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CALCULATION METHOD OF COLLAPSE TIME OF WOOD MEMBERS EXPOSED TO FIRE HEATING WITH HEAT AND WATER TRANSFER ANALYSIS: INFLUENCE OF INITIAL MOISTURE CONTENT ON CHARRING RATE AND MECHANICAL PROPERTIES OF REMAINING SECTION OF WOOD MEMBERS

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ABSTRACT: This study formulates a method to calculate the collapse time of wood members exposed to fire heating by considering the influence of temperature and moisture content. Moisture content affects the mechanical properties of wood members adversely during fire heating because of an increase in moisture content by water transfer and thermal softening at high temperature; however, the impact on mechanical properties of wood members during fire heating has been previously evaluated with respect to temperature alone. Consequently, this study formulates the calculation of the buckling time of a Japanese zelkova column under two conditions of initial moisture content (13.4% and 30.4%) and compares it with previous experimental results. This study showed that moisture content increased from 13.4% to 20.0% and from 30.4% to 39.1% at most for the two conditions, respectively, during fire heating. The buckling time could be predicted with good accuracy considering the moisture content dependence of Young's modulus. Although the moment of inertia was 1.67 times at 82 minutes when the column buckled in the experiment when the moisture content was high, the buckling time was only 3.5 min later than at low moisture content. Therefore, this calculation results show high initial moisture content increased in the remaining cross-sectional area and decreased Young's modulus significantly.

KEYWORDS: Fire Heating, Wood Members, Moisture Content, Mechanical Properties, Heat and Water Transfer

1 INTRODUCTION

In recent years, large wooden buildings have been constructed worldwide for the purpose of low-carbon construction or utilisation of forest resources. In Japan, high-rise and large-scale wooden buildings have been constructed due to supportive legislation and technological development. Therefore, the prediction of fire resistance of wood members exposed to fire heating has gained importance to improve the credibility of wooden buildings during fire and design appropriately sized members.

Regarding parameters affecting the mechanical properties of wood members during fire heating, not only temperature but also moisture content is important. Moisture content is significant because an increase in moisture content caused by vapourisation, transfer, and re-condensation of water in the remaining cross-sectional area required to bear load. The experiments in [1-3] showed that fire heating caused an increase in the moisture content of the specimens. Such an increase decreases the mechanical properties of wood members even at room temperature. Second, temperature dependence of mechanical properties of wood members increases significantly under the condition of high moisture content due to the thermal softening of lignin and hemicellulose, as shown in [4,5]. Hence, water transfer and moisture content increase by re-condensation, causing a probable decrease in mechanical properties.

Consequently, this study formulates a method to calculate the mechanical properties of wood members exposed to fire heating by considering the influence of temperature and moisture content. First, this study conducts heat and water transfer analysis, which calculates heat conduction and mass transfer. Second, the mechanical properties of wood members were calculated with distributions of temperature and moisture content given by heat and water transfer. Finally, the validity of the calculation was verified by comparing the calculation results and previous experiments' results.

2 METHOD

2.1 OUTLINE

Fig.1 shows the outline of the calculation method of the mechanical properties of wood members with heat and water transfer analysis.

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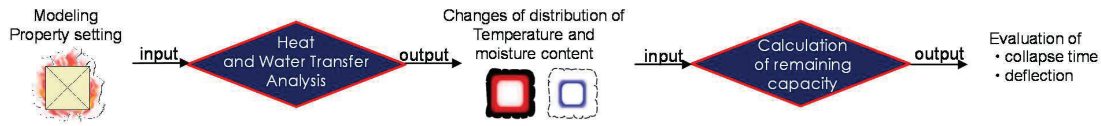

__Figure 1__: The outline of the evaluation method of the mechanical properties of wood members with heat and water transfer analysis

First, the cross-sectional area of a wood member is divided into finite elements. Moreover, the time variation of the distribution of temperature and moisture content are calculated with heat and water transfer analysis. Second, the remaining ratio of mechanical properties of each element is calculated with those temperature and moisture content. Finally, collapse time or deflection is calculated by adding all remaining

