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Publisher's version / Version de l'éditeur:

Japan-Canada Conference on Building Envelope [Proceedings], pp. 1-14, 2003-06-01

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NRCC-45140

A version of this document is published in / Une version de ce document se trouve dans:
Japan-Canada Conference on Building Envelope, Vancouver, B.C., Juen 4-5, 2003, pp. 1-14

Criteria for Unacceptable Damage on Wood Systems

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Abstract

Advanced hygrothermal models can predict temperature and moisture conditions in wall components subjected to actual weather conditions, but damage functions are required to predict consequences for building performance. This paper documents progress towards criteria for unacceptable damage and discusses the work underway to define damage functions.

Durability is addressed in Canadian building codes where it impacts safety or health. It, therefore, proposed that damage to building envelopes be considered in two ways. First, strength loss to the system, which determine its level of safety; second, effect on the health of the occupants from unacceptable levels of fungal spores or metabolites entering the living space.

Damage functions for strength loss require an improved understanding of the limiting conditions of humidity and temperature for decay and of load distribution in platform-frame construction weakened by decay. Work is underway or planned in each of these areas and some preliminary results on time to establishment of decay in OSB will be presented. Damage functions for health impacts are very complicated to derive because it requires the knowledge of many interacting aspects. These aspects include knowledge of conditions affecting the type and amount of mould in the wall, air leakage or diffusion into the living space, exposure levels from exterior air, other building systems, health risk factors, and threshold levels for spores and metabolites to be determined by medical authorities. These threshold levels are also very difficult to establish because they vary from age group to another end even among individuals.

Introduction

With the development of advanced mathematical models for heat, moisture and air transport in wood-frame construction, building scientists now have the tools to predict how variation in material properties and wall design will affect the distribution of moisture content and temperature of the wall components (*inter alia* Karagiozis and Kumaran 1997). In some cases, extensive efforts have been undertaken to validate these models (Hens 1996, Kumaran and Wang 1999, Nofal *et al*. 2001). The next critical step is to predict what effect that moisture will have on the durability and serviceability of the structure. This requires the development of damage functions to graft onto the hygrothermal models (Nofal and Kumaran 1999, 2000). While the adverse effects of excessive moisture accumulation and retention are well understood, the criteria for unacceptable levels of damage have not been decided and the thresholds for deterioration are not well defined. This paper attempts to develop such criteria and discusses some of the work done to define these thresholds.

The consequences of excessive moisture accumulation and retention in wood in a building envelope include fastener corrosion, the growth of bacteria, mould, stain and decay fungi, increased termite damage and the proliferation of other insects. Until recently, the only real concern was strength loss caused by wood-rotting basidiomycetes (WRB) and termites. Over the last few years the potential health effects of mould growth, have also come to the fore. Both of these aspects, therefore, need to be considered in determining the long-term performance of the building envelope.

Criteria for Unacceptable Damage

Defining unacceptable strength loss or health effects is not a simple process. Examination of buildings being demolished or deconstructed, for reasons other than moisture problems, reveals that many had exhibited limited decay and mould growth without impairing the function of the building or its occupants.

In Canada, decay and termite damage have normally been noticed and repaired before they have made the building, or parts of it, collapse under normal (non catastrophic) loads and usage. Because of the variability in wood strength, design values are based on the fifth percentile for strength properties of in grade lumber. Consequently, there is a considerable degree of redundancy in the platform frame components and a high probability that decay will begin on components with a considerable factor of safety in terms of strength. Platform frame construction efficiently distributes loads and provides an additional level of redundancy in the structural performance of the system. Of course, a wood-frame structure that has suffered sufficient damage due to decay or termite attack can collapse under a severe event, including a strong earthquake (Beall 1998). Definition of unacceptable damage, therefore, requires an improved understanding of load distribution in platform frame construction weakened by decay. Such work is at the planning stages at the University of California Forest Products Laboratory. This work will focus around joints, since these are the critical locations for load transfer, normally contain end-grain susceptible to absorbing liquid water and contain a mass of wood that will be slower to dry out.

As explained later, decay once started can be a very rapid process. Under ideal conditions, WRB can grow at rates of up to 10mm per day over wood surfaces. Complete strength loss of wood colonised by decay fungi occurs in days or weeks, while the design life of a building is measured in years. Consequently, damage to a system from decay fungi should be considered unacceptable if it is detectable as statistically significantly different from the original properties of the system.

The presence of detectable mould on wood components in a wall does not necessarily imply that there will be adverse effects on the health of building occupants. Good building practices appropriate to the climate, plus tightened wall construction serve to mitigate the spread of mould from wall cavities for the following reasons:
(1) The mould appears on the wood components is physically separated from human contact by other solid layers of the wall.

