Wood Protection by Design

OUR first article ("Wood Decay and Protection," TF 100) explicated biodeterioration agents and the processes they employ to return wood—the manufactured, dead organic material—back to nature. This article discusses what constitutes good design and skilled construction to avoid wood decay and degradation. Together these two practices make possible effective maintenance, the means of wood protection over time.

Archaeology and history record many examples of rudimentary wood protection such as single-stone pedestals and caps to reduce water entry into the end grain of wood columns, or broad eaves on thatched roofs to direct water away from the wall. The use of durable species for water exposure such as the cedars of Lebanon, or ancient concoctions such as cedar oil and pitch for preservation, provide other examples (Graham 1973).

Today's designers and builders increasingly turn to renewable, organic materials, which they want to last, if not forever, then for many decades or if possible centuries. All materials degrade over the long term, but wood's organic character determines its longevity and ensures its susceptibility to nature's genius for waste removal. Though not mutually exclusive, these two goals for the materials, that they be at once organic and long-lived, naturally conflict.

Yet ancient timber structures are scattered across Europe and parts of Asia. Their longevity demonstrates the achievability of these simultaneous goals and results from five key requirements: good design, skilled construction, consistent maintenance, the ability of the wood to dry quickly after wetting and, finally, a relatively termite-free environment. Additional tactics for durability today include chemical preservatives or modification as well as the designer's choice of a wider range of durable wood species.

Achieving these requirements, moisture control the most important, over the extended life of a building challenges the builder more today than it did historically. The consequences are sometimes apparent in spectacular failures such as extensive EIFS (exterior insulation finishing system*) leakage in the Southeast in the 1990s. Owners and users of buildings demand more from shelter today than in the past, and builders and designers struggle to meet these increasing demands. Moisture, the biggest threat to wood durability, has proved to be difficult to control. Today it is the source of one of the most litigated construction failures in the US (Easley 2010).

For centuries, builders in cold climates sought to limit the flow into buildings of air in the form of drafts and moisture in the form of liquid water. Interior moisture generated by inhabitants or their activities found its way to the outside atmosphere or was dried inside wall cavities by conducted heat or heated air that consistently flowed through these assemblies. With today's ever-rising interest in energy efficiency, control of the *outflow* of air has gained importance and has significantly contributed to moisture issues.

For improved energy efficiency, fitting insulation between studs and rafters of light-framed buildings gained acceptance as fiberglass insulation became widely available in the US ca. 1960. Insulation requirements became common in North America with the focus on energy efficiency and tight building construction during and after the Carter-era global cooling scare and the OPEC-induced oil shortage in the late 1970s. The Canadians led the way with their R2000 program to reduce energy consumption, in which they strived to limit the flow of air and moisture by installing polyethylene vapor barriers under wallboard and over 2x6 studs and 6 in. of insulation. Though successful in many colder areas of Canada, its application in different climates proved problematic. Limiting the flows of heat, air and moisture caused an increase in moisture issues. Without the necessary heat and circulating air, wall and roof assemblies no longer dried as quickly.

The building community is a subculture that exhibits strong traditions and practices passed on mostly through hands-on experience and word of mouth (not through vocational education), at least in the US. In particular for house-builders, this allows even uneducated laborers to work with less-detailed information in prints or specifications, relying instead on tried-and-true practices.

As a necessary consequence, change usually works its way slowly through the construction industry and is often resisted, often with good reason. Unlike evolved building materials embraced by builders such as plastic piping or Romex wiring, heat, moisture and vapor flows are complex and climatically diverse phenomena best understood by those with backgrounds in mechanical engineering or thermodynamics. And, unlike commercial work for which documentation runs into hundreds or even thousands of pages of drawings and specifications, domestic construction generally has not warranted or received the attention of mechanical engineers in the design process. The building industry is still working to integrate ratcheting performance demands and the products and processes to satisfy them. Like builders, many architects, engineers and designers do not understand the mechanics of moisture movement. Yet they must now devise systems that provide excellent primary barriers to energy, air and vapor flow and back-up systems for when they fail, and must work with builders and the labor force to guide their proper installation.

How moisture infiltrates—the physics Moisture movement requires a driver. Gravity drives liquid or bulk water. Capillary action or wicking, another driver, acts counter to gravity. Wicking arises from the surface tension of water at its boundaries. Water rising inside a straw against gravity to a higher level than the surrounding water provides a familiar example. The smaller the pore, the more dramatic the rise. In specific circumstances, wicking contributes significantly to moisture movement. Additionally, two gradients (local differences) act as moisture drivers: temperature and pressure. Under most conditions, heat is transferred from warmer to colder areas, and differences in pressures equalize.

Heat is energy but in the vernacular even most physicists speak of heat as a substance. As a measure of the excitation of the molecules of a body, heat always moves from the hotter body to the colder body. Colder air, however, can move toward hotter air if the pressure difference drives toward the hotter zone—consider drafts. The heat in the air will then equilibrate across the hotter and colder air. In a wall cavity heat is transferred by convection from the inside wall to the outside wall. Air moves up the inner surface of the wall as it warms, transfers the heat after crossing over at the top of the cavity and flows down the outer wall as it cools. Heat also radiates from a house as black-body radiation even without air movement.

