

Limit State Design for Biodeterioration - A New Paradigm for Management of Fungal Risks in Biobased Building Materials

by

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Bachelor of Applied Science (Honours), University of Waterloo, 2009

Master of Applied Science, University of Waterloo, 2012

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of the Requirements for the Degree of

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University of Victoria

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Abstract

Biodeterioration is the leading cause of failure in buildings. Organic materials, key components of our built infrastructure, are particularly vulnerable to biotic attack (i.e. fungal growth) and can suffer from pre-mature failure. These failures are responsible for billions of dollars of direct damage to wooden structures in Canadian buildings. The impacts of failure can range from mild surface disfigurement, allergic reactions, mycoses, to direct life-safety concerns from compromised building structures. These impacts all have different failure modes and it is therefore prudent to consider how these failures manifest.

The limit state design framework is an approach used by engineers to describe the risks of failure. It defines the probabilistic failure envelope of an inherent resistance being exceeded by a given load. The competing loads and resistances, in this case, consist of the fungal growth potential versus the intrinsic resistance of the substrate. Another key feature of limits state design is that it describes differing thresholds of failure depending on the potential impacts. This framework is desirable in application for biodeterioration in buildings. However, prior attempts to adopt these concepts into biodeterioration models have met with limited success. This dissertation is the first to effectively apply a limit state design framework to biodeterioration by considering two key states:

serviceability limit state (i.e. surface fungal growth), and ultimate limit state (i.e. incipient decay).

First, a database of fungal deterioration was created using *Penicillium chrysogenum* and *Gloeophyllum trabeum* fungi inoculated on jack pine (*Pinus banksiana*) prisms. These prisms were carefully controlled for both moisture content and temperature, while minimizing ambient contamination. Photo documentation using a 20x USB microscope permitted evaluation of the surface disfigurement of the ascomycete fungus (serviceability state), and non-destructive flexural testing permitted the identification of incipient decay with the wood rotting basidiomycete (ultimate limit state).

A serviceability limit state model was created using a population growth equation to describe the probability of detecting fungal growth as a function of substrate type (heartwood or sapwood), moisture content, temperature, and time. The model was contrasted with empirical tests on a mouldy roof in Vancouver, BC, and shows promising results that surpass the limitations of competing mould models. The method to develop the ultimate limit state model has been delineated in this dissertation, but further work is required.

Future scopes of work are provided to address the limits and areas of uncertainty revealed by this research, but the results can help reshape the narrative of biodeterioration risk assessments for the built environment.

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[Adapted from *Building and Environment*, Vol. 45(5), S.Johansson, L. Wadsö, and K. Sandin, “Estimation of Mould Growth Levels on Rendered Façades Based on Surface Relative Humidity and Surface Temperature Measurements,” pp. 1153–1160, © 2010, with permission from Elsevier.]20

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Author Contributions of Publications

The core of this thesis is comprised of three chapters that have been submitted as peer-reviewed manuscript. Below the citation, the author contributions are clarified. This thesis is based on the following published or accepted manuscripts:

- i. Lepage R, Glass S V., Knowles W, Mukhopadhyaya P. Biodeterioration Models for Building Materials: Critical Review. *J Archit Eng.* 2019;25(4):04019021. doi:10.1061/(ASCE)AE.1943-5568.0000366

RL conducted the literature review and wrote the manuscript. PM supervised and reviewed the manuscript. SVG provided input and reviewed the manuscript. WK reviewed the manuscript.

- ii. Lepage R, Glass S V., de la Bastide PY, Mukhopadhyaya P., Serviceability Limit State Model for Fungal Growth on Wood Materials in the Built Environment, Accepted in the Journal of Building Engineering (2022)

RL developed the concept and research methods, conducted the experiments, analysed the results, and wrote the manuscript. PM supervised and reviewed the manuscript. SVG and PdlB assisted in the preparation of the manuscript and provided guidance on experimental design, identification of appropriate laboratory methods, and interpretation of results.

- iii. Lepage R, Glass S V., de la Bastide PY, Mukhopadhyaya P. A Nondestructive Longitudinal Laboratory Test Method for Detection of Incipient Ultrastructural Changes in Wood. *J Test Eval.* 2021;49(6):1-13. doi:10.1520/JTE20190902

RL developed the concept and research methods, conducted the experiments, analysed the results, and wrote the manuscript. PM supervised and reviewed the manuscript. SVG and PdlB assisted in the preparation of the manuscript and provided guidance on experimental design, identification of appropriate laboratory methods, and interpretation of results.

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Lastly, I'd like to thank my parents, for whom, without them, none of this would be possible.

Dedication

This thesis is dedicated to my perseverant and relentless partner in crime, as well as the bundle of pure chaos that we somehow unleashed into this world.

Chapter 1 – Introduction

“All fungi are edible. Some fungi are edible only once” – Terry Pratchett

The inexorable passage of time leads the deterioration of all things. For some things, like those necessary for human survival, pre-mature deterioration is acutely undesirable. This is especially so for human shelter. Biotic and abiotic agents accelerate the process of deterioration, and those biotic agents originating from the Kingdom of Fungi are notorious in their propensity to obfuscate the human need for safe, healthy, and comfortable homes. We know this need as durability, and it is one of the driving concerns facing the building engineer.

When viewed in the context of shelter, trees are the essential source for critical structural materials – wood. Humans have been using wood as a primary structural material for shelter for millennia, due to its advantageous mechanical properties, availability, and affordability. In more recent times, it finds widespread use in low-, mid-, and high-rise construction, particularly with the advent of a suite of engineering wood products. These products enable ever long spans, higher capacity members, unique insulation products, and aesthetically desirable finishes, thrusting building typologies into novel applications. In pioneering these new frontiers, new challenges arise. With greater environmental forcings, coupled with greater structural loads, comes greater risks on these wood elements.

With these benefits comes drawbacks. As an organic material, wood is susceptible to myriad biodeteriorative agents, and many such organisms have specialized themselves to take advantage of this nutrient rich material. Few organisms have been more successful in leveraging this relationship than fungi. Fungi have established themselves in all six biological symbiotic niches with plants (mutualism, commensalism, parasitism, neutralism, amensalism, and competition) and are differentiated into 5 main heterotrophic levels: parasites, nekrophytes, sarkophytes, saprophytes, and symbionts (Schmidt 2006c). It is primarily saprophytic fungi that pose challenges to the built environment, as the plant matter we use in buildings is almost always dead. These fungi manifest either as surface moulds (sap-stainers, scavengers) or wood decaying fungi (white, brown, or soft rots) (Zabel and Morrell 1992), neither are particularly desirable as they lead to range of problems.

Premature deterioration of wood materials is a significant concern to the building industry. This deterioration can be superficial, in that of a sap-staining fungi, like *Ophiostoma piliferum*, or surface disfigurement, like *Aureobasidium pullulans*, leading to financial impacts for costs of remediation. This deterioration can also impact human health, via allergenic responses, such as *Cladosporium cladosporioides*, through severe mycoses, such as *Aspergillus fumigatus*, to life-safety risks from structural failure, from many of the wood rotting basidiomycetes, like *Gloeophyllum trabeum*. It is estimated that

10% of all timber cut in the United States is to replace decayed wood, much of it due to improper use and maintenance (Zabel and Morrell 1992). Assuming a similar rate and transferring this to a Canadian context, this could represent some \$1.5 billion of damages every year¹. It is an understatement to say that this constitutes a readily preventable expense.

In vernacular architecture, biological growth was indirectly controlled through water management (i.e. precipitation), as this has traditionally yielded success. Historical documents, such as Vitruvius' *De Architectura* or the Bible's Book of Leviticus have guidance around managing moisture and remediating moulds and mildew, hinting at an understanding of the effects of ventilation drying and biologically active extractives to manage fungal growth. Significant advancements have since accrued, with the middle of the 20th century leading to an understanding of the role of water vapour and air leakage condensation impacting durability (Baker 1969). In the 70s, describing the limits of fungal growth in terms of environmental parameters yielded isopleth and threshold approaches (Ayerst 1969a). Durability was often inferred based on known results from empirical testing (Scheffer 1970; P. Morris 1998; P. I. Morris 2009). From here, the rules of thumbs, such as maintaining RH's below 80%, are

¹ <https://cfs.nrcan.gc.ca/statsprofile/>, Accessed on November 14th, 2021

thus derived. From the 90s and 00s, more advanced fungal models were developed, with dynamic and empirical regressions providing the capacity to predict the occurrence of biological growth on simulated wall assemblies.

However, while the field of structural engineering adopted limit state design in the 1950s, using probabilistic failure envelopes under differing limiting failure conditions and designed to acceptable risk thresholds, such approaches have met limited success in describing biodeterioration in building engineering. This dissertation aims to shift the traditional approach of designing for biological durability by defining a serviceability limit state, or the probability of surface fungal growth, and an ultimate limit state, or the probability of the start of incipient decay in structural members. Synthesizing the inter-disciplinary elements of architecture, engineering, mycology, and ecology, this dissertation aims to provide a new narrative to provide pragmatic guidance on the management of biodeterioration of wood building elements of both surface staining and decaying fungi.

Delving into prior research, Literature Review reviews the prevalent literature in the modelling and characterisation of the risks of fungi to the built environment. Nearly all prior research activities have attempted to define the quantity of fungal growth, with myriad rating systems describing, oftentimes with extreme precision, the chaotic and unpredictable nature of a biological and inherently stochastic organism. These models

represent a significant leap in the ability to infer durability of building assemblies and quantitatively assess pre-mature risks of deterioration. Without them, building professionals had to rely on generic rules of thumb that necessarily result in overly conservative guidance.

In Serviceability Limit State (SLS), a new paradigm on fungal growth management is proposed. By providing a large-scale, carefully controlled and replicable experiments, logistic regressions were prepared to describe the probability of detecting fungal growth on the basis on favourable and hostile substrates as a function of temperature, moisture content, and time. Describing the probability of detection provides two key benefits: 1) mould abatement and remediation is frequently decided upon presence/absence of metrics, not the quantity of growth or a mould index, and 2) it permits taking risk tolerances of building owners into consideration. The results were validated with a field controlled experiment and show promising results, though further work is required.

Ultimate Limit State (ULS) provides a novel method to define the longitudinal effects of moisture, temperature, and substrate type on the risks of incipient decay. This forms the critical step towards expanding upon the scope discussed in Serviceability Limit State, into a comprehensive method to resolving the Ultimate Limit State failure conditions.

The desired goals of this dissertation are to provide new tools to building professionals to help ensure durable, long-lasting buildings. This, particularly in the face of climate change and amid a national housing crisis, is a necessary step to help eliminate the significant waste of resources, both financial and material, with premature failure of the existing and soon to be constructed building stock.

Chapter 2 – Literature Review

Biodeterioration Models for Building Materials: Critical Review

Robert Lepage, P.Eng.¹; Samuel V. Glass, Ph.D.²; Warren Knowles, P.Eng.³; and

Phalguni Mukhopadhyaya, Ph.D., P.Eng.⁴

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Abstract

Biodeterioration of building materials due to poor hygrothermal conditions is a major concern for the sustainability of buildings and the health and safety of occupants. The risks of biodeterioration are accentuated in high-efficiency buildings requiring further design considerations. Researchers across the world have tried to characterize this issue through a combination of field experience, modelling, and controlled laboratory investigations. However, integration of these research outputs in building enclosure design analysis is an unfinished agenda, partly due to the lack of coordination between engineering researchers, building enclosure designers, and biologists. This paper

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critically reviews the research done to date on biodeterioration models of building materials (e.g. wood) from the perspective of a building scientist and identifies the needs for further research initiatives that will facilitate the integration of biodeterioration models in building enclosure design analysis through national and international building code regulations and standards.

2.1. Introduction

Buildings pose an incredible burden on the environment, particularly with respect to climate change aspects, from their construction (embodied energy and carbon), their continued operation and maintenance, and demolition. Studies suggest that up to 45% of North American CO₂ emissions are created from building operation (EPA 2017), and the Intergovernmental Panel on Climate Change identifies the building sector as one of the most receptive for cost-effective carbon emission reductions (IPCC 2014). Energy efficiency measures, including the efficient use of material, can drastically reduce the environmental impact of buildings, leading to innovative materials and building enclosure assemblies that decrease building energy loads. However, the coupling of decreased heat flow with inadequate moisture management has led to severe premature damage of exterior building enclosures due to biodeterioration of building materials. Inadequate moisture management can also result in poor indoor air quality and

occupant health issues. Methods are therefore required to evaluate the potential impact of moisture on the durability and serviceability of building elements.

The challenge to characterize the biodeterioration, defined as biological activities which impair building function (e.g. mould, rot, stains), has been attempted by many North American and European building practitioners and researchers. A diverse range of experts from varied fields, such as biologists, food scientists, physicists, architects, and engineers, have tried to broach the subject from different angles leading to vast conceptual variations and occasional contradictions causing shortcomings in model predictive capacities and utility. A multi-disciplinary approach, with expertise in design and construction, mycology (study of fungi), statistical modeling, hygrothermics, and wood sciences is required to adequately address the complexity of biodeterioration in buildings.

This systematic review identifies and critically analyses some of the leading deterioration models, with the intent to provide a list of models and their best suited applications. As part of this analysis, the underlying experimental protocols are critiqued, which provides insight into the operating mechanisms, limitations, and strengths of the models. Lastly, based on the observed common limitations of the deterioration models, recommendations are made for future investigation. Predicted

durability guidelines (MacKenzie et al. 2007) and fungal growth tables (P. I. Morris, Minchin, and Zylkowski 2007) are beyond the scope of this paper.

2.2. Background

Building enclosure durability is a complex interplay of heat, air, and moisture flows combined with biological and chemical variables, such as type of biological agent, substrate nutrient density, alkalinity, and presence or absence of biological antagonists. Heat, air and moisture response, while well defined under idealized or static conditions, become similarly challenging under dynamic conditions. To assist in characterizing the hygrothermal behaviour (heat, air, and moisture), multiple transient computer based simulation tools have been developed (Delphin: Sontag et al. 2013; hygIRC: Cornick 2006; WUFI: Künzle 1995).

Transient hygrothermal simulation tools are used in two main functions: first, to create preliminary evaluations of proposed building enclosures; and second, to probe the underlying hygrothermal behaviour of existing building enclosures. The main benefit offered by biodeterioration or fungal models is as an extension to the hygrothermal simulation results to add a level of quantitative analysis that is otherwise left to subjective evaluation of the practitioner. Some of the extrapolations of the biodeterioration models include guidance for building codes to minimize durability risks.

The hourly hygrothermal outputs vary depending on the simulation tool, but typically include a moisture metric (e.g. relative humidity, moisture content, water content), and temperature. These serve as inputs to the biodeterioration model, usually with a set of assumptions. For many applications, fungi are used as the predominant indicator organism for deterioration, though bacterial, insectoid, and animal organisms may also affect durability.

The fungi domain is divided by wood scientists into two broad categories based on the impact on the substrate: 1) surface moulds, and 2) wood rotting basidiomycetes (WRB). Surface moulds pose little structural risk to the substrate, whereas WRB may create life-safety hazards from structural decay. This is contrasted by mycologists, which categorized fungi phylogenetically, with the two broad phyla of interest consisting of *Ascomycetes* (e.g. “moulds”) or *Basidiomycetes* (e.g. “decay”), though both phyla can behave both as surface moulds and decay agents. The variation in perspective between these two professions is their respective area of focus; the substrate or the fungi.

Types of decay are further identified by soft-rots, brown rots, sequential white rots, and simultaneous white rots, classified mainly by the metabolic residues and digestive pathways. However, this falls beyond the scope of this review and has been addressed by a number of researchers (Schmidt 2006a; Zabel and Morrell 1992). The health impacts of mould are similarly well-documented in multiple medical papers, journals, and

regulations (World Health Organization 2009; Institute of Medicine (US) Committee on Damp Indoor Spaces and Health 2004; Burge 2001; Uzunovic, Yang, and Morris 2011; Uzunovic et al. 2003). It should be sufficient to state that those with impaired immune systems are at high risk of mycoses, those with allergic responses may also experience negative symptoms, and those working in environments of high fungal spore loads may become sensitized and develop allergenic responses. For healthy individuals, the risks posed by mould appear minimal.

The interest in fungal modeling has led to previous literature reviews (Vereecken and Roels 2012; Gradeci et al. 2017). However, the novel approach contained herein includes both mould and decay, a focus on North American characteristics (wood and fungal species, construction practices), and extends the review to also evaluate the merits of the models based on mathematical and biological mechanisms.

2.3. Biodeterioration Models

Models are mathematical representations of reality, quantifying the relationship between explanatory variables to a response variable. Biodeterioration models typically incorporate environmental and material data and produce a durability risk score.

Temperature, moisture (relative humidity [RH]/moisture content [MC]/water activity [a_w]/ water potential [ϕ]), and substrate properties (alkalinity, nutrient density, hygroscopicity, etc.) are some of the known variables for fungal growth. However, the

relationships between these parameters to fungal growth are derived by various means and implemented in different ways. The method used in this article to evaluate the models is based on the adequacy of *the model structure* (e.g. mathematical representation), *selection of parameters, biological and mycological merits* (including experimental protocols), *and ease of use*. Summary tables of the models and their salient properties are provided in Table 2-5,

Table 2-6, and

Table 2-7.

2.3.1. Model Structures

Several model structures have been proposed, such as dose-response models (Altshuler 1981; Pliska 1987; Brischke and Rapp 2008; Isaksson et al. 2010), growth models (Klaus Sedlbauer, Krus, and Breuer 2003; Ayerst 1969a; Smith and Hill 1982), and regression models (H. A. Viitanen and Bjurman 1995), to relate biodeterioration to the explanatory variables (e.g. substrate type, temperature, water activity, etc.). These relationships may be causal, wherein a mechanism of action can be established, or correlative, where the interdependence is described mathematically. Generally, correlative relationships are less robust than causal relationships as the validity only applies under the set of circumstances by which the relationship was derived. Models are further categorized as deterministic or stochastic. Deterministic models are fully explained by the defining parameters and initial conditions, and provide unique solutions, whereas stochastic models are based on probability distributions of the defining parameters resulting in non-unique outputs.

2.3.2. Selection of Parameters

Multiple parameters may be used to fit the explanatory to the response variables. These include environmental data (temperature, moisture, etc.), biological data (fungal types,

biological inhibitors, internal competition), and substrate impacts (substrate type, substrate nutrient density, substrate hygroscopicity). The selection of these parameters for the individual models is scrutinized based on their known impact on fungal growth.

2.3.3. Biological and Mycological Merits

A fungal model based on mycological principles is a requirement for accuracy and robustness. An understanding of the condition required for fungal metabolic activities, and of the reproductive life-cycles, help clarify what the model is attempting to quantify. Inadequate consideration of biological parameters may generate models that are not representative of known fungal behaviour. While the results of the model may nonetheless be accurate, these may be a result of over-fitted parameters and may lose their accuracy at the extremes of the fitted value ranges.

2.3.4. Classification of Biodeterioration Models

The fungal models reviewed generally fall into three categories, roughly ascribed by the method of reasoning: deductive, inductive, and abductive. For simplicity, they are described functionally, as “Indices”; that correlate a degree of fungal growth with an index based on empirical observations (e.g. it ascribes a score to the environmental conditions X, which is then correlated to a fungal metric Y); “Thresholds”, which define the limiting conditions required for growth and infer extent of growth based on

environmental conditions (e.g. with environmental conditions 'X' which surpass the known limiting conditions, therefore we anticipate a 'Y' fungal metric); and "Empirical", which is not to say that empirical elements are not included in the other elements, but rather that the response variable is regressed to the explanatory parameters to describe the expected extent of fungal growth (e.g. X environmental conditions are known to correlate with a Y fungal metric).

2.3.4.1. Indices

Index models quantify environmental parameters and correlate the product with an extent of deterioration. The link function between the product of the explanatory variable may be regressed with empirical data. Mathematically, index models are categorically defined in equation (2-1),

$$\text{Fungal Growth} \propto g^{-1}(f(P_1, P_2, \dots, P_n)) \quad (2-1)$$

where ' P_1 ' to ' P_n ' are the explanatory parameters, ' f ' is the linear predictor, and ' g ' is the link function that relates the linear predictors to the extent of decay. Relative Humidity and Temperature – 80 (RHT80) or RHT95 indices, mould indices, and Dose-response models are examples of such models where the explanatory variables describe the relationship of the product with fungal growth but does not directly predict extent of fungal growth.

2.3.4.1.1. RHT Indices (80/95) (Mukhopadhyaya et al. 2009; Wang and Morris 2011)

The RHT index was conceived as part of the Moisture Management for Exterior Wall Systems (MEWS) project, tasked with identifying long-term moisture response indicators for risk of deterioration (P. Mukhopadhyaya 2003); it has also been adopted as part of the International Research Group on Wood Protection (Jieying Wang and Morris 2011). The index is a cumulative hourly sum of the moment about a minimum temperature and relative humidity threshold. To minimize corrosion and mould growth, a relative humidity threshold of 80% has been proposed; for decay, the proposed threshold is 95%RH, and a temperature baseline of 5°C is proposed. The relationship is shown in equation (2-2).

$$\text{RHT}_{x,y} = \sum (RH - RH_x) \cdot (T - T_y) \mid RH > RH_x, \& T > T_y \quad (2-2)$$

The model appears well correlated to decay risks at near saturated conditions (Jieying Wang and Morris 2011).

Structure: The model is deterministic and dynamic. It uses the RHT base value (80 for corrosion or moulds, 95 for decay) as an indicator for risk of deterioration. Temperature and RH are weighted equally and linearly.

Biology: The RHT index is used only as an indicator for risk of growth and does not predict initiation or extent of growth. There are no considerations for substrates, fungal

species, or dynamic effects. There are no upper limits to temperature, which may pose concerns for applications where temperatures may exceed 40°C (S. Johansson, Wadsö, and Sandin 2010). The model does provide capacity for desiccating events which may reduce the risks of fungal growth.

Applicability: The model is relative easy to use and transparent in application as it provides a useful metric to compare different cases. However, further validation is required to provide predictive capacities on acceptable levels of performance.

2.3.4.1.2. Mould Indices (S. Johansson, Wadsö, and Sandin 2010)

The mould index was developed to assess the potential for mould growth of rendered façades over insulation. The basis for the mould was on surface temperature and humidity monitoring over a 20-month period on a single test house with different constructions, colours, and orientations. The results are three indices with increasing layers of variables. The indices are the time integration of mould growth potential functions for surface temperature, surface relative humidity, and a recovery function, to simulate delays in growth after adverse environmental conditions. The most comprehensive is described in equation (2-3),

$$I_3 = \int_{t=t_0}^{t_i} f_r(\tau) f_T(\tau) f_\phi(\tau) d\tau \quad (2-3)$$

where ' f_T ', temperature score curve, and ' f_{RH} ', the RH score curve, are shown graphically in Figure 2-1, and ' f_r ', the recovery factor, is equal to 0 if the previous time-step did not result in any growth (I_3 is equal to or less than 0), otherwise it has a value of 1. The combined temperature and relative humidity scores closely resemble the isopleth plots discussed later.

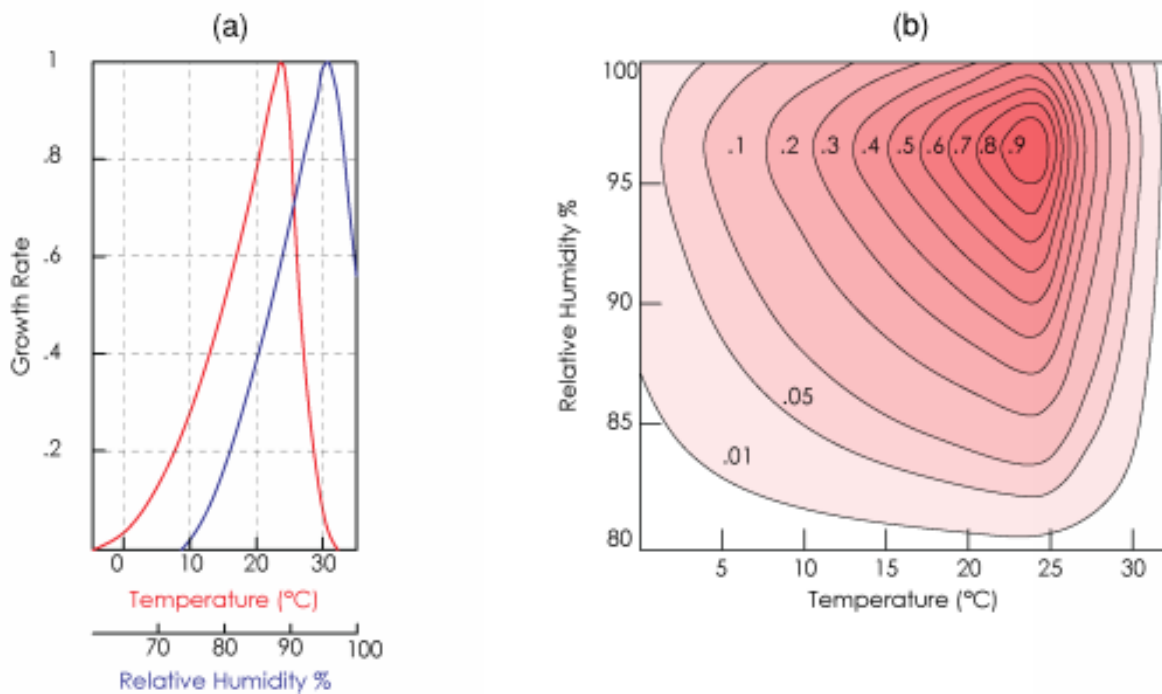


Figure 2-1– (a) RH and temperature weighting factors for *Cladosporium* spp (b) with RH (dark) and temperature (light), with combined RH and T scores. [Adapted from *Building and Environment*, Vol. 45(5), S.Johansson, L. Wadsö, and K. Sandin, “Estimation of Mould Growth Levels on Rendered Façades Based on Surface Relative Humidity and Surface Temperature Measurements,” pp. 1153–1160, © 2010, with permission from Elsevier.] (Source: S. Johansson, Wadsö, and Sandin 2010)

Structure: The model is deterministic and dynamic. The integration of temperature and relative humidity functions generates a mould potential. However, relative humidity and temperature are confounded, and may have interdependent functions which may

not be fully captured in this study. The model indicates only risk of growth and does not provide predictions on start to germination time or extent of growth or recession.

