博士論文（要約）

Research on hygro-deformation of wood and its digital simulations

（木材の水分変化に伴う横断面の変形とそのシミュレーション）

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My research topic is hygro-deformation of wood and its digital simulations. Wood is a kind of environmental sensitive material and dimensional changes occur along with the variable humidity. The deformation results vary among individuals according to tree species, growing environment, cutting locations and other factors. Although traditional carpenters can predict roughly how a given wood would shrink and crook according to their experience, they don't know the theory basis behind the appearance. And hence such prediction is not precious, and it is also difficult to skill other people to get such knowledge without long-term training and practice.

From around 1950s, scientists in wood physics field started to explore scientific principle of moisture-produced wood deformations. For example, Kitahara Kakuiti and Uemura Takeshi researched how invisible factors (for instance, chemical compounds, cell wall structure, wooden tissue and its element) would decide wood ability to absorb and desorb water and hence swell or shrink. However, such knowledge can hardly be used by other people directly without professional background and special equipment. In architecture field, it is still a problem that most architects don't have a good understanding of wood behaviors despite they use this material a lot in architectural design.

Under this background, this research tries to digitalize wood dimensional changes based on visible and measurable wood patterns. It started from wood properties and hygro-deformation relations, discussed how invisible factors affect visible parameter, and hence inferred both positive and negative correlation factors which could be scanned. Then experiments were made to test the speculations. By analyzing experiment data, more specific relativities were confirmed. Finally, wood tangential shrinkage and radial shrinkage could be calculated by density, ring width and late wood proportion. Based on experiment data and mathematical models, this research designed a unique software to predict wood deformation results in air dry condition and oven dry condition. By using this software, everyone was able to forecast wood complex performance without any professional background. It made simulation process simple, quick and precise. At last, this research presented such moisture-produced wood deformations would provide criteria for joints and structures in architectural design, as their load-bearing capabilities relate to dimensional changes can be predicted and controlled.

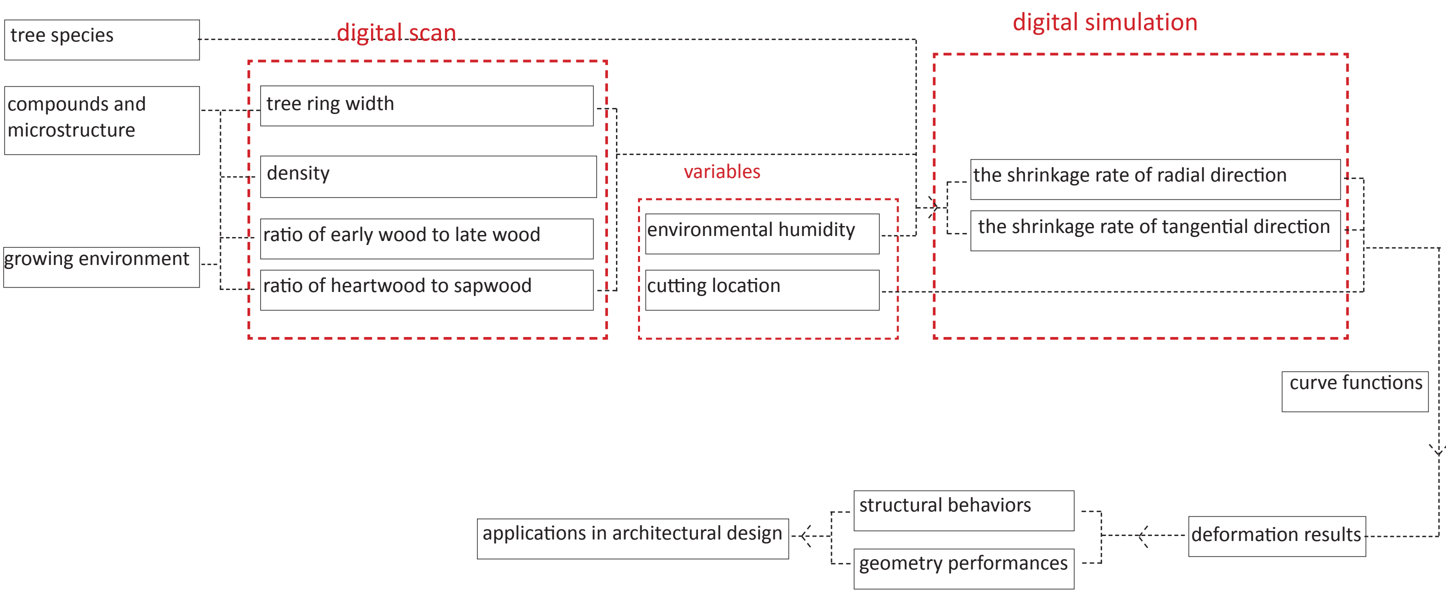

Figure 1. Process of this research

This research mainly consists of three parts: material study, software design, and wood deformation applications.

