within the cavities and pores along the fiber orientation. The transport of moisture transverse to the fiber direction is taking place in the rays and sap channels, see [1, 2].

The contribution at hand presents a phenomenological model of finite deformations based on continuum mechanics with respect to the finite element method, considering the moisture dependency of wood and is based on the developments made in [3].

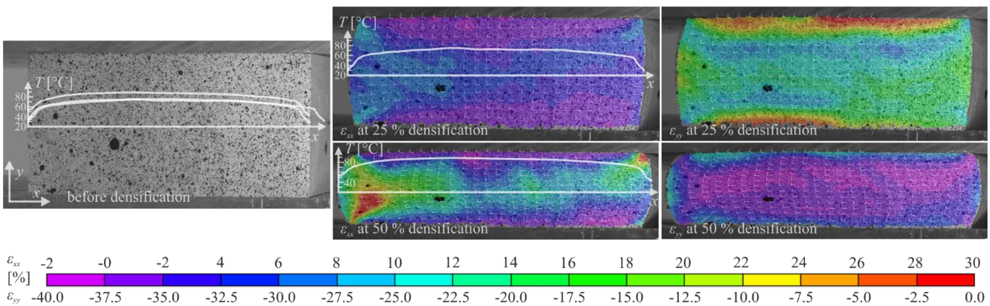


Figure 1: Photogrammetric and thermographic measurements of a densification experiment at beech wood (*Fagus sylvatica L.*); strain and temperature distributions over the cross-section before (left), at 25 % (centre) and at 50 % (right) of the densification.

The model consists of a fully coupled multi-physical finite element formulation as well as of constitutive descriptions accounting for anisotropic multi-surface thermo-plasticity. The swelling and shrinking phenomena, which occur due to the hygroscopic properties of wood, are considered by an appropriate processing of the fundamental balance of mass, since the absorption of water leads to a change of mass of the wooden structure. The presented approach evolves the mass of the system observed according to the amount of moisture, bound within the microstructure. The model approach is verified and validated by numerical benchmarks and experimental data of different experiments on beech wood.

The densification of wood at finite deformations, see e.g. [4], is accomplished at high temperature of 80°C to 110°C. Finally, the presented approach is applied to the simulation of such a densification procedure and validated by experimental data, compare Figure 1.

References

[1] Niemz, Peter; Physik des Holzes und der Holzwerkstoffe. DRW-Verlag, Leinfelden-Echterdingen, 1993.
[2] Reichel, S.; Kaliske, M.; Hygro-mechanically coupled modelling of creep in wooden structures, Part II: Influence of moisture content. International Journal of Solids and Structures 77, 45-64, 2015.
[3] Fleischhauer, R.; Kaliske, M.: A phenomenological approach to model large deformation inelasticity of wood and its application. Wood Science and Technology, (submitted for publication), 2016.
[4] Hartig, J. U.; Wehsener, J.; Haller, P.: Experimental and theoretical investigations on moulded wooden tubes made of beech (*Fagus sylvatica L.*). Construction and Building Materials, 126, 527-536, 2016.

The effect of surface emission, diffusion and initial moisture profiles on stress development in timber boards

S. Florisson[†*] and S. Ormarsson[†]

[†]Building Technology, Linnaeus University, sara.florisson@lnu.se

Heartwood of spruce and pine experiences moisture contents (MC) that ranges between values close to fibre saturation point (30-40%) when in green state. The sapwood, on the contrary, experiences much higher values (120-180%). In timber boards that contain both heartwood and sapwood these differences in MC result in significant cross-sectional moisture variations. Such a non-uniform moisture distribution can cause some areas of the cross section to start shrinking far before other parts do. This phenomenon has a marked effect on strain, stress and crack development [2].

The initial moisture variation is often neglected when it comes to simulating drying processes. A numerical approach was employed that takes into account this initial moisture state, and is able to show its effect on stress development during drying. The simulations were made with use of commercial finite element software ABAQUS [1] employing user-subroutines to simulate wood material behaviour. The model was made with use of scripting, and consists of a transient non-linear moisture analysis and a stress analysis. The acquired moisture history profiles counted as input for the stress analysis, which is able to determine the effect of elastic strain, mechano sorption and hygroscopic strain [3].

The simulation model was used to analyse several solid timber boards with a unique pith location and a unique geometric design with respect to the heartwood and sapwood parts. The moisture analysis was used to perform a parametric study that was focussed on the mutual relation between surface emission and diffusion on the development of moisture gradients. The purpose of the parametric study of the stress analysis was to observe the influence of the initial moisture distribution and drying time on stress and strain development.

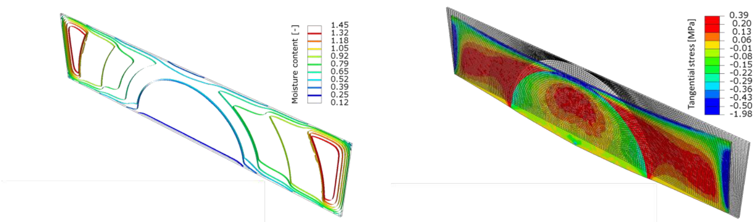


Figure 1: Simulated moisture content history profile after 95 hours of drying (left) and tangential stress profile after 12.5 days of drying (right). The stress profile is plotted over the distorted shape (magnification 3x).

It is observed that the mutual relation between surface emission coefficient and diffusion coefficient is of great significance for the shape of moisture history profiles. The obtained profiles show good agreement with experimental data presented in [4]. The stress analysis shows that moisture variation in green state, shrinkage coefficient and sawing pattern have a marked effect on stress development within timber boards. The analysis also shows the typical stress reversal that is to be expected in solid timber between beginning and end of drying. Proceeding studies are focused on more challenging initial green state moisture profiles. Additionally, the simulation model will be validated using experimental results obtained from different bending tests performed in cyclic climate conditions.

References

[1] ABAQUS (2016) *Theory manual v6.14*. SIMULIA
[2] Larsen, F. and Ormarsson, S. (2013) *Numerical and experimental study of moisture-induced stress and strain field developments in timber logs,* Wood Science and Technology, 47(4), 837-852.
[3] Ormarsson, S. (1999) *Numerical analysis of moisture-related distortions in sawn timber*, PhD Thesis, ISBN 91-7197-834-8, Göteborg, Sweden.
[4] Rosenkilde, A. (2002) *Moisture content profiles and surface phenomena during drying of wood,* PhD Thesis, ISBN 91-77283-407-2, KTH, Sweden.

VI:3

A numerical approach to study the effects of coatings on the moisture gradients and moisture induced stresses in glulam beams of timber bridges

Stefania Fortino†*, Petr Hradil†, Anna Pousette‡
†VTT Technical Research of Finland Ltd, stefania.fortino@vtt.fi, petr.hradil@vtt.fi
‡ SP Technical Research Institute of Sweden, anna.pousette@sp.se

The moisture gradients generated by continuous variations of external humidity in combination with changing temperatures can induce additional stresses in the structural elements of timber bridges, especially under the extremely variable climates of Northern Europe. These moisture induced stresses (*MIS*) can for instance increase the risk of cracks close to the external surfaces of glulam beams of bridges (see [1] and the related references). Such risk is further increased in places with high level of mechanical stress from the bridge loading.

In the present work the moisture gradients and the related *MIS* in a coated glulam beam of Älsvbacka bridge in North of Sweden are studied under the effects of different types of coatings by using a multi-Fickian method implemented in Abaqus FEM code and able to model the different water phases in wood under the fibre saturation point. The beam, having a cross section of 645×1100 mm^2 (Figure 1, left), was monitored by using wireless sensors in a previous study (see references in [1]). On the external side a protective cladding is also used. The governing equations of the adopted method are the following:

$$\frac{\partial c_b}{\partial t} = -\nabla\cdot(\mathbf{D}_b \nabla c_b) + \dot{c}; \quad \frac{\partial c_v}{\partial t} = -\nabla\cdot(\mathbf{D}_v \nabla c_v) + \dot{c} \qquad (1)$$

where c_b and c_v represent the concentrations of bound water in cell walls and lumens, respectively, $\mathbf{D}_b$ and $\mathbf{D}_v$ are the diffusion tensors for bound water and vapour water and dotted c is the sorption rate coupling the two equations. A third equation of energy conservation for the variable temperature is also included (see the details in [1]). Compared to the methods presented in [1,2], a different temperature-dependent hysteresis model is proposed. This is extrapolated from sorption isotherms measured by Hedlin in 1967 also at temperatures below zero [1]. The results of the hygro-thermal analysis are used within an orthotropic-viscoelastic-mechanosorptive model. The total strain of the model is expressed in vector form as $\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^{e}+\boldsymbol{\varepsilon}^{h}+\boldsymbol{\varepsilon}^{ve}+\boldsymbol{\varepsilon}^{ms}+\boldsymbol{\varepsilon}^{ms,irr}$ where the terms in the right side represent the elastic, hygroexpansion, viscoelastic, mechanosorptive and irrecoverable mechanosorptive strain, respectively [2].

The reference coatings used in the present study for the numerical analyses are alkyd oil paint, acrylate paint and glue paint with permeance [kg/m^2 s Pa] of 3E-10, 1E-9 and 4E-9, respectively. As shown in Figure 1 (right), the moisture gradients increase with increasing coating permeance. Coatings with permeance greater than the value for alkyd oil paint provide *MIS* perpendicular to grain near the surface that are higher than the Eurocode limits in tension. The proposed approach can be useful to optimize the choice of protective coatings in structural elements of timber bridges.

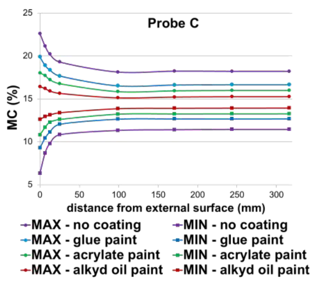


Figure 1: Left: Glulam beam of Älsvbacka bridge. Right: Envelopes of maximum and minimum moisture contents (MC) along half middle path of the cross section for different coatings.

References

[1] S. Fortino, P. Hradil, A. Genoese, A. Genoese, A. Pousette, P.A. Fjellström. A multi-Fickian hygro-thermal model for timber bridge elements under Northern Europe climates. Proceedings of World conference in Timber Engineering (WCTE 2016), August 22-25, 2016, Vienna, Austria.

[2] S. Fortino, L. Salokangas, A. Musci, G. Metelli. Effects of moisture induced stresses on the mechanical performance of glulam beams of Vihantasalmi bridge. Proceedings of World conference in Timber Engineering (WCTE 2016), August 22-25, 2016, Vienna, Austria.

Impact of moisture content changes on the mechanical behavior of *Pseudotsuga Menziesii*

Pambou Nziengui C.F. [†*], **Moutou Pitti R.** [*‡], **Fournely E.** [*], **Gril J.** [**]

[†]Ecole Nationale des Eaux et Forêts, BP 3960, Libreville, Gabon
[*] Université Clermont Auvergne, CNRS, Institut Pascal, F-63000 Clermont Ferrand, France
‡ CENAREST, IRT, BP 14070, Libreville, Gabon
[**] LMGC, CNRS, Univ. Montpellier, Montpellier, France
Rostand.moutou_pitti@univ-bpclermont.fr

One of the main objectives of this project is to set up an experiment and a numerical model using cast3m software, taking into account the effect of climatic variations, initial defaults of Wood and the deferred loading of wood structures. The results obtained during the first experimental phases will be presented, especially the mechanical characterization tests carried out on a notched beam made of *Pseudotsuga Menziesii* Franco wood, loaded in variable climate (outdoor creep) focusing on the influence of variations in the moisture content (MC) of the beam on the opening of the crack and the evolution of the deflection [1-2].

The curves show the effect of MC variations on the damage of the beam. Indeed, there is a correlation between the peaks of the crack opening curves D6A and D6C (figure 1a) and the MC peaks especially at 1200-1800-2100 hours. Figure 1b shows that for an increase in internal humidity there is an increase in deflection. It seems clear that there is a strong link between the reduction of the lifetime of a wooden structure, such as our notched beam, subjected to a constant load and MC variations. For future work, particular emphasis will be placed on the combined action of climatic variations and initial defects over the lifetime of the structures under test. The experimental results obtained will allow us to propose a numerical mechano-sorptive model taking into account the effect of climatic conditions, coupled with the initial defects of wood on the behavior of wood structures, using CAST3M software.

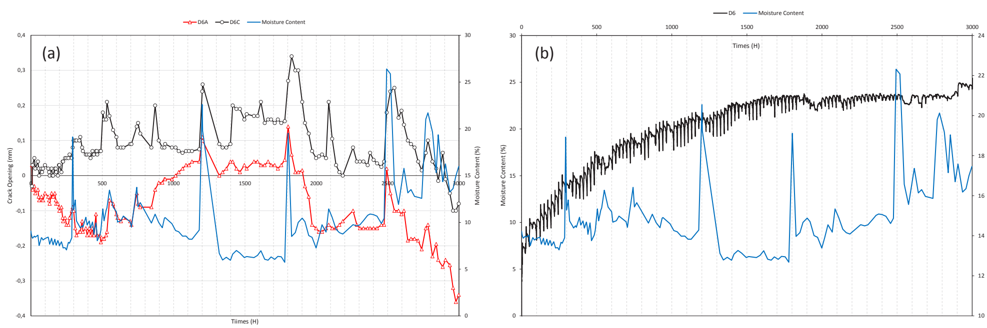


Figure 1: a) Crack opening vs moisture content in the time. b) Evolution of deflexion vs moisture content

References

[1] C.F. Pambou Nziengui, R. Moutou Pitti, E. Fournely G. Godi, and F. Dubois: Mechanical characterization of European species: Picea-Alba mill and Douglas-fir. SEMC, Cap Town; 09/2016.

[2] C.F. Pambou Nziengui, R. Moutou Pitti, E. Fournely, G. Godi, N. Angellier, P. Fargeix, D Chanal, F Dubois, S. Ikogou: Project ANR JCJC CLIMBOIS: Impact of climatic conditions on the propagation of cracks in Douglas girders in external creep. 5th day of the GDR 3544 "Sciences du bois" - Bordeaux, 8-10 November, 2016.

Acknowledgements

The authors wish to strongly acknowledge the National Agency of Research (ANR) for its financial support of this work through the project CLIMBOIS N◦ ANR-13-JS09-0003-01 labeled by ViaMeca and the laboratory of physical meteorology (Lamp) of University Clermont Auvergne for the regular sending of meteorological data.

VII:2

Multiscale Modeling of Hygromechanical Behavior of Wood Cell Wall S2 Layer

Chi Zhang[†‡*], Dominique Derome[‡], and Jan Carmeliet[†‡]

[†]Chair of Building Physics, ETH Zurich, zhangchi@student.ethz.ch, carmeliet@arch.ethz.ch
[‡]Laboratory for Multiscale Studies in Building Physics, Empa, dominique.derome@empa.ch

Wood, an orthotropic cellular biomaterial, interacts strongly with moisture and exhibits hygromechanical behavior, such as anisotropic swelling and shape memory. Wood complex hierarchical material structure is yet not fully understood experimentally. S2 layer is the thickest layer of wood cell wall, thereby playing a key role in the mechanical behavior of wood cell wall. Theoretical and numerical models are used to investigate the mechanisms of hygromechanical behavior beyond the scope of experiments.

Continuum methods such as finite element method (FEM) are commonly used in mechanical studies of wood on macroscopic level. Yet it has been shown that moisture-induced deformation originates at the sub-cellular scale[1]. Atomistic interactions between polymeric components and water molecules determine the hygromechanical behavior. Molecular dynamics (MD) and grand canonical Monte Carlo (GCMC) simulations are capable of capturing the atomistic interactions with high temporal-spatial resolutions.

Taking advantage of both continuum method and atomistic simulation approaches, we propose a multiscale modeling framework which combines MD and GCMC, and FEM with poromechanics. The essential polymeric components, namely cellulose (crystalline, paracrystalline, amorphous), hemicelluloses (galactoglucomannan, aribinoglucuronoxylan), lignin (condensed, uncondensed), and, as a non-trivial extension, their interfaces, are modeled by MD. Sorption isotherm and swelling coefficient, moisture diffusion, hydrogen bonding information, elastic moduli and Poisson's ratios, all dependent on moisture content, are extracted from atomistic model. Then these results are upscaled into a poroelastic model following the scheme developed by Carmeliet et al[2], and implemented in FEM. The geometry and material arrangement of FEM models are based on experimental observations with assumptions, as summerized by *e.g.* Salmen[3]. The achieved continuum model is validated by MD results and used to investigate mechanisms of anisotropic swelling and moisture-induced weakening.

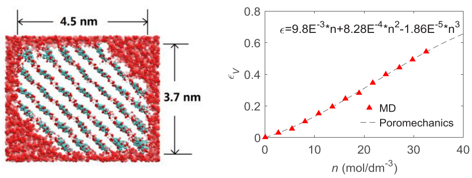


Figure 1: Multiscale modelling of wood cell wall S2 layer: left, atomistic model of microfibril; right, poromechanical upscaling of matrix

Good agreement of MD results with experiments is achieved in terms of sorption and swelling behavior, as well as moisture dependence of mechanical properties. Molecular simulations of microfibril show that swelling is nonlinear and anisotropic, and mechanical weakening stems from the breaking of hydrogen bonds between polymers which are replaced by water-polymer bonds[4]. Through poromechanical upscaling, sorption isotherm is found to be stress dependent[5]. The swelling anisotropy induced by moisture originates from the heterogeneous structure of the wood cell wall as laid out during exoskeleton genesis. This multiscale study sets up a framework of implementing molecular interactions into continuum modeling, which can have potential uses in many scenarios of further wood research.

References

[1] A. Rafsanjani, M. Stiefel, K. Jefimovs, R. Mokso, D. Derome, and J. Carmeliet, "Hygroscopic swelling and shrinkage of latewood cell wall micropillars reveal ultrastructural anisotropy," *J. R. Soc. Interface*, vol. 11, no. 95, p. 20140126, Mar. 2014.

[2] J. Carmeliet, D. Derome, M. Dressler, and R. A. Guyer, "Nonlinear Poro-Elastic Model for Unsaturated Porous Solids," *J. Appl. Mech.*, vol. 80, no. 2, p. 20909, 2013.

[3] L. Salmen and I. Burgert, "Cell wall features with regard to mechanical performance. A review: Wood machining - Micromechanics and fracture," *Holzforschung*, vol. 63, no. 2, p. 121, 2009.

[4] K. Kulasinski, R. Guyer, D. Derome, and J. Carmeliet, "Water Adsorption in Wood Microfibril-Hemicellulose System: Role of the Crystalline–Amorphous Interface," *Biomacromolecules*, vol. 16, no. 9, p. 2972, 2015.

[5] K. Kulasinski, R. Guyer, D. Derome, and J. Carmeliet, "Poroelastic model for adsorption-induced deformation of biopolymers obtained from molecular simulations," *Phys. Rev. E*, vol. 92, no. 2, p. 22605, Aug. 2015.