Biology: The fungal species are *Cladosporium* spp. on an unknown substrate, as no isopleth data were available to construct a species-specific temperature and humidity functions. The fitted temperature and humidity functions curves are based on a single study in a single climate and may vary depending on species and substrates.

Applicability: Conceptually, these models are easy to incorporate within a model; however, the temperature and relative humidity equations have not been provided within the paper, aside from graphical format, which renders adoption challenging for practitioners.

2.3.4.1.3. Dose-Response for Mould (Isaksson et al. 2010)

A dose-response relationship was proposed to describe the magnitude of the response to a given stressor. In fungal models, the stressor (dose) is a period of conditions suitable for fungal growth; the response is fungal growth. The cumulative dose is described by the product of a temperature and humidity function, described in equation (2-4) to (2-6) (Isaksson et al. 2010), respectively,

$$D = D_{\varphi}(\varphi_i) \cdot D_T(T_i) \quad (2-4)$$

$$D_{\varphi} = \begin{cases} \exp [15.53 \cdot \ln (\frac{\varphi}{90})] \rightarrow 75\% < \varphi \leq 100\% \\ (-2.7 + 1.1 \cdot \varphi/30) \rightarrow 60\% < \varphi < 75\% \\ -0.5 \rightarrow \varphi < 60\% \end{cases} \quad (2-5)$$

$$D_T = \begin{cases} \exp [0.74 \cdot \ln (\frac{T}{20})] \rightarrow 0.1^{\circ}\text{C} < T \leq 30^{\circ}\text{C} \\ -0.5 \rightarrow T < 0.1^{\circ}\text{C} \end{cases} \quad (2-6)$$

where ' D_{φ} ' is the dose generated by daily average relative humidity ' φ_i ', and ' D_T ' the dose created by the daily average temperature ' T_i '. The term ' D ' is expressed in number of days and ' N_{ref} ' is the reference number of days for a specific climate resulting in mould growth. Mould onset is anticipated when the ratio of ' D ' to ' N_{ref} ' is equal to 1. The equations describing the dose for relative humidity and temperature are provided in equations (2-5) and (2-6).

Structure: The model is deterministic and dynamic, with separation of the temperature and humidity variables to combine to create an aggregate 'dose' of fungal growth. This model predicts time until growth, but not extent or severity.

Biology: The concern with dose-response models is the response may vary non-linearly with time and other conditions (e.g. rate of fungal growth is not linear). It is uncertain whether such models are applicable for the growth of living organisms. The calibration data set was provided by Viitanen et al. (1991) and was based on fungal growth on pine and spruce under constant temperature and humidity conditions. Critically, this model

considers fungal recession under inclement conditions. Despite a statement of following a limit-state concept, no evidence was found indicating resistance factors for substrates.

Applicability: This model builds on other indices with additional layers of complexity but is nonetheless easily applicable for practitioners. As with other indices, the product of a temperature and RH function provides straightforward and transparent results.

2.3.4.1.4. Mould Resistance Design Model (Thelandersson and Isaksson 2013)

The Mould Resistance Design (MRD) model builds on previous work by Isaksson (Isaksson et al. 2010), but with a more generalized form and with a new data set.

Increased accuracy is provided by further subdividing the dose into 12h intervals. The framework of this model is based on a dose-response relationship to determine time of germination,

$$D_{12} = D_{\varphi}(\varphi_{i,12}) \cdot D_T(T_{i,12}) \quad (2-7)$$

$$D_{\varphi} = \begin{cases} 0.5 \cdot \exp [15.5 \cdot \ln (\frac{\varphi_{12}}{90})] \rightarrow 75\% < \varphi_{12} \leq 100\% \\ (-2.118 + 0.0286 \cdot \varphi_{12}) \rightarrow 60\% < \varphi_{12} < 75\% \\ -0.4 \rightarrow \varphi_{12} < 60\% \end{cases} \quad (2-8)$$

$$D_T = \begin{cases} \exp [2.0 \cdot \ln (\frac{T_{12}}{20})] \rightarrow 0.1^{\circ}\text{C} < T \leq 30^{\circ}\text{C} \\ -0.4 \rightarrow T < 0.1^{\circ}\text{C} \end{cases} \quad (2-9)$$

where ' D_{φ} ' is the dose generated by 12-h average relative humidity ' φ_i ', and ' D_T ' the dose created by the 12-h average temperature ' T_i '. The term ' D ' is expressed in number

of days and ' N_{ref} ' is the reference number of days for a specific climate resulting in mould growth. Mould onset is anticipated when the ratio of ' D ' to ' D_{crit} ', the point of fungal germination at 90% RH and 22°C, reaches a value of 1.

Structure: The model is deterministic and dynamic. Only 5 different test conditions were assessed; the lowest and highest temperatures were 10°C and 22°C, respectively, which therefore requires extrapolation for temperatures falling beyond these ranges leading to concerns of uncertainty. Once the equivalent dose is determined, it is normalized to a baseline growth (22°C and 90% RH). Negative doses are used to try to reconcile sub-optimal environmental conditions. The MRD is only able to predict onset of mould, and not projected extent.

Biology: A multi-species suspensions of common buildings moulds are used in the model and incorporates data with a different set of fungi. Normalizing the dose to a relative control helps resolve the non-linearity issue of dose-response models in describing biological growth, but nonetheless does not describe the actual extent of fungal growth, only the description of equivalent dose.

Applicability: The model is readily integrated with hourly output from hygrothermal simulation models. Validation with experimental evidence suggests further refinement is required to improve accuracy and reliability.

2.3.4.1.5. Dose-Response for Decay (Brischke and Rapp 2008)

The dose response relationship was used to establish the extent of decay from wood rotting basidiomycetes on 27 test sets in 23 different field exposure conditions across Europe over a period of 7 years. The samples consisted of prisms of Scots pine (*Pinus sylvestris* L.) and Douglas Fir heartwood (*Pseudotsuga menziesii* Franco) stacked in accordance with European standards EN335 -2006. The prisms are scored on the mean decay rating from EN252-1989. The dose as a function of moisture content and temperature are shown in Figure 2-2, derived from equations (2-10) to (2-12),

$$d_{daily} = d_{MC} \cdot d_T \quad (2-10)$$

$$d_{MC} = 6.75 \times 10^{-10} MC^5 - 3.50 \times 10^{-7} MC^4 + 7.18 \times 10^{-5} MC^3 - 7.22 \times 10^{-3} MC^2 + 0.34 \times MC - 4.98 \quad (2-11)$$

$$d_T = -1.8 \times 10^{-6} T^4 + 9.57 \times 10^{-5} T^3 + 1.55 \times 10^{-3} T^2 + 4.17 \times 10^{-2} T \quad (2-12)$$

$$for\ all\ -1^\circ C \leq T \leq 40^\circ C$$

where ' d_{mc} ' is the dose generated by daily average moisture content, ' MC ', and ' d_T ' the dose created by the daily average temperature ' T '.

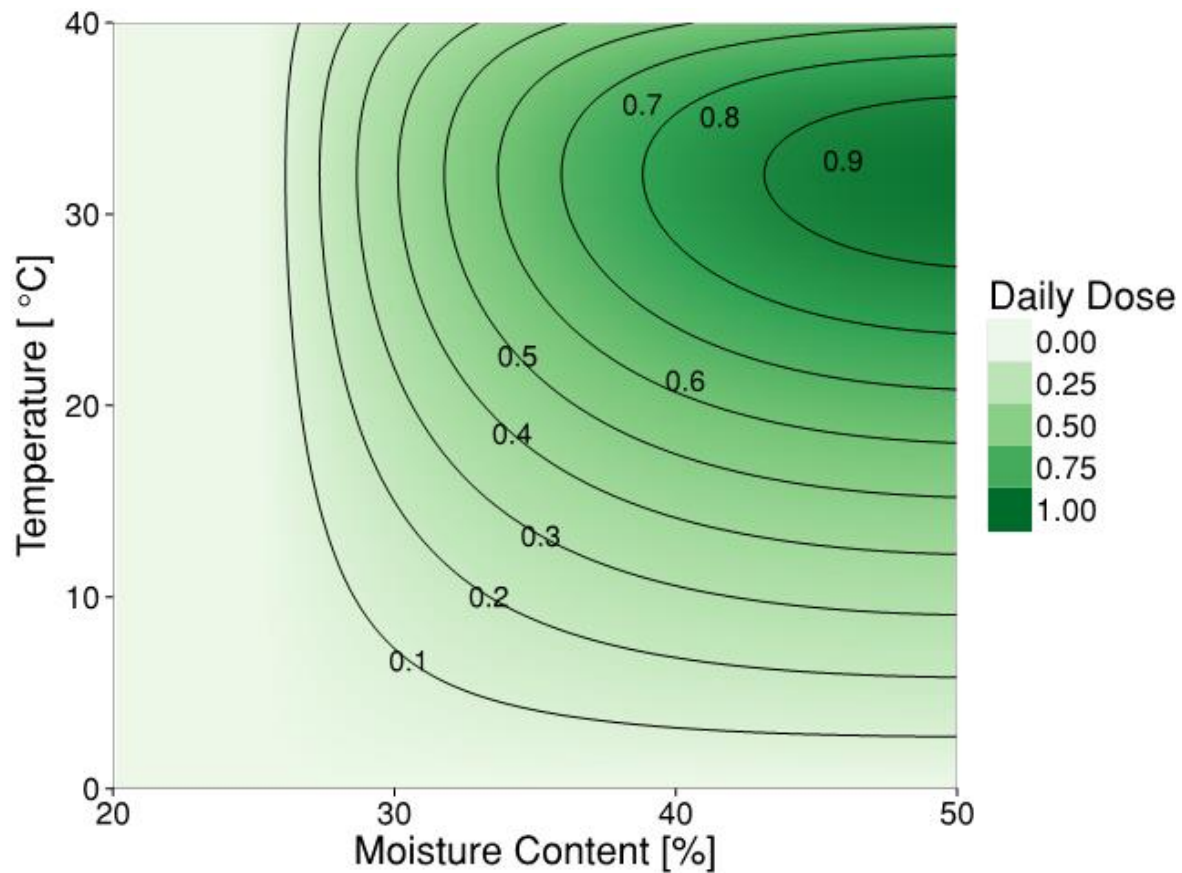


Figure 2-2 – Daily temperature and moisture content dose values for decay (Based on: Brischke and Rapp 2008)

Structure: The model is deterministic and dynamic and uses temperature and moisture content to describe the extent of decay, not fungal growth. The moisture content for the wood samples were calibrated, but the accuracy of electrical resistance based moisture content readings are unreliable beyond the fibre saturation point (Forest Products Laboratory 2010; Skaar 1988; J. F. Siau and Avramidis 1996).

Biology: The field exposure tests provide a broad-range of natural fungal inoculation, which causes difficulty in assessing effects of fungal spore loads based on the different

locations and even between samples. The applicability of the 'stacked prism' method does not provide realistic test conditions for building materials.

Applicability: This model is best applied for scenarios involving decay and exposure to liquid water. In situations where the wood moisture content is below the fibre saturation point (as in most mould-related problems), another model should be used. Recommendations on acceptable dose level are not provided, though a Mean Decay Rating of less than 1 can be achieved from dose ranges of 200 to 475.

2.3.4.2. Thresholds

Threshold models define the limiting boundary conditions for fungal growth under which a change in the response variable is anticipated. Isopleth models, which characterize the limiting conditions of temperature and relative humidity, are one such example; strict threshold limits for fungal growth under certain environmental parameters are another (i.e. not to exceed 80%RH over duration of 30 days). The biogrothermal model, while slightly different than other isopleth or threshold models, nonetheless uses the observed environmental conditions relative to the limiting growth conditions to infer extent of contamination. Threshold models are mathematically represented in equation (2-13),

$$\text{Fungal Growth} \geq \begin{cases} D_1 = f_1(P_1, P_2, \dots P_n) | \text{Condition 1} \\ \vdots \\ D_n = f_n(P_1, P_2, \dots P_n) | \text{Condition } n \end{cases} \quad (2-13)$$

where ' P_i ' to ' P_n ' are explanatory parameters used to define the decay functions, ' f_n ', (which may be a binary pass/fail), under a set of conditions.

2.3.4.2.1. Isopleths (Ayerst 1969a; Smith and Hill 1982)

Ayerst (Ayerst 1969a) provides one of the pioneering relationships between relative humidity and temperature for two fungal species on malt agar strips. The malt agar strips were placed in temperature-controlled chambers; humidity was controlled with salt solutions. A total of 30 isolates of 12 species of *Apergillus spp.*, *Penicillium spp.*, and *Stachybotrys atra* were tested over a range of water activity and temperatures. Smith & Hill (1982) replicated the study on *A. versicolor* and *A. restrictus* with relatively similar results, shown in Figure 2-3.

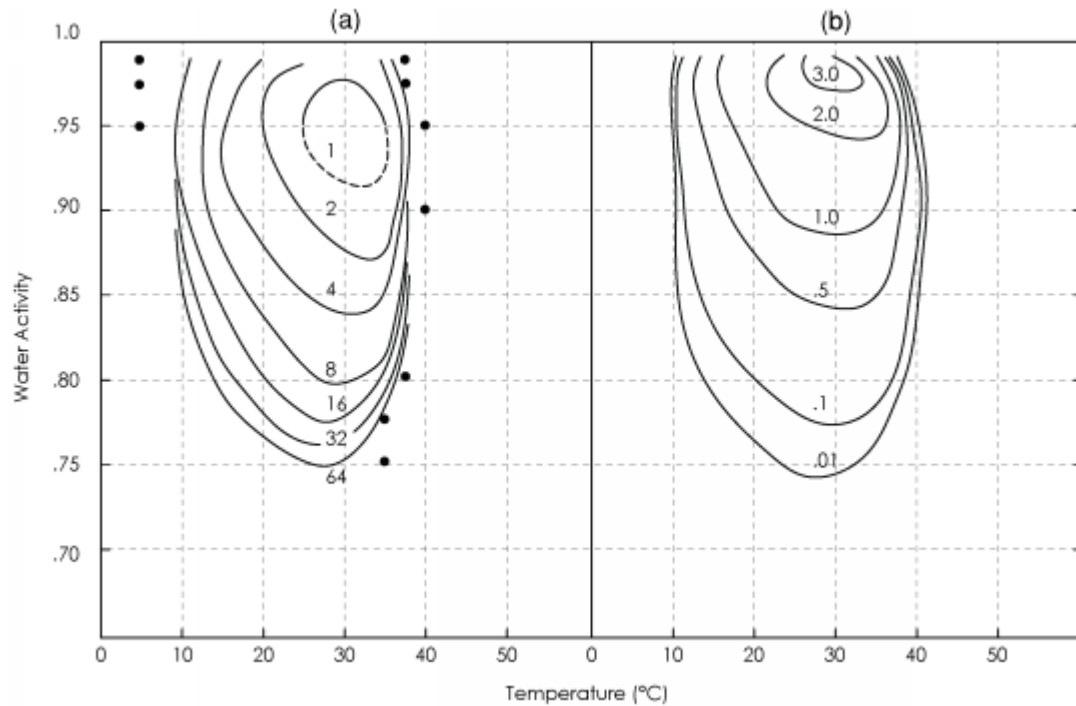


Figure 2-3– Germination time (days) (a) and growth rate (mm/day) (b) for *Aspergillus versicolor*. Black dots indicate conditions under which germination had not occurred after 95 days. [Reprinted from *Transactions of the British Mycological Society*, Vol. 79(3), S. L. Smith and S. T. Hill, “Influence of Temperature and Water Activity on Germination and Growth of *Aspergillus restrictus* and *A. versicolor*,” pp. 558–560, © 1982, with permission from Elsevier.]

Structure: The structure is steady state and deterministic. These isopleths provide the germination times and mycelial growth rates for a range of temperature and water activity conditions. The steady state nature of these experiments is unable to predict time until germination or extent of growth in dynamic environmental conditions. The effects of unfavourable conditions are not included.

Biology: The study focused on *Aspergillus restrictus*, and *A. versicolor*, on malt agar in constant temperature and RH conditions, which may yield significantly different results on different substrates.

Applicability: Simplicity lends itself to use as guideline. However, these models are unable to include exposure times and are thus unable to adequately predict fungal growth as a function of dynamic temperature and moisture conditions.

2.3.4.2.2. Temperature Ratio (H. Hens 1991a), RH Threshold (H. L. S. C. Hens 1999), and ASHRAE Standard 160 (2009) – Criteria for Moisture-Control Design Analysis in Buildings

These three threshold models are all incremental developments from the original International Energy Agency (IEA) Annex 14 final reports. The temperature ratio model was designed to implement a practical approach to minimize condensation and mould risk; the RH Threshold further refines the limiting RH conditions for fungal growth; and the ASHRAE 160 Standard provides explanatory material for assessing and modeling fungal growth risk.

Mould germination was assumed to be determined strictly on the fungi's minimum germination threshold as a function of the surface saturated vapour pressure. The IEA Annex 14 (1991) forms one of the first pioneering works for establishing minimum threshold for fungi as applied to the built environment. The ratios were devised from a heat and moisture balance on the surface of interior plaster. Mould germination was related to equation (2-14), whereas the minimum surface temperature to avoid mould growth is found in equation (2-15),

$$p \geq a \cdot p'_{si} \quad (2-14)$$

$$\tau = \frac{\theta_{s,min} - \theta_e}{\theta_i - \theta_e} \geq 0.7 \quad (2-15)$$

where ' p ' represents the surface vapour pressure, ' p'_{si} ' represents the saturated surface vapour pressures, and ' a ' represents the 'fungal coefficient' representing the minimum surface relative humidity to support mould germination. In equation (2-15), ' θ_i, e ' represent the interior and exterior air temperatures, and ' $\theta_{s,min}$ ' the minimum surface temperature.

The RH Threshold builds upon the definition of ' a ' in the original IEA Annex 14 work by determining the lowest relative humidity as a function of temperature (H. L. S. C. Hens 1999). The threshold relationship is shown in equation (2-16).

$$\varphi_{threshold} = 0.033\theta^2 - 1.5\theta + 96 \quad (2-16)$$

The IEA Annex-14 demonstrated that higher relative humidity conditions are required at shorter durations to stimulate fungal growth, and consequently Hens provides an updated logarithmic curve describing this relationship (equation (2-17)).

$$\varphi_{wT} = \min [1, 0.8 \cdot (1.25 - 0.0588 \ln(t))] \quad (2-17)$$

The ASHRAE 160 Standard builds upon the original IEA Annex 14 work by providing methods and protocols to specify performance-based design criteria for predicting moisture related damage risks to the building. It is divided into three sections; 1) criteria

for selecting analytic procedures, 2) criteria for input, and 3) criteria for evaluation. The conditions necessary for minimizing mould growth are a 30-day running average surface RH less than 80%, a 7-day running average surface RH less than 89% RH, and a 24-h running surface RH average less than 100%. Note that ASHRAE 160-2009 had a transcription error listing the 7-day average RH as 98% instead of 89%. It also goes beyond the IEA annex by also stipulating minimum and maximum temperatures, 5°C and 40°C, respectively.

Structure: These models only consider temperature as input variable which then provide the limiting RH conditions. These models do not provide risk of fungal growth nor anticipated duration until germination, but instead only provide a conservative threshold for avoiding mould growth.

Biology: Dynamic influences were discussed, but not included in the assessment. The assumed temperatures ranged only from 20°C to 25°C for the temperature index. The 'a' coefficient was intended to aggregate multiple fungal growth properties (species, nutrients, substrate, etc.), but the limiting values were established based *Aspergillus versicolor* on an agar substrate, observed to not grow at water activity (a_w) levels below 0.75, with growth on building materials infrequent for RH below 85%. A compromise to $0.8a_w$, the water activity or equilibrium RH of a material with its surroundings, appears to have been agreed upon by the IEA committee to provide a degree of safety. This

results in an '*a*' value as use of a coefficient for a factor of safety, as opposed to a descriptor of anticipated growth. To account for time-scale influences, the minimum RH thresholds were modified to 100%, 89%, and 80% for 1 day, 1 week, and 1 month, respectively.

Applicability: Simplicity lends itself to use as guideline. However, these models are unable to predict fungal growth. The ASHRAE 160 (2016) standard has since been updated to adopt the underlying foundation of the VTT Mould Growth Model (Hannu Viitanen, Vinha, et al. 2010).

2.3.4.2.3. ESP-r (Clarke et al. 1999)

ESP-r is a building energy simulation model with an ability for higher temperature resolutions at designated areas. This can provide time-series surface temperatures at areas of concern, such as thermal bridges. With surface temperatures, and modeled interior humidity conditions, evaluations based on mould growth risks are enabled. The internal fungal database is divided into 6 categories, based on the minimum level of relative humidity required for germination. Plotting the weekly average condition onto the isopleth plot is then used to infer the risk and type of fungi.

Structure: With the isopleth data derived from steady-state conditions, dynamic effects cannot be considered. The model is unable to predict time until germination but rather risk of growth and type of anticipated fungal classes.

Biology: A cross-sectional study on fungi in Scottish homes was used to develop and categorise the types of fungi (Clarke et al, 1996). It was stated that most of the fungi are from the *Deuteromycete* sub-group, but many of the represented fungi are from the *Ascomycete* phylum. It is also unknown under what conditions the isopleths were derived.

Applicability: As this is an extension to the ESP-r program, with little guidance on use, this model does not lend itself to widespread use. The minimum duration above the isopleth is also not explicitly stated, rendering application of this model challenging.

2.3.4.2.4. Biohygrothermal Model (Klaus Sedlbauer 2001; K. Sedlbauer et al. 2001; Klaus Sedlbauer, Krus, and Breuer 2003)

The biohygrothermal model is an extension module for the hygrothermal software WUFI (Künzel 1995). It is an improvement on the Fraunhofer lowest isopleth for mould (LIM) approach (K. Sedlbauer et al. 2001). The approach combines isopleth limits with a heat and moisture balance on a theoretical fungal spore. Germination is defined as the point in which the internal moisture content and temperature of the spore fall within an accepted range, which is dependent on the type of substrate. Sedlbauer suggests ranges between 20 and 25 [Vol%] based on the substrate LIM.

The extent of mycelium growth is determined on a modification of the isopleth graphs. Hazard classes are created for different fungi based on the potential pathogenic and

allergenic effects in humans, with distinguished LIM curves. Substrates are also considered to a greater extent than they have in other models, with the addition of four substrate classes, shown in Table 2-1.

Table 2-1- Category classes for Biohygrothermal Model

Substrate Category	Description
0	Optimal culture medium
1	Biologically recyclable building materials
2	Biologically adverse recyclable building materials
3	Building materials that are neither degradable nor contain nutrients.

Source: (Klaus Sedlbauer, Krus, and Breuer 2003)

Structure: The Biohygrothermal Model is deterministic and dynamic. A significant advantage is the dynamic heat and moisture flow outputs from the front-end software which permits greater precision than would otherwise be found in most other mould growth models. Estimates on the extent of growth are based on isopleth plots, which are based on steady-state experiments.

Biology: The theoretical hygrothermal properties of the conidia, such as vapour permeance of the spore wall and minimum moisture content for germination, were estimated from laboratory experiments on *Aspergillus restrictus* under steady state conditions, using laboratory data from Smith and Hill (1982). The LIM curve used for the model is a conservative estimate for a number of different fungal species, shown in

Figure 2-4.

