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Finite element modelling of interfacial stresses of asymmetrical laminated wood products subjected to moisture changes

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UNB

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Outline

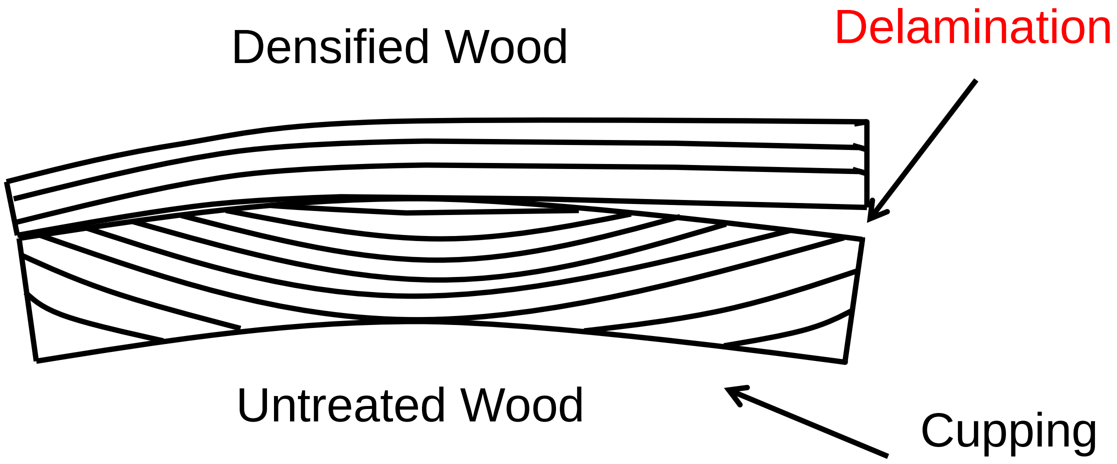
- ❑ Introduction
- ❑ Problem statement
- ❑ Objective
- ❑ Materials and methods
- ❑ Results and discussion
- ❑ Conclusions
- ❑ Acknowledgements

Introduction

- Market need for high quality wood that becomes less and less;
- Availability of softwood in Canada, but most of them are underutilized, such as balsam fir, due to low density and poor mechanical properties;
- Thermo-mechanical densification technology, making densified wood with superior mechanical properties;
- A two-layer laminated wood product made of densified wood (surface layer) and untreated wood (substrate), being used as flooring products.

Problem statement

- ❑ Quality issues of this wood product with an asymmetrical structure subjected to moisture change:
  - Dimensional change
  - Delamination due to interfacial stresses

