Wall Moisture Problems in Seattle

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ABSTRACT

In the past few years, major moisture-related problems have appeared in the northwestern U.S. and southwestern Canada. These problems have been catastrophic, amounting to billions of dollars in premature damage. Several forensic studies have been performed that attribute the problem to more than poor workmanship, as meticulous attention to details still has not completely resolved the reoccurrence of the moisture-related problems.

Moisture transport through a building envelope influences not only the durability, indoor air quality, health, and safety of the inhabitants but also the energy efficiency of the envelope system. The influences of moisture transport are experienced differently in lightweight (hygroscopic) or heavyweight (moisture massive) building envelope systems.

In almost all cases of moisture-related damage, the building envelopes were not designed to handle the moisture loads that were present due to the imposing environment. The moisture damage that has appeared clearly indicates the need for proper moisture control analysis of building systems. Solutions to moisture-induced problems may be difficult to achieve when several interacting mechanisms of moisture transport are present. Research is continuously upgrading existing knowledge of these complicated issues.

In this paper, the authors will provide a scope of the overall problem in Seattle, Wash., and the research activities currently underway. The paper will focus on the research approach undertaken in terms of "moisture engineering." Preliminary results will be provided to show the effect of stucco materials and interior vapor control strategies on the hygrothermal performance of a representative stucco-clad wall system.

INTRODUCTION

Controlling the accumulation of moisture in building enclosures has long been a topic of interest to building scientists and professionals, especially over the past decade and a half. Immediately preceding that period, governmental and environmental concerns about conserving energy and customer demands for improving interior comfort led to the development of national standards and building codes requiring tighter building envelopes and increased insulation levels. This narrow focus on improving building enclosure thermal performance affected other aspects of building enclosure performance, most notably moisture performance. Indeed, it could be argued that lack of a total system engineering approach in the development of increased thermal performance standards has created a host of building envelope and indoor air quality problems, the extent of which we are just now beginning to fully appreciate.

THE SEATTLE EXPERIENCE

In response to growing moisture damage problems in multi-family buildings in the Seattle metropolitan area, members of Seattle's Construction Codes Advisory Board (CCAB)[1] began investigating moisture intrusion and damage problems in July 1998. Based on their experience, CCAB members have seen a disproportionate number of relatively new (constructed since 1984) multi-story, multi-family resi-

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dential structures suffer premature building enclosure failures due to moisture accumulation. The CCAB established the Moisture Damage Committee, an open committee of CCAB members, public agency representatives, concerned building professionals, and industry representatives, to advise and guide CCAB's investigation of moisture damage issues.

Between November 1998 and March 1999, the Seattle Department of Design, Construction, and Land Use (DCLU) and the Moisture Damage Committee conducted an informal survey of multi-family residential structures in order to assess the approximate number of moisture-damaged structures in Seattle, the causes of moisture intrusion, and the cost to fix such damage. DCLU received 71 surveys representing 74 multi-story, multi-family residential buildings that were built between the early 1900s and the mid-1990s. Two-thirds of the surveys represented structures built between 1984 and 1998. Moisture Damage Committee members completed 38 of the 71 surveys based on projects on which they are working; condominium and apartment owners provided the remainder of the completed surveys.

Survey respondents listed interface details as the primary source of water intrusion, similar to the findings of the 1996 Vancouver, B.C., moisture damage survey (Ricketts and Lovatt 1996). The Seattle survey also found that moisture damage was not limited to walls clad with exterior insulation and finish systems (EIFS), but it affects all exterior cladding types. Fifty-one structures reported that the construction cost to fix damage caused by moisture intrusion totaled nearly $98 million, a figure that does not include the costs of investigation, attorneys' fees, and tenant and owner relocation costs.

Moisture Damage Committee members note that in addition to the 38 moisture-damaged structures for which they completed surveys, they have begun investigations into another 150-200 newer multi-family structures in the Seattle area showing signs of moisture damage. DCLU permit tracking data show that approximately 938 multi-family structures were built in Seattle between 1984 and 1998. By combining the survey results with the number of structures into which moisture damage investigations have begun, it appears that approximately 20 percent of the multifamily structures built in Seattle between 1984 and 1998 are suffering premature building enclosure failures due to moisture intrusion.