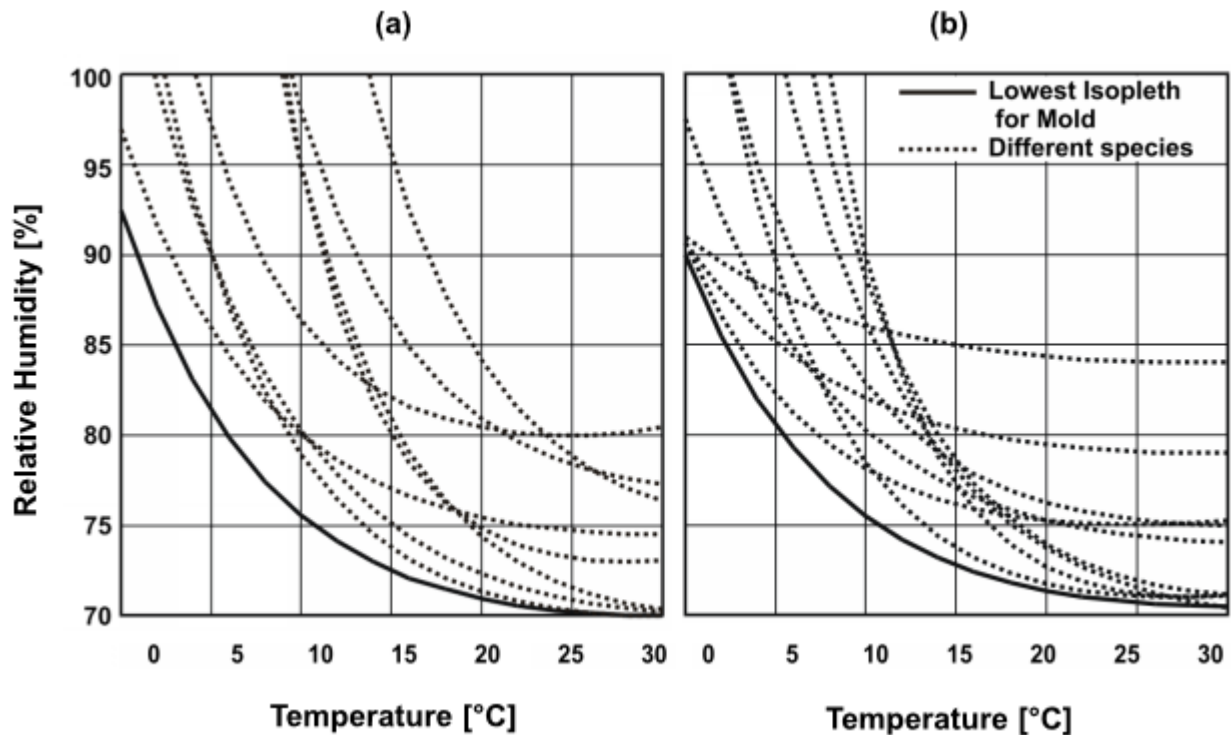


Figure 2-4– Lowest isopleths for Germination (a) and Mycelial growth (b). (Reprinted with permission from Sedlbauer 2001.)

The “water retention” curves for fungi spore were assumed to be similar to bacterial spores (K. Sedlbauer et al. 2001), which may not be compatible as the cell wall constituents of bacteria and fungi are different, including appreciable differences in lifecycles and niches (Schmidt 2006a). With the small size of conidia, it was assumed that hygrothermal properties are scalable from 3 μ m to 1cm dimension. However at these smaller scales, the assumptions of the Kelvin equation only appear to apply at relative humidities above 80% (Skaar 1988; Thygesen, Tang Engelund, and Hoffmeyer 2010), thus assumptions about water retention curves below this value are uncertain. The

lower values of the water retention curve may be explained by the hygroscopicity of the cell wall and osmotic pressures created by the cytoplasm.

Applicability: The biohygrothermal model is readily included as part of the WUFI Pro software, an industry standard hygrothermal simulation tool, and so does not present as great of a challenge for adoption. However, further validation of the biohygrothermal model is required, as preliminary results suggest poor relationship with 1,388 homes in the United Kingdom (Altamirano-Medina et al. 2009).

2.3.4.2.5. Mould Germination Graph Method (Moon 2005)

The mould germination model attempts to quantify uncertainty by using stochastic methods to define the risk of growth. Four causal categories are proposed sources of uncertainty: spore availability, substrate condition, mechanical system operation and maintenance, and building detail.

Structure: The model uses stochastic inputs and a dynamic approach to isopleth tables by tabulating the number of days in which conditions are sufficient for germination in accordance with the germination isopleths. The number of days for potential growth are tabulated over the year to determine the risk. The model only focuses on germination and does not address extent of growth.

Biology: It appears that the underlying data is derived from Smith & Hill (1982), and thus the limitations for a single fungal specie, grown on agar substrates under steady state conditions apply when considering dynamic environmental conditions.

Applicability: The germination graph method lends itself to ease of use within spreadsheet formats where the hygrothermal data are stored. Insufficient context is provided on whether the output consists of a major or minor risk for mould growth, and thus further guidance is required.

2.3.4.3. Empirical

Empirical regressions are the deductive result of identifying the impact of explanatory variables directly to the response variable without the use of an intermediary factor.

The equations generally predict extent or occurrence of fungal growth as a direct result of the explanatory parameters. The mathematical relationship is expressed in equation (2-18),

$$\text{Fungal Growth} = f(P_1, P_2, \dots P_n) \quad (2-18)$$

where ' P_1 ' to ' P_n ' are explanatory parameters used to define the fungal growth functions, ' f '.

2.3.4.3.1. VTT Mould Growth Model (H. A. Viitanen 1997; Hukka and Viitanen 1999;

Hannu Viitanen et al. 2005; Hannu Viitanen and Salonvaara 2010)

The Finnish Technical Research Centre (VTT) mould growth model is an empirical model based on controlled laboratory experiments. The output from the model is the mould index (M), with description provided in Table 2-2. and is derived from a linear regression on temperature, relative humidity, wood type (Spruce and Pine), and substrate quality (rough sawn or planed). The model has since undergone several iterations to now include different substrates types. The extent of growth was measured using the 'mean growth' method (Hannu, Viitanen and Ritschkoff 1991).

Table 2-2– Mould Growth Index and Description, Including New Determinations

Index	Description of Growth Rate
0	No growth
1	Initial stages of growth (microscopic)
2	Coverage <10% (microscopic), several local colonies
3	Fungal coverage <10% (visual), or <50% (microscopic): New spores produced
4	Fungal coverage 10-50% (visual), >50% (microscopic)
5	Extensive surface coverage, >50% (visual)
6	Heavy and tight growth, ~100% (visual)

Source: Reprinted from Ojanen et al. (2010).

The rate of mould growth is calculated if the relative humidity falls above the minimum RH, governed by equation (2-19),

$$RH_{crit} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13T + 100; T < 20^\circ C \\ RH_{min}; T \geq 20^\circ C \end{cases} \quad (2-19)$$

The mould index is the integration of the rate of mould growth with time, shown in equation (2-20). The time until a mould index of 1 or 3, critical in calculating the k_1 and k_2 coefficients, are provided in equations (2-21) and (2-22). In the updated model, values for k_1 and k_2 are provided in Table 2-3. Note that the time values are given in days, but in hours in equation (2-26).

$$\left(\frac{dM}{dt}\right) = \left(\frac{k_1 k_2}{7 \cdot t_{M=1}}\right)_{pine} \quad (2-20)$$

$$t_{M=1} = \exp(-0.68 \cdot \ln(T) - 13.9 \cdot \ln(RH) + 0.14 \cdot W - 0.33 \cdot SQ + 66.02) \quad (2-21)$$

$$t_{M=3} = \exp(-0.74 \cdot \ln(T) - 12.72 \cdot \ln(RH) + 0.06 \cdot W + 61.5) \quad (2-22)$$

The ' k_1 ' coefficients represent the time for germination and local growth, and ' k_2 ' coefficients corrects for asymptotic growth towards the maximum supportable mould growth index at the given environmental conditions. The material corrected values for ' k_1 ' and ' k_2 ' are shown in equation (2-23) and (2-24).

$$k_1 = \begin{cases} \frac{t_{M=1,pine}}{t_{M=1}}, \text{when } M < 1 \\ \frac{2(t_{M=3,pine} - t_{M=1,pine})}{(t_{M=3} - t_{M=1})}, \text{when } M > 1 \end{cases} \quad (2-23)$$

$$k_2 = \max[1 - \exp(2.3 \cdot (M - M_{max})), 0] \quad (2-24)$$

The maximum supportable mould growth M_{max} , based only on RH and substrate type, is shown in (2-25).

$$M_{max} = A + B \cdot \frac{RH_{crit} - RH}{RH_{crit} - 100} - C \left(\frac{RH_{crit} - RH}{RH_{crit} - 100} \right)^2 \quad (2-25)$$

The coefficients A , B , and C , describe the substrate sensitivity classes, as is provided in Table 2-3.

Table 2-3– Substrate Sensitivity Classes with Maximum Coefficients and Descriptions

Sensitivity Class	k1 (Max)		W	k2 (Max)			RHmin	Notes
	M<1	M>=1		A	B	C		
Very Sensitive	1	2	0	1	7	2	80	Untreated wood, includes lots of nutrients for biological growth
Sensitive	0.578	0.386	1	0.3	6	1	80	Planed wood, paper-coated products, wood-based boards
Medium Resistant	0.072	0.097	1	0	5	1.5	85	Cement or plastic based materials, mineral fibers
Resistant	0.033	0.014	1	0	3	1	85	Glass and metal products, materials with efficient protective compound treatments

Source: (Ojanen et al. 2010)

When the ambient relative humidity falls below the critical threshold, decline may occur. These ‘recessions’ in the mould index were observed from cyclical testing and vary depending on duration of the inclement period. The rate of decline is governed by equation (2-26).

$$\frac{dM}{dt} = C_{mat} \cdot \begin{cases} -0.00133, \text{ when } \Delta t \leq 6h \\ 0, \text{ when } 6h, t \leq 24hr \\ -0.000667, \text{ when } \Delta t > 24hr \end{cases} \quad (2-26)$$

The rate of decline was found to vary depending on substrate types, modified by the coefficient C_{mat} , shown in Table 2-4.

Table 2-4– Decline coefficients

C_{mat}	Description
1	Pine in original mode, short periods
0.5	Significant relevant decline
0.25	Relative low decline
0.1	Almost no decline

Source: (Ojanen et al. 2010)

Structure: The time to reach certain levels mould growth was regressed to temperature, relative humidity, wood species, and surface quality. It is uncertain if the regressions were verified for normality, heteroscedasticity, and independence of explanatory parameters, as any of these can invalidate the regression (Zuur, Ieno, and Elphick 2010). The surface water activity was assumed to be equal to the relative humidity in the chamber. During fluctuating humidity conditions, this may not be accurate.

Biology: The cyclical (non-steady state) conditions lend veracity to the models but were only conducted over a fairly short duration. The sensitivity classes and C_{mat} coefficient affect rate of growth and decline, respectively, assuming that they are a scalar of the original pine substrate, which may not necessarily hold as there can be significant variations in substrate hygroscopicity and nutrient availability.

Applicability: The model can be adopted within a spreadsheet format with some work. The number of computational steps required renders some challenges in adoption in

spreadsheet formats. The determination of the mould recession, as a function of the duration of humidity conditions below the limiting threshold, can be challenging to those not familiar with programming languages.

2.3.4.3.2. VTT Fungal Decay Model (H. Viitanen, Toratti, et al. 2010)

The VTT Fungal decay model builds upon the original doctoral work by Viitanen (1991). The model is divided into two components; the first quantifies the time until onset of decay (α), and the second is a quantification of mass loss as a representation of damage (ML). The time until onset of decay occurs when $\alpha=1$, described by equations (2-27) and (2-28),

$$\alpha(t) = \int_0^t d\alpha = \sum_0^t (\Delta\alpha) \quad (2-27)$$

$$\Delta\alpha = \begin{cases} \frac{\Delta t}{\left(\frac{2.3 \cdot T + 0.035 \cdot RH - 0.024 \cdot T \cdot RH}{-42.9 + 0.14 \cdot T + 0.45 \cdot RH} \right)}, & T > 0^\circ C \text{ } RH > 95\% \\ -\frac{\Delta t}{17520}, & \text{Otherwise} \end{cases} \quad (2-28)$$

where ' RH ' and ' T ' are the hourly relative humidity and temperature over the measured period of Δt , respectively. Once fungal germination has occurred, the rate of mass loss (ML) is integrated over the subsequent time period, as shown in equations (2-29) and (2-30),

$$ML(t') = \int_{t \text{ at } \alpha=1}^{t'} \frac{ML(RH, T)}{dt} dt \quad (2-29)$$

$$\frac{ML(RH, T)}{dt} = -5.96 \cdot 10^{-2} + 1.96 \cdot 10^{-4} \cdot T + 6.25 \cdot 10^{-4} \cdot RH \left[\frac{\%}{hour} \right] \quad (2-30)$$

where 't' is the elapsed period from which $\alpha=1$, ML is the mass loss that occurred during that period.

Structure: The model is deterministic and dynamic. Relative humidity is used as the describing parameter for moisture.

Biology: The extent of decay is measured by mass loss, which poses problems as reduction in structural capacity occurs prior to observable loss of material (S. Curling, Winandy, and Clausen 2000; Winandy and Morrell 1992; S. Curling, Clausen, and Winandy 2001). Two common European building decay fungi are used, *Coniophora puteana* and *Gloeophyllum sepiarium*.

Applicability: The model does not appear to be validated with field experiments but cross-referenced with hygrothermal simulations. Difficulties in measurement of very high relative humidity (e.g. 95%+) and reliability of material sorption isotherms at these higher ranges create some concerns on applicability of this model for in-situ applications.

2.3.4.3.3. IRC Fungal Decay Model (Nofal and Kumaran 2011)

The Institute for Research in Construction of the National Research Council in Canada (IRC) Fungal Decay model is derived from the data provided by Viitanen et al. (1991; 1997). The purpose was to provide method to determine the damage, performance, and service-life of building enclosure wood structural elements using mass loss as the indicator. As wood rotting fungi have greater tolerance once established, the life cycle is divided into three stages: 1) initial response time, 2) critical growth conditions and 3) survival conditions. For determination of the initial response time, a threshold relative humidity is established, shown in equation (2-31).

$$RH_{crit} = \begin{cases} -0.5T + 100, T \leq 15^{\circ}C \\ 92.5\%, T > 15^{\circ}C \end{cases} \quad (2-31)$$

The critical concern is mass loss, ' w_l ' caused by decay, showing the relationship between temperature ' T ', relative humidity ' RH ', and wood species ' W ', provided in equation (2-32).

$$w_l = f(T, RH, W) \cdot t + g(T, RH, W) \quad (2-32)$$

Differentiation of the equation with respect to time provides the incremental mass loss over the recorded conditions. The time dependent function, ' f ', is described in equation (2-33), and the intercept, ' g ', is defined in equation (2-34).

$$f(T, RH, W) = 0.1384T + 0.4370RH - 42.9450 + WS \cdot (0.0340T - 0.0210RH + 1.7210) \quad (2-33)$$

$$g(T, RH, W) = -2.227T - 0.0347RH + 0.0244T \cdot RH + WS \quad (2-34)$$

$$\cdot (-0.504T + 0.0096RH + 0.0047T \cdot RH)$$

With respect to the lowest relative humidity for survival of the chlamydospores, the critical RH was found to be described by equation (2-35).

$$RH_{min} = 75 - 8.0703 \exp \left(-0.5 \cdot \left(\frac{T - 17.2581}{3.5527} \right)^2 \right) \quad (2-35)$$

With periods of insufficient humidity, the number of viable spores will slowly decrease. This can affect speed at which fungal growth restarts upon return of suitable growing conditions. Species specific recommendations are provided.

To relate the mass loss to the functional decrease in structural capacity, the relationship between a change in modulus of rupture (*MOR*) to mass loss was defined (equation (2-36)), where '*NQ*' represents the natural quality of wood.

$$MOR_{loss} = 2.65w_l + 20.15 + NQ \cdot (1.21w_l - 0.94) \quad (2-36)$$

It important to note that even at zero mass loss, the *MOR* is already reduced by $\pm 20\%$.

Structure: The deterministic structure of this model is grounded upon the cyclical and steady state decay conditions collected by Viitanen (1991), and is thus not limited in the steady-state conditions derived in many of the other models. The partial derivatives, ' $\partial f / \partial t$ ' and ' $\partial g / \partial t$ ' therefore model the rate of change in both temperature and relative

humidity. The initial conditions pose a challenge to this model, as the basis for mass loss suggest onset of damage occurs *prior* to any extent of fungal growth.

Biology: The equation uses mass loss as an indicator for decay. However, mass loss is a poor analogue for decay, as significant ultrastructural changes occur in the incipient decay process (S. Curling, Winandy, and Clausen 2000; Winandy and Morrell 1992; S. Curling, Clausen, and Winandy 2001). The equation (2-36) used to derive the reduction in modulus of rupture is highly insensitive to initial mass loss. Interestingly, relative humidity was used as the moisture metric of choice, likely due to limitations in the original data set. As Brischke (2008) noted, the risk of decay are mainly governed by moisture contents exceeding the fibre saturation point, which all constitute as relative humidities between 97% to 100%. The accuracy of relative humidity to define decay is therefore uncertain.

Applicability: This model does not appear to have been used in field trials for validation. The extensive use of differential equations may position it as a more challenging equation for some practitioners. A greater repertoire of decay functions, '*f*' and '*g*', may be required to characterise the properties of different materials, such as plywood and its different subtypes, and other engineered wood products (cross laminated timber, oriented strand board, glulam, etc.).

2.3.4.3.4. Wood Degradation Model (Saito et al. 2008; Saito, Fukuda, and Sawachi 2012; Saito 2017)

The Wood Degradation Model was developed from experimental studies of mass loss of *Pinus densiflora* experiencing decay by *Fomitopsis palustris* (Berk & M.A. Curtis) subjected to different temperatures (from 5, 10, 20, 30, and 40°C) and humidity (93%, 97%, 100%) conditions. It is unique in that this model includes the added moisture from metabolic decomposition of cellulose by decay fungi. Inclusion of this mechanism is important, as the decay process could continue despite insufficiently high ambient relative humidity that would otherwise harbour fungal growth (Saito et al. 2008). The models make several simplifying assumptions, mainly:

- The substrate is in instantaneous moisture equilibrium with its environment and the boundaries are adiabatic
- Fungal growth is immediate, and secondary metabolic by-products (O₂ and CO₂) have negligible impact on growth, and
- Mass loss is directly correlated to fungal decomposition.

Fundamentally, mass loss, 'L', is defined by equation (2-37),

$$L = \frac{m_n - m_d}{m_n} \quad (2-37)$$

where ' m_n ' is the mass of wood before decay, and ' m_d ' the mass of the wood after decay.

The rate of mass loss at finite element ' i ' was assumed to begin when the critical humidity ratio, ' φ_c ', within the wood pores was surpassed, shown in equations (2-38). Progression to adjacent finite elements, ' $i+1$ ', could only occur upon mass loss within the initial element, shown in equation (2-39).

$$\left. \frac{dL}{dt} \right|_{x=0} = k_m(\theta) \quad (\varphi_i > \varphi_c) \quad (2-38)$$

$$\left. \frac{dL}{dt} \right|_{x>0} = k_m(\theta) \quad (L_{i\pm 1} > 0; \varphi_i > \varphi_c) \quad (2-39)$$

The rate of mass loss was linearly regressed and found to equal a rate constant ' k_m ', a function solely of temperature ' θ ', shown in equation (2-40).

$$k_m(\theta) = (2.77 - 3.23\theta + 0.865\theta^2 - 0.0189\theta^3) \cdot 10^{-10} \quad (2-40)$$

The hygrothermal evaluation is achieved by coupled heat and mass transfer equation. As wood rot produces non-negligible moisture amounts from the decomposition of cellulose (Saito et al. 2008), an additional term, ' W_L ', is added to the moisture balance equation, shown in (2-41).

$$W_L = h \cdot \rho_w \cdot \frac{dL}{dt} \quad (2-41)$$

Where ' ρ_w ' is the density of water and ' h ' is the moisture product ratio, corresponding to the ratio of moisture produced because of mass loss, and shown in equation (2-42). Due

to difficulties in measuring metabolic activity, this ratio is determined experimentally.

A value of 0.319 was determined for these experiments.

$$h = \frac{d\phi}{dL} \quad (2-42)$$

Structure: The deterministic structure of this model is founded upon equations of mass and heat balance on the substrate, with a component for added water as a by-product of cellulose digestion by fungi. However, the rate constant of decay, determined by linear regression, only uses temperature as the primary variable. Moisture contents exceeding the fibre saturation point are known to accelerate decomposition (Zabel and Morrell 1992; Schmidt 2006a). The simplifying assumptions of instantaneous substrate equilibration and fungal growth could pose challenges in applications when trying to predict time until start of decay.

Biology: The brown rot *F. palustris* was used due to its controlled dispersion and use within JIS K 1571 standard. The wood samples were inoculated by placing them adjacent to the fungal culture on agar, separated by a resin mesh. It is possible that both spore and hyphal fragments could have been transferred as part of the inoculum, leading to accelerated growth over spore-only inoculation. It is uncertain how the inoculum load was controlled between samples. The wood specie, *P. densiflora* was selected as a non-decay resistant wood, consequently leading to an overestimation of model results thus permitting practitioners an added margin of safety.

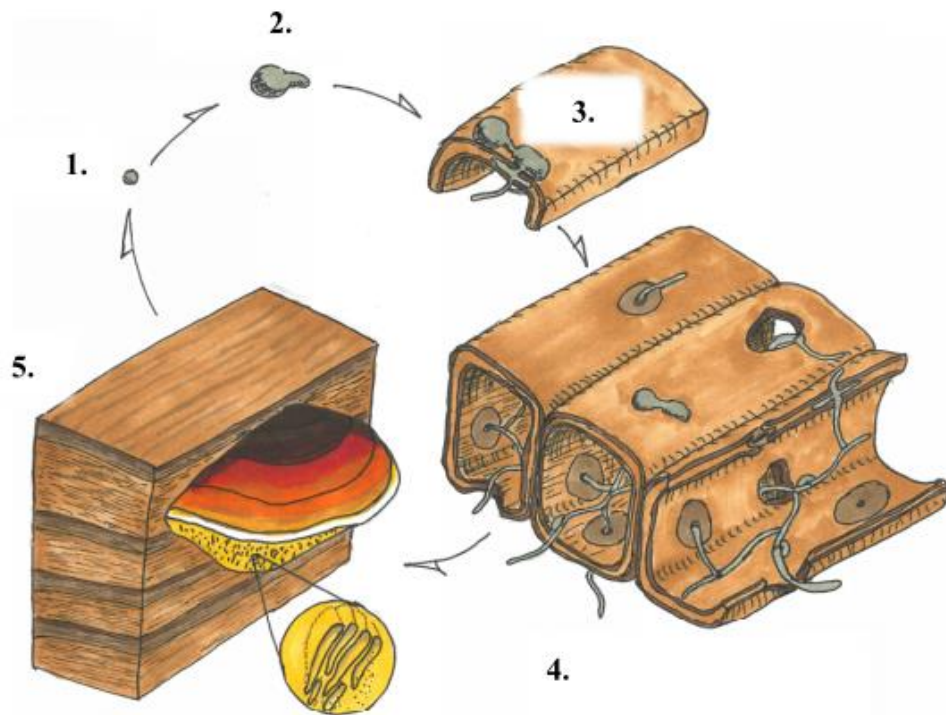
Similar to other decay models, the driving metric is mass loss of the substrate. As previously discussed, the principal concern is the structural capacity of the substrate, which is already reduced prior to measurable mass loss.

Applicability: The model's underlying design permits estimation of decay based on constant conditions nearing the fibre saturation point of wood. However, as in-situ conditions in buildings are subject to significant fluctuations, the predictive capacity of these models remain untested. Implementation of the finite element hygrothermal equations requires direction on reasonable assumptions not found within these papers.

2.4. Discussion

The durability concerns posed by fungi are evidenced by the significant effort to quantify the risks. This review identified three main categories of fungal models; indices, threshold, and empirical models. Diverse disciplines have attempted to address mould concerns in buildings. Most models are deterministic in nature, but several authors have tried stochastic methods, but the need for more absolute terms of risk has resulted in limited adoption within the building science community. Within the surveyed models, the majority attempted to characterise surface mould growth, whereas only a few tried to assess structural reductions caused by decay. The cause for this is that decay generally follows the original wave of pioneering fungi, generally the surface moulds (Zabel and Morrell 1992; Schmidt 2006a).

Many of the models were challenged by the dynamic conditions experienced by fungi in real world building envelope applications. For laboratory experiments, steady state conditions provide greater control of outputs and thus form the basis for most of the models, except for those certain models that incorporate oscillating temperature and humidity conditions or are based on field studies. Another issue is linearity. Most models assume that mould growth occurs at a linear pace given constant conditions until a steady state is achieved. Fungal growth is generally classified in to three phases: germination, vegetative growth, and reproduction, as shown in Figure 2-5, and the rate of growth is shown in Figure 2-6. With the various growth stages of fungi and the non-linear growth rates, many of the assumptions of linearity may not be valid.



