Gluing from wood for structural applications - basics and selected examples

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Gluing from wood for structural applications

-basics and selected examples-

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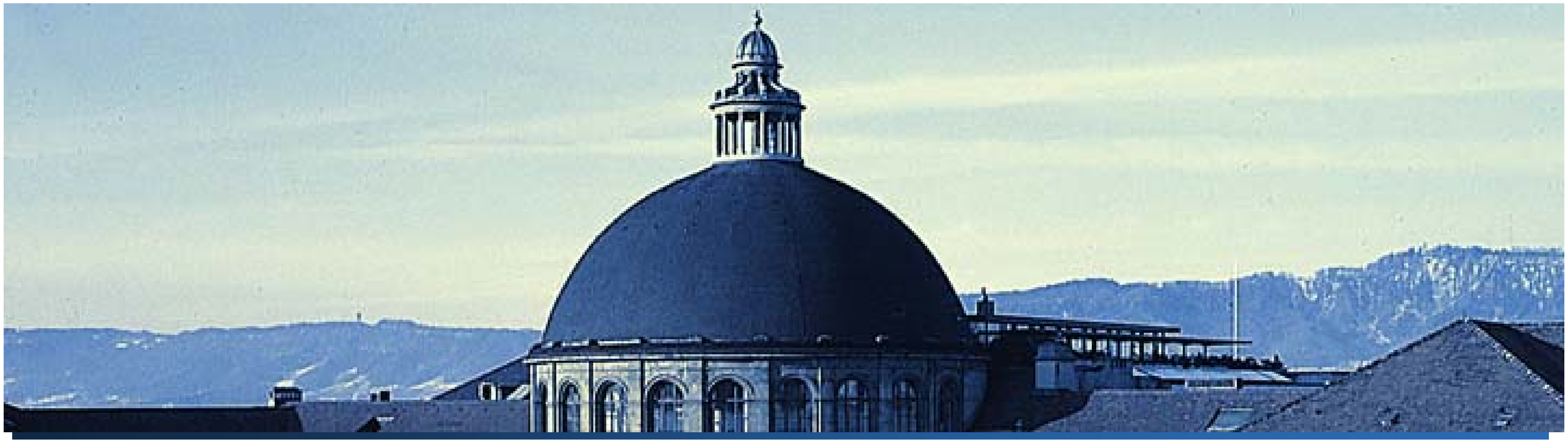


Structure

1. Introduction
2. Selected examples for buildings with wood and wood based materials
3. Wood properties -related to gluing
4. Gluing from wood for structural applications
5. Conclusions

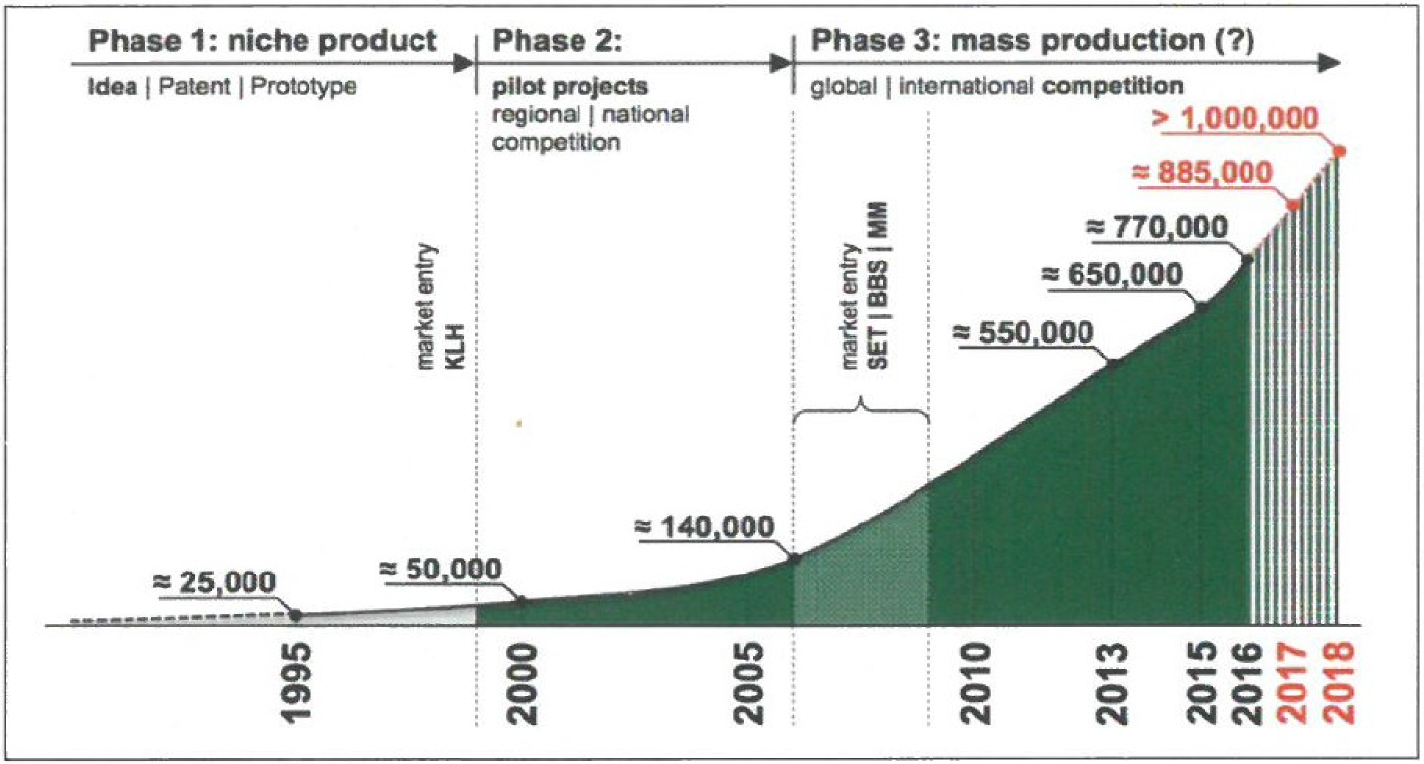
1. Introduction

- increased trend towards timber construction last 10-15 years
- Main focus now: multi-storey houses, high-rise buildings (up to 85m), 3D- structures (free forming), not only single-family houses
- Trend goes with further development of wood based materials:

- glulam (since more the 100 years), **CLT,** DLT, NLT, **LVL** from **soft-** and hardwood, wooden elements, hollow box systems) and more hardwood must used in the future (changes in the forestry)
- Automation (CNC- machines for the production (prefabrication))
- Gluing needed in the modern timber industry !

Glulam («neue Holzbau AG», Lungern/CH)

Cross laminated timber (CLT)/Schilliger Holz AG/CH

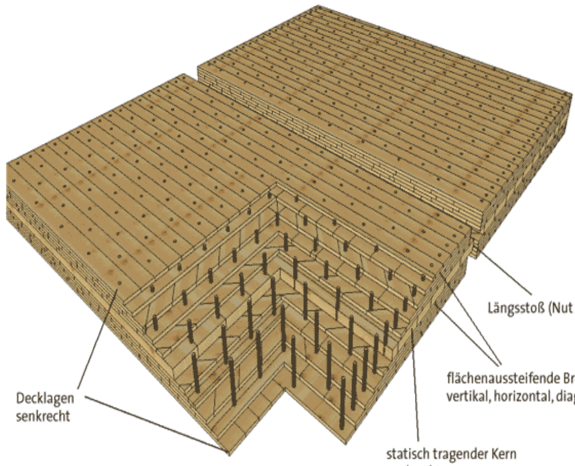


Development of the global production of CLT, based on Schickhofer et al., **now already capacity from 2 Mio m³/a in Europe, GLT: in A/D: >2 Mio m³ 2021**

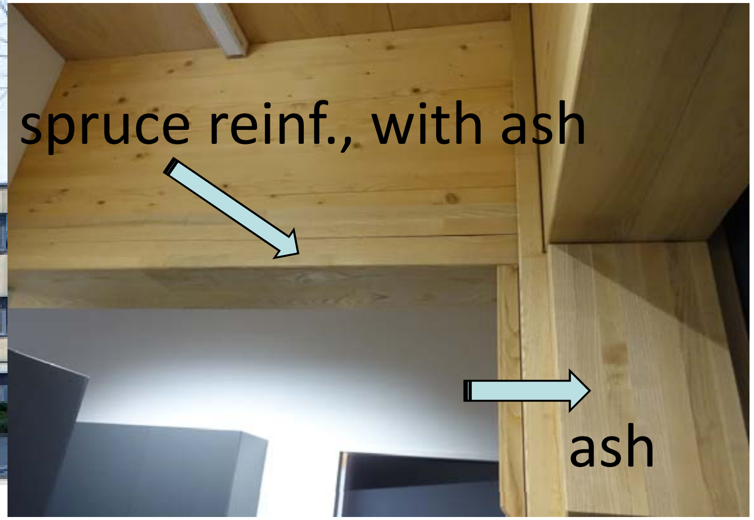
2. Selected examples for buildings with wood and wood based materials

single-family house: CLT connected with dowels

300m^3 wood used for the building, Nägeli AG/CH



ETH Zürich: House of Natural Resources ash glulam, spruce reinforced with ash, beech CLT, «Baubuche» (PhD thesis C. Leyder 2018, ETH Zurich)

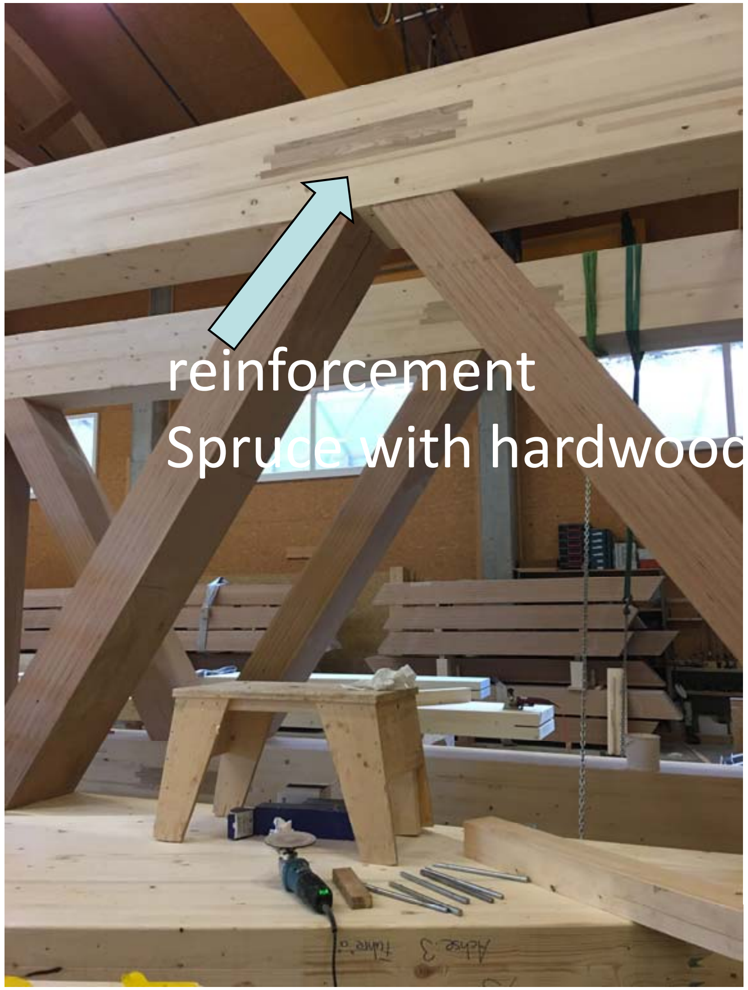


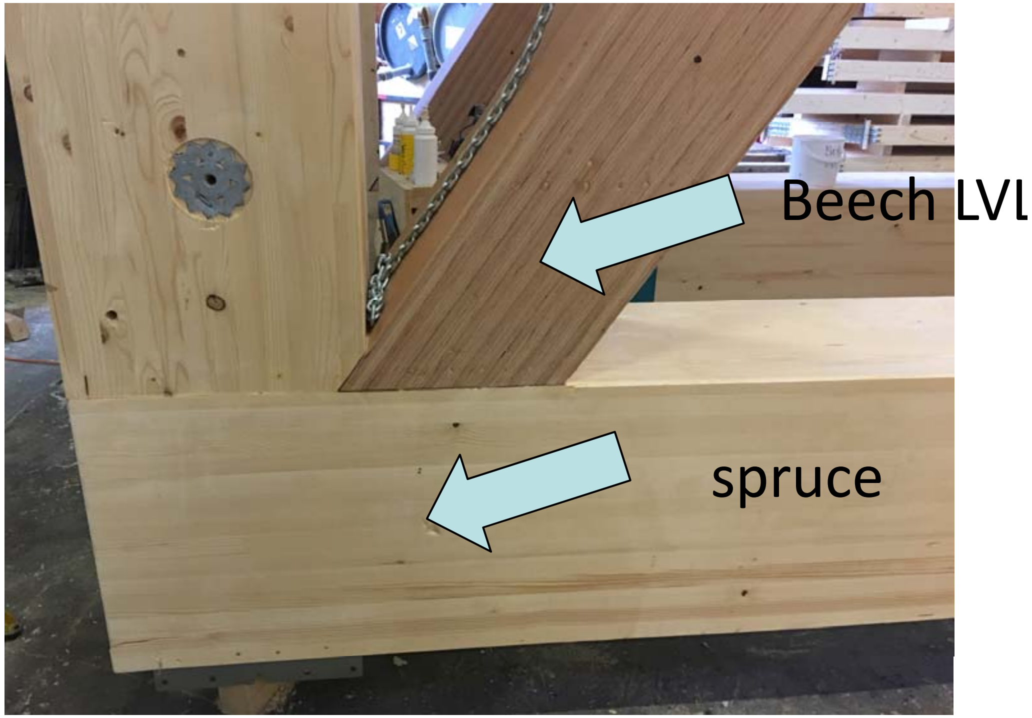
Multi storey buildings, now up to 80-85m high

Scaling effect for multi -storey buildings: We need higher dimension and/or hardwood or beech LVL

⇨ *high moisture induced internal stresses*

combinations soft- and hardwood (also «Stabbuche» from Fagus Suissse)





Free Forming: Omega, Biel/ CH

Timber construction: Blumer-Lehmann AG, Gossau AG/CH

3. Properties of wood (related to gluing)

- Macroscopic structure (difference: hard- and softwood, species): penetration from adhesives
- Physical and mechanical properties related with the structure: orthotropic properties, swelling, shrinking, MOE, strength
- Chemical structure (reaction with adhesives, e.g. pH- value, extracts)

Microstructure from soft and hardwood

(Bramwell 1976) Glulam/CLT: mostly softwood used

a) softwood (e.g. pine)

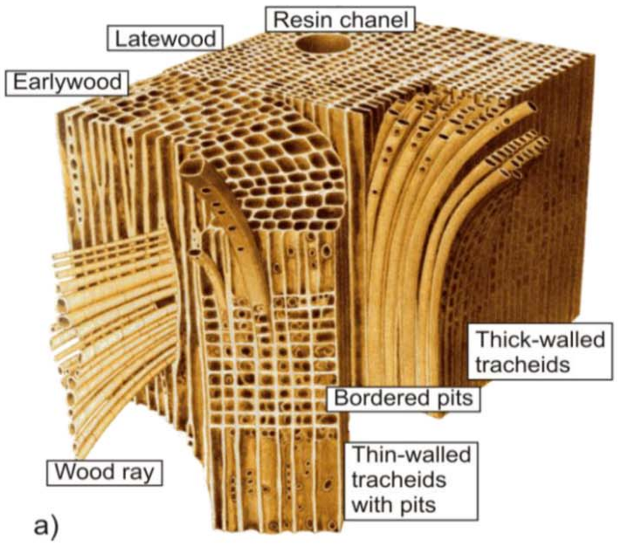
simple structure e.g.

- spruce
- pine
- larch

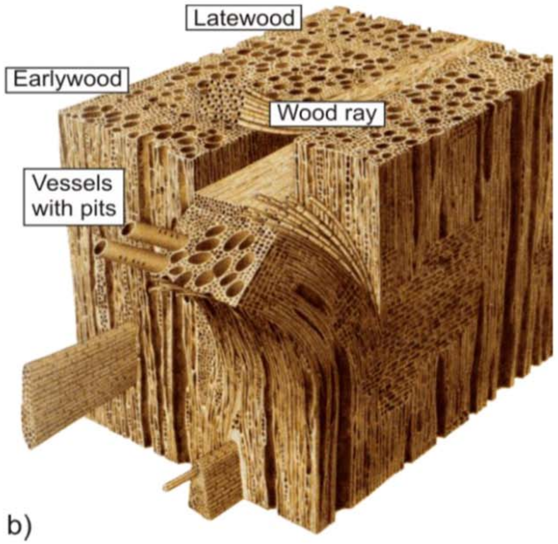
b) hardwood (e.g. beech)

more complicated structure e.g.