Because participation in the survey was voluntary and surveys were sent to a small percentage of apartment owners and condominium associations, the survey results cannot be said to be conclusive evidence that moisture damage problems are more prevalent in newer multifamily buildings. However, the experience of local building rehabilitation professionals and the appearance of attorneys specializing in moisture damage claims certainly weighs in favor of concluding that moisture damage problems are indeed growing in the greater Seattle/western Washington area.

[1] The Construction Codes Advisory Board (CCAB) is the city of Seattle's advisory board for the technical construction codes. The CCAB is composed of 13 members representing the construction industry, property owners, and the general public.

CALL FOR HYGROTHERMAL MODELING

Disastrous building enclosure failures in Vancouver, B.C., Wilmington, N.C., and the growing moisture damage problems in Seattle, Wash., alerted building scientists and professionals to the effect of the limited application of a systems engineering approach to increasing thermal performance (Barrett 2000). While concern over condensation in the building enclosure has been known for some time, it is not known what levels of thermal transmittance, vapor permeance, and air leakage together are necessary to ensure that any particular exterior wall assembly will perform as expected for a reasonably long period of time.

Convinced of the severity of moisture damage problems and the need to advance awareness and knowledge of hygrothermal performance and moisture engineering, the city of Seattle teamed up with building envelope and material researchers from the Oak Ridge National Laboratory (ORNL) and staff from the Washington State University Cooperative Extension Energy Program (formerly the Washington State Energy Office) to study the hygrothermal performance of typical exterior wall construction under the auspices of ORNL's State Partnerships Program.

The purpose of the research was

- to assess the effect typical western Washington building enclosure components have on the hygrothermal performance of building enclosures built in western Washington and Seattle area environment and
- to assess the relative thermal efficiency and hygrothermal performance of older (pre-1984) western Washington and Seattle area building enclosures versus new (1999) enclosures.

This paper reports on the preliminary aspects of this project and focuses only on the impacts of water penetration, interior environment, and mechanical ventilation on the hygrothermal performance of a typical wall system used in western Washington. To accomplish the stated objectives, this research project utilized the advanced computer model MOISTURE-EXPERT, developed by Karagiozis (2001).

Analysis of the computer modeling results are also expected to provide preliminary scientific evidence to support or refute widely held beliefs regarding hygrothermal performance differences between older and newer structures and to assess the role that state and local building, ventilation and indoor air quality, and energy codes play, if any, in affecting building enclosure hygrothermal performance. It is also hoped that analysis of the modeling results would reveal specific reasons for hygrothermal performance differences that may appear between older and newer structures and suggest improvements to Washington's residential construction codes and areas for further study. Each of these points will be addressed in a separate report analyzing over 20 exterior walls modeled by ORNL.

For the purposes of this paper, the following analysis represents a subset of the analysis that was performed for each Seattle exterior wall system. Specifically, this paper will address the following:

- The importance of developing/gathering accurate hygrothermal performance characteristics for each building envelope component;
- Use of the advanced hygrothermal computer model MOISTURE-EXPERT to predict the drying potential of a wall exposed to dynamic environmental conditions in the location where the wall will be constructed and varying amounts of water penetration;
- The integration of a new tool, the mold growth index, with hygrothermal performance data produced by MOISTURE-EXPERT to assess the potential long-term viability of a building envelope or specific envelope components under varying water penetration conditions;
- Use of MOISTURE-EXPERT to assess the effect of interior environmental conditions on a building envelope's drying potential;
- Use of MOISTURE-EXPERT to assess the effect of mechanical ventilation on a building envelope's drying potential; and
- Potential use of MOISTURE-EXPERT to guide the development of "designer" building envelopes and envelope components, i.e., envelopes and components specifically designed for optimum performance under the specific dynamic conditions of the location where the envelopes and components will be used.