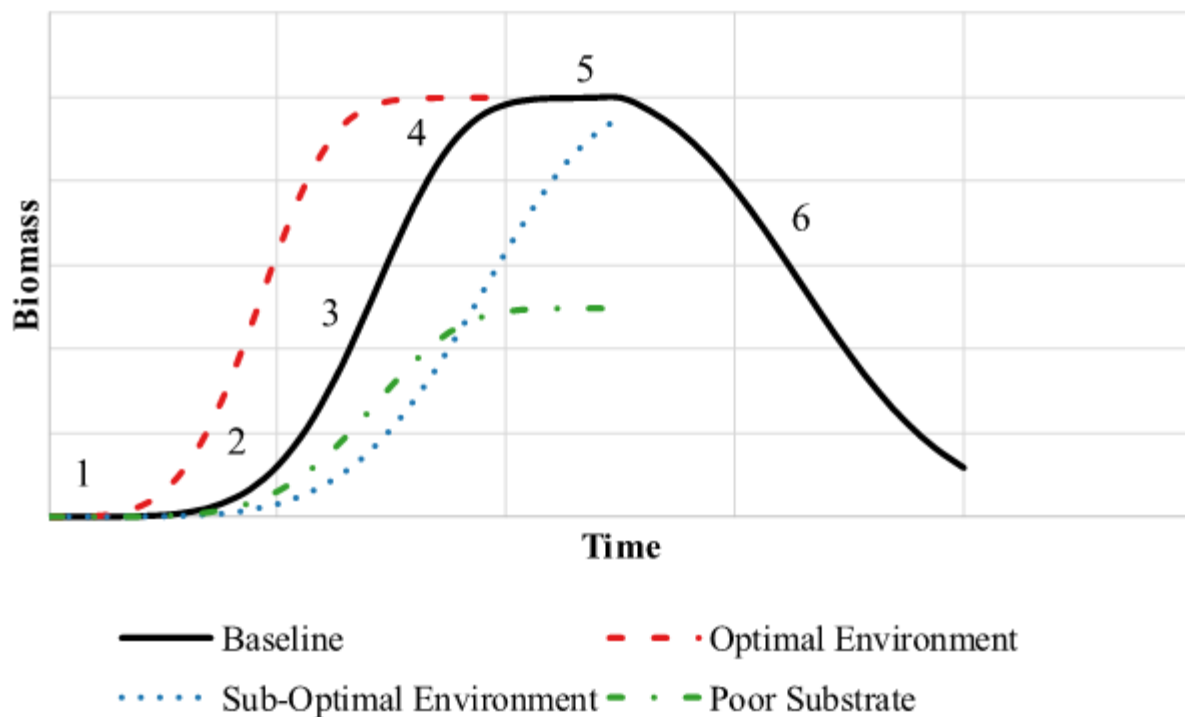
1: the spore swells and **2:** begins to germinate

3: the growth of an appressorium permits boring into the wood cell, with preliminary decay of the S2 cell wall cellulose.

4: vegetative growth, with hyphae decomposing the wood cell wall and expanding deeper into the wood superstructure.

5: the colonizing mycelium develops a basidiocarp, the fruiting body of the fungi, which releases spores through the pores of the hymenium.

Figure 2-5 – Lifecycle for a hypothetical teleomorphic brown-rot fungi on a woody substrate.



- 1: lag phase;
 2: acceleration phase;
 3: exponential growth phase;
 4: deceleration phase;
 5: stationary phase;
 6: death phase

Figure 2-6– Typical sigmoidal growth curve of fungi including conceptual effects of optimal (dashed) and sub-optimal (dotted) environments and nutrient poor (dash-dot) substrate. Based on a concept from Adan (1994).

Further, it is known that fungal growth is governed on suitable conditions for metabolic activity. There are a number of required conditions for fungal growth and survival (Zabel and Morrell 1992; Adan 1994):

- Water – free water on the surfaces of cell lumina
- Temperature– optimum ranges from 15 to 45 °C

- Substrate: Nutrition– Digestible substrate that provides energy and metabolites
- Chemical Growth Factors: nitrogen compounds, vitamins and essential elements
- pH– Favourable pH range, preference for ranges between 3 to 6
- Oxygen – atmospheric oxygen at relatively low levels for most fungi and very low levels of chemical oxygen only for some microaerobic and facultative anaerobic fungi
- Minimal Antagonistic Effects – A lack of biocides, nutrient competition, preservative treatments, extractives, ultraviolet radiation, or other toxins

Generally, water, temperature, and substrate conditions have been considered by nearly all models, with the other factors generally being too tedious for measurement and inclusion within the model. However, the choice of metrics for water is somewhat contentious (Griffin 1977; Griffith and Boddy 1991; Block 1953; Adan 1994; Laarhoven et al. 2015). Agriculture and food scientists have historically used water activity (a_w) to define the risk of fungal growth (see Skaar 1988 for further information). By extension, relative humidity, which approaches the same value as water activity under *steady-state* conditions, has been adopted as an approximate analogue despite the use of dynamic conditions. Other metrics, such as water potential (ϕ), are used by plant pathologists but has not found broad acceptance due to unfamiliarity. Curiously, moisture content has only been used to model decay, despite recent research indicating that it can have

significant effect on surface mould growth on hygroscopic substrates and appears to behave independent from water activity (Laarhoven et al. 2015). Consequently, the hygric properties of the substrate, especially in dynamic and cyclical environmental conditions, may play a larger role than originally thought.

Fungal growth is nearly impossible to model with any degree of certainty due to stochastic nature of biological processes. While deterministic approaches can sufficiently approximate real-world stochastic conditions, a lack of resources prohibits the ability to sufficiently quantify the relationships with absolute confidence.

Consequently, a limit state approach, which has been attempted by Isaksson (Isaksson et al. 2010) but not fully realised, which defines the probabilistic failure enclosure at constant conditions, may be one potential route to resolve the non-linear and stochastic processes of biodeterioration. Both a serviceability (mould), and ultimate (decay) state could provide a holistic approach to biodeterioration caused by fungi and may also yield a model suitable for other deteriorating agents as well. Lastly, consideration on improved moisture metrics may be required to countenance the different effects of water activity (a_w) and moisture content or other water metrics in hygroscopic materials. With the biological roles of fungi, particularly interspecies competition mostly ignored within the literature, ecological principles and approaches may prove useful in future work. Linear mixed-effects modeling may provide useful tools to

account for the dynamic uncertainty with biological organisms in fluctuating conditions.

2.5. Conclusions

The durability and health concerns posed by fungi have resulted in extensive study to better understand the risks in buildings. This has led to a broad range of fungal modeling tools, both for moulds and rot, which better help characterise the associated risks. Increased interest in high performance homes and mass-timber structures further emphasises the need to better understand moisture related effects, particularly with respect to fungal growth.

This study reviewed fourteen different models based on their mathematical structure, choice of variables, and biological merits. The diverse models can be approximately lumped into three approaches; *Indices*, which correlate environmental conditions to risk of mould growth; *Thresholds*, which characterise the limiting environmental conditions and growth rates for fungal contamination; and *Empirical* approaches, which use regressions from laboratory studies to infer time until germination and extent of contamination.

Many of the models require simplifications, significant assumptions, or are unable to properly quantify the complexity of the interaction of living organisms in a dynamic

environment. With these limitations, the accuracy of the models is uncertain, but strongly indicates the need for further work in this area.

Table 2-5 – Summary of Index Fungal Models

Name	Source	Fungi	Moistur e	Substrate	Germination ¹ Growth ²	Recession	Experimental Source
RHT80 Index	(Phalguni Mukhopadhyaya et al. 2009)	Mould	RH	N/A	N	N	N/A
RHT95 Index	(Jieying Wang and Morris 2011)	<i>Gloeophyllum trabeum</i> , <i>Trametes versicolor</i>	RH	Plywood, OSB, Solid Wood	N	N	Original
Mould Index	(S. Johansson, Wadsö, and Sandin 2010)	<i>Cladosporium</i> spp.	RH	Rendered façade	(1)	Y	(Grant et al. 1989)
Limit-State Dose-Response	(Isaksson et al. 2010)	<i>Aspergillus versicolor</i> , <i>Cladosporium sphaerospermum</i> , <i>Penicillium</i> spp., <i>Aureobasidium pullulans</i>	RH	<i>Pinus</i> , <i>Picea</i>	(1)	Y	(H. Viitanen 1997)
Mould Resistant Design	(Thelandersson and Isaksson 2013)	<i>Eurotium herbariorum</i> , <i>A. versicolor</i> , <i>Penicillium chrysogenum</i> , <i>A. pullulans</i> , <i>C. sphaerospermum</i> , <i>Stachybotrys chartarum</i>	RH	<i>Pinus</i> , <i>Picea</i>	(1)	Y	(H. Viitanen 1997)
Dose-Response	(Brischke and Rapp 2008)	Decay	MC	<i>Pinus Sylvestris</i> , <i>Pseudotsuga. menziesii</i>	(1)	N	Original

Table 2-6 – Summary of Threshold Fungal Models

Name	Source	Fungi	Moistur e	Substrate	Germination1 Growth2	Recession	Experimental Source
Temperature Ratio	(H. Hens 1991a)	<i>A. versicolor</i>	N/A	agar	N	N	N/A
RH Threshold	(H. L. S. C. Hens 1999)	<i>A. versicolor</i>	RH	agar	N	N	N/A
ASHRAE 160	(ASHRAE 2009)	<i>A. versicolor</i>	RH	agar	N	N	(H. Hens 1991b)
Isopleth	(Ayerst 1969a; Smith and Hill 1982)	<i>Aspergillus. restrictus</i> & <i>A. versicolor</i>	RH	agar	N	N	Original
ESP-r	(Clarke et al. 1999)	<i>Aspergillus repens</i> , <i>A. versicolor</i> , <i>P. chrysogenum</i> , <i>C. sphaerospermum</i> , <i>U. consortiale</i> , <i>S. chartarum</i>	RH	agar	N	N	N/A
Biohygrothermal	(Klaus Sedlbauer 2001; Klaus Sedlbauer, Krus, and Breuer 2003)	LIM	RH	Types 0, I, and II	Y	N	(Smith and Hill 1982)
Mould Germination	(Moon 2005)	LIM	RH	Types 0, I, and II	Y	N	(Klaus Sedlbauer 2001)

Table 2-7 – Summary of Empirical Fungal Models

Name	Source	Fungi	Moistur e	Substrate	Germination ¹ Growth ²	Recession	Experimental Source
VTT	(H. A. Viitanen 1997; Hannu Viitanen and Ojanen 2007; Ojanen et al. 2010; H. Viitanen, Vinha, et al. 2010)	<i>A. versicolor</i> , <i>C. sphaerospermum</i> , <i>Penicillium</i> spp., <i>A. pullulans</i>	RH	<i>Pinus sylvestris</i> , <i>Picea abies</i> , Others	Y	Y	Original
VTT Fungal Decay	(H Viitanen, Toratti, et al. 2010)	<i>C. puteana</i> , <i>G. sepiarium</i>	RH	<i>Pinus sylvestris</i> , <i>Picea abies</i>	(1)	Y	(H. A. Viitanen 1997)
IRC	(Nofal and Kumaran 2011)	<i>C. puteana</i> , <i>G. sepiarium</i>	RH	<i>Pinus sylvestris</i> , <i>Picea abies</i>	(1)	Y	(H. A. Viitanen 1997)
Wood Degradation Model	(Saito et al. 2008; Saito, Fukuda, and Sawachi 2012; Saito 2017)	<i>Fomitopsis palustris</i>	RH	<i>Pinus densiflora</i>	(2)	N	Original

Chapter 3 – Serviceability Limit State

Serviceability Limit State Model for Fungal Growth on Wood Materials in the Built Environment

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Phalguni Mukhopadhyaya, Ph.D., P.Eng.⁵

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Abstract

Fungal (mould) growth in wood based building components could have significant detrimental effects on the operational and structural requirements of the built environment. Quite naturally, building designers and material scientists are keen to predict mould growth in wood and wood based building materials. Available surface mould growth models primarily predict the levels of mould growth in different environmental and material conditions. However, modern design practices allow acceptable limit of risk in the design process. Hence, a

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probabilistic mould growth model is required which takes into account risk tolerance thresholds for mould growth. This paper presents a research initiative that shifts the mould growth narrative from predicted levels to probabilistic predictions, which is the foundation block associated with limit state design approach, widely used in structural design codes and standards. More specifically, this paper presents a serviceability limit state mould growth model for wood using jack pine (*Pinus banksiana*) wood and the fungal species *Penicillium chrysogenum*. The outputs from this model were verified using the results obtained from an experimental roof study that investigated the impacts of different surface treatments on mould growth in ventilated roofs.

3.1. Introduction

Through natural processes, buildings succumb to biotic and abiotic deteriorating forces. Biotic factors, mainly those of bacteria, fungi, and invertebrates, are orders of magnitude more destructive than abiotic factors, and as a result, are keenly researched in efforts to minimize damages. For buildings, the environmental disturbances caused by construction and material manufacturing provide suitable organic substrates sufficient to sustain microbial succession from the more pioneering and damaging of organisms: the fungi.

The damages caused by fungi on buildings can be extensive: they include life-safety risks by way of rot and decay of primary structural members; short- and long-term health impacts from surface moulds that can cause a range of allergic responses, from mild to fatal, or mycoses of immunocompromised persons; monetary damages, from reduced property value and fungal abatement expenses; to psychological symptoms, including psychosomatic effects and concerns for surface fungal contamination and aesthetics. As a result, significant interest is placed in understanding the epidemiology of fungal contamination in buildings, which is reflected by the significant literature that attempts to quantify the risk of building damage due to fungal contamination.

Currently, most surface mould growth models attempt to quantify or qualify the amount of mould growth that could be expected, given numerous environmental and material parameters over time. However, decision making for remediation of fungal damage occur not based on the quantity of fungi, but rather on its presence or absence. As such, a model that assists in evaluating the risk of fungi is needed, one that provides the range of probabilities of finding growth such that, when taking risk tolerance thresholds into account, appropriate design metrics can be devised. The objective of this research is to shift the mould growth narrative from predicting states and quantities of mould into a probabilistic

prediction, which is conceptually aligned with limit-state approach to design. This paper provides a serviceability limit state (SLS) model for surface mould growth on wood building materials.

3.2. Background

3.2.1. Fungi Growth Requirements

The field of mycology has identified many of the fundamental environmental characteristics needed to support the growth of fungi (Schmidt 2006b; Adan 1994; Zabel and Morrell 1992). In no particular order, these include

- Presence of viable fungal spores and/or mycelium
- Adequate temperature,
- Sufficient moisture,
- Nutrient substrate (including trace chemical growth factors),
- Oxygen (species dependent), and
- Lack of biocidal agents (suitable pH, no toxic materials)

Most of these conditions are present in the built environment and so could pose a range of risks to both building and occupants, from potential health impacts to physical damage of the building.

3.2.2. Fungal Growth Models

Many existing fungal growth models incorporate a wide-range of techniques and equipment, from long-term in-situ field studies with qualitative evaluations to

laboratory studies of fungal growth on agar plates. A summary of mould models and their input assumptions is provided by Lepage et. al. (2019a), Gradeci et. al. (2017), and Vereecken et. al. (2012),. However, a pressing need in the building industry is a biodeterioration model that is calibrated to the procedures, equipment, and skillsets available to building professionals.

Building condition assessments frequently use a suite of tools to evaluate the condition of the building, ranging from instantaneous, short-term, or long-term readings that may be qualitative and non-destructive (visual, olfactory, tactile), quantitative and non-destructive methods (RH readings, IR thermography, dielectric surface moisture readings), nominally destructive (electrical resistance moisture readings), to destructive (coring, sampling). Therefore, the methods used to define a fungal growth model should ideally incorporate these same procedures and techniques such that the results may be readily transferable to those building practitioners.

3.2.2.1. Limit State Design

Limit State Design (LSD) is a design methodology commonly used in structural engineering whereby a limit state (e.g., a potential failure mode), is defined by a probabilistic failure envelope. A serviceability limit state (SLS) is primarily concerned with fungal surface disfigurement and growth, with a focus on the

potential health impacts to the occupant. However, for fungal growth, the definition of failure is challenging to identify. The theoretical limiting failure state for surface fungal contamination is the point at which it starts to negatively affect human health human. Unfortunately, these limits are highly variable among persons and are thus challenging to use as a quantitative threshold (Pope, Patterson, and Burge 1993; Burge 2001; Uzunovic et al. 2003).

The fields of fungal epidemiology and industrial hygiene have extensively studied the effects of fungi on occupants. These matters are best discussed in the more relevant literature, but in general, it is safe to conclude that the effects of fungi are minimal on healthy occupants (Burge 2001; Hardin, Kelman, and Saxon 2003) but may be severe for the immunocompromised and those susceptible to allergic responses with exposure to fungal contaminants (Uzunovic, Yang, and Morris 2011). As it is a matter of prudence and good ethical practice to design safe and healthy buildings for all potential occupants, the failure threshold for fungi for this research is defined as the point where it is just visible with the unaided eye. This roughly corresponds to the point at which the pigmented conidia are visible, and dispersed conidia and hyphal fragments are known to cause allergenic responses in persons (Garrett et al. 1998).

Limit state frameworks have been used in the development of other fungal growth models (Isaksson et al. 2010; Thelandersson and Isaksson 2013); however, their output, as a relative dose or a growth index, is not as conducive towards estimating probabilities of growth. As such, an SLS model for fungal contamination is the point at which the probability of fungal growth detection exceeds the authority having jurisdiction's acceptable risk tolerance threshold.

3.2.3. Objectives

Following the review of the existing mould model literature, the primary objective of this research is to develop a fungal growth model with the following key attributes:

- Accepts dynamic and varying environmental conditions in multiple time formats
- Yields a probability of mould growth, with guidance on proper interpretation based on risk thresholds
- Provides the flexibility to readily incorporate preservative treatments or a range of different substrates
- Requires no special training and is intuitive and feasible for use in spreadsheet type software

The underlying research used for the development of the model must also be:

- Founded on the tools and training available to many building practitioners (e.g., specialized equipment should be avoided)
- Readily repeatable by other researchers to expand the model's functionality by controlling as many of the variables as possible

A secondary objective is to develop a database of fungal growth on a North American wood specie with a relevant and easily accessible fungus.

3.3. Methods

Fungal growth is influenced by a number of parameters, many of which cannot be readily identified or controlled. Those controllable and known parameters, as well as a short list of potential unknown effects, are provided in Table 3-1.

Table 3-1– Explanatory and response variables used in fungal modeling

Category	Code	Variable	Description
<i>Explanatory Variables</i>			
Environmental Variables	T	Temperature	Ambient climate chamber set point temperature (°C)
Internal Variables	MC	Moisture Content	Specimen total moisture content as measured gravimetrically
	S / H	Substrate	Jack Pine (<i>Pinus banksiana</i>) sapwood (S) or heartwood (H)
	S _f	Fungal Spore Load	Fungal potential, viability, and inoculum spore load, determined through laboratory procedures
Uncontrolled Variables	S _B	Biological Antagonist	Inherent substrate biological resistance
	S _f	Fungal Variability	Inherent variability in fungal growth patterns
	S _n	Substrate Nutrition	Inherent substrate nutritional profile
	S _c	Contamination	Contamination and fungal competition
<i>Response Variable</i>			
	P(G)	Probability of Growth	Probability of detecting growth (0-100%)
	dP(G)/dt	Rate of Change of Probability of Growth	Rate of change of probability of growth per unit time.

The wood specimens were carefully prepared to control their moisture level; after sterilization in an oven, they were immediately placed in labelled and sterile plastic bags. They were then raised to their target moisture content using sterilized and distilled water and, upon equilibration, were then carefully inoculated with a known fungal suspension. The bags were then placed in temperature controlled climate chambers. The specimens were periodically

photo-documented and their moisture contents were adjusted to their target levels.

3.3.1. Specimen Preparation

Small wood chips, 12mmx12mmx6.3mm, in longitudinal, radial, and tangential orientations respectively, of either sapwood or heartwood were cut and planed from the same jack pine (*Pinus banksiana*) tree. *P. banksiana* was selected due to its widespread geographical distribution and its susceptibility to fungal growth (Rao et al. 2009). It is also closely related to lodgepole pine (*Pinus contorta*) and both find use in lumber for rough construction (Panshin and de Zeeuw 1980; Forest Products Laboratory 2010). A total of 265 specimens were prepared with 130 sapwood specimens, 108 heartwood specimens, and 27 mixed specimens, which contained both sapwood and heartwood. ASTM D4442, *Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials* (ASTM 2016), was followed in general conformance in drying the specimens, with the exception of setting the drying temperature to $74\pm2^{\circ}\text{C}$ instead of $103\pm2^{\circ}\text{C}$, to minimize drying damage to wood cellular structures. This temperature is also aligned with the final drying temperature in the kiln drying process (Forest Products Laboratory 2010) and should therefore be reflective of sterilization potential in store bought kiln dried (KD) lumber. The specimens

were verified for heartwood content at the end of the experiments by following AWP A49-15, *Standard for Determination of Heartwood in Pines and Douglas-Fir* (AWPA 2017).

The dry mass for each specimen was recorded and specimens were sealed in their own individual 6mil (0.15mm) polyethylene bags (see Figure 3-1), to minimize contamination and control the moisture content of the specimen. Prior to placement in each bag, each specimen was subjected to 45 minutes of UV-C light for additional surface sterilization. The specimens were prepared in accordance with the test protocols; they were brought to their target moisture content using sterilized distilled water on February 7th, 2021 and left to equilibrate until they were inoculated with the fungal suspension on February 15th, 2021. The bags were then placed in their respective climate controlled chamber, set to 2°C, 12°C, 22°C, and 32°C.

The experiment was terminated on June 20th, 2021, when the specimens were washed in o-Anisidine Hydrochloride and Sodium Nitrite heartwood indicator to confirm their conditions, in accordance with AWP A49-15 (AWPA 2017). The total duration of the experiment was 126 days.

3.3.2. Fungal Inoculation

Successful colonization depends on several factors. Pre-colonization time, larger inoculum, and reduced fungal competition all have a strong impact on competitive dynamics when other biodeteriorative agents are introduced (Song et al. 2015). To minimize the variables, it is simplest to use a single fungal species that best represents the most typical conditions experienced. This reduces variability, and thus potential sources of error, while also ensuring greater repeatability of the experimental system for other researchers. Due to its ubiquity in the built environment (Miller et al. 1988), low health risk (Level 1 biohazard), dark pigmentation for visibility, and ease of conidial harvesting, *Penicillium chrysogenum* was the selected fungus of choice. The culture derives from the UAMH mycological herbarium (UAMH #6525, MycoBank #165757). The process of preparation of the spore suspension closely follows those of Mil-Std-810G Method 508.6 (USA Department of Defence 2008) and ASTM C1338, *Standard Test Method for Determining Fungi Resistance of Insulation Materials and Facings* (ASTM 2015).

Penicillium chrysogenum was cultured in accordance with the producer's instructions, on 2% potato dextrose agar (PDA) in 100 mm x15mm plates and incubated at 20-25°C. In a sterile environment (biohazard safety cabinet), the

cultured plates were flooded with a non-toxic detergent (0.1% Triton X-100) while the culture was scraped with a sterilized glass rod. The suspension was then passed through an autoclaved glass funnel with approximately 6mm of glass fiber filter placed in the stem. An aliquot of the suspension was taken and diluted with purified water to obtain a spore count estimate with a haemocytometer. The aliquot was vortexed for approximately 15 seconds to ensure a homogeneous distribution of the spores and the counted volume was extracted near the middle of the conical tube. A second aliquot was taken to assess the spore viability. This aliquot was diluted with purified water to target approximately 100-200 spores and inoculated on 2% PDA plates. These viability plates were then incubated at 20°C and counted for Colony-Forming Units (CFUs). The ratio of CFUs to the estimated spore count delivered provides the spores viability ratio.

Once the spore density estimates and viability estimates were completed, the suspension was vortexed again and diluted with purified water to obtain the final spore suspension. The wood specimens were inoculated with identical concentrations of spore suspensions of *P. chrysogenum* one week after they were brought to their target moisture content to enable moisture equilibration. A 10µL

aliquot of the 100x diluted spore suspension was deposited in the middle of each specimen, yielding approximately 1000 ± 100 spores per specimen.

A crucial challenge with growing fungi is controlling contamination from ambient sources, as well as re-colonization from other specimens within the sample set. For repeatability, establishing a single colonization event is essential in determining the net probability of fungal growth. As such, inoculation of a set of specimens that are individually contained, but able to be readily photo-documented to estimate growth parameters is required. The selected solution was to use a sealable transparent polyethylene bag as shown in Figure 3-1.

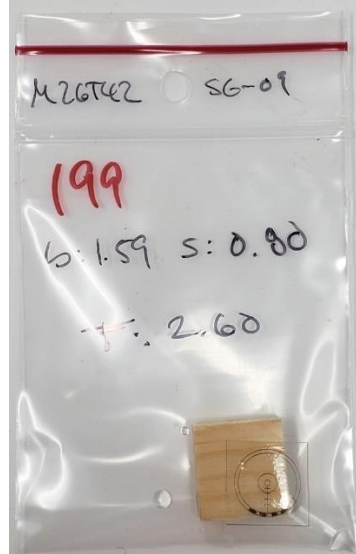
























Figure 3-1– Individually wrapped specimen in a sealed polyethylene bag, with labels for mass of each component

3.3.3. Environmental Parameters

It is known that environmental parameters have a significant impact on fungi. The primary environmental variables of concern are the moisture level of the wood specimens and their ambient temperature. Several experiments have already yielded isopleths of germination time and growth for various species of fungi (Ayerst 1969b; Smith and Hill 1982; Hocking and Pitt 1979). This experiment uses similar temperature ranges, which also occur commonly in the built environment, but the moisture metric used was water activity. The proposed moisture parameter for this research is moisture content, and the merits are discussed in further detail below. Figure 3-2 shows the temperature ranges and moisture content ranges, with the approximate relative humidity value determined from the equilibrium moisture content to relative humidity relation (EMC-RH) of Chapter 4 of the Wood Handbook (Forest Products Laboratory 2010). The coloured icons represent the specimen substrate type for each permutation.