2.2 CALCULATION OBJECT

2.2.1 EXPERIMENTS TO COMPARE

In this study, we compare calculation results with the experimental results in [6] to clarify the influence of initial moisture content on the charring rate and mechanical properties of wood members during fire heating. If the initial moisture content is high, On the on hand, the increase in the latent heat of water causes a decrease in the charring rate. On the other hand, the mechanical properties of wood members decrease under conditions of high moisture content and high temperature. Thereby, high initial moisture content has both positive and negative influences as it causes a decrease in the charring rate and decrease in the mechanical properties of wood members, respectively. In the experiments in [6], specimens in an air-dry state and with high moisture content were heated. Therefore, in this study, we use the initial moisture content as a parameter to calculate the collapse time of wood members due to fire heating and compare the results with the experiments in [6].

Table 1 shows the results of the two experiments in [6]. The buckling time of a full-scale Japanese zelkova cylindrical column was measured during the load heating experiment under the ISO 834 fire heating curve conditions. Before the load heating experiment, the charring rate of a short column was measured during the non-load heating experiment to predict the buckling time in the load heating experiment. Meanwhile, the difference in the initial moisture content levels between the two experiments caused a difference in the charring rate of specimens. Japanese zelkova (Zelkova serrata) is hardwood often used for constructing Japanese shrines and temples.

If the cross-section of a wooden member is large, the interior may continue to remain with a high moisture content because of the difficulty of drying the interior.

2.2.2 CALCULATION CONDITONS

Table 1 shows the calculation conditions with experimental conditions. The initial moisture content in the calculation was set to the same value for each experiment. In the two cases, the mechanical properties of the specimen were calculated by considering and not-considering moisture content dependence, respectively. The diameter of the wood member used in the calculation was the same in both cases, despite the difference in the experiments.

2.3 CALCULATION METHOD

2.3.1 MODEL

Fig.2 shows the calculation model. Heat and water transfer analysis was conducted with a one-dimensional model because the section in the experiment was a circle. The length of the calculation model was half of the experimental diameter since the side of the centre was under adiabatic conditions. Mechanical properties of the specimen were calculated with the assumption that each element has a doughnut-shaped cross-sectional area.

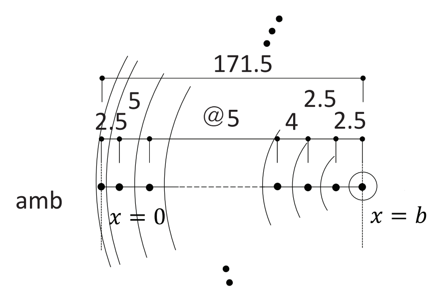

***Figure 2:** Calculation model (Unit: mm)*

***Table 1:** The experimental condition and the calculation results*

Case		Initial moisture content [%]	Experiment [6]			Calculation			
			Diameter [mm]	Charring rate [mm/min]	Buckling time [min]	Diameter [mm]	Charring rate [mm/min]	Moisture content dependence of mechanical properties	Buckling time [min]
A	A-1	13.7	354	0.77	– (Not Loaded)	343	0.78	valid	78.0
	A-2							invalid	89.5
B	B-1	30.4	343	0.54	82	343	0.56	valid	81.5
	B-2							invaid	116.5

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2.3.2 HEAT AND WATER TRANSFER ANALYSIS

Time variation of temperature and moisture content are calculated with heat and water transfer analysis developed in [9]. In the calculation method in [9], temperature, moisture content, vapour pressure, and total pressure are assumed to be the four main variables, and their time variations are calculated.

Equations (1) ~ (4) show the basic formulas for calculating the four variables.

Temperature is calculated by considering the influences of latent heat of water evaporation, thermal decomposition, water adsorption/desorption, and heat generation by oxidation. In this study, heat generation is restricted to 0.4 times the volume to represent the time variation of temperature in the experiment. Consequently, this calculation method has the task of accurate temperature prediction.

