Mold and Decay in TriState Homes

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Abstract

This paper examines the potential merits of two new approaches to building design for more durable buildings: moisture engineering design analysis and the use of a durability assessment protocol. Discussed is whether these approaches could have prevented mold and decay in plywood sheathing of exterior walls that occurred in Tri-State homes, a group of manufactured modular homes in the Midwest, in the mid-1980s. ***An*** exterior weather barrier that probably acted as an exterior vapor retarder and the lack of, whole-house ventilation were identified as the main culprits behind decay. Decay could have been prevented by replacing the plywood with a more "durable" material such as treated plywood, but most likely this would not have eliminated the mold problems. Analysis with the computer program MOIST using proposed interior moisture design loads, revealed a potential for mold and decay in the walls, especially with penetration of indoor air into the walls. Removal of the exterior vapor retarder or substantially increased whole-house ventilation could not completely eliminate the potential for mold. Only a combination of whole-house ventilation, a permeable exterior weather barrier, and elimination of indoor air leakage through the wall appeared to eradicate all potential for decay and mold growth. Providing more durable materials might have alleviated structural damage but it would not have addressed problems with mold and indoor environmental quality. Moisture engineering analysis, using design moisture loads, would have alerted the building designer that the existing design had a high potential for decay and mold and would have enabled the designer to make effective changes to the building design and operation.

Introduction and Objectives

Many building failures are related to excessive moisture, and mold is increasingly recognized as a source of indoor air pollution. This has prompted the emergence of "moisture engineering," a formal methodology to moisture design analysis that includes design moisture loads, computer analysis tools, and limit state evaluation criteria. This approach is being pursued by ASHRAE Standard Committee 160P, Moisture Design Criteria for Buildings. Another approach involves rating individual building materials or systems using a durability assessment protocol (2). This paper examines how these two methods might have been used, had they been available, in the case of Tri-State homes, a group of modular homes in which severe mold and decay occurred during the 1980s. Could moisture engineering or a durability assessment protocol have alerted the designer to the potential for mold and decay, and would the designer have been guided toward appropriate design solutions?

Moisture Engineering

Moisture engineering is an effort to put moisture design on a more rational basis. Moisture engineering involves using interior and exterior design moisture loads as input conditions and established performance evaluation criteria for the analysis and evaluation of the performance of the building envelope. Figure 1 shows a schematic of this process. Current recommendations and rules for moisture control are not based on a set of consistent, performance-based assumptions. This lack of adequate design criteria has often led to pointless discussions about the need for various design features, because the need often depends on what indoor or outdoor

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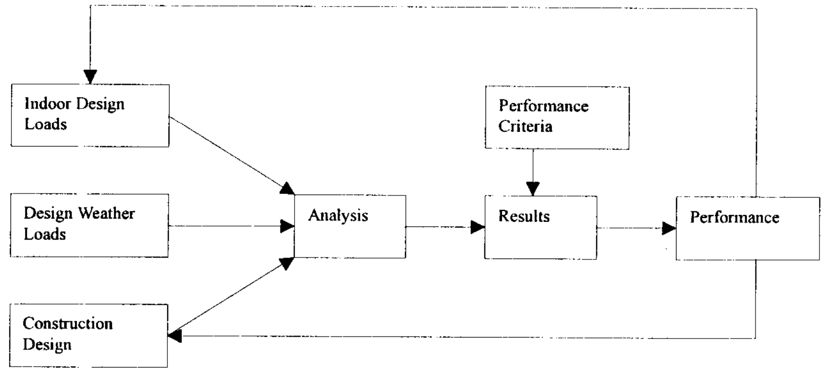

Figure 1.—*Schematic of moisture engineering design analysis process.*

conditions are assumed. While it is difficult to imagine structural design decisions without knowledge of the appropriate design loads, thus far we have made moisture control decisions without defining "moisture design loads."

ASHRAE Standard Committee 160P is in the process of formulating the criteria for analytical procedures and performance evaluation and is developing values for moisture design loads.

Durability Rating of Materials and Systems

The Protocol for Durability Assessment of Building Products and Systems (5) was developed to guide the conduct of durability assessments on building materials, products, systems, and subsystems. The protocol outlines procedures to estimate the anticipated service life of building materials and systems. This prediction may be based on past experience or test results, or both. The protocol prescribes an extensive description of the product or system, quality control procedures, limits to its use, and potential factors that affect its service life. There is also a requirement to determine the uncertainty of the estimate and to provide separate estimates for each service condition anticipated. The protocol does not, however, provide guidance on how to determine what the service conditions will be nor how to gauge how service conditions might be influenced by other factors, such as building operation or the effect of building design features. The protocol also requires that installation and maintenance procedures be taken into account, but it provides no clear guidance on how to accomplish this.