CONCEPTUAL APPROACH FOR MOISTURE CONTROL AND DRYING POTENTIAL OF ENVELOPE SYSTEMS

Any wall system can be characterized as being composed of a few basic subsystems. The outermost subsystem is identified as the cladding or façade system. Others include the following: the weather resistive barrier system, the sheathing system, the insulation system, the framing system, the vapor diffusion control system, and the air barrier system. A multitude of variations may exist along these fundamental systems. In some cases, the functions of several systems can be accomplished by one system if proper performance criteria can be satisfied. The drying capability of a building envelope system with initial construction moisture and recurring water penetration critically depends on the climatic conditions in which the wall is placed and the system and subsystem performances of these wall systems/components. The drying rate mechanisms by which walls redistribute and transport moisture must be incorporated directly into the wall designs. When a wall is not properly designed with adequate drying capacity, the potential for moisture-induced damage significantly increases. The drying potential becomes a distinct property of each wall system.

The challenge is developing building envelope designs that incorporate high drying potentials. This may be achieved by allowing the wall systems to dry both to the outside and inside whenever possible. Several successful walls systems have been around for centuries that allow and control moisture flow without moisture-induced damage. However, by today's standards, such wall systems typically require a tremendous amount of energy to heat the space bounded by the walls, and the interior environments could never be considered comfortable places in which to live or work, despite mankind's ability to survive through the ages dwelling in such structures.

Simulation Activity

In this paper, the state-of-the-art research hygrothermal model MOISTURE-EXPERT version 1.0, developed by Karagiozis (2001), was employed to parametrically investigate the moisture performance of a typical stucco-clad wall system built in Seattle, Wash. This wall was investigated for five different water penetration rates, two different interior vapor environments, and two interior ventilation conditions (mechanical ventilation according to code or none). The present work assessed the moisture engineering performance of this wood frame stucco-clad envelope system, not only in terms of the development of temperature and relative humidity distributions, but also in terms of the risk for mold growth using results from ORNL's advanced hygrothermal modeling tool, MOISTURE-EXPERT.

Boundary Conditions and Initial Conditions

The analysis was conducted while subjecting the exterior boundary of the wall to real weather data (including temperature, vapor pressure, wind speed and orientation, solar radiation, wind-driven rain, sky radiation, and cloud indexes). A 10% cold and 10% hot year was developed for Seattle from 30 years of hourly data from the National Climatic Data Center. This approach is currently being proposed by ASHRAE SPC 160P and ASTM Manual 40 (Künzel et al. 2001) and has been examined in detail by IEA Annex 24. All wall systems investigated in this paper were subjected to the same climatic conditions of Seattle, Wash.

Interior conditions were also allowed to vary depending on the time of day and exterior conditions and by adding additional moisture sources. To investigate the influence of interior moisture generation, two cases were simulated, one assuming five inhabitants and the other none.

All material layers of the wall were assumed to be in equilibrium at 20°C and with a relative humidity of 85%.

Material Properties

Prior to initiating the simulation exercise, the author solicited material properties from several building material manufacturers. The basic material properties required in the modeling analysis are as follows:

- Water vapor permeance as a function of relative humidity
- Liquid diffusivity as a function of moisture content
- Sorption + suction isotherm as a function of temperature
- Thermal conductivity, density, and heat capacity

These properties are not single valued but may also depend on time, history, or other dependent variables. Directionally dependent material properties were employed for the wood-based and insulation materials. Because the existence and reporting of basic material properties varied widely from manufacturer to manufacturer, the material properties employed in these simulations were taken from Künzel (1994), Künzel et al. (2001), and Karagiozis and Salonvaara (1998).

DESCRIPTION OF THE HYGROTHERMAL MODEL

The MOISTURE-EXPERT hygrothermal model was developed by Karagiozis (2001). The model was developed to predict one-dimensional and two-dimensional heat, air, and moisture transport in building envelope geometries. The model treats vapor and liquid transport separately. The moisture transport potentials are vapor pressure and relative humidity and temperature for energy transport. The model includes the capability of handling temperature-dependent sorption isotherms and liquid transport properties as a function of drying or wetting processes.