Moisture content is calculated with the transfer of liquid water and adsorption/desorption. As a matter of fact, the influence of liquid water transfer is insignificant because the transfer speed of liquid water is slow as compared to gas transfer.

The basic formula of vapour and total gas represents mass conservation. Transfer speeds of gases depend on Darcy's row. In Darcy's row, specific permeability differs for each tree species.

(a) Heat transfer

$$\rho_{wood} c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) - Q_{desorp} - Q_{evap} - Q_{decomp} + Q_{ox} \tag{1}$$

(b) Water transfer

$$\rho_{wood\ dry} \frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(\rho_{wood\ dry} D_w \frac{\partial M}{\partial x}\right) - R_{desorp} - R_{evap} \tag{2}$$

(c) Mixture gas conservation

$$\frac{\partial \varepsilon \rho_g}{\partial t} + \frac{\partial \rho_g u}{\partial x} = R_{desorp} + R_{evap} \tag{3}$$

(d) Vapour conservation

$$\frac{\partial \varepsilon \rho_v}{\partial t} + \frac{\partial \rho_v u}{\partial x} = \frac{\partial}{\partial x}\left(D_v \frac{\partial \rho_v}{\partial x}\right) + R_{desorp} + R_{evap} \tag{4}$$

An increase in the moisture content is represented by the following algorisms: water evaporation in a higher temperature area, vapour transfer, increase in vapour pressure in a lower temperature area, increase in relative humidity, increase in equilibrium moisture content, and increase in adsorption rate. Thereby, moisture content does not increase above the equilibrium moisture content with the calculation method in [9]. However, if the initial moisture content is higher than the equilibrium moisture content, moisture content increases above the equilibrium moisture content possibly.

In this study, the algorism of water condensation was changed based on Equations (5,6).

(i) Adsorption ($P_v \geq P_{v,max}$)

$$R_{desorp} = \frac{\rho_v - \rho_{v,max}}{\Delta t} = \frac{M'_v(P_v - P_{v,max})}{R\bar{T}\,\Delta t} \tag{5}$$

(ii) Desorption ($P_v < P_{v,max}$)

$$R_{desorp} = 0 \tag{6}$$

Table 2 shows the boundary conditions. Boundary conditions of every four variables on the unheated surface were set to adiabatic. On the heated surface, the temperature was calculated by considering conduction and radiation. The boundary condition of moisture content was adiabatic because liquid water was not exchanged. For total pressure, ambient total pressure was set to constant. The exchange of vapour pressure was calculated with the vapour transfer coefficient and the difference in vapour pressure via conductive heat transfer.

Table 3 shows the setting of properties for the calculation. Specific humidity was set to 3.96 [10^{-17} $m^2/(Pa \cdot sec)$], which is the value of Japanese Elm in [16]. This is hardwood and rings porous wood similar to Japanese zelkova.

2.3.3 CALCULATION OF MECHANICAL PROPERTIES

Buckling time was calculated and compared with previous experimental results because the column collapsed due to buckling in the experiment. Buckling time was regarded as the period after which the load-bearing capacity fell below the load. Load-bearing capacity was calculated with Equation (7), and the load was 640 [kN].

$$P_k = \frac{\pi EI}{{L_k}^2} \tag{7}$$

Young's modulus is calculated with initial moisture content and Young's modulus remaining ratio. Young's modulus remaining ratio is calculated via the equation in

Table 2: *The boundary condition of the calculation (Words in [ ] mean types of boundary conditions)*

Boundary	Temperature	Moisutre content	Total pressure	Vapour pressure
Heated surface	$-\lambda \left.\frac{\partial T}{\partial x}\right\|_{x=0} = h_c\,(T_{amb} - T) + q_{rad}$ [mixed : convection and radiation]	$-D_w \left.\frac{\partial M}{\partial x}\right\|_{x=0} = 0$ [2nd : adiabatic]	$\left.P_g\right\|_{x=0} = P_{g\ amb}$ [1st]	$-D_v \left.\frac{\partial P_v}{\partial x}\right\|_{x=0} = h_v\,(P_{v\,amb} - P_v)$ [3rd]
Unheated surface	$-\lambda \left.\frac{\partial T}{\partial x}\right\|_{x=b} = 0$ [2nd : adiabatic]	$-D_w \left.\frac{\partial M}{\partial x}\right\|_{x=b} = 0$ [2nd : adiabatic]	$-\left.\frac{\partial u\rho_g}{\partial x}\right\|_{x=b} = 0$ [2nd : adiabatic]	$-D_v \left.\frac{\partial P_v}{\partial x}\right\|_{x=b} = 0$ [2nd : adiabatic]

