Rainwater Intrusion in Light-Frame Building Walls

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Abstract

The design of light-frame buildings to resist damage from rainwater intrusion is an art guided by the knowledge, experience, and opinions of practitioners. Confusion encountered by designers could be reduced by developing a consensus on the terms relating to rainwater management in building walls and by developing an engineering approach to the design of light-frame buildings with respect to preventing leakage-induced damage. Development of an engineering approach will require consensus on 1) means to characterize rain/wind exposure for design purposes, 2) means to evaluate the leak resistance, moisture tolerance, and moisture dissipation potential of constructions, 3) ways to determine or estimate reasonable limit states, and 4) identification of a desirable level of "robustness" for light-frame buildings with regard to their ability to resist water-induced damage.

The Problem

Rainwater intrusion has always been a threat to the durability and serviceability of light-frame buildings. Water intrusion into light-frame walls remains a serious problem; many recent cases have resulted in significant monetary losses (16,21,23,25), with some suggestion that the problem is becoming more serious (8). Over the last decade, the term "leaking condominium" has become familiar (12). While the incidence of leakage-induced damage has apparently been particularly prevalent in recently constructed multi-family dwellings in coastal regions, instances of such damage have also occurred in recently constructed single-family homes inland (Fig. 1).

Causes of the Problem

Some individuals have blamed energy-efficient construction practices for making buildings more susceptible to water-induced damage. Such a view probably has some validity, but it is simplistic. Furthermore, such a view cannot be applied in any practical way; building to the energy-efficiency norms of the 1960s would ignore present-day consumer preference for buildings that are affordable to heat or cool.

In most cases, a well-insulated and relatively airtight wall will not dissipate water that leaks into it as rapidly as one that allows for large amounts of air movement through it. In contrast, however, a substantial body of evidence, both theoretical and empirical, indicates that uncontrolled air leakage through walls can result in damaging accumulations of condensation within the walls. In snowy climates, air leakage and inadequate insulation levels are almost universally recognized by building scientists as the primary culprits for ice dam formation on roofs. Furthermore, although some recently constructed residential light-frame buildings have suffered significant damage from water intrusion, the majority of modern energy-efficient residential light-frame buildings have not suffered such damage.

In summary, it is uncertain to what extent energy-efficient construction has increased the susceptibility of light-frame buildings to damage induced by water intrusion, although it is plausible that preventing or restricting water intrusion is more important from a du-

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rability standpoint than it was in pre-energy-efficient construction.

Lawton (18) outlined the primary factors that resulted in the “Vancouver Condo Crisis”-the leaking and rotting of recently constructed multi-story wood-frame residential buildings. Lawton’s factors (slightly paraphrased) are as follows:

- General building design and siting; relatively tall buildings without roof overhangs, in a climate with significant potential for wetting by rain and limited potential for drying.
- Inclusion of architectural features difficult to construct in a leak-resistant manner-cantilevered decks, bow and bay windows, and complicated (in some cases intersecting) inside and outside corners-and constructed using components and materials without a proven record of performance in the specified exposure.
- Generally poor quality in water protection detailing, resulting from a combination of inadequate design detailing, poor construction, and inadequate site supervision and inspection.

Economic expedience and aesthetic preferences underlie these factors, but they do not fully explain how the crisis occurred. Probable contributors were a) the failure to evaluate building designs or design details with regard to their ability to withstand rain exposure and b) misunderstanding among design professionals, between designers and contractors, and between contractors and people in the trades.

In North America, there is no established methodology for designing light-frame buildings so that they resist damage from rainwater intrusion. Part of this report explores the possibility of developing an established methodology based in the engineering sciences and discusses why such a methodology has not yet been developed. This report also addresses sources of confusion for design professionals, given that the current practice is based on experience, expert opinion, and qualitative judgment.

Rain-Control Engineering

Feasibility

Buildings are generally designed and constructed so as to withstand quantifiable structural loads: dead loads induced by the weight of the building and its contents and live loads (loads induced by building occupants, wind, snow, or seismic events). There are standardized methodologies based in the engineering disciplines for characterizing the structural loads imposed on a building[1]. Adopting an engineering approach to designing a building to resist water intrusion damage would probably reduce the confusion encountered by designers, builders, and building owners. An engineering approach would allow evaluation of building designs and details with regard to some objective and quantifiable judgment criteria when the construction is subjected to quantifiable rain exposures.