Air and vapor produce the pressure differences necessary for moisture movement. They often act in concert. Air pressure gradients occur under several circumstances. Wind as it hits and flows around buildings causes higher pressure on the exterior face of the windward wall than normally exists on the interior face of that wall. Simultaneously, air flowing around a building induces a partial vacuum on the leeward exterior face of a building relative to the

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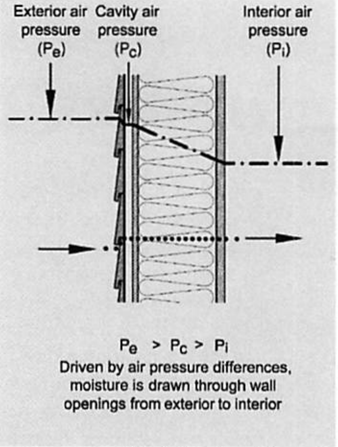
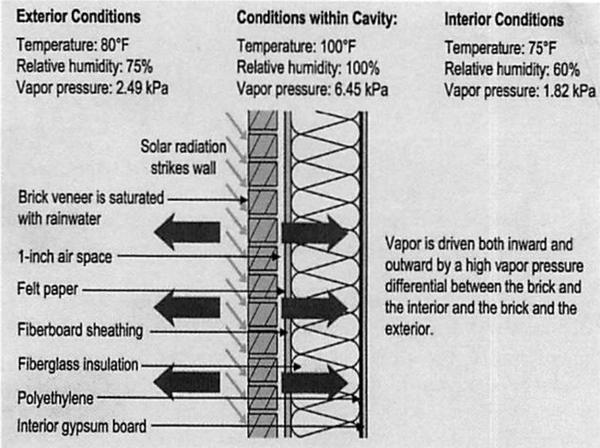
*EIFS is described by professional building inspector Dan Schilling as "a vulnerable surface coating as thin as a soda cracker applied over the top of foam insulation board that has the structural density of a Styrofoam cup" (residentialinspections.com). See also dspinspections.com.

pressure at the interior face of that wall. Wind also induces lower pressures as it flows around corners or over roofs just as it does when it travels over an airfoil such as an airplane wing. Other key sources of air pressure gradients include the stack effect—warmer air rises because of its lower density (think of a hot-air balloon)—and the pressure differences generated by heating and cooling structures with forced air. Forced-air heating and ventilating systems pressurize or depressurize buildings or specific rooms. For example, forced air will pressurize a bedroom that has no return air ducts. The curious sucking sound that sometimes accompanies the opening of a door indicates a depressurized space. Air pressure gradients move moisture if air moves from higher to lower zones. Arrest the air movement and the moisture movement stops, too (Fig. 1).



After Lstiburek and Carmody

1 Air pressure differences alone can move moisture.



J. Lstiburek ©Building Science Corporation, reprinted with permission

2 Solar radiation, vapor pressure and resulting movement of water through wall cavity. 1 kPa (kilopascal) = 20.89 psf.

A less familiar phenomenon, vapor diffusion, is caused by vapor pressure differences (Fig. 2, from Lstiburek 2006). Vapor diffusion is the movement of moisture into and through building materials even without air movement. Vapor pressure is the weight of the water in the air—the more water in the air, the higher the vapor pressure. Vapor will diffuse through a permeable substance, even substances with limited permeability like wood or stone, to equilibrate the unbalanced vapor pressures on either side of the material barrier. In many circumstances, vapor diffusion moves moisture too slowly to contribute significantly to wood degradation.

How moisture infiltrates—the ways All three phases of water—vapor, liquid and solid (ice and snow)—act on structures and should be considered in design. Rain, snow, ice, sprinklers, respiration, heating, washing and cooking provide the water that affects structures and their subassemblies.

Water might enter a wall or roof assembly in four general ways: liquid flow, capillary action, carried on moving air as vapor, and water vapor diffusion (Lstiburek and Carmody 1994). But, in the case of a wood-framed wall, research has shown it might enter in more than a dozen specific ways (Tsongas 2007). Nine conditions, according to Tsongas, cause serious damage:

1. Liquid water wicking up between the laps of cedar siding (this specific species only).
2. Liquid water leaking behind or around siding and trim (e.g., window trim, or corner boards) including through water-resistant barriers.
3. Liquid water wicking into gypsum sheathing behind siding (gypsum sheathing outside the studs—not frequently used by timber framers or SIPs builders).
4. Siding in contact with wet concrete or too close to soil and landscaping.
5. Liquid water wicking into poorly- or un-painted siding edges.
6. Water vapor migrating into wall cavities from inside house.
7. Solar-driven moisture transfer from siding into sheathing.
8. Indoor moisture entry from or through wet (moisture-laden) concrete slab-on-grade floors (or from foundations).
9. Moisture entry into walls from wet lumber.

