Analysis for Wood Decay within Building Envelops Considering Moisture Production by Biochemical Reactions

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ABSTRACT

In this study, a durability assessment model for building envelopes design based on hygrothermal and wood rot decay analysis is presented. The durability assessment model can quantitatively predict hygrothermal conditions within the building envelopes, and progress of wood rot decay of timber frame under variable conditions. The followings are characteristics of the durability assessment models in this study. One is that development of wood rot decay is represented by a differential equation with a variable of mass loss; the other is that moisture production by wood rot decay is added into moisture balance equations. Hence, the model can assess long term performance regarding both durability and drying potential for building envelopes. In this paper, sensitive analyses were implemented to better understand impact of the moisture production on the decay process. Additionally, progress of the wood rot decay within an external wooden wall is demonstrated.

1. INTRODUCTION

Moisture accumulation within building envelops of wood frame constructions significantly affects problems related to durability, such as wood decay, mould and termite. To avoid these moisture-related damages, various building components and wood preservatives have been developed and applied to actual constructions until recently. However, health issue for occupants, e.g. the indoor air quality, has potential to remove the chemical wood preservatives from the lumber in the building components, and energy issue such as the Kyoto Protocol has made the wood frame constructions airtight. The drying capability related to the durability of the building envelopes has consequently decreased. Therefore proper design for moisture control within the building envelopes is necessary to achieve both durable structure and healthy environment.

On the other hands, advanced hygrothermal analysis models can accurately predict temperature and moisture behavior within building assemblies under various climate conditions. The calculation results by these models (e.g. Hens, 1996) are useful in design and assessment for the moisture control. Mostafa and Kumran (1999) presented an approach to develop durability assessment system that links the hygrothermal analysis model with the moisture related damages. As well Krus (2001) tried similar approach regarding the mould growth, and implemented damage analysis that integrates the hygrothermal model with the biological damage predictions. In these models, the calculated temperature and moisture profiles are applied to prediction for progression of the biological damages.

However these challenges did not completely simulate decay process regarding degradation of wood substance in terms of moisture balance. Wood rot fungi that can degrade cellulose, e.g. Sepula lacrymans and Coniophora puteana, produce non-negligible moisture through the decay process. Consequently, this mechanism makes the decay process continue even though relative humidity of the surrounding air is below saturation point (e.g.Viitanen, 1997). Impacts of the moisture production on the biological prediction need to be verified in terms of safety evaluation for the wood constructions.

With these points as background, this study proposes a wood decay model to which the moisture production due to the decay process is introduced. Furthermore progress of the wood rot decay in exterior wall assemblies is demonstrated to better understand the impact of the moisture production.

2. MODELING FOR WOOD DECAY CONSIDERING MOISTURE BALANCE

2.1 Hypothesis of Proposed Model Contributed

Wood rot fungi degrade mainly cellulose within the wood substance by enzymatic reactions, and consequently produce both H_2O and CO_2 through this degradation. This wood brake down mechanism consists of two step biochemical reactions, which are hydrolysis and aerobic degradation. Both the biochemical reactions and moisture transfer occur simultaneously within the decayed wood, shown in Figure 1. In this study, these phenomena are expressed as a numerical simulation model regarding the mass loss and the moisture content. Additionally, we define a rate constant that is determined by experiments to predict the mass loss, on the basis of deterministic un-structural model. The followings are hypothesis for the simulation model.

(1) Material properties for hygrothermal analysis are stable before and after the wood decay.

(2) Quantity of the mass loss has a single correlation with that of the moisture production by the biochemical reactions.

(3) Impacts of both O_2 and CO_2 concentrations to the wood decay can be neglected.

(4) Impacts of diversity of wood and fungus species are presented by experimental coefficients.