		Temperatures [°C]			
Moisture Content [%]	~RH (%)	2	12	22	32
40	~100%				
30	~100%				
26	~99.3%				
20	~90%				
16	~80%				
14	~72%				



-  Heartwood
-  Sapwood

Figure 3-2– Temperature and moisture content parameters, with RH approximates, for sapwood and heartwood specimens indicated by green or orange, respectively.

3.3.3.1. Moisture

Multiple moisture metrics are available and have been discussed at length in published literatures (Skaar 1988; J. Siau 1984; Bravery 1985). Generally, water activity (A_w) is used by food scientists, relative humidity (RH) and equilibrium relative humidity (RH and ERH) are used by building scientists and engineers, moisture content (MC) is used by wood scientists, and water potential (Φ) is used by mycologists and plant pathologists. From a cellular metabolism level, water potential appears the most closely related to the relations between the fungal cell

wall and the environment, but due to its extreme challenge in direct measurement, an alternative is required. While air humidity levels (A_w and RH) are frequently used in mould models, these have limited resolution as water vapour pressures approach saturation. Moisture content, on the other hand, can account for liquid water effects (condensation, leaks), whereas these would be considered practically the same using an air-based moisture metric (e.g., at or near saturation). Further, moisture content is a direct measurement of the substrate surface and sub-surface conditions; relative humidity characterizes a general area in proximity to the surface but is subject to significant spatial variations due to temperature variations. Lastly, the moisture storing capacity of a porous substrate lends itself for use with a moisture content metric as it retains a degree of memory of prior conditions (e.g., a leak that occurred a few days prior could still be detected). These factors favour moisture content when evaluating fungal growth on wood substrates. Moisture content is also known to influence fungal growth independently from just water activity (Laarhoven et al. 2015).

3.3.4. Apparatus

3.3.4.1. Climate Chambers

Climate controlled chambers were designed and constructed to house the specimens. Heat was provided through a large surface area electric resistance mat, and cooling, for those chambers that required it, was provided with Peltier cooling fans. Internal mixing of the airspace was provided with two continuously running fans. The heating and cooling devices were operated by Love Controller switches (TS2 and TSS2). Temperature and humidity sensors (Hobo UX100-01) were placed centrally in each climate chamber. One was also placed within the laboratory space to determine ambient conditions. The sensors have an accuracy of $\pm 0.21^{\circ}\text{C}$ and a resolution of 0.024°C .

3.3.4.2. Moisture Content Measurements

The moisture content of the specimens were determined gravimetrically using a Sartorius Quintix scale (Quintix 5102-1S), with 10mg resolution. For the average weight of the specimens (2.64g), this provides a moisture content resolution of approximately $\pm 0.4\%$.

3.3.4.3. Microscopy

Each specimen was photographed periodically with a digital USB microscope set to a 20x magnification. A total of 24 readings were taken, spaced on average every 6 days, with a standard deviation of 2.1 days, with the shortest elapsed time being 1 day (early in the tests to capture initial growth), and the longest being 10 days, near the end of the testing once the growth rates were plateauing.

A USB microscope (x10-x220) (Dino-Line AM7915MZT) was used to photograph the specimen. At a x20 magnification, it has a field of view of 19 mm x 14 mm and depth of field of 2.5mm. A jig was devised to ensure uniformity in depth and placement for each specimen shown in Figure 3-3. For consistency in lighting conditions, the specimens were photographed in a light-box (see Figure 3-3).

Each individual specimen bag had a label and target adhered to the surface, with dimension features (circles and bars) to assist in measurement of fungi growth characteristics (Figure 3-4).



Figure 3-3 – Photo documentation set-up, with USB microscope showing individually sealed specimens

The photographs for each specimen were evaluated for any signs of fungal growth by sequential comparative analysis using Timelapse2.0 software and were exported as a file to be processed in the R programming language (R Studio Version 1.3.1093). The post-hoc tests (final moisture content and heartwood indicator) permitted the samples to be reclassified into respective moisture classifications and labelled into either heartwood, sapwood, or mixed wood.



Figure 3-4 – Specimen target, labelled with MC, Temp, Type, and ID Number. In increasing size, the inner to outermost rings represent 1mm², 10mm², and 100mm² in area; the vertical bars are in units of 1mm lengths.

3.4. Results

The recorded data from the temperature sensors in the climate chambers and the individual gravimetric moisture readings and mould growth ratings for each specimen are provided in the respective sections below.

3.4.1. Climate Chamber Temperature

Temperature control was lost briefly due to a short-duration power outage. The 2°C and 12°C climate chamber transformers also failed briefly during the test and were replaced within two days. The replacement transformer on the 2°C climate chamber failed again at the end of May and so the specimens were relocated into

a laboratory refrigerator. The replacement transformer for the 12°C chamber also failed at the end of June, but as the experiment was nearing its end-date, a replacement was not procured.

The quantitative statistical description on the temperature setting for each sensor is provided in Table 3-2. The 2°C chamber experienced the largest variations, with a standard deviation of 3.2°C, with a mean temperature of 2.19 ± 0.12 °C. The standard deviation of the temperature on the remaining climate chambers were below 1°C.

Table 3-2 – Climate chamber statistical values, including mean, including the 95% confidence interval, and the standard deviation

Temperature Setting	Mean [°C]	Standard Deviation [°C]
2	2.19 ± 0.12	3.280
12	11.9 ± 0.16	0.157
22	22.7 ± 0.02	0.654
32	30.8 ± 0.01	0.241
Ambient	23.3 ± 0.03	0.868

3.4.2. Specimen Moisture Contents

Each specimen was measured periodically to ensure it remained within the targeted moisture content level. For each specimen, the 95% confidence interval for the targeted MC was $\pm 0.71\%$, with a mean spread of 2.5%MC over the 135 days that the experiment took place. Only 5 of the 265 specimens had significant short-term deviations from their target MC. During the drying process, there was

a delay in measuring some of the specimen dry moisture content mass, and so at the end of the experiment, all specimens were redried and their updated moisture contents were corrected. It is for this reason that not all of the specimens necessarily land near their target, but they were maintained at the same moisture content throughout the duration of the test.

3.4.3. Surface Mould Growth

A boxplot showing the relationship between moisture content, specimen type, and whether growth is observed is shown in Figure 3-5.

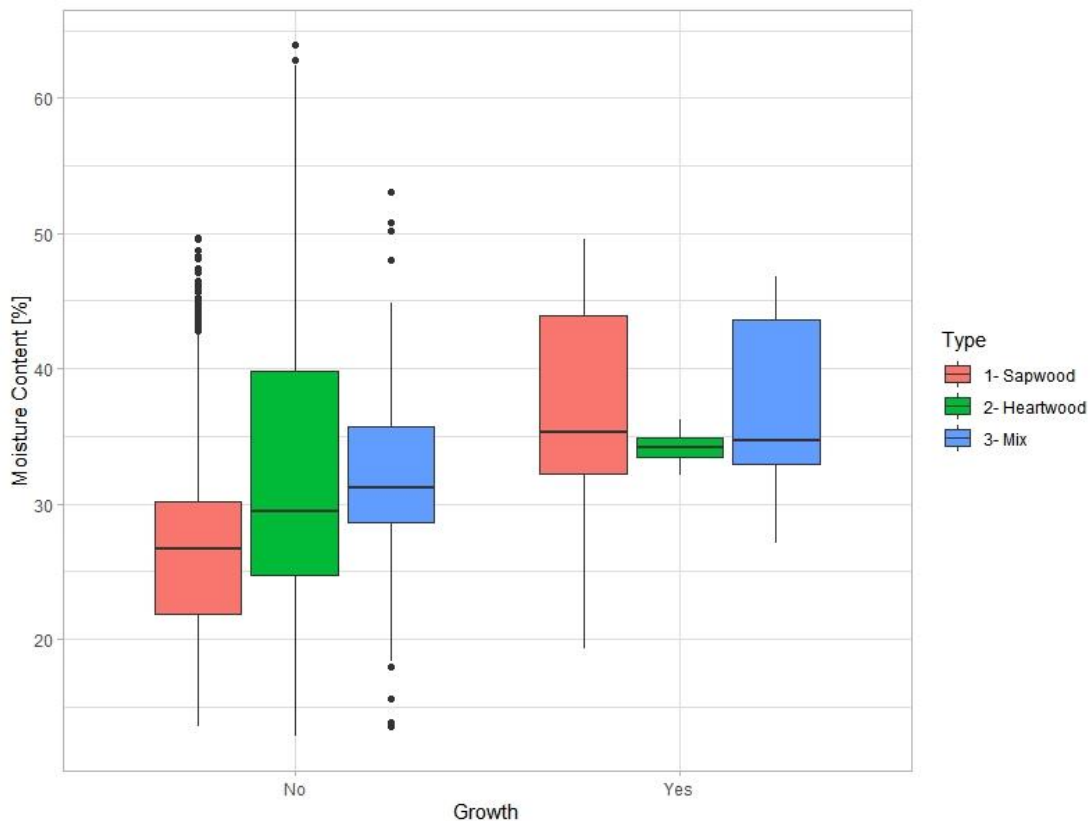


Figure 3-5 – Boxplot showing range of moisture contents by specimen type as a function of whether growth was observed.

This preliminary visualization of the relationships between the data clearly show that moisture content and type of substrate have a significant impact on growth.

For each temperature and moisture content category pairing, the number of specimens showing evidence of fungal growth and the total number of specimens is shown in Table 3-3, with the intensity of the cell shading indicating the quartile fraction of total specimens experiencing growth (i.e., darkest shade of green indicating 100% growth, no shading indicating no growth).

Table 3-3 –Number of specimens exhibiting fungal growth and cohort replicates by moisture content, temperature, and type, with colour shading into quantiles

Moisture Class	Type	Temperature (°C)			
		2	12	22	32
<20	1- Sapwood	0 / 1	0 / 10	0 / 6	1 / 11
<20	2- Heartwood	0 / 2	0 / 9	0 / 5	0 / 4
<20	3- Mix	0 / 2	0 / 2	#N/A	#N/A
~22	1- Sapwood	0 / 5	0 / 8	4 / 9	0 / 8
~22	2- Heartwood	0 / 4	0 / 4	0 / 5	0 / 9
~22	3- Mix	0 / 1	#N/A	#N/A	0 / 1
~28	1- Sapwood	0 / 2	2 / 7	6 / 9	2 / 9
~28	2- Heartwood	0 / 2	0 / 8	0 / 7	0 / 8
~28	3- Mix	#N/A	1 / 2	1 / 3	#N/A
~32	1- Sapwood	0 / 1	8 / 8	6 / 7	2 / 6
~32	2- Heartwood	#N/A	0 / 4	1 / 7	0 / 7
~32	3- Mix	#N/A	3 / 3	1 / 4	#N/A
~42	1- Sapwood	#N/A	6 / 6	9 / 10	3 / 6
~42	2- Heartwood	#N/A	0 / 8	0 / 7	0 / 8
~42	3- Mix	#N/A	2 / 3	1 / 1	3 / 5

A photograph of Specimen M26-T22-SG-ID09 is provided in Figure 3-6 to show a readily visible fungal growth on the sapwood of a mixed specimen, with no growth on the heartwood side.

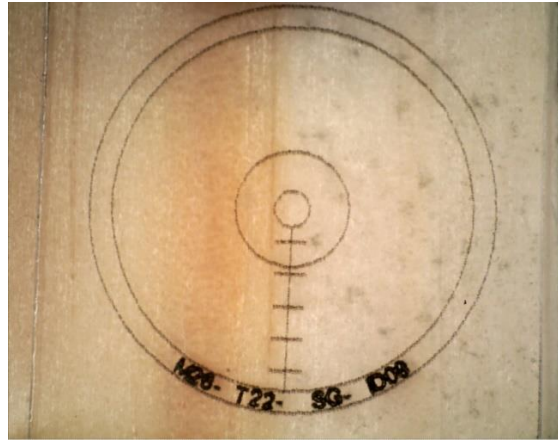


Figure 3-6 – Mixed sapwood/heartwood specimen at 26% MC and 22°C after ~3.5 months, exemplifying fungal growth on the sapwood (right side)

3.5. Analysis

The population growth equations describe the relationship between organism abundance to its environmental carrying capacity. Fungi growing on a substrate are subjected to similar growth parameters and can therefore be described by the population growth rate equation (3-1),

$$\frac{dP}{dt} = r \cdot P \left(1 - \frac{P}{K} \right) \quad (3-1)$$

where, P is the number of organisms in a given environment, r is the intrinsic growth rate, and K is the environment's carrying capacity. More elaborate models will use a K parameter that is itself a function of other explanatory variables. Integrating equation (3-1) yields the population growth function (3-2):

$$P(t) = \frac{K}{1 + \left(\frac{K - P_0}{P_0}\right) e^{-rt}} \quad (3-2)$$

where, P_0 represents the initial starting conditions. This equation is a variation of the generalized logistic equation (3-3) (Agresti 2009),

$$f(t) = \frac{L}{1 + e^{-r(t-t_0)}} \quad (3-3)$$

where, L is the asymptote, r is the growth rate, t is the time-step and t_0 is the translational shift for the $t=0$ value. In this application, fungal growth is defined as a binary condition, with 0 representing no observed growth and 1 representing observed growth, and is described by the binomial distribution and modeled using a binomial logistic regression.

A logistic regression function describes the log probability of an occurrence, or logit, providing a continuous probability output as a linear function of a set of predictor variables shown in equation (3-4).

$$l = \log_b \frac{p}{1-p} \quad (3-4)$$

$$= \beta_0 + \beta_1 x_1 + \beta_2 x_2 \dots$$

where p denotes the probability of occurrence in the form of the logistic equation, x_n are the predictors variables, and β_n are the regression coefficients. The regression coefficients are iteratively determined using the maximum likelihood estimation.

A significant advantage of the logistic equation is that its derivative is a function of the original equation and a condition-dependent growth-rate coefficient, shown in equation (3-5),

$$f'(t) = r \cdot f(t) \cdot (1 - f(t)) \quad (3-5)$$

By determining the value of the growth-rate coefficient, r , conversion of steady-state empirical data into a dynamic model is possible. To describe the probability of fungal growth in dynamic conditions, the product of the growth coefficient at a given-time step and the current probability of growth is calculated to yield the rate of growth in probability of fungal detection.

3.5.1. Binomial Logistic Regression

Describing fungal growth through a binomial logistic regression requires appropriate parametrization of the predictor variables. From prior research (see: Smith and Hill 1982; Ayerst 1969b), we know that the growth rate r varies non-linearly with MC and T; at the extremes of MC and T, the fungi goes dormant or dies. This relationship was therefore described using a second order polynomial for these two parameters. The resulting regression equation takes the form of equation (3-6) and (3-7),

$$P(t) = \frac{K}{1 + e^{-(\beta_0 + r \cdot t)}} \quad (3-6)$$

$$r(MC, T) = (\beta_1 \cdot MC + \beta_2 \cdot MC^2 + \beta_3 T + \beta_4 T^2) \quad (3-7)$$

where $P(t)$ is the probability of growth (continuous on [0-1]), t is elapsed time, r is the growth rate coefficient (as a function of MC and T), and K is the upper carrying capacity of the substrate. For this preliminary research, the K coefficient is set to 1, but in future work with fungicide treated substrates, this parameter could be further modified to characterize antagonistic effects. The predicted probability of growth at the temperature and moisture content permutations is

provided in Figure 3-7, with the points in green representing empirical results and the lines in black representing the predicted growth.

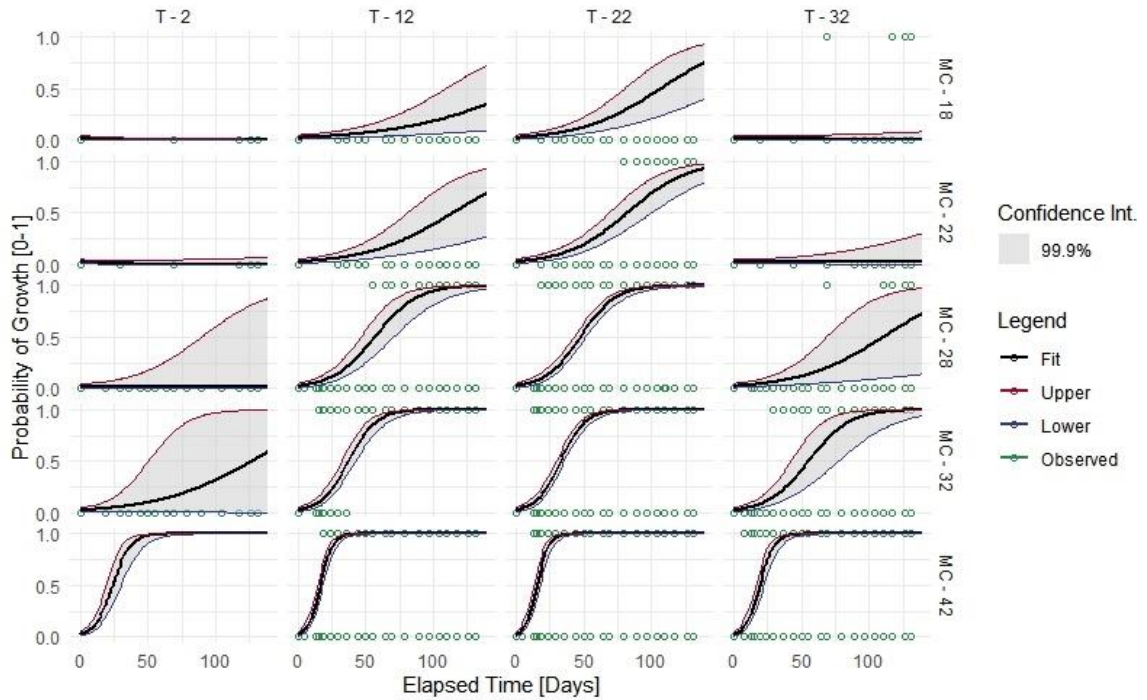


Figure 3-7 – Predicted and measured growth by elapsed time for temperature and moisture classes. Predicted probability of growth curves are shown in black, with red and blue Lines Representing the 99.9% confidence intervals, whereas empirical binary growth is shown in green.

Fungal growth was not conducted or observed in all MC and T classes, and so the projected growth probability requires further confirmation. The experimental limits on moisture content range from 12.7% MC to 63.9%MC and the temperatures from -3.5 to 31.6°C; any values exceeding these limits should be careful considered on their impact on the growth rates. The growth rate coefficient as a function of T and MC is shown graphically in Figure 3-8.

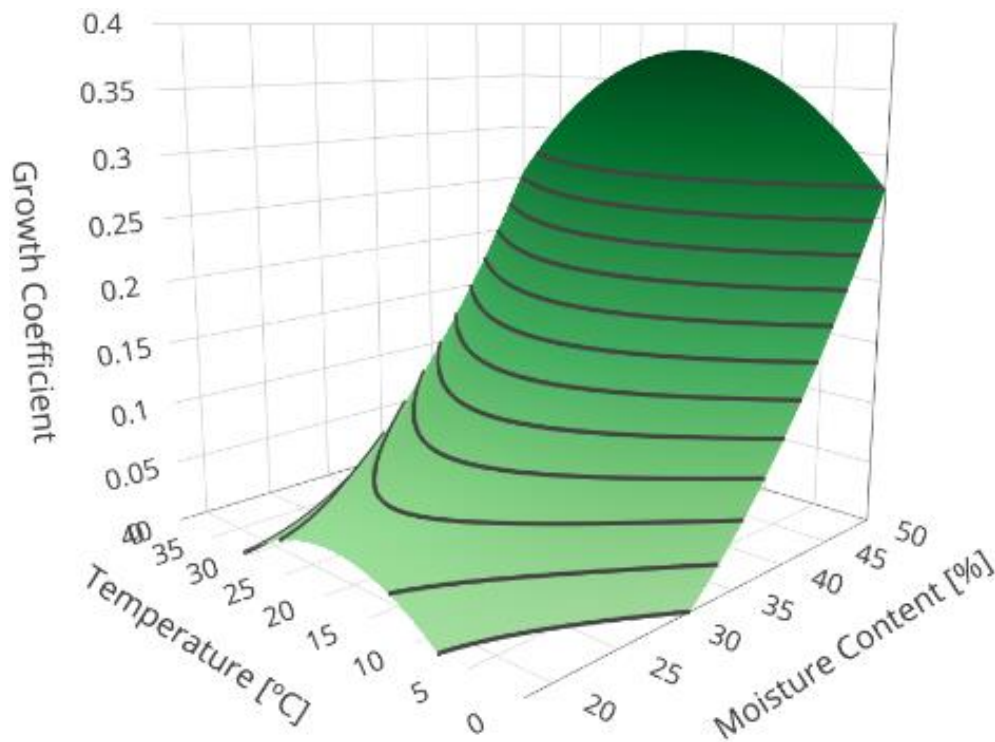


Figure 3-8 – Calculated growth rate coefficient for given MC and T conditions.

As an artefact of the parabolic assumption in the regression formula and limited experimental duration, two unique occurrence are observed near the experimental limits: 1) negative growth rates at extreme temperatures, and 2) non-zero growth-rate at low moisture content.

- 1) As this experiment was monotonic in nature, any negative growth coefficients have no physical meaning and should be set to zero. Negative probability rates of occurrence can be determined in future research where intermittent inclement conditions are introduced.
- 2) The local minimum growth coefficient, on the basis of moisture content, occurs around 16% MC and is non-zero. This value corresponds to approximately 80% RH in the EMC-RH relation which describes the lower

water activity limit known for many fungi. Until further confirmation on these limiting moisture content values is completed, it is recommended to set the growth coefficient to 0 for any MC values less than 16%MC.

Rate of growth coefficients are provided in Table 3-4 for four different regression sets. The probability of growth given the specimen will grow mould is the $P(G|G)$ set, whereas the $P(G|G)^+$ represents the 99th percentile growth parameter. The $P(G\forall)$ represents the probability of growth for all specimens, including those that do not grow mould, and is therefore more representative of environmental systems which do not necessarily assure growth, such as unsuccessful colonization, predation by fungi consuming organisms, or the stochastic nature of a fungal spore landing in a nutritionally deficient part of wood element. All the regression coefficients are significantly statistically ($p < 0.01$) for the three sets. The last curve, $P(G|\in H)$, provides the coefficients for fungal growth given that the heartwood specimen would grow mould. As this was a rare occurrence, and often found on mixed specimens, the statistical significance of the coefficients for the heartwood regressions are low and should be used with caution.

Table 3-4 – Regression coefficients and significance level for probability of growth given growth (upper 99% confidence interval and mean), probability of growth for all specimens, and probability of growth for heartwood given growth

Model	Coefficients				
	Intercept (β_0)	MC (β_1)	MC ² (β_2)	T (β_3)	T ² (β_4)
P(G G)+	-3.262***	-4.946x10 ⁻³ ***	2.055x10 ⁻⁴ ***	6.623x10 ⁻³ ***	-1.801x10 ⁻⁴ ***
P(G G)	-3.650***	-8.991x10 ⁻³ ***	2.890x10 ⁻⁴ ***	1.090e-02***	-2.835x10 ⁻⁴ ***
P(GV)	-1.883***	-1.711x10 ⁻³ ***	6.485x10 ⁻⁵ ***	2.252x10 ⁻³ ***	-8.234x10 ⁻⁵ ***
P(G G€H)	-2.251***	2.968x10 ⁻⁴	1.072x10 ⁻⁵ **	1.753x10 ⁻⁴	-2.336x10 ⁻⁵ **

Significance Codes (p-value): p<0.01 (***), p≤0.01(**), p≤0.05(*), p≤0.1('), p≤1.

3.5.2. Substrate Treatments

To control the number of variables, inhibitory substrate effects were limited to heartwood and sapwood from the same boards. Heartwood harbors several extractives (terpenoids, phenolics, etc.) which are antagonistic to fungal growth (Stirling, Kus, and Uzunovic 2016; Valette et al. 2017) and their presence is used in this study as an analogue for possible preservative treatments. Recalling that the K coefficients in equation (3-6) represents the upper carrying capacity, it could be modified to suit specific treatments. Equating the P(G|G) and P(G|G€H) models, the required reduction in the K coefficient is represented by the ratios given in (3-8),

$$K = \frac{1 + e^{-(\beta_{Heart} + r_{Heart} \cdot t)}}{1 + e^{-(\beta_{Sap} + r_{Sap} \cdot t)}} \quad (3-8)$$

with the β and r variables representing their respective treated or untreated substrates. The K coefficient therefore becomes a function of MC, T, and elapsed time. The values for K with time, for a fixed MC at 28% and T at 22°C, are shown in Figure 3-9.