Multi-Fickian Hygro-mechanical Investigation of Wooden Cultural Heritage

D. Konopka[†*] and M. Kaliske[†]

[†]Institute for Structural Analysis, Technische Universität Dresden, 01062 Dresden, Germany,
daniel.konopka@tu-dresden.de, michael.kaliske@tu-dresden.de

Museums with collections of historical music instruments have the conflict between conservation of the original substance and maintenance of original use. Especially playable stringed keyboard instruments are complex wooden structures under heavy mechanical loading. Hygrical loadings as alternating climate conditions induce additional mechanical loadings and influence the physical properties enforcing damages to the structure like large deformations and cracks. This recent research field of the Institute for Structural Analysis is focused on two kinds of structures, with respect to the external loads: The purely hygrically loaded structures, like furniture and panel paintings on the one hand, and the more complex stringed wooden music instruments, like pianofortes, violins or guitars, on the other hand. The latter, additionally loaded by mechanical forces, are strongly susceptible to plastifications and creeping deformations, enhanced by moisture dependent mechano-sorptive effects. The goal is the development of an objective simulation tool for museums and conservators in order to support conservation strategies and to be able to evaluate these wooden structures.

To handle the natural and complex material wood and to analyze the hygro-mechanical load-bearing behavior under static mechanical loads by the finite element method, several material models have been developed and implemented. The elastic range is used to be considered as orthotropic formulation basing on a stress-strain relation according to Hooke's law. Compressively loaded wood, especially perpendicular to the grain, leads to ductile failure with plastic deformations beyond the elastic range. For the numerical simulation, a multi-surface plasticity model has been developed [1] and expanded to moisture dependency [2]. Exposed to tensile or shear loading, wood shows distinctive brittle failure. This property can be captured by interface-elements and corresponding moisture dependent material models [2, 3]. Due to the distinct hygroscopicity of wood, not only the mechanical material properties need to be modeled accurately. The moisture transport plays an important role within the analysis of transient processes, i.e. climate changes. Thus, the moisture transfer at the surface is captured by a boundary-layer model, while the inner transport is characterized by a multi-Fick'ian diffusion approach [4]. The two phases of bound water in the cell walls and the water vapor in the lumens are coupled via sorption isotherm.

First results of the transient simulation of a clavichord under tensioned strings and weekly changing climate can reproduce experimentally determined deformations qualitatively. The simulation can give an insight into the process of time-dependent stress peaks due to internal constraints, caused by the anisotropic swelling and shrinking behavior of wood.

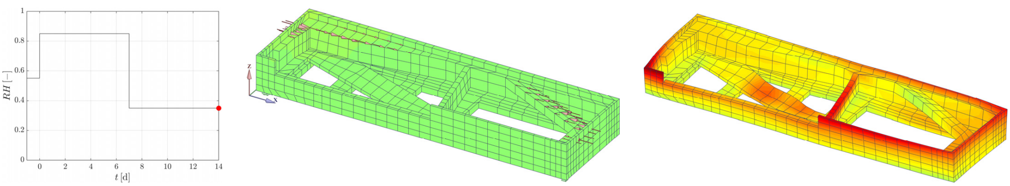


Figure 1: Relative humidity of ambient air (left), initially unloaded clavichord (center), absolute deformations (magnified) of the clavichord after 14 days

While the material models for the short-term phenomena could be applied successfully, current research aims to consider the influences of bond-lines, material inhomogeneities and long-term behavior like creep. Further investigations in the experimental material parameter characterization, especially in the long-term behavior and the dependency of the moisture content, would support the quality of the numerical simulations.

References

[1] Resch, E., Kaliske, M., Three-dimensional numerical analyses of load-bearing behavior and failure of multiple double-shear dowel-type connections in timber engineering, *Computers and Structures* 88 (2010) 165–177.

[2] Saft, S., Kaliske, M., Numerical simulation of the ductile failure of mechanically and moisture loaded wooden structures, *Computers and Structures* 89 (2011) 2460–2470.

[3] Schmidt, J., Kaliske, M., Simulation of cracks in wood using a coupled material model for interface elements, *Holzforschung* 61 (2007) 382–389.

[4] Konopka, D., Kaliske, M., Hygro-mechanical Fe-analysis of Wooden Structures: Implementation and Application of Reliable Moisture Transport Models, in: J. Eberhardsteiner, W. Winter, A. Fadai, M. Pöll, World Conference on Timber Engineering (WCTE 2016) August 22-25, 2016, 2117-2126.

VII:4

Numerical sensitivity study of moisture induced stress levels in glulam cross sections

M. Schiere[†*], S. Franke[††], B. Franke[†‡], A. Müller[‡‡]

[†]Bern University of Applied Sciences, Institute for Timber Construction, Structures and Architecture, Solothurnstrasse 102, CH-Biel, marcusjacob.schiere@bfh.ch
[††]Bern University of Applied Sciences, S. Franke, steffen.franke@bfh.ch
[†‡]Bern University of Applied Sciences, B. Franke, bettina.franke@bfh.ch
[‡‡]Bern University of Applied Sciences, A. Müller, andreas.mueller@bfh.ch

Wood is a hygroscopic material of which dimension and strength change as moisture content varies. Expected moisture content of timber during service life is an important parameter for structural engineers to ensure structural safety and design extra measures if necessary. Internal stresses generated during moisture content changes are capable of developing internal and surface cracks in a glulam cross section. Earlier findings on moisture induced stresses have not found their way yet towards a practical application in today's building standards. Neither are methods available for structural engineers or building planners to include reduction of load capacity perpendicular to the grain in their daily design or building maintenance planning. This knowledge could be used in the design of large span timber structures of which glulam is a main structural component.

After study of diffusion speed and moisture content distribution in larger glulam cross sections, both through experiments and numerical simulations [1], research continued towards calculation of moisture induced stress distributions. A simpler 1D-model [2] was rebuilt along with a 2D-FEM model [3]. In the 2D-FEM model, similar equations were used as in the 1D-model, except that distinction between radial and transverse material parameters was possible instead of the need to average them over the glulam's cross section. The development of the stresses is calculated by using the derivative of the total strain ε_t to time. The total strain is a summation of the reversible contribution of the hygro-mechanic strains ε_s and the elastic strains ε_E and the time-dependent components ε_{ms} and ε_c better known as the mechano-sorptive and the creep strains, respectively:

$$\dot{\varepsilon_t} = \dot{\varepsilon_s} + \dot{\varepsilon_E} + \dot{\varepsilon_{ms}} + \dot{\varepsilon_c} \qquad (1)$$

Good agreement was found between the stresses calculated through the 1D-model, the 2D-model, and those obtained from experiments on a 90 mm wide cross section [4]. The numerical models were subsequently used to perform sensitivity studies of generated stress levels to cross section size, aspect ratio, and ambient climate variations, see Figure 1. All studies were performed with glulam beams composed of identical boards. Slight horizontal variations in layup reduced potential stress levels more than 10 %. The relation between load duration and stress level could also be observed with the performed simulations. The numerical models can be used to further research critical moisture load scenarios, board layups, and possibilities to reduce generated stresses through reinforcements or application of surface coatings. This can lead to improved glulam products and subsequently keep on encouraging application of timber in modern architecture.

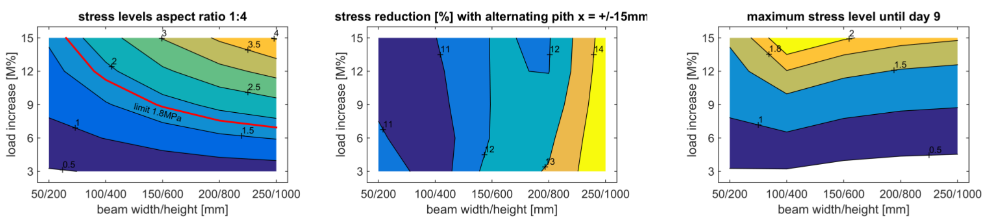


Figure 1: Study of effect cross section size, board layup, and load variation on absolute stress limits

References

[1] S. Franke, B. Franke, A. Müller, M. Schiere: Long-term behaviour of moisture content in timber constructions – relation to service classes, INTER conference proceedings, Graz, Austria, 2015.
[2] M. Häglund: Varying moisture content and eigen-stresses in timber elements, Wood Materials Science Engineering, Vol. 3, pp. 38–45, 2008
[3] V. Angst-Nicollier: Moisture induced stresses in glulam - effect of cross section geometry and screw reinforcement, PhD thesis, NTNU Trondheim, Norway, Thesis number 2012:139, 2012
[4] J. Jönsson: Internal stresses in the cross-grain direction in glulam induced by climate variations, Holzforschung, Vol. 58, pp. 154–159, 2004

VII:5

Why tangential shrinkage of wood is greater than radial shrinkage

K. Schulgasser

Ben-Gurion University of the Negev, Beer Sheva, Israel, kalmans@bgu.ac.il

In a previous paper [1] a cell model was proposed to explain why the transverse shrinkage of wood on drying increases with density. The cell was modelled as a hollow cylinder. Based on the anatomy of the cell wall it was argued that stiffness of the wall in the tangential direction is much greater than the stiffness in the radial direction and conversely shrinkage in the tangential direction, α_t , is appreciably lower than shrinkage in the radial direction, α_r . ("Radial" and "tangential" here refer to directions with respect to the cell cross-section, not globally as far as the tree trunk cross-section.) After homogenization with respect to cell wall thickness the problem of overall shrinkage was solved by means of linear elasticity theory. Based on reasonable assumptions as to stiffness constants and after linearization of the results it was found that the fractional outer volume shrinkage of the cell (equal to area shrinkage since longitudinal shrinkage is negligible) is given by

$$\Delta v/v = 2\alpha_t + \tfrac{1}{2}(\alpha_r - \alpha_t)V \qquad (1)$$

where V is the volume fraction of solid material in the cell and v is the volume fraction based on the outer diameter of the cell.

In the present work the cell cross-section is modelled as a square (Fig. 1a). It is found that the cell walls warp inward (Fig. 1b), but the fractional change of the "outer volume" (represented by b^2) is the exact same expression as above. Such inward warping of wood cells on drying has been observed [2,3]. Such a phenomenon explains the fact that global tangential shrinkage in whole wood is greater than radial shrinkage. In the *global* radial direction the cells are arranged in files (see Fig. 1c) and thus the change of *b* essentially represents *radial* shrinkage; however in the global *tangential* direction the alignment is random (especially for earlywood) and thus the inward warping increases global shrinkage. The orderly arrangement shown in Fig. 1c is of course not realistic; this is only to illustrate the add-on effect, relating to the tangential shrinkage. The fact that the global radial-to-tangential shrinkage ratios are generally greater for less dense woods is also explained by this model.

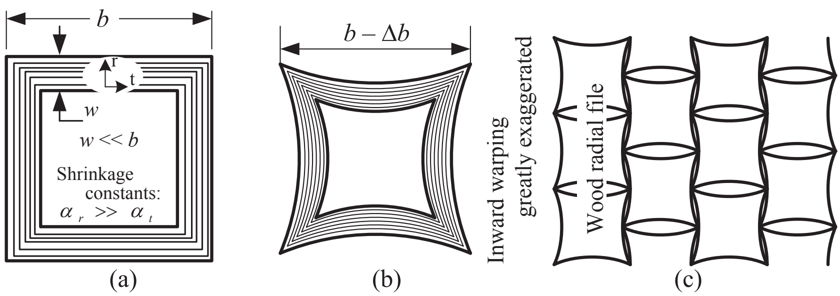


Figure 1: Cell shape before and after shrinkage, showing inward warping

References

[1] K. Schulgasser and A. Witztum, How the relationship between density and shrinkage of wood depends on its microstructure. *Wood Sci Technol* **49** (2015) 389-401.

[2] G. Almeida, F. Huber and P. Perre, Free shrinkage of wood determined at the cellular level using an environmental scanning electron microscope. *Maderas – Ciencia y Technologia* **16** (2014) 187-198.

[3] U. Watanabe, M. Norimoto, M. Fujita, R. Mokso, and J. Gril, Transverse shrinkage anisotropy of coniferous wood investigated by the power spectrum analysis.. *J Wood Sci* **44** (1998) 9-14.

VII:6

A numerical simulation tool for coupled heat and mass transfer in wood

Maximilian Autengruber[†*], Markus Lukacevic[†], Josef Eberhardsteiner[†], and Josef Füssl[†]

[†]IMWS TU Wien, maximilian.autengruber@tuwien.ac.at

Knowledge about the wood moisture condition in a timber component is essential to predict its mechanical behavior. Not only stiffness and strength properties are highly dependent on the wood moisture content but also diffusion coefficients, density, specific heat capacity and the thermal conductivity. Therefore, modern prediction tools, which are able to describe these effects, can be of great benefit for the development of new wood-based products. Especially if these products exhibit complex geometries and are made of materials with different moisture characteristics.
For this reason, a numerical model is proposed in this contribution, able to describe moisture transport processes below and above the fiber saturation point as well as heat transfer. Moisture transport below the fiber saturation point, characterized by three coupled differential equations describing bound water and water vapor transfer as well as energy conservation, is thereby modelled according to Krabbenhoft and Damkilde [1] and Fortino [2]. Free water transport within the wooden pore structure, occurring above the fiber saturation point, is considered according to the concept proposed in Perré and Turner [3]. Moreover, through an additional air conservation equation, pressure states in wood are taken into account. These five coupled differential equations are implemented through an user element into the finite element software Abaqus.
The resulting simulation tool was validated by means of experimental results (below the fiber saturation point) given in Frandsen [4], and by means of numerical results (above the fiber saturation point) presented in [3]. As a practical example, this simulation tool was applied to assess the performance of a newly developed formwork beam. These beams were tested in varying climate conditions, whereas one loading cycle is shown in Figure 1 (right). The related moisture field at the end of water immersion is displayed in Figure 1 (left). In a second step, the resulting moisture and temperature fields were applied to the formwork beam for a detailed stress analysis. The deformation as well as the distribution of the normal stress component in vertical direction is also given in Figure 1 (left).
Important information on critical stress and moisture states as well as good deformation predictions, sometimes unidentifiable from experiments, can be obtained therefrom.

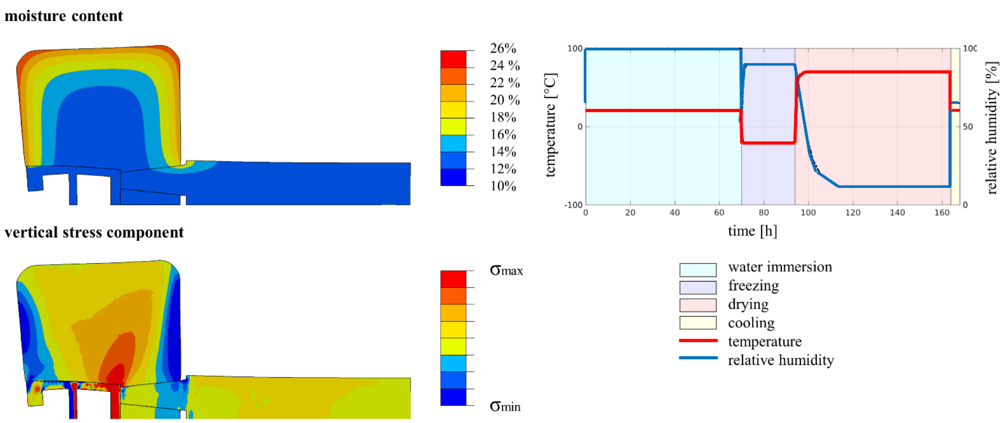


Figure 1: Moisture and stress states after water immersion

References

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

[2] S. Fortino, A. Genoese, A. Genoese, L. Nunes, und P. Palma. 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, October 2013.

[3] Perré P, Turner IW. A 3-D version of TransPore: a comprehensive heat and mass transfer computational model for simulating the drying of porous media. *Int J Heat Mass Transfer* 1999;42:4501–21.

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

Evaluation of computational models for timber-concrete composite beams

Johan Pyykkö[†*], Staffan Svensson[‡]

[†]University of Borås – Faculty of Textiles, Engineering and Business
Uppsala University – Division of Applied Mechanics, Ångström Laboratory, johan.pyykko@hb.se
[‡] University of Borås – Faculty of Textiles, Engineering and Business, staffan.svensson@hb.se

In this study different methods of calculating the stresses in and deflections of a timber-concrete composite (TCC) beam were evaluated. The three different methods were the γ-method found in the Eurocode 5, a model based on the basic differential equations found in [1] and [2] and solid models in 2D and 3D calculated with finite elements and accounting for the orthotropy of timber. The relevant geometric data of the beam studied are shown in figure 1.

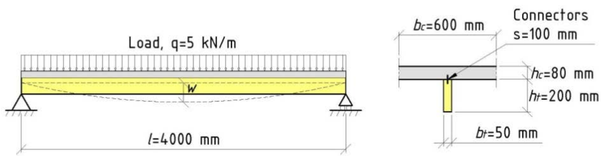


Figure 1: The studied TCC beam with geometric parameters

The basic differential equation for deflection used in this study is expressed as:

$$w^{IV} - e_2 w'' = e_3(M_t'' - e_4 M_t) \quad (1)$$

where e_n are constants depending on the composition of the cross-section and materials of the beam[2].
Results shown in Table 1 imply that the solid models give a deflection slightly larger than the other models, which is a consequence of shear and compression deformations in the timber.

Table 1: Mid-span deflection (mm) calculated with the different methods, the left column indicates the type of composite action (No, Partial and Full Composite Action).

	w_γ	w_{DE}	w_{2D}	w_{3D}
NCA	13.2	13.2	13.5	13.5
PCA	9.5	9.5	9.9	9.9
FCA	5.1	5.1	5.6	5.6

The results from the stress and deflection calculations shown in tables 1 and 2 indicate a good consistency between the different models. Interesting is, however, that the tensile stresses in the concrete just above the shear layer are rather high, even in the case of FCA. For the concrete modelled, the mean tensile strength is approximately 3.5 MPa, i.e. the concrete will crack (or at least be close to cracking) independently of the connector stiffness. Preliminary results show that the studied TCC beam with PCA and partially cracked concrete will deflect more than the case with NCA. Notable is that the connectors are assumed to behave linear-elastically, a more developed method taking the cracking of the concrete into consideration should also include the full load-slip behaviour of the connectors. This type of analysis is ongoing and will be presented.

Table 2: Largest and smallest normal stresses (MPa) in mid-span cross-section in concrete and timber calculated with the different methods

		σ_γ		σ_{DE}		σ_{2D}		σ_{3D}	
NCA	concrete	11.1	-11.1	11.1	-11.1	11.1	-11.11	11.2	-11.2
	timber	8.7	-8.7	8.7	-8.7	8.7	-8.7	8.6	-8.6
PCA	concrete	7.6	-8.4	7.5	-8.4	7.7	-8.5	7.7	-8.5
	timber	8.3	-4.3	8.3	-4.2	8.1	-4.0	8.1	-4.0
FCA	concrete	3.3	-5.2	3.3	-5.2	3.4	-5.3	3.7	-5.5
	timber	7.8	1.1	7.8	1.1	7.7	1.1	7.6	1.1

References

[1] Granholm, H.: Om sammansatta balkar och pelare med särskild hänsyn till spikade träkonstruktioner. Chalmers, Gothenburg, Sweden, 1949.
[2] Norlin, B.: Two-Layered Composite Beams with Nonlinear Connectors and Geometry – Tests and Theory, Doctoral Thesis, Royal Institute of Technology, Stockholm, Sweden, 1993.