Moisture Problems in Tri-State Homes

Between 1970 and 1982, the Tri-State Homes Company of Mercer, Wisconsin, manufactured modular homes. Most of these homes were erected in Wisconsin, Minnesota, and Michigan. In July 1986, it became apparent that decay of the plywood sheathing had developed in a significant portion of these homes. Mold was also apparent on the interior walls of many homes. An extensive survey and medical examinations revealed a high incidence of respiratory illness among occupants. Although it was assumed that the respiratory problems were linked to the decay and mold spores, no particular pollutant (biological or nonbiological) could be identified as the main contributor (4,6,7).

It was clear that most decay of the plywood was the result of winter condensation, but there has been a drawn-out discussion between building scientists concerning the main reason for this condensation. Merrill and TenWolde (4) argued that lack of ventilation, resulting in high indoor humidity, was the principal cause for condensation, while Tsongas and Olson (10) blamed the low vapor permeance of the exterior weather barrier paper. Angell (1) listed both these factors as contributors to the problem. The paper presented here does not intend to resolve this question, but instead examines whether a "moisture engineering" approach, had it been in existence and applied to the Tri-State home design, could have averted the disastrous building failures.

The Tri-State homes were relatively small by today's standards; most of them ranged between 1,000 and 1,300 ft.^{2} (93 and 121 m^2) in floor area. The exterior walls were nominal 2 by 4 (standard 38 by 89 mm) wood construction, with 0.5in. (13-mm) gypsum board, mineral fiber insulation, and 0.5in. (13-mm) plywood sheathing, covered with a laminated asphalt-coated fiber-reinforced paper, and lap wood-based siding on the exterior. The asphalt-coated building paper was determined to have a dry-cup permeance of 0.65 perm (37 ng/Pa·s·m^2) and could be considered a cold-side vapor retarder during winter (10). The insulation was faced, usually on both sides, with polyethylene, kraft paper, or aluminum foil, depending on the year of house construction.

MOIST Analysis

I used the MOIST version 3.0 moisture computer model to analyze moisture contents in walls with construction designs similar to those used in the Tri-State homes. MOIST is capable of predicting one-dimensional heat and moisture flow simulating hourly temperatures and moisture contents inside a wall. Burch and Chi (2) described the capabilities and technical basis of MOIST The software, weather data, and the publication can be downloaded free of charge from a NIST web at http://www.bfrl.nist.gov/863/moist.html.

In addition to analysis of the Tri-State wall design as built, I analyzed the effect of several proposed corrective measures: making the wall airtight, replacing the low-perm exterior weather barrier with a high-perm barrier, and installing a 200-cfm (94-L/s) whole-house ventilation system to lower indoor humidity during winter.

Building Parameters

The floor area of the home used in the analysis was 1,200 ft.^{2} (111 m^2). The built-in MOIST property database was used for all materials except the low-perm weather barrier, which was given the same properties as asphalt building paper but with a vapor permeance of 0.65 perm (37 ng/Pa·s·m^2) (10). Although a variety of exterior sidings had been used for the Tri-State homes, for reasons of simplicity we used the MOIST data for sugar pine for the exterior siding, as did Tsongas and Olson (10). In this case, the properties of the siding are not nearly as critical to the results as are the properties of the weather barrier and plywood sheathing. Tsongas and Olson (10) also provided permeance values for the interior and exterior facings of the insulation: 4.1 perms (236 ng/Pa·s·m^2) for the inside interior facing and 7.1 (408 ng/Pa·s·m^2) perms for the exterior facing. The permeability of hygroscopic materials such as plywood varies with moisture content in the MOIST data set. The permeance of the interior paint was assumed to be 12 perms (690 ng/Pa·s·m^2) and that of the exterior paint 5.5 perms (316 ng/Pa·s·m^2), the same values as used by Tsongas and Olson (10).

Angell (1) reported that leakage of warm indoor air into the wall was the more likely moisture transport mechanism, rather than vapor diffusion. I support this opinion based on my own inspections of several Tri-State homes. MOIST does not explicitly simulate the effect of air movement, but the effect of a small amount of warm air leaking to the cold sheathing can be mimicked by increasing the equivalent permeance of the layers interior to the sheathing (8). When air leakage was included, the permeance of the interior paint and the facings of the insulation was increased to 33 perms (1,897 ng/Pa·s·m^2) (the gypsum board already has a high permeance). This approximates the effect of about 0.7 ft.^{3} of indoor air leaking into 1 ft.^{2} of wall area every hour (0.2 m^3/m^2.h), or between 2 to 3 air changes per hour in the wall cavity. This amount of air leakage degrades the thermal performance of the wall by about 15 percent, but this effect was ignored in the analysis.