- beech (diffuse- porous)
- ash (ring- porous)
- oak (ring- porous)



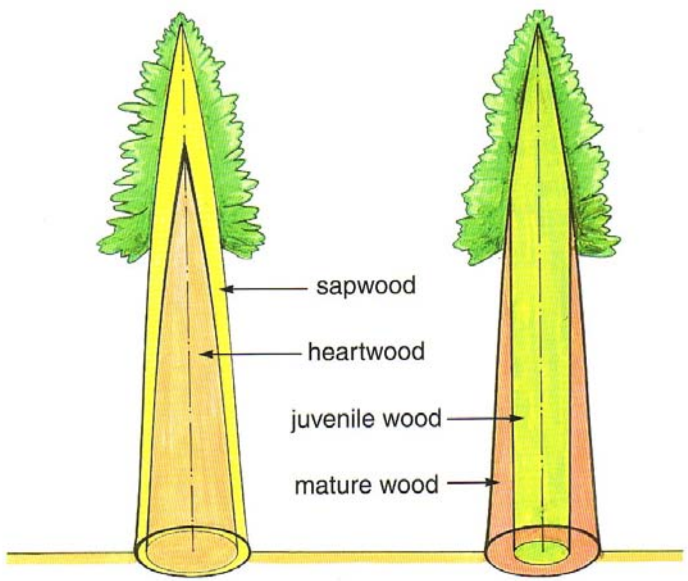
a)

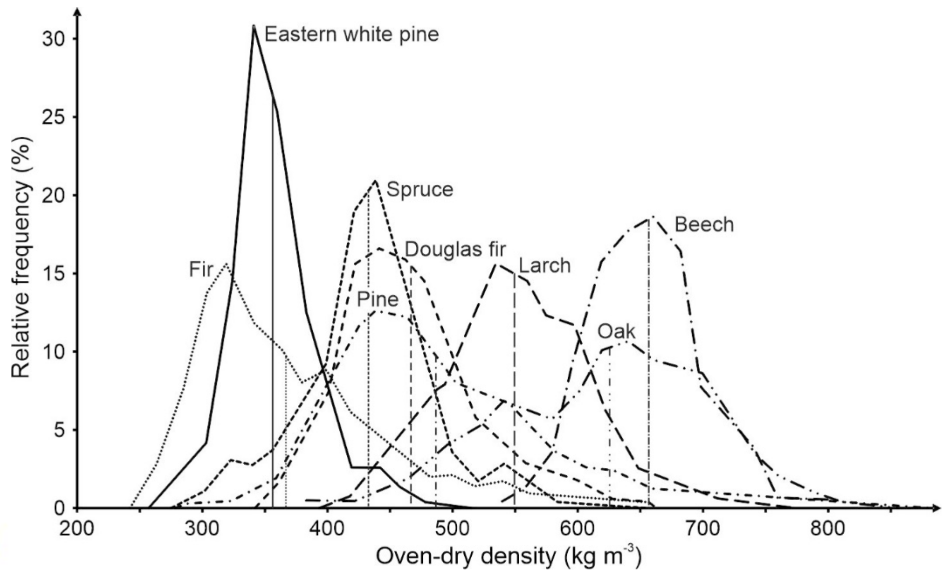


b)

Variability from wood properties

a) juvenile and mature wood, density
b) sapwood and heartwood –different properties
c) influence from growing conditions (e.g. Knigge und Schulz 1966)
d) microscopic structure (MFA, growth rings, density between growth rings etc.)

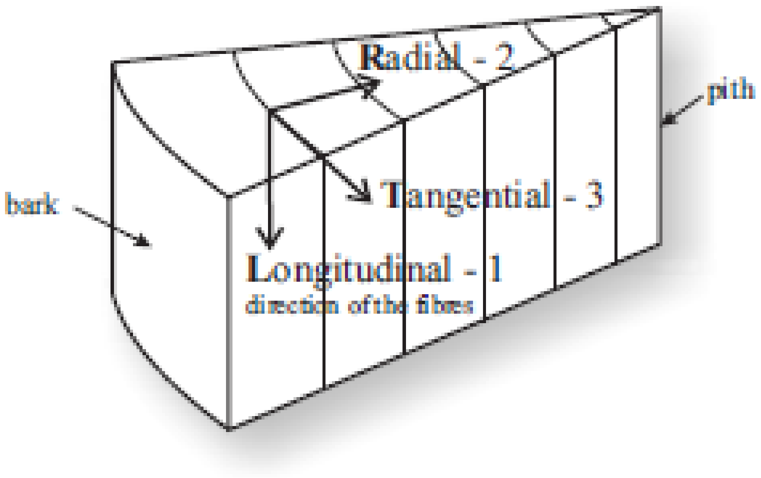




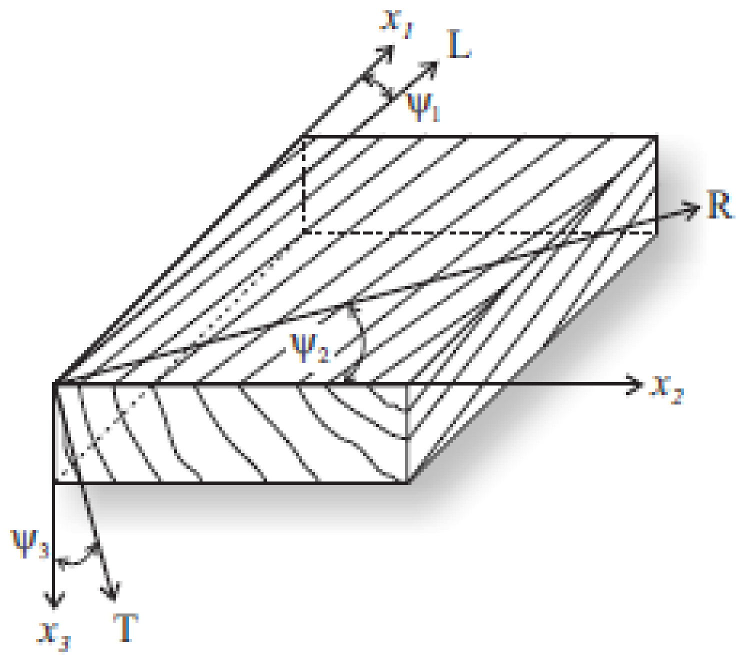
Orthotropic properties from wood

Important for: mechanical properties, swelling etc.)

coordinate system

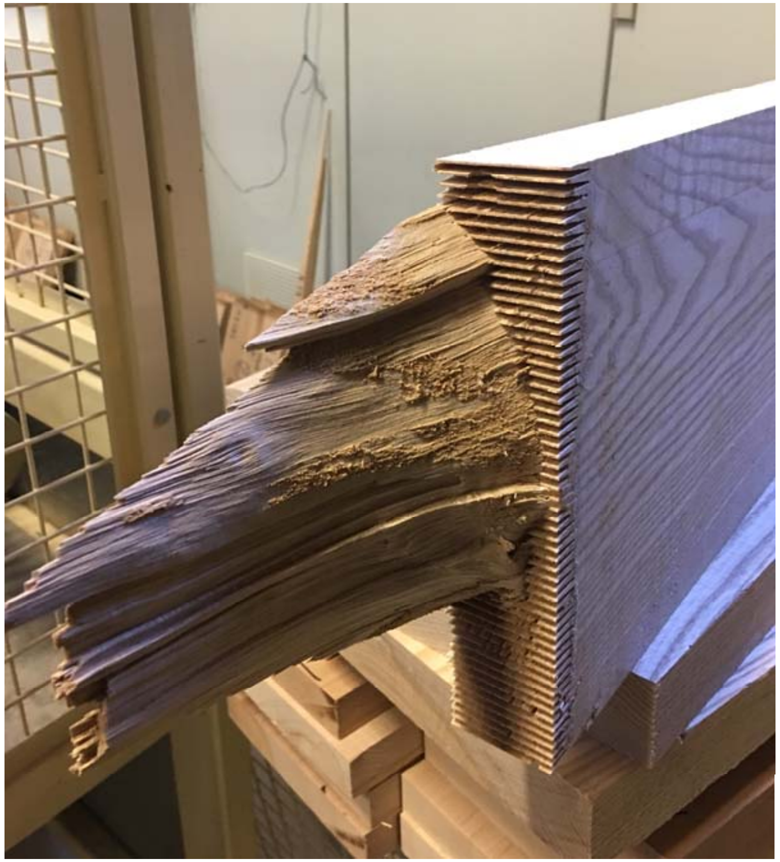


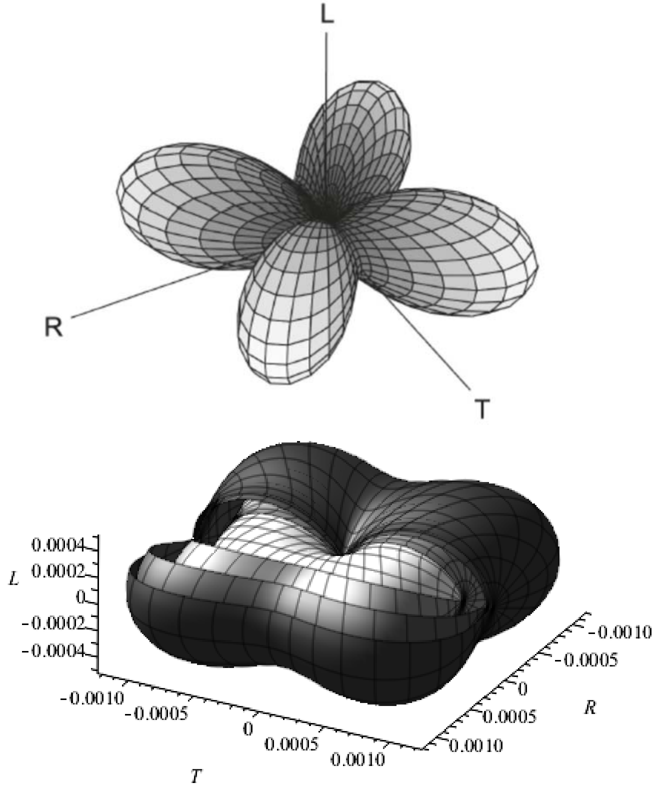
polar coordinates
(grain- and ring angle)



Influence grain angle on strength from finger jointed ash wood

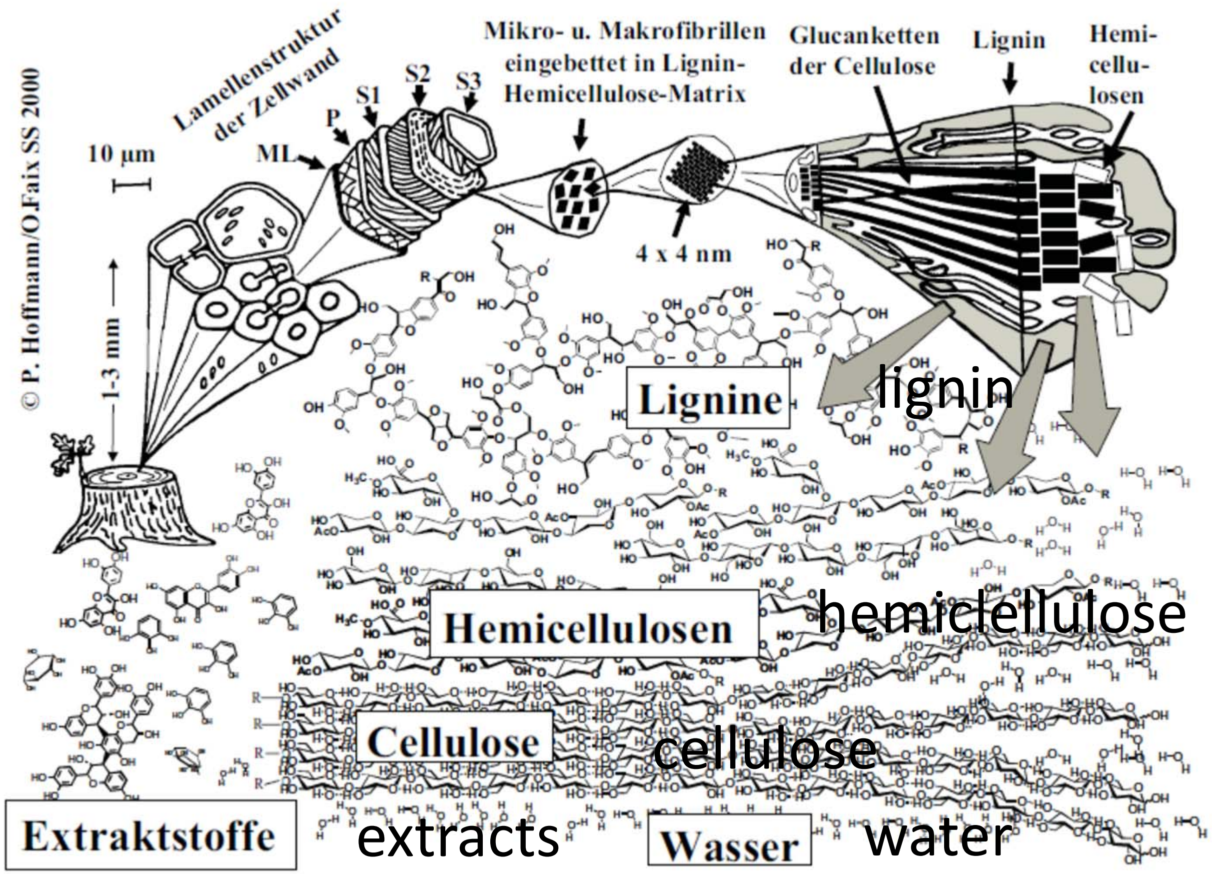
(industrial quality control: «neue Holzbau AG», Lungern/CH)



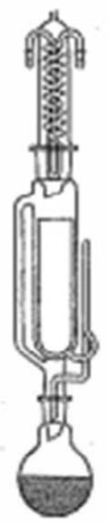


Deformation body from spruce and Walnut for different EMC,

Chemical structure from wood (O. Faix, 2012)



Extracts from wood (methods for testing)

Extractant		Extracted compound
 soxhlet extractor	1. Petroleum ether	Fatty acids, fats, fatty alcohols, sterols, steryl esters, terpenes, resin acids
	2. Diethyl ether	Partially oxidised fats, terpenes, resin acids
	3. Acetone-water (9:1)	Phenolic compounds, glycosides (contains extractives from extraction step 1 and 2, if these are omitted)
	4. Ethanol-water (8:2)	Monomeric and oligomeric sugars, glycosides, partly low-molecular lignin precursors, colorants, tannins
	5. Water	Starch, partly hemicelluloses, colorants, tannins
	6. Alkaline water	Polyphenols (tannins), phlobaphenes, hemicelluloses, lignins

pH value from extracts (Jung and Roffael), important for MF/MUF

Beech: 5.14

Oak: 3.93

Spruce: 4.93

Pine: 4.08

4. Gluing from wood for structural applications

Which properties do we need ?

- High strength from the glued wood and the bondline (wet and dry conditions)
- No aging under cyclic climatic conditions
- Long time resistance (static: creep, fatigue, no chemical destruction (e.g. from extractives), no aging)
- Temperature resistance (in the case of a fire 200°C or 220°C in US)
- No or very low emission (e.g. formaldehyd)
- Low cost !!
- etc.

