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DURABILITY ASSESSMENTS OF WOOD-FRAME CONSTRUCTION USING THE CONCEPT OF DAMAGE-FUNCTIONS

Durability assessments of wood-frame construction

M. NOFAL and M.K. KUMARAN
Institute for Research in Construction, National Research Council Canada, Ottawa, Canada

Abstract

Review of the state-of-the-art on fungal damage of wood materials showed that a combination of period of cumulative time when moisture and thermal regimes are above specified minimum is needed for fungal activities to cause biological decay in wood. The long-term performance of a typical wall assembly was evaluated using an existing computer model of heat, moisture, and air transfer in conjunction with a biological damage-function model. The hygrothermal behaviour and the associated biological damage were evaluated using virgin materials properties. The damage results are rather conservative because test results revealed that subsequent wetting and drying change the microstructure features of typical engineered wood products.

Keywords: construction, building, envelope, house, wall system, material, wood, wood-frame, durability, moisture, temperature, time, lifecycle, mold fungi, wood-rot fungi, analysis, fracture, failure, damage, model.

Résumé

Une étude de la documentation récente a montré qu'il faut une accumulation de périodes où les régimes d'humidité et de température dépassent les valeurs minimales prescrites pour que les moisissures provoquent la pourriture du bois. On a évalué la performance à long terme d'un mur type à l'aide d'un modèle informatique portant sur la chaleur, l'humidité et les échanges d'air, en parallèle avec un modèle des dommages-fonctions biologiques. Le comportement hygrothermique et les dommages biologiques qui en résultent ont également été évalués en fonction des propriétés de produits vierges. Les résultats obtenus invitent à la prudence, car des essais ont montré que le mouillage et l'assèchement successifs de produits du bois sophistiqués en modifiaient la microstructure.

Mots clés : construction, bâtiment, enveloppe, maison, système de mur, matériaux, bois, ossature en bois, durabilité, humidité, température, temps, cycle de vie, champignons, champignons lignivores, analyse, rupture, défaillance, dommage, modèle.

1 Introduction

The problem of durability is not just due to over-stressing of structures. A wide range of physical, biological, chemical, and mechanical processes, as well as improper design and construction practices are responsible for the onset of the damage in building envelopes. Moisture and temperature fluctuations as well as mechanical loads are leading causes of the continuous deterioration of building materials. About 90% of damage in houses, with the exception of that caused by mechanical loading, result from temperature and moisture effects (Zabel and Morrell 1992). Wood and wood based products (engineered wood) are widely used in most housing and low-rise residential and office buildings in Canada. Wood materials are very susceptible to degradation due to fungal attack under certain combinations of time, moisture and temperature conditions. Houses may experience moisture-related damage within 3-10 years of service life. The building continues to be serviceable for a longer period but its durability remains an economical issue. Damage prevention of building envelopes is the most cost-effective measure compared to repairing or replacing the whole envelope. Thus, improvements in the analysis, design, and damage predictions of materials and structures can have great economic and safety implications.

This paper reviews the state-of-the-art on fungal damage of wood materials. It discusses the critical time needed for given moisture and thermal regimes for fungal activities to cause damage in wood. The paper, as an example, assess the long-term performance of wood-frame constructions in Ottawa, Canada using fungal damage models (Hukka and Viitanen 1998).

2 Damage types in wood materials

Engineered wood materials are susceptible to degradation under certain hygrothermal and/or mechanical loading conditions. For example, oriented strand board (OSB) and plywood exhibit dimension changes when they get wet.

The onset of biological damage is considered differently by various researchers. For instances, Zabel and Morrell (1992) stated that the process of biological damage commences when moisture content reaches more than 35% by mass in wood materials. Baker (1969) reported that moisture content of less than 20% might not cause structural wood decay. However, Zabel and Morrell (1992) reported that some experiments showed that moisture contents below 20% could become suitable for bacterial and fungal growth that ultimately destroys wood materials. This result is debatable because no other work has ever been able to repeat mold growth for this particular condition. Measurements in typical housing indicate that moisture content of wood varies between 5% in the winter and 15% in summer months. Improperly designed or built wood envelopes, however, may accumulate and retain higher moisture content, leading to rotting. Baker (1969), and similar work conducted by Zwick (1985), indicated that moisture condensation is not a problem when properly dried wood is used for the construction. Although the wood structure may be capable of resisting loads, the home becomes uninhabitable because of the poor health environment that results from fungus spores.