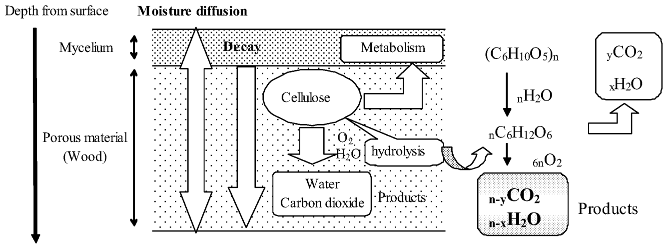

Figure 1. Scheme for wood decay and moisture transfer within the wood substance

2.2 Progression of Wood Decay

The proposed wood decay model supposed that the progression of the mass loss is determined by hygrothermal conditions, such as temperature and relative humidity, at a control volume for finite difference analysis. The mass loss by the wood decay is defined as:

$$L = \frac{m_n - m_d}{m_n} \tag{1}$$

where L is the mass loss by the wood decay (-), m_n is the mass of the wood material before the decay, and m_d is the mass of the wood material after the decay respectively.

The wood rot fungi need liquid water to progress the mass loss based on the biochemical reactions. Thus the mass loss on the surface node of wood material progresses when the relative humidity within micro-pore is above the critical relative humidity φ_c (%RH) in Equation (2). As well, Equation (3) is applied to the progression of the mass loss at the inner node, because grown hypha of the wood rot fungi needs to reach this node for the decay progression.

$$\left.\frac{dL}{dt}\right|_{x=0} = k_m(\theta) \qquad (\varphi_i \geq \varphi_c) \tag{2}$$

$$\left.\frac{dL}{dt}\right|_{x>0} = k_m(\theta) \qquad (L_{i-1} or L_{i+1} > 0, \varphi_i \geq \varphi_c) \tag{3}$$

where t is the time (s), φ_i is the relative humidity (%RH) at the node i,φ_c is the critical relative humidity for the beginning of the wood decay (%RH), $k_m(\theta)$ is the rate constant that corresponds to a time factor for decay development by the wood rot fungus, as a function of temperature θ (°C). The rate constant needs to be determined experimentally, because various conditions (e.g. wood species and hygrothermal conditions) affect development of the wood decay.

Concentration of the hypha in the each node may affect the rate constant. Gooding (1966) pointed out that growth rate of the hypha within the wood material is several millimeter per day. Thus this model assumes that the hypha concentration has already been uniformed within the node i, at the stage of beginning of the mass loss of the node $i+1$ or $i-1$.

2.3 Heat and Moisture Balance in Decayed Wood Material

Heat and moisture balance coupling the moisture production by the biochemical reactions is presented by Equation (4) and (5). The reaction fever with the biochemical reactions is neglected in Equation (4), and the third term of right side of Equation (5) corresponds to the moisture product.

$$\rho_m c \frac{\partial T}{\partial t} = \nabla\{(\lambda + r\lambda'_{Tg})\nabla T + r\lambda_{\mu g}\nabla\mu\} \tag{4}$$

$$\rho_w \frac{\partial \phi}{\partial \mu}\frac{\partial \mu}{\partial t} = \nabla(\lambda'_{\mu}\nabla\mu + \lambda'_T\nabla T) + W_L \tag{5}$$

where ρ_m is the material density (kg/m^3), T is the Kelvin temperature (K), c is the material specific heat (J/kg), λ is the thermal conductivity (W/mK), r is the latent heat of moisture (J/kg), λ_{Tg} is the moisture conductivity in gaseous phase related to temperature gradient (kg/msK), $\lambda_{\mu g}$ is the moisture conductivity in gaseous phase related to water chemical potential gradient (kg/ms[J/kg]), ρ_w is the density of liquid water (kg/m^3), ϕ is the moisture content per volume of material (m^3/ m^3), μ is the water chemical potential (J/kg), and W_L is the the moisture product quantity (kg/sm^3).

Since this model assumes that quantity of the mass loss has a single correlation with the moisture product, moisture product ratio h (-) that corresponds to relation between them in a closed moisture system regarding moisture balance can be defined as:

$$h = \frac{d\phi}{dL} \tag{6}$$

The moisture product ratio h can not be determined from reaction formulae regarding the biochemical reactions for the decay process, because quantitative details of the metabolism regarding wood rot fungi within the wood substance is uncertain. However the moisture product quantity is expressed as Equation (7), where the moisture product ratio can be determined experimentally.

$$W_L = h\rho_w \frac{dL}{dt} \tag{7}$$

2.4 Coefficient for the Model

Saito (2008) tried to determine these coefficients by decay tests for sapwood of *Pinus densiflora* (wood species: Japanese red pine) under sterile condition shown in Figure 2. In this decay test, surrounding air of wood samples was controlled close to saturation point. The moisture product ratio h was determined as 0.319 (-) by relation between the mass loss and the moisture contents of wood samples in Figure 3.