VIII:2

Computer modelling of hybrid wooden beams for window frames

Aljaž Kovačič[†,a*], Barbara Šubic[‡,b], and Gorazd Fajdiga[†,c]

[†]University of Ljubljana, Biotechnical Faculty, Department of Wood Science and Technology, Slovenia
[‡]M Sora d.d., Slovenia
[a]aljaz.kovacic@bf.uni-lj.si, [b]barbara.subic@m-sora.si, [c]gorazd.fajdiga@bf.uni-lj.si

This contribution presents an example of numerical modelling for direct application to wood industry. The addressed end products are windows with wooden frames. As the architectural design in the last years shifted towards large dimensions of windows (Figure 1 – left), often covering multiple storeys of the building, the resistance of window frames to wind-induced pressure loads is becoming more important than ever. Although wood has many beneficial properties compared to metals, its stiffness and strength are lower in comparison. Therefore, to improve the performance of window frames, hybrid composition of wood with metallic reinforcements is currently extensively studied [1], [2]. Reinforcements made of other materials, like fibre reinforced polymers and certain hardwoods, are also of interest [3].

Investigations and optimisations of the reinforced hybrid beams can be substantially accelerated with parametrical computer simulations [4], for example Figure 1 – right. The aim of our work was therefore to develop verified and validated computer models, which would allow for computational evaluation of different reinforcement designs in individual window members, as well as complete window frames.

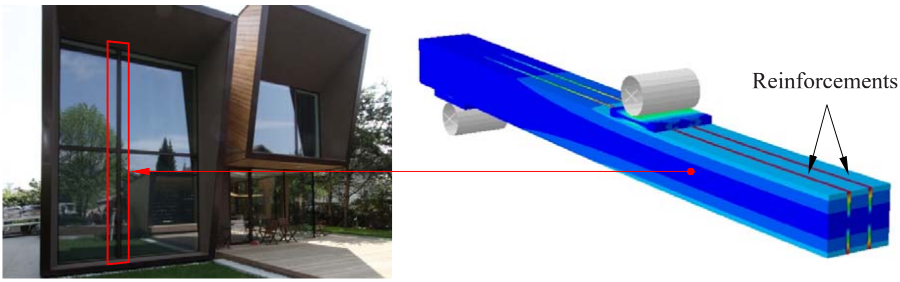


Figure 1: Critical vertical member in a window of large dimensions [5] (left) and computer modelled stress distribution in its reinforced version (right).

The developed computer models are based on the finite element method (FEM) and implemented in the commercially available code Abaqus [6]. The emphasis on the geometrically accurate composition of the beam produces larger models, but allows for more accurate representation with regard to technologic feasibility. For the same purpose, two cohesive models were implemented simultaneously to more accurately simulate the adhesion between the wooden parts and reinforcements. The beam model was verified with convergence analysis of mesh dependency. Validity of the model was confirmed with good agreement between computational and experimental results.

The model allows for variation of mechanical and geometrical properties, and enables observation of irreversible change initiation in the window frame member. It was used in parametrical simulations to find the optimal layout of reinforcements in the member, as well as for estimations of maximum performance for a certain design. In the future, the model will be used in combination with more detailed frame member cross-sections, while the inclusion of the glass panel influence is also envisaged.

References

[1] V. De Luca and C. Marano, "Prestressed glulam timbers reinforced with steel bars," *Constr. Build. Mater.*, vol. 30, pp. 206–217, May 2012.

[2] A. Borri and M. Corradi, "Strengthening of timber beams with high strength steel cords," *Compos. Part B Eng.*, vol. 42, no. 6, pp. 1480–1491, 2011.

[3] Y. L. Yang, J. W. Liu, and G. J. Xiong, "Flexural behavior of wood beams strengthened with HFRP," *Constr. Build. Mater.*, vol. 43, pp. 118–124, 2013.

[4] H. R. Valipour and K. Crews, "Efficient finite element modelling of timber beams strengthened with bonded fibre reinforced polymers," *Constr. Build. Mater.*, vol. 25, no. 8, pp. 3291–3300, 2011.

[5] "M Sora - Company - References," 2017. [Online]. Available: http://www.m-sora.si/en/company/references.

[6] "SIMULIA : Products : Abaqus FEA.," vol. 2011, no. 10.11.

Computational examination of the effect of Beech LVL reinforcing modules on the bending stress of glulam beams with shear failure

Matthias Frese

Karlsruhe Institute of Technology (KIT), matthias.frese@kit.edu

Even under design load, certain material defects may trigger shear failure in apparently intact glulam (Fig. 1.1). Possible defects are for example invisible cracks caused by shrinking or by poor quality of bonding. Such failure can lead to complete separation into two halves; the consequence is a doubled bending stress ($\sigma_{d,2}$) in each of the two new members compared to the intact one (Fig. 1.2). Tension members made of Beech LVL, screwed on in a truss-like pattern with fully threaded screws at both sides of the failed glulam beam (= reinforcing modules), were experimentally examined regarding its suitability to reduce a bending stress increase to a certain level. These modules are designed to act more cinematically compared to screws, inserted into the beam to rise the local shear capacity or to restore it after failure [1, 2]. The test results show sufficient load-carrying capacity and purposeful axial stiffness of the reinforcing modules to provide a truss-like load transfer of the original shear flow (Fig. 1.3). The reinforcing effect of the modules on the load-carrying behaviour of beams failed in shear was examined computationally. In doing so, the study focuses on the influence of the number of reinforcing modules (n_{mod}) and the influence of the magnitude of the static friction coefficient (μ) on the varying bending stress $\sigma_{d,4}$ (Fig. 1.4).

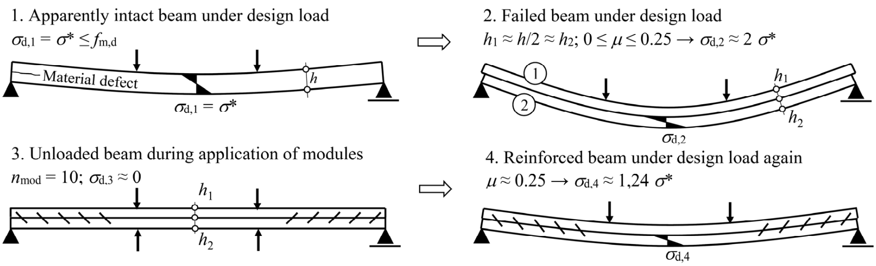


Figure 1: Stages from an apparently intact beam to a reinforced system

The results, obtained by means of an idealised finite element model, show that the reinforcing modules effectively limit the arising bending stresses. This is mainly due to the truss-like load-carrying behaviour rather than the static friction activated by compressive stresses between the contact surfaces of the shear crack. For a purposeful estimation of the bending stress ($\sigma_{d,4}$) with Eq. (1) the coefficients η in Table 1 were determined. The computationally examined parameter configurations show that a repair measure with 10 reinforcing modules (5 at each end of a beam with idealised failure, Fig. 1.3 and 1.4) and the effect of a static friction coefficient of $\mu = 0.25$, commonly accepted in timber engineering, may effectively restrict the bending stress to approximately 120-130 % of the initial value σ^*.

$$\sigma_{d,4} = \eta \cdot \sigma^* \tag{1}$$

Table 1 : Coefficients η for the calculation of the maximum bending stress $\sigma_{d,4}$ in the lower beam 2

η		n_{mod}					
		0	2	4	6	8	10
μ	0 (conservative)	***1.98***	***1.63***	***1.50***	***1.41***	***1.34***	***1.28***
	0.125 (realistic)	***1.96***	***1.60***	***1.47***	***1.38***	***1.31***	***1.26***
	0.250 (realistic)	***1.95***	***1.58***	***1.45***	***1.36***	***1.29***	***1.24***
	$\rightarrow \infty$ (unrealistic)	**-**	***1.07***	***1.01***	***1.01***	***1.01***	***1.01***

Beech LVL reinforcing modules are therefore a purposeful means to repair glulam beams failed in shear. However, certain preconditions regarding the location of the shear crack, its length and actual loading must exist. These conditions are very important features, which have to be considered adequately in a corresponding finite element analysis. Further work concerns among others the realistic estimation of the magnitude of the static friction coefficient and the analysis of reinforced failed beams for test purposes in order to validate the computational predictions.

References

[1] P. Dietsch, H. Kreuzinger, S. Winter: Design of shear reinforcement for timber beams. CIB-W18 (2013) Paper 46-7-9
[2] H.J. Blaß, O. Krüger: Schubverstärkung von Holz mit Holzschrauben [..]. Bd. 15, KIT Scientific Publishing, 2010

VIII:4

Introducing a virtual technological model for the formation of wood-based composites

Martin Riegler†, Sabine Dworak†*, Ulrich Müller‡

†Kompetenzzentrum Holz, m.riegler@kplus-wood.at
‡University of Natural Resources and Life Sciences, ulrich.mueller@boku.ac.at

Nowadays, the industrial production of wood-based composites is a highly complex process with many possible sources of influence, such as the varying raw material properties, several production processes (e.g. disintegration, drying, gluing, pressing) or disturbance variables such as climatic conditions. Thus, statistical models have been developed within the last decades to reduce this complexity and apprehend the interdependencies when manufacturing wood-based composites [1]. Although all available information is initially incorporated into statistical models, there is always a certain level of unpredictability. Hence, the aim of statistical models is to minimize this level of uncertainty. To obtain more reliable statistical models, a virtual technological model is introduced in the present study that tries to explain the formation process of a wood-based composite. Outputs of this virtual model are subsequently meant to serve as input parameters of statistical models.

To simulate individual wood particles, ellipsoids with defined geometry were used (Figure 1). The advantage of using ellipsoids is that size and shape parameters of individual particles can be actively defined and thus used for simulation, in contrast to other approaches were the shape and size of particles are derived from experimental data [2]. In the present study, the generated ellipsoids were oriented, positioned and stacked in a predefined three-dimensional area. Afterwards, particles were tilted at the initial contact point to simulate the positioning behavior of particles in gravity. Here, the center of mass of individual ellipsoids as well as the resulting new contact areas were considered (Figure 1).

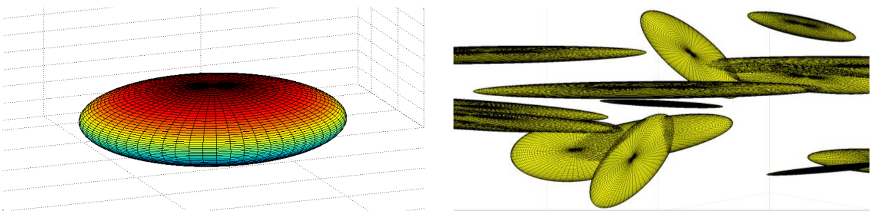


Figure 1: Ellipsoid representing a single particle (left), stacked ellipsoids simulating the formation of a wood-based composite (right)

Possible outputs of the model are the sum of contact areas between ellipsoids, the number of contact areas per particle (bridging effect), the total number and size of voids or the effect of different particle parameters, such as size, geometry or orientation, which can be achieved by simulation.

In a next step, the model will be further developed by adding additional technological information such as the statistical allocation of glued areas. Furthermore, the simulated particles will be equipped with material properties, which are essential during the formation process of wood-based composites such as compression, heating or mass transfer through porous media. Additionally, methods such as discrete element models, which are used for modeling granulate systems [3] or contact forces between particles during collision [4], will be subject to future research.

References:

[1] M. Riegler, B. Spangl, M. Weigl, R. Wimmer, U. Müller: Simulation of a Real-time Process Adaptation in the Manufacture of High-density Fibreboards using Multivariate Regression Analysis and Feedforward Control. *Wood Science and Technology* 47 (2013), 1243–1259.

[2] M. Faessel, C. Delisée, F. Bos, P. Castéra: 3D Modelling of random cellulosic fibrous networks based on X-ray tomography and image analysis. *Composites Science and Technology* 65 (2005), 1931–1940.

[3] G. Lu, J.R. Third, C.R. Müller: Discrete element models for non-spherical particle systems: From theoretical developments to applications. *Chemical Engineering Science* 127 (2015), 425–465.

[4] K. Dong, C. Wang, A. Yu: A novel method based on orientation discretization for discrete element modeling of non-spherical particles. *Chemical Engineering Science* 126 (2015), 500-516.

The influence of damaged zones in wood columns on its load bearing capacity

Martin Schneider[†], **Jakub Mareš** [‡] **and Sebastian C. Gigli** [†*]

[†]Carinthia University of Applied Science, m.schneider@cuas.at
[†*]sebastianclaudio.gigli@edu.fh-kaernten.ac.at
[‡]Czech Technical University Prague, jakubmares21@gmail.com

During lifetime wood is exposed to different environmental influences. Often some zones in a 3D section reduce the strength due to damage of high moisture or critical overload. For this situation a validation method is needed. In this work some different steps are given, how this validation can be estimated. The first step was to simulate damage by drilling holes into the wood. An exponential function for calculation of the modulus of elasticity of damaged wood was derived from direct measurements on specimens with certain artificial porosity. Based on results of static load tests it was proven that compressive strength depends linearly on the remaining cross section area.

Following this, two sets of columns (in scale of approximately 1:3 to columns typically used in structures) containing artificially damaged zone in the middle of the length were subjected to the static load test. Determined load bearing capacity was compared with results obtained by calculation using the composite cross section method and material properties determined from previously derived formulas. The average difference between calculated and measured values was 11%.

In a second step the micro-resistance drilling was used for localization and rating of the damaged zones in a partially rotted piece of timber. For the purpose of this thesis it was used as a column. Based on the developed procedure the load bearing capacity of this column was predicted with precision of 1%. Validated procedure was used for examining a theoretical real-sized column and a significant influence of the damaged zone was detected.

IX:1

A full-scale finite-element model of the Vasa ship

R. Afshar [†*], N. Alavyoon [†], A. Ahlgren [‡], N.P. van Dijk [†], A. Vorobyev [†] and K. Gamstedt [†]

[†]Applied Mechanics Division, Department of Engineering Sciences, Uppsala University, Uppsala, Sweden
[‡] Swedish National Maritime Museums, the Vasa Museum, Stockholm, Sweden
[*]reza.afshar@angstrom.uu.se

A full-scale model of the 17th century Vasa shipwreck has been developed to assess its current and future structural stability as well as design an improved support structure. A wireframe model, consisting of only lines, points and curves to describe the geometry of the ship, has been provided by the Vasa museum. It has been developed based on geodetic measurements using a total station. From this wireframe model, a three-dimensional (3D) model comprising solid bodies for solid-like parts (i.e. hull and keel), surfaces for the shell-like components (deck planks) and lines for beam-like constituents (deck beams) has been developed in Creo Parametric 3D software. This geometric model has been imported in finite-element software, Ansys, for further development of the stiffeners (knees, riders, stanchions, masts, etc.), adjustment of the correct location of deck beams and, finally, structural analyses of the entire ship (Figure 1). The procedure for selection of the different types of elements in the finite-element (FE) model, the definition of orthotropic material properties for the timber structure and preliminary results are discussed in this paper. Experiences drawn from this engineering project may also be useful in development of finite element models for structural assessment of other complex wooden structures in cultural heritage.

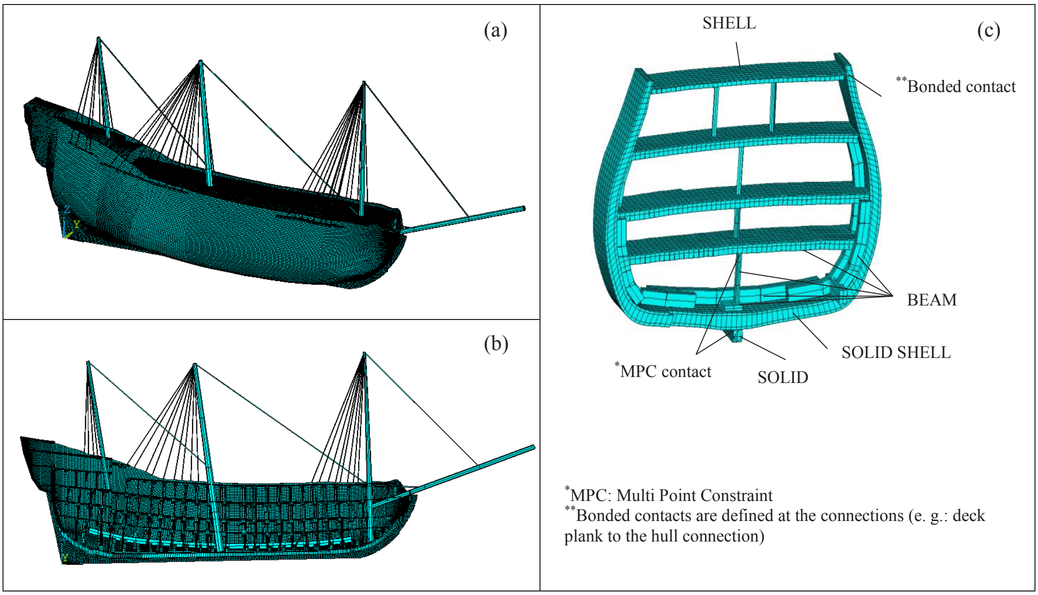


Figure 1: (a) The full-scale FE model of the Vasa ship; (b) a middle section of the ship model; (c) a longitudinal cross-section, showing different element types and connections.

During development of the FE model other similar historical shipwreck projects, in particular [1-3], have been used.

References

[1] Fenton R.F., Fowles R.J. HMS victory: modelling and structural analysis: how this contributes to the conservation of Nelson’s famous flagship. Historic Ships, 25-26 November 2014, London, UK.
[2] Invernizzi S., et al. Numerical modelling and assessment of the Ebe schooner-brig., International journal of Architectural Heritage: Conservation, Analysis and Restoration, 6:5, 453-477, 2012.
[3] Stoyanov S., Mason P.,Bailey C. Smeared shell modelling approach for structural analysis of heritage composite structures – An application to the Cutty Sark conservation. Computers and Structures 88 (2010) 649–663.

Risk assessment for buckling of the original foremast of the Vasa ship

N. P. van Dijk [†*], A. Ahlgren [‡], A. Vorobyev [†], R. Afshar [†] and E. K. Gamstedt [†]

[†]Applied Mechanics Division, Department of Engineering Sciences, Uppsala University, Uppsala, Sweden
[‡] Swedish National Maritime Museums, Vasa Museum, Stockholm, Sweden
[*]nico.van.dijk@angstrom.uu.se

The foremast of the seventeenth-century warship Vasa is the only original mast in its current configuration in the Vasa museum in Sweden. The foremast, which was found in two parts, was considered in good condition and placed in the ship structure after repair. At the time of installation, the mast still contained a relatively high amount of moisture. During drying long longitudinal cracks, *i.e.* checks, appeared in the mast and metal bands were placed around its circumference at several elevations to retain its bending stiffness [1]. In addition, increasing deflection of the top towards port has been observed, causing concerns about the structural integrity of the foremast.