The MOISTURE-EXPERT model includes porous airflow through insulation and cracks by solving a subset of the Navier Stokes equations: Darcy's equations. The MOISTURE-EXPERT model accounts for the coupling between heat and moisture transport via diffusion and natural and forced convection air transport. Phase-change mechanisms due to evaporation/condensation and freezing/thawing are incorporated in the model. The model includes the capability of handling internal heat and moisture sources, gravity-driven liquid moisture, and surface drainage capabilities. The model also captures experimentally determined system and subsystem performances and anomalies of the building envelope. One of the model's unique features is its capability to handle temperature-dependent sorption isotherms and directional and process-dependent liquid diffusivity.

DESCRIPTION OF MOLD GROWTH MODEL

The essential ingredients required for the reproduction of molds are as follows: spores, adequate temperature, food source, and moisture. Mold growth in the building structures was estimated using a model equation that employs temperature, relative humidity, and exposure time as inputs. The mold growth model and differential mathematical equations were developed and presented in detail by Hukka and Viitanen (1999) and Viitanen (1997a, 1997b), and only a short description is given here. Quantification of mold growth in the model is based on the mold index first employed in biological experiments during visual inspection (Viitanen 1996). The mold growth model is based on mathematical relations for growth of exposure time, temperature, relative humidity, and dry interrupt periods. The model is purely mathematical in nature, and as mold growth was only investigated with visual inspection, it does not have any connection to the biology in the form of modeling the number of live cells. Also, the mold index resulting from computations with the model does not reflect the visual appearance of the surface under study because traces of mold growth remain on wood surface for a long time. The correct way to interpret the results is that the mold index represents the possible activity of the mold fungi on the wood surface. The model makes it possible to calculate the development of mold growth on the surface of wooden samples exposed to fluctuating temperature and humidity conditions, including dry periods. The numerical values of the parameters included in the model are fitted for pine and spruce sapwood, but the functional form of the model can be reasoned to be valid also for other wood-based materials. The mold index scale employed in the analysis is explained in Table 1. The details on the set of equations that are solved for each time step are presented in a paper by Viitanen et al. (2000) at the BETEC Bugs, Mold, and Rot III symposium.

TABLE 1
Mold Index Values and Description

Index	Descriptive meaning
0	No growth
1	Some growth detected only with microscope
2	Moderate growth detected with microscope
3	Some growth detected visually
4	Visually detected coverage more than 10%
5	Visually detected coverage more than 50%
6	Visually detected coverage 100%

Simulation Cases

The basic stucco-clad wall, as shown in Figure 1, was composed of the following layers starting from the outside to the inside:

- 1/8 in. acrylic stucco
- 7/8 in. conventional cement stucco
- 15 # felt paper
- 1/2 in. oriented strand board
- 6 in. fiberglass insulation
- polyethylene sheet
- 1/2 in. gypsum board

The exterior was exposed to hourly Seattle weather conditions, while the interior was exposed to relative humidities and temperatures that were dependent on outside conditions and the number of inhabitants. The wall was assumed to be centrally located in the middle of a two-story building. The inside surface of the gypsum board was coated with a vapor-