(2) If there is a vapour-retarding layer on or immediately behind the interior drywall (typical in much North American construction), this reduces the diffusion of volatiles from the stud space into the living space.
(3) If there is an air barrier between the cavity and the interior space, this limits air-borne transportation of mould spores or volatiles into the living space. However, construction deficiencies that permit air leakage will allow fungal products into living spaces.

The linkage between mould and health effects on building occupants has not been adequately studied and remains unclear. Fungal spores are found everywhere, in indoor and outdoor air. Moulds can also be found in the ducts of the heating and ventilation system. Moulds can grow on drywall, paint, wallpaper, insulation, acoustic tiles, wood products and a variety of other building materials, particularly if they get wet during transport, storage, and construction or in service. They can also grow on carpets, curtains, clothes, footwear and furniture if these get damp. They are common in house plant soil.

There is no simple relationship between fungal spore concentration and health effects, and there are no accepted threshold limit values for fungal spore concentrations in air. The health of building occupants, and especially that of hypersensitive individuals, is associated with the overall quality of indoor air, their immune systems, age, weight, and other factors.. The factors contribute to indoor air quality, include outdoor air pollution, interior finishes and furnishings, indoor activities of the occupants, cleaning products, and the condition of the heating and ventilating system as well as the presence of bets and animals sharing the living space. Environments conducive to mould growth also favour development of other organisms, such as house mites, that are more strongly associated with negative health impacts than mould. For example, Finnish tests of children attending schools with moisture problems indicated more children were allergic to house mites (19%), pollen (16%) and animal dander (11%) than were allergic to mould (5%) (Taskinen *et*. *al* 1997).

The latter discussion clearly indicate that definition of an unacceptable level of mould growth will require an improved understanding of the potential for air leakage or diffusion into the living space, exposure levels resulting from exterior air and other building systems (e.g. HVAC), health risk factors, and threshold levels for allergens, mycotoxins and toxic volatiles to be determined by medical authorities. Consequently, it is impossible to propose a criterion for unacceptable health impacts now.

It may be recalled that durability is addressed in the context of the Canadian building codes where it impacts one of the root objectives, such as safety or health. The National Building Code of Canada states “deterioration resistance is not required where it can be shown that uncontrolled deterioration will not adversely affect any of a) the health or safety of building users, b) the intended use of the building or c) the operation of building services.

It is, therefore, proposed that damage to wood in building envelopes be considered in terms of detectable strength loss, which can adversely affect the structural capacity of the building. Additionally, damage to building envelopes (rather than the wood) may also be considered in terms of corrosion of metallic components or cracking of brittle materials used in the wall system such as concrete, stucco, and/or brick. The damage criteria may also include the impact on the health of the building occupants resulting from an unacceptable level of allergens, mycotoxins or toxic volatiles entering the living space.

Development of Damage Functions

Strength Loss

For the purposes of developing a model for strength loss of wood components, the decay process under fluctuating conditions can be divided into three stages:
(1) Establishment (2) Growth and decay (3) Survival (Nofal and Kumaran 2000).

Times to establishment, and threshold moisture contents for growth and decay of *Coniphora puteana* (the cellar fungus) on sapwood of European wood species have been determined through extensive work at VTT in Finland (Viitanen and Ritschkoff 1991, Viitanen 1997b). These data have been used to develop preliminary damage function for wood components (Nofal and Kumaran 2000). However, the Finnish results need to be confirmed for Canadian and US wood products. In addition, the work needs to be done, using fungi prevalent in buildings in North America.

The key issue in stage 1, is the time required for the WRB to get established on the wood and this is controlled by the development of suitable conditions for germination of WRB spores and the probability of their arrival at that location. Spore germination requires the coincident occurrence of moisture content above a threshold, adequate temperatures, nutrient availability, non-durable wood and the absence of antagonistic influence of other fungi.

Other than that from Finland, relatively little work has been reported in the literature on establishment under marginal moisture conditions. One reason for this is the difficulty in being certain what relative humidity (RH) the wood is exposed to. Sorption isotherm data of solid wood and plywood always show that at RH between 90 and 100% the corresponding equilibrium moisture contents ranges from 20 to 60% at 20^{o}C. For oriented strand board (OSB), the relative humidity corresponding to the 20% to 60% moisture content range varies from 94% to 100%. A slight drop in temperature can cause a major change in RH and condensation. These data are based on NRC measurements, which will be published later.