Figure 1.—*Extensively decayed OSB wall sheathing on a single-family residence in Middleton, Wisconsin, less than a decade old. Sheathing deterioration was associated with water intrusion around cladding details.*

An engineering approach is predicated on the following:

- An ability to quantitatively characterize loads and/or consensus on how to make reasonable estimates of anticipated loads.
- An ability to quantitatively characterize or predict the ability of a building to resist loads, taking into account that replications of a given design will vary in their load resistances.
- Consensus on criteria for judging adequate resistance to loads (so-called “limit states”).

[1] Structural loads are not always calculated for individual low-rise light-frame buildings. However, structural load calculations are reflected in the requirements of the *National Design Specification® (NDS®) for Wood Construction* (1), and these requirements in turn influence the prescriptive requirements of building codes.

- Consensus on the extent to which constructions, on average, need to be overbuilt to account for variability in loads and resistances and to provide for a margin of safety.

As implied previously, these requisites have been developed for structural design of light-frame buildings. Structural adequacy of light-frame buildings is generally viewed as critical to the safety of building occupants. In contrast, resistance to damage by water intrusion has primarily been viewed as an economic issue. Although water-induced damage can influence the structural integrity of a building, to a great extent the safety concerns associated with such damage have not been addressed. Wood decay has been recognized as having potential life-safety consequences, but there is no standardized methodology for quantifying the influence of decay on structural integrity. Concerns over structural safety posed by leakage-induced damage have apparently been allayed by two notions: a) that leakage will be obvious before much damage occurs (at which point the building owners can intervene to stop or slow the leakage), and b) that if chronic water intrusion causes structural damage, some sign of the damage will appear before it poses a safety hazard.

Developing an engineering approach to design for preventing water-induced damage has not been judged to be as important as developing such an approach to structural design. Furthermore, the challenges to developing an engineering approach to preventing leakage-induced damage are more complex than those involved in developing an engineering approach to structural design.

Characterization of Rain Exposures for Design

There are no standardized methodologies in North America for characterizing rain exposure of a given low-rise building wall for design purposes. The most basic approach is to consider annual average rainfall. Lstiburek (20) proposed the recognition of five rain exposure zones in North America for categorizing moisture accumulation hazard in building envelopes[2]. Adoption of this concept allows for relative comparisons of expected moisture loads on different building projects. Given a sufficient number of documented benchmarks (i.e., specific constructions recognized by consensus as performing acceptably within a given exposure zone), reference to exposure zones allows a semiquantitative basis for estimating whether constructions will work acceptably in zones in which they do not have a documented history.

The adoption of rain exposure zones based on annual average rainfall provides a logical and numeric means of characterizing rain exposure of building walls. However, it does not address two issues: a) whether an average year is the appropriate basis for design and b) whether the amount of rainfall by itself (i.e., without consideration of the combined effects of rain and wind) is the appropriate basis for design. Consensus on these issues does not exist in North America at this time.

Quantitative predictions for exposure of a wall to windblown rain can be made using computational fluid dynamics (7,15). These computations are rather complicated, and they have been primarily applied to high-rise buildings. The predicted values can be markedly influenced by terrain and surrounding buildings, as well as surrounding trees. Neighborhood characteristics (surrounding buildings and vegetation) may change considerably over the anticipated lifetime of a building. Furthermore, if building-specific calculations are necessary to obtain valid characterizations of windblown rain exposure, such characterizations may not be satisfied in practice for light-frame buildings. There seems to be an established tradition within the low-rise building industry to avoid building-specific calculations if possible.

Finally, there is no consensus on how quantitative predictions for windblown rain exposure should be approached or how their results should be used. Rational design for any quantifiable parameter assumes professional consensus on the appropriate level for that parameter. In the case of windblown rain exposure, the question of appropriate level might be one of an agreed-upon probability of occurrence, calculated from historic weather data, of a combined wind and rain event of given intensity and/or duration over some specified period. Saunders (22), a researcher in the United Ringdom, suggests that a 10-year return period would be appropriate for rain-control design. This represents a more strenuous level than is typically considered in energy design of buildings (where mean values over a number of years are typically used), but a less strenuous level than is typically considered for structural wind resistance of buildings (where return periods of 100 years or more are deemed necessary). Greater thought has been expended in the United Kingdom on the subject of rain-control design than has been expended on this subject in North America. Consensus on how to select an appropriate level for a windblown rain exposure pa-

[2] As used in this paper, moisture refers to water, regardless of its momentary phase. Because water may change phase within a building construction, distinguishing between water vapor and liquid water is sometimes of questionable accuracy or utility.

rameter (which might be termed a "design storm") does not exist in North America.