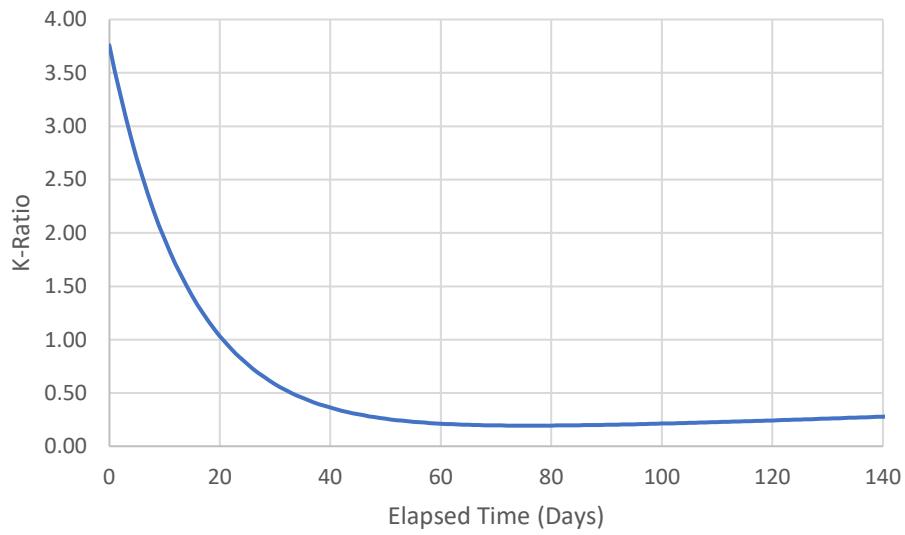


Figure 3-9 – K capacity reduction coefficient with elapsed time, at MC=28% and T=22°C

Extracting the minimum K value and applying it uniformly as a reduction to the probability of growth for the untreated specimen yields the curves found in Figure 3-10.

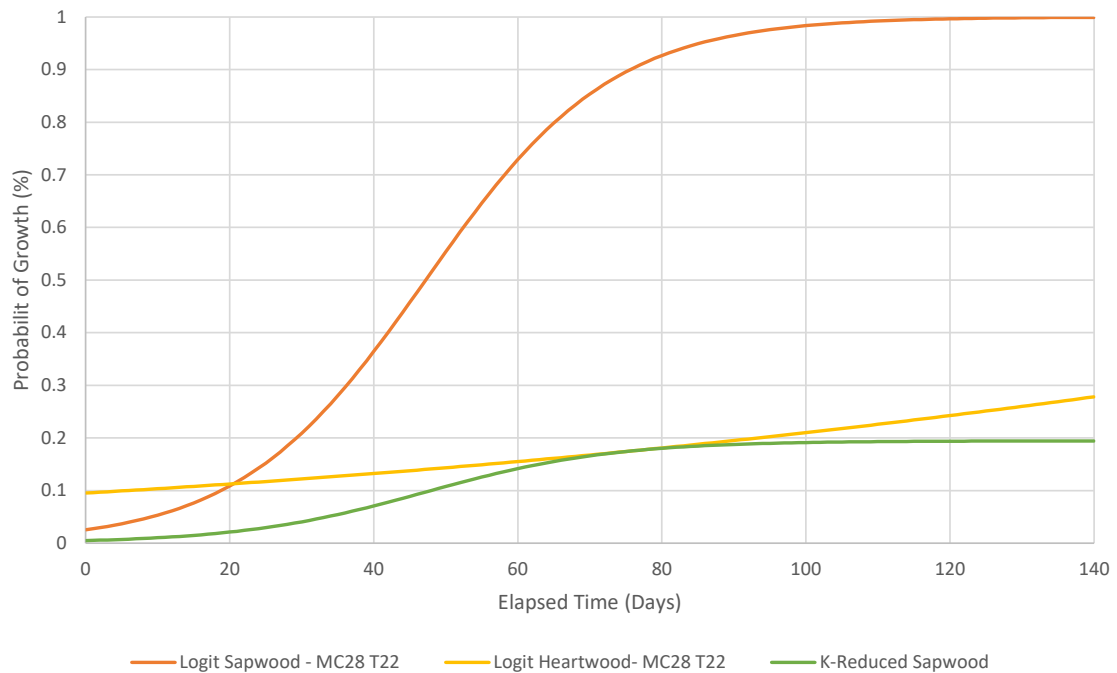


Figure 3-10 – K-reduced sapwood compared with sapwood and heartwood regressions at MC=28% and T-22°C.

Whereas the results show that the K-Reduced Sapwood and Heartwood Regression predict a 10% difference in the probability of growth, this process is nonetheless suggestive of promising approaches in using the K coefficient for preservative treatments.

3.6. Discussion

A binomial logistic regression on fungal growth on a North American wood species shows promising results in projecting the probability of fungal contamination as a function of dynamic environmental parameters. Description of the probability failure envelope is a required first step in further development

of a limit state design approach to biodeterioration of building materials. Further, identification of risk tolerances and thresholds is also critical in understanding what probability of fungal growth is acceptable. As these tolerance levels may depend on a number of factors, it is important that the model user understand the uncertainty associated with the model. This section discusses how the regression equations can be applied as a tool to evaluate the risks of fungal growth on wood materials. It is followed by a preliminary validation in an attic roof study. Lastly, the caveats of the tool and limits of this research are discussed.

3.6.1. Application of Tool

The model provides a range of probability outputs for differing assumptions. Conversion of these outputs into actionable recommendations by building practitioners requires translation into language that is understandable by laypersons. The process whereby this model can be incorporated with spreadsheet data, which may originate from either empirical records from a data logger or an output from a hygrothermal model, is shown conceptually in Figure 3-11.

Date Time	MC (%) - N312	T (°C) - N312	r	P	dP/dt
2012-10-17 17:00	20.0	13.7	0.032	2.53%	3.30E-05
2012-10-19 18:00	19.7	12.4	0.027	2.54%	2.75E-05

Figure 3-11 – Application of P(G|G) model in spreadsheet given hourly input data.

The process follows:

Step (1) – The growth rate coefficient (r) is calculated from the environmental parameters (MC and T) using Equation (7). The probability of growth (P) for the first time step is calculated using Equation (6).

Step (2): the growth rate coefficient and the current time-step's probability of growth value are then used to compute the rate of probability growth (dP/dt) with Equation (5). The dP/dt value is normalized according to the time-step length (e.g., divided by 24 should the values be hourly, or by 1, if average daily values are used).

Step (3): the probability of growth for the next time-step is calculated as $P + dP/dt$ from the previous time-step.

Depending on the audience, translation of probability into common language may be preferred. Table 3-5 provides guidance on mould growth classification level, the range of likelihood outcomes, and a plain language equivalent to assist

in communications with building decision makers. The table is based off of the likelihood scales from the IPCC (2014).

Table 3-5 – Likelihood scales for terminology on probability of growth

Classification	Term	Likelihood of Outcome
1	Very Likely	90-100%
2	Likely	66-90%
3	More likely than not	50-66%
4	Less likely than not	33-50%
5	Unlikely	10-33%
6	Very unlikely	0-10%

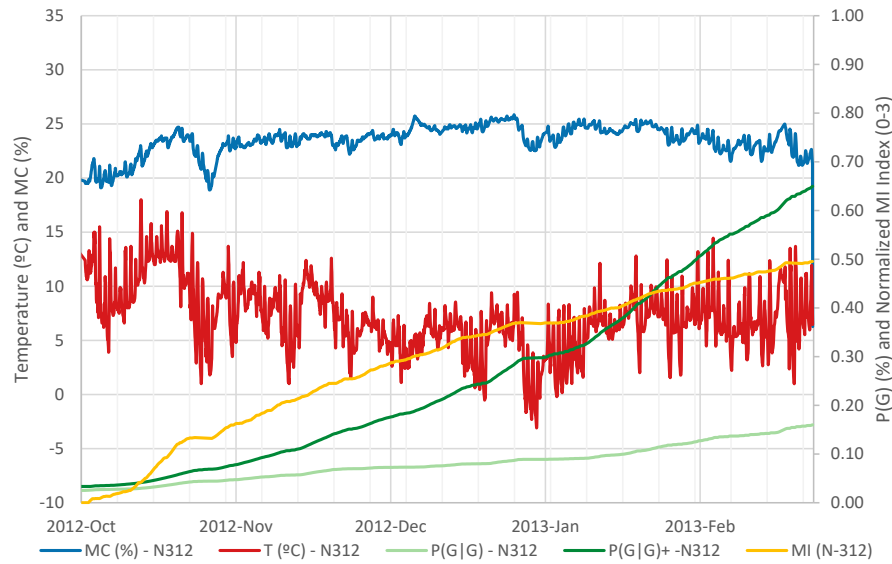
The combination of the $P(G|G)$ and $P(G|G)+$ models can be used to describe upper limit and most likely mould growth occurrences, whereas the $P(G\forall)$ can be used to describe lower-limits of anticipated growth on suitable substrates.

3.6.2. Preliminary Validation

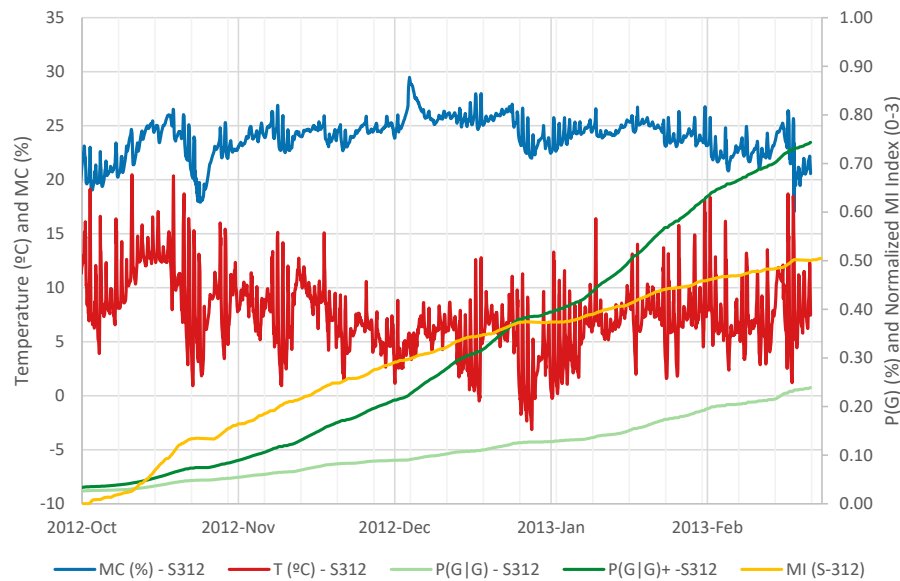
The model was compared with an experimental roof study that investigated the impacts of different surface treatments on mitigating mould growth in ventilated roofs. Further detail may be found in Finch et al. (2015). Two ventilated attic roofs were constructed in Vancouver, BC, and were instrumented with temperature, relative humidity, condensation, and moisture content sensors and connected to a data logging system that made hourly recordings. The test roofs were constructed in September 2012 and preservative treatments were applied on October 15th, 2012. This also coincides with the activation of the

meteorological station that recorded ambient humidity, and so therefore is considered the start of this test. The substrate conditions depart from the original assumptions in this model on three fronts: 1) the substrate is a Douglas-fir plywood, not jack pine, 2) an application of bleach was applied to disinfect the plywood of any fungus at the start of the test, and 3) fungal inoculation occurred naturally with ambient spores. However, these three conditions are assumed to have a smaller impact relative to the contribution of the environmental effects, the salient concern for this model.

The moisture content and temperature values were used as input variables into the model, and the resulting probability of growth output was compared with the photographed results. The hourly input data (MC and T) and the projected $P(G|G)$ and $P(G|G)+$ models are shown in Figure 3-12. The model is contrasted with the VTT model (H. Viitanen et al. 2015; Hannu Viitanen et al. 2005), with a mould index (MI) rating scale of 0-6, with a value of '3' representing visual mould growth. For ease of plotting the VTT and $P(G|G)$ models, the VTT model was normalized to an MI of 3. A sensitivity class of "Sensitive" and a decline coefficient C_{eff} was selected for the VTT model. The relative humidity input was from the nearby meteorological station and may pose some variance from the surface relative humidity of the sheathing.



(a)



(b)

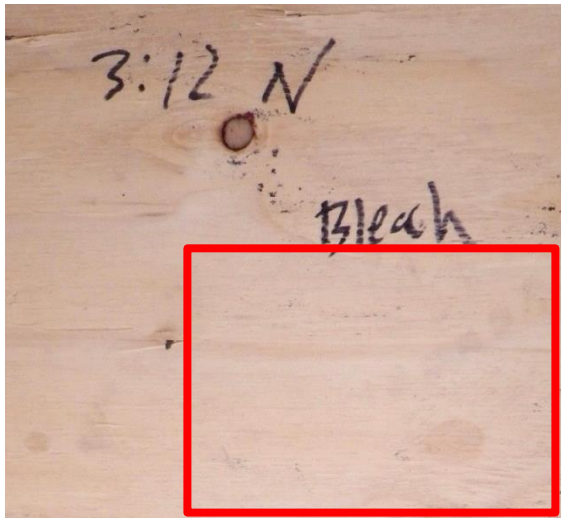
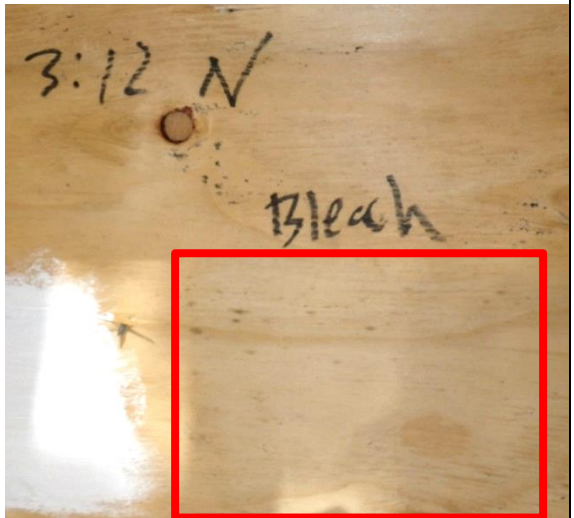
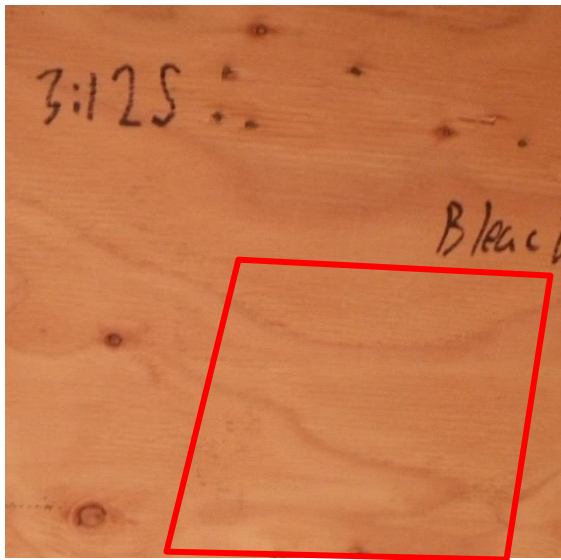
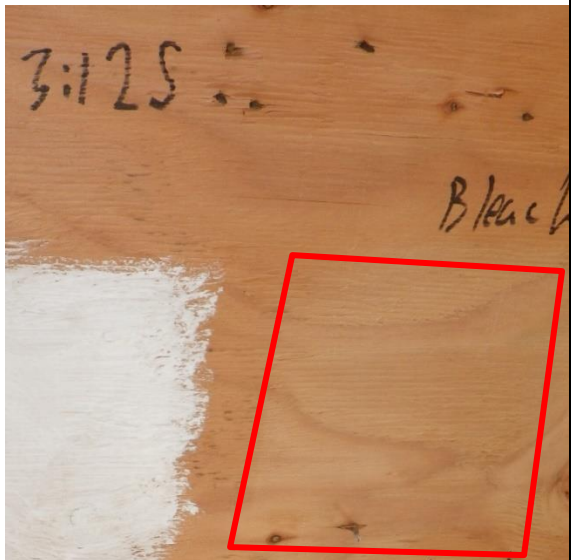
Figure 3-12 – Moisture content and temperature for ventilated attic on North (a) and South (b) orientation, with normalized VTT mould index (relative to an MI = 3) in yellow, $P(G|G)$ projection in light green and $P(G|G)+$ in dark green

The VTT model with the sensitive material class (representative of some plywood) suggests that no visible mould should be present on either the North

or South elevations. In the $P(G|G)$ model on the other hand, suggests that it is unlikely to find mould on either elevation, on average, but that the maximum probability of finding mould is in *more likely than not* on the North elevation, and *likely* on the South elevation, 99 times out of 100.

Review of the attic plywood sheathing photographs in Table 3-6 shows that the North elevation has a few patches of fungal growth in the treated area, with virtually no growth around its perimeter. The South elevation shows no fungal growth within the treated area but some staining around its perimeter. In both cases, the VTT model suggests no observable fungal growth, which is not accurate. The $P(G|G)$ models suggest a large range of probabilities of detecting fungal growth. On the North and South elevation, there's only about a 15% and 25% chance of mould growth, on average, with the 99% confidence interval suggesting possibilities as high as 65% and 75% chance of detecting growth, respectively. The large variability in probability encompasses both low and high likelihood of growth conditions, which is supported by the visual evidence. Some areas grew mould, others did not, due to unknown biological and substrate factors. This is an improvement over deterministic models, which provide a fixed estimate of a biological growth model, which is not fully represented in this test.

Table 3-6 – Surface mould photographs for North and South elevation, bleach treated attic roofs, treatment area outlined in red, on 2012/10/15 and 2013/02/15

	2012/10/15: When Applied	2013/02/15: 4 Months Later
North		
South		

3.7. Recommendations

This research indicates that a logistic regression to determine the probability of finding mould growth is an appropriate method for use with limit state design

concepts. This research could be further enhanced in three ways: 1) improvements to the range and duration of the underlying dataset, 2) investigation of delaying or reducing impacts from inclement conditions and treated substrates, and 3) verification of the effects of natural sources of inoculum and fungal competition.

3.7.1. Model Caveats

There are several important caveats in these models. The most important is the assumption of monotonic growth. As this model does not currently incorporate delays or reductions in probability of growth, over long enough time horizons, some degree of growth is guaranteed. Despite observance of negative growth rates, this may be an artefact of the regression and may not necessarily be reflective of actual delay in probability of detecting growth. Until such experiments are conducted, it is instead suggested to set all negative growth coefficients to a value of 0. This approach yields conservative growth estimates but may be justifiable as once fungal resting spores are developed, the fungi can quickly resume growth upon resumption of adequate environmental condition. Investigations into delaying effects, as identified by Bekker (2014), may be a method to counteract this limitation until further research is completed.

The second important caveat is experimental limitations. The experimental duration was limited to 4 months. As a result, some of the specimens that did not grow mould could have been prematurely terminated. This applies both to limiting experimental environmental conditions (low moisture or temperature) as well as those specimens in optimal growing conditions that did not yield growth.

The third caveat lies within incorporation of the model within simplified spreadsheets. The experiment carefully controlled for contamination and is therefore only reflective of a single colonization event. In reality, the substrate may be continuously inoculated from local spores. Initial germination of early colonizers may be interrupted or terminated with inhospitable environmental conditions, which, upon resumption of suitable conditions, subsequent spores may be more successful. An iterative approach, whereby a continuously running 4-month period of growth check over longer-durations, in which only the highest amount of growth at the end of the 4 month running period, may be a suitable work-around in the short-term. Further investigation is required.

The last caveat lies within the use of a single fungus species, *P. chrysogenum*. Many other fungi have varying environmental and substrate preference, different growth rates, and abilities to compete with other organisms. Further

investigation into probability of growth rates with other fungi, including potential competition effects with antagonizers is warranted.

3.8. Chapter 3 – Commentary

There are two primary limitations to the SLS model that were not explicitly covered within the published manuscript. This addendum discusses some of these limitations and their context.

Substrate

One of the primary objectives of developing an SLS model was to minimize the amount of uncertainty to identify intrinsic variability in a controlled manner. The substrate used for this research, Jack Pine (*Pinus banksiana*) originated from a single board harvested from a single tree in Ontario, Canada. This necessarily represents a known departure from anticipated inter-tree variation. However, by drawing all specimens from a single board, the intra-tree variability and its interaction with a mono-culture of the fungal inoculum permits a better understanding of the inherent variability that could be expected in quasi-ideal conditions.

Estimation of the McFadden pseudo- R^2 of the SLS model yields a result of 0.61, meaning that the explanatory variables, of Temperature, Moisture Content, and Substrate, are capable of explaining around 60% of the observed variability in the

data. The remaining 40% is a combination of undefined variables and properties. The underlying assumption within the application of this SLS model to other wood species derived from the S-P-F mixture is that the intra-tree variation captured by the SLS model is on a similar order of magnitude as the potential inter-tree variation that could be observed. For context, variation of inter-tree mechanical properties for a given species have coefficients of variation of less than 40% for all surveyed mechanical properties of clear wood specimens (Forest Products Laboratory 2010). Between species, greater variation occurs. However, given that *P. banksiana* is known to be susceptible to fungal colonization (Rao et al. 2009), it represents a conservative limit for biological growth (e.g. if no growth is detected on *P. banksiana*, it is probable that no growth would be found on a more resistant tree species). Methods to resolve this assumption would be a repeat of this experiment at select climate conditions to verify similar ratios of detection/absence of fungal growth on different tree species.

Fungi

Minimizing the variability in fungal growth necessitated the use of a single fungal species, as it is known that microbial competition can impact the result in overall fungal biomass (Song et al. 2012; Boddy 2000). The fungal species selected

for this SLS model was *Penicillium chrysogenum*. This fungi was selected for the following reasons:

- It is identified as a Risk Group 1 biohazard safety level by Public Health Agency of Canada's Biosafety ePATHogen Risk Group Database, meaning minimal protective measures are required to ensure safety of any users (agent last modified date: 2018/02/19).
- Its conidia are highly pigmented, enabling easier visual identification
- It is moderately xerophilic, with a minimum water activity of ~0.79, meaning its growth occurs within some limiting moisture conditions (Clarke et al. 1999)
- It is a frequently occurring fungi in Canadian Homes, with the taxa identified in over 80% of surveyed Canadian homes (Miller et al. 1988), commonly found in dust samples collected around the world (Visagie et al. 2014), and identified as one of the most common fungal species in water-damaged budlings (Andersen et al. 2011). This species is also frequently used within other biodeterioration research (P. Johansson et al. 2012; Madsen et al. 2016; Adan 1994; Nielsen et al. 2004).
- It is readily acquired through multiple mycological herbariums. The strain used was ordered from the UAMH Centre for Global Microfungal Biodiversity, strain number #6525, (Mycobank ID #165757).

Chapter 4 – Ultimate Limit State

A Non-Destructive Longitudinal Laboratory Test Method for Detection of Incipient Ultrastructural Changes in Wood

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Abstract

The established methods for determining the effects of ultrastructural changes in structural wood members rely upon traditional, possibly outmoded, testing paradigms. These methods usually involve destructive testing of wood specimens that are exposed to environmental conditions infrequently experienced in buildings. Understanding how the ultrastructure changes with time within the same specimen is crucial for building practitioners in assessing risks to life-safety, remaining service life of structural components, and to aid in

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the identification of mitigation or remediation measures. The primary agents causing ultrastructural modifications to wood are wood rotting basidiomycetes but may also include other biotic and abiotic agents; the methods contained herein should be applicable to all such longitudinal experiments. This paper reviews existing literature on decay testing and validates a new method to assess longitudinal changes in mechanical properties with time using non-destructive test measures at relevant moisture contents. The validation testing shows this method has a good degree of repeatability and should permit the initial detection and monitoring of ultrastructure changes (e.g. decay). The method uses a repeatable, non-destructive 4-point testing procedure for specimens controlled to specific moisture contents using energy dissipation as the salient performance metric. Recommendations are provided to refine this novel test method.

4.1. Introduction

Wood has been used in buildings for millennia due to its advantageous mechanical properties, availability, and affordability. Structural wood components find widespread use in low and mid-rise construction, and more recently, in high-rise construction as engineered wood products. With the advent of newer engineered wood products that are finding use in novel building environments, understanding how environmental factors can incrementally

impact the structural performance of wood elements is beneficial with respect to evaluations of long-term durability.

One of the main concerns of wood structures is the risk of biodeterioration, which may result in mechanical property losses should these structures be exposed to conducive environmental conditions. The exact costs of premature wood failure to the building industry is unknown but estimates place it at \$7 billion for the North American market in the 1990's (Zabel and Morrell 1992). The fungi responsible for the majority of these are grouped either as brown or white rots, and form, collectively, the term of wood rotting basidiomycetes (WRB).

Decay differentiates itself from other fungal attacks in that deterioration occurs in the ligno-cellulose matrix, causing ultrastructural changes affecting macroscopic properties such as stiffness and modulus of rupture. Ideally, detection of incipient decay, prior to non-recoverable damage, is preferable to preserve the quality of the structure. Efforts to predict service life of these wood elements have been attempted with varying success and are summarized by Lepage et al. (2019b).

Traditional methods use destructive tests, which require large numbers of replicates and may have great variability between specimens, exacerbated by the heterogeneity and orthotropic properties of wood. The destructive nature of

these tests prohibits the direct measurement of the point of departure in structural properties; it must be inferred by population statistics. Further, to permit comparisons between the experimental variables, prior to the destructive testing, the specimens must be returned to identical testing conditions (e.g. 12% MC at 20°C) which are not representative of conditions conducive to decay.

Non-destructive test methods minimize experimental errors by permitting re-use of the same specimen in subsequent tests. Incorporation of longitudinal testing parameters, including a range of biotic or abiotic deterioration effects (such as oxidation, thermal degradation, or chemical modification, or biological decay as the concern in this paper), will permit the ready incorporation of time factors into the incremental changes in ultrastructure.