It is well known that maintaining wood below 20% moisture content provides a margin of safety against fungus damage (Wood Handbook, ASHRAE Fundamentals). The 20% rule was developed at a time when the majority of wood was air-dried and may well have become infected with decay fungi during the drying process. The decay process produces water, so it is more difficult to stop than it is to prevent from starting. Today, we recognise that while existing decay may continue until the wood is dried below 20%, infection of kiln dried (normally sterile) lumber cannot occur until the moisture content is higher than around 25%. Viitanen (1997b) demonstrated colonisation of non-sterile sapwood of European wood species by artificial inoculation with *C. puteana* when the moisture content remained at 22-23% for about a year or 25% for around three months. Heartwood with a higher natural durability would be expected to take much longer for establishment. Different decay fungi may also respond differently.

Establishment of WRB is normally preceded by a sequence of micro-organisms, such as bacteria, moulds, staining fungi that are very effective at rapidly colonizing wet wood and excluding WRB (Clubbe 1980). Not until these bacteria and fungi have used up the non-structural carbohydrates can decay fungi get a foothold. At that point, the probability of arrival of a WRB spore has to be considered. Basidiospores can constitute up to 50% of the air-spora at certain times of the year (Gregory 1973), but many of these will not be WRB. Even when equally susceptible wood samples are exposed outdoors, not all of them get infected immediately. Figure 1 illustrates the change in percentage of hem-fir L-joint samples showing decay with time. This suggests that there is a 0.18 probability of infection each year. Wood components within a wall would be expected to have considerably lower exposure to the air-spora unless there is a deficiency or opening in the façade allowing them to enter the wall.

Forintek Canada Corp. has a current project titled Limiting Conditions for Decay investigating the time to establishment and threshold moisture contents for WRB on Canadian wood products under non-sterile conditions. Since hygrothermal models (Nofal *et al*. 2000) and full scale experiments (Hazleden and Morris 2001) have shown the sheathing to be the wood component that stays wet longest, this project is focussing on oriented strand board (OSB) and plywood. The method exposes test pieces to various temperature and humidity combinations under non-sterile conditions, with regular air exchange, inoculating every two weeks with WRB, and testing for bending strength at intervals. Preliminary work to develop the test method has already shown that OSB exposed to 100% RH at 20^{o}C does not start to decay for 9-10 months despite inoculation every two weeks with WRB (Figure 2).

Nofal and Kumaran (2001) have developed an equation to predict time for establishment of decay fungi:

$$t_i = -\frac{g}{f} \qquad (1)$$

Where g and f are both functions of temperature, relative humidity, and wood species.

The key factors in stage 2 are the wood moisture content, the durability of the wood and the type of decay fungus. To date, the overwhelming majority of experiments on the effect of fungi on the strength properties of wood have been done using wood in contact with a source of liquid water and surrounded by air at close to 100% RH (*inter alia* Schmidt *et al* 1983). Optimum moisture contents for decay range from 40 to 80% (Zabel and Morrell 1992, Viitanen and Ritshkoff 1991). Under ideal moisture and temperature conditions, established brown-rot fungi can cause extremely rapid loss in strength. From a literature review, Wilcox (1978) reported loss in compression strength, important for wall plates, up to 60% in one week, in sapwood under ideal conditions (optimum moisture content and no antagonistic moulds). Under the same conditions, moderately durable heartwood lost 25%. For compression parallel to grain, important for studs, sapwood might lose up to 40% and moderately durable heartwood up to 15% in one week under ideal conditions. Of course, ideal conditions rarely occur in properly built envelopes. At just above threshold moisture contents, in the presence of competing fungi the rate of strength loss will be much slower (REF). The Forest Products Laboratory of the US Department of Agriculture currently has a project underway to determine rates of decay under marginal conditions using a method described by Curling, Clausen and Winandy (2001).

Nofal and Kumaran (2001) have developed an equation to predict weight loss over time:

$$\text{Rate of weight loss} = f + \frac{\partial f}{\partial t} t + \frac{\partial g}{\partial t} \qquad (2)$$

The key factors in stage 3 are the type of decay fungus, and the speed with which the wood dries out. Some decay fungi are better than others at resisting antagonistic secondary mould fungi that can attack once the wood dries below the minimum for growth of WRB (around 25%) and before it drops below the minimum for mould growth (around 16%). The faster the drying rate, the shorter the time for attack by secondary moulds. When the dried rapidly, WRB can survive for years at moisture contents to which wood in buildings will equilibrate once moisture sources are removed (Viitanen and Ritschkoff 1991). We are not aware of any data on loss of viabilityof WRB under cyclical wetting and drying conditions. Long term planning for Forintek's project Limiting Conditions for Decay includes investigation of the effect of cyclic wetting and drying on establishment, growth, decay and survival of WRB.