Selected parameters for testing gluing properties

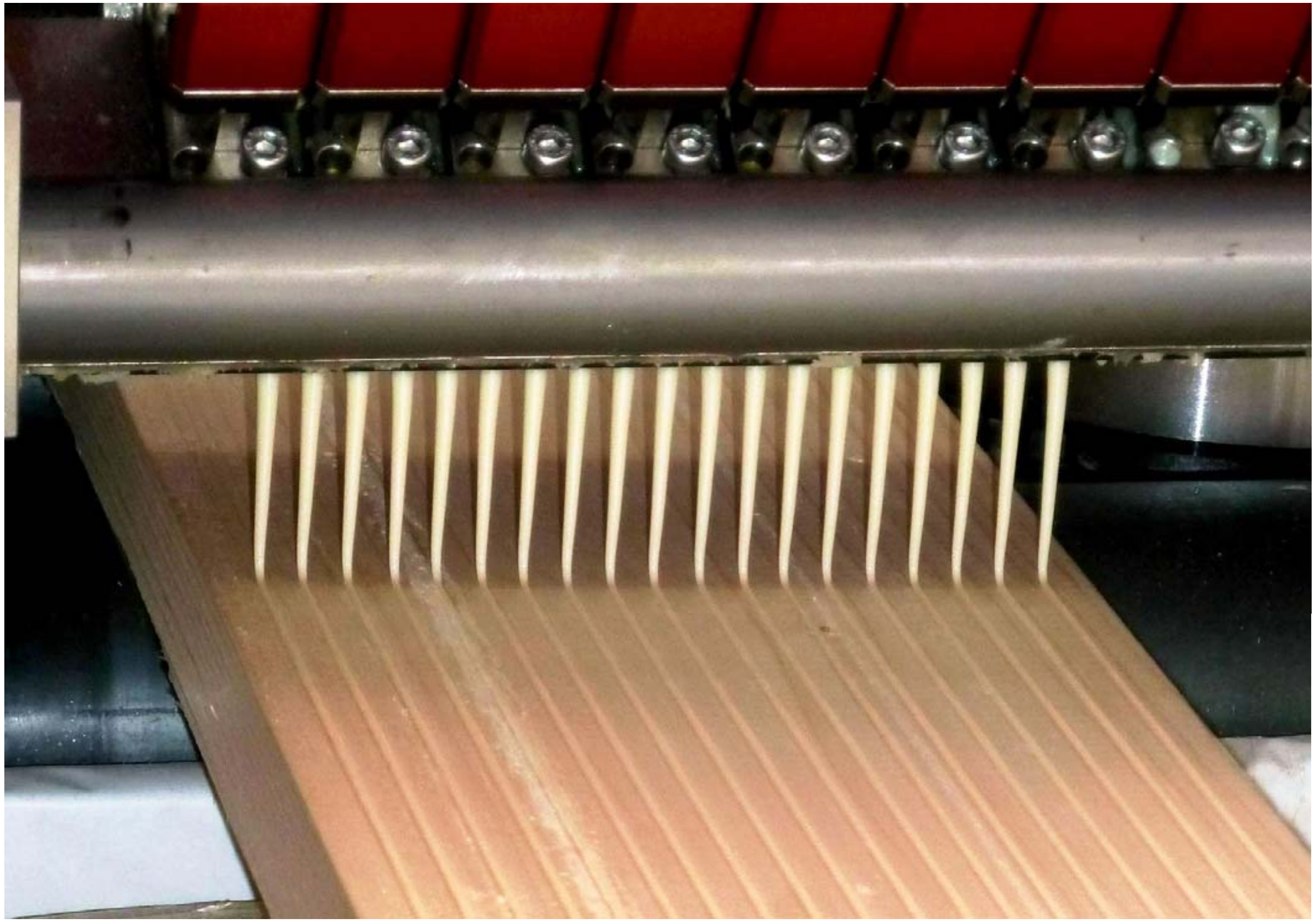
- EN302-1: tensile shear strength A1≥10N/mm^2, A4 ≥ 6N/mm^2
- EN302-2: delamination, length of delaminated bondlines ≤5%

Delamination from beech glulam EN302-2

foto: M. Schmidt et al. (2010)

1C-PUR (without primer) and special MUF/MF/PRF/ special 1C-PUR with primer

Adhesive application (1C-Pur, Henkel AG/CH)



Basics from gluing for structural applications

- We have to use only adhesives with a approval by the building authorities (e.g. German «Institut für Bautechnik», Berlin)
- We need different adhesives for longitudinal bonding of the wood (finger joints) **and** for surface bonding, different reactivity (open and closed assembly time)
- We need more and more formaldehyd free adhesives (PUR,EPI) and/or adhesives with reduced formaldehyd emission (MF, MUF)
- At low level we already use biobased adhesives (tanine, lignin)

(focus for investigation)

- Also some times mechanical connections (e.g. dowels, Alu nails etc.) used

Failure from glulam Bad Reichenhall/D

winter 2006, 15 peoples died

Problems with gluing

- Softwood:
  - spruce, pine etc.: no problems
  - problems: with some softwood species like larch, southern yellow pine
- Hardwood/tropical species:
  - more problems: higher strength, higher extracts, higher swelling/shrinking, higher pressure needed, adapted adhesivs necessary

Properties of wood related to gluing

property	spruce	beech	ash
Density ,ϖ12 % (kg/m³)	300-**430**-640	540-**700**-900	450-**690**-860
MOE (bending) (MPa)	7.300-**11.000**-21.400	12.300-16.400	4.400-**13.400**-18.100
Compression strength (MPa)	33-**50**-79	41-**62**-99	23…**52**…80
Tensile strength (MPa)	21…**90**…245	57-**135**-180	70…**165**…293
Bending strength (MPa)	49-**78**-136	74-**123**-210	58..**105**…210
Max. swelling (%)	R=3,5-3,7 T=7,8-8,0	R=5,8 T=11,8	R=4,5-5,0 T=8,0-8,4
pH-Wert	4.0-5.3	5.8	5.8
Hot water extract (%)	2,0	1,9	2,9-6,8

<u>hardwood</u>

- Higher density
- Higher MOE, higher strength
- Hardwood higher swelling ratio in relation to softwood

Problems: delamination test according EN 302-2

<u>why:</u>

- higher stress during delamination test
- different extractives

Variant	Acidic acid [mg/kg]		Formic acid [mg/kg]		∑ [mg/kg]		Ø	pH
	Sample 1	Sample2	Sample 1	Sample2	Sample 1	Sample2		
Beech	113.9	114.5	9.58	9.58	123.5	124.1	123.8	5.39
Ash	225.6	227.5	50.72	50.72	276.3	278.2	277.3	5.18
Spruce	421.3	423.8	13.17	13.21	434.7	437.0	435.9	4.74

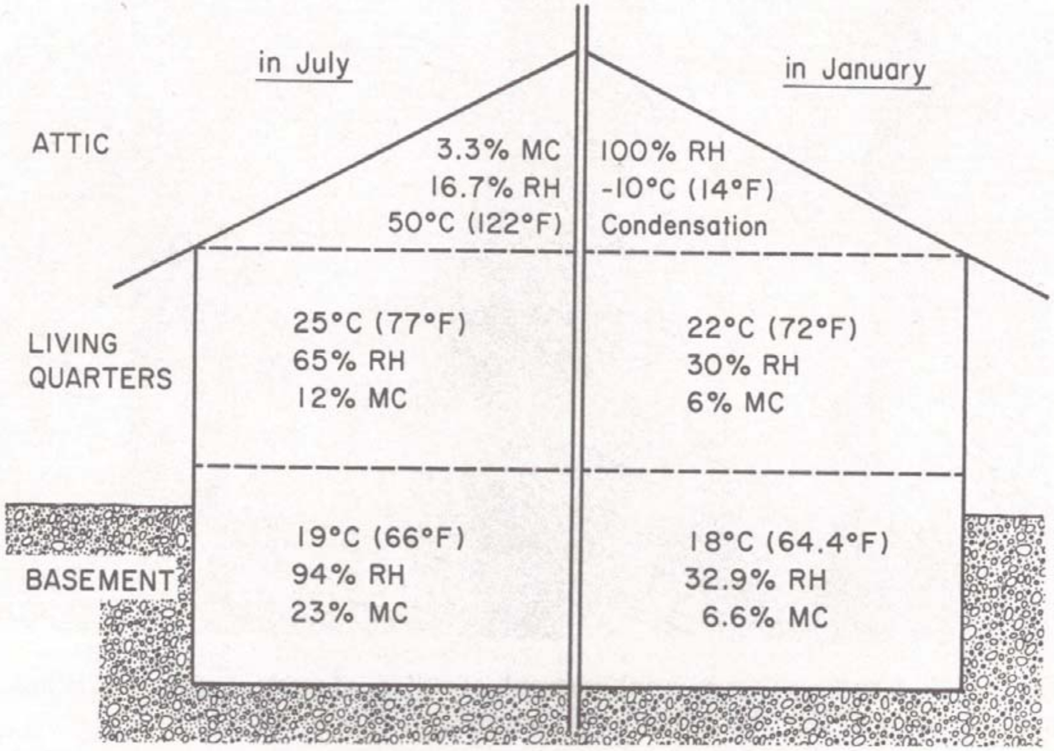
Influence from climatic conditions/service classes and cross section

- Service class 1: 20°C/65%RH
- Service class 2: 20°C/85%RH
- Service class 3: moisture content higher as in class 1

➢ In the moment: more **problems in class** 1 (cracks, delamination, especially in the European winter with RH in heated rooms RH<20%)

➢ The higher the cross section, the bigger the problem

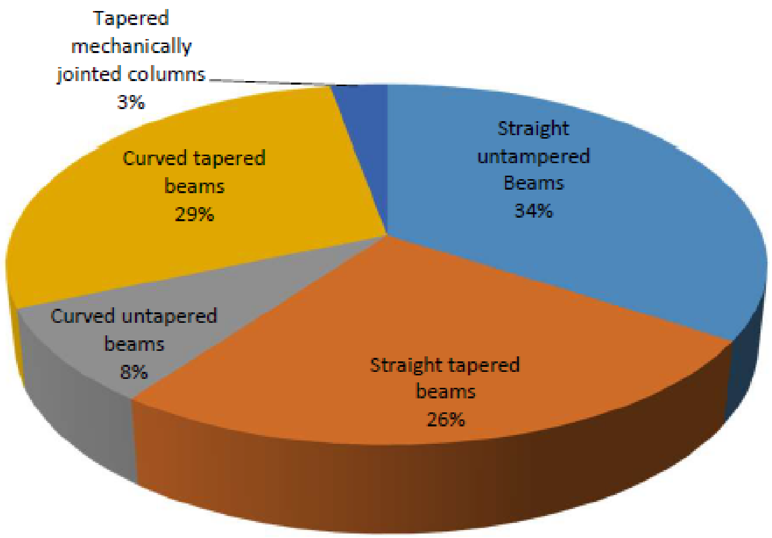
Climatic conditions in a farmer house in the middle west from US (Wilox, Botsai and Kubler, 1991)



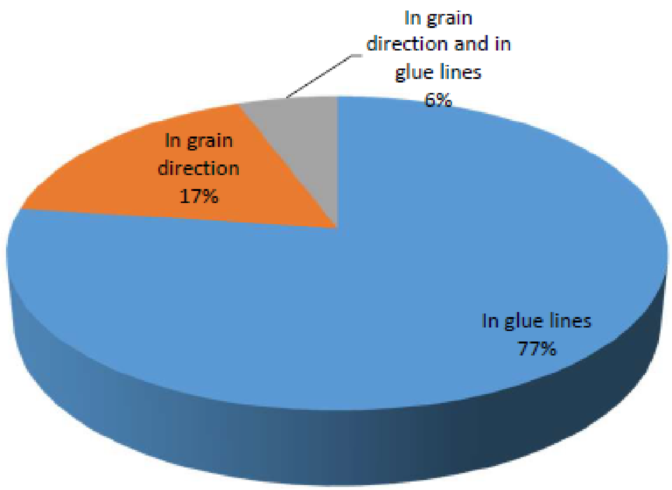
Cracks in glulam service class 1 and 2

(workshop, Paris 17.7.2017)

beam shape



defects: cracks, delamination



63% are straight members

Delamination from glulam under dry conditions in a building, *also this is a problem, **not only the test** EN302-2*

ash (ETH Zurich) beech (TU Munich)

problems with delamination also under low (RH 30%, temperature 20-23^{o}C: *influence of cross section from the samples, surface coating (higher diffusion resistance) and air movement etc.*

Equation of performance for GLT

(Marra 1992)

$$GP = c + \Sigma AC + \Sigma WP + \Sigma SP + \Sigma AA + \Sigma WG + \Sigma PS$$

where: GP: glued product performance, **c:** constant for the adhesion, **AC:** adhesive composition, **WP**: wood property, **SP**: wood surface preparation, **AA:** adhesive application, **WG:** wood geometry, **PS:** product service factor

***Important:** interaction between the different factors*

General: more problems with hardwoods (beech, oak, ash, etc.) then softwood (spruce), but also problems with selected softwoods (larch, southern yellow pine etc.)

Lit.:**Hänsel, A.**; Sandak, J.; Sandak, A.; Mai, J.; Niemz, P:,Selected previous findings on the factors influencing the gluing quality of solid wood products in timber construction and possible developments: A review .Wood Material Science & Engineering (2021) on line first

used adhesives in the timber construction

Used adhesives in EU, Nordamerika und Asia/Pacific (Henkel 2021)

% in the different adhesives groups	1C PUR	MUF/MF	PRF/PF	EPI
CLT	69 %	18 %	–	13 %
Glulam	**8 %**	**48 %**	**9 %**	**35 %**
I-Joist	1 %	6 %	78 %	15 %

In Switzerland: often 1C-PUR, also MUF/MF/PRF, MF

for CLT often 1C- PUR used

Selected producers:

- MUF/MF: e.g.. Dynea; BASF; AkzoNobel (GripPro, MF)
- PRF/PF: Dynea/N, Oxiquim/RCH
- 1C-PUR; Henkel/D; Jowat/D; Collano; Sika; Gyso (Geistlich)/CH, DowChemical; Bostik/USA, Oxiquim/RHC etc.
- EPI (Jowat/D, Dynea/N)
- ❖ High difference between the systems and in a system

Factors influencing bonding quality

Wood

specie
- grain and ring angle
- density/strength
- swelling /shrinking
- heardwood /sapwood
- growth ring structure
- extractives
- chemcial composition
- variation from wood properties

wood modification
- e.g. thermal, chemical, densification

Adhesive

type of adhesive (PRF; MF; MUF; 1 C-PUR; EPI)
- chemical and mechanical properties (also variation in a adehesive type)
- penetration into wood (viscosity)

bondline thickness

sorption and mechanical properties from the bondline (MOE, strength, MC)

adhesion on wood in dry and wet condtions

aging during service and testing

Machining and Technology

method of preparation and elaboration
- planing, surface milling, sanding etc.
- surface quality (roughness, waviness etc.)
- moisture content from lamellas and variation between lamellas
- pretreatment: priming, water, plasma, laser

quantity of appleid adhesive/accurancy of applied amount

pressing conditions
- open and closed assembly time,
- pressing time
- specific pressure
- room temperature and air humidity during pressing

Glulam structure

lamella thickness

mechanical properties of lamellas properties
- variation in and between species, moisture content

dimension from glulam beam

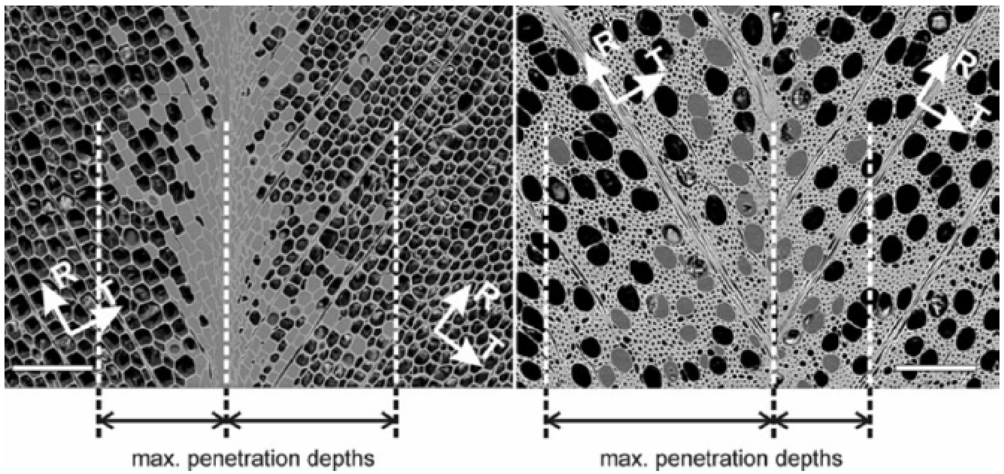
surface coating
- buffering water diffusion, reducing moisture profiles and moisture induced stresses

Hänsel et al. 2021: Wood Material Science and Engineering

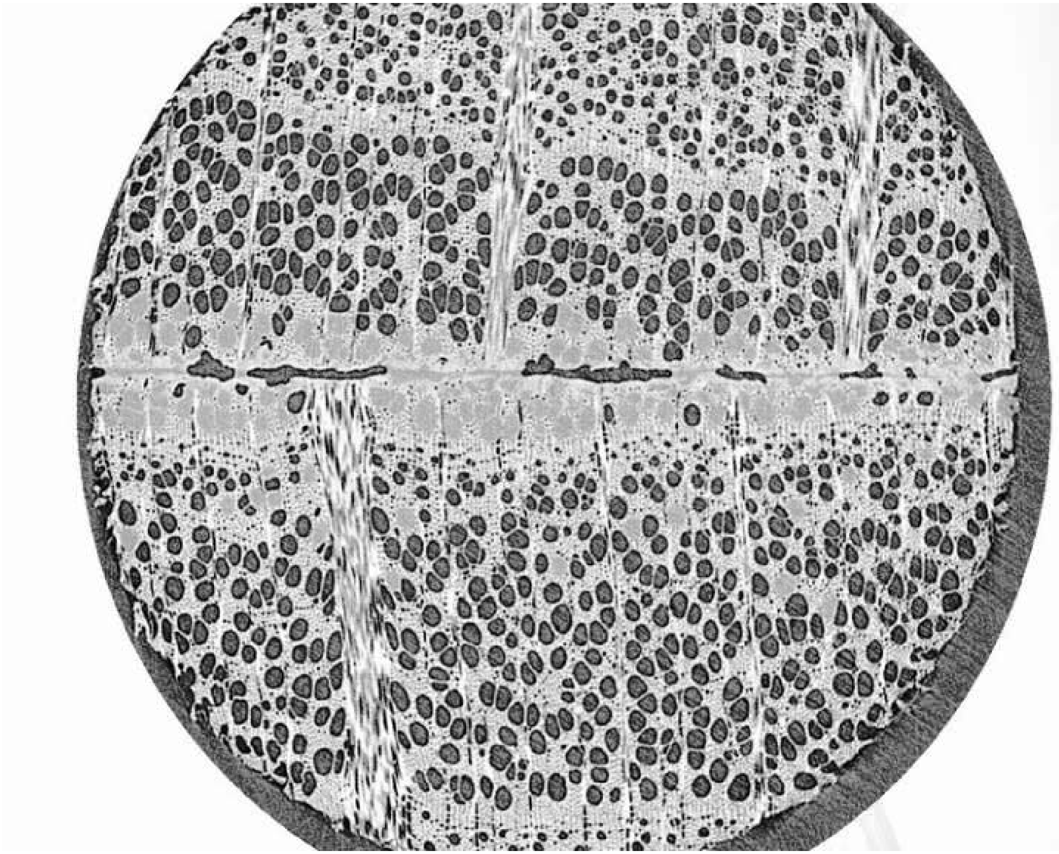
Model of a bondline and penetration from 1C-PUR into wood:

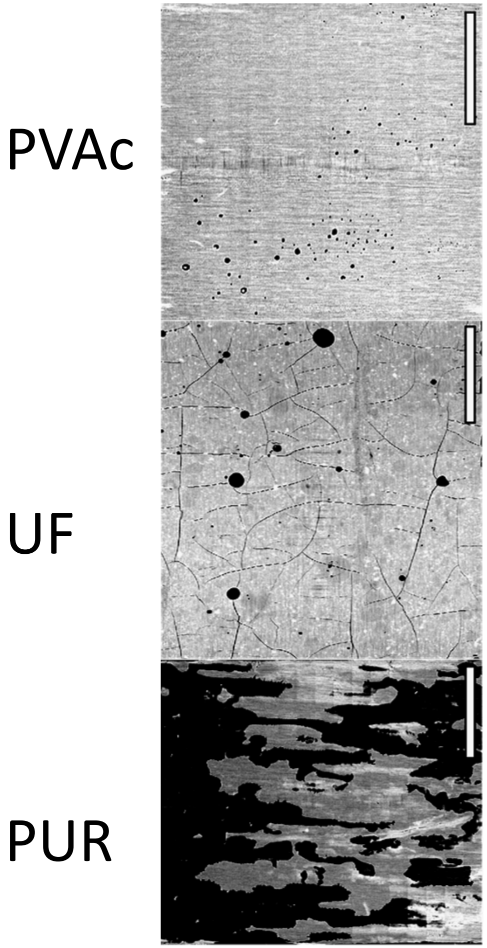
different penetration into hard- and softwood

Ph. Hass ETH (2012), J. Paris, Oregon State (2015) for hardwood
O. Suchsland (1958) for softwood



Adhesive penetration into wood (Hass 2012)





working areas in the field of gluing (mostly hardwood)

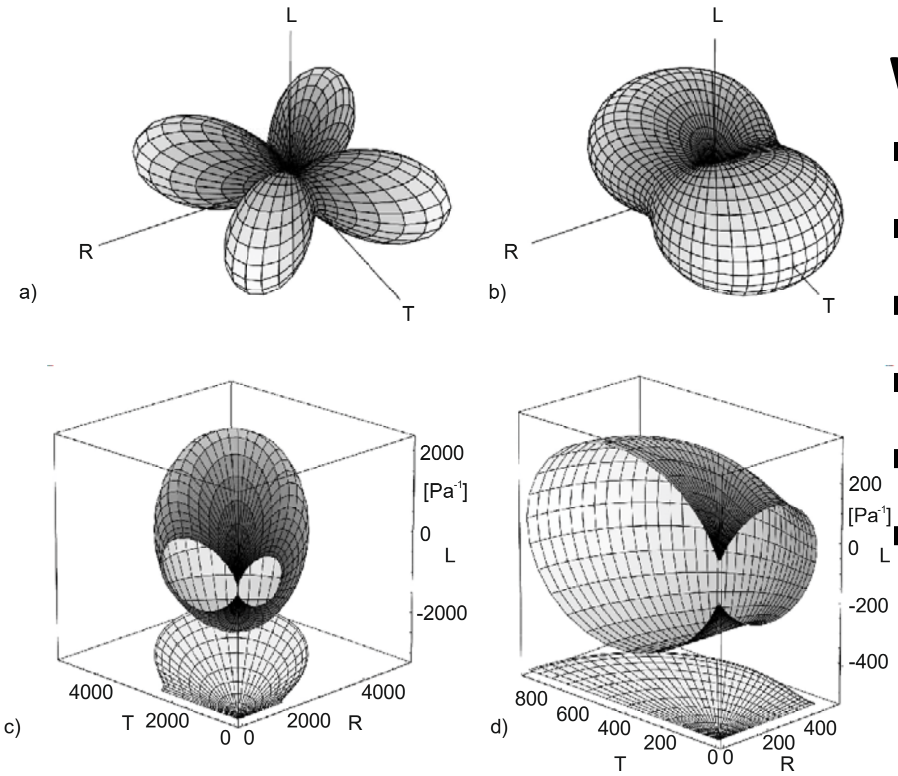
- **<u>Characterization</u>** from **wood** (anatomical, chemical, physical properties) and **adhesives:** (wetting, penetration) and adhesive films (MC, MOE, strength, viscoelastic) (Hering, Ozyhar, Bachtiar, Sonderegger et al.)
- *<u>Gluing:</u> macro level* A1, A4, A5, delamination, moisture induced drying stresses, fracture mechanical tests (Ohnesorge 2009, Follrich 2008 Kläusler 2014, Ammann 2015, Schmidt 2014, Knorz 2015, Lüdtkemeier 2017, Karami 2020, Bockel 2020, Clerc 2020)
- *<u>Micro level:</u>* NI, RAMAN, AFM, DVS (Konnerth, Gindl-Altmutter, Wimmer Burgert, Keplinger), Synchrotron: Baensch (2015), Zauner (2014)
- <u>Modelling</u> (Serrano 2000, Serrano and Gustafsson 2001, Gerecke 2009, Hering 2011, Hassani 2015, Wittel /Niemz ETH 2017)

orthotropic wood properties

deformation body

spruce beech

(Grimsel 1999)



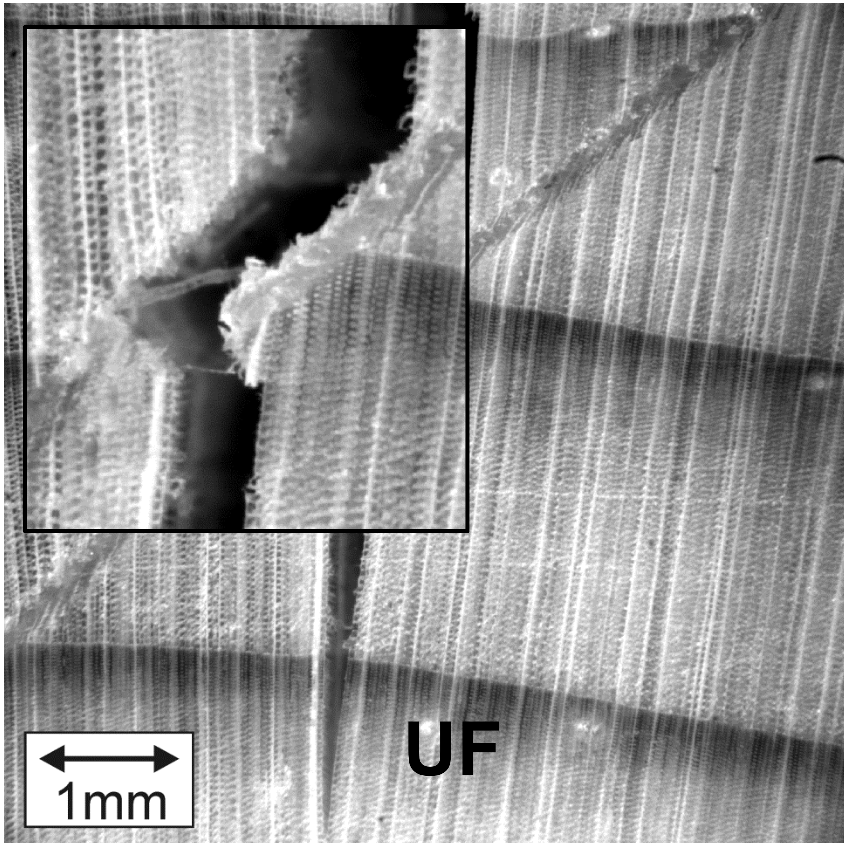
We need

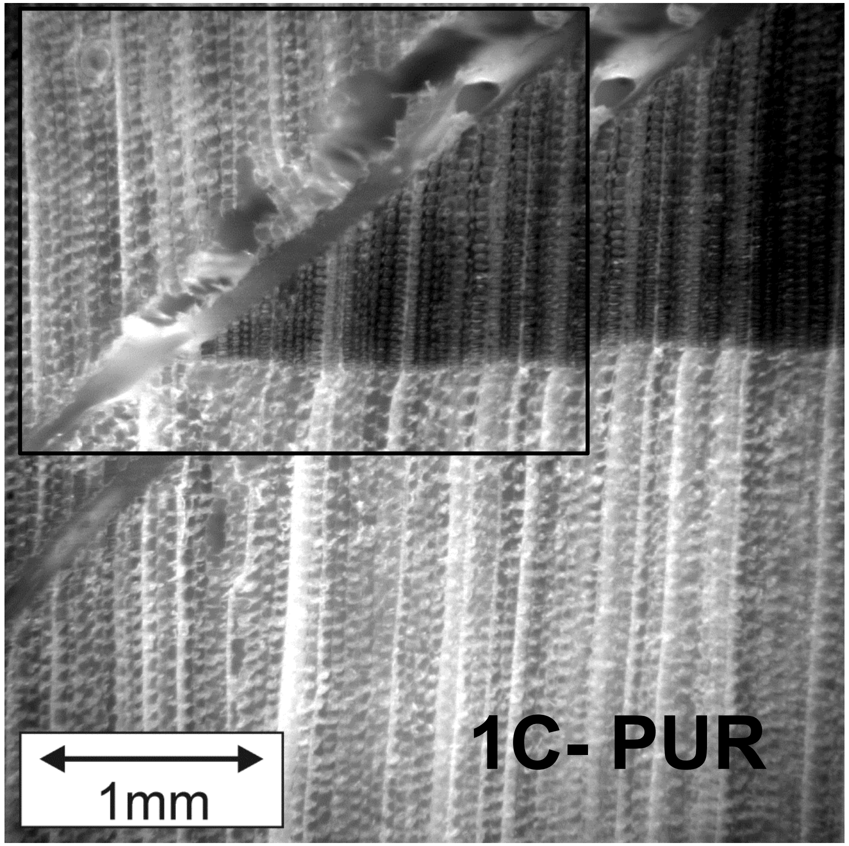
- MOE, MOR in main directions
- Influence grain and ring angle
- Growth rings
- Influence moisture content
- Creep, relaxation, fatigue
- See works ETH «Wood Physics»

e.g. T. Ozyhar 2013, S. Hering 2011, Bachtiar 2017, free download from ETH library

Fracture in glued wood (Hass 2012)

high stiffness from adhesives for high wood failure needed, influence grain- and ring angle important

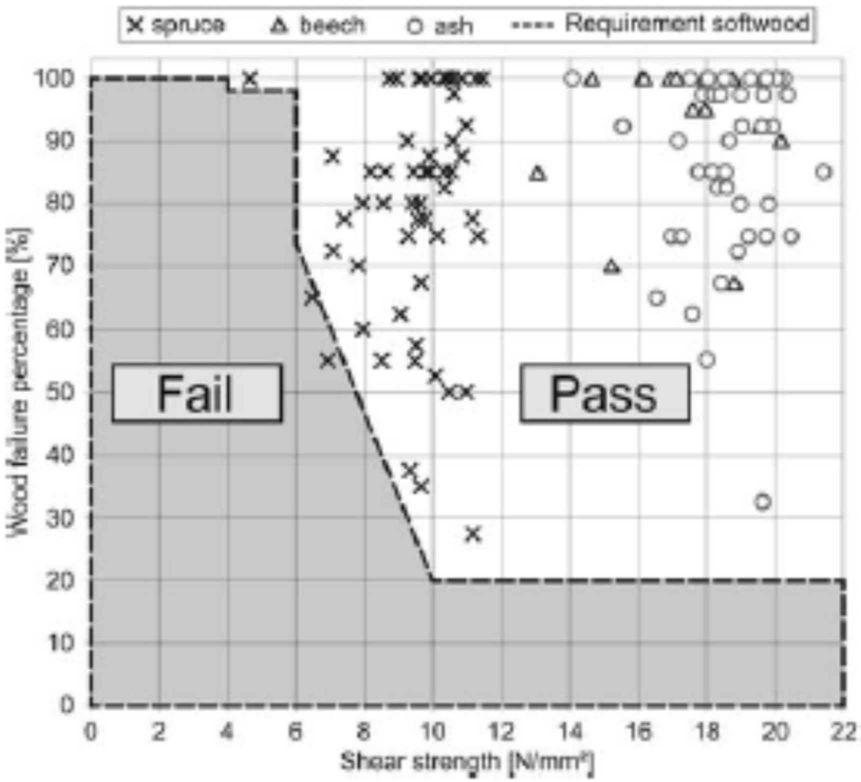




Gluing from hardwood, general problems

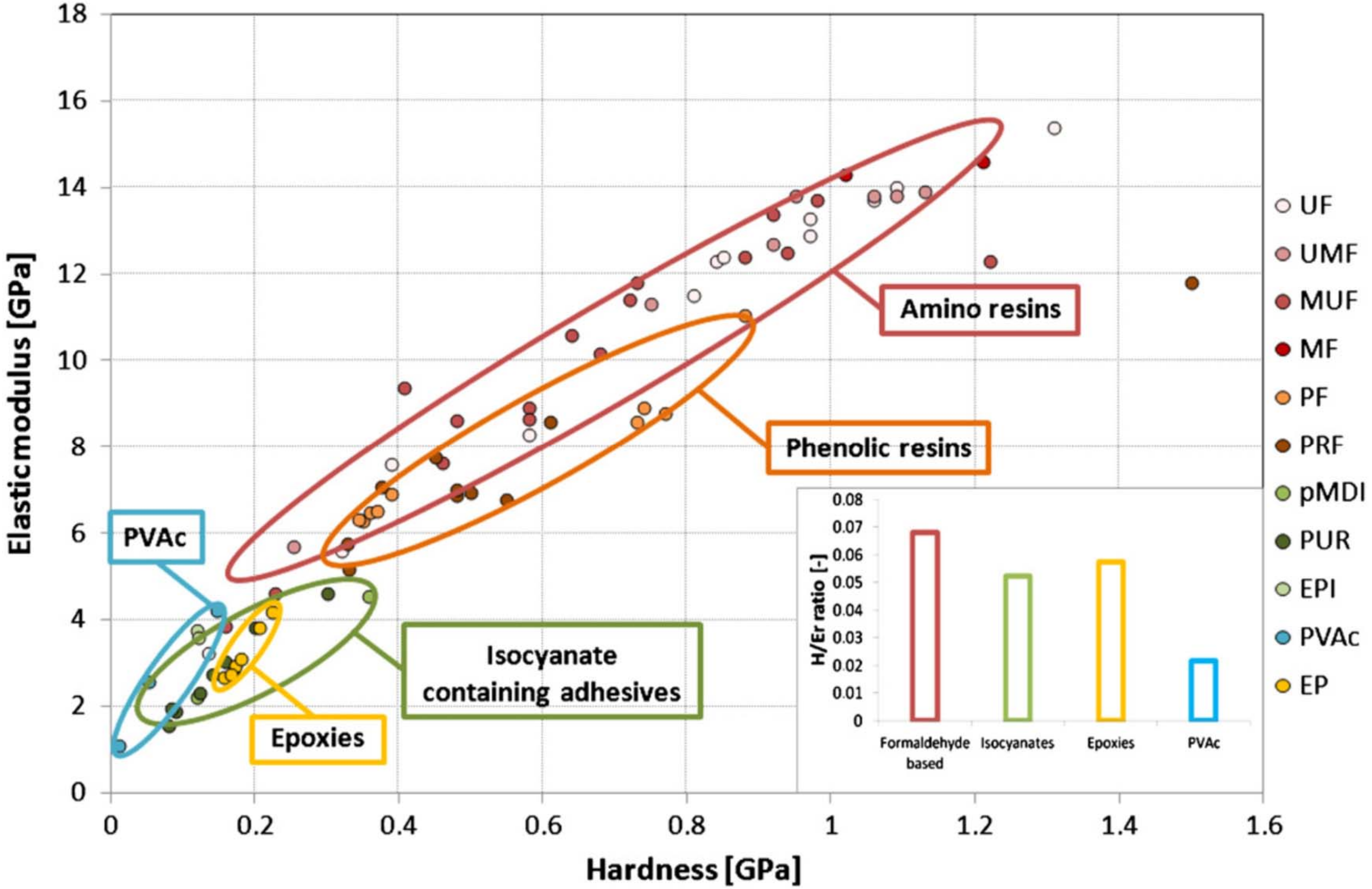
Shear strength- wood failure

for spruce, ash, beech: A4 test (M. Arnold 2019)