This contribution presents the results of a structural assessment of the foremast focusing on its buckling behavior. To this end, the material behavior of the archaeological pine wood of the foremast has been measured. Its geometry has been determined by radar- and laser-scanning measurements. Additionally, the loading and supports have been investigated, taking into account the self-weight of the mast, pretension in the shroud and stay and contact with the weather deck. Pretension and the corresponding stiffness as felt by the mast has been calculated using the catenary (hanging cable) equation, relating tension to slack and mass per meter.

All resulting information was combined and processed into finite-element models of the foremast ex- and including the shrouds and stay. These models were used to perform several types of analyses. Euler critical loads (*i.e.* analytical results for a cylindrical mast) are compared to linear eigenmode analyses for, on one hand, a cylindrical mast and, on the other hand, the actual geometry of the foremast, see Figure 1. Finally, linear eigenmode and full nonlinear buckling analyses of the actual geometry including the lines have been performed. The corresponding safety factors have been compared against each other and previous calculations by Béha and Ahlgren [2].

The longitudinal stiffness of the archaeological pine wood was approximately a quarter of that of recent pine. The Euler critical loads were in good agreement with the results of linear eigenmode analyses excluding and including the lines. The full nonlinear buckling analyses, see Figure 2 for the deformed shape, resulted in safety factors of approximately 7-8, whereas previously the lowest factor was about 9 [2]. In Figure 2, the stress concentrations up to 21 MPa are still less than the measured strength of the material, but most likely caused by irregularities in the geometrical model.

Particularly interesting were the differences between a linear definition of the load-deflection definition of the shroud and stay and a nonlinear definition taking into account the strong decrease in stiffness for decreasing tension (*i.e.* no compressive forces possible).

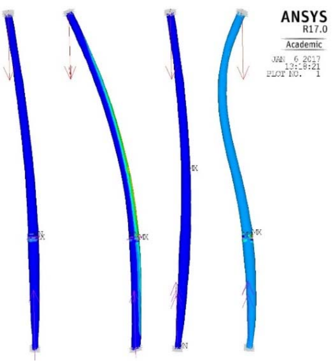


Figure 1 Linear mode shapes.

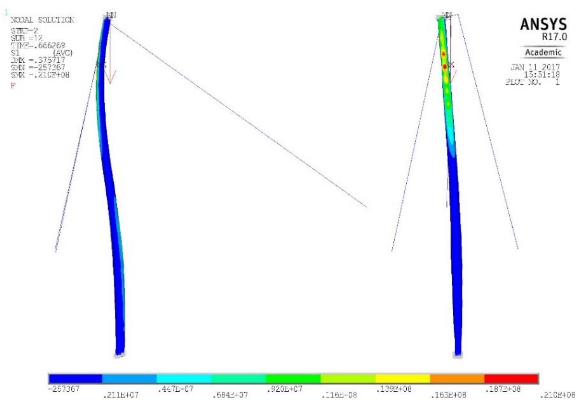


Figure 2 Deformed shape and principle stresses in Pa just before buckling.

References
[1] Pipping, O. (1995). Projekt riggning av regalskeppet Vasa. Technical report, Vasa museum.
[2] Béha, L. and Ahlgren, A. (2008). Lastutredning samt riskanalys för knäckning av vasaskeppets master. Technical report, Statens maritima museer, Vasaenheten.

IX:3

Evaluation of displacements of a wooden hull section of the Vasa ship by means of 3D laser scanning

Alexey Vorobyev[†*], Florian Garnier[†], Nico P. van Dijk[†], Reza Afshar[†], Olle Hagman[‡], and Kristofer Gamstedt[†]

[†]Applied Mechanics Division, Department of Engineering Sciences, Uppsala University, Uppsala, Sweden
[‡]Division of Wood Products Engineering, Department of Engineering Sciences and Mathematics, Luleå University of Technology
[*]alexey.vorobyev@angstrom.uu.se

For development of full-scale finite-element models of large objects in cultural heritage it can be useful to mechanically test replicas of key parts to investigate their structural behaviour and identify structural properties which would otherwise not be available. This contribution presents full scale tests on a replica of a section of the hull of the 17th century warship Vasa (Figure 1a) in three load configurations. We focus on determining displacements of the loaded replica from a three-dimensional (3D) laser measurements (Figure 1b). Two measures were found useful, namely (i) 3D displacements at well-defined intersections of surfaces of the wooden replica, and (ii) normal displacements of larger surfaces [1]. Wood surfaces were preferred to steel parts of the rig since the latter showed more scatter in displacement values in their point clouds due to their reflective properties [2].
The measurements were verified with draw-wire sensors. Some of these sensors were attached to the steel rig supporting the replica and, therefore, measured relative displacements. The scanning data was very useful in quantifying the absolute movement of the steel rig, which improved the precision of the measurements of replica deformation. Finally, it is discussed how the replica test results can be used in a model of the complete museum ship.

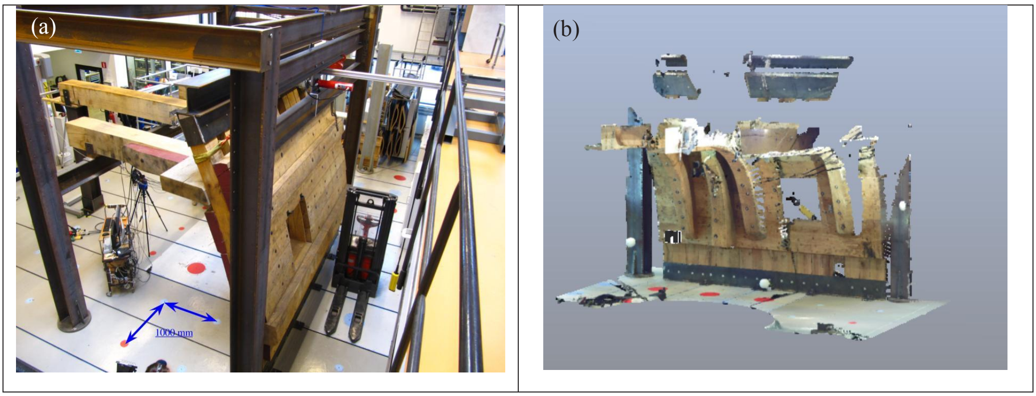


Figure 1: (a) Real size replica of Vasa hull structure. (b) Point cloud of the replica acquired with 3D laser scanner

References

[1] Gruen, A. Akca, D:Least squares 3D surface and curve matching. *ISPRS Journal of Photogrammetry and Remote Sensing* 59 (3) (2005), 151–174.
[2] Clark, J. Robson, S: Accuracy of measurements made with a cyrax2500 laser scanner against surfaces of known colour. *Survey Review* 37 (2004) 626–638E.

Modelling of a historic timber roof using the finite element method.

Filippo Frontini[†*], Jan Siem[‡].

[†] PhD candidate, Department of Architectural Design, History and Technology, Norwegian University of Science and Technology, filippo.frontini@ntnu.no
[‡] Professor, Department of Architectural Design, History and Technology, Norwegian University of Science and Technology, jan.siem@ntnu.no

Værnes church is one of the oldest medieval stone churches with an original wooden roof in Norway. The roof is made with several crossed layers of wooden boards connected with a large number of wooden dowels and stands for centuries but there are visible deformations in the lower parts of the structure. One may assume that the roof diaphragm had a significant influence on the load-bearing capacity of the roof.
From a structural point of view, the roof has two main functions working as a membrane carrying in-plane shear forces. The first one is the truss stabilization under static loads at global level and the second one is the bracing regarding the wind loads in the longitudinal direction.
In this preliminary work, detailed finite element models of the roof are presented in an attempt to characterize the behaviour of the wooden connection. Two main models are analysed: one with parallel layers of wooden boards and one with the inclined upper layer of boards. Værnes church shows the latter configuration, while the first one represent the general configuration of medieval churches roof.
The pegs are modeled with a Cartesian wire feature adding spring behaviour (linear and non-linear behaviour) in the three directions to simulate the displacement of the peg. At both ends of the wire feature, a coupling constraint is added to simulate the influence of the radius of the wooden peg. The behaviour of the pegs is derived from the results of an experimental campaign and used in the finite element models.
For the first model, three different configurations were analysed. At each overlapping of the boards, 1,2 and then 4 pegs were modeled as mechanical constraints. In first approximation, the boards are considered frictionless. The model was tested with different sets of loads.
The second model has only one configuration and it is representing the case study. In both configurations, hard contact between boards is considered.
Regarding future works, the global structure will be analysed. The roof will be represented by springs (behaviour derived from FEM model) to simulate the shear resistance and by a beam with rotational stiffness in the plane equal to zero to simulate the bending resistance. In this way, it will be possible to better understand the structural behaviour of the roof.

IX:5

Accuracy of N2 inelastic spectra for timber structures

Rinaldin G.[†]**, Fragiacomo M.**[†*]**, and Amadio C.**[‡]

[†] Department of Architecture, Design and Urban Planning, University of Sassari, grinaldin@uniss.it
[†*] Dept. of Civil, Construction-Architectural & Environmental Engineering, University of L'Aquila, massimo.fragiacomo@univaq.it
[‡] Department of Engineering and Architecture, University of Trieste, amadio@units.it

In this work, the accuracy of N2 method in estimating the inelastic spectrum as proposed by Fajfar [1] is investigated by comparing the rigorous inelastic spectrum of a seismic record obtained non-linear analysis of a SDOF structure to N2 estimation. Such operation was conducted with a purposely-written software able to process a set of seismic records and to produce as output the inelastic spectrum for each earthquake, by using a simple non-linear dynamic analysis. Newmark method was employed to carry-on such analyses and a simple bisection algorithm allowed to obtain spectra at constant ductility.

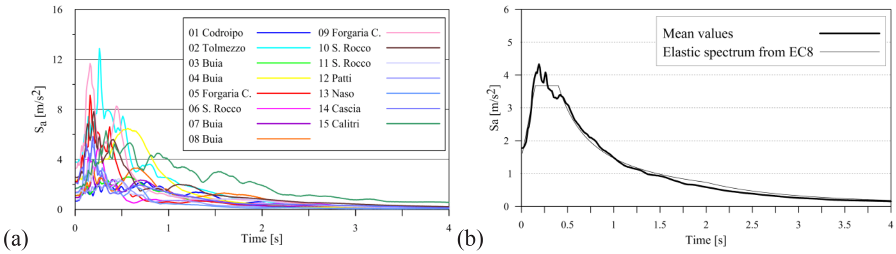


Figure 1: Elastic spectra of the second set of seismic records (a) and comparison between average spectrum of the set and EC8 spectrum (b), from [2].

A set of 15 records, as reported in Figure 1, has been used for the calculations. Such record is spectrum consistent in acceleration with the Eurocode 8 spectrum on soil A and with a_g=0.15g. All the records have been selected from the Italian Accelerometric Archive and the upper and lower tolerances with respect to the design spectrum are 20%, in the period range [0.01,4.0]s.

All the results are presented in Acceleration-Displacement format (ADRS) with the aim to investigate the accuracy of N2 method both in displacement and in acceleration. The collected differences are showed and commented, with particular reference to ductility levels 2, 4 and 6.

A further discussion involving overdamped spectra, as proposed by Freeman [3] and as currently used in the Equivalent Linearization Procedure (ELP) in US codes of practice [4] is reported, with a special focus on the determination of the equivalent damping ratio for timber structures on the base of the their dissipated energy amount.

Finally, some comparisons with MDOF structures are shown with the main purpose of validating the previous analyses.

It will be shown how the N2 method can be considered more accurate than the ELP procedure in estimating the inelastic spectra, mainly due to the strong dependence from the shape of the hysteresis cycle of the latter.

References

[1] Fajfar P. Capacity spectrum method based on inelastic spectra. Earthquake Engineering and Structural Dynamics, **28**(9):979-993, 1999.

[2] Amadio C, Rinaldin G, Fragiacomo G. Investigation on the accuracy of the N2 method and the equivalent linearization procedure for different hysteretic models, *Soil Dynamics and Earthquake Engineering*, **83**, 2016: pp. 69-80, DOI: 10.1016/j.soildyn.2016.01.005.

[3] Freeman SA. The Capacity Spectrum Method as a Tool for Seismic Design, *Proceedings of the 11th European conference on earthquake engineering*, pp. 6-11, Paris, 1998.

[4] FEMA, NEHRP, Improvement of Nonlinear Static Seismic Analysis Procedures, FEMA 440, Prepared by ATC for FEMA, Washington, D.C., June 2005.

Realistic modelling of the interface between wood and dowel in connections

Michael Dorn†*, and Karin de Borst‡

†Linnaeus University, Department of Building Technology, michael.dorn@lnu.se
‡University of Glasgow, School of Engineering, karin.deborst@glasgow.ac.uk

Dowel-type connections in timber engineering are frequently used and a secure way to transfer loads of very different magnitude. Still, they are under constant survey and are the topic of research to improve the capabilities and reliability in order to make them safer and even more efficient. For this purpose, numerical simulations are increasingly performed to study the mechanical behavior instead of conducting cost- and time-expensive laboratory studies.

A simple principle makes dowel-type connections work: two structural members are joined together by an interlocking dowel, placed perpendicular to the direction of the load. By this, the relative displacement of the members is restricted, allowing for the transfer of loads. Using several dowels, placed in a row or in any other pattern, normal forces, shear forces and bending moments can be transferred. However the two connected members are loaded, the dowel and the wood member are in contact and forces are transferred by pressure and shear in between. The interface between dowel and wood is therefore of uttermost interest and plays an important role in the overall behavior. The dowel usually comprises of a smooth surface with a certain roughness. The wood part on the other hand shows a distinctive texture, showing the features of annual rings with often torn-out or bent fibers so that an uneven surface is visible. The drilling technique and the shape of the tools also play a significant role in that.

The contact between the dowel and the wood surface is not fully established at the beginning of the loading so that loads are transferred only very locally in the beginning. Due to the high stresses at these contact points, the wood becomes softer and larger regions are subsequently activated (also called consolidation phase), a phenomenon clearly visible in experiments [3]. The other influencing parameter in the load transfer between the dowel and the surrounding wood regards the tangential behavior, i.e. frictional behavior. From experiments, it can be concluded that a higher frictional coefficient between the two surfaces (e.g. by a roughening of the dowels' surface) increases the width of the sop that a larger contact area is activated. This influence the overall load-bearing capacity and the stress distribution in the vicinity of the bore-hole in particular [3].

In order to expect realistic results from simulations, the interface must therefore include both a compliant behavior in normal direction and reasonable values for frictional behavior. Figure 1 shows results from a parametric study on single-dowel connections, varying the compliance behavior (left) and the coefficient of friction (right).

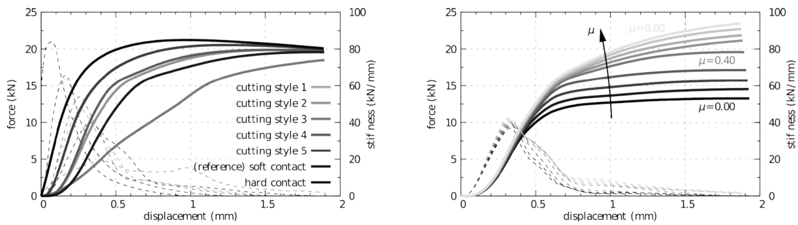


Figure 1: Load-displacement curves from simulations for varied interface compliance (left) and coefficient of friction (right).

In a number of numerical studies, though, the interface zone's complexity is frequently neglected or its behavior much simplified. Contact between the surfaces is e.g. simulated by a hard-contact model without any compliance or a wood-foundation material is assumed around the dowel thus allowing for some overall compliance. Frictional coefficients have been found to have values of between 0.00 and 0.80, a very large span strongly influencing the results.

In order to provide a sound basis for those assumptions, a study aims on describing the compliance of the interface from the surface properties of the bore-hole and experimentally deduced pressure-overclosure relations [1,2]. Additionally, frictional coefficients are experimentally determined including a large variety of fiber-to-shear plane-angles and contact pressures [4]. Both parts will feed the simulations with realistic values and actual behavior.

References

[1] M. Dorn, K. de Borst, Determination of surface texture properties of wood, Preparation. (n.d.).
[2] M. Dorn, K. de Borst, Compliance of wood in contact with steel surfaces, Preparation. (n.d.).
[3] M. Dorn, K. de Borst, J. Eberhardsteiner, Experiments on dowel-type timber connections, EngineeringStructures. 47 (2012) 67–80.
[4] M. Dorn, E. Serrano, Determination of coefficients of friction for LVL on steel, Preparation. (n.d.).

X:2

Strategies to model wood behavior and progressive failure

Iraola, B.[†], Cabrero, J.M.[†*]

[†]Wood Chair, Department of Building Construction, Services and Structures,
University of Navarra, 31009 Pamplona (Spain), bisaenz@unav.edu

Timber is a challenging material to model by means of finite element analyses. It has been already outlined the need to model its heterogeneity in order to get more accurate models [1–5]. Predictive methods and models for the simulation of structural behavior are required.

This study proposes an algorithm to model wood behavior and its progressive failure in FEM. The algorithm features two different solution-dependent strategies: a sequential application of different failure criteria, and the modeling of post-elastic response by means of damage and stress reduction parameters. It allows the use of different elastic moduli for tension and compression and it provides a more realistic way to model wood, even when failure is not accounted for. Two different degradation models are defined, an instantaneous model for brittle tensile failure and a constant stress model for ductile compressive failure.

The algorithm performs the following sequence for each analysis step and element: information from previous step, verification of the stress quadrant, redefinition – if required – of the elastic material properties, check of the failure state, modification of the damage parameter (d_i) and/or reduction stress parameter (r_i) accordingly. To model the damage process, the stress state at each integration point is monitored. Then, by comparing the current stress state with a specific failure criterion, the failure state is assessed. The material properties are degraded independently for each material direction. The progressive failure is reproduced by two strategies: progressive dismissal of the already failed material directions in the failure criterion and degradation of the material properties for each material direction, according to the type of failure detected.

The previously described methodology to model progressive failure in wood has been implemented in ABAQUS using an USDFLD subroutine. It has been evaluated in two different scenarios, with different loadings and failure modes: a structural beam in bending and an embedment test. It shows a good agreement with the experimental data in both scenarios. Figure 1 shows the results for one configuration of the embedment test.

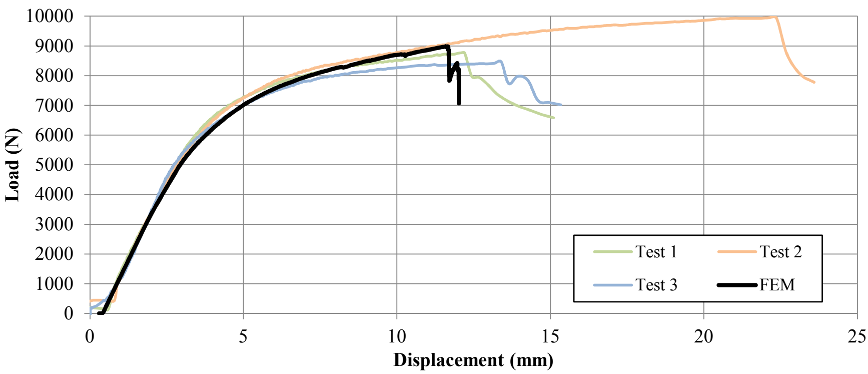


Figure 1: Comparison between the FEM results using the proposed algorithm with the experimental results.