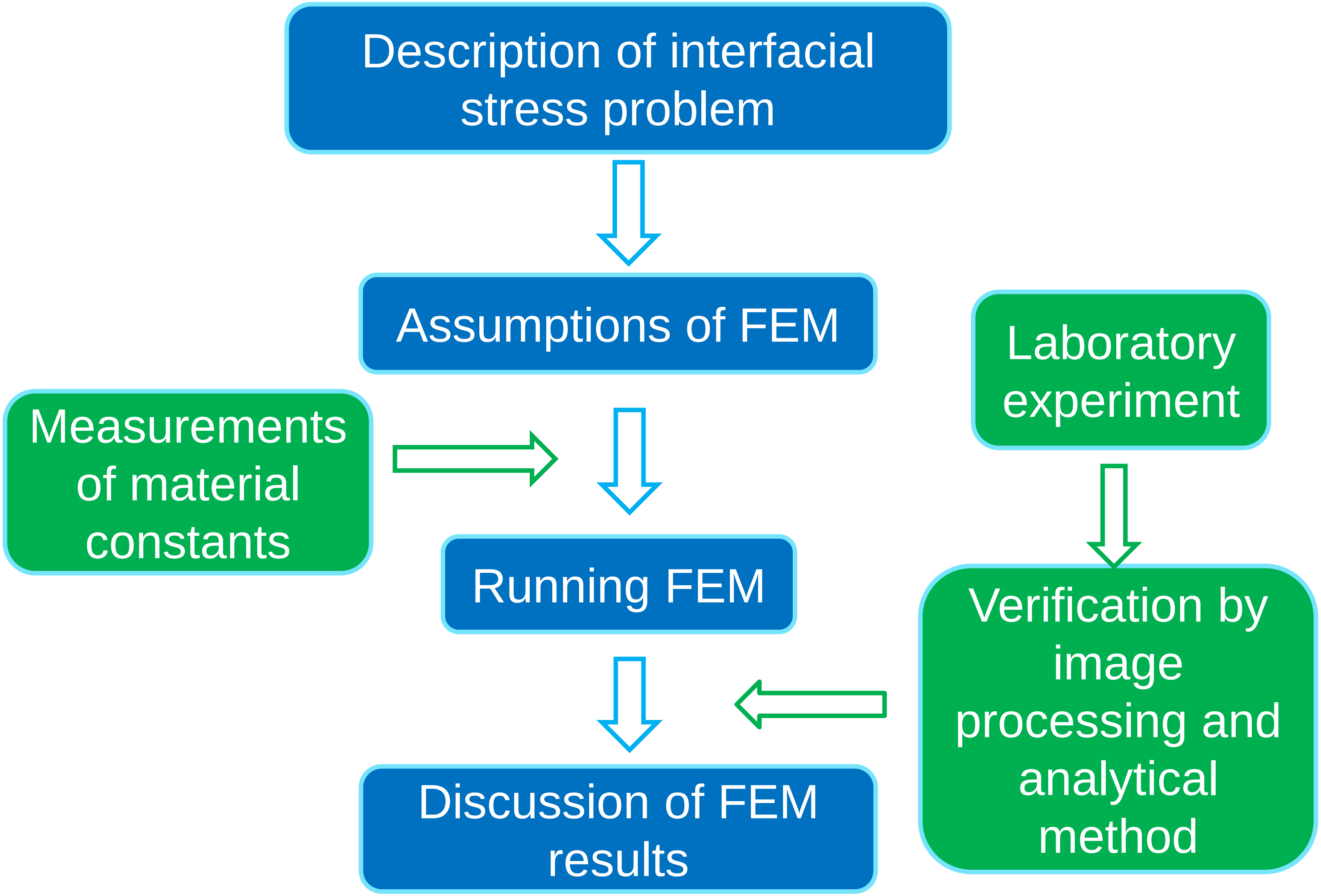


Objective

- The aims of this study are to develop a finite element model (FEM) to predict the interfacial stresses caused by the moisture changes and to study the influence of thickness ratio of densified wood and untreated wood on the magnitude of interfacial stresses.

Why is FEM?

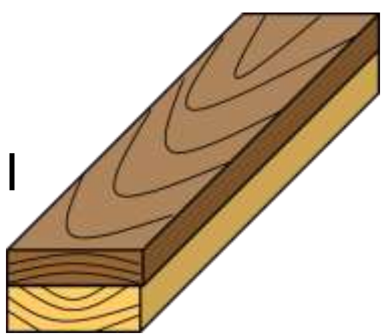
FEM method vs. Analytical method		
Problems	FEM method	Analytical method
Transit moisture gradient inside wood	✓	
State moisture gradient inside wood	✓	✓
Difference in moisture changes between densified and untreated wood	✓	
Division of complicated interfacial adhesive layer	✓	
Avoidance of singularity of interfacial normal stress at the edge of a beam		✓

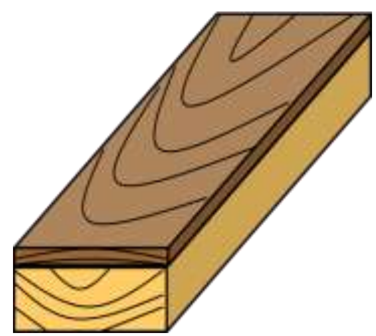

Description of interfacial stress problem
Assumptions of FEM
Laboratory experiment
Measurements of material constants
Running FEM
Verification by image processing and analytical method
Discussion of FEM results

❑ Design of specimens made of densified and untreated wood

Type	Components	Thickness (mm)	Total thickness (mm)	Width (mm)	Length (mm)
Type I	DW	7	19	50	280
	UW	12			
Type II	DW	3	19	50	280
	UW	16			
Note: DW= Densified wood; UW= Untreated wood					