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Table 3: Setting of properties for the calculation

Symbol	Parameters		Values	Unit
T_{amb}	ambient temperature		20	°C
$h_{c\ amb}$	convective factor of heat surface		0.04	kW/(m^2·K)
$\varepsilon_{r\ amb1}$	emissivity of heat surface		0.9	-
h_v	vapour transfer coef.		0.002	kW/(m·K)
T_0	initial temperature		20	°C
U_0	initial relative humidity		0.40	-
$\rho_{wood\ 0}$	bone-dry density		580 *1	kg/m^3
c_{wood}	heat capacity of	wood	1.236 [12]	kJ/(kg·K)
c_w		water	4.186	kJ/(kg·K)
c_{char}		char	0.883 [13]	kJ/(kg·K)
λ	conductivity of wood and char		1.39×10^{-4} [14]	kW/(m·K)
L_{decomp}	heat of decomposition		2000	kJ/kg
$T_{decomp1}$	decompositon temperature	start	250	°C
$T_{decomp2}$		finish	400	°C
L_w	heat of adsorption and evaporation		2257	kJ/kg
D_w	diffusivity of water		1.94×10^{-10} [15]	m^2/s
K_{wood}	specific permeability of	wood	3.96×10^{-17} [16]	m^2/(Pa·sec)
K_{char}		char	3.96×10^{-15} *2	m^2/(Pa·sec)
D_{v0}	diffusivity of vapour		3.8×10^{-5} [17]	m^2/s

*1 The value of the specimen was aplied.

*2 The value was set to 0.01 times of wood[2].

[5], which considers the decrease caused by both temperature and moisture content. For instance, Young's modulus remaining ratio of Cryptomeria japonica at 95°C and high moisture content was 0.59, equivalent to that at 200°C and bone-dried state.

Initial Young's modulus was set to 9500 N/mm^2, which is the same value as the experiments in Case A, and 11020 N/mm^2, which is calculated by considering the increase by drying as 2% at 1% moisture content increase.

3 RESULTS

3.1 HEAT AND WATER TRANSFER ANALYSIS

3.1.1 TEMPERATURE AND MOISTURE CONTENT

Figs.3,4 show the calculation results of temperature and moisture content at the initial moisture content of 13.7% and 30.4%, respectively.

Regarding temperature, temperature rise stagnates due to the latent heat of water evaporation and thermal decomposition. The temperature fluctuations at high temperatures result from temperature falls when the heat generation of each element stops. In other words, the fluctuation results from the discretisation of the space. Thus, the temperature transition is smooth if the elements are made finer, or in reality.

The influence of the initial moisture content on the charring rate of wooden members due to fire heating can be represented in the calculation. Comparing the temperature transitions under the two cases, the temperature increase was fast at low initial moisture content. Fig.5 shows that the charring rate calculated with temperature reached 260° C. The charring rate was determined as the gradient of the charring depth with respect to the time to reach 260°C when the intercept was set to 0. These values of the charring rate are also shown in Table 1. The difference in the charring rate was caused by the difference in the latent heat of water evaporation. Comparing the charring rate derived from the calculation

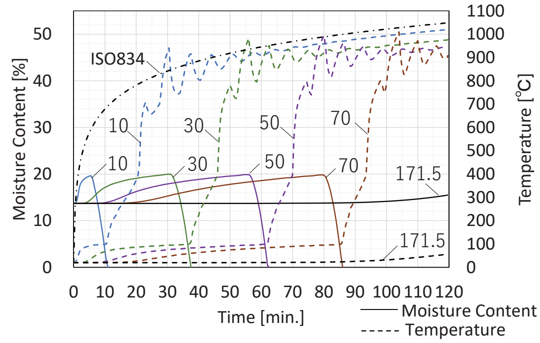

Figure 3: *Results of the calculation of temperature and moisture content at the initial moisture content of 13.7%*
(The values indicate distance from the heated surface)