The material study part is divided into two chapters. The former chapter organized existing theories about wood hygroscopicity and anisotropy. It also revised a little mistake by 井阪三郎 in his paper"木材の狂いに関する研究 板の反りを考慮した木取法". New functions developed by this research was tested by a computer and proved to be true. The later chapter gave new development of simulating hygro-deformations. Special experiments were made to research relationship between wood patterns and shrinkage rate of Chinese fir. It was found that density had a strong positive relationship with both tangential shrinkage and radial shrinkage. Late wood proportion had positive correlation with radial shrinkage but not tangential shrinkage in oven dry condition. The influence of ring width was even smaller than late wood ratio, the coefficient was just -0.00003 in radial direction and -0.00005 in tangential direction. This chapter also made an experiment to compare whole shrinkage and sum of parts shrinkage. And it showed that hydro-deformations of wood products in any size could be predicted.

SUMMARY OUTPUT
αR-oven dry

Regression Statistics	
Multiple R	0.590370258
R Square	0.348537042
Adjusted R Square	0.332517461
Standard Error	0.004325556
Observations	126

ANOVA

	df	SS	MS	F	Significance F
Regression	3	0.001221245	0.000407	21.75694	2.35819E-11
Residual	122	0.002282673	1.87E-05		
Total	125	0.003503918			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.018838064	0.005926707	3.178505	0.001876	0.007105556	0.030570572	0.007105556	0.030570572
X Variable 1	0.022554996	0.013248402	1.702469	0.091214	-0.003671539	0.048781532	-0.00367154	0.048781532
X Variable 2	-0.000491231	0.000126782	-3.8746	0.000173	-0.000742209	-0.00024025	-0.00074221	-0.00024025
X Variable 3	0.009129992	0.006340865	1.439865	0.152467	-0.003422383	0.021682367	-0.00342238	0.021682367

SUMMARY OUTPUT
αT-oven dry

Regression Statistics	
Multiple R	0.294907868
R Square	0.08697065
Adjusted R Square	0.066061581
Standard Error	0.007369997
Observations	135

ANOVA

	df	SS	MS	F	Significance F
Regression	3	0.000677788	0.000226	4.15947	0.007506339
Residual	131	0.007115508	5.43E-05		
Total	134	0.007793296			

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	0.062033509	0.009315011	6.659521	6.88E-10	0.043606195	0.080460822	0.043606195	0.080460822
X Variable 1	0.00465689	0.02109023	0.220808	0.825586	-0.037064616	0.046378397	-0.03706462	0.046378397
X Variable 2	-4.83785E-05	0.000200882	-0.24083	0.810063	-0.000445771	0.000349014	-0.00044577	0.000349014
X Variable 3	-0.032249244	0.009231654	-3.49333	0.000651	-0.050511658	-0.01398683	-0.05051166	-0.01398683

Figure 2. part of wood deformation research

The next part, which was also a key chapter in this research, was about hardware and software design. Firstly, tests were made to check if special hardware was necessary. In this section, images of wood surfaces taken by digital x-microscope and taken by iPhone were compared. The advantage and disadvantage of two methods were also discussed. The conclusion was additional hardware was not needed for the following software. In the section of software for wood simulation, it explained how this software was built. An example was given to show the whole process, from reading related data from wood surfaces and calculating tangential shrinkage and radial shrinkage, to selecting cutting site and size, and then to deciding simulation condition, and finally to predict deformation results. The last section of this chapter was testing the precision of this software. Physical experiment measurements and digital simulation results were compared. Their difference were within the allowed error range.

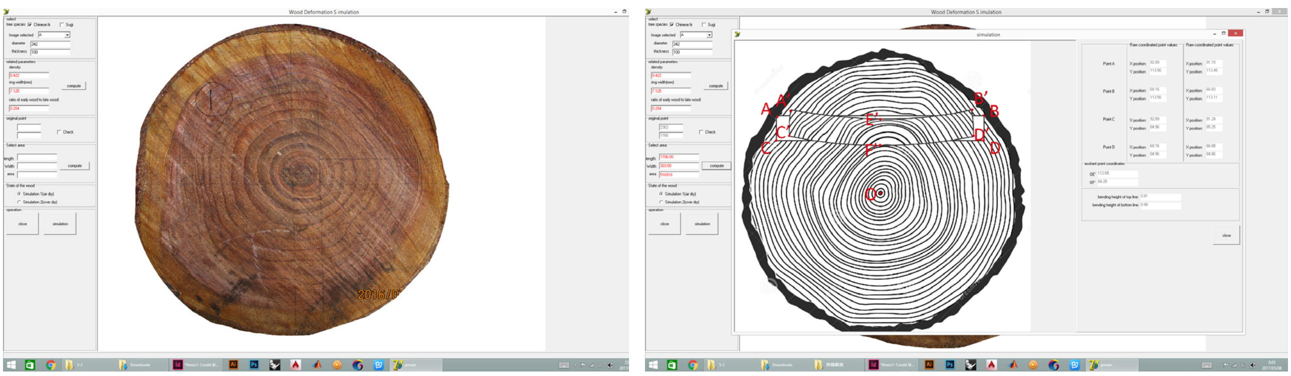

Figure 3. software for wood simulations

In prior research, people were weighted in favor of reducing or preventing wood warps. In most cases, the hydro-mechanical behaviors of wood were treated as unwelcomed because it usually resulted in crack of wood products and damage of structure. So there were several researches about reducing or preventing wood warps, carbonization and coating for instance. But there were few researches about making use of wood deformations.