Type I

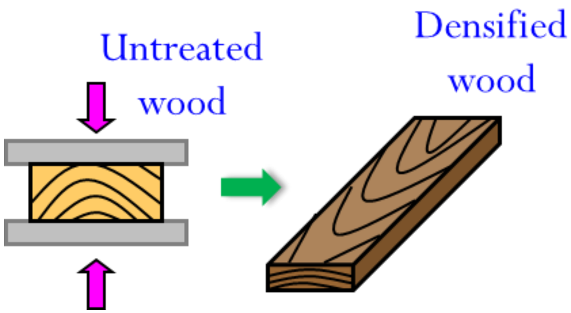




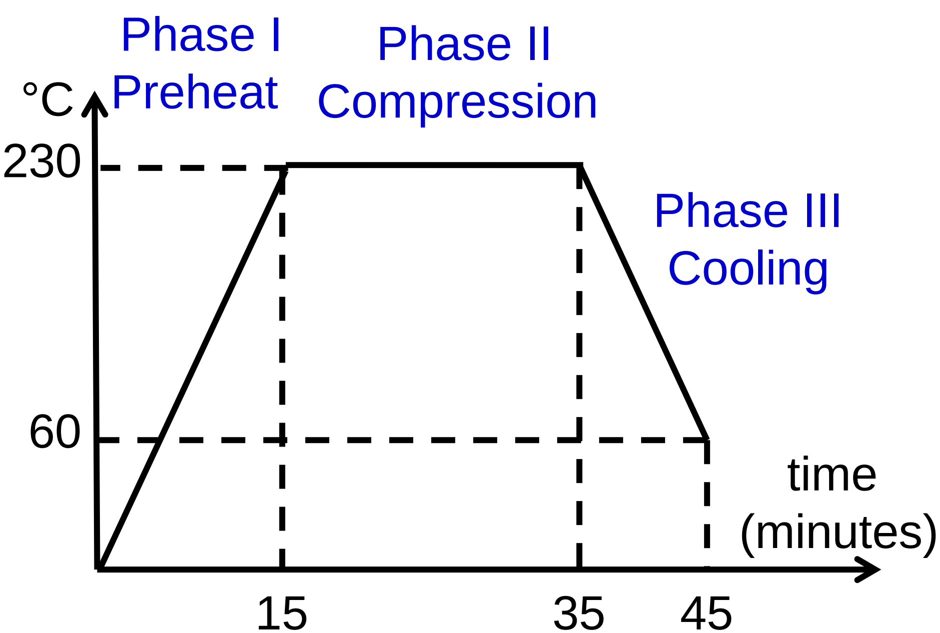
Type II

- Polyurethane (PUR) adhesive

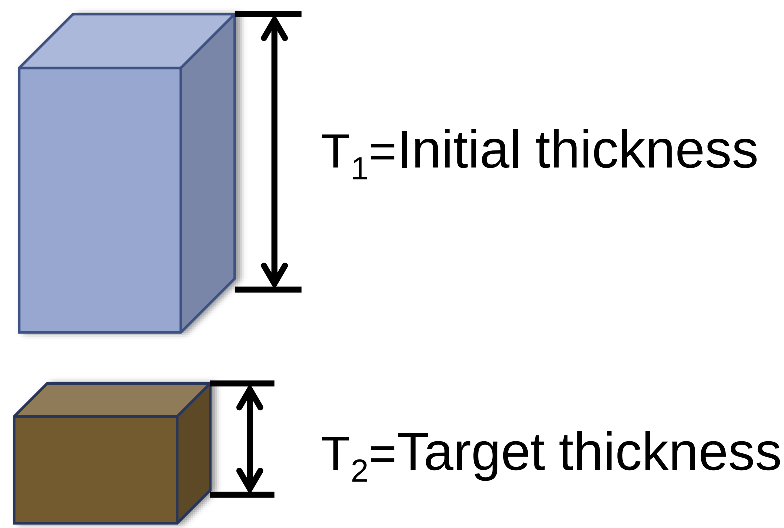
Materials and methods-Wood densification



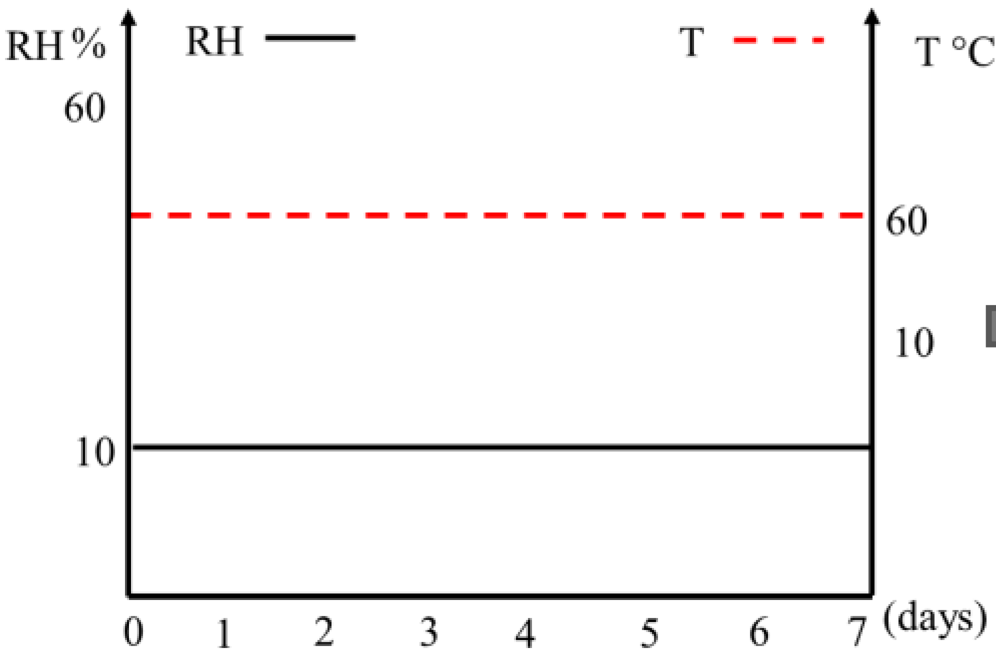
- Balsam fir (*Abies balsamea (L.)* Mill.)
- Density: 350kg/m^3- 400kg/m^3
- Moisture content: about 12%
- Compression ratio (CR) of 60% (Radial)
- CR (%) = $(T_1-T_2) / T_1 \times 100$