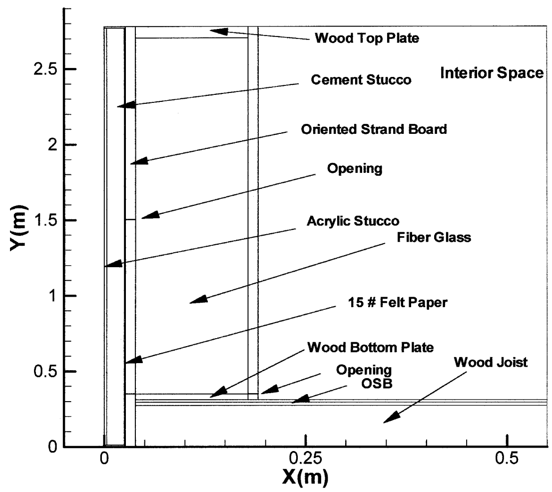

Figure 1 *Basic stucco wall system.*

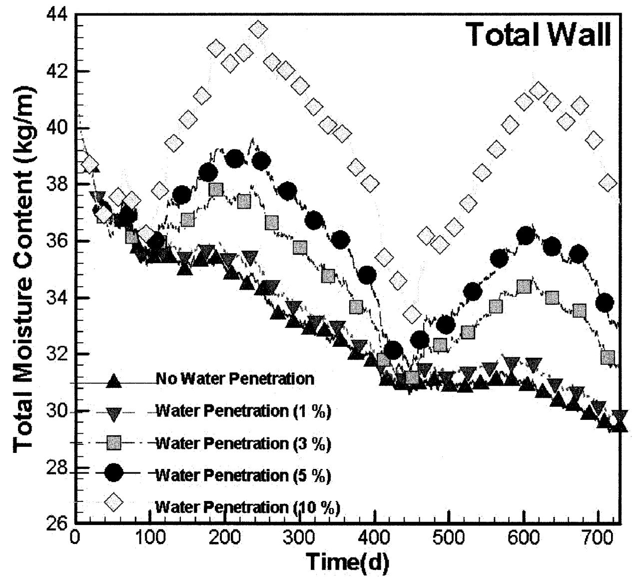

Figure 2 *Transient total moisture (kg/m) in the wall systems as a function of time.*

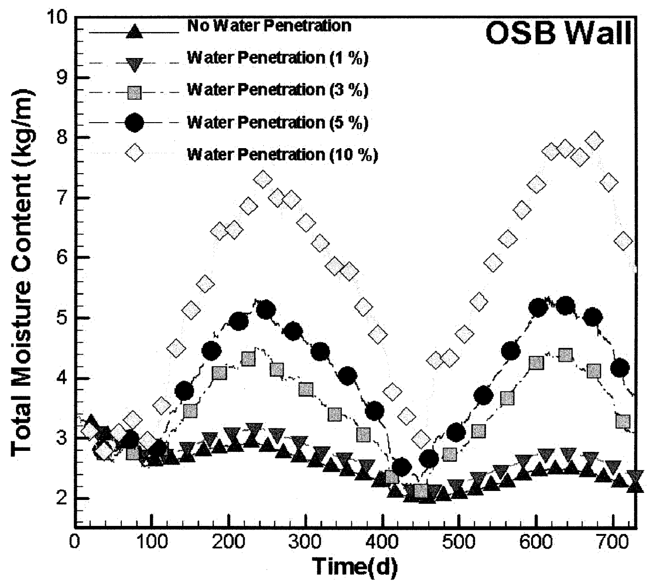

Figure 3 *Transient moisture content (kg/m) in OSB layers.*

permeable paint (permeance approximately 400 ng/(m^2·s·Pa) or 8 perms). The oriented strand board (OSB) moisture content was assumed to be in equilibrium with 85% relative humidity initially. This represents initial moisture condition in the OSB layer that would be above acceptable moisture contents permitted by building inspectors. The simulations were carried out for a two-year exposure (365 days) starting on July 1. The solar radiation and longwave radiation from the outer surfaces of the wall were included in the analysis.

Five simulations were performed to determine the effect of water penetration on the drying out performance of the walls. The following five levels of exterior water penetration were considered in the simulations: 0%, 1%, 3%, 5%, and 10% of the water striking the south-facing wall surface and distributed at the interface of the building paper and the oriented strand board. Two simulations were also performed to investigate the influence of interior environmental conditions (WALL6) and (WALL7) at respectively high moisture generation loads and none. Finally, another two simulations were performed to examine the influence of interior pressure loads on the hygrothermal performance of a wall. These last two simulations present conditions with eight hours per day ventilation requirements (WALL8) and with no ventilation requirements (WALL9).