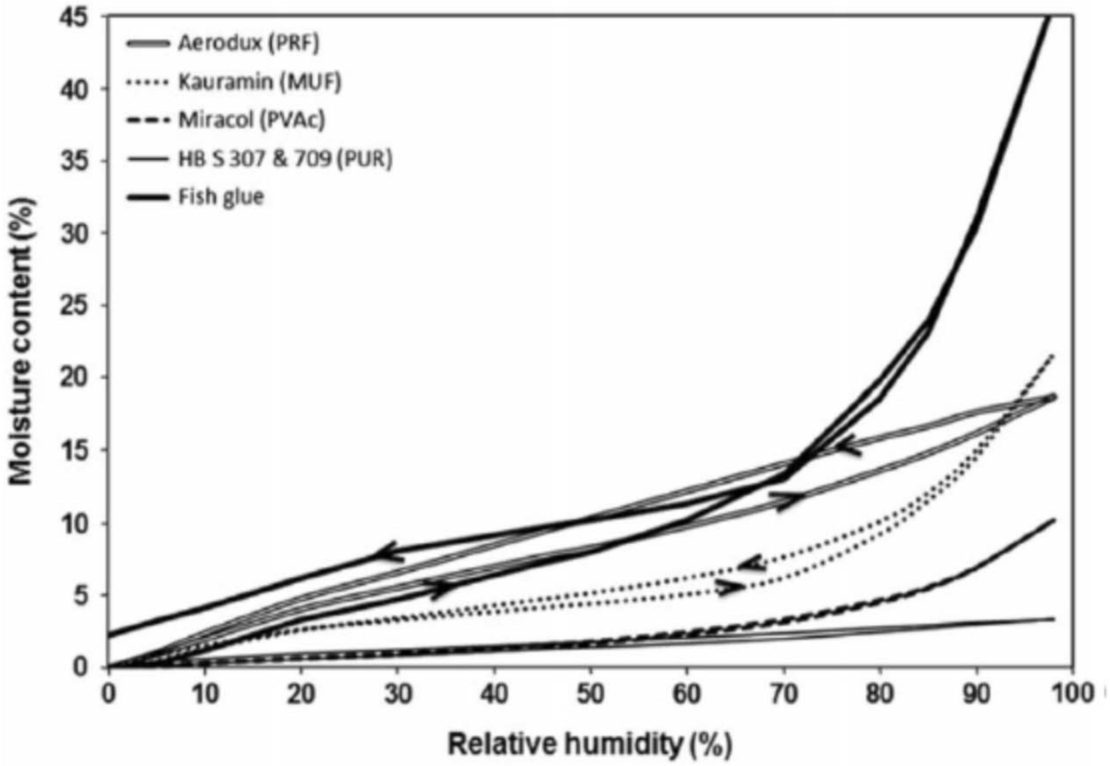
Higher shear strength from hardwood related to softwood

MOE from adhesive films (F. Stöckl et al., Boku/A) 2013)



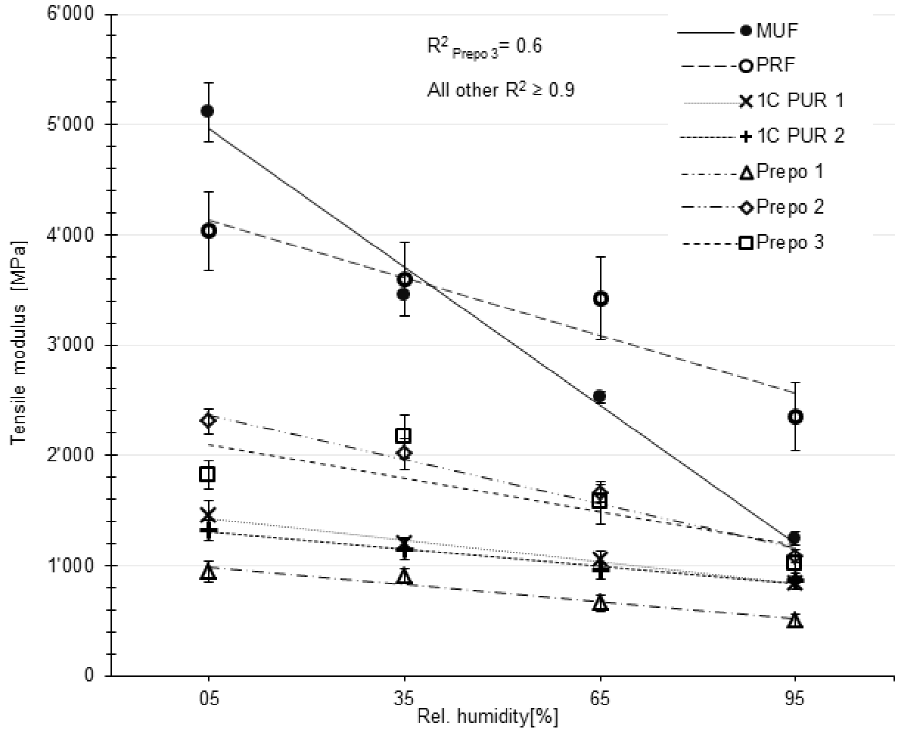
Moisture dependend properties from adhesive films

Wimmer et al. 2013

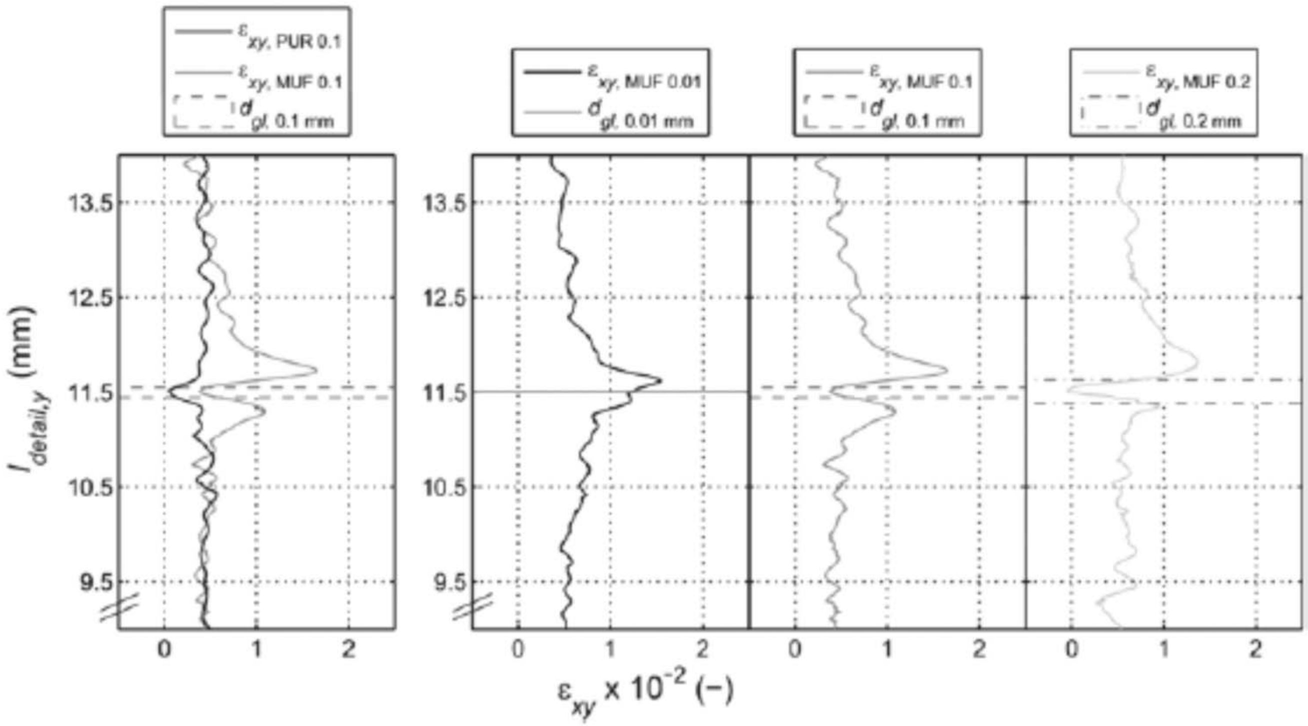


Influence from MC on properties of adhesive films

O. Kläusler, ETH Zurich, Wood Physics (2014)

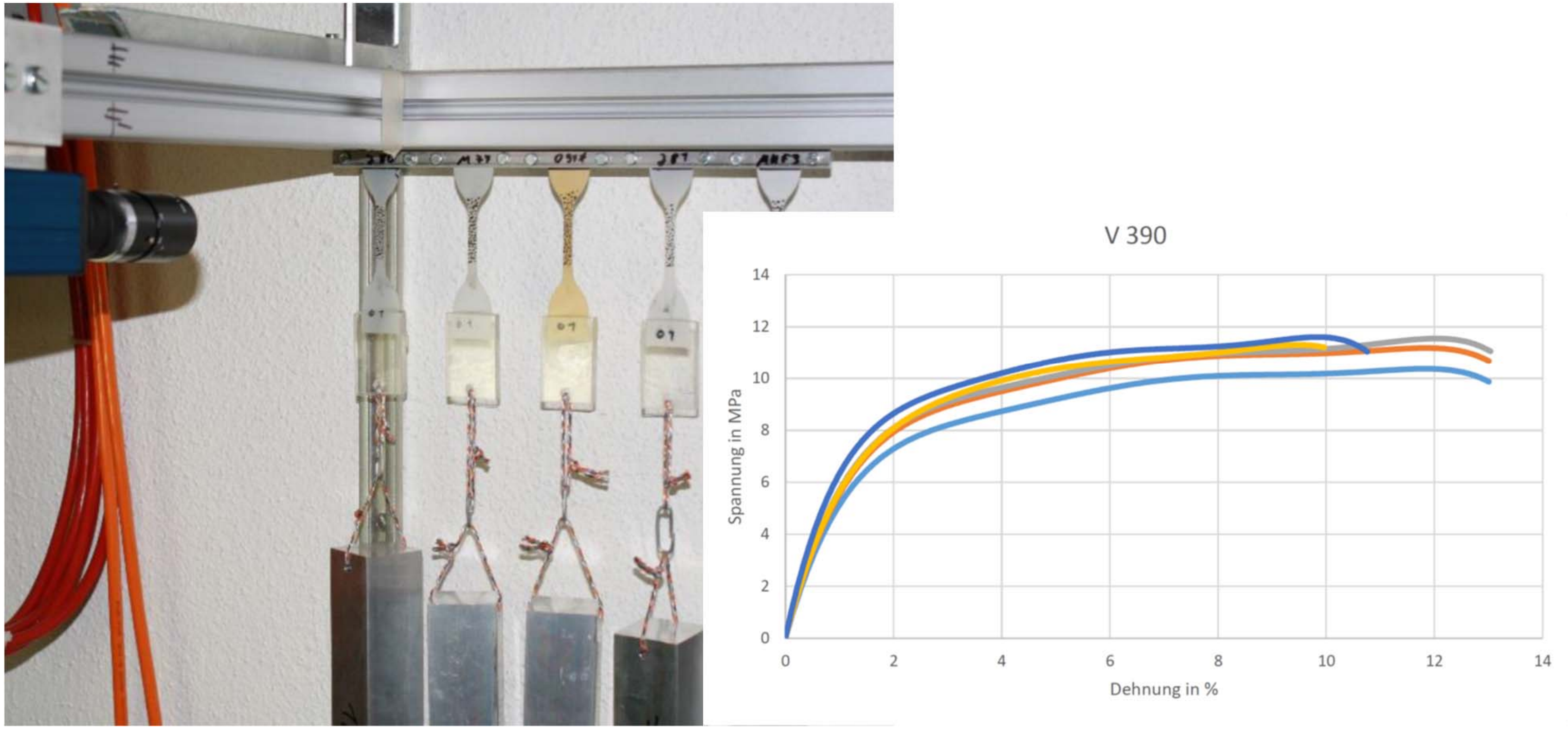


Strain distribution in bondlines for different adhesives (M. Knorz et.al. 2016)

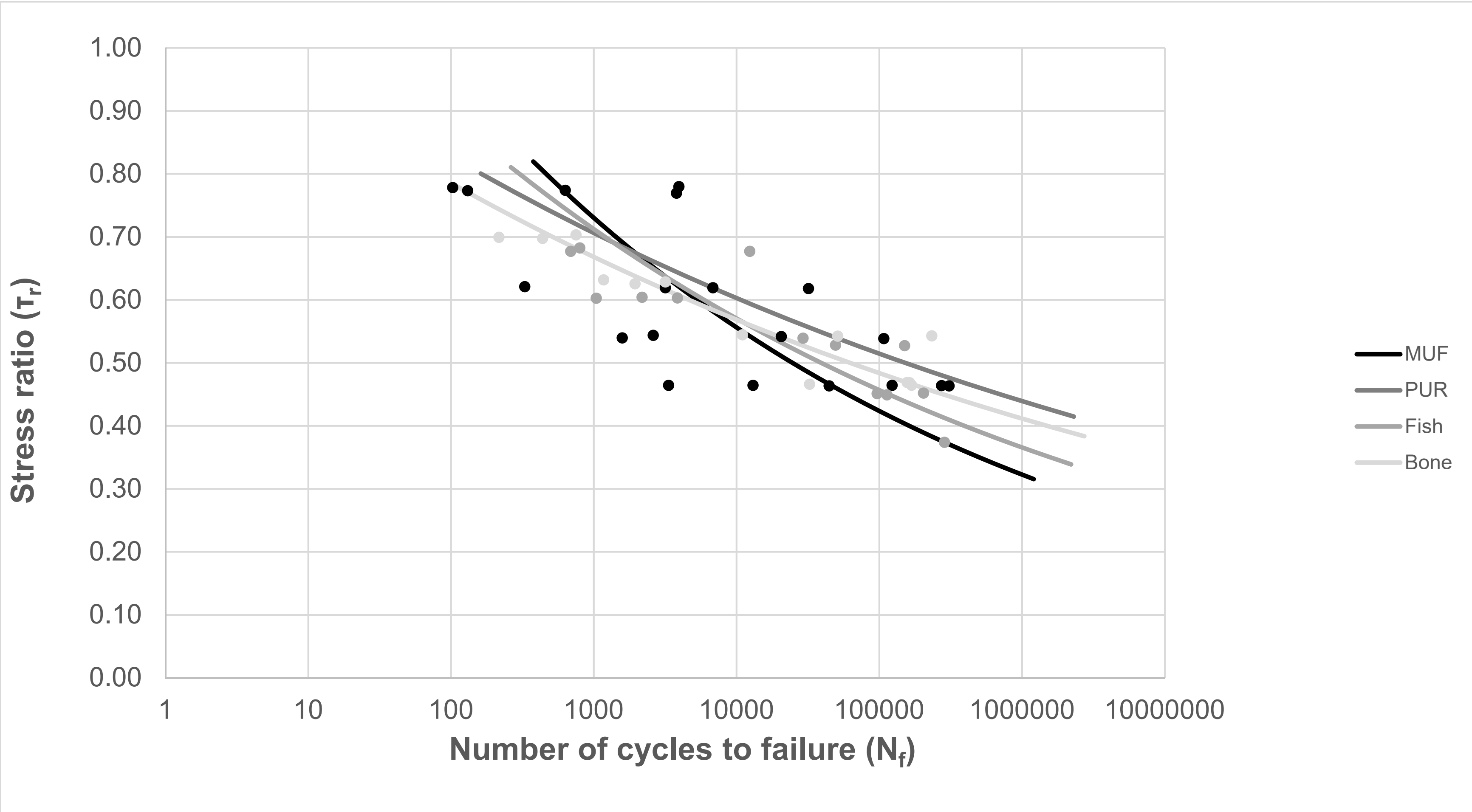


Creep/relaxation from adhesive films (ETH S. Schlegel 2014)

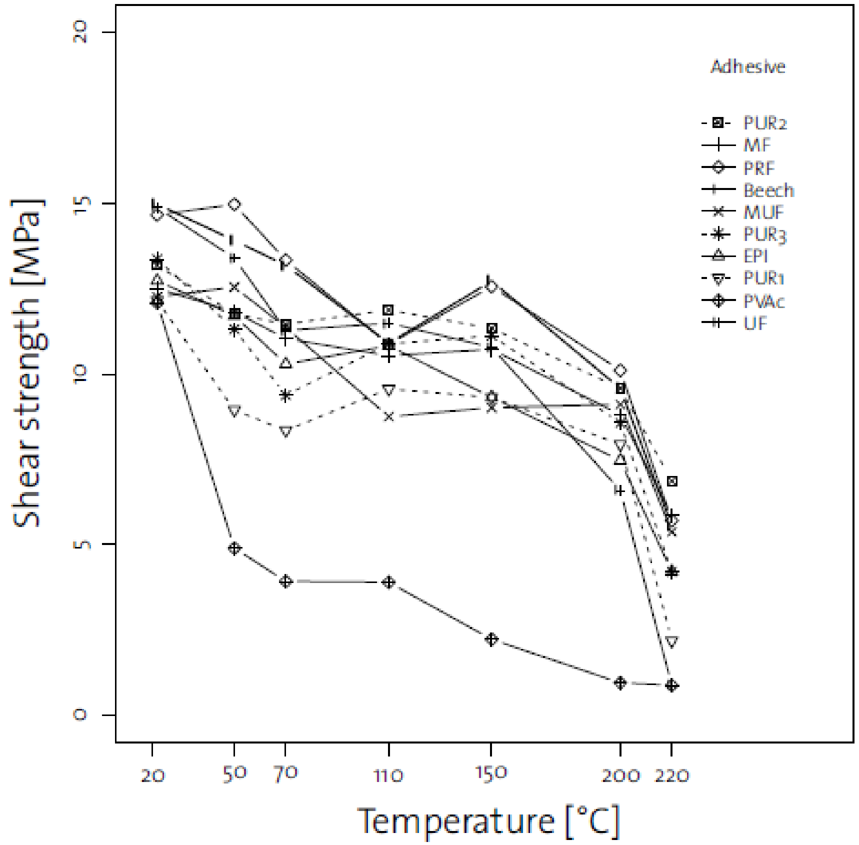
needed for modelling (M. Hassani (2015))