Environmental Parameters

I used the WYEC (Weather Year for Energy Calculations) hourly weather data for Madison, Wisconsin, that are supplied with the MOIST model. The WYEC data represent average weather; for design purposes, more severe weather would have been preferable, but such moisture design data are not yet available.

The indoor temperature set points were 68°F (20°C) during winter and 75.9°F (24°C) during summer. Temperatures were allowed to float between these two set points. Indoor humidity was allowed to float as a function of moisture generation in the house and whole-house ventilation. This is more realistic than setting a constant humidity level and parallels design procedures considered by the ASHRAE Standard 160 committee. MOIST requires an effective leakage area for the house, which it then uses to compute hourly ventilation rates. A leakage area of 50 in^2 (323 cm^2) was used, which approximately corresponds to 0.28 air changes per hour. The indoor moisture generation was also based on proposed Standard 160 design procedures, which call for a design rate of 31.2 lb./day (14 kg/day) for a three-bedroom house.

Evaluation Criteria

The results were evaluated for the potential of mold and decay in or on the plywood. It has been long established that for wood to decay it has to remain at fiber saturation or higher, Decay of the plywood was therefore assumed to require a moisture content above 30 percent for extended periods. Criteria for mold growth are not as well established, but the International Energy Agency Annex XIV (3) established a criterion of 80 percent surface relative humidity. TenWolde and Rose (9) proposed combining this criterion with a concurrent temperature criterion of 32° to 104°F (0° to 40°C). Subsequent discussion within ASHRAE Standard Committee 160P led to a temperature range of 50° to 104°F (10° to 40°C). Thus, for the purposes of this analysis, mold was assumed to be able to grow when the monthly average surface relative humidity on the plywood rose above 80 percent and the minimum temperature needed for significant growth of both mold and decay fungi was assumed to be 50°F (10°C). However, we assumed that for significant mold or decay to occur, these conditions had to persist for at least 1 month.

Table 1.—*Summary of results from MOIST simulations.*

Remedial measures	Parameters			Results	
	Air exfiltration	Weather barrier	Mechanical ventilation	Significant mold	Significant decay
Base case	yes	low-perm	none	yes	yes
Airtight construction	no	low-perm	none	yes	yes
High-perm weather barrier	yes	high-perm	none	yes	yes
Whole-house ventilation	yes	low-perm	yes	yes	marginal
High-perm weather barrier with ventilation	yes	high-perm	none	yes	no
Airtight construction, high-perm weather barrier, and ventilation	no	high-perm	yes	no	no

Results

Base Case

The first wall design evaluated was the wall as it was actually built, with a low-perm weather barrier, indoor air leakage through the wall (air exfiltration), and no mechanical house ventilation, and assuming design indoor moisture release. We found that the simulation indicated that the criterion for plywood sheathing decay was met for approximately 11 weeks of the year, more than sufficient to allow serious decay The conditions for mold growth were met for over 12 weeks. Thus, the simulation correctly predicted the decay and mold that actually occurred in some Tri-State homes. Without ventilation, the indoor humidity varied between 40 percent and 50 percent relative humidity during midwinter.

Remedial Measures

Airtight Construction.—The first remedial measure evaluated was airtight construction, eliminating air leakage through the wall. The results indicated that conditions for decay were met for approximately 6 weeks, a significant reduction from the base case but still a significant risk. The potential for mold growth was not significantly reduced.

High-Permeability Weather Barrier—Next, replacement of the low-perm weather barrier by a high-perm barrier was evaluated. The wall was not airtight and air exfiltration was assumed to take place, as in the base case. The results showed that the criterion for decay was met for about 8 weeks, and the criterion for mold growth for over 12 weeks. Thus, this measure was not as effective as airtight construction.

Whole-House Mechanical Ventilation, With and Without Barrier Replacement.—The effect of a robust 200-cfm (94-L/s) ventilation system, running continuously, was then evaluated. This system lowered the interior humidity to a range of about 25 to 40 percent relative humidity during midwinter. I assumed air exfiltration through the wall, and the low-perm weather barrier was left in place. Nevertheless the effect of this level of ventilation was significant. Conditions for decay only existed for about 2 weeks during the year, probably not sufficient for rapid deterioration of the wall. However, potential for mold growth, though reduced, remained high- 8 weeks of surface relative humidity above 80 percent with temperatures conducive to mold growth.

I also evaluated the effect of combining whole-house ventilation with replacement of the low-perm weather barrier with a high-perm barrier. The wall was not airtight, however. Although this combination of measures eliminated the potential for decay, mold would still have been able to grow on the plywood for about 6 weeks.