However, such hydro-produced shrink and swell are not always useless if they could be simulated, controlled, and used in a smart way. In the last application part of this research, a new method of making wood joints was designed based on wood deformations. The new designed wood joints were made of 100% of wood without any adhesive. They were pollution-free and environment-friendly, and resisted not only compression but also tension. Tests were made to research the relationship between moisture-produced dimensional changes and load bearing capability.

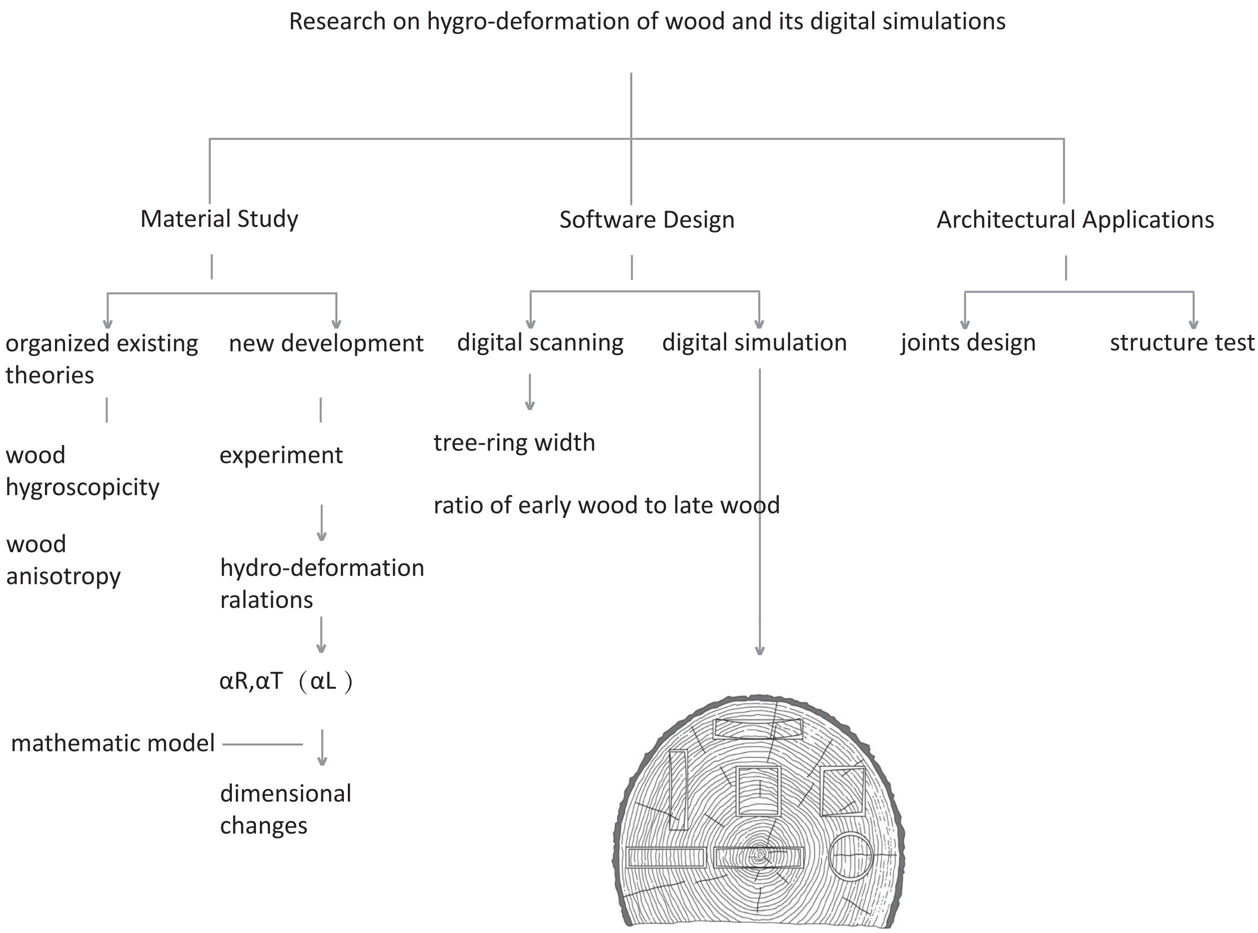

Figure 4. research strcture