Rain and gravity drive water more readily into and behind nonwood siding materials such as stone, stucco and brick, depending upon their porosity and coatings. Capillary action and vapor pressure also move significantly more water into and behind these materials and potentially into the sheathing and the wall cavity. Sunlight, by heating wet siding material, creates a vapor pressure differential, which can be as high as 80 lbs. per sq. ft. (Fig. 2). Moisture driven through wood members that pierce the building envelope should be added to this list. Moisture can be driven by all means described, around or through the wood, though condensed liquid water does the most damage. Checks and separations in the seals around the wood result from drying and moisture cycling (shrinking and swelling) even in engineered wood such as glulams, laminated veneer lumber (LVL) and parallel strand lumber (PSL), allowing both liquid and vapor to bypass the building envelope.

Besides being driven in by gravity or rain, liquid water occurs on or within building assemblies when it condenses from vapor (items 6 and 8 in Tsongas's list). This happens in heating climates when warm, moisture-laden air travels from inside the building through the wall assembly. At some point, the building material surfaces are cool enough that the water vapor in the air hits its dew point and condenses out. Alternately, in cooling climates, when warm, humid air travels from outdoors inside the building envelope, it too will eventually hit a surface that is cool enough to condense the vapor to water, usually on the backside of gypsum wallboard. If the flow of humid air in either direction continues for a protracted period of time, and the temperature is conducive to the growth of fungi (greater than 1 degree C or 35 degrees F), decay fungi will attack the wood. If the moisture is being carried on air, stopping the air flow will stop the moisture flow.

Mildews and molds Though they affect human health rather than cause decay, mildews and molds remain on the surface of materials and act to increase the susceptibility of wood to decay. They raise the moisture content of wood and soften the fiber cell structure. (See the previous article.) Molds and mildews form on building materials when the surface relative humidity (RH) rises above 70 percent.

Surface RH should not be confused with ambient RH. Within a conditioned room or insulated wall cavity, the ambient RH may be considerably lower than 70 percent, but at a cold surface such as an outside wall in winter or on the backside of the interior gypsum wallboard of an air-conditioned room, a thin layer of air at the surface of the wall will be above 70 percent or higher. A familiar example of this phenomenon occurs at cold window surfaces that fog or frost within heated spaces.

Weathering and decay Like mildews and molds, ultraviolet (UV) radiation and weathering contribute to wood degradation by making it more susceptible to decay. Although UV and erosion generally result in wood fiber loss of no more than ¼ in. per century, weath-

Expected Strength Loss at an Early Stage of Decay (5–10% Weight Loss) In Brown-Rotted Softwoods

PROPERTY	Strength Loss (% of original property)
Toughness	80+
Impact bending	80
Static bending (MOR and MOE)	70
Compression perpendicular to grain	60
Tension parallel to grain	60
Compression parallel to grain	45
Shear	20
Hardness	20

After W. W. Wilcox

3 Above, strength property loss as a result of decay.

4 At right, generally direct relationship between relative humidity and permeance. Each line represents a particular material numbered in key at top.

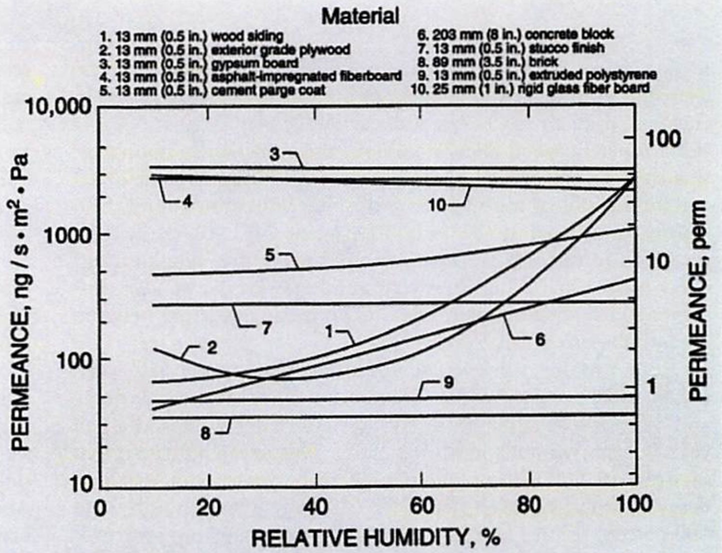


Fig. 2. Plot of permeance of materials versus relative humidity.

US Department of Energy

ering processes cause finish wood and timbers to warp and crack. Photodegradation strips away hemicellulose and lignin and increases surface area and the absorption of water (Williams 2010). These processes create more opportunity for decay fungi.

Of the nonbioagents of wood degradation, water often aids the processes of weathering and erosion. (Fire destroys wood more effectively and rapidly than any other agent, but lies outside our scope.) Water in its several forms plays the leading role in this drama with UV radiation and weathering processes playing minor parts. Limiting exposure to water limits wood's susceptibility to all of the agents and extends its longevity for decades and maybe centuries. (If exposure to water cannot be limited, then other means such as chemical treatment or modification of the fiber can be used to poison the food for bioagents or to increase the physical resistance of the fiber to weathering.)