References

[1] Baño V, Arriaga F, Soilán a, Guaita M. Prediction of bending load capacity of timber beams using a finite element method simulation of knots and grain deviation. Biosyst Eng 2011;109(4):241–9.

[2] Pellicane PJ, Franco N. Modelling wood pole failure. 1. Finite element stress analysis. Wood Sci Technol 1994;28(3):219–28.

[3] Cramer S, Shi Y, McDonald K. Fracture model of lumber containing multiple knots. Proceedings of the international wood engineering conference, vol. 4. New Orleans, L.A: Lousiana State University; 1996. p. 288–94.

[4] Itagaki N, Mihashi H, Ninomiya S, Yoshida N, Esashi T. Influence of knots on tensile strength of sugi lamina. Mokuzai Gakkaishi 1999;45(5):367–74.

[5] Guindos P, Guaita M. A three-dimensional wood material model to simulate the behavior of wood with any type of knot at the macro-scale. Wood Sci Technol 2012;47(3):585–99.

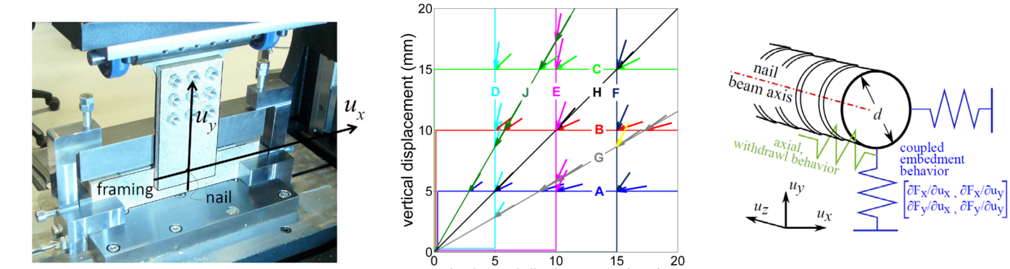
Modeling displacement path dependence in nailed sheathing-to-framing connections

Thomas K. Bader[†*] **and J. Vessby**[†]

[†]Department of Building Technology, Linnaeus University, thomas.bader@lnu.se

A numerical model for sheathing-to-framing, small diameter nailed connections is proposed in this contribution. Thorough experimental evaluations of such fasteners have been performed in the past, and models have been suggested for how to represent them in finite element software. Not much however has been said regarding their dependence on the displacement path. Hence, we herein numerically and experimentally examine a specific sheathing-to-framing connection with respect to its possible dependence on the displacement path undertaken.

Modeling efforts build upon an experimental investigation of the components as well as of the connection behavior for model validation purposes. Annular-ringed shank nails with a diameter of 2.5 mm and a length of 60 mm were used to connect an 11 mm thick oriented strand board (OSB2) with C24 graded Norway spruce timber. Embedment characteristics of OSB and wood in the two principal material directions, as well as the yield strength of the steel wire have been derived in a previous test series [1]. The displacement path dependence of the connection was investigated by means of a biaxial test set-up by prescribing nine different displacement paths (Figure 1). The path dependence of the connection was well visible in the comparison of the total force vector at intersections points of the different displacement paths (Figure 1). The force components parallel to the displacement direction were higher at these points. Consequently, a pronounced difference between the load and the displacement directions became obvious.



(a) (b) (c)

Figure 1: (a) Biaxial test set-up, (b) prescribed displacement paths and reaction forces, (c) beam on foundation model.

The connection is modeled by means of a beam on nonlinear elastic foundation approach [2]. The steel dowel was represented by quadratic beam elements with elastic-ideal plastic material behavior. The embedment behavior of the wood-based products is modeled by pairs of translational springs with a non-conservative coupling [3] as regards their properties parallel and perpendicular to the principal material directions. Moreover, the axial behavior of the annular ringed shank nails was considered by means of nonlinear springs parallel to the axis of the nail.

Experimental and numerical data was evaluated with respect to total force, i.e. the vector sum of the vertical and the horizontal force components, its orientation with respect to the grain orientation of the timber framing, and the work of the connection system, along the displacement path. The results show that there is strong path dependence with respect to the direction of the total force at the points where the paths coincide. Sudden changes in the displacement direction resulted in a decrease in total force in the connection, while a continuous force increase and decrease respectively was found for diagonal displacement directions. However, the size of the total force, as the vector sum of the force components, and the work carried out showed comparably small dependence of the path undertaken.

References

[1] Vessby J., Enquist B., Källsner B. Direction dependency in an OSB sheathing-to-framing mechanical connection. World Conference on Timber Engineering, Quebec, Canada, 2014.
[2] Bader T.K., Schweigler M., Serrano E., Dorn M., Enquist B., Hochreiner G. Integrative experimental characterization and engineering modeling of single-dowel connections in LVL. *Construction and Building Materials*, 107:235–246, 2016.
[3] Vessby J., Serrano E., Olsson A., Coupled and uncoupled nonlinear elastic finite element models for monotonically loaded sheathing-to-framing joints in timber based shear walls. *Engineering Structures* 32:3443–3442, 2010.

X:4

Use of an optimization procedure for the ULS design of bolted glulam timber joints

Nicolas COUVREUR[†*], David LAPLUME[†], Thierry DESCAMPS[‡]

[†*] University of Mons - Faculty of Architecture and Urban Planning, nicolas.couvreur@umons.ac.be
[†] University of Mons - Faculty of Architecture and Urban Planning, david.laplume@umons.ac.be
[‡] University of Mons - Faculty of Engineering, thierry.descamps@umons.ac.be

Bolted connections are widely used in glued-laminated portal frame connections. Usually, an elastic method is used to compute the strength of these connections. The applied forces and moments are considered uniformly distributed between the bolts. It is generally assumed that the first bolt that reaches its embedment strength under the considered loading conditions the overall joint strength. Typically, the load carrying capacity of a given bolt is calculated from the Johansen equations [1] which take the embedment strength into account. However, this computation method is conservative: clearly, once the most loaded bolt in the joint reaches its load carrying capacity, the joint does not collapse because the other bolts don't reach their respective load carrying capacities yet.

Therefore, an ultimate limit state (ULS) design can be considered in order to go further in terms of strength, taking into account the capacity of *all* the bolts in the joint. Indeed, if the load exceeds the load carrying capacity of a set of bolts, the excess forces will redistribute, until all the bolts reach their capacity. This approach obviously leads to higher strength values, and consequently, to potential material savings.

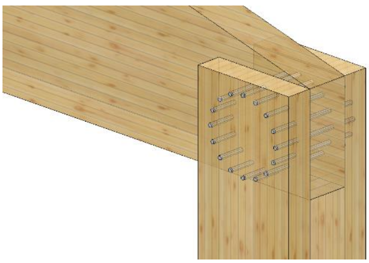


Figure 1 : Bolted joint

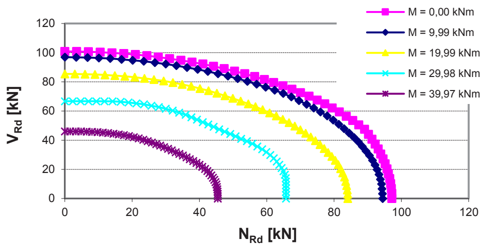


Figure 2 : Example of yield surface

The studied method uses the static theorem of limit analysis [2], also known as the lower bound theorem: if statically and plastically admissible generalized stresses can be found, the associated load is a lower bound of the limit load. Therefore, maximizing a load related to a statically and plastically admissible generalized stress state allows to approach the actual limit load of a system. In the present study, the generalized stresses are in fact the forces acting on each bolt of the joint. The related load is the set of internal forces and moments (axial force, shear force and bending moment) the joint is subjected to.

The problem is solved as an optimization problem. The objective function is the load to maximize, and the main constraints are provided by the equations of Johansen and the equations of equilibrium of the joint. Since the load must depend on only one parameter, the three above-mentioned forces and moments are considered dependent on each other, by means of two parameters.

By fixing a value for these parameters, it is possible to obtain a point of the so called yield surface of the joint. Running the algorithm for a large set of parameters values allows to build, in a "point by point" approach, the complete yield surface, in the sense of limit analysis. For portals with long spans, the results show that the proposed ULS design method allows to increase the joint strength up to 15% compared with the traditional method. Moreover, this procedure allows to highlight the impact of the main parameters (such as the thickness of timber and the diameter of bolts) on the yield surface and on the improved performances. It is then possible to adjust the characteristics of the joints in order to improve its behavior.

References

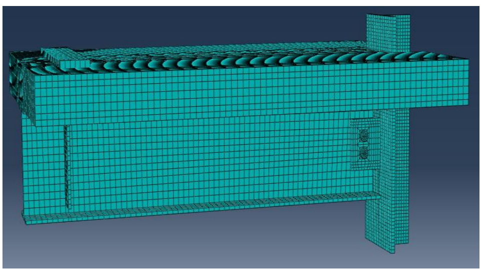
[1] NBN EN 1995-1-1: 2004, Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings, January 2005.
[2] W. PRAGER, Limit analysis and design, November 1952.

Finite element modelling of steel-timber composite beam-to-column joints

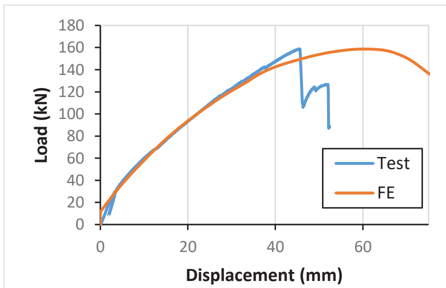
F. Nouri†* and H.R. Valipour‡

†The University of New South Wales, f.nouri@unsw.edu.au
‡The University of New South Wales, h.valipour@unsw.edu.au

Replacing conventional reinforced concrete slabs in steel-concrete composite (SCC) floors with prefabricated cross laminated timber (CLT) panels can significantly improve speed and reduce cost of construction and also drastically reduce the negative environmental impacts of building industry. In steel-timber composite (STC) floors, CLT panels can be connected to steel beams using mechanical connectors such as bolts and screws. Recent push-out and 4-point bending experiments and finite element simulations have demonstrated that the composite action between CLT slab and steel beams can significantly improve the load carrying capacity and stiffness of simply supported beams [1, 2]. Considering the high tensile strength of CLT slabs, it can be hypothesized that the STC beams have the capacity to develop large negative/hogging bending moments where STC beams frame into the columns. Furthermore, the continuity of CLT slab panels across columns can increase the stiffness of beam-to-column connections, reduce the mid-span deflection and human induced vibrations in STC floors [3]. However, there is no reliable experimental data or detailed finite element models that adequately represent behavior of STC beam-to-column connection. Accordingly, this paper deals with nonlinear 3D finite element (FE) analysis of STC beam-to-column connections with fin plate. First, benchmark test data on a cruciform STC beam to column sub-assemblage with fin plate connections (Figure 1a) is provided to demonstrate the significant influence of CLT slabs on local and global behavior of sub-assemblages. Then, a 3D continuum-based FE model of the sub-assemblage is created and analyzed using implicit solver of ABAQUS software. In the FE models, a layer-wise approach is adopted to exactly model orientation of grains in different lamellas of the CLT panels. Each timber lamella is modelled by a constitutive law formulated in the framework of continuum damage mechanics and implemented in the ABAQUS software by user material (UMAT) feature [4]. To capture the partial shear interaction between the CLT slabs and steel beams, nonlinear springs are used at the interface between the CLT slabs and steel beams and the nonlinear load-slip behavior of springs representing the shear connectors are defined with respect to the results of push-out tests conducted on STC joints [1]. Apart from nonlinearities of steel, timber and connections, the geometrical nonlinearities and the contacts between different components are taken into account. Crack band approach is used to resolve the spurious mesh sensitivity associated with softening of timber. It is shown that the adopted material models and assumptions made for developing FE models can adequately capture the local and global behavior of STC beam-to-column connections (Figure 1b). Further details on nonlinear FE analysis of STC beams and connections are discussed.



(a)



(b)

Figure 1. (a) FE mesh for one-half of the sub-assemblage (b) load-deflection response obtained from FE model and experiment.

References

[1] A. Hassanieh, H. R. Valipour, and M. A. Bradford, "Load-slip behaviour of steel-cross laminated timber (CLT) composite connections," *J. Constr. Steel Res.*, 2016.

[2] A. Hassanieh, H. R. Valipour, M. A. Bradford, and C. Sandhaas, "Modelling of steel-timber composite connections: Validation of finite element model and parametric study," *Eng. Struct.*, vol. 138, pp. 35–49, 2017.

[3] L. . Fang, S. . Chan, and Y. . Wong, "Strength analysis of semi-rigid steel-concrete composite frames," *J. Constr. Steel Res.*, vol. 52, no. 3, pp. 269–291, 1999.

[4] C. Sandhaas and J. G. Van De Kuilen, "A 3D Constitutive Wood Model Using the Concepts of Continuum Damage Mechanics," no. January, pp. 4–5, 2011.

X:6

New concepts for the development of a formula for the embedment strength of timber

M. Yurrita†, J.M. Cabrero†*

†Wood Chair, Department of Building Construction, Services and Structures,
University of Navarra, 31009 Pamplona (Spain), jcabrero@unav.es

The calculations of structural timber joints are currently based on the European Yield Model (EYM) proposed by [1]. The embedment strength appears in all the formulae as a main factor, and it is regarded as a material property of wood. However, as previously stated [2]: *"the embedding strength depends on the type of fastener, the joint configuration (..), the manufacturing of the joint (..), and the wood species or the quality of the wood-based materials. Thus, the embedding strength is not a special material property, but a system property"*.

Additionally, it has been already noticed that, especially for hardwoods, the embedment strength formulae proposed in the Eurocode 5 do not fit well with the results of the experimental results [3].

In this study, a new formula for the embedment strength is proposed. It is valid for a wide range of wood species and densities, both hardwood and softwood. The tests carried out by [3] (which feature a wide range of timber densities, two different types of steel and two different dowel diameters) have been taken as the database for its calibration.

As expected, the analyses show a major influence of the timber density. However, the role of the dowel diameter (usually regarded as another major parameter) is not clear. On the other hand, a clear influence of the type of steel of the dowel is noticed. Therefore, the new proposal requires not only timber properties, but also material properties of the dowel.

To further assess the accuracy of the formula, it is additionally validated against the set of embedment tests results gathered by [4] and different joints tests from the literature, and its performance assessed by means of statistical analyses. An improved agreement in comparison to previous proposals is obtained.

The proposal proves that embedment strength is a system property [2], and not a timber property. In the future, it should be considered how to deal with it in a more physical manner, based on material properties, instead of fitted formulae such as the one herein presented.

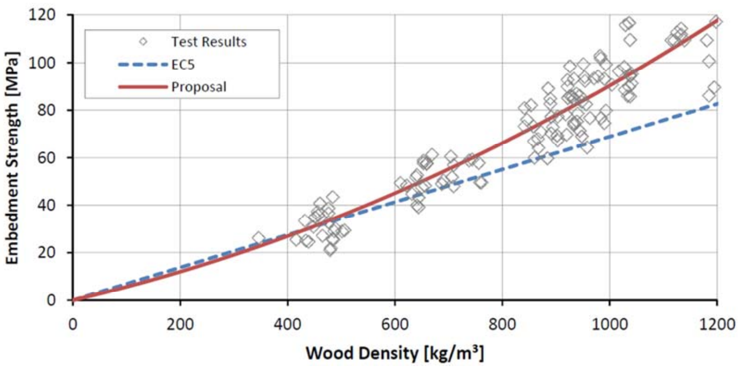


Figure 1: Comparison of the proposed formula results against the Eurocode 5 formula and the experimental results by [3].

References

[1] K.W. Johansen: Theory of Timber Connections. *International Association of Bridge and Structural Engineering*, 9 (1949), 249-262.

[2] J. Ehlbeck, H. Werner, H. Softwood and Hardwood Embedding Strength for Dowel-type Fasteners. CIBW-18 25-7-2, 1992.

[3] C. Sandhaas. Mechanical Behaviour of Timber Joints with Slotted-in Steel Plates. PhD thesis. Delft University of Technology, 2012.

[4] A.J.M. Leijten, J. Köhler. Evaluation of Embedment Strength Data for Reliability Analyses of Connections. CIB W-37, 7–12, 2004.

Combined CFD and solid FEM numerical modelling of imperfections in wooden materials

A. Khaloian Sarnaghi[1*], J-W. van de Kuilen [1,2]

[1] Holzforschung München, TU München, Munich, Germany, sarnaghi@hfm.tum.de
[2] Faculty of Civil Engineering and Geosciences, TU Delft, Delft, Netherlands, vandekuilen@hfm.tum.de

Natural imperfections in wood influence their strength properties. Especially for the case of species such as spruce, the presence of knots and (local) fiber deviation makes it difficult to accurately predict and simulate the mechanical behavior. Steep angle of knots combined with non-uniform and asymmetric geometries, and different connections of knots to the surrounding bulk material are other aspects, considered for this study. Such aspects are making it difficult to justify simplifications for simulations. The natural scatter is considerable, also in almost ´defect free´ wood with very low knot area ratios [1]. Additionally, for this purpose, methods of flow-grain analogy [2] and previously developed three-dimensional models [3, 4] have been modified by consideration of different flow analogy models in some locations containing knots and fiber deviations. ABAQUS and a programming language of PYTHON have been used, where two different steps, consisting CFD followed by solid FEM analysis have been performed. By getting the CFD results for fiber deviations, local coordinate transformation has been performed to transfer the data to solid analysis. The geometry and location of the knots are presented in figure 1.

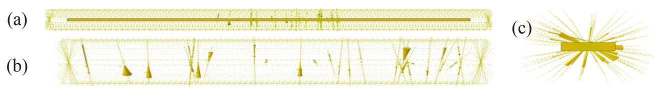


Figure 1: Sample 2239, a) Full Board with Location of Knots, b) Combination of Conical and Cylindrical Alive Knots with Different Axis, Directions and Properties, c) Side View of Board with Planes of Knots

Finally, solid analyses have been performed for each board, by applying uniform tension load to predict the stress concentration factors. Based on the results from ultrasound imaging, a profile for fiber deviations has been predicted, to which the results of the simulations have been compared. It has been shown that the results of both cases are matching well together for these patterns (Figure 2).