Rain (or even windblown rain) is not the only potential source of moisture that can accumulate and damage building walls. In addition to the rain exposure zones, Lstiburek (20) proposes the recognition of hygrothermal climatic regions and interior climate classes, to permit a holistic approach toward design for limiting moisture accumulation in building envelopes, whether that moisture enters the envelope in vapor or liquid phase. Thus, characterizing rain exposure (or windblown rain exposure) may not by itself be adequate input for an engineering approach to design for resistance to moisture-induced damage.

It should be possible to quantitatively characterize rain exposure (and other moisture exposures) of low-rise building walls. At this time, however, no comprehensive, quantitative, and consensus methodologies are available to building designers. The guidelines available to practitioners (20) are based on semiquantitative methods and have not yet been recognized as standard guidelines.

Quantitative Characterization of Resistance to Leakage Damage

The resistance of a wall to leakage-induced damage is determined by

- the resistance of the wall to leakage,
- the resistance of the materials within the wall to damage by wetting, and
- the ability of the wall to rapidly dissipate intruding water.

In aggregate, these three factors are significantly more difficult to quantify than is the resistance of a construction to a structural load.

The resistance of walls or construction details to water leakage can be evaluated by spray testing (13,17,26). The preponderance of spray testing has been performed on large (generally heavy steel frame) institutional or commercial buildings[3]. To an overwhelming extent, this testing has been project specific, reflecting the facts that large institutional or commercial buildings are often intended to display a moderate to substantial degree of architectural uniqueness and that a given detail may be replicated hundreds of times within such a building, allowing the cost of mock-up testing to be spread over a large number of individual installations. Using spray testing for generic wood-frame constructions (26) suggests that the methodology may be applicable in a manner more consistent with practices in the residential light-frame construction industry.

The resistance of materials within a wall to damage by wetting could be viewed as a basis for construction-specific limit states (i.e., the basis for adjustable judgment criteria) rather than as a purely quantifiable resistance. For a considerable number of construction materials, however, uncertainties remain over what moisture conditions (or moisture-time combinations) would represent a reasonable limit state. For the purpose of preventing wood decay, keeping untreated wood or wood-based products at moisture contents below 20 percent has been prescribed since the 1930s (11). Carll and Highley (6) reevaluated the 20 percent moisture content rule and conclude that there is no evidence to refute it, while also noting that short-term cyclic wetting (which, strictly speaking, violates the rule) does sometimes occur without calamitous consequence and is an issue fraught with uncertainty.

The ability of a wall to dissipate moisture (by drainage and evaporation) can be quantified using simulation modeling, although doing so requires selection of realistic inputs for the model used. Moisture dissipation is also related to air movement and vapor diffusion within the wall. This, in turn, indicates the importance of a holistic approach to moisture control, which also considers the influence of indoor and outdoor atmospheric conditions on moisture conditions within the wall.

Rain-Control Engineering for Low-Rise Building Walls

As indicated previously, the considerable challenges in developing an engineering approach to rain control have not been addressed to the extent necessary to establish an engineering discipline. Sophisticated numerical analyses have occasionally been performed to predict moisture conditions in walls, taking into account rain exposure, wall leakage characteristics, and wall drying potential (5,14). Numerical analytical methods are essential tools for an engineering approach, but they do not by themselves constitute an engineering discipline.

The requisites for an engineering approach can be developed only by a consensus-based process, insofar as engineering disciplines are not proprietary. An industry can benefit from the existence of an engineering discipline if the discipline encourages innovation within that industry, or if the discipline (as an accepted standard of care) provides for a more predictable marketplace or protection from liability. Thus far, only a limited number of players in the North American industry

[3] These buildings often incorporate architectural-grade windows that are structurally stronger and have higher leak resistance compared with windows normally found in residential construction. Installations of these windows are sometimes proof-tested by spraying (10).

seem convinced that the potential benefits of an established engineering discipline in this field will be commensurate to the efforts that will be required to develop that discipline.