Health and safety too motivate an interest in wood protection. Wood infected by mildew and decay fungi affects indoor air quality and invites other bioagents such as mites, termites and beetles, which themselves affect human and pet health.

Additionally, insect-ridden wood suffers loss of strength as the wood fiber disappears. Significant loss of strength and stiffness results from even microscopically detectable decay. This fact is poorly understood by builders and engineers (Wilcox 1978, and see Fig. 3).

Timber framers whose designs may depend upon the structural properties of foam-core panels should be mindful that the panels themselves typically rely upon slender, oriented-strand board (OSB) skins 7⁄16 in. thick to carry the building's vertical and lateral loads. Even low levels of decay of these wood-and-glue skins, often unseen within a wall or roof assembly, impair the panels' ability to carry design loads and thus the building's performance.

Moisture that drains or collects on OSB from poor construction such as improper flashing or improperly installed water barriers most often causes decay and structural degradation. Even very small holes allow a significant amount of water to drain, and unless the wall can dry in a reasonable time frame, decay and strength loss will occur. Decay ultimately turns OSB to an oatmeal consistency.

As is the case with all vapor and air flow-control technologies—and panels should be considered one such technology—panels must be properly installed to avoid moisture issues. The OSB skin provides excellent barriers to air flow, and thus to moisture borne on air. Vapor permeability** of OSB ranges from 1 to 10 perms, increasing with increasing relative humidity—changing vapor categories from semi-impermeable to semipermeable. Most foams, however, are categorized as impermeable to semi-impermeable, only allowing vapor to diffuse very slowly (Fig. 4).

While unbreached panels do not themselves experience moisture problems, the connections at their perimeters or holes cut in them, if not properly configured and sealed, permit moisture-laden air flow. Panels are connected in a variety of ways, some inherently difficult to configure properly. Where OSB splines are used in panel-to-panel connections, sealing the two foam faces with expanding foams generally performs very well. When solid lumber or engineered wood splines are used, however, sealing is more difficult and more likely to fail. First, there are now two foam-wood faces to be sealed—one on either side of the wood. Second, wood is susceptible to checking that may provide direct avenues for air and moisture flows through the wall system. And third, since it is hygroscopic, wood absorbs and desorbs moisture reacting to the relative humidity of the surrounding air. Shrink-and-swell cycles may lead to failure at the interface of wood and sealant, providing moisture flow paths.

When panels are installed against green timbers, significant timber movement as it dries can also cause failures at a sealant-wood interface. This is much more likely with relatively high-shrinkage species such as oak than with lower shrinkage species such as Eastern white pine. Timbers in timber frames, unless they pierce the wall or roof and are exposed directly to moisture, generally do not suffer significant decay before the problem is noticed. But the timber frame and panel structural system can be compromised, particularly when panels are engineered to be the lateral resisting system for the timber frame, or in hybrid systems where panels also support horizontal timbers on the exterior walls.

Durable building The key to durable framed buildings is to keep moisture out of the wood. Though measures may be taken that minimize or eliminate wetting exposures, it is not always possible to keep moisture out of wood; it will find ways into the walls and roof assemblies. Designers and builders are wise to expect this eventuality and to construct buildings that dry quickly when water intrudes. They must recognize that wood takes much longer to dry than to wet. Like clothes that get wet in an instant and take hours

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**Vapor permeance measured in perms is defined as the rate of transfer of vapor through a material. Brick veneer is permeable at 40 perms (category *vapor permeable*) whereas 6 mil polyethylene is permeable at 0.03 perms (category *vapor impermeable*). One US perm = 1.0 grain/sq. ft./hour/inch of mercury (7006 grains = 1 lb).

to dry absent significant applied air flow or heat, wood can be wetted in minutes and take weeks or months to dry, particularly in enclosed, dead air spaces like wall cavities (Easley 2010).

Fortunately, wood decay does not start immediately upon wetting. It does not occur below 20 percent moisture content (MC) and for most fungi must be above the fiber saturation point (FSP), usually considered to be near 30 percent MC. (A devastating exception to this rule is *Meruliporia incrassata*, the "house-eating" decay fungus that brings its own groundwater to the wood it consumes.) Little documentation exists on decay occurring between 20 and 30 percent MC levels.

Recent testing, however, demonstrated that even at MC levels as high as 26 percent, OSB and hemlock did not show visible decay and did not lose strength or stiffness even after three and a half years (Clark, Symons and Morris 2007). This research suggests that moisture in liquid form might need to be present for incipient decay in wood building materials. (At normal temperatures and 100 percent relative humidity, the equilibrium moisture content is less than the FSP.) Even at 40 percent MC, OSB and hemlock did not exhibit any loss of strength until after 21 weeks, suggesting that at least some woods must be exposed to liquid moisture for an extended period of time for decay to initiate.

Barriers to water in its several forms must deflect or drain water to eliminate opportunity for wood decay. And, accepting the inevitable failure of wall and roof water barriers, good design allows wetted wood to dry out rapidly enough to limit decay potential.