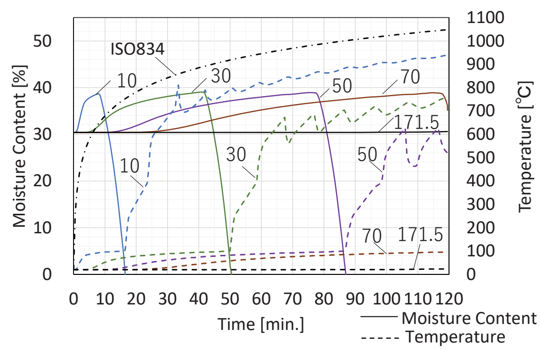

Figure 4: *Results of the calculation of temperature and moisture content at the initial moisture content of 30.4%*
(The values indicate distance from the heated surface)

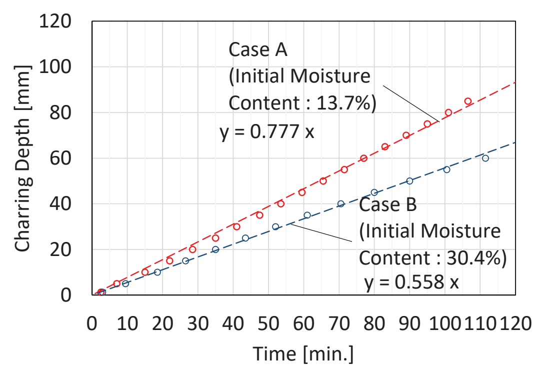

Figure 5: *Calculation results of the charring rates*

and the experiments, the agreement of the results was good. In the two cases, the charring rate was a little higher than the value of the charring rate in the experiments. However, this calculation method should be improved in the future because limits of the heat oxidation made agreement of the charring rate.

Moisture content was increased with temperature increase in the two cases. Maximum moisture content was 20.0% and 39.1%, for the initial moisture content of 13.7% and 30.4%, respectively.

Moisture content of the elements 10, 30, 50, and 70mm from the heated surface increased once and subsequently decreased due to evaporation. Moisture content increased of the elements near the heated surface and, with a

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relatively large moment of inertia, decreased the overall bending stiffness. Conversely, the moisture content of the element closest to the non-heated surface also increased gently. Moisture content increased in the area away from the heated surface and at a relatively low temperature, indicating a decrease in the mechanical properties due to moisture content in the areas bearing the load during and after fire heating.

In the calculation method formulated in this study, the maximum moisture content of each element immediately before evaporation was almost constant for each initial moisture content. The amount of increase in moisture content was 19.6 ~ 20.0% and 38.6 ~ 39.1% by the end of evaporation for initial moisture content of 13.7% and 30.4%, respectively. These upper limits of moisture content increase were determined by water adsorption, temperature increase, vapour pressure increase, and difference in vapour pressure decrease. Specifically, when water adsorbs, the latent heat gradually increases the temperature until just before evaporation. Vapour does not flow into the element itself when vapour pressure becomes higher just before evaporation. Moisture content increases only by a small extent at the temperature just before evaporation. As evaporation begins, moisture content starts decreasing. Since it takes a long time for evaporation to start, the amount of increase in moisture content was greater with higher initial moisture content.

These time variations of moisture content should be compared and verified with experimental results. However, the method that can measure local moisture content with electric resistance cannot accurately measure at conditions of high moisture content. For instance, the upper measurement limit in [2] is shown as 30%. Thus, the measurement method at high moisture content conditions should be developed in the future.