Parameters of densification

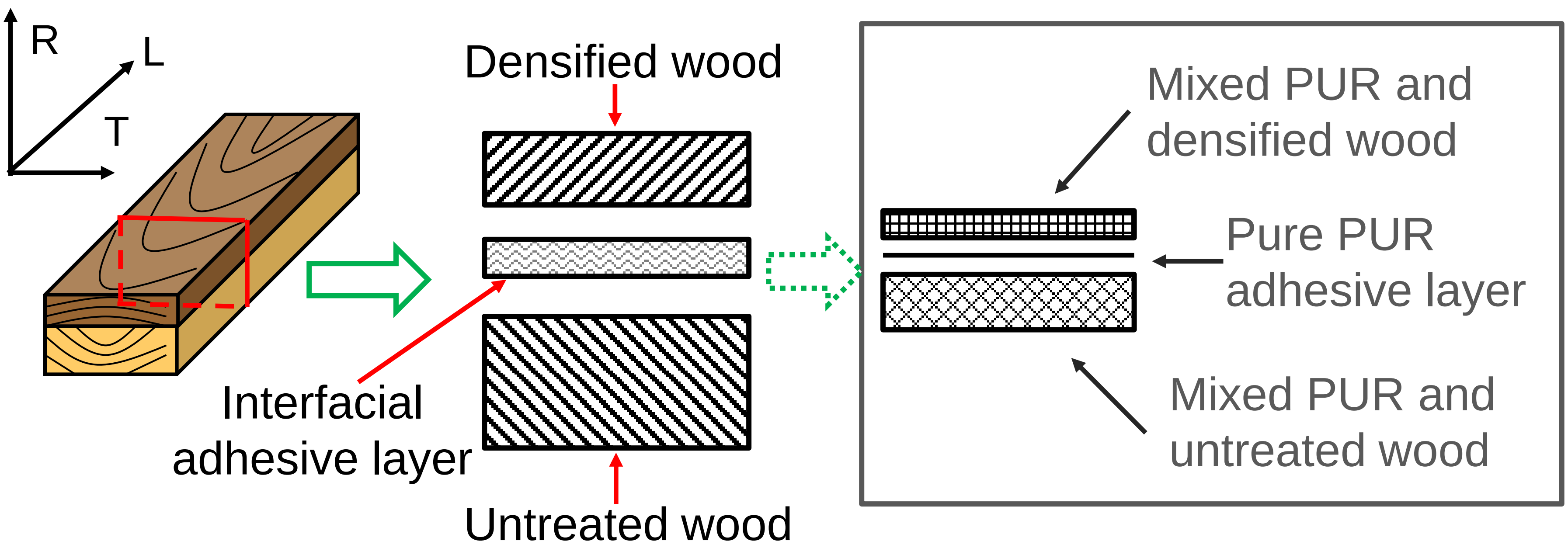


- Laboratory experiment
  - Before experiment, all specimens were stored in a conditioning chamber with 60±5% relative humidity (RH) and 20±2°C temperature (T) until their moisture content came to a stable state.
  - Testing schedule of RH and T in a conditioning chamber in laboratory experiment.



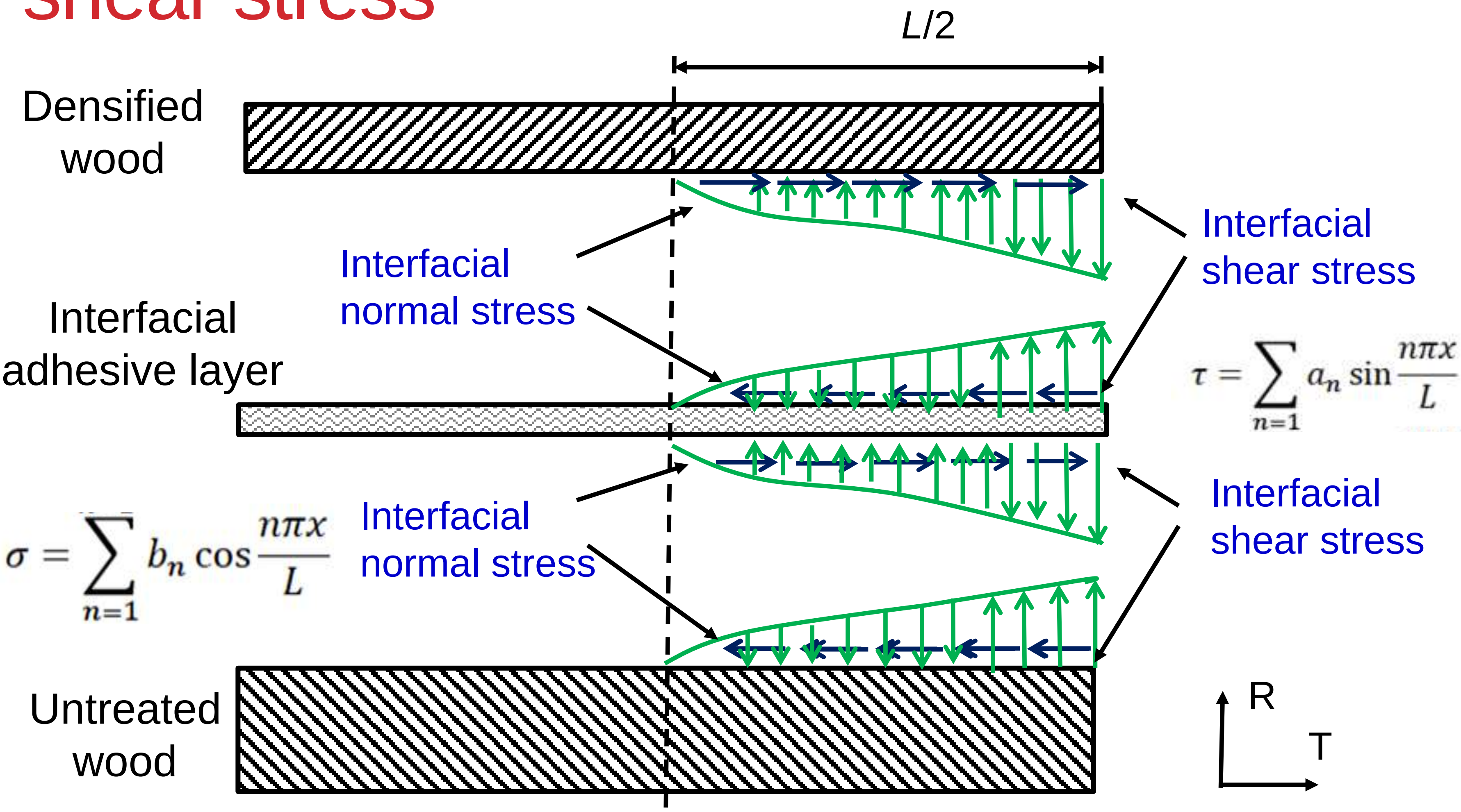
- Moisture content changes:
  - Densified wood: 6% to 2%
  - Untreated wood: 12% to 5%