Keeping moisture out: good design and construction Good design protects wood by minimizing its exposure to the physical and biological agents that would return it to its constituent elements. Others have noted that well-designed structures—structures that serve their inhabitants well—are loved and, being loved, are well treated and maintained. Certainly, vernacular architecture constitutes an excellent source of ideas for protecting wood and achieving longevity. Research into the morphology of vernacular wood-protecting building techniques suggests that climate rather than geography drives their use (Aho 2007).

Durable buildings, whether of wood or other materials, are protected from water. Design starts with quickly draining away the water to which a building is exposed. "The fundamental principle of water management," according to Lstiburek's *Water Management Guide*, "is to shed water by layering materials in such a way that water is directed downwards and outwards out of the building or away from the building. The key to this fundamental principle is drainage. . . . Drain the site, drain the ground, drain the building, drain the assembly (e.g., the wall or roof), drain the opening, drain the component (e.g., door or window), and drain the material." Simplifying this fundamental if perhaps self-evident principle, we might intone, "Drain, baby, drain."

Steve Easley, in *Moisture Control in Commercial Wood Buildings* (2010), proposes another comprehensive strategy that he calls the Four Ds of moisture management: Deflection, Drainage, Drying, and Durable components.

Easley uses the word "deflection" rather than Lstiburek's "drain" for the redirection of water that strikes the building directly, and "drainage" to describe removing water or moisture that succeeds in getting into building assemblies. Both authors accept that water cannot always be prevented from entering a structure and recommend draining the water that bypasses the defenses, as well as providing means to dry wetted components.

The roof of any structure constitutes the first defense. A Chinese symbol for *building* consist of two characters, one that represents *shield* and another *roof* (Aho 2007). Arguably, this describes the minimum requirements for a human shelter: shelters without walls are common (pavilions), but few roofless structures feel like shelters. As their primary purpose, roofs provide protection from precipitation and UV radiation. Besides shielding UV radiation, roofs redirect rain (or hold it for later draining if in the form of snow or ice), deflecting it away from inhabitants, their possessions and the building itself, particularly the roof's support structure.

Aho's studies of vernacular architecture and its literature demonstrate that culturally and geographically separated builders used very similar roof designs in similar climates, and that climate more than culture drove the development of building styles.

For drainage, the three variables of roof design are roof pitch, roof style and length of eaves. Researchers noted that roof pitch increases with increasing local precipitation whether in the form of rain or snow. In regions closer to the equator in such widely disparate places as the Mediterranean, Latin America and China, roof slopes tend to be low. In their more northern counterparts, roof slopes increase, signaling the local need to shed more rain or snow. Aho suggests that the increasing popularity of the gambrel roof beginning in the mid 17th century in New England, New York, New Jersey and Pennsylvania can be explained by its greater tendency to shed rain and snow from the steep lower pitch.

In coastal areas, however, even in northern latitudes with heavy precipitation, low roof slopes predominate to limit wind loading, minimal when bearing on 20 to 25 degrees of pitch.

Designers cannot always orient a building ideally because of zoning requirements or other site considerations, but when possible should limit the exposure of the building to the weather and the summer sun and maximize exposure to the winter sun. When designing the roof or the rooms below the roof, designers should consider reducing roof complications on the sides most exposed to weather and summer sun.

Though not currently fashionable, simple building shapes such as local archetypes with their roofs of little complication deflect water and weather most effectively. Breaks in planar surfaces such as valleys in roofs and corners in walls not only cost more time and money to build, such discontinuities also create greater opportunity for envelope failures, allowing energy and moisture to move more freely into and out of the structure. In particular, closely spaced dormers faciung away frim the sun in wet and cold climates challenge the building envelope with water, snow and ice, and with little drying potential.

Eaves protect buildings in two ways: they deflect rain that would otherwise strike the walls and they divert water some distance away from the foundation. P. Roy Wilson writes that the overhangs of the Québecois pavilion roof grew from 9 in. in the mid 17th century to 36 in. by 1720 (Wilson 1975). And Les Walker reports that Tidewater cottages first built in the southeast US around 1680 had little eaves projection, but that early in the 18th century the projections developed into south-facing porches that protected the building from wind-driven rain as well as solar gain (Walker 1981).

Eaves drain water off the roof and away from walls, but this falling water may splash the wall or drain back toward the building's foundation unless collected and diverted. (Drain the site.) Of course, properly sized and sloped gutters at the eaves provide the means to collect this water and redirect it down and away from the building, using downspouts, splash blocks and foundation drains. (But flora growing from the gutter is not a good sign.)

Shed roofs are easiest to build but, with one wall mostly unsheltered, do not protect a building as well as gable roofs. Hip roofs protect walls better than gable roofs, as well as spreading roof load on much more wall length. Hip roofs and hipped gables reduce or eliminate otherwise tall gable walls, making buildings less susceptible to wind-driven rains (Aho 2006). Certainly, the thatched, hipped-gables of Eastern Europe better protect gable-end walls by putting water-deflecting eaves over them.