3.1.2 TOTAL PRESSURE AND VAPOUR PRESSURE

Figs.6,7 show the calculation results of total pressure and vapour pressure at the initial moisture content of 13.7% and 30.4%, respectively. The stepped transitions resulted from sudden falls of vapour pressure when evaporation in each element was over. Since these discontinuous behaviours are due to the discretisation of the space, vapour transitions are smooth if the elements are made finer or in reality.

Vapour pressure is the highest in the element where evaporation occurs, and the vapour transfer is caused by the difference in vapour pressure. Vapour transferring to a heated surface is released to ambient air. Vapour transferring to an unheated surface causes an increase in the relative humidity to 100% and water adsorption.

Total pressure is the same as the atmospheric pressure at initial moisture content conditions and increases with vapour pressure. Total pressure of the element closest to the unheated surface gradually increases because the boundary condition of the unheated surface was similar to the adiabatic condition.

Comparing the two cases, the maximum values of vapour pressure are almost equal because vapour pressure is limited by saturated vapour pressure, and saturated vapour pressure is calculated with temperature and evaporation

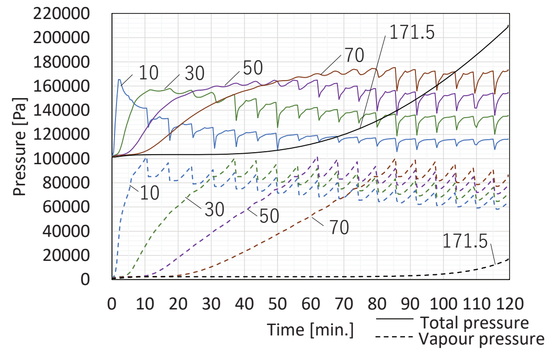

Figure 6: *Results of the calculation of total pressure and vapour pressure at the initial moisture content of 13.7%*
(The values indicate distance from the heated surface)

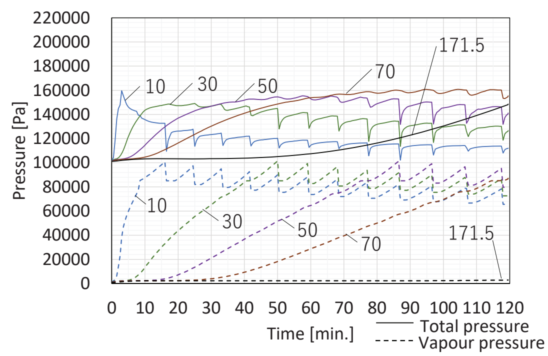

Figure 7: *Results of the calculation of total pressure and vapour pressure at the initial moisture content of 30.4%*
(The values indicate distance from the heated surface)

temperature, which is the same in the two cases. Total pressure of the element closest to the unheated surface at the initial moisture content of 13.7% is higher because temperature and saturated vapour pressure are higher.

3.2 MECHANICAL PROPERTIES

3.2.1 MOMENT OF INERTIA

Fig.8 shows the time variation of the moment of inertia in the two cases. Sudden falls of the moment of inertia occur because mechanical properties are considered 0 when the temperature of each element reaches 260°C.

The moment of inertia remains low as the initial moisture content is low. Comparing the moment of inertia at 82 minutes when the column buckled in the experiment, Case

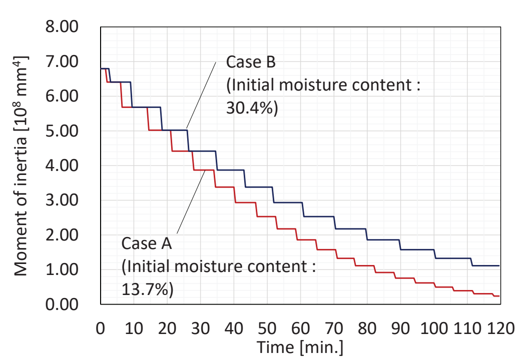

Figure 8: *Calculation Results of time variation of the moment of inertia*

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B has 1.67 times more remaining than Case A.