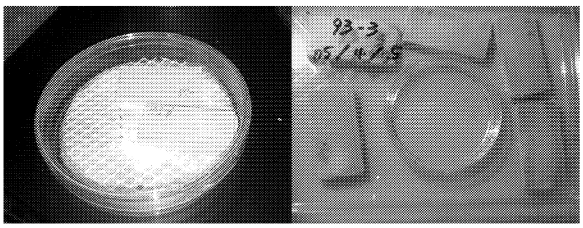

Figure 2 Decay tests for sapwood of *Pinus densiflora* under sterile condition (Saito, 2008)

The rate constant was also determined by linear regression analysis for the time dependent change of the mass loss in each temperature conditions of the decay tests. A regression curve in Figure 4 presents relation between the determined rate constants and temperature. The empirical formula regarding the rate constants is given by Equation (8).

$$k_m(\theta) = 2.77 - 3.23\theta + 0.865\theta^2 - 0.0189\theta^3 \quad (8)$$

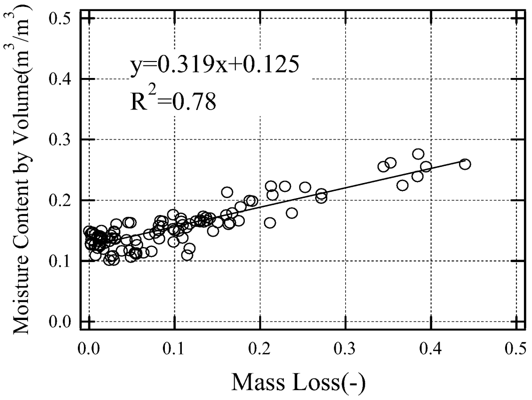

Figure 3 Relation between mass loss and moisture contents on decay test (Saito, 2008)

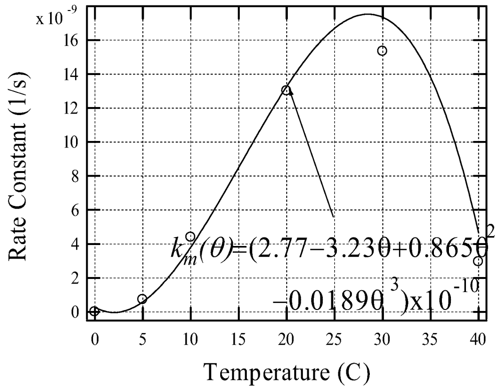

Figure 4 Relation between rate constant and temperature (Saito, 2008)

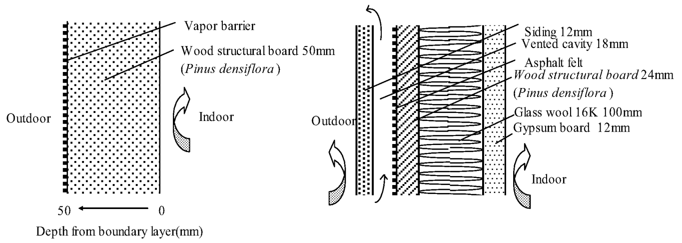

Figure 5 Wall assembly for analysis (Left:Wood substance, Right:Wall assembly)

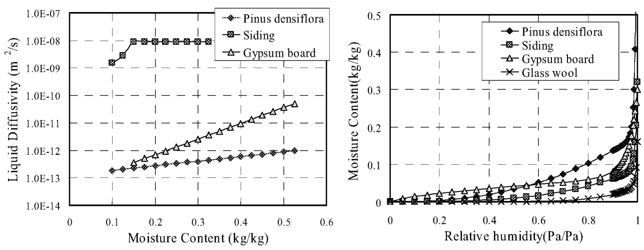

Figure 6 Moisture diffusivity and sorption curve

Table 1 Calculation conditions

case	Indoor		Outdoor		Initial moisture content w(kg/kg)	Rate constant k_m(1/s)	Process
	T(C°)	RH(%)	T(C°)	RH(%)			
case1	20	98.5	20	-	0.2	1.30×10^{-8}	Condensation
case2		75.0			0.3		Evaporation
case3	Eq.(9)	60	Climate data in Osaka Japan		0.66(=99%RH)	Eq.(8)	Condensation