In Louisiana plantation houses of the 18th and 19th centuries, the porch wrapped all the way around the house, shielding the walls from most wind-driven rains. Adding a belvedere to the roofs of these structures also promoted their cooling and drying. The induced stack-effect of air drawn into the building via the porches and then upward through the belvedere conferred comfort as well as adding drying potential and thus durability.

Vernacular architecture such as Tidewater cottages demonstrates an important means of protecting wood from the rising damp: raise buildings off the ground. Wood floor framing, if close to wet or moist soils, suffers from decay and from insect damage. Raising the structure allows ventilation of the floor framing, reducing the potential for both, particularly in the South.

Even for buildings in less humid climates, good design dictates a first-floor height well above the landscaping level, to ensure that groundwater splashing from rain or sprinklers does not strike the wall siding or that bushes and other plantings do not deflect or hold moisture against it. Water upwardly directed from these sources may well find an easier path into the wall assembly. The designer should also consider the potential for snow accumulation around a structure or a structural element such as a post. Water from snow readily wicks into wood end grain or siding edges, or into timber and lumber checks or cracks, thoroughly soaking the wood during the day and possibly freezing during the night. Significant damage from freeze-thaw cycling, not to mention moisture cycling, can lead to water infiltration, damage, decay and premature wood failure.

When structural elements are intentionally exposed to the elements as in overhangs, walkways, trellises, galleries and porches, designers should make every effort to hold structural wood back from the eaves edge, allowing the roof surface to extend beyond the structural wood in both horizontal directions (Billups 2010). Where possible, wood should not be exposed to direct UV rays when the sun is high in the sky. A projection of a given member's exposure to direct overhead sunlight through the year will indicate how it can be protected by an extension of roof eaves or by an angled end cut. (It is seldom structurally necessary for a joist, purlin or rafter to extend fully to the edge of the eaves.)

The tactics, then, are to hold the member back from the edge, taper the main carrying member toward its end and consider cutting the end on an angle that reduces its exposure to rain and keeps it in shadow for a large part of the time when the sun is high. As does limiting wood's southern exposure, limiting its exposure to only the long UV rays in early morning or late afternoon reduces the potential for UV damage and reduces the likelihood of it being struck by wind-driven rain.

Designers and builders should make every effort to cover end grain and ensure water is not shed on exposed wood members such as rafters, joists, braces and struts. Besides metal end caps, sacrificial wood end caps may be added to flat or pitched members to limit the decay. Caps, unless glued on, can be easily removed and replaced when they degrade. Some glulam manufacturers glue side-grain caps on the ends of exposed members. Though effective in forestalling degradation, glued end caps may make maintenance more difficult, undermining their purpose.

A special challenge to the designer is the shed or butterfly roof with exposed, downward sloping, wall-piercing timber rafters. Usually supporting large protective overhangs, sloping rafters, whether solid sawn or engineered wood, can drain water into and beyond the wall through separations between the rafter and the wall or directly through the rafters internally via checks and cracks. Cracks and checks can open long after construction, created by drying of the timber or moisture cycling. A surprising amount of water, gallons per minute, can drain through very small holes (Easley 2010). Though large overhangs and lower pitched rafters diminish water drive, there is no perfect design solution to this problem. Exposure should dictate use or avoidance of the design.

Connections Care should be taken with exposed pitched wood members that terminate at a vertical surface, such as a rafter terminating at a post, an outrigger brace abutting its vertical strut or a kingpost truss with angled struts. Water will run down and accumulate at the connection on the upper surface of the inclined member and wick into its end grain. If the connection is by mortise and tenon, water will drain into the mortise of the vertical member, creating conditions for decay in both members. If the pitched member is painted or well sealed, the required drying time may be long for any water that intrudes into a crack or the end grain.

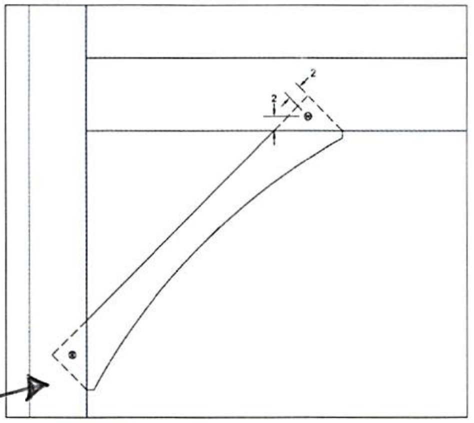
Water can be caught or can wick between tightly spaced or in-contact members exposed to bulk water. When possible space members to allow water to drain between them. Horizontal or pitched members sitting on top of posts should be significantly wider than their supporting posts so that the lower corners of the horizontal member form a natural drip edge allowing water to separate from the timber. If a timber post or strut supporting an open-air pavilion must pierce the roof, the designer should consider stopping the roof well short of the piercing member and flashing the opening. The opening at the timber will allow more water to drain directly down the timber through the pavilion, but water will be less likely to intrude into the roof assembly or the timber itself if the opening is properly constructed (Billups 2010).