Nofal (1998) showed that engineered wood materials suffer biological and structural damage when subjected to hygrothermal loading. Also, Nofal (1998) summarized the damage-accumulation approach to model the time-dependent strength properties of wood structures. Structural damage will not be further discussed here because it is outside the scope of the current paper. This paper will focus only on the biological decay aspects and their influence on the long-term performance of engineered wood materials.

3 Biological damage in wood materials

A wide range of organisms including fungi, termites, carpenter ants, wood-boring beetles and marine borers can live in and consume wood. Water is the essential element for the growth of most of those organisms in wood. Termites are a serious threat to untreated wood in tropical locations (Morris 1998, Zabel and Morrell 1992). However, termites cause also serious problems in temperate climate such as in Canada especially in some parts of southern Ontario, particularly downtown Toronto, and in some of the drier areas in British Columbia (Morris 1998). Grubs are the most larvae of wood-boring beetles that feed on the wood. Marine invertebrates chew tunnels in wood stored or used in salt waters. Carpenter ants do not eat wood but they excavate it to live in. Fungi are the most important organisms that destroy wood under relatively mild climate condition.

Most of the reported damage in European and North American houses and low-rise buildings are mainly due to fungal attack on the wood materials. Therefore, this paper summarizes only the-state-of-the-art on fungal damage in wood materials.

4 Studies of fungal damage

Fungi are those organisms that feed on organic matter and grow by extension and branching of tubular cells (*hyphae*). Fungi reproduce through microscopic spores that are smaller than the pollen grains of plants. Fungi species differ from one place and material to another depending on the microclimate. In general, fungi that live in wood can be divided into four groups: mold, stain, soft-rot, and wood-rotting basidiomycetes fungi.

4.1 Mold-fungi damage

The presence of mold fungi in homes is an early indication of increased humidity and moisture levels in these buildings. Mold fungi are undemanding organisms and are able to grow on any building material, including wood. Mold fungi growth on non-organic materials will not start unless there is some nutrient existing on their surface (e.g. dirt). Growth rate of mold fungi depends on the surface quality (kiln dried or fresh sawn) not on the wood species (Viitanen 1997 a). Wood surface quality reflects the nutrient content of the surface. White (1996) and Andersson *et al.* (1997) also found that mold fungi could reproduce and evolve on any surface, depending on the amount of free sugar regardless of material type.

Mold fungi will rapidly develop at a relative humidity of 75% or higher. These fungi types go dormant under dry conditions but they will be replaced by wood rotting fungi if the wood material remains wet. Mold fungi cause damage in terms of discoloration, odor and health but do not significantly affect the strength of wood (White 1995, 1996, Andersson *et al.* 1997).

Viitanen and Ritschkoff (1991) divided mold and stain fungi into wood colonizing fungi and airborne mold fungi. They collected from European homes some typical wood colonizing mold fungi that include *Alternaria alternata*, *Aspergillus* -species, *Aureobasidium pullullans*, *Cladosporium cladosporioides*, *Chaetomium globsoum*, *Paecilomyces variotii*, *Penicillium* –species and *Tirchoderma viride*. Schmidt *et al.* (1983) indicated that these mold fungi species could be found in North American homes. The intensity of the fungal damage may be different for the two continents because of differences in weather and occupants living habits and wood species. These differences need to be studied.

4.2 Wood-rot fungi damage

Wood-rotting basidiomycetes cause most serious damage in buildings. These fungi types can be classified into three main categories: (1) soft-rot, (2) white-rot, and (3) brown-rot fungi. Oak and maple species are very susceptible to soft-rot fungi. White-rot fungi destroy hardwoods such as aspen and maple. Brown-rot fungi prefer softwoods such as pines, spruces, hemlocks, and firs. All these fungi have considerable ability with varying degrees on reducing the wood material strength. Wilcox (1978) showed that white- or brown- rot fungi affect several strength and mechanical properties of wood before significant weight loss is detected. The slow reduction in material strength is the result of the break up of lignocellulose, lignin and cellulose depending on the fungi type.