The Art of Building Design

As practiced, design to prevent damage induced by water intrusion in low-rise buildings is an art, based on conceptual understanding and experience. In essence, designers are guided by

- local experience,
- qualitative realization that rain exposure (and therefore required leak resistance) varies with geographic location, and
- intuition, perception, or some assurance voiced by a person or persons (judged as knowledgeable) that given building designs and design details can be reliably executed using given combinations of materials and components.

The guidance obtained from these sources serves as the basis for making prescriptive decisions on building designs, components, and design details, or combinations of these, for a given geographical location. The judgment criteria on which to base prescriptive decisions are rarely quantitative. If faced with differing opinions regarding the appropriateness of a given prescriptive decision, building designers use their intuition and qualitative judgment to assess the relative validity of the differing opinions. Building designers can use numerical analyses (computer simulation models) or hire specialists to perform such analyses, but this is rarely done for low-rise residential construction. If numerical analyses are used, they are performed according to the judgment of the designer or specialist.

The general operating principle for designers of light-frame buildings is that water should not intrude into the wall as far as the framing members. In most cases, the objective is also to prevent water from intruding as far as the sheathing. In general, wall sheathing is at least moderately susceptible to water damage[4], and its long-term ability to withstand chronic rewetting is neither established nor quantified. Cladding systems[5] (e.g., cement-plaster stucco, brick veneer, and wood shingle, wood lap, plywood, and vinyl siding) and interfaces of cladding systems with other wall components (windows and doors for example) have an influence on whether water reaches the wall sheathing.

According to Bateman (3), there is a dearth of useful published information on how to design and execute architectural details that will prevent water intrusion in light-frame buildings. Bateman's focus is on window installation, although much of what he addresses also applies to the more general endeavor of design of light-frame building facades to prevent water intrusion. Bateman points out that designers, builders, material and component manufacturers, trade associations, and building code officials (both writers and executors of codes) often assume that some other entity has primary responsibility to provide adequate guidance and installation details. Manufacturer's instructions and drawings are almost always incomplete because of the considerable variation in materials and architectural features with which a given product may interface. When trade associations provide recommendations or sketches, they are sometimes contradictory and incomplete, or even faulty. It would be naïve to assume that recommendations given and statements made by trade associations are wholly impartial, although Bateman diplomatically does not point this out. Finally, building code provisions frequently provide no tangible criteria by which to evaluate whether a detail or design meets code requirements for leak resistance or durability.

Cladding Systems

Mechanisms of Action

Rain deposited on any given layer of a building envelope can react in three different ways (24):

1. the water can be shed (drained) to the exterior,
2. the water can be stored within the layer, by adhering to the layer surface(s) or by absorption into the material that makes up the layer, and/or
3. the water can be transmitted through the layer further into the wall, essentially through holes in the layer itself or through larger holes that allow water to bypass the layer.

Water deposited on the outside of a cladding system may in fact react in all these ways. For example, rain falling on a brick veneer can be expected to be shed in part to the exterior, stored in part (by absorption into the brick and mortar and by adhesion to front and back surfaces of the veneer), and transmitted in part to the next wall layer (the outer surface of building felt, paper, or housewrap

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[4] Foam sheathing is largely immune to water-induced damage. Fiberboard, gypsum, and oriented strandboard (OSB) sheathing contain water repellents, but this does not wholly prevent water absorption.

[5] In this paper, cladding system refers to a non-load-bearing wall covering system that serves protective and ornamental purposes. This usage is in accordance with ASTM E 631 (2). The term non-load-bearing refers to gravity-induced loads. Cladding systems may be "load resisting," serving a structural function with regard to wind or seismic loads.

that covers the sheathing). With a brick veneer, the storage of water is likely to be substantial. With vinyl siding, little water is stored, only that which adheres to the front and back surfaces of the siding. The water storage potential of wood-based cladding lies somewhere between that of brick veneer and vinyl siding.

Confusion in Nomenclature

Straube and Burnett's (24) approach to a conceptual understanding of how cladding systems function is fairly new. The traditional approach to a conceptual understanding of rainwater management has been to consider the design intent for a wall. Parlance for classifying wall types based on design intent includes terms such as mass walls, barrier walls, and drainage walls. One might assume that the traditional approach, because it has gained the status of tradition, has proven to be at least moderately successful. However, despite its apparent success, this approach is not devoid of confusion. The sources of confusion are that

- uncritical usage of terms for classifying walls on the basis of design intent can lead to misunderstanding, and
- there is no universal consensus on the terms used to convey design intent.