All Three Remedial Measures.—Combining all three measures-airtight construction, ventilation, and replacement of the weather barrier-eliminated all potential for decay and mold on the plywood.

Summary of Results

The results are summarized in Table 1.

Discussion

This exercise was aimed at establishing the value of moisture analysis and using design moisture loads in the analysis by applying these ideas to a known example of moisture failures, i.e., in Tri-State homes. The conclusion seems to be that had a design analysis been applied to the Tri-State home design it would have exposed the potential for mold and mildew. This assumes that the analysis would have been done using the appropriate value for permeance of the weather barrier. The permeance was actually not measured until well after the failures had occurred. However, even a higher perm value would have alerted the designer to a high probability of mold growth on the plywood.

An analysis might also have led the designer to the solution: whole-house ventilation, elimination of air leakage, and a higher permeance weather barrier. Alternatively, the air leakage could have been addressed by designing an exhaust ventilation system that maintains a slight negative air pressure in the house. This would have led to dry outdoor air penetrating the walls during winter, rather than the humid indoor air. A combination of airtightening measures and pressure management would have been the ideal solution.

It is less certain whether a durability assessment, as envisioned by the National Evaluation Service, would have prevented the Tri-State home failures. The mold and decay problem was most likely caused by a combination of high indoor humidity, air leakage, and low permeance of the weather barrier. It is unlikely that the designer would have been alerted to the potential for these problems without an analysis with appropriate environmental and building design parameters. Even if the designer had been aware of a potential problem, replacing the plywood with a more "durable" sheathing might have eliminated the decay problem but mold growth could still have occurred. Although the procedures call for an evaluation under all expected service conditions, how is a designer to know what these conditions might be? Service conditions are a function of many parameters, including building design and operation. I believe it is unlikely that the durability assessment protocol would have alerted the builder or designer to the fundamental problems with this home design and would have consequently guided the designer to solutions that would have improved the durability of the whole structure and the indoor environment for the occupants.

Conclusions

A moisture design analysis using appropriate moisture loads and evaluation criteria could have alerted the Tri-State home designer to potential problems with mold and decay, and it could have guided the designer to effective solutions.

It is uncertain whether a durability assessment protocol for materials and building systems by itself would have prevented the mold and indoor environmental problems in Tri-State homes.

References

1. Angell, W.J. 1987. Condensation-related problems in cold-climate panelized houses. *In*: Condensation and related moisture problems in the home. American Association of Housing Educators and Small Homes Council, Building Research Council. Univ. of Illinois at Urbana Champaign.
2. Burch, D.M. and J. Chi. 1997. MOIST-a PC program for predicting heat and moisture transfer in building envelopes. NIST Special Publication 917. National Institute of Standards and Technology. Gaithersburg, MD.
3. International Energy Agency. 1991. Condensation and energy: Sourcebook. Report Annex XIV Vol. 1. Leuven, Belgium.
4. Merrill, J.L. and A. TenWolde. 1989. Overview of moisture-related damage in one group of Wisconsin manufactured homes. ASHRAE Transactions. 95(1):405-414.
5. National Evaluation Service. 2000. Protocol for durability assessment of building products and systems. Falls Church, VA.
6. Sieger, T.L, M.C. Fiore, H.A. Anderson, L.P Hanrahan, M.E. Ziarnik, and J. Guzik. 1987. An environmental assessment of the air quality within tightly constructed manufactured homes. In: Condensation and related moisture problems in the home. American Association of Housing Educators and Small Homes Council, Building Research Council. Univ. of Illinois at Urbana Champaign.
7. Sieger, T.L, M.C. Fiore, H.A. Anderson, M.E. Ziarnik, R.K. Bush, G.A. Dopico, L.P Hanrahan, and J. Guzik. 1987. The health effects and environmental assessment of tight homes. *In*: Proc. 80th Annual Meeting of Air Pollution Control Association. New York.
8. TenWolde, A. and C. Carll. 1992. The effect of cavity ventilation on moisture in walls and roofs. *In*: Thermal performance of the exterior envelopes of buildings V. American Society of Heating Refrigerating and Air-Conditioning Engineers. Atlanta, GA. pp. 555-562.
9. TenWolde, A. and W.B. Rose. 1994. Criteria for humidity in the building and building envelope. *In*: Bugs, mold and rot II. Proc. of workshop on control of humidity for health, artifacts, and buildings. National Institute of Building Sci. Washington, DC.
10. Tsongas, G. and J. Olson. 1995. Tri State homes: a case study of extensive decay in the walls of older manufactured homes with an exterior vapor retarder. *In* : Thermal performance of the exterior envelopes of buildings VI. American Society of Heating Refrigerating and Air-Conditioning Engineers. Atlanta, GA. pp. 207-218.

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