Duncan and Lombard (1965) identified *Antrodia serialis*, *Antrodia vaillantii*, *Coniophora puteana*, *Gloeophyllum trabeum*, *Meruliporia incrassata*, *Postia placenta*, *Sepula lacrymans*, and *Tapinella panuoides*, as the fungi causing decay in building in the United States of America. In the Nordic countries, *Coniophor*a *puteana* fungi are the most lethal fungi species attacking homes (Viitanen 1997 b). Morris (1998) indicated that there is no extensive studies have been done to determine which fungi species are the most important in Canada. Morris (1998) suggested that those fungi species identified from USA buildings might be common to Canadian environments.

4.3 Optimal conditions for fungal growth

Some of these fungi can survive and grow at low moisture concentrations causing decay and weakening or discoloration of the building envelope materials (Zabel and Morrell 1992). The process of fungal attack in building envelope requires five critical requirements: (1) wood type, (2) free or unbound water, (3) favorable temperature, (4) oxygen and (5) available digestible carbon compound. Wood-inhabiting fungi require optimal levels of those essential elements for viable growth.

4.3.1 Optimum moisture conditions

The exact optimal moisture levels for the growth of fungi are not well known (Zabel and Morrell 1992). Scheffer (1973) reported that in laboratory decay tests, the optimal moisture contents lie between 35% and 80%.

Most wood-inhabiting fungi cannot grow effectively in water-saturated wood because they are obligate aerobic organisms that require moderate amounts of oxygen for respiration. The upper limits of moisture contents that may cause decay vary between 100% and 250% depending on the void volume of wood, which varies inversely with wood specific gravity. Higher moisture contents will slow fungal growth in high-density wood. Optimal moisture levels for fungal growth in actual building envelopes are not exactly known and need to be identified.

4.3.2 Optimum oxygen levels

Another critical ingredient for fungal growth is the amount of free oxygen available for their metabolism. The process of aerobic respiration uses atmospheric oxygen as a reactant. Many fungi have optimal growth rate at oxygen levels between 19% to 20% of ambient air. Fungi are, however, very tolerant of low oxygen levels and their growth decreases when oxygen concentration drops below 1% to 2%.

Fungi growth rate depends also on the combination of oxygen and carbon dioxide. Build-up of carbon dioxide limits the amount of oxygen and consequently stops fungal growth but fungi are not necessarily killed.

4.3.3 Optimum temperature ranges

Fungal growth also depends on temperature levels. Temperature directly affects the many integrated metabolic activities of fungi such as digestion, assimilation, respiration, relocation, and synthesis. The metabolic reaction rate increases with increase in temperature until the heat denatures enzymes required for growth. Every fungus possesses three cardinal growth temperatures: a minimum, an optimum and a maximum. These levels indicate, respectively, the beginning of growth, the best growth, and the ceasing of growth.

Ambient air temperature limits for the growths of most fungi are between $0°C$ and $45°C$. The optimum temperatures for fungal growth lie between $20°C$ and $30°C$. Some Fungi such as *Gloeophyllum* species can grow faster at higher temperature ranges of $34°C$ to $36°C$. Growth rate of all wood-inhabiting fungi will stop at temperature higher than $46°C$ and will be killed at temperature higher than $60°C$. Growth rate is often reduced in halves for each ten degrees drop in temperature.

Apart from temperature and moisture content, time is an important factor in fungal wood decay. Fungi are resistant to prolonged exposure to lower temperatures and are killed by short exposure to high temperatures. For example, staining fungi are particularly susceptible to high temperatures and some species are killed by prolonged storage at $35°C$. Some wood-rotting fungi exhibit strange resistance to lower temperatures and can resume growth within a few hours after warming.

4.3.4 Other factors affecting fungal growth rate

Fungal growth also depends on other factors, such as the pH value, vitamins, minor metals, and light. In general, optimum fungal growth requires pH ranging from 3 to 6. Mold and wood-stain fungi are highly pH sensitive and their growth ceases or diminishes as pH exceeds 5. Brown-rot fungi, on the other hand, have the lowest optima of pH, approximately 3.