Consequently, this paper seeks to evaluate the accuracy and utility of a longitudinal non-destructive test method using energy dissipation as an analog for ultrastructural changes in 4-point bending at representative moisture contents. This will provide insight into testing of wood prisms at ranges of moisture contents, thus permitting treatments to investigate long-term, incremental changes to mechanical properties. The focus of this paper is to evaluate a method that detects the impact of decay, but the approach could be extended to any factors that cause incremental changes in the wood cellular

structure over time. It will be contrasted with anticipated reductions in decay from contemporary models.

4.1.1. Literature Review

Evaluation of the degree of decay in wood has been of great importance to wood scientists and engineers for many years. Hartley(1958) concluded that mass loss was likely the best metric for evaluation of wood decay. This is further elaborated by Wilcox(1978), as other properties such as changes in mechanical properties can be unreliable due to difficulty in measurement of wood strength, type and degree of fungal activity, variations in moisture content, and spatial/temporal variability of decay. However, from an engineering perspective, the primary concern is change in mechanical properties, specifically as caused by incipient decay, as this results in a loss of structural capacity prior to visible signs of decay.

Reductions in toughness and impact bending are considered the most sensitive to incipient decay, where a 50% loss in toughness can occur with 1% weight loss(Richards 1954), with reductions of up to 85% by the time 10% weight loss was measured. Reductions of mechanical properties in static bending were found to be the next most sensitive to incipient decay, including modulus of elasticity (MOE), modulus of rupture (MOR), and compression perpendicular to grain.

Toole (1971) found that 5% compression had the highest correlation with weight loss.

Further research confirms that incipient decay is characterized by significant decreases in mechanical properties with modest reductions in components and minimal change in appearance (Winandy and Morrell 1992), and that incipient decay is best measured by a reduction in strength loss instead of mass loss (S. Curling, Winandy, and Clausen 2000). The process by which this strength reduction occurs is through depolymerization of hemicelluloses encrusting the cellulose microfibril.

Winandy and Morrell (1992) conducted experiments by using 4-point bending tests on wood inoculated in accordance with ASTM D2017, *Accelerated Laboratory Test of Natural Decay Resistance of Woods* (ASTM 2005), which uses a soil block inoculum, whereby an inoculated feeder strip is used to decay the specimens. Their approach also included non-destructive test methods, by using sound wave transit time, to estimate the MOE. The four-point bending tests were destructive in nature and the specimens were all dried to 12% moisture content (MC) before mechanical testing. A four-point test was preferred as it maximised the volume of material under pure flexural stress. As the weakest point of wood governs failure and can vary spatially, maximizing the stressed volume reduces

errors associated with spatial uncertainty. Their results showed that strength loss did not occur without weight loss and that the relationship between the two was linear. Degradation of hemicellulose was closely related to wood strength losses.

Subsequently, Curling, Winandy, and Clausen (2000) found that strength loss could be measured before significant weight loss by following standard decay tests EN 113(Standard 2004) and ASTM D2017(ASTM 2005). They found strength loss is a more sensitive measurement of incipient decay than weight loss. They re-confirmed the direct relationship between strength and weight loss.

Curling, Clausen, and Winandy (2002a) further extended the relationship of incipient decay to mechanical loss with the inclusion of chemical analysis of the composition of the wood specimens. Similar to previous work, they used ASTM D2017(ASTM 2005) as their inoculation approach and used a 4-point bending test to obtain mechanical properties of the specimens. Their findings were that the main chain hemicellulose likely undergoes depolymerization (without dissociation) as part of the incipient decay. The two wood rotting basidiomycetes used were *Postia placenta* and *Gloeophyllum trabeum*. They found that a 30-40% difference in mechanical property loss could be attributed to a white rot vs brown rot when used on a softwood. As brown rots preferentially decay

softwoods, and can be more aggressive, this observation is important for future work dealing with Spruce-Pine-Fir softwood species.

Their results found considerable bending strength loss before significant weight loss, with up to 80% reduction in work-to-maximum limit (WML), and up to 20% reduction in MOE before 5% weight loss was recorded. This was associated with minor reductions in hemicellulose (galactan and arabinan). With the complete degradation of hemicellulose, between 80-95% of WML was measured, and a 20-35% reduction in MOE, corresponding to weight losses of 5-20%. A rate of 3.6% per day reduction in WML was reported. Interestingly, appreciable reduction in MOE only occurred once the cellulose (glucans) were degraded, which suggests the loss of crystallinity in the cellulose is most likely responsible for the stiffness of the wood.

A study on time to initiation of decay in plywood, OSB, and solid wood was undertaken by Wang et al.(J Wang et al. 2010). Natural inoculation with basidiospores was ensured by providing 1 hour of fresh outdoor air, twice daily, to specimens that were kept in chambers with varying relative humidity. The specimens were tested in accordance with the modified ASTM D3043, *Standard Test Method for Structural Panels in Flexure*(ASTM 2017b), outlined by Clark, Symons, and Morris(2006). The specimens were dried to approximately 12% MC

prior to testing. While this study did 4-point flexural testing, the results were not correlated to mass loss, but rather reduction in mechanical properties with environmental conditions.

In all of these tests, the specimens were dried to a reference moisture content, typically 12% MC. Testing specimens at different moisture contents could influence the mechanical properties of concern. The work to proportional limit (WPL) is the deformation energy dissipated up to the transition point from elastic to plastic material behaviour. Hoadley(2000) suggests it typically occurs around one-half to two-thirds of the maximum stress. The WPL is known to fluctuate with moisture content; higher moisture contents have reduced stiffness requiring less energy to cause deformation. Changes in WPL with moisture content level off at moisture contents much beyond 20% MC. The relationship between many of the mechanical properties to moisture content is shown in Figure 4-1(Wilson 1932). Tiemann(1906) introduced the concept of fiber saturation point (FSP), based on moisture content below which properties start to change.

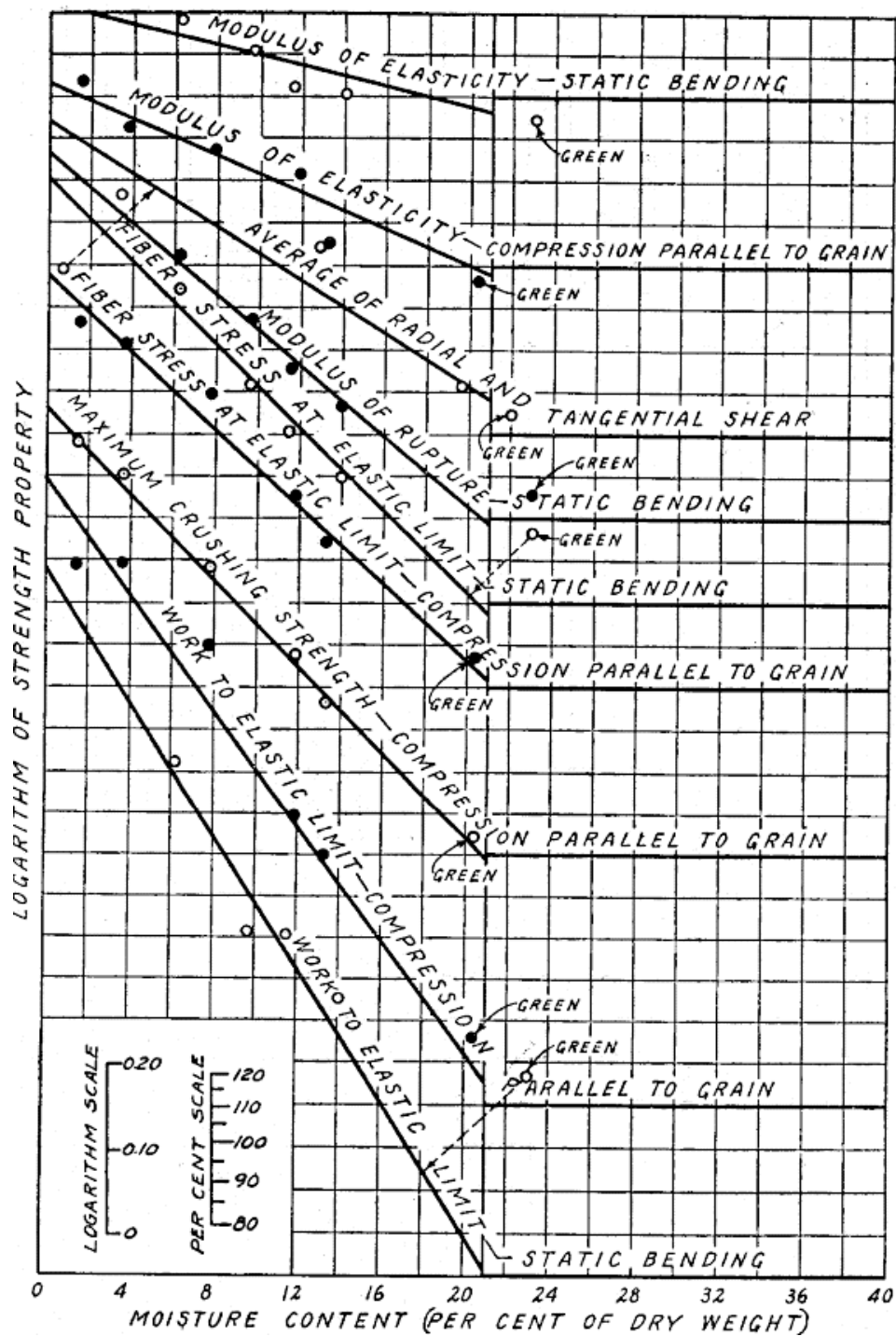


Figure 4-1 –Mechanical properties as a function of moisture content (Wilson 1932)

All previous tests were destructive in nature, which eliminates the potential to measure the incremental change of decay with time within the same specimen. Non-destructive methods, which remain within the elastic range, may prove beneficial in describing a rate of loss within the same specimen including effects of moisture content.

4.2. Methods

Review of the literature suggests two approaches to optimize the resolution of non-destructive flexural testing. First, 4-point bending is preferred as the middle portion of the prism is placed under constant and maximum flexure, compared to 3-point bending, where the moment peaks at the centre and shear effects could affect results. Further, 4-point bending also places a larger volume of the prism under flexure, which is advantageous if attempting to capture phenomena that affect the volume of wood, such as decay. Second, measurement of energy dissipation, in the form of work to ultimate limit (WUL) or work to proportional limit (WPL), has a greater resolution to identify incremental changes in structural properties at varying moisture contents than all other non-destructive methods. The proportional limit was calculated for the first repetition for each specimen at its target moisture content. The associated displacement at this first repetition was then used as the maximum limit for determination of the work on all

subsequent repetitions. Comparisons within specimens over time is thus the amount of work required to achieve the same deflection.

Consequently, the proposed method is to prepare pristine wood prisms, determine their dry mass, equilibrate them to a range of specified moisture contents, and periodically test them in a non-destructive 4-point flexure with load regimes within the elastic range. Once the specimens are at equilibrium conditions, based on ASTM D4933 (ASTM 2004), *Standard Moisture Conditioning of Wood and Wood-Based Materials*, the intra-specimen variations between repetitive tests should be negligible. It is anticipated that the only variation in mechanical properties between moisture content groups would be in general accordance with Tiemann (1906).

The test protocols followed, in general conformance, with ASTM D4761, *Standard Test Methods for Mechanical Properties of Lumber and Wood-Base Structural Materials under the Bending Flatwise – Third Point Loading*. However, to increase the volume placed under pure flexure, a quarter-point 4-point test was conducted and at span-to-depth ratios more closely aligned with ASTM D6272 (ASTM 2017c), *Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials by Four-Point Bending*, as wood at elevated moisture contents has features more closely aligned with some polymers, with

respect to stress relaxation and creep. These standards were preferred over ASTM D3043(ASTM 2017b), which focuses on panelized wood products. ASTM D 2915(ASTM 2017a), *Evaluating Allowable Properties for Grades of Structural Lumber*, was referenced with respect to identification of suitable specimen dimensions.

4.2.1.1. Specimen Preparation

A total of 21 prisms of Lodgepole Pine (*Pinus contorta*) sapwood were cut from the same piece of wood. Lodgepole pine was selected due to its ubiquity in the Spruce-Pine-Fir (S-P-F) mix in North America. The prisms were planed to a 12.7 mm x 12.7 mm x 101.6 mm dimension. Prisms were selected to ensure approximate uniformity in grain orientation. A reference corner and face were identified such that the loading was applied perpendicular to the radial axis at consistent loading-points. The specimen cross-sectional dimensions were measured at the quarter-point loading points to obtain an average value of the region under flexure. ASTM D4442, *Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Base Materials*(ASTM 2016), was followed in general conformance in drying the specimens, with the exception of setting the drying temperature to $74\pm 2^{\circ}\text{C}$ instead of $103\pm 2^{\circ}\text{C}$, to minimize drying damage to

wood cellular structures. The number of replicates and their target moisture content are provided in Table 4-1.

Table 4-1 – Specimen description, target moisture content, and replicate number

Moisture Content (%)	Specimen ID [Sample Size]
20	5,6,7 [3]
25	1,2, 8,9,10 [5]
30	3,4,11,12,13,14,15,16 [8]
40	17,18,19,20,21 [5]

The specimens were sealed in conical tubes with airtight lids, following the addition of the required quantity of moisture with a pipette. All specimens were maintained at room temperature for 3-5 days to permit absorption of the initial moisture. To estimate the time until full moisture redistribution occurs throughout the cross-section of the specimen, a preliminary investigation using the hygrothermal simulation tool WUFI Pro 5®, from the Fraunhofer Institute and Oak Ridge National Laboratory, was undertaken. It suggests that the time until full equilibration under tangential flow of a 97.5%RH environment (equal to approximately 30% MC for the material file “transverse pine” in the Norwegian University of Science and Technology material database) should take approximately 30 days. The tubes were inverted intermittently, between 7-10 times, to allow distribution of any residual liquid moisture across the entirety of the wood specimens.

4.2.1.2. Apparatus

A 4-point jig was prepared in general accordance to ASTM D6272 (ASTM 2017c). However, to ensure test repeatability, three small pins were positioned to ensure the specimen was placed in nearly the exact same location for each test (Figure 4-2). The base consists of two 25.4mm (1 in.) diameter rollers, whereas the top was 12.7mm (½ in.) rollers. Each of these rollers are held supported by a 12.7mm (½ in.) steel plate.

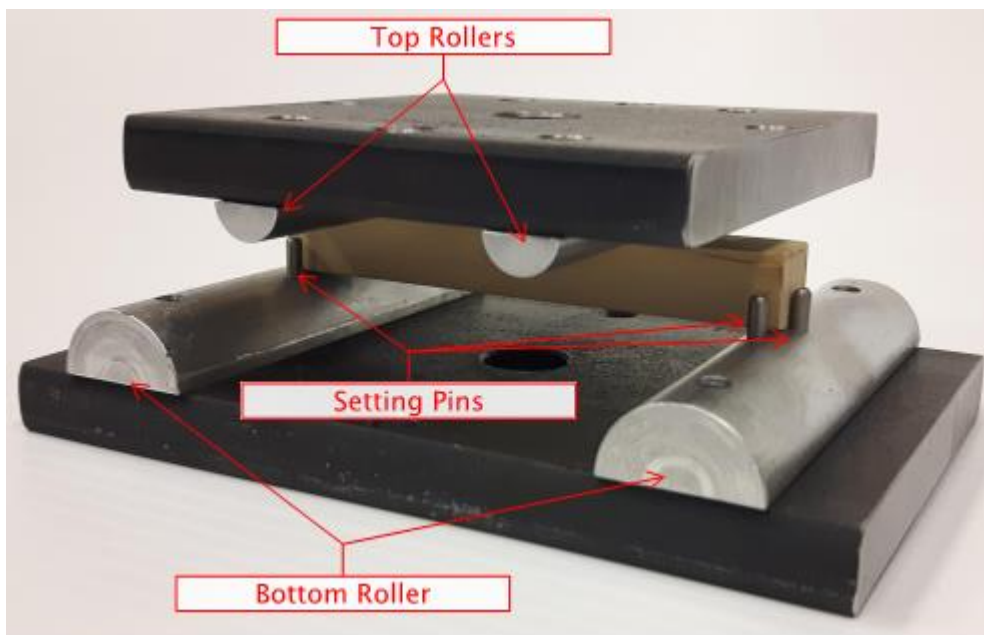


Figure 4-2 –Repeatable 4-point test jig

The jig was positioned into an MTI-10K universal testing machine. The machine has an internal displacement resolution of 0.00127mm, representing an error of 0.0254% on 5mm of deflection, neglecting load-cell/jig deformation. While an

LVDT to measure center-point deflection would be preferred, as the comparison is based on energy dissipation, the use of the internal displacement measurement was calibrated with an external LVDT. The load cell consists of an Interface 1210AJ-10K, with a 0.02% full scale output (FSO) accuracy to 44545N maximum load, leading to an error of 0.9% at a 1000N load.

4.2.1.3. Test Protocols

The following parameters were defined for the test protocols, as outlined in Table 4-2. They are derived from pilot test results outlined in the Results section. The process involves removing the specimens from their containers, positioning them against the reference pins in the jig, loading the specimen to the maximum load, unloading, then returning the specimen back into its container.

Table 4-2– Loading Parameters

Parameter	Value
Load Limit	750N
Deflection Limit	12.7mm
Loading Rate	2.54mm/min

Upon completion of the test, the specimens were weighed on an electronic scale and distilled water is added with a pipette to achieve the target moisture content. Post-processing involves zeroing the results to the nearest data point where the load exceeds 10N, as this is the minimum load that exceeds the error associated

with the load cell. The loads and displacements were converted using the simply supported beam formulae for two equal concentrated loads symmetrically placed at quarter points. While the conversion to stress and strain is an approximation, provided that all tests are subjected to the same calculation, inter-test comparisons remain valid.

Each load-deflection curve is then fitted with a third order polynomial to ease calculation for differentiation or integration. The area under the curve is integrated to measure the work done to the specimen. The proportional limit was calculated from the first test and converted to a displacement, which was used as the reference point for all calculations of energy dissipation for each specimen.

4.3. Results

Validation of the methods first required verification that the underlying assumptions hold. Several pilot studies were first conducted for validation. The main assumptions were:

- all stresses remain within the elastic range,
- the within-sample inter-test error is insignificant, and,
- hysteresis effects are minimal.

These assumptions were tested by completing a destructive test method to identify the elastic range of the specimens.

4.3.1. Evaluation of Elastic Range

Development of the test protocols first required characterisation of the anticipated mechanical properties of the prisms, which was completed in a small pilot study. As the objective is to ensure a non-destructive test, estimates on the proportional limits of wood specimens are required. To evaluate these limits a series of destructive 4-point static flexural bending tests were completed on dry (~12%MC) replicates derived from the same source material to estimate the proportional limit of the wood prisms (see **Figure 4-3**). Five replicates were used to evaluate the modulus of rupture of the prisms, derived from the same source of *Pinus contorta* wood and placed in the test jig with the applied load in the radial direction.

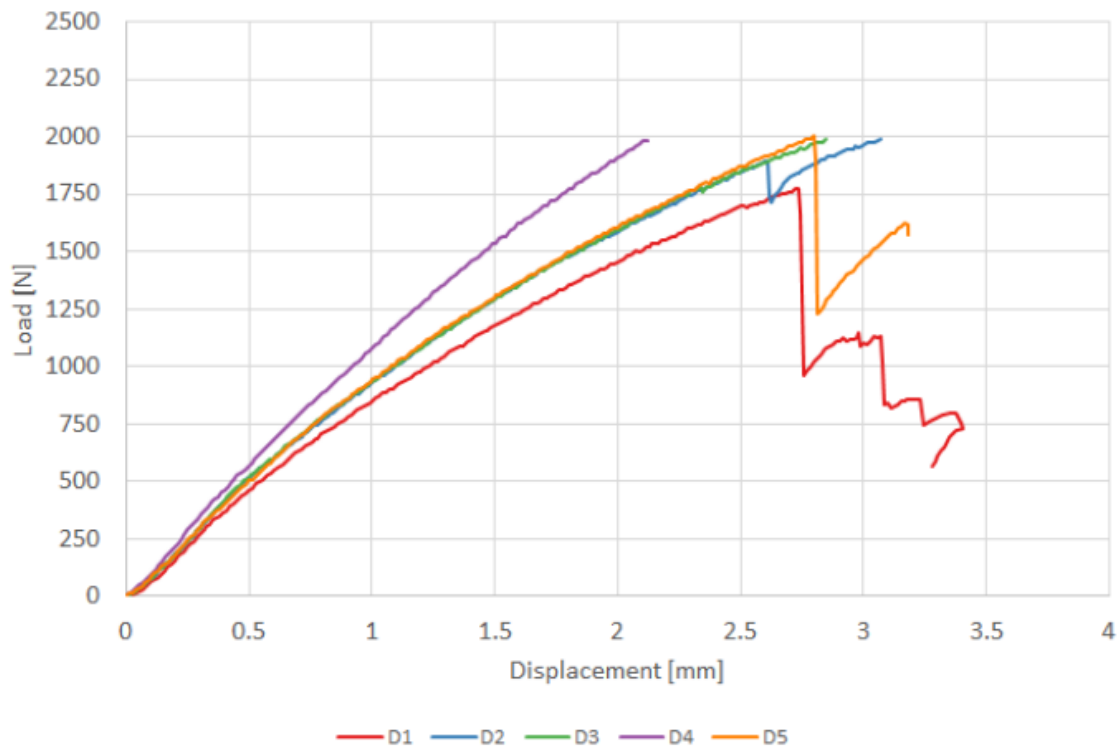


Figure 4-3 – Destructive testing of 5 Lodgepole Pine (*Pinus contorta*) prisms in the 4-point Flexural Jig

The sample failure load was $1,940 \pm 98 \text{ N}$ at displacement of $2.6 \pm 0.2 \text{ mm}$ (mean and 90% confidence interval). Generally, good agreement among the specimens were observed. These data were fitted to a Ramberg-Osgood model (Ramberg and Osgood 1943) and the 5% proportional limit was estimated. The original Ramberg-Osgood model is provided in equation (4-1), the simplified variables in equation (4-2), and the 5% proportional limit in equation (4-3) (Yoshihara and Oka 2001).

$$\varepsilon = \frac{\sigma}{E} + \beta \cdot \left(\frac{\sigma}{E}\right)^n + c \quad (4-1)$$

$$\delta = \frac{P}{E^*} + \beta \cdot \left(\frac{P}{E^*}\right)^n + c \quad (4-2)$$

$$P_{prop} = E^* \left(\frac{5}{95 \cdot \beta}\right)^{\left(\frac{1}{n-1}\right)} \quad (4-3)$$

Where ε , σ , and E represent the strain, stress, and Young's modulus, respectively, and β , n , and c are fitting coefficients. As the loads are maintained within the elastic range, the conversion from loads and displacements to stress and strain are linear transformations, and so the governing form of the Ramberg-Osgood equation is translated in Equation (4-2) with the applied load, P , displacement, δ ; and E^* representing the apparent stiffness. The fitting coefficients and apparent stiffness (E^*) were fitted using a non-linear least-squares model using the Levenberg-Marquardt fitting algorithm set to a maximum of 100 iterations. The 5% load to proportional limit, the intersection of the 95th percent modulus of elasticity with the load-displacement curve, identified as P_{prop} , is determined by equation (4-3), and the associated proportional displacement may be back-calculated using Equation (4-2).

The proportional limit for the 5 pilot specimens had a mean of 466 N, with a standard deviation of 187 N. To ensure the proportional limit was captured by a

standardized loading scheme, a value of 750N was selected as the load limit for the experimental protocol as it encompasses 90% of the proportional loads for all specimens and is less than 40% of the maximum load.

4.3.2. Experimental Results

The pilot study results informed the testing parameters for determining the WPL of the wood prisms. The prisms were prepared in accordance with the outlined protocols and equilibrated to their target moisture content. Table 4-3 provides the timeline for material preparation and testing.

Table 4-3– Testing timeline

Event	Date	Elapsed Time [Days]	Notes
Dry Mass	2017/04/04	-28	Dried at 70°C
Wetted	2017/04/25	-7	
First and Second Rep	2017/05/02	0	Approx. MC Equilibrium
Third Rep	2017/05/16	14	
Fourth Rep	2017/05/30	28	
Fifth Rep	2017/06/16	45	
Sixth Rep	2017/09/19	140	
Seventh Rep	2018/07/21	445	
Eighth Rep	2018/08/04	459	
Ninth Rep	2018/11/06	553	
Tenth Rep	2018/11/25	572	
Eleventh Rep	2018/12/27	604	

Due to the time for moisture redistribution across the section of the prism, the 4th test (1 month after initial wetting) represents the situation whereby the wood is near full moisture equilibrium. Consequently, all effects refer back to test #4 (1

month after wetting) as the reference baseline. The gravimetrically measured moisture content of each specimen is plotted in **Figure 4-4**.