3.2.2 BUCKLING TIME

Figs.9,10 shows the calculation results of buckling time at the initial moisture content of 13.7% and 30.4%, respectively. Buckling time is also shown in Table 1. Buckling time in the calculation was regarded as the period after which the smoothed curves of the load-bearing capacity fell below the load. The smoothed curves were drawn in order to estimate buckling time accurately. The smoothed curves were the result of averaging the calculation results of a total of 11 points every 30 seconds, adding 5 points before and after. Not-smoothed calculation results fell suddenly with changes in the moment of inertia. Additionally, elements close to the heated surface may temporarily recover Young's modulus due to evaporation. If the space is not discretised, the load-bearing capacity of the entire cross-section will not recover temporarily but will gradually decline.

There are two calculation results in Figs.9,10. The blue plots were calculated by considering temperature and moisture content dependence on Young's modulus.

Conversely, the red plots considered only temperature dependence in such a way as to evaluate the influences of moisture content. These temperature and moisture content are derived from the calculations of heat and water transfer in Section 3.1.

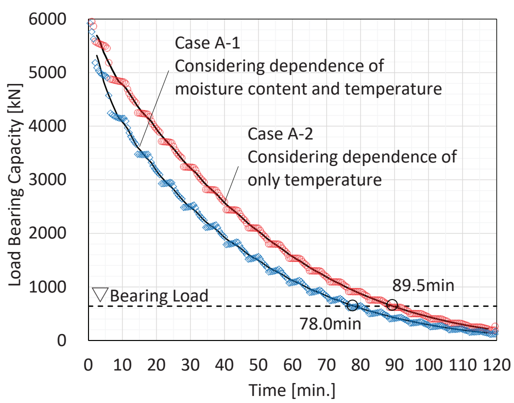

Figure 9: *Calculation results of buckling time at the initial moisture content of 13.7%*
(The plots indicate calculation results every 30 seconds, and the solid lines indicate calculation results after smoothing)

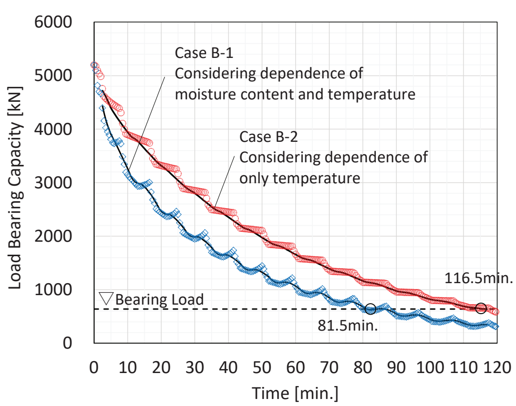

Figure 10: *Calculation results of buckling time at the initial moisture content of 30.4%*
(The plots indicate calculation results every 30 seconds, and the solid lines indicate calculation results after smoothing)

In both cases, the load-bearing capacity decreased when moisture content dependence was considered. The longest buckling time was 116.5 min in Case B-2 because the moment of inertia was greater, and moisture content dependence was not considered. Comparing the case with and without consideration of moisture content (Cases A-1 vs A-2 and B-1 vs B-2), the difference in the buckling time was 11.5 min and 35 min at the initial moisture content of 13.7% and 30.4%, respectively. The load-bearing capacity was further reduced at a high temperature and high moisture content; hence the difference in the buckling time was larger when the initial water content was higher.

In Table 1, comparing the buckling time derived from the experimental results and the calculation in this study (Cases B-1,2 vs the experiment), the buckling time was estimated to be almost the same or slightly earlier with consideration of moisture content. Conversely, for the condition of no consideration of moisture content, the buckling time was evaluated much to be later than that derived from the previous experiments. Therefore, when the initial moisture content is high, the buckling time is assumed to be long except for the condition of consideration of moisture content dependence.

In Fig.10, comparing the buckling time in the case with and without consideration of moisture content (Cases B-1 vs B-2), the difference in buckling time was 35 minutes, and both evaluated the buckling time to be earlier than that derived from previous experiments. The load-bearing capacity was 562kN and 627kN at 82 minutes when the column buckled in the experiment in Cases B-1 and B-2, respectively. This difference is insignificant compared to the difference in the moment of inertia (1.67 times). Although the cross-section remains large due to the high initial moisture content, the decrease in Young's modulus due to the high moisture content is large. Therefore, buckling time does not change significantly.