Fastened connections present another challenge for the designer. Bolts and other metal connectors catch and hold water, often right against the wood. Exposed saddle connectors for horizontal members should be avoided. Even if equipped with weep holes, dirt and debris can clog the holes and turn the saddle into a bucket. Flat steel plates on the surfaces of timbers hold water against wood, too, whether from rain or condensation. Bolted connections (with or without steel plates) can wick water into the wood or can expose the wood interior to wind-blown rain when green timber shrinks and the steel plates, washers, nuts and bolt heads are no longer tight. (Bolt-hole drill sizing should always meet *National Design Specification for Wood Construction* requirements, but making sure the holes are not oversized for an outdoor structure is particularly important for wood protection.) Undermining even the best efforts, checks often occur at or near bolts and other connectors, providing deep ingress for bulk water.

Using dry material—seasoned solid-sawn timber, glulam, parallel strand lumber or laminated veneer lumber—reduces but does not eliminate the potential for water intrusion. Use of malleable washers on bolts in dry timber will go a long way to eliminate ingress, however. Countersinking and plugging holes to cover bolt heads and nuts, another tactic, reduces the capacity of a connection because effective widths of side members are reduced, possibly forcing the designer to use a larger timber, so the practice is not often specified commercially.

Slotted-in knife plates can be an excellent connection choice, particularly if the plate enters the wooden member from underneath. Because bearing on the perimeter edge of the plate is not typically a consideration, the slots can be configured to drain. The slots also should be large enough to accommodate timber movement and avoid water surface tension. If the knife plate includes an additional bearing plate welded on at right angles, the designer should ensure that the steel bearing surface is narrower if below the timber or wider if above it, and sloped to drain water that otherwise might intrude.

Hidden connectors such as mild steel shear plates and split rings should generally be used only in covered structures and have upper surface protection from water intrusion. Structural screw connections, especially if stainless steel, provide a good option for exposed



Mack Magee

5 Draining brace mortises for exterior use.

timber connections. As long as screws are not countersunk to any extent (unless plugged), there is little opportunity for intrusion.

Epoxy connections should be avoided unless it is known that moisture cycling will not be significant. Over time, shrinking and swelling of timber fibers around an epoxy-fiber interface will degrade connection capacity.

Pegged mortise and tenon connections, particularly if in a durable species, typically fare better in wet environments than ferrous connections. The dry pegs are squeezed by the seasoning shrinkage of surrounding wood at the connection. Vertical mortise lower ends, however, typically flat or inwardly sloped surfaces, become exposed and accessible when girts or plates shrink up toward their peghole centers. Water then drains or is blown into the lower end of the mortise, whence it cannot drain. Braces and struts drain a significant amount of water into their mortises, exposing the post and brace to decay. Sloping the bottom of brace mortises to be perpendicular to the brace axis, though in some cases more difficult to cut, allows the mortise to drain but does not diminish the capacity of the connection (Fig. 5).

For horizontal members, creating large-enough shoulders at the top and bottom of the tenon (how much is species dependent) reduces though does not eliminate the exposure of the mortise. A drying, shrinking post pulls away from the horizontal member exposing end grain and the mortise perimeter to bulk water intrusion. Sloping the bottom of the mortise is not recommended unless using a wedged through-tenon, in which case the sloped mortise bottom can drain. Open-air structures, more readily than enclosed structures, can be designed with orthogonal members meeting posts at different elevations, allowing opposing wedged through-tenons with caps on the exposed tenon ends. Dovetail and other blind tenons, particularly in green timber, will not fare well in wet conditions. After the timber shrinks, water drains into the gaps and soaks the end and side grain of both members.

Post bottoms The usual objective applies: to drain water down and away. And the tactics remain the same: keep the bottom of a post as far as practicable from exposure to snow, puddling and splash, and drain water off wood surfaces as quickly as possible. Set posts on pedestals significantly above rain splash and snow lines. Keep a post, like a rafter end, as far from the edge of the eaves as practicable. A post, unless pressure treated, should not sit on concrete. Setting the post on stainless, galvanized or otherwise properly coated steel minimizes the potential for degradation and decay.

At times, setting a post on a pedestal of a famously durable species (greenheart for example) or preservative-treated wood will work if the water that reaches the pedestal is also drained away quickly so that it and the post end can dry quickly. This arrangement should not be used in wet exposures unless little water is expected to strike the pedestal.

Keep the bearing surface at the bottom of a post smaller than the post section and slope the bearing surface when it makes engineering sense. Mortise any steel bearing surface (such as a knife connection, with or without a bearing plate) into the post bottom to keep the surface from exposure. Leave sharp edges at the post bottom cut—do not chamfer the cut lest water crawl around to the end grain of the post—and gap the bottoms of doubled members so that water will drain between them.

A post connection to a foundation is subject to the same moisture hazards as all other connections. Design connectors in a single row with the grain and, when this is not possible, minimize the spread of the bolts. Because of their greater exposure, post bottoms cycle moisture more frequently and to a greater degree than other members in open structures. This can cause post bottoms to split if bolts unduly restrain their swelling or shrinking. Assume the timber will shrink and swell with varying humidity and UV exposure and ensure that any mortise or slot for steel is large enough to accommodate the resulting movement.