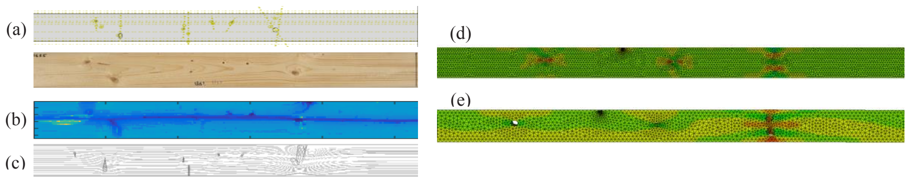


Figure 2: Left: Sample 2241 a) First Picture Represent the Top View of This Board in Simulations and Second One Represent the Same View of The Real Board, b) Ultrasound Results, c) Streamlines of CFD Analysis. Right: Sample 1225, d) Stress Distribution on Boards with Alive Knots, e) Stress Distribution on Boards with Dead Knots

References

[1] Stapel, P., Van de Kuilen, J.W.G. Efficiency of visual strength grading of timber with respect to origin, species, cross section, and grading rules: a critical evaluation of the common standards. Holzforschung DOI 10.1515/hf-2013-0042.
[2] Goodman J.R. and Bodig J. (1978). Mathematical model of the tension behavior of wood with knots and cross grain.Proceedings from the first International Conference on Wood Fracture. August 14−16, Banff. Alberta.
[3] Lukacevic M. and Füssl J. (2014). Numerical simulation tool for wooden boards with a physically based approach to identify structural failure. Eur J Wood Prod, 72:497−508.
[4] Baño V (2009) Numerical analysis of wood strength loss due to the presence of knots. Dissertation (in Spanish), University of Santiago de Compostela

XI:2

Life cycle assessment of high-rise residential timber building located in urban context

Y-H. Yeh[†], Y-S. Tsai[*], and M-F. Hsu[‡]

[†]Institute for Urban Timber and Hybrid Architecture, corresponding author, yeh1212@mail.ncku.edu.tw
[*]Institute for Urban Timber and Hybrid Architecture, onlyaajax@gmail.com
[‡]Institute for Cultural Heritage and Conservation, minfu@mail.ncku.edu.tw

The purpose of this paper is to evaluate the CO_2 emission and energy consumption of multi-storey residential timber building located in urban context of Taiwan. The estimation is based on the concept of life cycle assessment (LCA) and the calculation is carried out by means of SimaPro, which is a widely applied program for environmental impact assessment. The result reveals the environmental efficiency of modern timber structure compared to other materials and constructions.

The entire research comprises three steps. The first one is to establish a building model whose structural elements are made of wood. Then, the LCA is carried out based on this building model. The appraisal quantifies the environmental burdens caused by the timber construction. Finally, alternative building models made of other materials are developed and their environmental impacts are simulated as well in order to compare the ecological efficiency of diverse building constructions.

First, a multi-storey residential timber building is figured out. In Taiwan, however, the height and scale of timber construction remain restricted. Thus, the high-rise residential timber building for this appraisal is inevitably a conceptive model. Nevertheless, the development of the timber building attempts to conform to the practical reasonability as possible as it could [1]. For example, the development chooses the post-and-beam layout for the structural system. The dimension of the structural element is determined according to representative high-rise timber buildings. The connections are designed based on reliable technique available in Taiwan or Europe. Although the timber building is a virtual model, it is highly realistic for modern building industry.

The second step is the LCA for the multi-stroey timber building. The four sections announced by ISO go through in the impact evaluation. The system boundary is focused on the early life cycle stages and disposal scenario after the end of life, without the implication from using phase. The material inventory is established according to the benchmark building model and only the structural components are taken into account in the impact assessment. The impact assessment needs sufficient database and generally applied method for simulation. In this study, Eco-invent Database provides the desired materials or processes. CML and Eco-indicator 99 are the calculating methods for the estimation about global warming potential (GWP) and fossil energy consumption [2].

Third, alternative building models made of other materials are developed based on the benchmark building model and their environmental burdens are simulated according to the same processes as the step two. Since the benchmark building is post-and-beam system, its layout and dimension can be reasonable for reinforced concrete (RC) and steel construction (SC). The RC building consists of rebar and its amount is determined according to general design outcome. The cross-section of the components of SC model has to be adjusted in order to conform to the general layout of steel building. For example, while wooden and RC structures comprise solid or massive elements, SC normally applies shaped or hollow cross-section [3].

Finally, the environmental performance of three building models is quantified and compared. The results demonstrate that the timber building causes the smallest amount of environmental impacts in terms of GWP and energy depletion among three materials. When the disposal scenarios of different building materials are integrated in the assessment, the efficiency of timber is further highlighted. The wooden construction and demolition waste (C&DW) possesses two strategies to deal with it, both resulting in mitigating effect for climate change and energy depletion. A series of simulation and comparison verifies the sustainability of timber construction, particularly its advantages during design phase of a building, which are consistent with former studies [4].

References

[1] Haller, P., Helmbach, C., & Yeh, Y-H. (2013). Bauweisen, Konstruktionen, Tragwerke und Verbindungen im Holzbau. Institut für Stahl- und Holzbau, Technische Universität Dresden. ISBN: 978-3-86780-344-1.

[2] Dodoo, A., Gustavsson, L., & Sathre, R. (2014). Lifecycle primary energy analysis of low-energy timber building systems for multi-storey residential buildings. *Energy and Buildings*. 84, 84-97.

[3] Yeh, Y-H., & Chiao, C-K. (2016). Environmental performance of timber constructions located in highly utilised area - based on realised buildings made of sawn timber or CLT. Proceedings in: *World Conference on Timber Engineering*, Vienna.

[4] Basbagill, J., Flager, F., Lepech, M., & Fischer M. (2013). Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts. *Building and Environment*, 60, 81-92.

Identification of the Mechanical Properties of Particle Boards and Stochastic Simulation of the Behavior of Furniture

CHEN Zhou[*1,2], PLED Florent[1], CHEVALIER Luc[1], MAKHLOUF Heba[1], LAUNAY Eric[2]

[1]Université Paris-Est, Laboratory Modélisation et Simulation Multi Echelle, zhou.chen@univ-paris-est.fr
[2]Technical Insitute Forêt Cellulose Bois-construction Ameublement FCBA, eric.launay@fcba.fr

In furniture industry, the European committee for standardization suggests to manufacture a prototype which undergoes a series of mechanical validation tests to ensure its strength and durability. Furniture are then designed and optimized from the experimental test results. The development of simulation tools adapted to the furniture industry would help analysts and designers to carry out upstream validation studies in order to accelerate the design process and reduce the costs incurred by experimental tests. The present work aims at (i) characterizing the material properties of particle boards and (ii) developing numerical tools for the simulation of the mechanical response of furniture to external loads.

Numerous 3D calculation tools allow to perform such simulations, but the field of furniture presents some specificities. On the one hand, the furniture elements generally have simple geometry and then can be assimilated to an assembly of plates and/or beams. On the other hand, (i) the material properties of particle boards exhibit strong variabilities due to their heterogeneous and anisotropic behaviors, and (ii) the connections between the different furniture parts can be complex and may induce some non-linear local effects that cannot be represented by simplified models based on plate or beam theories.

Figure 1: Test device

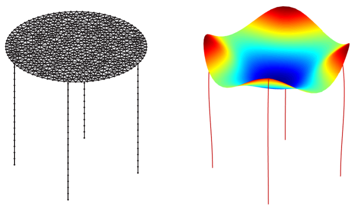


Figure 2: Finite element mesh and associated displacement field

An in-house computer code dedicated to furniture is developed and presents two specific features: (i) a library of link elements is provided to take into account local effects and (ii) the uncertainties in the material properties are modeled by random variables in a parametric probabilistic framework. This work deals with the second point and presents the identification of the elastic properties of wood materials (particleboards) from digital image correlation (DIC) [1]. A finite element plate model is also developed to simulate the furniture response under various load conditions.

Three-point bending tests are performed on samples of particle boards (see Figure 1). The macroscopic material properties (Young's modulus E and shear modulus G) are identified by minimizing the gap between the analytical displacement field for 3-point bending test and the measured displacement field using DIC [2]. A strong dispersion in the mechanical properties is observed between the different samples. The probabilistic model for the uncertain parameters E and G is constructed by using the maximum entropy principle (under the constraints defined by the available information on E and G) and the maximum likelihood method (using the experimental data collected on E and G) [3]. Two different plate models are implemented to simulate the behavior of a table (see Figure 2): (i) the classical thin (Kirchhoff-Love) plate model, which neglects the influence of transverse shear, and (ii) the thick (Reissner-Mindlin) plate model that takes account the transverse shear deformations. Both finite element plate models have been validated by benchmarks. The stochastic boundary value problem (which models the piece of furniture) is solved using a standard Monte Carlo method. Numerical virtual tests are performed to propagate the input uncertainties through the plate models and deduce probabilistic quantities of interest, such as first- and second-order statistical moments (mean and variance of the displacement field), confidence regions... It is then possible to assess the impact of the variabilities in the material parameters on the overall response of the structure.

References

[1] L. Chevalier et al.: Digital image correlation used to analyze the multiaxial behavior of rubber-like materials. *European Journal of Mechanics - A/Solids,* 20(2):169-187, 2001.

[2] H. Makhlouf et al.: A stochastic approach for the evaluation of the reliability of wood furniture in an industrial context: managing virtual standardization tests. *Mechanics & Industry*, 17(5):503, 2016.

[3] C. Soize: Random Matrix Models and Nonparametric Method for Uncertainty Quantification. *Handbook of Uncertainty Quantification*. Springer International Publishing, Cham, 1-69, 2016.

XI:4

Wood Cell Elastic Model for Stress and Deformation Analysis - Implementation

Takashi Yojo[1*], Cassiano O. Souza[2], Maria José de A. C. Miranda[3], Sergio Brazolin[4]

[1] Takashi Yojo, Institute for Technological Research – IPT, ZIP 05508-901, Brazil, yojos@ipt.br
[2] Cassiano O. Souza, Institute for Technological Research – IPT, ZIP 05508-901, Brazil, cassianos@ipt.br
[3] Maria José de A. C. Miranda, Institute for Technological Research – IPT, ZIP 05508-901, Brazil, mmiranda@ipt.br
[4] Sergio Brazolin, Institute for Technological Research – IPT, ZIP 05508-901, Brazil, brazolin@ipt.br

This paper presents the parametrization of three dimensional wood cell model, formulated as a multi-layered tube based on [1 - 2], composed by the compound middle lamella and three layers of the secondary cell wall presented in [3]. Each layer was considered as a composite material derived from matrix and fiber, where lignin and hemicellulose represent the matrix and the cellulose microfibrils the fiber. The resulting composite in each layer was obtained from rule of mixtures in local axis defined by microfibril orientation, but it can be anisotropic in the global coordinates. A cylindrical coordinate has been used to obtain the theoretical wood cell model considering compatibility, equilibrium, constitutive equations and boundary conditions. The elastic constants considered were those available in [4 - 7], but the values used here followed rigidy constants suggested in [4] and presented in Table 1.

Table 1: Elastic constants for for crystalline native cellulose (from [4])

Symbol	Elastic constant	Fiber	Hemicelulose	Lignin
$E_{FL(1)}$	Modulus of elasticity in polymer (GPa)	134	8,1	4,1
$E_{FTf(2\ or\ 3)}$	Modulus of elasticity normal to polymer (GPa)	27,2	4,1	4,1
$G_{FLT(1,2;\ 1,3\ and\ 2,3)}$	Shear modulus of rigidity (GPa)	4,4	2,1	1,5
$\nu_{FLT(2,1;\ 3,1\ and\ 2,3)}$	Poisson's ratio	0,10	0,2	0,33

Based on the analysis of [4] the CML (M+P) was composed of lignin and for secondary wall (S_1, S_2 and S_3) the proportion of fiber and hemicelulose was 65% to 35%, respectively. The fibril angle adopted was between 0^0 and 20^0 for S_2 and 70^0 for S_1 and S_3. The thicknesses of layers were taken 1% for P, 15% for S_1, 76% for S2 and 8% for S_3. To compose the layers the rule of mixture was used, where the fiber must be always stiffer than matrix. The elastic constants considered in this implementation are shown in Table 1. The results were compared with those presented in [4], [5], [8] and [9], after the analysis it was posible to conclude that the elastic stiffnesses are similar.

Differently of formulations presented in [4] and [5], this model took into account for the couplings between the layers as well as tridimensional stresses and deformations satisfaying all conditions of structural mechanics.

References

[1] Herakovich, C. T.: Mechanics of Fibrous Composites. John Wiley & Sons, New York, 1998.
[2] Tsai S. W. and H. T. Hahn: Introduction to composite materials. Technomic, Westport, USA, 1980.
[3] Yojo T. et al. Wood Cell Elastic Model for Stress and Deformation Analysis, *World Conference on Timber Engineering,* August 22-25, 2016, Vienna, Austria.
[4] Salmén L. and Alf de Ruyo A Model for Prediction of Fiber Elasticity, *Wood and Fiber Science*, 17(3), 1985, pp. 336-350.
[5] Mark, R. E. Cell wall mechanics of tracheids. Yale university press, New Haven and London, 1967.
[6] Schniewind A. P.: Concise encyclopedia of Wood & Wood-based Materials. Pergamon Press New York, 1989.
[7] Bodig, J. Mechanics of Wood and Wood Composites. Kluwer Academic Publisher, 1993.
[8] Les Groom; Laurence Mott and Stephen Shaler. Mechanical Properties of Individual Southern Pine Fibers. Part I. Determination and Variability of Stress-Strain Curves with Respect to Tree Height and Juvenity. *Wood and Fiber Science*, January 2002. V. 34(1).
[9] Laurence Mott; Les Groom and Stephen Shaler. Mechanical Properties of Individual Southern Pine Fibers. Part II. Determination and Variability of Stress-Strain Curves with Respect to Tree Height and Juvenity. *Wood and Fiber Science*, January 2002. V. 34(2).

Numerical simulations of structural behaviour of volume modules used for construction of multifamily timber houses

S. Ormarsson†, M. Johansson†*

†Building technology, Linnaeus University, sigurdur.ormarsson@lnu.se
†*SP Technical Research Institute of Sweden, marie.johansson@sp.se

Properly utilized wood is a useful, affordable and renewable material that has a high industrial potential in the field of building construction. There is a great interest in Sweden to explore new ways of using wood as the main load-bearing material in different types of multi-story timber buildings. This is a major challenge for the wood building industry, researchers and engineers because the available design procedures for timber design have not been implemented jet for these types of houses.

This work presents results from a pilot study financed by Smart Housing Småland (SHS). The purpose of this study was to investigate whether it is possible to use computer models to predict the overall structural behavior of a typical volume module used for the construction of modular based multi apartment buildings in wood. The project is also a first step in exploring opportunities to develop advanced design tools for design of these types of houses in a digital environment before real prototypes/buildings are built.

A parametric FE-model was created to study how stiffness properties of different mechanical connections have influence on the global deformation behavior of the studied modules. To reduce the computational time various types of structural elements (springs, beams and shells) were considered. To simulate all nail, screw and bolt connections in an optimal way, the model includes a great number of connector and coupling elements. The model also considers different geometries since it is controlled by a number of geometrical parameters.

The model was used to study the global deformation and stiffness behavior of various timber walls and module elements subjected to different load situations. How different stiffness properties of mechanical connections (weak parts of the structure) affect the overall structural behavior of elements has been an important task of this study. Figure 1 shows deformed timber walls and volume modules loaded with horizontal forces at the top corners of the considered structure. Similar objectives have previously been addressed in two dimensions on individual timber walls in [1].

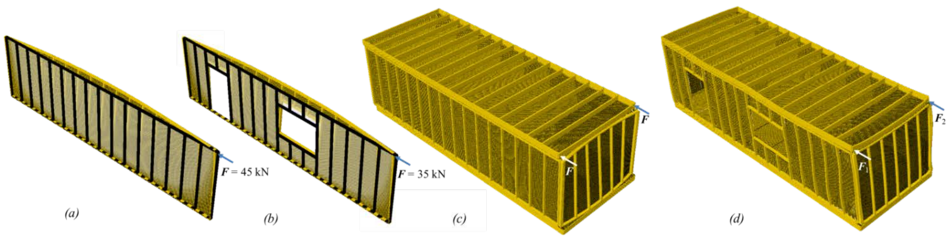


Figure 1: Simulated deformations of two timber walls and two volume modules loaded with horizontal forces at the top corners of the structures, *(a-b)* out-of-plane deformations of walls corresponding to 10 mm horizontal displacement at the force location, *(c)* slip deformations of a volume module with weak shear connections between the walls and the floor elements *(d)* highly magnified shear deformation of a volume module with openings and strong shear connections.

The results show that the deformations of the structural elements are reasonable. Nevertheless an experimental verification needs to be performed. The wall elements have a clear tendency to bend out of plane because the gypsum boards were only attached to the inside of the wall elements. The simulations of the modules also showed that the connection stiffness between the walls and the floor structure elements needs to be large to avoid significant slip deformations. The main conclusion is that it was possible to create a fast and effective three dimensional finite element model for this type of structure. The calculation time for a full volume module was only 5.5 minutes on a standard laptop computer. Therefore it can be assumed that there are good prospects of being able to simulate and analyze an entire apartment building within reasonable computational time.

References

[1] Vessby, J. 2011, Analysis of Shear Walls for Multi-Storey Timber Buildings. PhD Thesis. Linnaeus University Press.

XII:2

Effect of variations in material properties on low-frequency vibrations in wood structures

K. Persson†* and O. Flodén†

†Div. of Structural Mechanics, Lund University, Sweden, kent.persson@construction.lth.se,
ola.floden@construction.lth.se

The main challenge in predicting structure-borne sound in wood buildings is to accurately model the vibration transmission between the source and the receiving room. Studies on human annoyance caused by noise and vibrations indicate that frequencies below 100 Hz are particularly problematic for residents in wood buildings [1]. Hence, it is important to enable predictions at those frequencies. Standardized prediction models for noise and vibration transmission in buildings are based on statistical energy analysis (SEA) methods; these methods consider the energy flow between subsystems and require high modal density of the subsystems to yield accurate results. This is not the case at lower frequencies in which small sets of vibration modes govern the response. Low-frequency vibrations can instead be analyzed using deterministic methods such as the finite element (FE) method.

Wood is a material with large variations in its properties, a fact that will affect the accuracy of predicting vibration transmissions in wood buildings. A step towards establishing prediction models is to investigate the possibilities and limitations of using deterministic methods, which requires correlations between simulations and measurements. By use of a developed numerical model of a wood building [2] that was correlated by an experimental procedure, the influence of variations in wood properties on predicted vibration transmission was studied. The model have been shown to capture the dynamic behavior of the experimental structure to a great extent. The correlated model structure used for the investigation is shown in Figure 1.

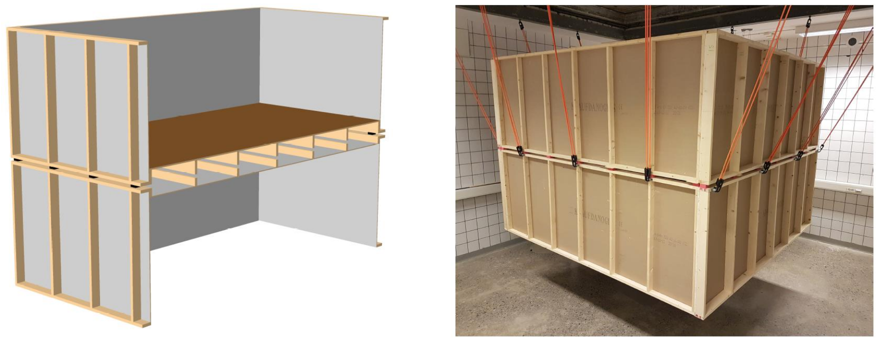


Figure 1: The experimental wooden building structure representing a part of a two-storey TVE building. To the left: a rendering of the correlated structure cut perpendicular to the wood beams and to the right: photograph of experimental setup.