SIMULATION RESULTS

Effect of Water Penetration Loading

In Figure 2, the total amount of moisture per meter depth (kg/m) present in the wall system as a function of time is presented to show the relative hygrothermal performance of the stucco wall system for the five different levels of unintentional water entry. Natural and forced convection were present in all these wall cases. It is evident that all the walls manage to dry out, with the diurnal yearly wetting cycle present during the late fall and winter months. While all walls dry out over time, the question that this graph does not address is whether the wall is drying out fast enough to prevent moisture-induced damage. The influence of water penetration is more significant for the 3%, 5%, and 10% penetration cases. With the exception of the 10% penetration case, the total moisture in the wall never exceeded that imposed by the initial conditions (RH at 85% in equilibrium). The walls displayed a net yearly moisture accumulation when water penetration levels exceeded 5%.

Figure 3 displays results for the transient moisture content profile of the OSB layers. This part of the wall is the most sensitive part as the water was distributed at the most exterior

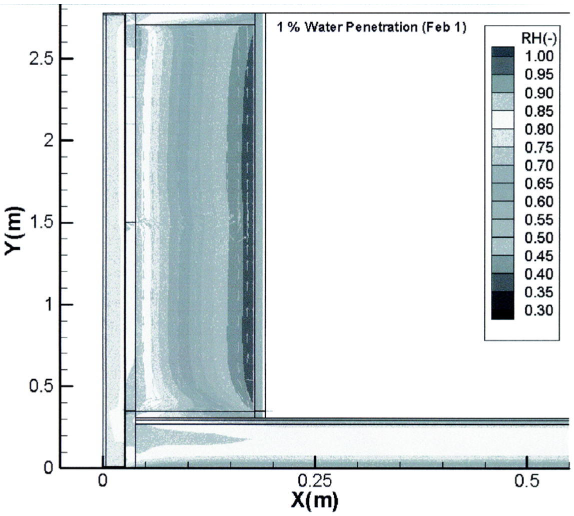

Figure 4 *Spatial relative humidity distribution for wall 2, 1% water penetration.*

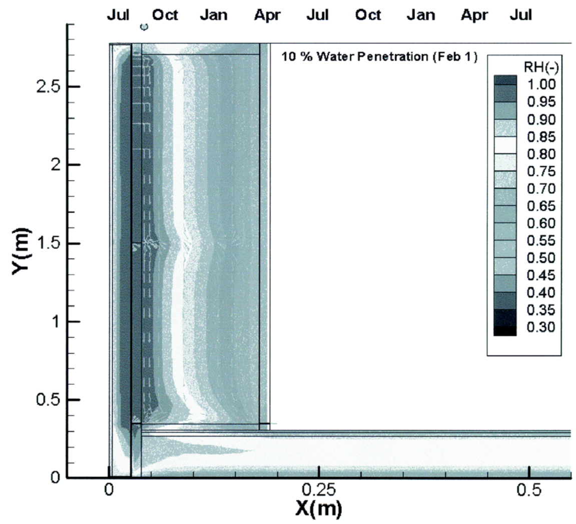

Figure 5 *Spatial relative humidity distribution for wall 5, 10% water penetration.*

surface of the wall. The wall system that was exposed to the largest water penetration, the 10% penetration case, displayed the slowest drying. Indeed, it is evident from Figure 3 that this particular wall may only exhibit acceptable hygrothermal performance if water penetration is 1% or less. The wall with the lowest water penetrations exhibited the fastest drying potential, 0% and 1%. From the transient moisture content distributions for ideal conditions where the wall was not exposed to either wind-driven rain or water penetration, the wall showed an inherent ability to dry out. The differences between the "perfect" 0% penetration wall system and the "real" (all other wall cases) show clear differences.

Figures 4 and 5 show the spatial relative humidity distributions in the 1% and the 10% water penetration cases at a snapshot in time (February 1). From these two-dimensional representations, it is obvious that both natural and forced convection significantly influence the dynamic moisture performance of these stucco-clad walls.