In conclusion, buckling time can be predicted with heat and water transfer analysis and consideration for moisture content dependence of Young's modulus. Moreover, as a result of the calculation considering the positive and negative influence of moisture content on charring rate and Young's modulus, both effects largely cancelled out in these cases. However, the balance of both effects will change if the calculation conditions change. Considering that Young's modulus decreases as the moisture content increases at room temperature, we conclude that initial moisture content is desired to be controlled in an air-dry state as before.

In the future, the study of other tree species is desired because the behaviour of heat and water transfer and the influence of moisture content differ among tree species. Furthermore, the study of collapse for reasons other than buckling is important to predict the collapse time of wood members other than columns.

4 CONCLUSIONS

This study predicted the buckling time of a Japanese zelkova column exposed to fire heating using heat and water transfer analysis. The results were compared with those of a previous study [6]. The calculations were conducted under two conditions, at the initial moisture content of 13.7% and 30.4%, to evaluate the following positive and negative effects of high initial moisture content: decrease in the charring rate and decreasing of the mechanical properties at a high temperature and high moisture content.

(1) An increase in the moisture content caused by water evaporation, transfer, and re-condensation was represented. Moisture content increased from 13.4% to 20.0% and from 30.4% to 39.1% at most, respectively.

(2) The phenomenon that the higher the initial moisture content, the slower the carbonisation rate was represented by calculation. The agreement between the calculated charring rate and that derived from the previous experiment was good; however, the heat oxidation was intentionally limited so as to reproduce the remaining sectional area.

(3) The buckling time was predicted by considering the dependence of mechanical properties not only on temperature but also on moisture content. Considering the dependence of the mechanical properties of wood members on temperature and moisture content, the calculated buckling times were similar to or slightly faster than the experimental results. Conversely, considering the dependence of the mechanical properties of wood members on temperature alone, the calculated buckling times were longer. Thus, the buckling time should be calculated by considering the moisture content dependence at high initial moisture content.

(4) Under this calculation condition, the effect of the high initial moisture content on slowing down the charring rate and decrease in the mechanical properties of the remaining cross-sectional area of wood members were largely cancelled out by the following results: although the moment of inertia was 1.67 times at 82 minutes when the column buckled in the experiment, buckling time changed by only 3.5 minutes.

In the future, the behaviour of water transfer at high initial moisture content should be measured, compared, and verified after the development of the measurement method. Furthermore, there is a need to conduct this study by considering other tree species; additionally, researchers should also study the collapse of wood members due to reasons other than buckling.

Symbols and Greeks

c	heat capacity [kJ/(kg・K)]
D	diffusion coefficient [m^2/s]
E	Young's modulus[N/mm^2]
e_r	emissivity [-]
h_c	convective heat transfer coefficient [kW/(m^2・K)]
h_v	vapour transfer coefficient [m/s]
I	moment of inertia
K	specific permeability [m^2]
L	latent heat [kJ/kg]
L_k	buckling length
M	moisture content [-]
M'	molecular weight [kg/kmol]
P	pressure [Pa]
P_k	load
q_{rad}	radiant heat [kW/m^2]
Q	heat generation [kW/m^3]
R	rate of water desorption [kg/(m^3・s)]
T	temperature [℃]
$\bar{T}$	absolute temperature [K]
t	time [s]
u	apparent velocity of gas filtration [m/s]
ε	void fraction [-]
κ	Darcy's permeability [m^2/(Pa・s)]
λ	thermal conductivity [W/(m・K)]
ρ	density [kg/m^3]
ρ_{ture}	true density [kg/m^3]

Subscripts

amb	ambient air on heated surface
char	char
decomp	decomposition
desorp	desorption
dry	bone-dry state
evap	evaporation
g	gaseous mixture
max	maximum value
ox	char oxidation
v	vapour
w	water
wood	wood
0	initial

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