Wood-decay fungi can utilize many types of nitrogen, especially the amino forms found in wood (Huntgate 1940). Light, especially the ultraviolet wavelengths at high intensities, is usually harmful to the growth of wood-decay fungi. Some studies (Duncan 1967), however, suggest that periodic exposure to light may increase decay rate. Current knowledge cannot explain this apparent contradiction and further research is needed. Other environmental factors may also affect the growth and production of wood-decay fungi. Osmotic concentrations, atmospheric pressure, sound vibrations, gravitational forces and radioactivity are examples of these additional effects. Little is known, however, about their effects on the reproduction of fungi and the wood decay process.

4.4 Fungal damage in housing

Relatively new homes in many regions in North America and Scandinavia show signs of damage induced by fungal activities in their wall systems. Canada Mortgage and Housing Corporation (CMHC) monitored the health of the occupants of 400 moldy houses located in Wallaceburg, Ontario. The study measured the development of mold fungi that is hazardous to the health of occupants (Fugler 1996, White 1996). Their damage assessment was related to the allowable tolerance for carbon dioxide levels in an infant's lung. They did not quantify the growth of these mold fungi for specific construction materials or environmental conditions. They based their finding on the assumption that mold fungi appearance indicates a rise in humidity in the dwellings. Andersson *et al.* (1997) conducted a similar study to measure the toxicity effects of mold fungi growth on the health of toddlers at a child's daycare center in Helsinki, Finland. They investigated the toxic level that emanated from water-damaged gypsum boards attached to wood-frame construction. The results of these two useful studies were based on subjective evaluation of the damage response and so cannot be easily linked to hygrothermal loads.

Other researchers (e.g. Viitanen and Bjurman 1995) attempted to evaluate fungal damage in pine and spruce softwood materials due to growth of known fungi species with respect to moisture control. The main objectives of these studies were to evaluate the critical time required for common mold and wood-decay fungi to latch onto the surface of wood materials subjected to specific environmental conditions. They measured the growth activities of harmful bacteria and fungi to the applied moisture and thermal loads. They developed empirical damage functions of mold and wood-decay fungi in terms of moisture and thermal loads using laboratory experiments. These models will be employed later in this study to assess the long-term performance of wood frame construction in Ottawa, Canada.

5 Measurements of fungal damage

According to Morris (1998), Viitanen (1997 a) and Andersson *et al.* (1997), wood damage will occur provided that mold or wood-decay fungi succeed in latching on the wood to start their colony under favorable conditions. Biological damage in wood is often measured using laboratory experiments because the exact analysis of combined effect of humidity, moisture content, temperature, time and bio-deterioration of material in buildings is difficult. Other studies (e.g. Schmidt *et al.* 1983) focused on measuring the strength reductions in particleboard as a result of fungal damage under constant moisture conditions that favor fungal growth. They found out that particleboard would loose strength significantly when attacked by wood-rotting fungi.

Moisture and temperature distributions in wall system vary with season and many other factors. Moisture and temperature fluctuate depending on indoor air conditions, exterior weather, and wall system details. Thus, the results of previous studies using constant moisture and thermal loads cannot be used effectively to develop damage functions for actual building envelopes. Viitanen (1997 a, 1997 b) tested pine and spruce sapwood under changing moisture and thermal loads. In these experiments, two separate sets of testing for mold and wood-rotting fungi were conducted. The reason is that mold fungi growth depends on the relative humidity of the environment while wood-decay fungi activities are functions of the moisture content of wood (Viitanen and Bjurman 1995, Viitanen 1997 a, 1997 b). However, in actual life cycle of fungal growth, the wood would be attacked first by mold fungi and then may be replaced by the dangerous wood-rotting fungi.

6 Durability assessments using damage functions models

The TCCC2D two-dimensional heat, air, and moisture model (Ojanen and Kumaran 1992, 1996) was used to analyze the wall system shown in Figure 1. Ojanen and Kumaran (1992, 1996) used this model to determine the effect of exfiltration on the hygrothermal behavior of wall systems. Here, the effect of different indoor relative humidity and varying rates of exfiltration on the behaviour of the wall of wood-frame construction was investigated for Ottawa weather. Figure 1 also shows the tested range of recommended indoor relative humidity (ASHRAE 1995). The results of the TCCC2D computer model were the input for another computer program developed for the purpose of damage assessments in wood-frame constructions. The biological damage module in the new computer damage model was based on the theoretical mold index model proposed by Hukka and Viitanen (1998). The authors for easy implementation in heat air and moisture transport modified the mold index model of Hukka and Viitanen (1998) computer models. A summary of the enhanced mold index model and its damage prediction capabilities will be presented here. A detailed discussion is given elsewhere.