Simplification of a real case



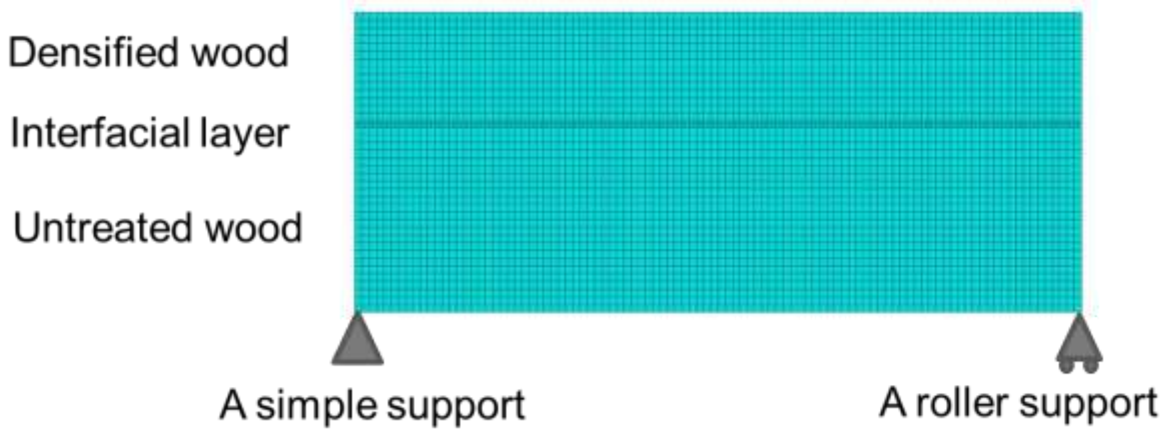
- A two dimensional plane in the cross-section (RT plane) of this two-layer laminated wood product at macro level.
- Interfacial stresses only caused by the moisture gradient.
- Neglect of effect of the curvatures of anural rings on mechanical properties of untreated wood.

Distributions of interfacial normal and shear stress



(Chang 1990)

Assumptions in a 2-D FEM



- Element types:
  1) Modified thermal analysis element for transit moisture gradient analysis;
  2) Plain strain element for mechanical analysis.
- Sequent analyses:
  1) Transit moisture gradient;
  2) Hydro-mechanically interfacial stresses.

Step 1:Transit moisture diffusion equations in FEM

$$\frac{d_b}{100}\frac{\partial M}{\partial t} - \left\{ \frac{\partial}{\partial x_1} \; \frac{\partial}{\partial x_2} \; \frac{\partial}{\partial x_3} \right\} \left[\begin{pmatrix} K_{M11} & 0 & 0 \\ 0 & K_{M22} & 0 \\ 0 & 0 & K_{M33} \end{pmatrix} \begin{Bmatrix} \frac{\partial M}{\partial x_1} \\ \frac{\partial M}{\partial x_2} \\ \frac{\partial M}{\partial x_3} \end{Bmatrix} \right] = 0$$

with

$$K_{Mii} = \frac{D_{ii}\, d_b}{100}$$

1) Moisture diffusion part

Step 2: Linear elastic stress-strain equations in FEM

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{Bmatrix} = \begin{bmatrix} \frac{1-\nu_{23}\nu_{32}}{E_2E_3S} & \frac{\nu_{21}+\nu_{23}\nu_{31}}{E_2E_3S} & \frac{\nu_{31}+\nu_{21}\nu_{32}}{E_2E_3S} & 0 & 0 & 0 \\ \frac{\nu_{21}+\nu_{23}\nu_{31}}{E_2E_3S} & \frac{1-\nu_{31}\nu_{13}}{E_1E_3S} & \frac{\nu_{23}+\nu_{21}\nu_{13}}{E_1E_3S} & 0 & 0 & 0 \\ \frac{\nu_{31}+\nu_{21}\nu_{32}}{E_2E_3S} & \frac{\nu_{23}+\nu_{21}\nu_{13}}{E_1E_3S} & \frac{1-\nu_{21}\nu_{12}}{E_1E_2S} & 0 & 0 & 0 \\ 0 & 0 & 0 & G_{23} & 0 & 0 \\ 0 & 0 & 0 & 0 & G_{13} & 0 \\ 0 & 0 & 0 & 0 & 0 & G_{12} \end{bmatrix} \left(\begin{Bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{Bmatrix} - \begin{Bmatrix} \beta_1 \Delta M \\ \beta_2 \Delta M \\ \beta_3 \Delta M \\ 0 \\ 0 \\ 0 \end{Bmatrix} \right)$$

$$S = \frac{1}{E_1E_2E_3}(1 - 2\nu_{21}\nu_{32}\nu_{13} - \nu_{13}\nu_{31} - \nu_{23}\nu_{32} - \nu_{12}\nu_{21}) \quad (3$$

2) Mechanical part

(Blanchet et al. 2005)

Material parameters used in FEM model

- Physical properties

Parameter		Densified wood [a]	Untreated wood [b]	PUR adhesive [c]
Moisture diffusion coefficient D_i (m^2s^{-1})	D_L	1.3×10^{-8} - 10^{-10}	1.3×10^{-8} - 10^{-10}	1.0×10^{-14}
	D_R	4×10^{-8} - 10^{-11}	4×10^{-8} - 10^{-11}	
	D_T	4×10^{-8} - 10^{-11}	4×10^{-8} - 10^{-11}	
Convective mass transfer coefficient h ($kgm^{-2}s^{-1}\%^{-1}$)		3.2×10^{-4}	3.2×10^{-4}	3.2×10^{-4}
Shrinkage coefficient β	β_L	0.018	0.015	0.001
	β_T	0.18	0.45	
	β_R	0.09	0.19	