Fatigue from glued wood, E. Bachtiar et al. 2017



Influence from temperature on the shear strength (S. Clauss, ETH 2011)



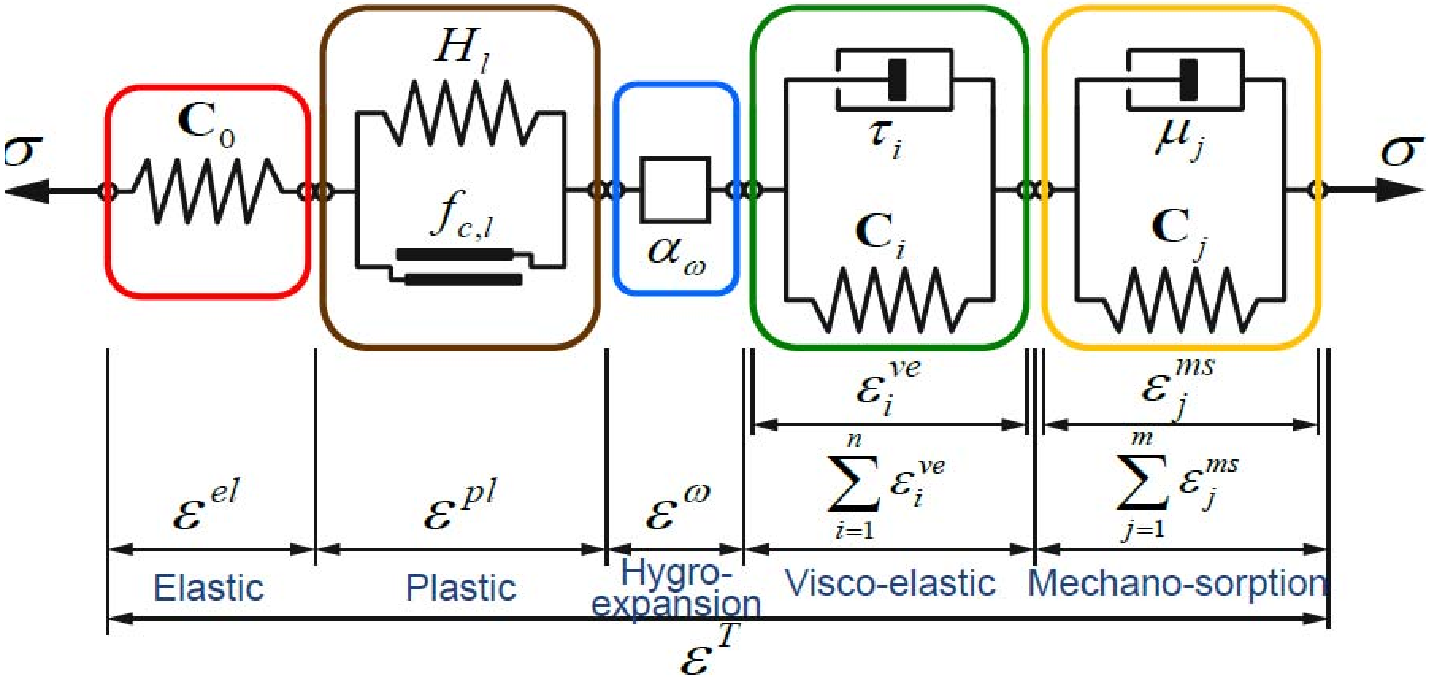
Henkel: HBX System for US market for high fire resistance

Modelling stresses in glued wood

(Hassani 2015/ETH, running works from F. Wittel ETH)

really complicated and very complex model

<u>diffusion included </u>(PhD thesis W. Sonderegger , ETH 2011)



Problems with hardwood and any softwoods, why we have this problems?

- hardwood: higher MOE, higher strength, higher swelling in relation to softwood, **different extractives, extractives also for larch and southern yellow pine important**
- different strain distribution from bondline into wood (depending on the adhesive stiffness and wood) → correlation with wood failure

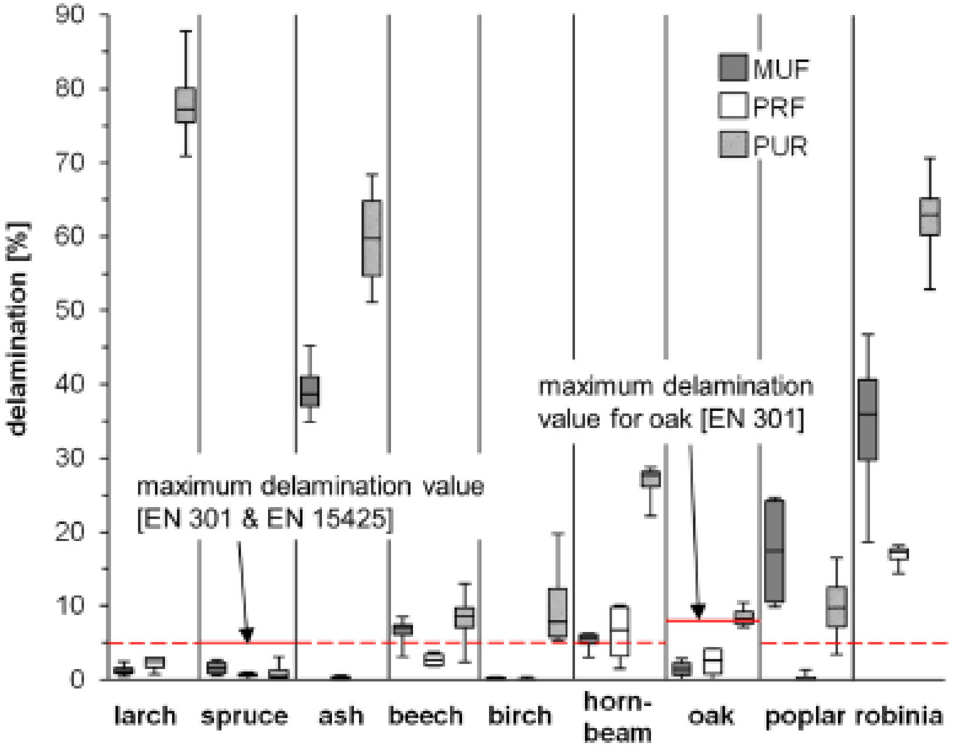
  stiffness: UF>MUF>PRF>PUR
- penetration from adhesive into cell wall (only PRF), no penetration PUR, different strain distribution?, swelling from wood by using water based adhesives (PRF; MF; MUF)
- adhesion properties in wet conditions different in relation to dry

  (problems with 1C-PUR and MUF under wet conditions

  MUF and ash wood) → low wood failure, priming needed for

  1C-PUR

Delamination for different adhesives and wood species (J. Konnerth et al. 2016)



Wood species	Primer concentration in weight percent (%)	Primer quantity (g/m^2)
Ash	5	10
Beech	10	20
Birch	5	
Hornbeam	10	
Oak	20	
Poplar	10	
Black locust	5	

Results ETH Zürich and BFH Biel «Gluing from hardwood» (2011-2020)

Peter Niemz, Presentation 8.10.21 , niemzp@retired.ethz.ch

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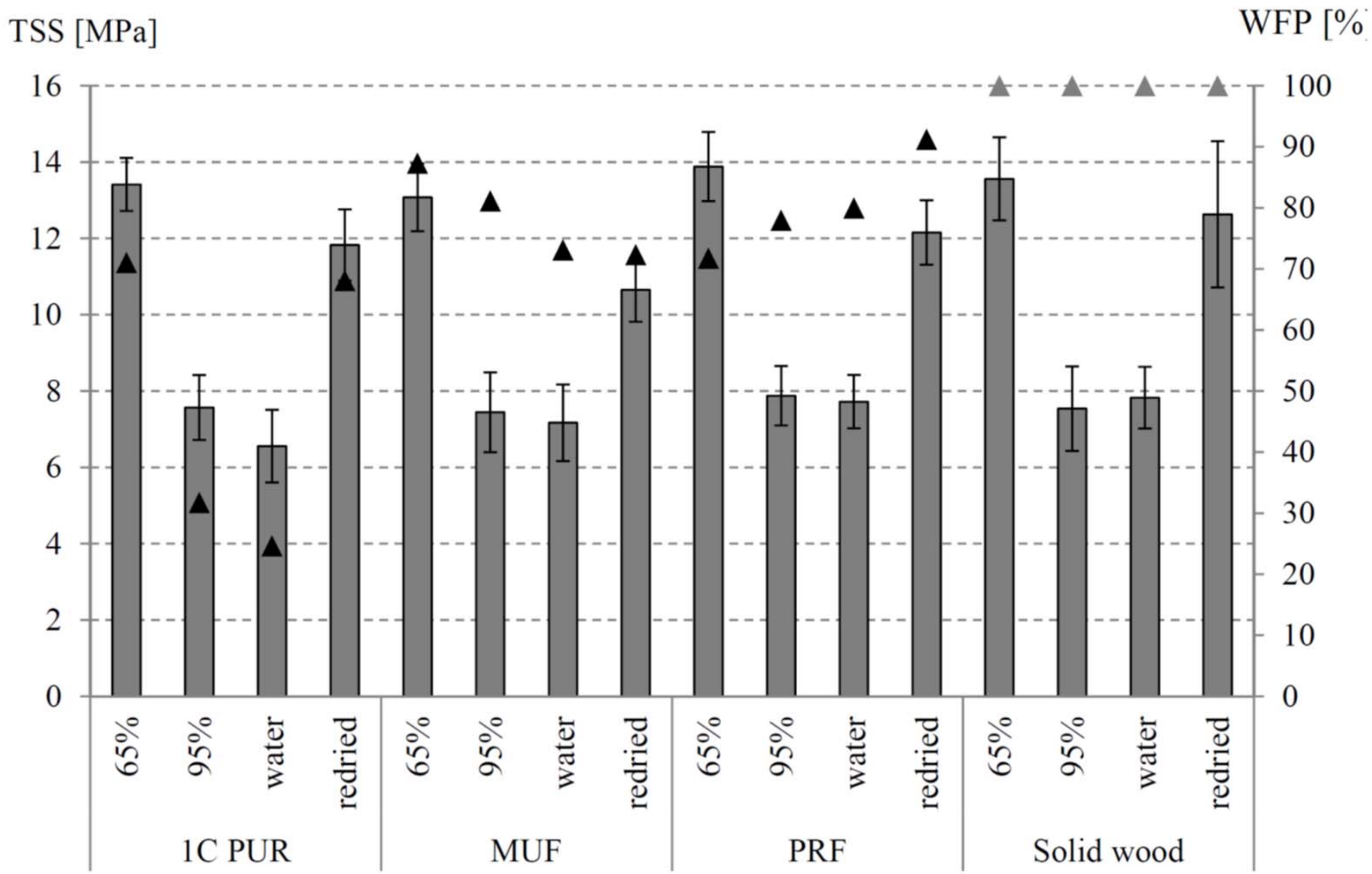
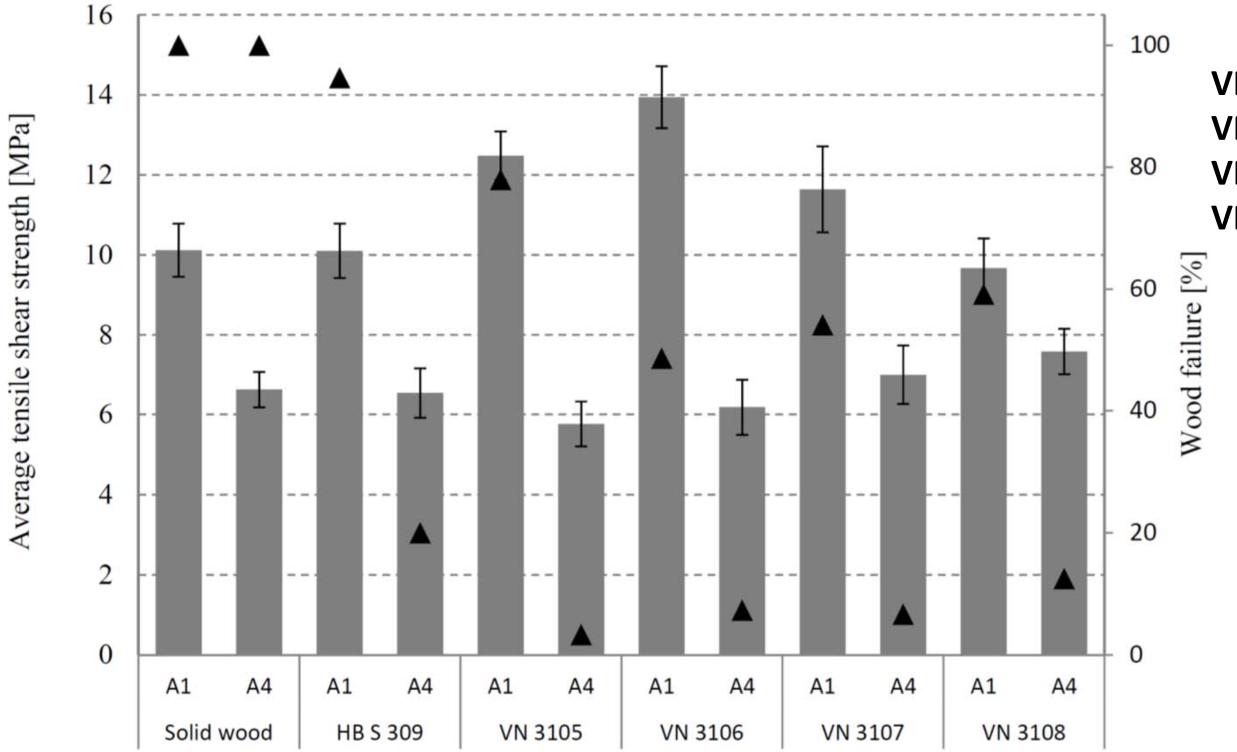
Beech wood: tensile shear strength for different adhesives and RH (O. Kläusler 2014)



Beech wood

HBS 309 and different fillers (chalk) and pMDI (O. Kläusler 2014)
influence from Prepolymer (filler content 10-30%, filler chalk)

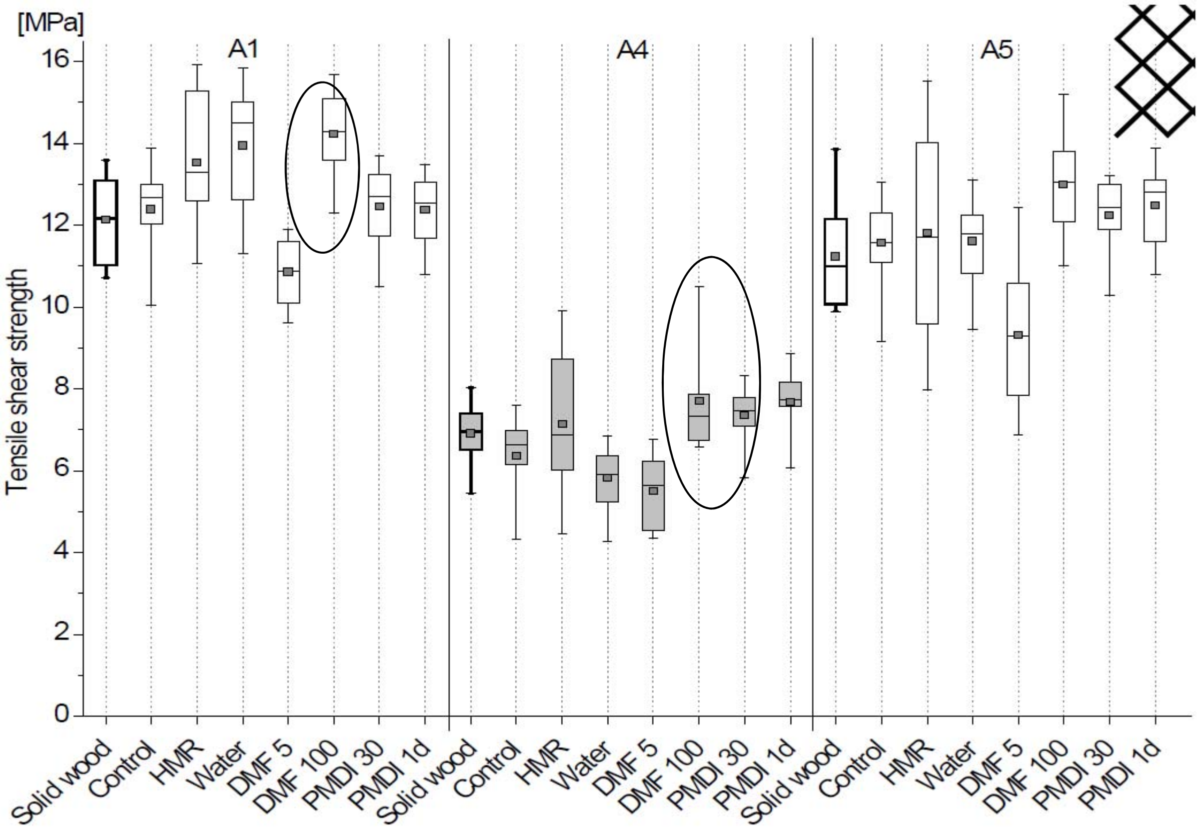


VN3105:5% chalk
VN 3107:10% chalk
VN 3107: Isocyanat lower mol. pMDI
VN 3108: more hydrophilic pMDI