6.1 Enhanced mold damage model

Viitanen (1997 a, 1997 b) developed a mold index model based on the results of decay experiments of pine and spruce sapwoods. The mold index will be interpreted in this paper as the damage index. Viitanen's (1997 a, 1997 b) models are mathematical in nature and were developed to fit his test results. The test samples were subjected to relative humidity in the ranges of 75% to 100% and temperature varying from 5°*C* to 40°*C*. Hukka and Viitanen (1998) extended Viitanen's (1997 a) damage model to estimate mold growth under fluctuating moisture and temperature.

The mold index of Hukka and Viitanen (1998) can be calculated by

$$M_{max} = 1 + 7\left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right) - 2\left(\frac{RH_{crit} - RH}{RH_{crit} - 100}\right)^2 \qquad \textbf{(1)}$$

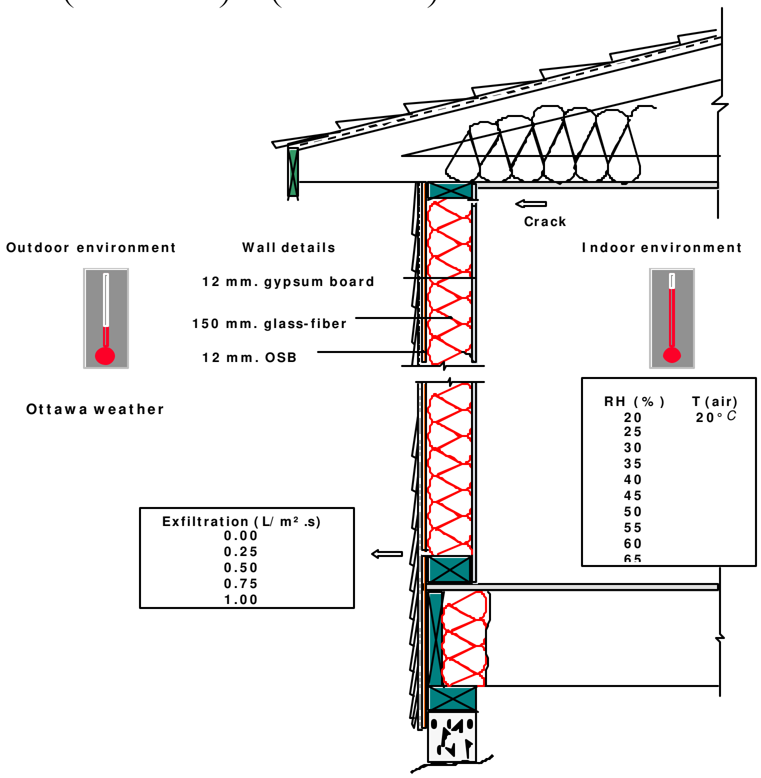

Fig. 1: Typical wall analyzed for the specified boundary conditions

where M_{max} is the mold index that varies from 0 to 6 (Hukka and Viitanen 1998) depending on the appearance of mold on material surface and RH is the test relative humidity. RH_{crit} is the critical relative humidity obtained from experiments as a function of the test temperature, T.

$$RH_{crit} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13T + 100 & T \le 20^\circ C \\ 80\,\% & T > 20^\circ C \end{cases} \qquad \textbf{(2)}$$

If the ambient relative humidity maintained above the critical value, RH_{crit}, for a period, t_m, fungi will start their reproduction process. Viitanen (1997 a) proposed formula fitted to experimental results to estimate the critical time, t_m, that is needed for initial response of mold or wood-rotting fungi. Hukka and Viitanen (1998) used the initial time, t_m, to calculate the rate of mold growth under favorable conditions using

$$\frac{dM}{dt} = \frac{k_1 k_2}{7 t_m} \qquad \textbf{(3)}$$

in which k_1 and k_2 are constants depending on the growth rate level and could be calculated as