3. ANALYSIS FOR WOOD DECAY CONSIDERING MOISTURE BALANCE

3.1 Outline for the Analysis

To better understand progress of the wood decay, the wood decay model was applied to wood structural board and an exterior wall shown in Figure 10. The numerical simulations for the wood decay that employed Equation (2) – (7) assumed one-dimensional heat and moisture flow in finite differential approximations. The critical relative humidity φ_c (%RH) for the beginning of the wood rot was set on 98%RH, on the basis of the experimental results (Saito, 2008). Initial response time that is period to start the wood decay after reaching the critical relative humidity proposed by Mostafa and Kumaran (1999) was neglected.

Table 1 shows calculation conditions. In case 1 and case 2, constant condition for boundary conditions was assumed in order to clarify impact of the moisture production on moisture accumulation. Additionally both condensation and evaporation process were implemented in the numerical simulations.

In case 3, long term variations of wood decay were examined on the wall assembly under variable conditions. Vapor retarder for the wall was removed intentionally, because the wood rot never progresses less than the critical relative humidity. For the similar reason, the initial moisture content of the structural wood board (*Pinus densiflora*) was set 0.66 kg/kg. The moisture properties of the building components are shown in Figure 6, and Equation (9) shows indoor temperature at case 3.

$$\theta_r = 25.0 + 5.0\cos\left[2\pi(DAY - 212)/365\right] \qquad (9)$$

where θ_r is indoor temperature the material density (C^o), *DAY* is the number of days from January 1st.

3.2 Results and Discussion

3.2.1 Sensitive analysis (case1,case2)

Distributions of moisture contents within wood structural board are shown in Figure 7. Impact of the moisture product on the moisture accumulation and the mass loss can be observed from inner layer of case1. According to the sorption curve of *Pinus densiflora* in Figure 6, the moisture content never exceeds approximately 0.3kg/kg even though equilibrium state under 98.5%RH could be reached. However the moisture content reached to 0.37kg/kg on 12month because of the moisture production by the biochemical reactions.

As well, significant differences at the inner layer can be observed on the moisture contents of the evaporation process. These results suggest that quantity of the moisture products within the wood exceeded moisture that evaporated on the surface.

3.2.2Long term variation (case3)

In order to understand long-term progress of the wood decay, Long term variation of the mass

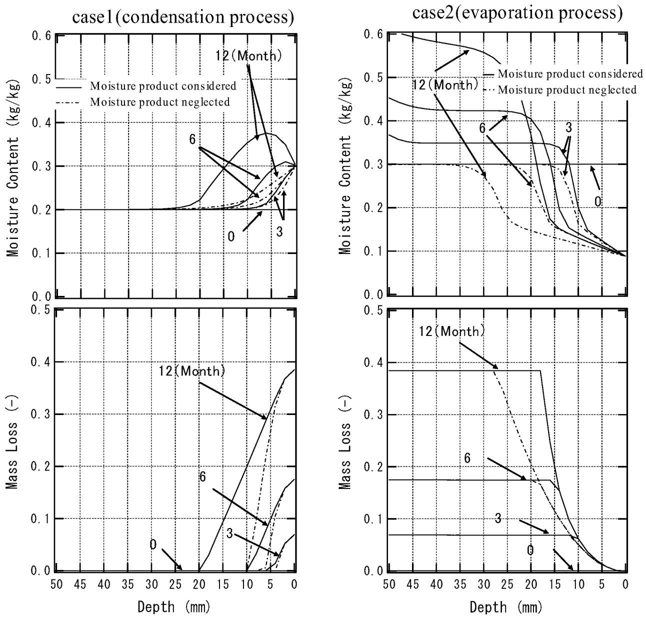

Figure 7 Distributions of the moisture content and mass loss at constant conditions (case1, case2)

loss and the moisture contents are presented in Figure 8 and Figure 9 respectively. The mass loss at the surface node of the structural wood board (i.e. 0mm) increased mainly in the spring rather than the mid winter because of the temperature dependence regarding the rate constant. As well the moisture product that is attributed to increase of the mass loss was observed in this period in Figure 9. Monthly increase of the mass loss on the January and February was smaller than the value of spring according to Figure 8 (approximately 0.01). Hence, significant point in terms of the prevention of the moisture damage is that the moisture contents of wood products should be controlled below the critical relative humidity by the early spring in this climate region.