The classification of a wall with respect to design intent may be interpreted as implying that only one water movement or storage phenomenon occurs in that wall. Under certain conditions, the predominant movement and storage phenomena may differ from the phenomenon implied by the term used to classify the wall. For example, when a wall is clad with cement-plaster stucco, a concealed weather-resistant membrane' is incorporated behind the cladding as are weep screeds at the base of the wall. This kind of wall is commonly referred to as a "drainage wall," under the assumption that water reaching the outer surface of the concealed membrane is principally drained downward and away from the location at which it first contacts the membrane, regardless of whether the water actually drains to the exterior. Drainage to the weep screeds frequently occurs, but this can take days. Drainage occurs only if there is free water, and the cement plaster can store considerable quantities of water at moisture contents below that at which free water is present. Stucco-clad walls appear to dissipate considerable quantities of water by evaporation, despite the fact that they are often classified as drainage walls. As suggested by this example, an uncritical assumption that the only important transport or storage phenomenon that comes into play within a wall is the one inferred from the classification term used for the wall can sometimes lead to misunderstanding.

There is no universal agreement among practitioners on definitions for the terms used to classify wall systems with respect to design intent. For example, some practitioners apply the term drainage wall to any wall incorporating a concealed weather-resistive membrane. In contrast, other practitioners do not consider a wall to be a drainage wall unless it provides for positive drainage to the exterior; they may use the term "dual-stage barrier wall" for a wall with a concealed weather-resistive membrane that does not provide for positive drainage to the exterior.

The terms "primary barrier" and "secondary barrier" have also generated disagreement within the design profession. These terms are frequently used within the context of wall systems that incorporate a concealed weather-resistive membrane. In this context, "primary" and "secondary" can be used to denote any of the following:

1. the chronological order in which rainwater reaches the respective barriers,
2. the relative amounts of water prevented from further intrusion by the respective barriers, or
3. the relative importance of the respective barriers.

According to the first two of these judgment criteria, the cladding system is always the primary barrier, because it is the first part of the wall to be exposed to water and it is exposed to large quantities of water. The cladding system always sheds and/or stores some water, so the concealed membrane is never exposed to as much water as is the cladding. For this reason, a significant proportion of design professionals consider the cladding system to be the primary barrier.

The issue of which barrier is most important is usually moot. For most light-frame walls, omission of either the cladding system or the concealed weather-resistive barrier usually results in a wall that leaks. However, for buildings clad with stucco or brick veneer, noticeable quantities of water generally do not enter building walls during the time between installation of the concealed weather-resistive barrier and installation of the stucco or brick veneer, even if appreciable construction delays occur. By contrast, installation of the veneer without first installing a concealed weather-resistive barrier usually results in immediate, observable, and objectionable leakage. For this reason, some indi-

[6] A concealed weather-resistive membrane is termed "concealed" because it is not visible without partial disassembly of the wall. Asphalted building felts or building papers and housewraps are used as concealed weather-resistive membranes in light-frame construction.

viduals argue that the concealed weather-resistive barrier is the primary barrier.

In summary, full consensus on a seemingly simple nomenclature issue has not been reached. This issue is not addressed by ASTM Standard E 631 (2), nor does this standard include definitions of "flashing" or "weather-resistant barrier."

Contentious Issues: Two Examples

In the Midwest, it is fairly common practice for nailing-flange windows and vinyl siding to be installed directly over oriented strandboard (OSB) sheathing (i.e., without asphalted building paper/housewrap and flashing sheets around window openings). This same practice is sometimes used for gypsum-sheathed walls. Until the adoption of a supplement in 1998, one model building code apparently condoned the omission of a concealed weather-resistive barrier membrane (9).

The argument given in defense of omitting a concealed weather-resistive membrane is that because the sheathing panels contain water-repellent additives, the outer surfaces of the panels serve as a concealed weather-resistive barrier and, therefore, asphalted building paper or housewrap is unnecessary. At least one builders' trade association has supported this argument, as have some suppliers of sheathing materials. Within some (as yet undefined) limits, the practice perhaps can be argued to work acceptably, insofar as widespread failure of wall sheathing behind vinyl siding that is unprotected by a concealed weather-resistive barrier has not been reported thus far. On the other hand, the practice of installing nailing-flange windows directly over OSB or gypsum sheathing is not backed by decades of experience; it is plausible that failures may be occurring that we are of yet unaware.