Note: a: estimated data; b: Blanchet et al. 2005; c: Blumer, 2006; Deteix et al. 2008; Mendicino, 2010

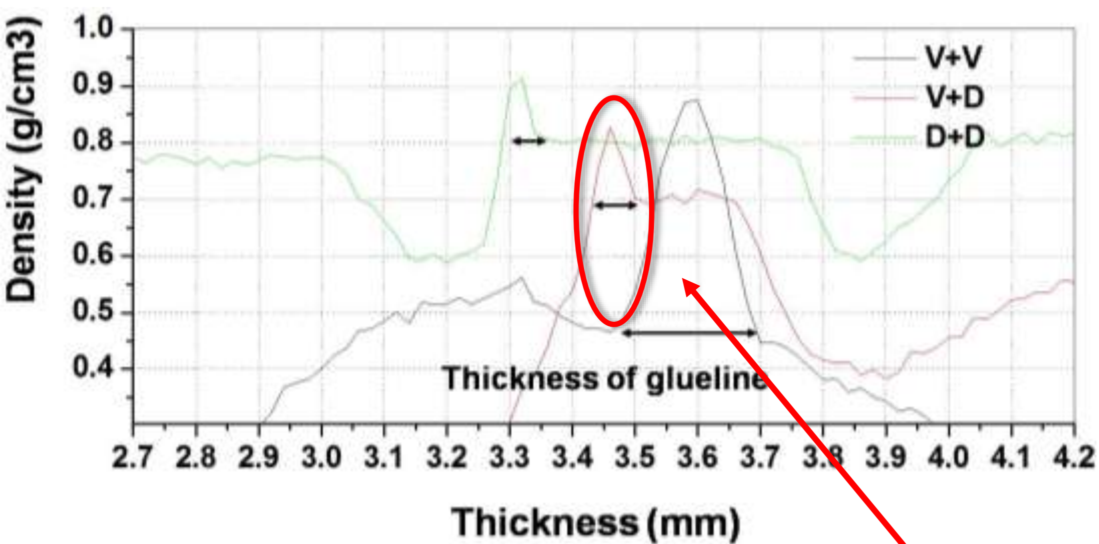
Mechanical properties

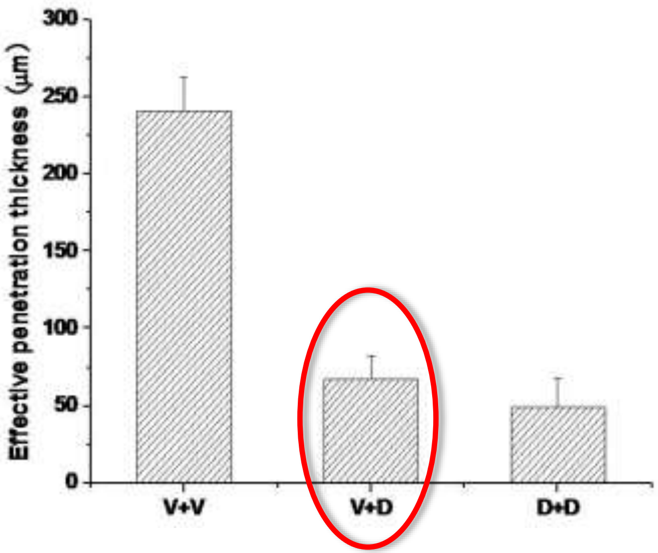
Parameter		Densified wood [a]	Untreated wood [b]	PUR adhesive [c]
E (MPa)	E_L	21000	13000	480
	E_R	1300	500	
	E_T	2000	200	
μ	μ_{TR}	0.42	0.36	0.03
	μ_{TL}	0.025	0.018	
	μ_{RL}	0.014	0.035	
G (MPa)	G_{TR}	500	350	/
	G_{TL}	750	700	
	G_{RL}	800	900	

Note: a: Kitamori et al. 2008; b: Wood Handbook; c: Scheffler et al. 2007

Thickness of an interfacial layer

- The thickness of PUR adhesive layer between densified wood and untreated wood was about 80±20μm (mean and standard deviation), which was measured via X-ray density scanner.