As for impact of the moisture production to the mass loss and the moisture contents, the differences in the calculation condition against the moisture product appeared at the internal node of the structural wood board (e.g. 4mm or 10mm) rather than the surface node in Figure 8 and Figure 9. This result suggests that quantity of the moisture product at the internal layer is larger than that removed by the moisture diffusion. Therefore, addition of the moisture product term to the moisture balance equations is significant in terms of assessment of the wood decay, where the moisture content at the internal layer is kept above the critical relative humidity.

4. CONCLUSION

The wood decay model considering the moisture balance due to the decay process has been presented. Furthermore the wood decay analysis due to the moisture accumulation within a building assembly was implemented to better understand the impact of the moisture product on the decay progression. The analysis results suggested that the moisture product significantly affects the increase of the mass loss and the moisture contents at the internal layer of the wood substance. These consequences should be verified under various conditions experimentally to enhance reliability of this model. However, significance of this study from viewpoint of the building simulation is that the integration of biochemical reactions into hygrothermal analysis was presented as an advanced model.

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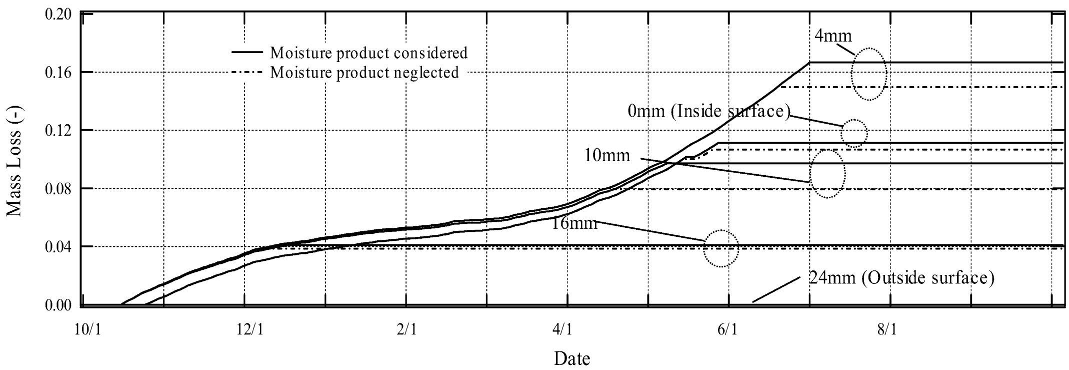

Figure 8 Long term variation for the mass loss of structural wood board in each depth (case3)

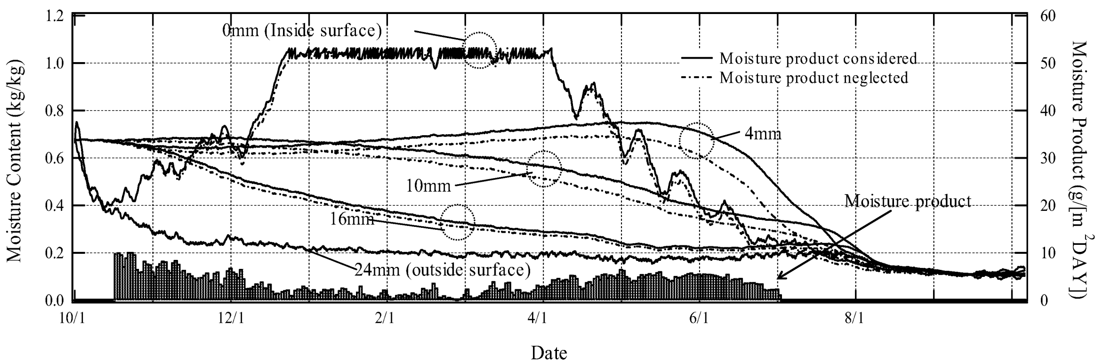

Figure 9 Long term variation of the moisture contents of structural wood board in each depth (lines) and daily summation of moisture product (Bar) (case3)