To assess the mold growth potential, the hourly thermal and moisture distributions in the wall assembly were included in a mold growth model. The mold growth index model of Hukka and Viitanen (1999) was employed. The interpretation of the mold growth index was presented earlier in Table 1. Figure 6 shows the mold growth indexes for the innermost location in the OSB layer at a height of two meters from the bottom. The mold growth index for the innermost locations rises to a maximum value less than 2 (moderate growth detected only with a microscope) for the 0% and 1% water penetration cases, then falls drastically to negligible values. In the 3% water penetration case, the maximum mold growth index is 4, which is high enough to have a visually detected coverage for more than 10% of the area. The last two cases, the 5% and 10% water penetration cases, show significant risk for mold growth, having values ranging between 5 and 6 for most

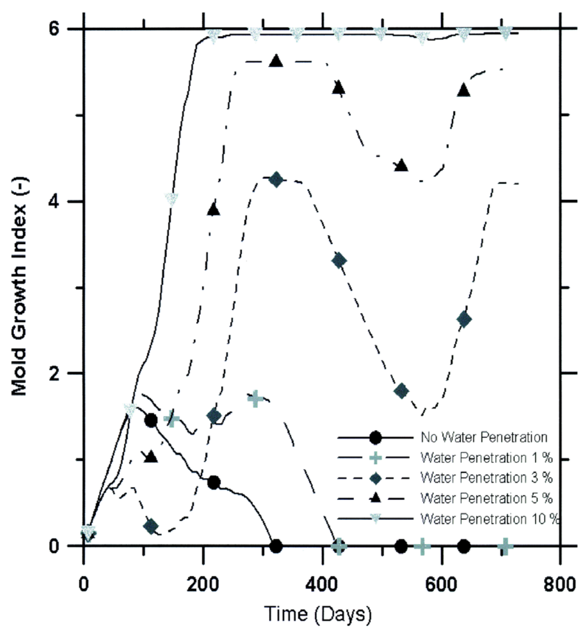

Figure 6 *Mold growth indexes for the innermost location in the OSB layer (2.0 m height).*

of the two-year period. Until biological growth models become available to building scientists, it is evident that the use of the mold growth index has the potential to provide a useful basis for comparing the relative predicted performance of a wall with various amounts of water penetration.

Effect of Interior Environment

In Figure 7, the transient total moisture content in the OSB as a function of time is displayed for the 1% moisture penetration case. Results of two simulations are presented, one for a relatively high moisture load production of 10 kg/day, which corresponds to five inhabitants living in an 800 ft^2 apartment (WALL 6) and another apartment that had no moisture production at all (WALL 7). The second simulation was chosen to provide the lower bounds of the analysis and the first simulation the upper bounds. The results clearly depict the importance of interior moisture conditions in the hygric performance of the wall. The influence was more important during the heating season, especially during the late fall and winter periods. The maximum difference was about 0.7 kg/m in the OSB.

Effect of Mechanical Ventilation

In Figure 8, the transient total moisture in the OSB is plotted out as a function of time for the mechanical ventilation and no mechanical ventilation case. These two cases represent conditions that correspond to new and old code requirements. The current Seattle mechanical code requires that the mechanical system operate at least eight hours per day, while the pre-1984 Seattle mechanical code did not require mechanical ventilation. As the mechanical system operates, it produces a positive pressure of the interior space. The results shown here demonstrate the effects of exfiltration on the hygrothermal performance of a stucco-clad wall system. Mechanical pressurization is critical as pressure differences drive moisture to accumulate within the building envelope.

CONCLUSIONS

The hygrothermal performance/moisture engineering assessment approach to analyzing the building enclosure used in this paper provides a useful and fair method of evaluating and ultimately optimizing wood-frame envelope designs. The intent of this study was to demonstrate the advantages of using advanced hygrothermal modeling in the design stage of exterior walls. The concept of the mold growth index was also employed with advanced hygrothermal modeling to assess the potential durability performance of a stucco-clad system. Drying rates of any wall system are controlled by the water vapor permeance properties of all layers of the wall system: stucco-cladding, OSB layer, insulation layer, vapor barrier, interior paint coating, weather resistive barrier, system air leakage of wall (openings and cracks), air permeability, interior environment, and exterior weather conditions. This study investigated a subsection of all parameters that influence the overall drying potential of a stucco-clad wall. The major assumptions employed in this study were that the wall system was air-open and material properties were identical to those prescribed in the study.