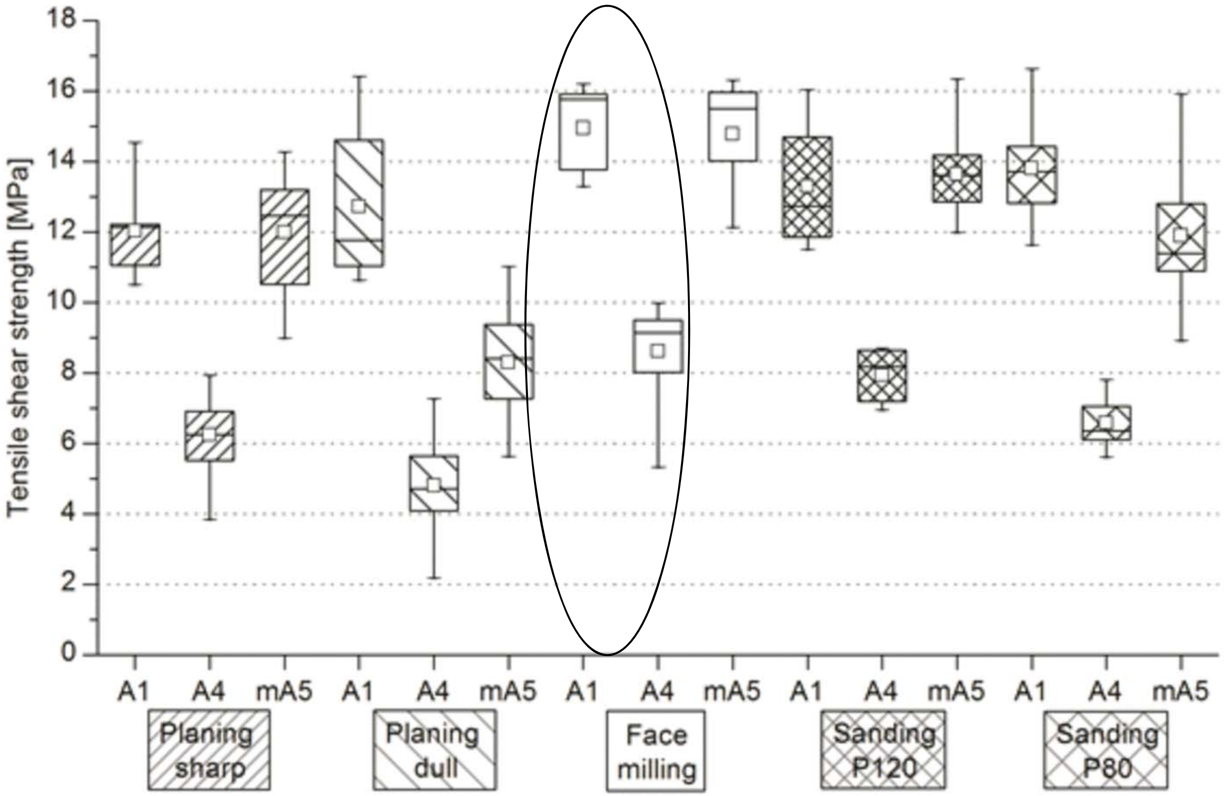
Influence from priming (water, DMF, PMDI) for 1C-PUR and beech wood

(O. Kläusler 2014) DMF: good results

Buche + HB S 309 + Primer

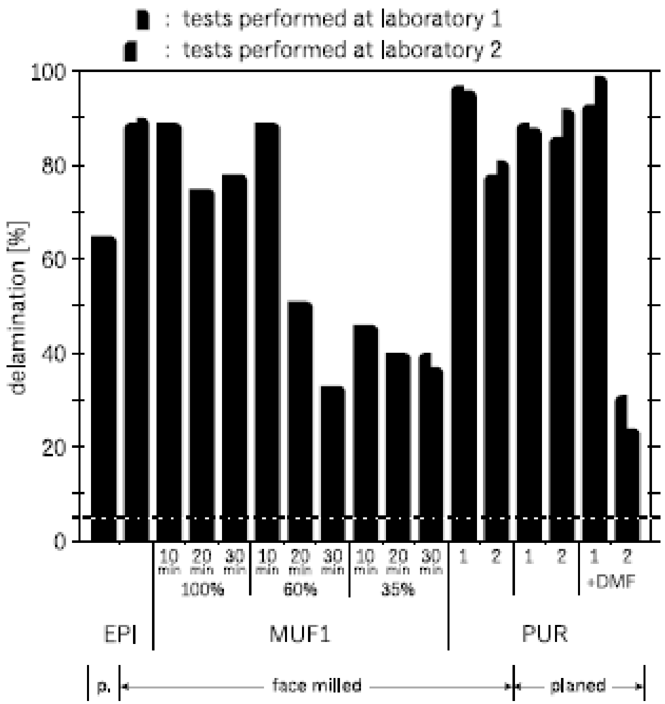


Influence from surface elaboration on gluing properties for 1C-PUR (O. Kläusler 2014)

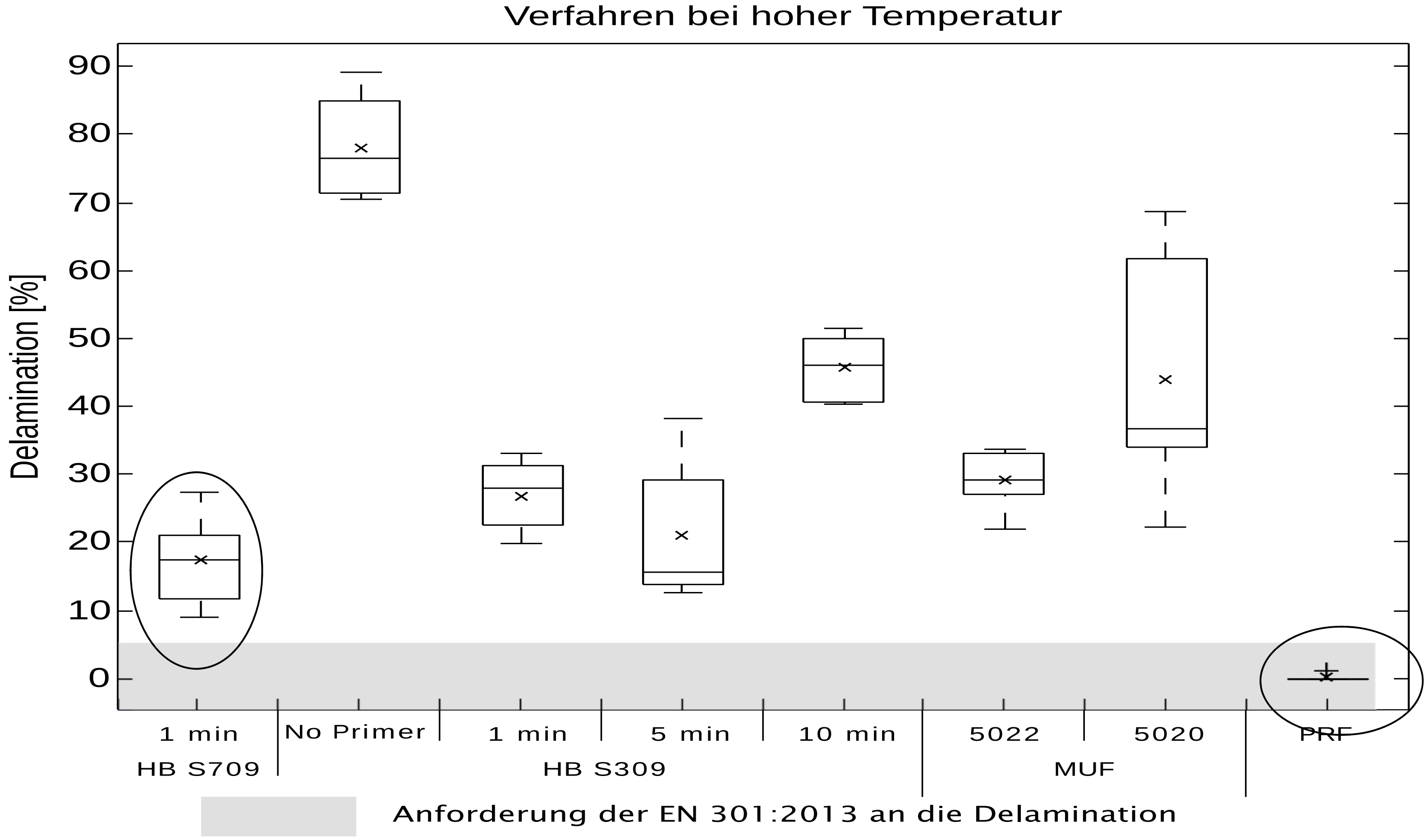


Delamination EN302-2 of ash wood, serie 1 **(gluing under industrial conditions), Ammann 2015, (SNF project ETH)**

different adhesives (MUF adhesive /hardener=MR 100,60,35% Härter), PUR producer 1 priming with DMF (Ammann et al. 2016)

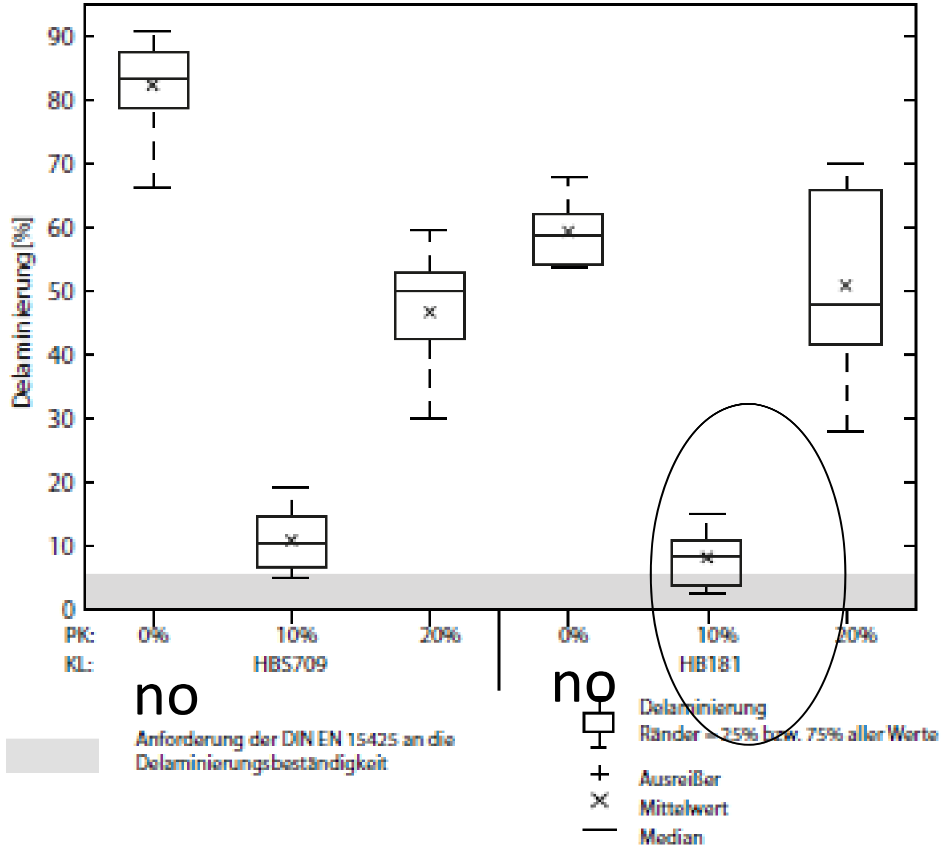


Delamination of ash serie 2, PUR producer 2, priming for PUR PUR with low reactivity (pressing time 12h)

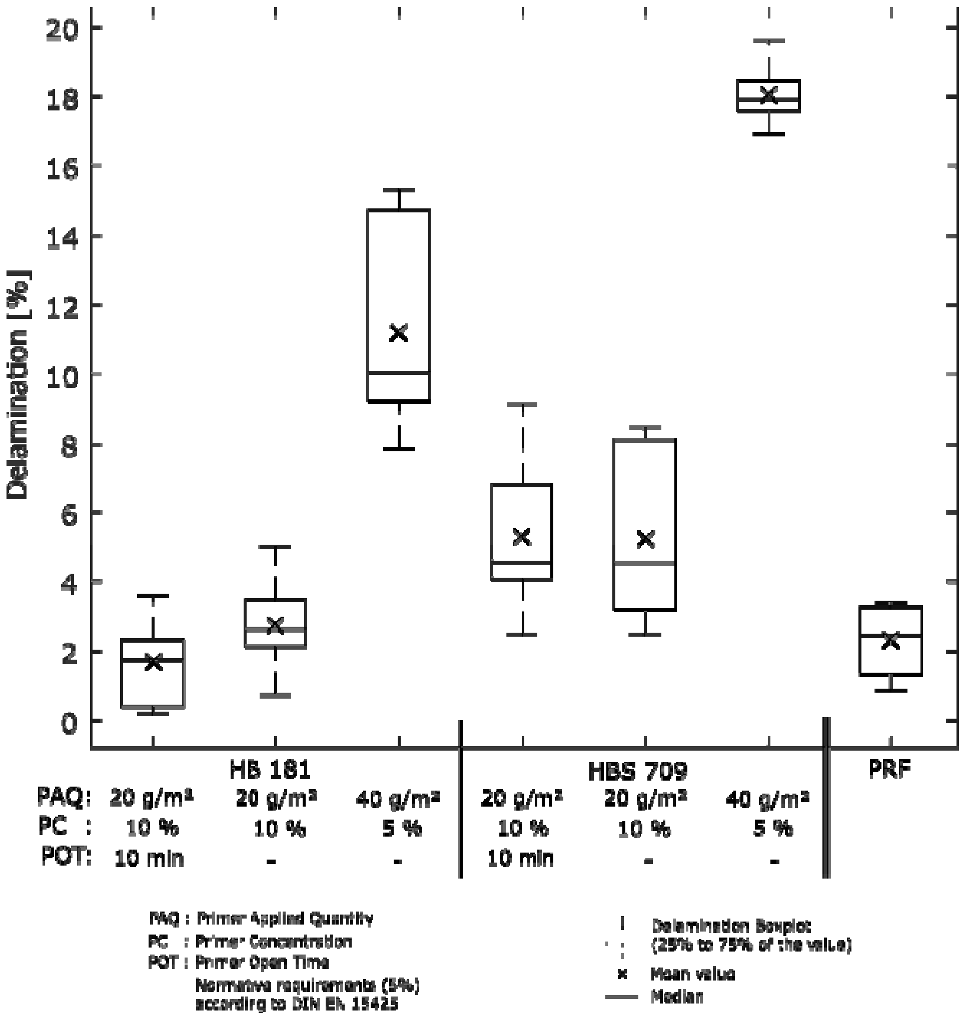


Delamination ash, serie 3

PUR product 3 and 4 and Primer PR 3105, primer concentration



Delamination EN 302-2 of ash wood, serie 5



5. Conclusions

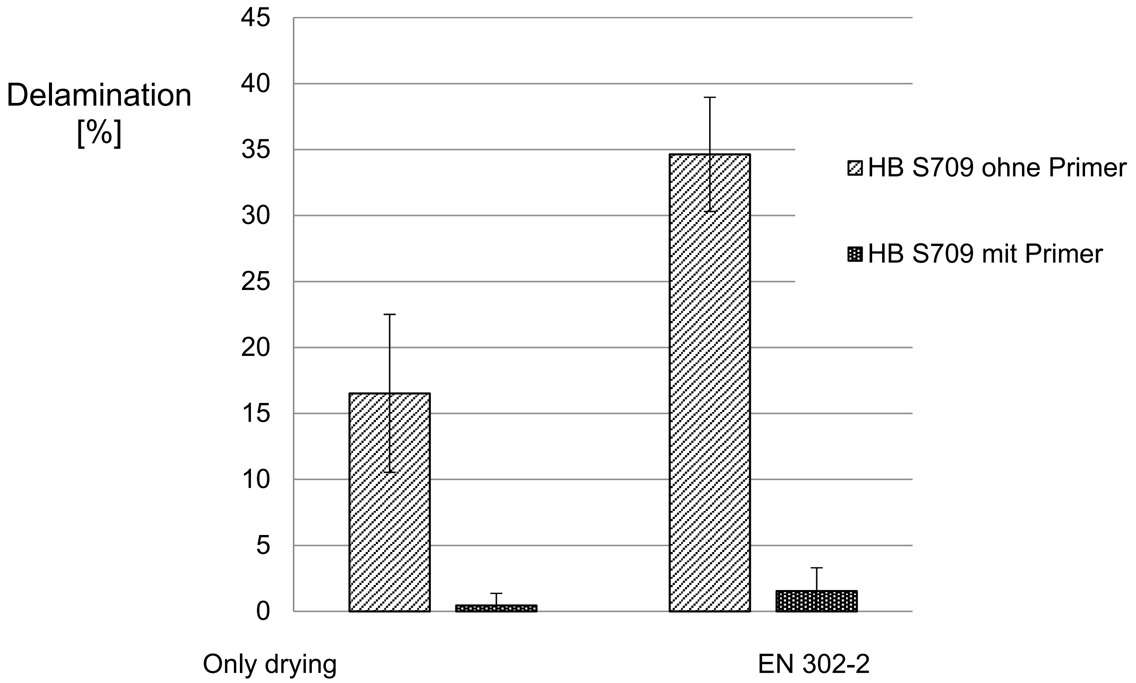
- Special adhesives (MF, PRF, MUF, PUR with primer) needed for hardwood gluing and also for some softwoods
- Adaption from technology (planing, lamella thickness reduced for beech, moisture content, quality control) for hardwood needed
- Sometimes grading from lamellas used (density, MOE, low difference between lamellas)
- Costs mostly higher for hardwood in relation to softwood (3-4 times), often also optical reasons for only important for using hardwood
- A lot of open scientific questions open (priming, why difference between adhesives etc.)
- A lot of experiance needed !!