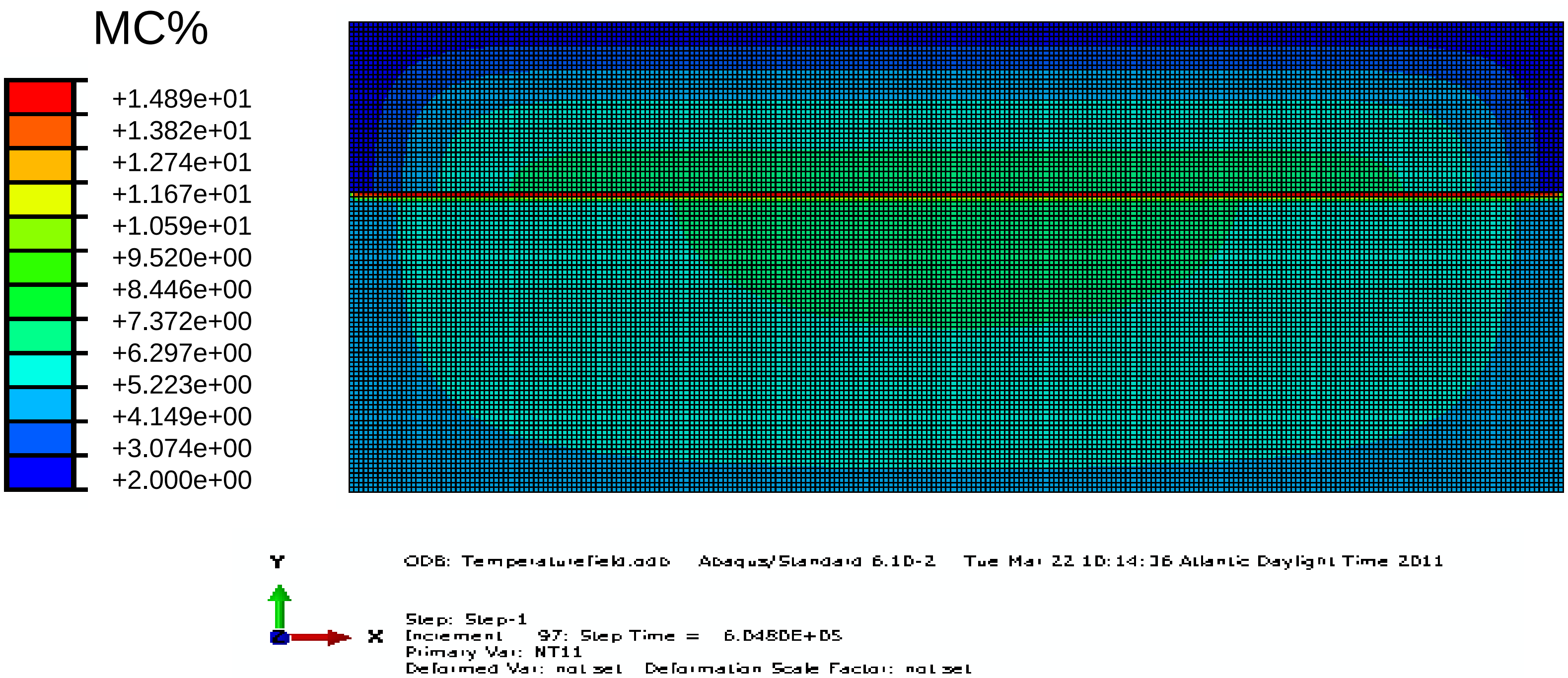




Interfacial thickness of densified wood and untreated wood

Results and discussion

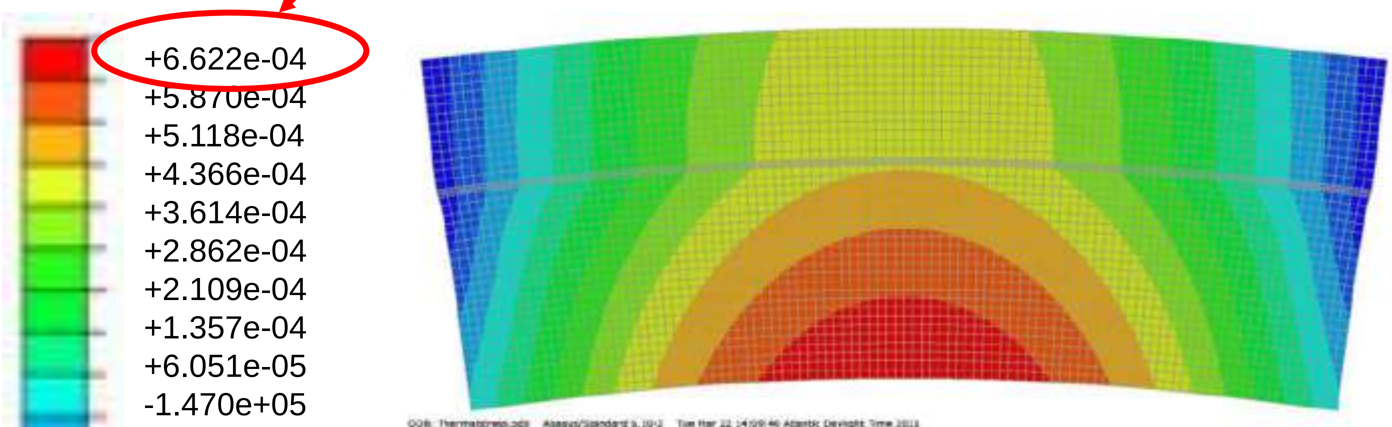
(ABAQUS software)



- ❑ Distribution of moisture gradient after 7 days (Type I as an example)

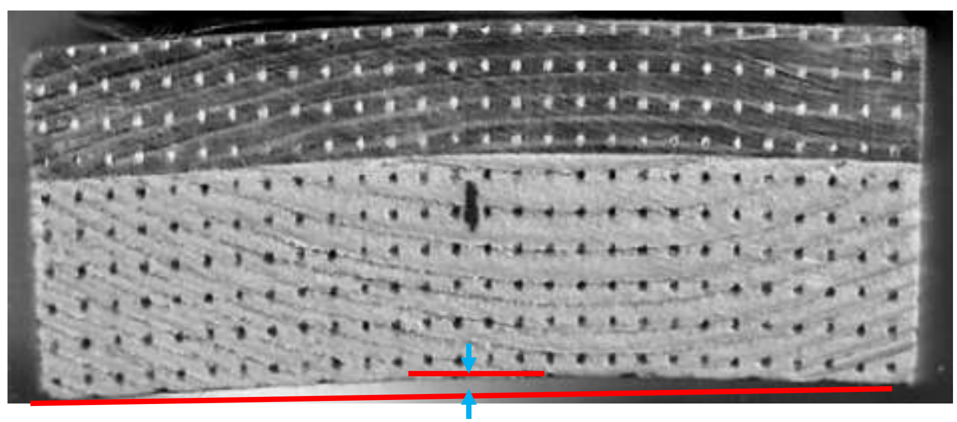
Verification of FEM model by comparing the deformation of FEM result with image analysis