Joints in the sheathing can be expected to allow passage of water if appreciable quantities of water breach the cladding system or its interface with windows. The ability of the sheathing panels to withstand repeated wetting (or wetting followed by slow drying) and the ability of the wall to dissipate intruding water are not known with any precision. The leakage characteristics of the cladding system and its terminations and interfaces with other components have not apparently been quantified. Window manufacturers apparently will not condone the practice of installing nailing-flange windows directly over OSB or gypsum sheathing, and trade associations for window manufacturers discourage it. The salient point is that a building designer will encounter conflicting opinions on whether the sheathing surface behind vinyl siding can function as an adequate concealed weather-resistive barrier.

The North American experience with the surface-barrier External Insulation and Finish System (EIFS) provides another example of how building designers are exposed to widely divergent opinions from different trade associations and presumed experts. Surface-barrier cladding systems rely on complete prevention of water penetration past the outermost wall surface. As such, they incorporate neither concealed barriers nor features to provide for dissipation of water that may breach the outermost surface. The prevailing view among building scientists is that surface-barrier EIFS systems are not suitable for use on light-frame buildings, except where annual rainfall amounts to less than 20 inches (50.8 cm) (4,19,20). Two EIFS manufacturers, who pioneered the development of "drainable EIFS," strongly concur with this assertion. The EIFS trade association no longer promotes the use of surface-barrier EIFS on light-frame buildings without caveats (the association now promotes its use on such buildings in dry climates). Certain individuals in the EIFS industry, however, continue to defend the use of surface-barrier EIFS systems on light-frame buildings regardless of climate. Some have blamed decay behind surface-barrier EIFS in moderate to heavy rainfall climates on factors other than the cladding system, in some cases implying that deficiencies in the quality of window units played a significant role. Window manufacturers and their trade associations strenuously dispute such implications.

Concluding Remarks

Designing light-frame buildings to resist damage from water intrusion is an art, guided by the knowledge, experience, and opinions of practitioners. Opinions vary, even on matters of seemingly simple nomenclature. To a great extent, useful guidance from building codes is lacking. Recommendations from material suppliers and trade associations are usually available, but they may be contradictory and incomplete and may even be faulty. Trade associations can give widely disparate recommendations.

The confusion encountered by designers of light-frame buildings could be reduced by the following:

- Developing consensus on the use of parlance relating to rainwater management in building walls, including terminology used to classify wall systems with regard to design intent; concurrently, recognizing the imperfection associated with wall system classification with regard to design intent.
- Developing an engineering approach to the design of light-frame buildings in respect to preventing water intrusion.

An engineering approach to water-intrusion-resistant light-frame building design will require consensus on the following issues:

- The means used to characterize rain (or rain and wind) exposure for design purposes, taking other moisture sources into account as well.
- The means to evaluate the leak resistance, moisture tolerance, and moisture dissipation potential of constructions.
- Ways to determine or estimate reasonable limit states.
- Identification of a desirable level of "robustness" for light-frame buildings with regard to their ability to resist water-induced damage.

Acknowledgments

Robert Bateman and Peter Nelson, of Simpson Gumpertz and Heger, independently provided the author with comments that were of significant help to developing this manuscript. The author also recognizes the input of Robert Kudder, of Raths, Raths, and Johnson and task group leader of ASTM E06.55.15. Statements in this manuscript that can be interpreted as controversial are the sole responsibility of the author.

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Proceedings of the 2nd Annual Conference on

Durability and Disaster Mitigation in Wood-Frame Housing

November 6-8, 2000
Monona Terrace Convention Center
Madison, Wisconsin

This conference was sponsored by the PATH Consortium for Wood-Frame Housing in cooperation with the Forest Products Society. The PATH Consortium for Wood-Frame Housing is made up of the National Planning Committee for Forest Products (consisting of the Forest Products Laboratory, USDA Forest Service; universities with forest products programs; and USDA Cooperative State Research, Education, and Extension services); the American Forest & Paper Association (AF&PA); APA-The Engineered Wood Association; and the National Association of *Home Builders Research Center (NAHBRC).*

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