Selected furthure works (outlook, ideas)

- Improving adhesion from 1C- PUR under wet conditions
- Internal adhesion promotors e.g. for 1C-PUR, priming
- Fracture mechanical works for glued wood (first works: Serrano (2001), Ammann (2015), Clerc (2020)
- Studies about aging process from bondlines
- Improve models for calculation from the delamination
- Improve test methods for glued wood and delamination (NDT)
- Use machine learning for gluing optimization (big factories)
- Bio based adhesives needed

Different methods for delamination tests?

(Rugenstein TU Dresden/BFH Biel 2017)
beech wood: only drying, no wetting, better than EN302-2??,
more practical oriented



HBS 709 without priming

HBS 709 with priming

Drying: 65°C/12.5%RH   Delamination test: EN302.2
(chamber: test EN302.2)

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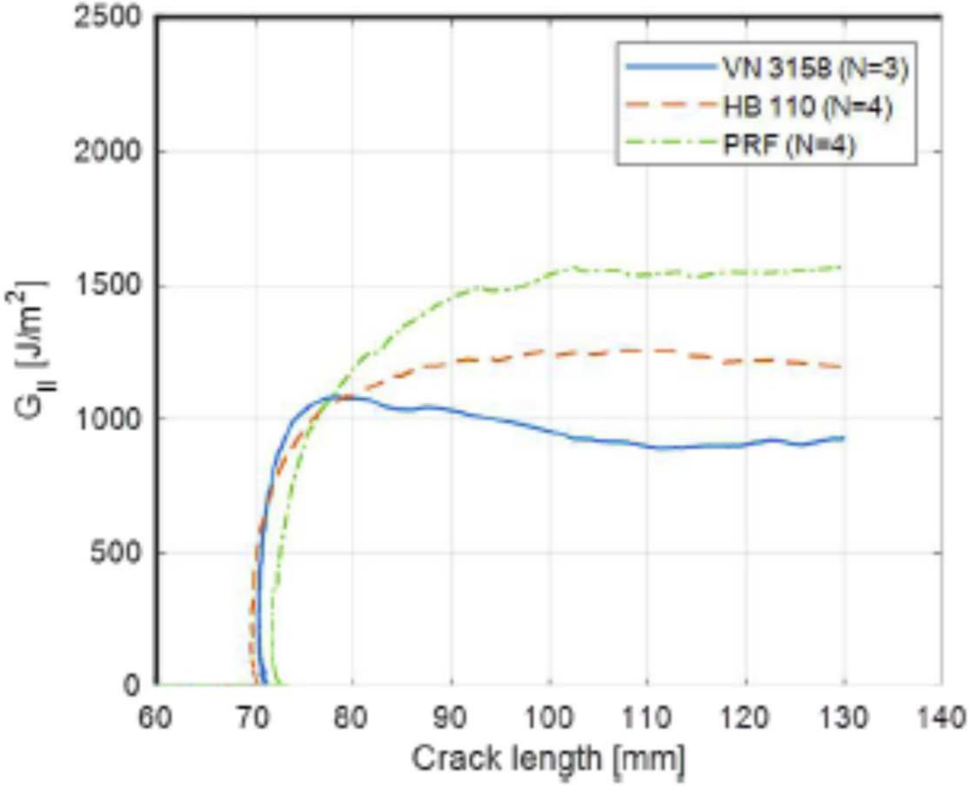
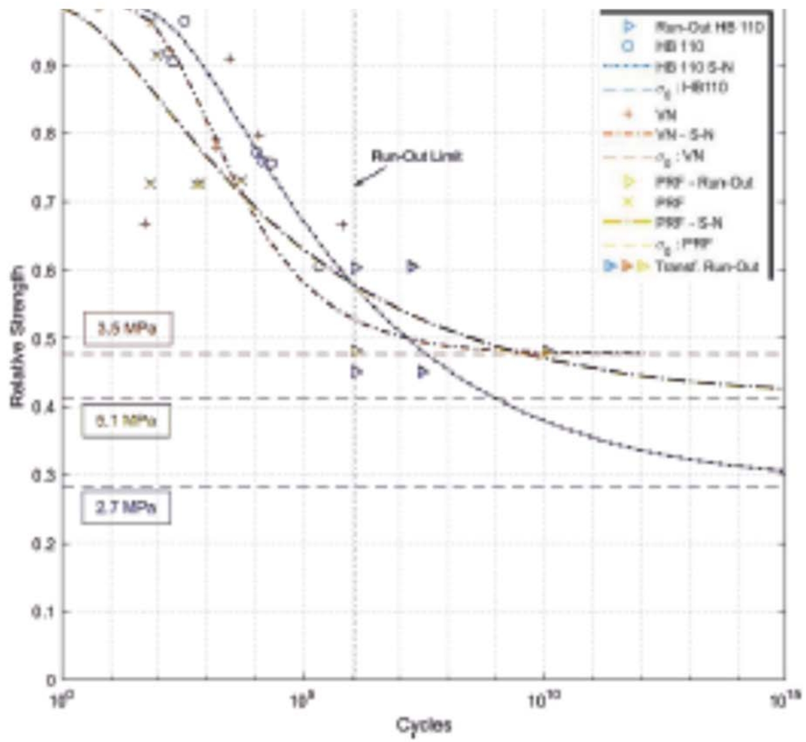
Fracture energy for different adhesives

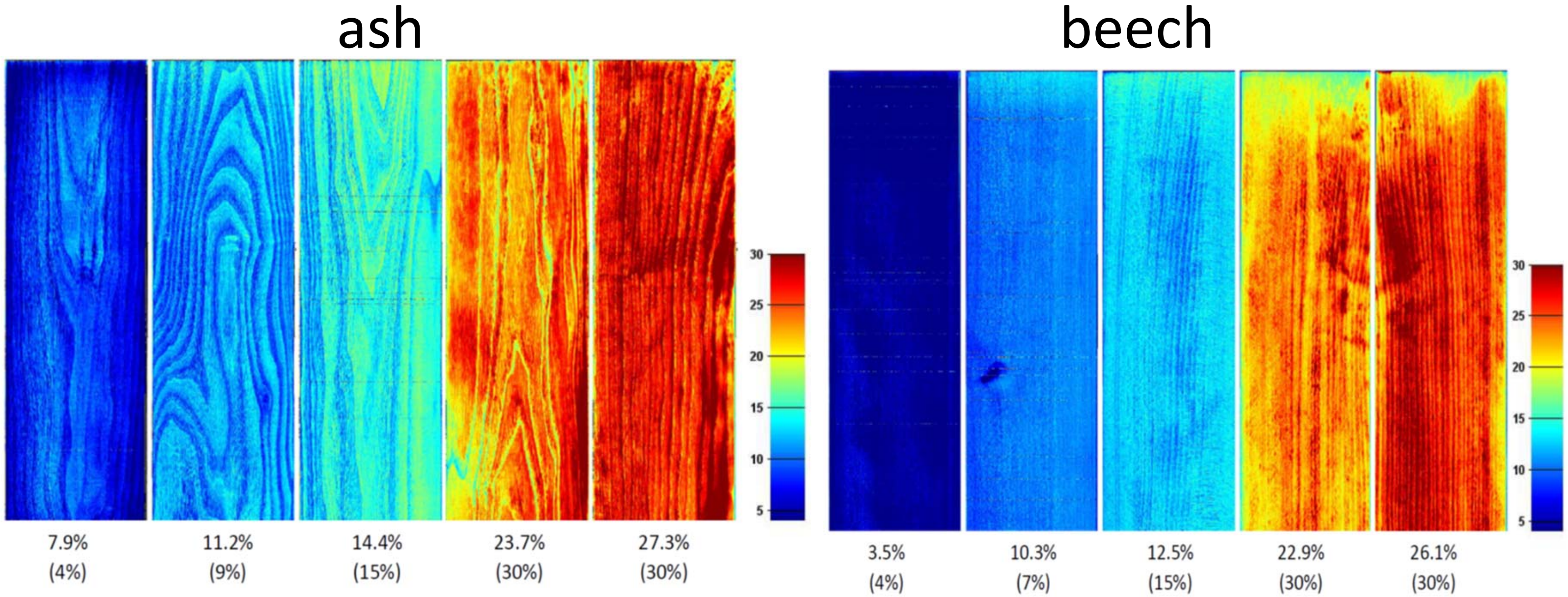
G. Clerc, BFH 2020





Hyperspectral Imaging NIR

distribution from MC at the surface from lamellas (J. Sandak, P. Niemz et al. 2021)



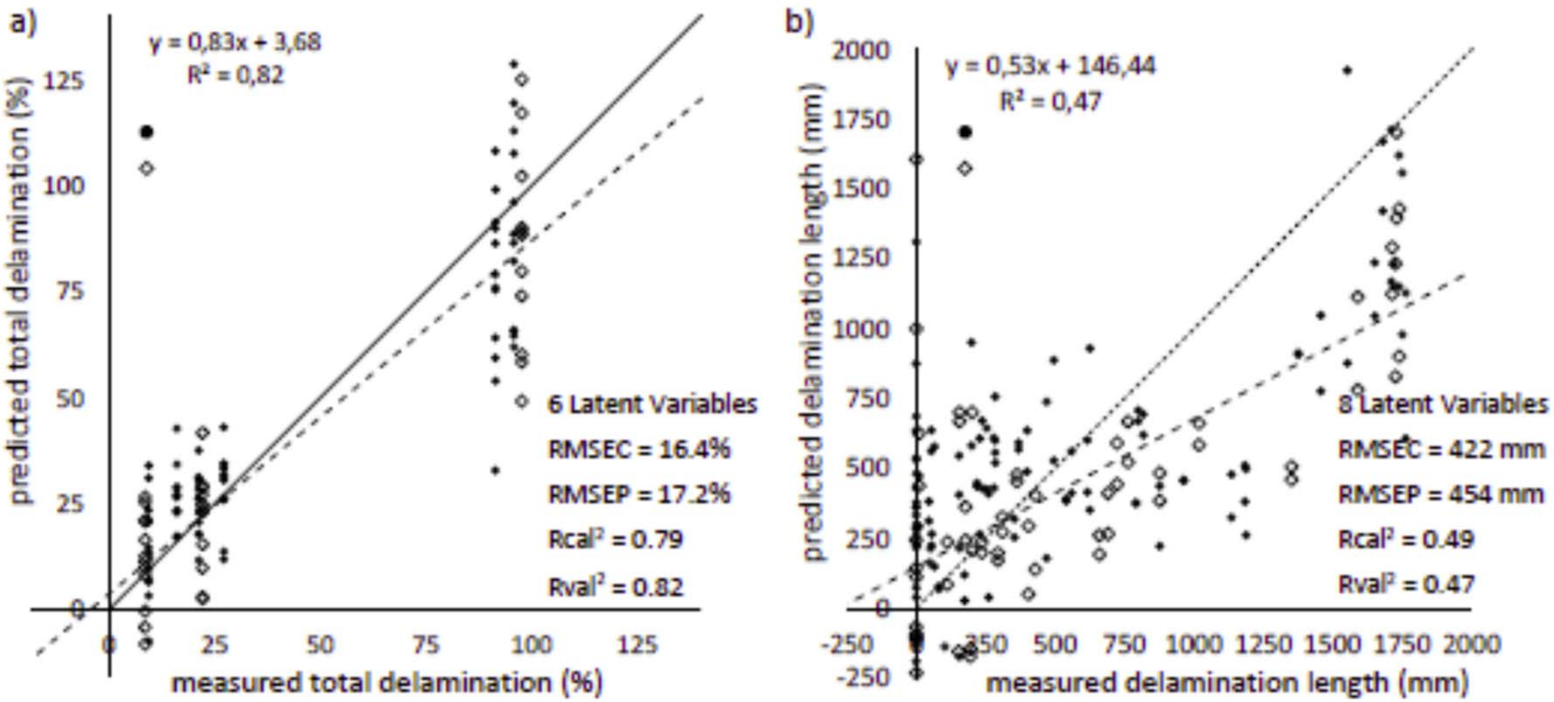
Distribution of moisture content at the surface of wooden

MicroNIR OnSite-sensor

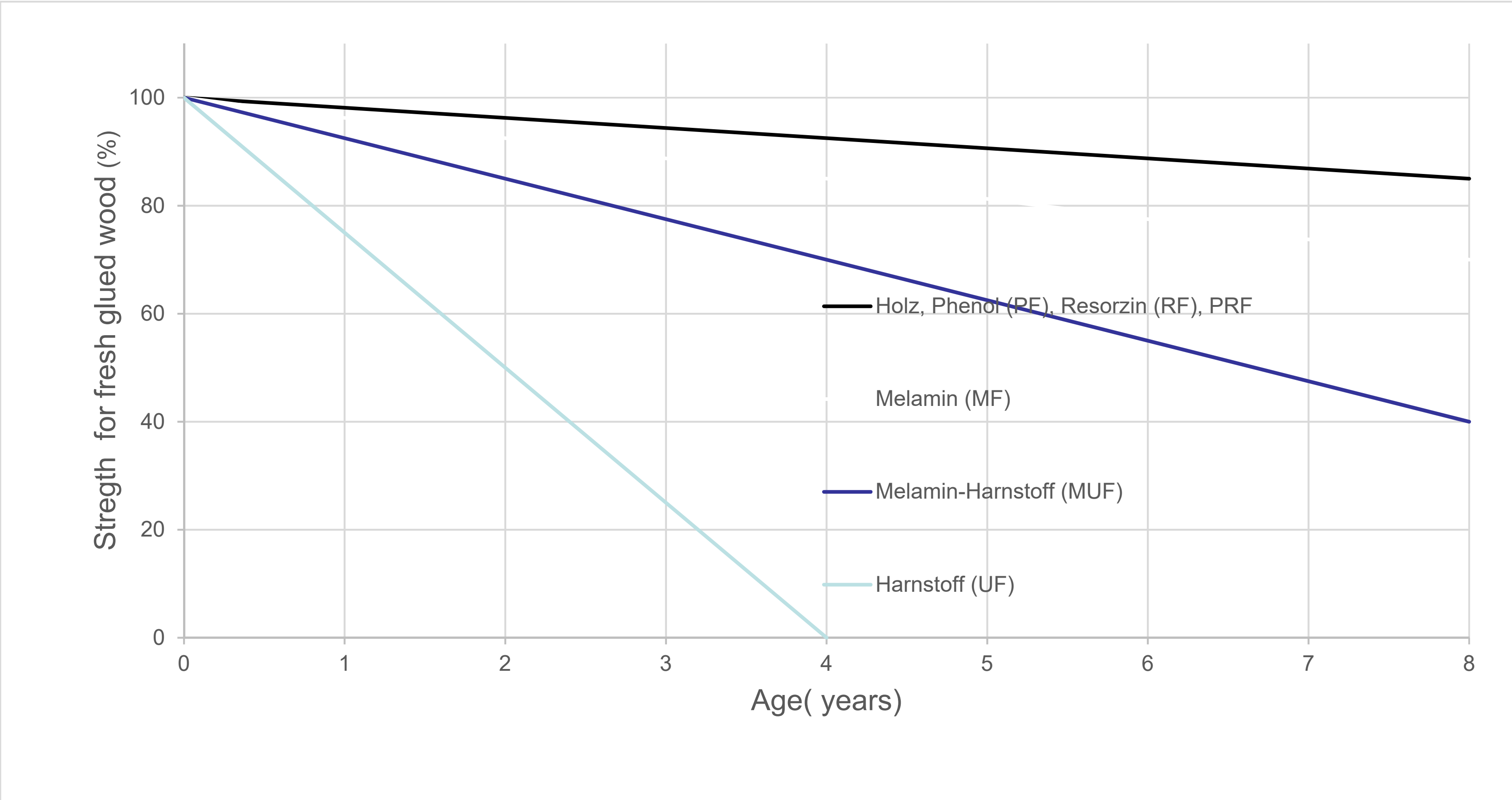
Delamination

tested and predicted delamination EN302-1

(J. Sandak et al. 2021 «Construction and Building Materials» 2021)



Aging from bond lines (Wood Handbook 2010), (no works for 1C-PUR!!!)



Thank you very much

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