Nofal and Kumaran (2001) have developed an equation to predict the loss of viability with drying periods:

$$V = ae^{-bN} \qquad (3)$$

Where:
V represents viability
N is the number of dry periods
a and b are constants yet to be determined for North American wood species.
Nofal and Kumaran (2001) also developed an equation to relate strength (modulus of rupture) loss to weight loss:

$$MOR_{loss} = cw_l + d + E(hw_l + j) \qquad (4)$$

Where:
W_l represents weight loss
E represents a factor for engineered wood products
c, d, h and j are constants depends on the wood species and their natural durability. All these constants are yet to be determined for North American wood species.

Taking into account all these factors Nofal and Kumaran (2001) have developed an equation to predict the rate of damage of components from 0 = sound to 1 = failed:

$$\text{Rate of damage} = \left(\frac{c}{100} + \frac{h}{100}E\right) \times V \times \left(f + \frac{\partial f}{\partial t}t + \frac{\partial g}{\partial t}\right) + C_i \tag{4}$$

Where Ci represents the initial condition of the wood related to natural durability of the wood species.
The values of the coefficients used in these equations need to be checked for North American wood species and prevalent fungi. Damage functions for wood systems will require the information to be generated from the University of California Forest Products Laboratory work on the effect of decay on platform frame construction. This will determine the effect of strength loss in key locations on the bearing capacity of the entire system. Data being generated by Forintek Canada will be used to evaluate these coefficients and determine their importance on the overall perdiction of damage.

In the absence of the complete data set required to develop a reliable decay damage function for North American conditions, NRC-IRC have proposed using a function that captures the duration of co-existence of moisture and thermal conditions above threshold levels. Viitanen (1997b) suggested the cumulative sum of periods of RH 95-100% and temperatures above 0-5^{o}C can be used to predict the risk of decay. The thresholds were therefore selected as 5^{o}C and 95% RH and the index has been termed RHT(95). This allowed researchers to use various hygrothermal models to predict the impact of climate, wall design, material properties, and construction deficiencies on the development of conditions required for decay (REF). Any adjustment to these factors that reduces the value of the cumulative RHT can be assumed to reduce the risk of decay. Hygrothermal models can thus be used to suggest design considerations while the work continues towards a full damage function.

Health Impacts

As with strength loss, a model for the development of mould growth can contain three phases (1) Establishment (2) Growth and decay (3) Survival. Time to establishment and threshold moisture contents for mould growth on sapwood of European wood species has been determined through extensive work at VTT in Finland (Viitanen 1997a, Viitanen and Bjurman 1994, Viitanen and Ritschkoff 1991).

Time to initial establishment is predicted by an equation such as:

$$t_m = e^{-a\ln(T) - b\ln(RH) + cW - dSQ + f} \tag{5}$$

Where *W* takes the value 0 or 1 to reflect the mould susceptibility of the wood species and *SQ* takes the value 0 or 1 to reflect the surface quality (kiln dried with redistributed nutrients or re-sawn surface with lower nutrient content).

Time from establishment to the occurrence of visible mould is predicted by an equation such as:

$$t_v = e^{-g\ln(T)-h\ln(RH)+iW+j} \qquad (6)$$

The values of factors *a*, *b*, *c*, *d*, *f*, *g*, *h*, *i*, and *j* have yet to be determined for North American wood species.

Hukka and Viitanen (1999) presented a model for the simulation of mould growth on wood

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

Where k_1 and k_2 are correction coefficients yet to be determined for North American wood species.

The decline in mould viability was given the following form:

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

These equations have also been used to model mould growth in North American wall systems (Nofal and Kumaran 1999, 2000).

The values of the constants used in these equations were developed for European solid wood and need to be checked for Canadian and US wood products. Forintek Canada Corp. has initiated a project titled Limiting Conditions for Mould investigating the time to establishment and the threshold moisture contents for growth of moulds on Canadian wood products under laboratory conditions. IRC/NRC, PWGSC and other private researchers are developing non-destructive test methods to depict any harmful biological growth. They are trying to measure the effect of mould growth on the hygroscopic properties of the wood materials. In addition, the potential for transfer of spores and metabolites into the living space will be determined by work planned in collaboration with the Building Engineering group at Concordia University. Using their environmental chamber, wood frame walls will be exposed to conditions conducive to mould growth. Measurements of allergens, mycotoxins and toxic volatiles will be conducted in the "living space" adjacent to these walls. It is anticipated that by the time this work is completed, thresholds for these fungal products will have been determined by medical research. Contact will be maintained with Health Canada to monitor progress in this direction.

Conclusions

Criteria for unacceptable damage to wood systems should be defined in terms of:

1. statistically significant strength loss to the platform frame system and

2. threshold levels of allergens, mycotoxins and toxic volatiles that have yet to be determined by medical authorities.

There are currently insufficient data to define valid damage functions for North American wood systems in terms of either strength loss or health impact on building occupants. However, there is a considerable amount of work underway designed to generate the required data.

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