Details on correlating the structure in a multi-level fashion will be presented and a numerical study of how variations in material properties of wood will affect the prediction of vibration transmission will be presented. The accuracy of deterministic models will be discussed and detailed information regarding the modelling of the mechanical behavior of joints will be given. The work has shown that it is relevant to employ deterministic models to predict the vibration transmission provided that measurement data for calibration purposes is available. The authors would like to show their gratitude to the European Union for financial support via the Interreg V project "Urban Tranquility".

References

[1] F. Ljunggren, S. Simmons and K. Hagberg, *Correlation between sound insulation and occupants' perception – Proposal of alternative single number ratings of impact sound,* Applied Acoustics **85**, 57–68, 2014.

[2] O. Flodén, K. Persson and G. Sandberg: *A multi-level model correlation approach for low-frequency vibration transmission in wood structures*, submitted for publication, 2016.

The road from creating a material model to a structural component of wood for automotive applications

Ulrich Müller[†*], Georg Singer[†], Stefan Kirschbichler[‡], Werner Leitgeb[‡], and Thomas Jost[‡]

[†]University of Natural Resources and Life Sciences, Vienna, Austria, ulrich.mueller@boku.ac.at
[‡]Das virtuelle Fahrzeug Forschungsgesellschaft mbH, Graz, Austria, thomas.jost@v2c2.at

Current and future strategic challenges in the automotive industry (i.e. fuel reduction, CO2- balance, self-driving cars, electro-mobility, small city cars and special vehicles) require innovative vehicle concepts. Novel materials, material combinations and composites are urgently needed. Wood provides high stiffness, strength, excellent damping, high resistance against fatigue and very low density. Properly applied, modern wood composites are competitive to metals and fiber-reinforced polymers. Wood is a carbon-neutral and renewable resource paired with low material cost. Especially in Europe high quality wood materials are available. Decades of experience in aeronautical, nautical and even automotive engineering provide abundant proof of wood and wood composites being a reliable construction and engineering material.

However, the application of wood and wood composites in automotive engineering requires precise and reliable data for material selection and further numerical crash simulations. A few selected car components were used as an example to show that wood can compete and outperform the baseline products (made of aluminum and fiber-reinforced polymers) in terms of structural properties, weight and cost.

Input data for the FE-models and crash simulation was generated through quasi-static material tests. Therefore solid wood (beech, ash, pine and birch), laminated wood (beech and birch) and plywood (pine, beech and birch) were investigated. Tensile-, compression-, flexural properties and density were measured in fiber direction and across the grain. For an initial validation of the material models, the quasi-static tests were simulated with very good correlation of the results.

All dynamic tests of the components yielded high reproducibility within each test setup. Only minor deviations in the load-displacement behavior and failure characteristics could be observed. The comparison between crash simulations and real crash tests of the components could show once more a good correlation of deformation and failure behavior. The characteristic difference of quasi-static and dynamic loads could be reproduced in the simulation model with high accuracy. The crossbar beam was used to prove the applicability of the material model in the simulation of a full car. The computational effort did not increase as the element size and time increments were not altered. Hence it could be shown that challenging crash situations can be simulated and evaluated. In this study it has been proven that wood and wood-based products can be sufficiently well simulated by means of finite element methods under static and dynamic loads as well as in crash situations.

XIII:1

Mechanical contributions of the adhesive layer to the dimensional stability of multi-layered wood based panels

A. Rindler[†*], C. Hansmann[†], Ul. Müller[‡] and J. Konnerth[‡]

[†]Area Wood Materials Technologies – Wood K plus – Competence Centre for Wood Composites and Wood Chemistry, Konrad Lorenz Straße 24, 3430 Tulln, Austria, a.rindler@kplus-wood.at

[‡]Institute of Wood Technology and Renewable Materials – Department of Material Science and Process Engineering – University of Natural Resources and Life Science, Vienna, Konrad Lorenz Straße 24, 3430 Tulln, Austria, johannes.konnerth@boku.ac.at

The effort of hydrophilic polymer materials to reach equilibrium moisture and temperature conditions to its surrounding environment leads to a couple of challenges in creating reliable and dimensionally stable panels out of these materials. The deformation of wood due to swelling and shrinking induced by water absorption and desorption of cell wall components leads to in-plane movements in multi-layered wood based panels and as a consequence causes an out-of plane deformation. This process is still a challenging factor in the engineering of dimensionally stable multi-layer wood based panels and complicates the usage of natural materials in high-tech products. To overcome this problem and to accelerate the developing process of new wood based panels, numerical methods, developed to describe the deformation stability of man-made composites could possibly be applied to wood materials too [1, 2]. Therefore it could be necessary to consider multi-layered wood based materials on a multiscale level and gain relevant influencing factors and parameters that are essential for a numerical description of the material behaviour [3].

However, moisture dependent properties of the wood layers and their orientation in the panel had been given more attention to as to the second material component involved in the multi-layered assemblies. The adhesive layer in wood based panels is mostly neglected in terms of mechanical contributions to the entire assembly. Also in micromechanical computation models a perfect bound between the layers is mostly assumed. But the elastic properties of adhesives commonly used for wood based panels were found to have a significant influence on the material assembly [4]. Also the viscoelastic properties of the adhesive could significantly contribute to the intention of the entire multi-layered assembly to deform or stay stable at certain in-plane stress/strain states of the single wood layers. In the present work different commonly used adhesive polymers were investigated by means of nanoindentation to better understand their viscoelastic behaviour.

For the experiments spruce (*Picea abies*) lamellas were adhesively bonded under laboratory conditions. Micro-mechanical properties of adhesive layers as elasticity, creep and relaxation were investigated by means of nanoindentation. Therefore different humidity levels were adjusted at a constant temperature to achieve defined equilibrium moisture contents within the involved wood and adhesive polymers.

This work provides insights into the viscoelastic properties of different adhesive layers at microscale in relation to varying climatic conditions. Based on the hereby derived findings the influence of the adhesives on the dimensional stability of wood based panels was evaluated. The necessity to consider these properties in future computational models was approximated. Mechanical contributions of the adhesive layer to the total dimensional stability of multi-layered panels are discussed.

References

[1] Müller, U., *Relationship between structural and mechanical properties of wood based materials*. University of Natural Resources and Life Science Vienna, 2006.

[2] Eberhardsteiner, J., *Mechanisches Verhalten von Fichtenholz: Experimentelle Bestimmung der biaxialen Festigkeitseigenschaften*. 2013: Springer-Verlag.

[3] Gamstedt, E.K., T.K. Bader, and K. de Borst, *Mixed numerical–experimental methods in wood micromechanics*. Wood Science and Technology, 2013. **47**(1): p. 183-202.

[4] Stöckel, F., J. Konnerth, and W. Gindl-Altmutter, *Mechanical properties of adhesives for bonding wood—A review*. International Journal of Adhesion and Adhesives, 2013. **45**: p. 32-41.

Finite element approach to simulate cellulose molecules

Carlos Felipe Guzmán, Erick I. Saavedra Flores, Juan Carlos Pina and Sergio Yáñez

Departamento de Ingeniería en Obras Civiles, Universidad de Santiago de Chile,
Av. Ecuador 3659, Estación Central, Santiago

The mechanics of wood is not fully understood due to the complex wood microstructure. At small scales, wood shows a complicated hierarchical structure distributed across different spatial scales. At the nanometer scale, it contains three basic constituents: cellulose, hemicellulose and lignin. These three fundamental constituents form the fiber-reinforced composite, with cellulose fibrils as reinforcing materials in a matrix of lignin and hemicellulose. From all the components, cellulose plays a significant role in the mechanical behavior of the composite with its highly arranged crystalline structure. The reinforcing cellulose is made up of periodic alternations of crystalline and amorphous fractions. Its been shown that the volume fraction and length of the crystalline portion plays an important role in the macroscopic behavior of the macroscopic wood. In this work, the role of crystalline cellulose is investigated by simulating its behavior at a molecular level. In order to obtain the mechanical properties of the cellulose, m olecular dynamics (MD) can be used to simulate the behavior of the crystalline structure (Chen et al. 2004). In this work, a novel approach is used. Following the methodology proposed by Li and Chou (2003), the interatomic bonds and potentials are simulated using structural finite elements. The finite element method (FEM) is faster than MD and extensively used by engineers. The boundary conditions and stiffness coefficients are studied in order to reproduce MD results. The results are useful as inputs for models describing the macroscopic media, such as homogenization models.

References

[1] Chen, W., Lickfield, G. C., & Yang, C. Q. (2004). Molecular modeling of cellulose in amorphous state. Part I: model building and plastic deformation study. *Polymer*, *45*(3), 1063-1071.

[2] Li, C., & Chou, T. W. (2003). A structural mechanics approach for the analysis of carbon nanotubes. *International Journal of Solids and Structures*, *40*(10), 2487-2499.

XIII:3

Micro-mechanical multi-scale models for spruce with generic modifications

F.K. Wittel*, D. Mora, S.O. Olaniran, M. Rüggeberg

Institute for Building Materials, ETH Zurich, Stefano-Franscini-Platz 3; CH-8093 Zurich, fwittel@ethz.ch

Spruce is a natural cellulose - hemicelluloses - lignin composite with hierarchic length scales, highly optimized on all scales by evolution, to maximize the fitness for survival. In technological applications, however, evolutionary optimized behavior can render disadvantageous with respect to durability, dimensional stability or appearance under moisture changes. Wood modification aims at altering material behavior to overcome or ameliorate one or more of these disadvantages that inter-depend on modification treatment and wood microstructure. However, typically the entire hygro-mechanical response gets modified in non-trivial ways, calling for numerical means of *a priori* predictions.

A hierarchical, micro-mechanical three-dimensional Finite Element Model (FEM) is employed, that combines features of micro-structural disorder on the tissue scale, based on statistical evaluations [1], with non-linear hygro-mechanical constitutive relations. Material properties of individual layers of a cell wall were calculated via the commonly used Halpin-Tsai and Chamis equations, using moisture dependent stiffness tensors of lignin, hemicellulose and cellulose and their relative amounts and orientations following Ref. [2]. We make use of the composite solid material description of Abaqus, where the element properties are calculated for a given composite layup with the layers of the cell wall (see Fig.1) using first order shear deformation theory. Generic micro-mechanical models with modifications on the cellular scale of spruce are proposed and studied, such as partial (**B**) and entire (**C**) lumen filling with isotropic materials, as well as modification of S2-layer properties (**D**) (see Fig.1).

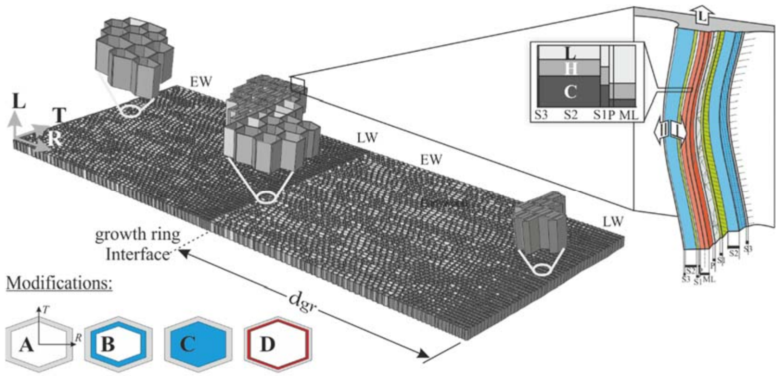


Figure 1: Hierarchical wood tissue model with close-up of latewood (LW) on the right, growth ring interface in the middle and earlywood (EW) on the left. The sketch shows the composition of doubly cell walls with respective layers, local cell-wall coordinates and chemical composition (lignin (L), hemicelluloses (H), cellulose (C)). The generic modifications are A the unmodified tracheid, B the modification by partially filling of the lumen, C the modification by complete filling of the lumen, and D the modification of S2 cell wall properties.

From a representative volume (RVE), hygro-mechanical response surfaces of the modified, orthotropic material are predicted with typical ranges of values of modifying agents for the different modification types **B-D** and related to the response of the unmodified RVE **A**. We compare the outcome to measurements on micro-samples under climatic changes, tension, and shear with and without modifications, such as methacrylation of the OH-groups in the wood cell wall and in situ polymerization with styrene, showing good agreement. Due to the generic nature of the model, the outcome can be employed for design purposes of a vast amount of modification treatments, as well as for calculating the behavior with graded situations, common to treatments with limited modification depth.

References

[1] C. Lanvermann, P. Hass, F.K. Wittel, P. Niemz: Mechanical Properties of Norway Spruce: Intra-Ring Variation and Generic Behavior of Earlywood and Latewood until Failure. *BioResources* 9 (1/2014) 105-119.

[2] S. Holmberg, K. Persson, H. Petersson: Nonlinear mechanical behavior of wood and fibre materials. *Computers & Structures,* 72 (1999), 459-480.

A continuum micromechanics approach to the strength of planar fiber networks: paper material applications

Pedro M. J. S. Godinho[1*], Marina Jajcinovic[2], Thomas K. Bader[3], Wolfgang J. Fischer[2], Ulrich Hirn[2], Wolfgang Bauer[2], and Christian Hellmich[1]

[1]Institute for Mechanics of Materials and Structures, Vienna University of Technology, A-1040 Vienna, Austria, pedro.godinho@tuwien.ac.at, christian.hellmich@tuwien.ac.at
[2]Institute of Paper, Pulp and Fiber Technology, Graz University of Technology, A-8010 Graz, Austria, marina.jajcinovic@tugraz.at, wolfgang.fischer@tugraz.at, ulrich.hirn@tugraz.at, wolfgang.bauer@tugraz.at
[3]Department of Building Technology, Linnaeus University, 351 95 Växjö, Sweden, thomas.bader@lnu.se

Given the eminent role of structure-property relations in paper material production, it is not surprising that various mathematical models for the mechanical interaction of pulp fibers within the overall material “paper” have been proposed. However, none of these models explicitly accounted for the scale difference between the loads applied to the overall material and those acting on the level of the individual fiber. In a first research stage, we filled this essential conceptual gap with the development of a new micromechanics-based linear elastic model: We first recalled the fundamental micromechanical concept of the representative volume element and the corresponding stress and strain average rules, before we specified these rules for planar fiber networks such as paper material. Then we introduced elastic material behavior at the fiber level, and derived so-called concentration relations for upscaling this behavior to the planar network level. Combination of these relations with matrix-inclusion problems of the Eshelby-Laws type yielded closed-form semi-analytical expressions for the paper stiffness tensor, as a function of fiber stiffness and porosity. The self-consistent linear elastic model, which highlighted the importance of the fiber's anisotropy for the overall elastic behavior, was confirmed by various multiscale experiments [1]. We here build upon our excellent results for the linear elasticity of planar networks to predict their strength. Given the self-consistent nature of our linear elastic model, stresses in single fibers are stresses in fiber-fiber bonds, and vice-versa. Therefore, we use a self-consistent linear elastic model-adapted Tresca-like function to connect the elastic limits of fiber-fiber bonds (that is “of single fibers”) and planar networks. More specifically, we use the concentration relations derived from the linear elastic model, as well as the aforementioned function, to upscale 5-, 50-, and 95%-quantiles of a lognormally distributed sample of ultimate in-plane (mode II) shear strength of “unbeaten” unbleached softwood pulp fiber-fiber bonds – $\sigma^{us,exp,5\%}_{II,plfib-fib}$, $\sigma^{us,exp,50\%}_{II,plfib-fib}$, and $\sigma^{us,exp,95\%}_{II,plfib-fib}$ – respectively; to the yield in-plane uniaxial tensile strength of corresponding networks – $\Sigma^{yt,hom,5\%}_{in-plane,pap}$, $\Sigma^{yt,hom,50\%}_{in-plane,pap}$, and $\Sigma^{yt,hom,95\%}_{in-plane,pap}$. Predictions based on $\sigma^{us,exp,50\%}_{II,plfib-fib}$ almost perfectly agree with experiments on the yield in-plane uniaxial tensile strength of laboratory paper sheets of variable porosity, $\Sigma^{yt,exp}_{in-plane,pap}$ (see Figure 1). These results emphasize the role of inter-fiber bond shear strength in the overall strength behavior of the planar network and suggest that the presented linear elastic strength model may very well constitute an additional support tool in the design of paper production processes.

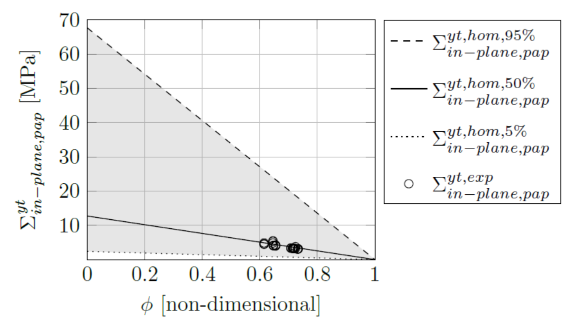


Figure 1: Experimental validation of micromechanics-based linear elastic strength model

References

[1] P.M.J.S. Godinho, L. Wagner, V. Vass, J. Eberhardsteiner, C. Hellmich: A continuum micromechanics approach to the elasticity of planar fiber networks and its application to paper. In: “*CD-ROM Proceedings of the World Conference on Timber Engineering* (WCTE 2016)”, J. Eberhardsteiner, W. Winter, A. Fadai, M. Pöll (Eds.); published by: Vienna University of Technology; Grafisches Zentrum HTU GmbH, Vienna, 2016, ISBN: 978-3-903039-00-1 (2016), Paper-Nr. 1074.

XIII:5

Numerical limit analysis approaches for strength predictions of cross-laminated timber plates

Mingjing Li†*, Josef Füssl†, Markus Lukacevic†, Josef Eberhardsteiner†

†Vienna University of Technology, mingjing.li@tuwien.ac.at

In recent years, wood, as a natural building material, has undergone a revival and gained importance in civil engineering. However, due to the complexity and variety of the raw material properties, the existing numerical tools for the prediction of mechanical properties are not sufficiently satisfying, especially in comparison to other building materials, such as concrete and steel.

The main goal of this contribution has been the development of numerical limit analysis formulations for the prediction of the ultimate load bearing capacity of cross-laminated timber (CLT) plates. Numerical limit analysis, known as direct method, exclusively focuses on the time instant of failure, and therefore, has significant advantage over the step-by-step iterative methods regarding computational efficiency.

Within this approach, two nonlinear optimization problems need to be solved, leading to a rigorous lower and upper bound of the ultimate load. The difference between these two solutions is referred to as bound gap, and, as soon as this gap is smaller than the required accuracy, a sufficient prediction quality is obtained. In this work, 3D models of wood based products were discretized by tetrahedron elements, and the numerical limit analysis formulations were implemented in Fortran code. Since the Tsai Wu yield function is applied to measure the failure behavior of wood, which can be formulated as second-order cones, the nonlinear optimization problems can be solved efficiently by the mathematical concept of second-order cone programming (SOCP) [1-2].