$$k_1 = \begin{cases} 1 & M < 1 \\ \dfrac{t_m}{t_v - t_m} & M > 1 \end{cases} \qquad \textbf{(4)}$$

$$k_2 = \begin{cases} 1 & M < 3 \\ 1 - e^{2.3(M - M_{\max})} & M \geq 3 \end{cases} \qquad \textbf{(5)}$$

where M is the previous damage index and t_v is the time required for visual growth of mold fungi. t_m and t_v can be calculated according to Viitanen (1997 a) as

$$t_m = e^{-0.68\,\mathbf{ln}(T) - 13.9\,\mathbf{ln}(RH) + 0.14W - 0.33SQ + 66.02} \qquad \textbf{(6)}$$

$$t_v = e^{-0.74\,\mathbf{ln}(T) - 12.7\,\mathbf{ln}(RH) + 0.06W + 61.50} \qquad \textbf{(7)}$$

in which W and SQ are constants that take values either 0 or 1 to reflect the wood species and its surface quality, respectively. When the relative humidity levels are below the critical value, RH_{crit}, (dry condition) Hukka and Viitanen (1998) proposed the following mathematical form for the decline in mold growth rate.

$$\frac{dM}{dt} = \begin{cases} -0.032 & t - t_1 \leq 6\text{ h} \\ 0.000 & 6\text{ h} \leq t - t_1 \leq 24\text{ h} \\ -0.016 & t - t_1 > 24\text{ h} \end{cases} \qquad \textbf{(8)}$$

where $(t - t_1)$ represents the drying period.

Figure 2 shows the damage index variation at the bottom of the wall, shown in Figure 1, due to indoor relative humidity of 50% for different air leakage. The temperature and relative humidity output from the TCCC2D simulations are coupled with the mold damage index model. Figure 2 indicates that mold damage increases in a nonlinear fashion and depends on the rate of air leakage and season. Mold damage occurs in the spring and fall period, as illustrated by Figure 2, which agrees with observations in actual houses.

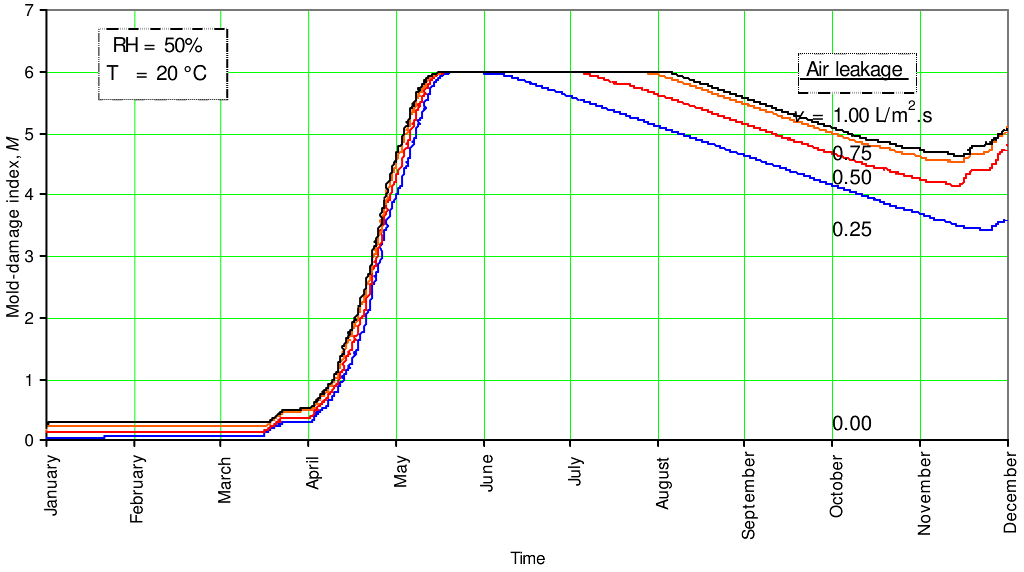

Fig. 2: Damage (mold) index variation with time for different air leakage rate

The simulation results also showed that the airflow rates as well as internal relative humidity affect the extent of mold growth. This is demonstrated in Figures 3 and 4 using the damage index at the end of simulation period (December). Figure 3 shows the variation of the damage index with respect to air leakage for different relative humidities. The figure indicates that damage growth rate is a nonlinear function of air leakage. According to the results shown in Figure 3, damage will not occur for a combination of air leakage rate less that 0.2 L/m^2.s and indoor relative humidity below 35%. Furthermore, air leakage equal or less than 0.001 L/m^2.s will not cause growth of mold for all possible indoor relative humidities. Figure 3 shows as expected that higher levels of indoor relative humidity would increase the probability of mold damage.