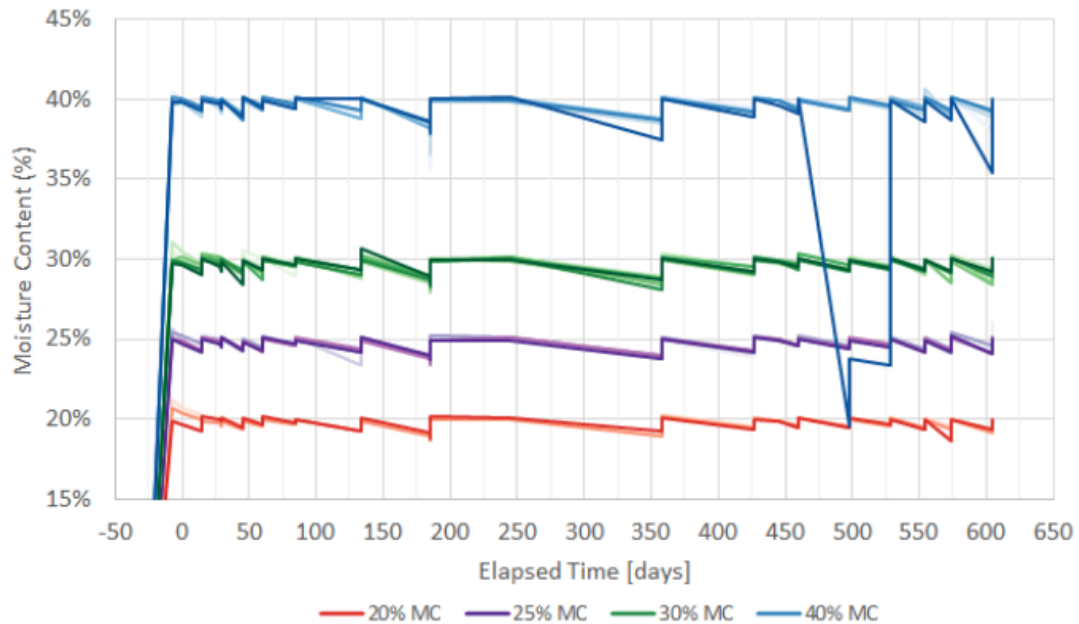


Figure 4-4 – Moisture content of all 21 samples over the measurement period. With the exception of Specimen 21 (dark blue), all specimens stayed within 1% of their target MC.

4.3.2.1. Determining the WPL

The WPL was calculated by first completing a polynomial regression, to obtain a best-fitted curve, on each load-displacement curve (e.g. each repetition) for each specimen. Integration of the regression line provides the energy dissipation for that specific test at a given deflection. Out of the repeated tests on the same specimen, the cut-off deflection was set to the associated displacement at the load

to proportional limit, which was determined for the first test of each specimen at its target equilibrium moisture content, as outlined in equation (4-3).

The output for a single specimen C3 held at a 30% MC is provided as an example in **Figure 4-5**. The measured data from the universal testing machine are shown as filled dots, the 3rd order polynomial regression is shown as a solid line; the colour of the dots and lines represent each repeated test (“Rep”). The shaded area under the curve represents the WPL for the first test. Comparison of the work among specimens is referenced to this maximum deflection value.

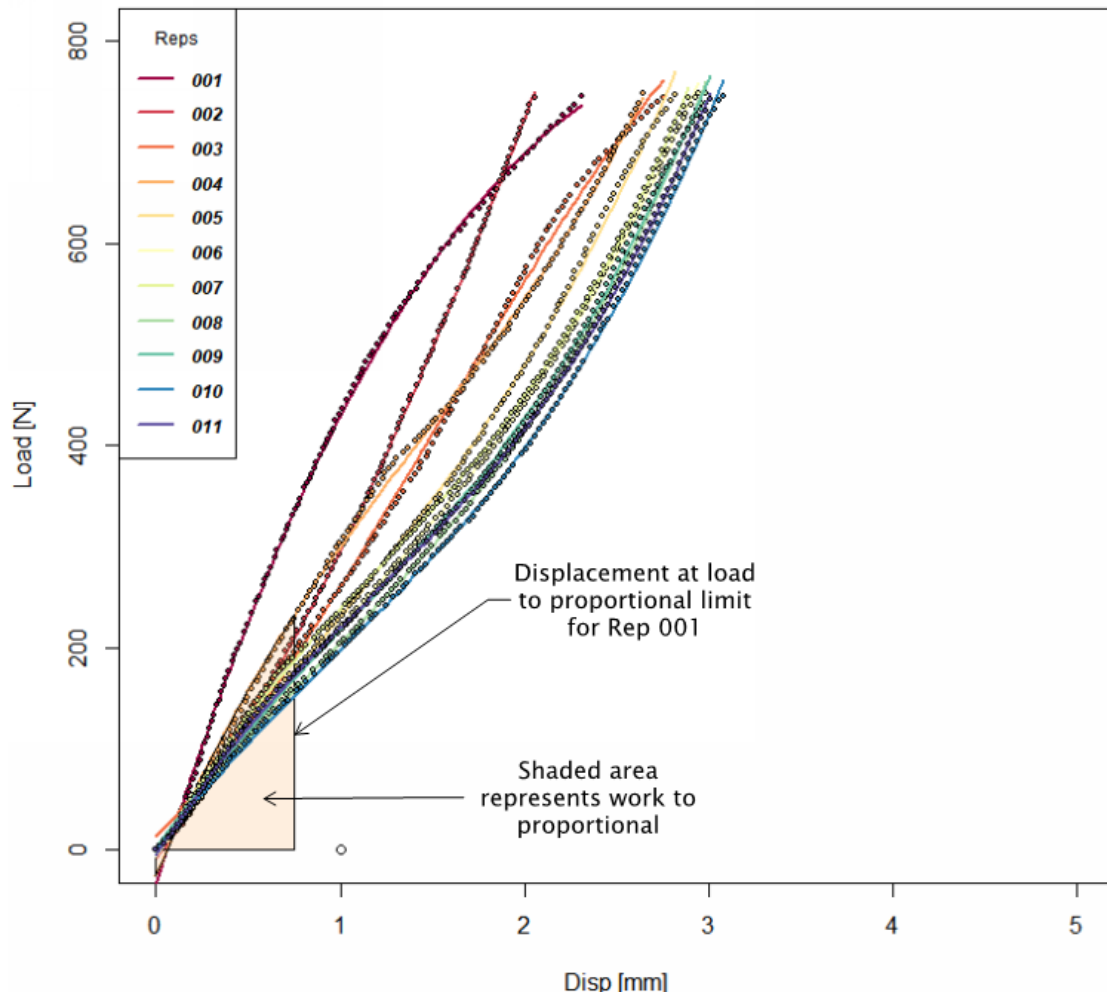


Figure 4-5 – Repetitions 1 through 11, shaded colours for Specimen ID – C3, at 30% MC. Dots represent measurements, lines represent 3rd order polynomial regression for each repetition. The shaded region represents the work to proportional limit for Rep #4; assumed at moisture equilibrium. Subsequent WPL measurements are made from the displacement at the proportional load limit.

The WPL results for each test are plotted in Figure 4-6. Individual tests are represented by points and the group averages are shown by lines; the colour represents moisture content.

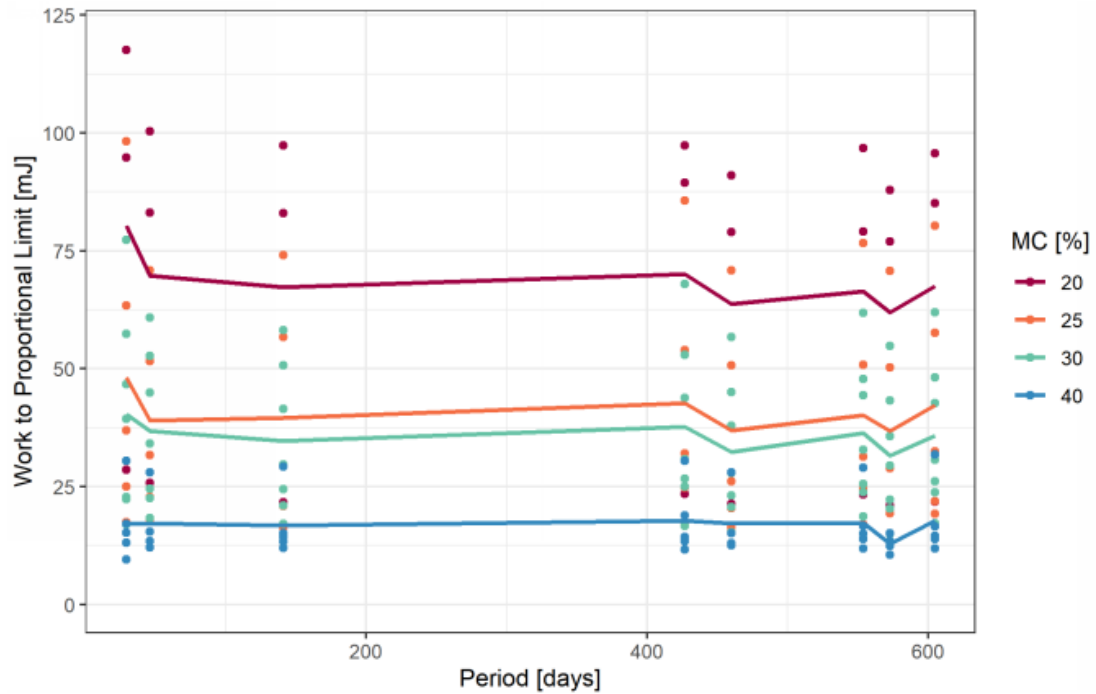


Figure 4-6 – Energy dissipation with time, coloured in accordance with the respective moisture content (red, 20%, orange, 25%, teal, 30%, and blue, 40%MC, respectively).

In each case, the initial WPL is larger than the subsequent values as deformation energy is dissipated through localized plastic deformation. Further, the initial 30 days also represent the wood prisms achieving moisture equilibrium. Assuming the core is dryer than the exterior, the elevated outer moisture content of the shell would realise a decrease in the modulus of elasticity. The amount of energy dissipation for the dryer specimen (MC 20%) is higher than those nearing the FSP (MC 25% and 30%), and significantly higher than the specimens well above the FSP (MC 40%).

To better show the relative impact of testing with time, the results were normalized to the 4th test, which was estimated to be the point at which the moisture content within the specimens reaches equilibrium. A linear mixed effects model, with the specimen ID as the random effect, was conducted to estimate the change in WPL as a result of subsequent tests, shown in equation (4-4).

$$WPL_{rel} \sim Period + 1 | Sample ID \quad (4-4)$$

The slopes (Period), intercepts (random effect for “1|SampleID”), and standard errors are provided in Table 4-4.

Table 4-4 – Linear random effect regression coefficients

Moisture Content [%]	Slope	Standard Error	Intercepts
20	-0.00021	0.00005	0.917
25	-0.00011	0.00005	0.897
30	-0.00012	0.00004	0.917
40	-0.00001	0.00007	0.893

The results indicate that there is no statistically significant difference between the 20, 25, and 30% MC specimens, and no difference between the 25, 30, and 40% MC specimens. A slight difference between the 20 and 40% specimens was observed, but the effect size is very small. These data are shown visually in **Figure 4-7**, with the grayed area representing the 95% confidence band.

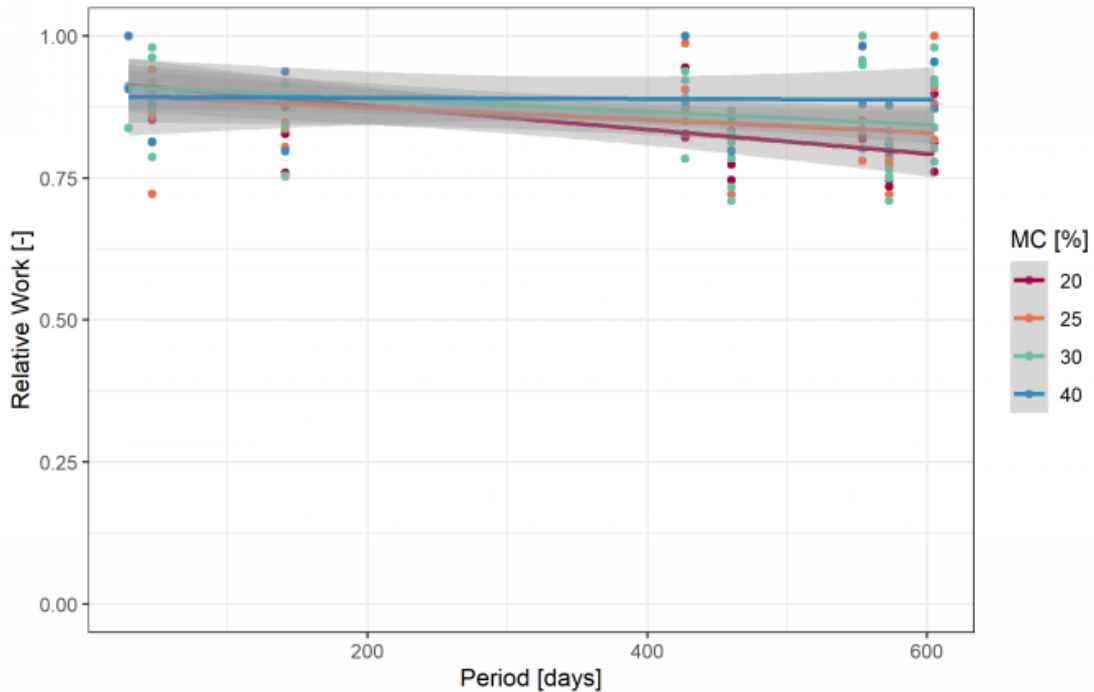


Figure 4-7 – Relative energy dissipation with time, including linear regression lines for specimens at 20, 25, 30, and 40% MC. The shaded gray fill represents the 95% confidence band.

Relative comparison of the specimens shows that after the span of a year, a difference of less than 7.6% is expected. This is contrasted with data by Curling, Clausen, and Winandy (2001), which shows a reduction in the work to maximum limit as high as 3.6% per day for decaying wood. Conversion from WML to WPL suggests a reductions in the range of 40%(Mulholland 1954). However, even a 1.4% daily reduction in WPL nonetheless has a signal that is over 70 times stronger than observed in these repeated tests, suggesting that the protocols identified in this paper are promising in the detection of incipient decay. When using this test to detect the departure of structural behaviour from expected

values, a piece-wise regression can be used to detect the inflection point. For added statistical rigour, controls specimens may be included.

4.4. Discussion

The standard destructive testing approach towards evaluating incipient ultrastructural changes to mechanical properties of wood specimens requires large number of replicates and is unable to measure the change in property within the same specimen over time. These limitations add uncertainty to the data collected, as appreciable variation between wood prisms is not uncommon. Furthermore, as most specimens are dried down to a reference moisture content (e.g. 12%MC) before destructive testing, the results are not directly comparable to in-situ wood elements that are subjected to the biotic and abiotic factors under consideration.

By maintaining loads within the quasi-elastic range and comparing intra-sample energy dissipation, a compromise between repeatability and resolution occurs. However, any observed variation must therefore be a result of ultrastructural modifications, assuming a constant MC between the testing points. As a result, the repetitive NDT of 4-point static bending of wood prisms appears to be a promising approach towards measuring ultrastructural changes in wood following exposure to factors known to affect structural properties.

4.5. Recommendations

Static bending tests on wood prisms at moisture contents exceeding the fiber saturation point (FSP) demonstrated atypical deformation curves. At the rollers, significant local deformation occurred, in addition to what appears to be shear-deflection. The reduction in the shear and flexure modulus at higher moisture contents suggest that the span ratio originally used may be insufficient.

Changing the span to depth ratio, closer to 16:1, as recommended by ASTM D6272 (ASTM 2017c), should reduce these effects and better capture changes in stiffness of the prisms. Consideration for the decreased load requirements must be made to minimize the trade-off in load-cell accuracy.

4.6. Chapter 4 – Commentary

Supplemental commentary on the context and concerns within the Chapter 4 protocols are provided below. These relate to the choice of fungi for future work and some of the simplifications in the 4-point bending procedures. Note that the prisms used in the development of this test method are different than those used to develop the fungal database for the ULS research. The discussion below is focused around the ULS experimental data.

Wood Rotting Basidiomycete

The test methods developed within Chapter 4 form the basis upon which incipient decay could be detected. Using the logistic regression framework developed in Chapter 3, a survival analysis for time until detection of incipient decay can be completed. This experimental work has been completed using recommendations in Section 4.5 on wood prisms of Jack Pine (*P. banksiana*), treated identically in Chapter 3, with the primary variation being the use of a wood rotting basidiomycete instead of an ascomycete.

Due to its frequency of detection in the built environment and aggressive deterioration potential (Pers. Comms with Dr. Paul Morris, FP Innovations), *Gloeophyllum trabeum* was the chosen species. The specific strain of *Gloeophyllum trabeum* (Persoon : Fries) Karsten is designation Madison 617 (ATCC 46150), from ATCC strain number #11539. The Biosafety in Microbiological and Biomedical Laboratories identifies this strain of *G. trabeum* to be a biohazard safety level 1 fungus. Further, it finds frequent use in other decay research (Gonzalez and Morrell 2012; S. F. Curling, Clausen, and Winandy 2002b; Bader et al. 2012).

Proportional Limit

The true proportional limit of wood is difficult to properly identify. Hoadley (2000) suggests it lies somewhere between 50% and 66% of the maximum stress for wood fibers in flexural bending. A series of pilot tests were completed on 12 prisms of Jack Pine, 12.4 mm x12.4 mm x203 mm in dimension, divided equally into a dry/wet and heartwood/sapwood groups (i.e. 3 dry sapwood specimens, 3 dry heartwood specimens, 3 wet sapwood specimens, and 3 wet heartwood specimens).

The pilot tests on dry and wet prisms revealed a maximum load 1120N ($\sigma=195\text{N}$) and 508N ($\sigma=94\text{N}$), respectively. On the saturated specimens ($\sim 40\%\text{MC}$), rupture did not occur, but rather excessive deflection limited the tests (deflections exceeding 10mm where the specimens bottomed-out on the rollers). Determination of the proportional limits was estimated using the Ramberg-Osgood relation. The 3% proportional limit is sometimes used (Yoshihara and Oka 2001), which represents varying the modulus of elasticity to 97% of its value and identifying the intercept with the measured stress-strain curve. Given the inherent variation in wet and dry specimens, a 5% proportional limit was selected to try to capture the variation in the effective stiffness of the prisms. This therefore looks at the 95% apparent MOE of the beams. The resulting application

of the 5% proportional limit of the Ramberg-Osgood relation provides a proportional limit for the dry and wet prisms of 582N ($\sigma = 87.5\text{N}$) and 296N ($\sigma = 60.8\text{N}$), respectively. Calculating the upper 90% confidence interval on the wet prisms gives a maximum load of approximately 350N, and this was therefore selected as the maximum load parameter for the ULS tests.

UTM Displacement Measurements

A level of uncertainty within the test protocol is that the deflection of the prism, relative to its mid-point, is not directly measured. Rather, the deflection was measured with an LVDT between the actuator and the crossbeam. This simplification was required due to the large number of specimens being tested, as the set-up time between specimens would constitute a significant time burden. While this necessarily represents a degree of error within the process, there are two mitigating factors: 1) the applied load, of 350N, creates insignificant deflection within the large section of the aluminum and steel frame of the UTM, and 2) all measurements are relative within each specimen. The crucial elements to ensure validity within the relative work to proportional limit are thus consistency between tests and that the maximum load remains within the proportional range of the material. Both aspects are maintained within this protocol.

Chapter 5 – Conclusion and Future Scopes of Work

5.1. Conclusions

Premature failure of wood elements in buildings poses an incredible burden on society. The billions of dollars spent annually on repairs represents just the financial aspect of this failure, it doesn't include time, effort, and disruption to the building occupants and owners. As this is a major concern for the building industry, significant efforts have been placed on protecting and preserving wood members. However, understanding the limiting conditions for biological growth can better permit allocation of resources to resolve only those areas that require enhanced durability. Following the hierarchy of hazard controls principle¹, the most effective method of dealing with a hazard is prevent. It is only through a refined understanding of the environmental parameters, that could create a biological hazard, building professionals can avoid such conditions in a safe and justifiable manner.

Traditionally, these limiting conditions were established by general rules of thumb and guidance, accompanied by extensive empirical research on known service lives of varying wood protection agents and the personal experience of

¹ <https://www.cdc.gov/niosh/topics/hierarchy/>, Accessed on November 19th, 2021

inveterate practitioners. More recently, biodeterioration models have been developed to help provide guidance on the effect of environmental parameters on deterioration, now including the crucial element of time to the biodeterioration equation. The primary issue with many of these models is that they attempt to predict absolute quantities of fungal growth. To advance models into the limit state design concept, frequently used in building codes and standards, the next step is to describe the probabilities of detection of fungal growth. In so doing, threshold risk tolerances can be defined, and the probabilistic occurrence of growth can be determined based on environmental parameters and substrates characteristics.

This dissertation reviewed the outstanding literature, identified weaknesses in the current biodeterioration models, developed a database of fungal growth on relevant North American materials in a controllable and replicable manner, and used this dataset to create a serviceability limit state model for fungal growth. As part of this exploration, methods for establishing an ultimate limit state model were also devised.

5.1.1. Limit State Design – Serviceability Limit State

Limit state design is characterized by the identification of different failure modes. It is complemented with load and resistance factors to ensure acceptable

probabilistic failure envelopes. From a biological perspective, it is reasonable to justify two primary modes: a serviceability limit state (SLS), representing surface fungal growth, and an ultimate limit state, representing the start of incipient decay. These can both be described in terms of probability of occurrence given a set of dynamic environmental parameters.

The SLS model developed in Serviceability Limit State, enables assessment of the probability of fungal growth on wood substrates in dynamic environmental conditions. A biodeterioration database on fungal growth was created, using common North American wood species, *Pinus banksiana*, and a replicable application of a common and readily accessible fungi, *Penicillium chrysogenum*. Multiple logistic regressions were completed on the data to characterize the probability of growth as a function of moisture content, temperature, and elapsed time. The model outputs a mean probability of detecting fungal growth as well as the 99% confidence interval and provides good explanatory power when validated with empirical test results from a mouldy roof attic study in Vancouver, BC. The results were contrasted with the VTT model (ASHRAE 2016), one of the leading fungal growth models currently in use.

Exploration into preservative treatment effects were evaluated by comparison between sapwood and heartwood specimens derived from the same board. By minimizing the variability of the substrate, a ratio of projected probabilities could

be determined. It was found that while the use of a fixed preservative treatment coefficient provides a rudimentary scaling to account for the reduced incidence of fungal growth observed on heartwood specimens, it nonetheless provides relevant estimates and shows promise for future work. Further research is required, but the concept appears to be valid.

5.1.2. Limit State Design – Ultimate Limit State

This dissertation provides a starting point upon which the ultimate limit state model can be derived. A novel test method was developed which permits the detection of ultrastructural changes to wood materials. Through periodically testing wood prisms subjected to a known wood rotting basidiomycete, *Gloeophyllum trabeum*, inoculum in 4-point bending, the departure of the work to proportional limit from the pristine condition defines the time to incipient decay. Using the time to incipient decay as a function of temperature and moisture therefore permits establishment of an ultimate limit state model. This constitutes the next major research endeavour for this Limit State Design for Biodeterioration research programme.

5.2. Future Scope of Work

The development of a limit state framework for biodeterioration is conducive towards adoption within codes and standards. With the SLS model available for

immediate use in building durability evaluations, it can be applied to infer acceptable designed assemblies for new construction, novel applications, and in new climates. It could also be adopted to complement forensic investigations for the probability of detection of mould in occluded building spaces. Suitable risk thresholds can be established by committee or the building owners, and the probabilistic design is permissive to finding truly acceptable limits of biological growth.

Further development on the ultimate limit state results can follow in the same framework provided by the SLS model; identify the point of incipient decay and use a logistic regression to describe its occurrence as a function of moisture content, temperature, and elapsed time parameters. The experiment has already been completed for this phase of the work and the next step is to proceed with the analysis developed for the SLS model.

Enhancement on the substrate features on the SLS model is another area that require further work. This includes the expansion of substrates to the multiple engineered wood products available, like oriented strand board, plywood (Douglas-fir or aspen), or the variations of veneered lumber. This is also a moment to also incorporate effects of preservative treatments on the substrates and verify whether the coefficients and K-factor are fully represented by the new data. Further development of the underlying database will require concerted

efforts with a number of industry stakeholders (manufacturers, builders, industry associations).

Lastly, this framework provides a promising step towards adoption of a limit state approach for biodeterioration within the framework of the National Building Codes of Canada. The governing standard for wood design, CSA Standard O86 – Engineering Design in Wood, is referenced within Part-4 of the NBCC and is only called as a required design reference for structural purposes. The development of a biodeterioration chapter of CSA O86, for which the limit state design for biodeterioration could form a fundamental basis, would need to be called within Part 5 – Environmental Separation of the NBCC, requiring a minor code change update. In parallel with development of a biodeterioration chapter in CSA O86, concurrent efforts could be made in other standards relating to biodeterioration risks. The ASHRAE 160 – Criteria for Moisture Control Design Analysis in Buildings standard is another promising standard. With a design intent to assist with hygrothermal simulations, the convenient spreadsheet format of the SLS model paper is conducive towards use within such applications.

The end goal of a limit state design for biodeterioration is to permit an ease of comfort for building designers and practitioners to make informed decisions on minimizing biodeterioration risk in buildings. However, this paradigm shifting

research is only the first step in the long-journey of ensuring the durability of our buildings.

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