Experimental observations have shown that failure mechanisms in CLT are highly localized. Thus, for upper bound calculations, it is reasonable to introduce so-called velocity discontinuities between tetrahedron elements, serving as additional degrees of freedom. Additionally, to the plastic deformation within 3D elements, plastic failure can then also be represented by the separation of interfaces, taking the nature of local failure into account. It could be shown that this implementation leads to higher accuracy and efficiency of the calculations [3]. Since wood is highly anisotropic, the interactive strength on the element interfaces is anisotropic too and should be consistent with the material strength in the tetrahedron elements. Through a mathematical transformation which projects the stress-based yield function for the solid phases to a traction-based yield function for interfaces [4] this consistency could be achieved.

The new numerical approach is verified by means of bending test results on CLT plates presented in [5]. A good agreement between numerical results and experimental data was obtained. Due to the high efficiency of this numerical approach it could be extended to stochastic considerations, in which the probability distribution functions of the effective bending strength of CLT plates were derived according to the grade of wooden boards. The results may serve as basis for CLT optimization and / or support complex fracture mechanical approaches by providing information about failure mechanisms in advance.

References

[1] A. Makrodimopoulos, C.M. Martin: Lower bound limit analysis of cohesive-friction materials using second-order cone programming. *International Journal for Numerical Methods in Engineering*, 66(4): 604-634, 2006.

[2] A. Makrodimopoulos, C.M. Martin: Upper bound limit analysis using simplex strain elements and second-order cone programming. *International Journal for Numerical and Analytical Methods in Geomechanics*, 31(6): 835-865, 2007.

[3] A. Makrodimopoulos, C.M. Martin: Upper bound limit analysis using discontinuous quadratic displacement fields. *Communications in Numerical Methods in Engineering*, 24: 911-927, 2008.

[4] J.-Y. Wu, M. Cervera: On the equivalence traction- and stress-based approaches for the modeling of localized failure in solids. *Journal of the mechanics and Physics of Solids*, 82: 137-163, 2014.

[5] G. Hochreiner, J. Füssl, E. Serrano and J. Eberhardsteiner: Influence of wooden board strength class on the performance of cross-laminated timber plates investigated by means of full-field deformation measurements. *Strain*, 50(2): 161-173, 2014.

Experimental and numerical investigations of the stiffness of in-plane loaded CLT beam elements

Henrik Danielsson[†*] and Erik Serrano[†]

[†]Division of Structural Mechanics, Lund University, Sweden, henrik.danielsson@construction.lth.se

The work concerns the stiffness of in-plane loaded cross laminated timber (CLT) beam elements. Results relate both to experimental tests on full scale CLT elements and results from 3D finite element analysis as well as results according to simplified beam models. In-plane loading of CLT beam elements is of general interest for structural application since the orthogonally arrangement of the board layers significantly increases the element strength regarding forces acting perpendicular to the beam axis. The orthogonally layered composition does however, in general, introduce greater challenges regarding calculation of beam strength and stiffness, compared to beams made of timber, glued laminated timber or laminated veneer lumber.

Experimental tests on in-plane loaded CLT beam elements were carried out at Lund University during the fall of 2016. The test programme consisted of a total of five test series and included prismatic beams (test series C and E), beams with a hole (test series A and B) and also notched beams (test series D) according to Figure 1. Bending and shear stiffnesses were determined from test series C and E, based on the test procedures specified in the European standard EN408:2010 [1]. The beam stiffness is affected not only by the material stiffness and the gross cross section dimensions, but also to a great extent affected by the ratio of layer thicknesses in the longitudinal and transversal directions and also by the cross section dimensions of the individual laminations of the different layers.

3D finite element (FE) analyses were performed in order to find appropriate modelling approaches and to gain further understanding about the mechanical behaviour of in-plane loaded CLT beam elements. The FE-analyses include investigations of the influence of different geometry and material parameters on the beam stiffness. Comparison between theoretically and experimentally found stiffness is made considering test series C and E. Comparison to stiffness predictions according to simplified beam models, e.g. according to [2] are also performed. The 3D analyses form the base for finding appropriate general modelling techniques to be used for future work with more detailed numerical analysis of beam stiffness and strength including also e.g. nonlinear strength and fracture course analyses.

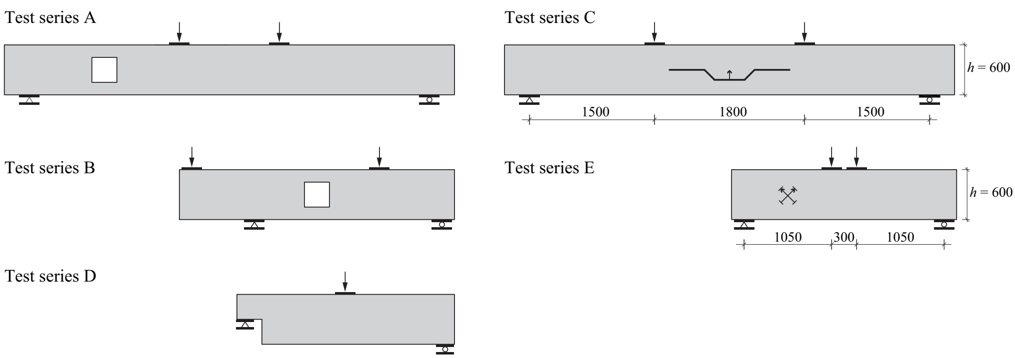


Figure 1: Overview of experimental test series for in-plane loaded CLT beam elements, dimensions in mm.

References

[1] European Committee for Standardization (CEN): EN 408:2010, Timber Structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties. Brussels, Belgium, 2010.

[2] M. Flaig, H.J. Blass: Shear strength and stiffness of CLT-beams loaded in plane. In: *Proceedings of the International Council for Research and Innovation in Building and Construction,* CIB-W18, Meeting 46, Vancouver, Canada, Paper 46-12-3, 2013.

XIV:2

Experimental and numerical investigations on a glass fiber reinforced molded wooden tube made of beech exposed to lateral vehicle impact

Jens U. Hartig†*, Sebastiano Facchini‡, and Peer Haller†

†Technische Universität Dresden, Faculty of Civil Engineering, Institute of Steel and Timber Construction, 01062 Dresden, Germany, jens.hartig@tu-dresden.de/ peer.haller@tu-dresden.de
‡Alumnus University of Trento, Italy, s.facchini@alumni.unitn.it

The wood molding technology enables the production of technical profiles of wood by means of quasi-plastic bend forming similar to metals. Prerequisites for the wood molding technology are a preliminary densification of the wood transverse to the grain under temperatures in the range of 80-110°C and a hot-steam treatment to enable the recovery of the previously imposed compression set [1]. The heating of the material is necessary to soften the lignin within the cell walls. Under ambient conditions, molded wood has qualitatively the same material behavior as common wood but some of the material properties have higher values, like tensile strength and Young's modulus parallel to the grain, or lower values like Young's modulus transverse to the grain in densification direction [2]. As for common wood, the brittleness under tensile loading is usually an undesired property and a drawback compared to alternative materials like steel.

Nevertheless, for some applications brittleness can be an advantage. One of such applications is infrastructure equipment where it can be desirable to decrease the energy consumption in a crash event as much as possible in order to reduce potential injuries of passengers in the crashing vehicle. An example for infrastructure equipment are lighting poles where molded wooden tubes might be applied as competitive alternatives for concrete or steel poles. A first test with an unreinforced molded wooden tube of beech showed the desired brittle failure behavior but also splitting into debris moving in an uncontrolled manner, which is potentially harmful for pedestrians [3]. Thus, an additional test with a glass fiber reinforced molded wooden tube was carried out, which showed a small increase in energy consumption during the crash event but an effective confinement of the wood leading to a controlled movement of the debris.

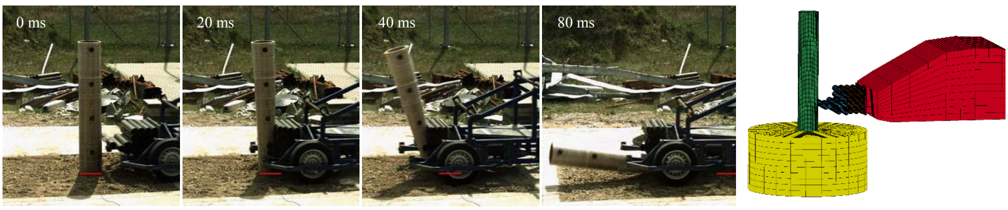


Figure 1: Crash test and finite element model of a bogie vehicle (100 km/h, 900 kg) impacting on a glass fiber reinforced molded wooden tube (diameter 0.33 m, wall thickness 0.02 m, length 3 m with 2 m above the ground)

Besides the results of the crash test, a simulation approach applying the commercially available explicit finite element code LS-DYNA for investigating the failure behavior is presented. The finite element model will serve as an optimization tool for advancing pole constructions of molded wooden tubes.

Acknowledgements

The authors gratefully acknowledge the financial support from German Federal Ministry of Education and Research for the Leading-Edge Cluster BioEconomy project under Grant No. 031A441A. The investigations were carried out in collaboration with our partners from industry: OM Maschinenbau GbR – Olbernhau, Europoles GmbH & Co. KG – Neumarkt/Opfl. and Eurocoatings GmbH – Werl. The simulations were performed on the SGI Ultraviolet HPC server at the Center for Information Services and High Performance Computing (ZIH) of Technische Universität Dresden.

References

[1] Kutnar, A.; Sandberg, D.; Haller, P.: Compressed and moulded wood from processing to products – a review Holzforschung, 2015, 69, 885–897
[2] Hartig, J. U.; Wehsener, J.; Haller, P.: Experimental and theoretical investigations on moulded wooden tubes made of beech (Fagus sylvatica L.). *Construction and Building Materials*, 126 (2016), 527-536.
[3] Facchini, S.; Hartig, J.; Haller, P. Experimental and numerical investigations on a moulded wooden tube made of beech exposed to lateral vehicle impact. In: Eberhardsteiner, J.; Winter, W.; Fadai, A.; Pöll, M. (Eds.): *CD-ROM Proceedings of the World Conference on Timber Engineering (WCTE 2016)*, Vienna University of Technology, Austria, 2016, paper 393

Estimation of the bending stiffness of GLT beams: a novel procedure based on enhanced analysis of the boards' stiffness and first order beam models

Giuseppe Balduzzi†*, Georg Kandler†, and Josef Füssl†

†Institute for Mechanics of Materials and Structures (IMWS), Vienna University of Technology, Vienna, Austria,
Giuseppe.Balduzzi@tuwien.ac.at, Georg.Kandler@tuwien.ac.at, Josef.Fuessl@tuwien.ac.at

Timber beams show high variability of both stiffness and strength since wood is a naturally grown material. As a consequence, in order to guarantee a certain performance of a Glued Laminated Timber (GLT) beam, the manufacturing procedure demands that timber boards should be classified in homogeneous groups with specified global characteristics (e.g., density, lowest longitudinal resonance frequency, and/or global bending stiffness within specified ranges) that determine both stiffness and strength of the finished product [1-2].
Unfortunately, due to the continuously evolving technologies and needs, the production approach so far introduced turns out to be more and more inadequate for at least two reasons. The former is that, despite the usage of boards classified according to their global properties, the resulting GLT beams could be characterized by high variability of their mechanical properties [3], leading to an extremely inefficient exploitation of the material. The latter is that enhanced and reliable grading technologies (like high resolution laser scanner for the recognition of local fiber orientation or X-ray for the density measurements) allow the collection of high-resolution information on the local mechanical properties of wood and more refined analysis [4].

A recent paper [3] provides an alternative strategy for the prediction of GLT beam stiffness. Specifically, the authors scan the fiber orientation on the boards' surfaces and determine the mechanical properties of clear wood on the basis of an enhanced micro mechanical model. Thereafter, considering the local fiber orientation, they determine both local and global the boards' mechanical properties trough accurate homogenization techniques. Finally, they calculate the bending stiffness of GLT beams trough accurate 2D Finite Element (FE) analysis. An extensive experimental campaign demonstrates that the proposed analysis is effective in predicting the GLT beam stiffness, leading the proposed procedure to be promising for an enhanced GLT beam stiffness evaluation. Unfortunately, the 2D FE analysis is computationally expensive and could represent a bottleneck of the whole procedure.

This contribution aims at exploring the effectiveness of enhanced first order beam model in the estimation of the GLT beam bending stiffness. Specifically, the beam is assumed to be made of homogeneous layers corresponding to the boards. According to the procedure proposed in [3], the boards' mechanical properties are determined on the basis of the micro mechanical model and take account of the local fiber orientation through accurate homogenization techniques. Furthermore, accurate procedures for the reconstruction of stress distribution within the cross-section are applied and an energetically consistent evaluation of the shear correction factor is considered.
The results highlight that the first order beam model has the capability to provide estimation with an accuracy similar to 2D FE, but it needs negligible computational efforts. As a consequence, it could represent a promising tool for the development of enhanced grading system of GLT beams.

References

[1] DIN EN 14081–4 (2009) Timber structure-strength graded structural timber with rectangular cross section - Part 4: machine grading-grading machine settings for machine controlled systems; German version EN 14081–4:2009. DIN Deutsches Institut für Normung e.V, Berlin.

[2] DIN EN 408 (2010) Timber structures-structural timber and glued laminated timber-determination of some physical and mechanical properties; German version EN 408:2010 A1:2012. DIN Deutsches Institut für Normung e.V, Berlin.

[3] G. Kandler, J. Füssl, E. Serrano, J. Eberhardsteiner: Effective stiffness prediction of GLT beams based on stiffness distributions of individual lamellas. *Wood Science and Technology*, 49-6 (2015), 1101-1121.

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

Author Index

A. C. Miranda M.J. XI:4
Adam C. IV:4
Afshar R. KL V:1, IX:1, IX:2, IX:3
Ahlgren A. IX:1, IX:2
Alavyoon N. IX:1
Amadio C. IX:5
Autengruber M. VII:6
Avez C. I:2
Bader T.K. X:3, XIII:4
Balduzzi G. XIV:3
Bardet S. V:3
Bauer W. XIII:4
Bedon C. KL I:1
Blaß H.J. KL II:1
Brancheriau L. II:2
Branco J.M.G. I:2 , III:1
Brazolin S. XI:4
Cabrero J.M. X:2, X:6
Capron M. V:3
Carmeliet J. VII:2
Chen Z. XI:3
Chevalier L. XI:3
Collet R. II:2
Couvreur N. X:4
Danielsson H. XIV:1
De Borst K. X:1
de Palacios P. II:3
Derome D. VII:2
Descamps T. I:2, III:1, X:4
Dorn M. X:1
Dworak S. VIII:4
Eberhardsteiner J. I:4, VII:6, XIII:5
Facchini S. XIV:2
Fajdiga G. VIII:2
Faydi Y. II:2
Ferri D. III:3
Fischer W.J. XIII:4
Fleischhauer R. VI:1
Flodén O. XII:2
Florisson S. I:1, VI:2
Foret G. IV:1
Fortino S. VI:3
Fournely E. VII:1
Fragiacomo M. KL I:1, IX:5
Fraile de Lerma A. IV:3
Franke B. VII:4
Franke S. VII:4
Franzoni L. IV:1
Frese M. VIII:3
Frontini F. IX:4
Furtmüller T. IV:4
Füssl J. I:4, II:6, VII:6, XIII:5, XIV:3
Gamstedt E.K. KL V:1 , I:6, IX:1, IX:2, IX:3
García Esteban L. II:3
García Fernández F. II:3
García-Iruela A. II:3
Garnier F. IX:3
Giger B. IV:4
Gigli S. VIII:5
González Rodrigo B. II:3, IV:3
González P. IV:2
Gril J. KL IV:1, VII:1
Guzmán C.F. IV:2, V:2, XIII:2
Hagman O. IX:3
Hairstans R. III:4
Haller P. VI:1, XIV:2
Hamdi S.E. V:5
Hansmann C. XIII:1
Hartig J.U. VI:1, XIV:2
Hellmich C. XIII:4
Hinojosa J. IV:5
Hirn U. XIII:4
Homerin B. V:4
Hozjan T. V:1
Hradil P. VI:3
Hsu M.-F. XI:2
Hu M. II:1
Huč S. V:1, V:6
Iraola B. X:2
Izzi M. KL I:1
J. S. Godinho P.M. XIII:4
Jajcinovic M. XIII:4
Johansson M. XII:1
Jost T. XII:3
Kaliske M. KL III:1, VI:1, VII:3
Källsner B. II:4
Kandler G. II:6, XIV:3
Khaloian Sarnaghi A. XI:1
Kirschbichler S. XII:3
Konnerth J. XIII:1
Konopka D. VII:3
Kovačič A. VIII:2
Kuo T.-Y. II:5
Laplume D. X:4
Launay E. XI:3
Lebée A. IV:1
Leitgeb W. XII:3
Li M. XIII:5
Livingstone A. III:4
Lukacevic M. I:4, II:6, VII:6, XIII:5
Lyon F. IV:1
Makhlouf H. XI:3
Malo K.A. I:3
Mareš J. VIII:5
Marthin S.O. I:6
Matsuo M. V:3
Mora D. XIII:3
Mosquera Feijoo J.C. IV:3
Moutou Pitti R. V:5, VII:1
Müller A. VII:4
Müller U. VIII:4, XII:3, XIII:1
Nathan E. III:6
Nouri F. X:5
Olaniran S.O. XIII:3
Olsson A. II:1
Ormarsson S. III:5, VI:2, XII:1
Ostapska-Luczkowska K. I:3
Pambou Nziengui C.F. VII:1
Panella F.W. III:2
Pantaleo A. III:2, III:3
Patlakas P. III:4
Persson K. XII:2
Petersson H. II:4
Pina J.C. IV:2, V:2, XIII:2
Pled F. XI:3
Pot G. II:2
Pousette A. VI:3
Pyykkö J. VIII:1
Rhême M. V:4
Riegler M. VIII:4
Rinaldin G. KL I:1, IX:5
Rindler A.M. XIII:1
Roensmaens B. I:2
Rüggeberg M. XIII:3
Saavedra Flores E.I. IV:2, IV:5,

	V:2, XIII:2
Saavedra K.	IV:5
Saifouni O.	V:5
Schiere M.	VII:4
Schneider M.	VIII:5
Schulgasser K.	VII:5
Sejkot P.	III:5
Serrano E.	XIV:1
Siem J.H.	IX:4
Singer G.	XII:3
Sisay Habite T.	I:1
Smith S.	III:4
Souza C.O.	XI:4
Šubic B.	VIII:2
Sujan K.C.	V:3
Svensson S.	V:1, V:6, VIII:1
Tsai Y.-S.	XI:2
Tsalkatidis T.	III:6
Valipour H.R.	X:5
van de Kuilen J.-W.	XI:1
van Dijk N.P.	KL V:1, IX:1, IX:2, IX:3
Verbist M.	I:2, III:1
Vessby J.	I:1, II:4, III:5, X:3
Vorobyev A.	KL V:1, IX:1, IX:2, IX:3
Wahrhaftig A.	I:5
Wang W.-C.	II:5
Wittel F.K.	XIII:3
Yamamoto H.	V:3
Yáñez S.	IV:2, V:2, XIII:2
Yeh Y.-H.	XI:2
Yojo T.	XI:4
Yurrita M.	X:6
Zhang C.	VII:2