The drying-out performance of the wall system was simulated for five water penetration conditions. Results showed the existence of a critical moisture penetration threshold at or above which the wall may not be able to eliminate quickly enough to prevent moisture-induced damage from occurring. These thresholds can be related to the quality of workmanship or difficulty to implement wall design. Each wall has a critical threshold for the particular climate in which it is built. Both interior relative humidity and interior pressures are important and must be considered during the design stage for stucco-clad wall systems and, by extension, all wall systems.

The work clearly shows that one may need to install materials specifically designed for optimizing/enhancing the

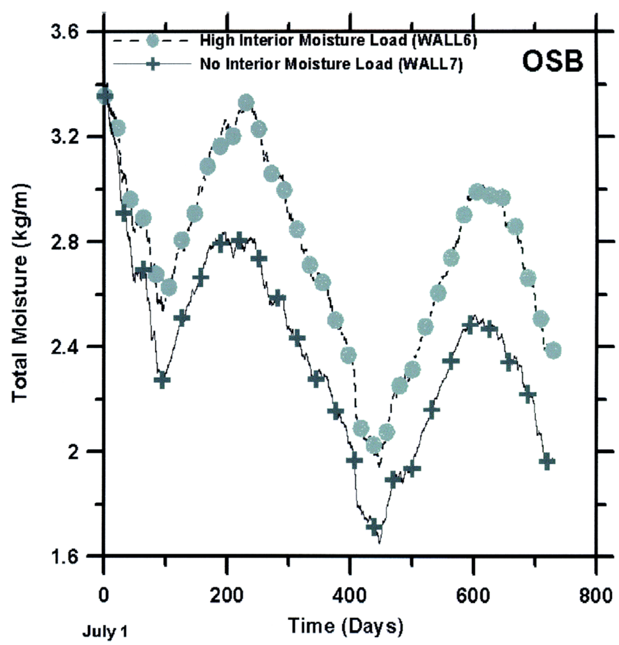

Figure 7 *Total moisture content as a function of time. Two different levels of interior relative humidity environments, one high load and the other no moisture production.*

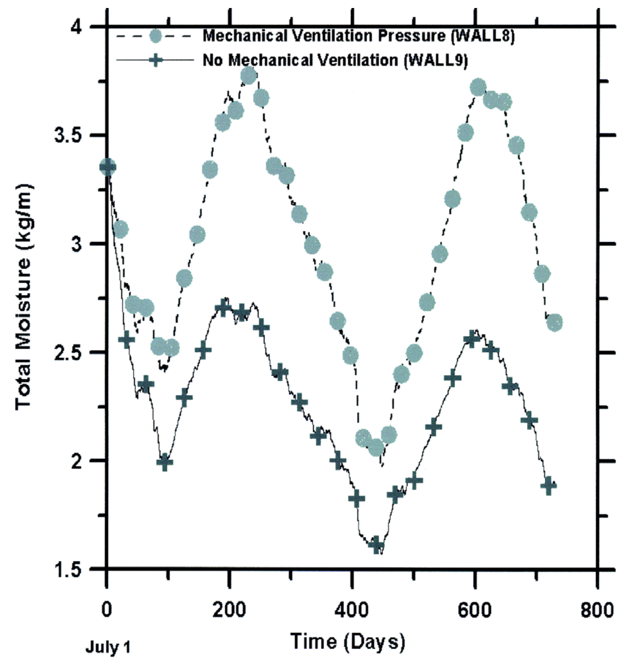

Figure 8 *Effect of mechanical ventilation on moisture accumulation in OSB.*

performance of specific wall systems in specific climates. Orientated strand board may be one of these "designer materials" that could be customized for applications, using an approach outlined in this paper.

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