0.622 mm Error= **20%**

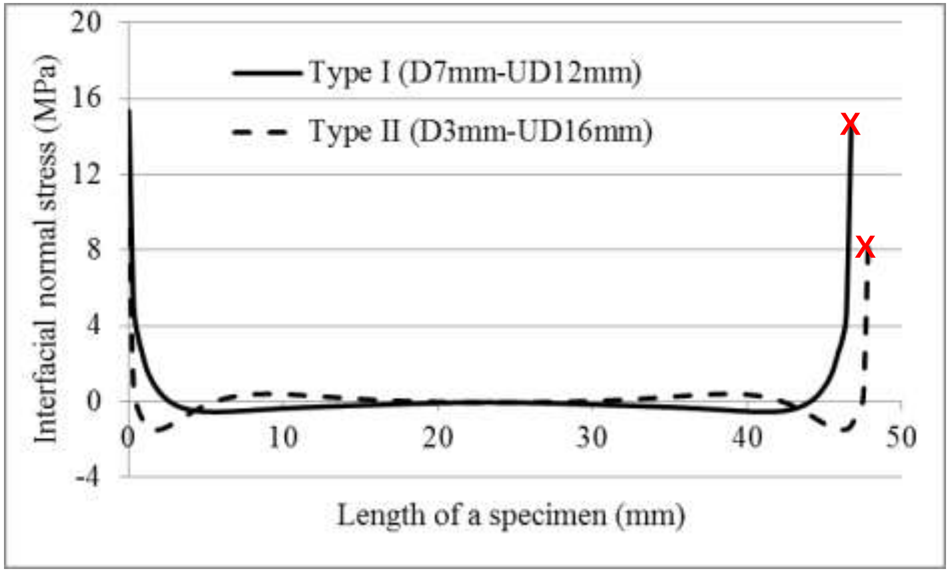


Vertical direction
Unit: m

(Type I as an example)

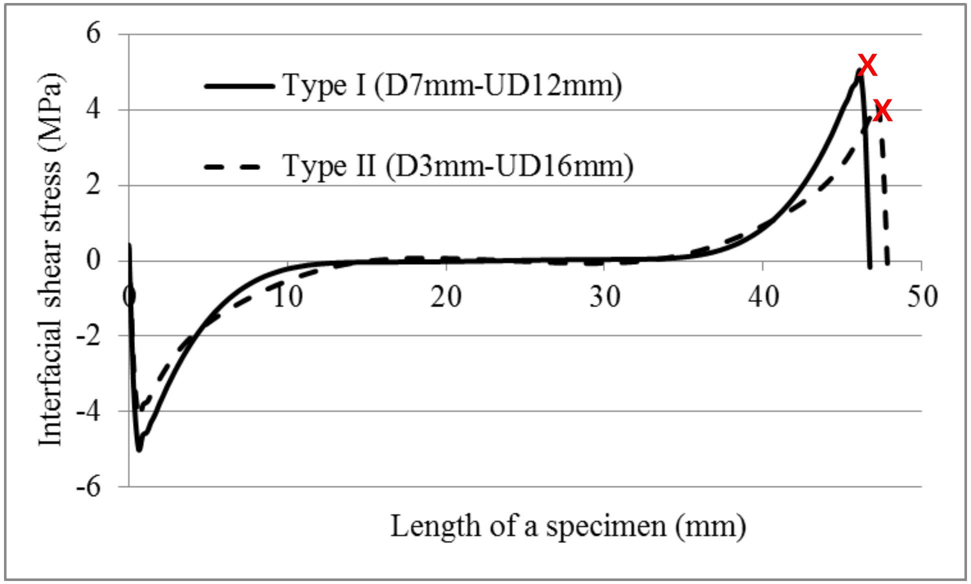


0.52mm



Maximum interfacial normal stress:
Type I = 15.37 MPa
Type II = 9.01 Mpa
The interfacial normal stress of type II is about **40%** lower than that of type I.

Maximum interfacial shear stress:
Type I = 5.02 MPa
Type II = 4.16 MPa
The interfacial shear stress of type II is about **16%** lower than that of type I.



Notes: Average interfacial normal and shear stress on the top and bottom surfaces of an interfacial layer.

Limitations in FEM model developed

- Most parameters used in FEM model were estimated or referred to published data;
- No influence of moisture content on the mechanical properties of densified and untreated wood;
- No future divisions of interfacial layer;
- No analysis of the changes of interfacial stresses with changing moisture.

Conclusions

The FEM model developed in this study could predict the moisture gradient distribution with time and the interfacial stresses along the bondline:

- The maximum interfacial normal stress was distributed at the two edges of the bondline and the maximum value in type II (3mm-thick densified wood) were about 40% lower than that in type I (7mm-thick densified wood);
- The maximum interfacial shear stress was very close to the two edges of the bondline and then vanished at the two edges, while the maximum value in type II were about 16% lower than that in type I.

Thanks for your attention !

Any questions

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