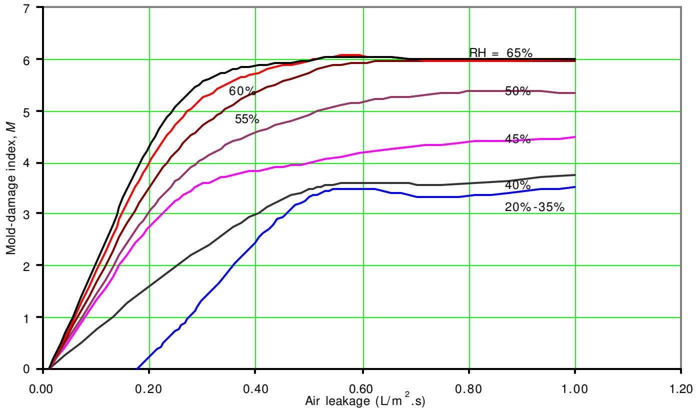

Fig. 3: Effect of air leakage on mold damage index

Figure 4 depicts damage index variation with respect to indoor relative humidity at the end of the simulation period. The figure shows that the damage index appreciably increases when the indoor relative humidity varies in the range 35% to 45%. Damage is much higher for higher levels of indoor relative humidity. The figure shows that damage values are the same for relative humidity in the range of 20% to 35%. Figure 4 shows that for all practical purposes, air leakage in the range of 0.5-1.0 L/m^2.s have the same effect on mold growth. Finally, Figure 4 shows also that damage values for a combination of indoor relative humidity equal to 20% or lower and airflow rate less or equal to 0.2 L/m^2.s are insignificant.

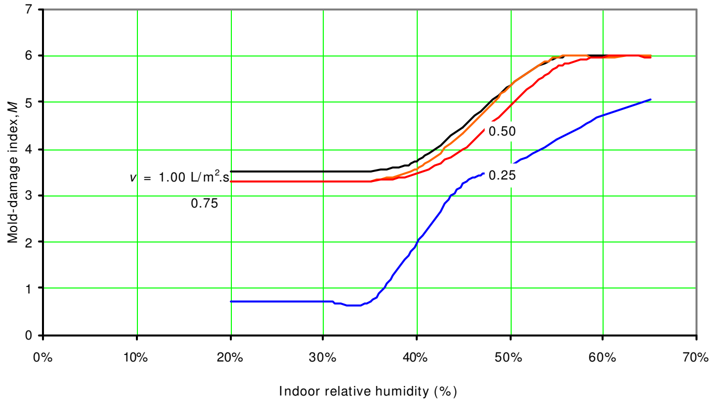

Fig. 4: Effect of relative humidity on mold damage index

It is very important to mention, once again, that the results presented for mold damage index variation are based on pine species experimental results. These results are conservative for OSB materials because the wood species often used in producing OSB panels are less durable than those of pine species.

7 Concluding remarks

In this paper, an approach has been presented to link hygrothermal models with damage functions concept. To illustrate this approach, results from a well-established hygrothermal model (Ojanen and Kumaran 1992, 1996) have been combined with a modified model of mold growth. The original mold model was reported in the literature (Hukka and Viitanen 1998, Viitanen's 1997a). The example case was exfiltration in wood-frame construction in Ottawa. Based on the mold growth index model, the following conclusions may be drawn. Damage analysis showed that air leakage rate had an impact on the wall system performances. The results showed that the mold growth index depends on the indoor relative humidity. Higher indoor relative humidity increases the damage rate. For the present case of exfiltration mold growth will dominate at the bottom of the wall.

The proposed system for durability assessments requires further experimental evidences and verifications. The damage in building envelope is not only due to biological growth, but it could be also due to structural or physical damage. Thus, the authors have conducted a series of experiments to measure physical damage in wood based products. The results of these experiments would be presented in future publications.

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