Primary defenses: caps and flashings Good design makes extensive use of caps and flashings, which can form a primary line of defense against water intrusion. They deflect water away from wood members, siding and wall and roof assemblies, and they have sharp edges that readily shed water. Caps embody the important if obvious principle that a sloping surface sheds water away and down.

When capping is deemed unacceptable, such as on flat or pitched rafters in a trellis or open pergola, the designer can specify 15-degree flat slopes or hip backings for top surfaces. Sloping surfaces offer a simple approach to extend wood longevity. The wall plates of open-air structures should be sloped as well to shed water and ideally include sloped birdsmouth seats (this fabrication challenge will be worth the effort). Convention dictates that top surfaces of all thresholds and sills be sloped 15 degrees to shed water away and down and that all window and door head casings be protected by projecting drip caps pitched at 15 degrees (and back-flashed). Builders should avoid nailing into the top surfaces of caps where dimples or dents lead to water intrusion.

For exposed posts, the designer should use caps to protect wood from direct water intrusion. Wood end grain should not be exposed to direct wetting. Water that soaks into end grain can accumulate and keep a timber wet for an extended period of time. The moisture cycling works to prematurely weather the wood and creates checks and cracks for decay. Top caps should be noticeably larger than the post section and fabricated with sharp vertical edges to allow water to separate cleanly and drip off without running back toward the post surfaces.

When using metal caps to protect the top surface of horizontal or vertical wood members, designers should consider the tendency of water to condense on the metal surface in contact with the wood. In temperate, wet climates, narrow pressure-treated spacers or furring can be added between the metal and the timber to admit air flow and reduce condensation leading to decay. Copper and lead caps and flashings, unlike aluminum, also discourage decay because of the toxicity of their leachate, though the latter may stain nearby wood.

Flashing of openings plays a critical role in limiting water intrusion into walls, roofs and foundations, and draining water down and away from building surface components such as windows and doors. Tracing how water flows defines how to layer flashing and how it should direct water. Proper flashing includes the layering of water-resistant membranes, each layer successively moving water farther away from the building and down. Building papers, the last line of defense before the wall and roof assemblies and typically up against the sheathing, should generally be draped over the all-important flashing which then directs water away from the building. The final layer of flashing should direct the water at a downward angle away from the building and include a sharp drip edge.

Flashing basics may be simply summarized, but are no simple matter. For wall and roof openings alone, ASTM International offers the excellent *Standard Practice for Installation of Exterior Windows, Doors and Skylights* (2007), an 89-page document with no fewer than 147 defined terms to guide a builder. Of course, there are any number of circustances in building construction. (See the posted version of this article at tfguild.org/woodprotection.)

Poor flashing leads to many construction failures, some of which result in serious building damage and lead to structural collapse and injury. (Improperly flashed and maintained ledgers on an elevated deck represent one scenario where decay can lead to serious structural damage.) Flashing failures often seem obvious after the fact—"tucking your raincoat into your underwear"—yet they occur with surprising frequency (Easley 2010). The reader is encouraged to review at least the building construction guides included in the bibliography.

Secondary defenses: skilled construction Easley's admonitions to drain and dry once water intrudes past primary defenses such as flashings, or once vapor infiltrates, fall to construction practice. Given that moisture will get into wall and roof assemblies, the builder had best provide the means to drain it out of the assemblies and components or to allow enough air flow to dry the wood and the other building materials when wetted.

The best means for draining and drying wall and roof assemblies is the construction of screen assemblies to provide a second layer of moisture management. Historically, masonry walls are the best example of screen construction. The siding material of brick or stone is separated from the load-bearing components, whether wood frame or more masonry, creating an air gap. This gap not only provides a separate, internal drainage plane but also provides a capillary break and a drying channel.

Screen construction for wood wall assemblies has proved effective in improving building durability. Furring strips are often used to set siding off sheathing; for the gap to function, it need be only a minimum of ⅜ in. Brick and stone gaps are usually an inch. Bulk liquid driven through or around the siding will drain down this plane and out the bottom of the gap, redirected down and away from the building by flashing installed at the bottom of the wall. The gap's relatively large size short-circuits capillary action. Additionally, if air is allowed to enter this cavity from below and to vent at the eaves height, the stack effect–induced air flow dries the materials.

The gap also reduces vapor diffusion. Recall that vapor pressure, vapor diffusion's driver, is the amount of the water or vapor in the air. In the case of a wall sheathed and sided in wood, solar radiation drives moisture absorbed by the siding behind it, significantly increasing vapor pressure. Vapor can diffuse into the sheathing layer and then into load-bearing components of the wall. But drier air flowing into and up through the gap flushes the vapor, reducing the vapor pressure and diffusion.

Roof screens function similarly, though they require a second layer of sheathing as a nailing surface for shingles, shakes or tiles. Herringbone or diagonal furring, or other batten systems with openings to the eaves, have been used instead of solid sheathing to create drainage planes under metal standing-seam roofing.

A critical component of any screen is the building paper installed over the wood sheathing. Historically, a tar paper or asphalted felt membrane functioned as a water barrier under siding or roofing to drain water that managed to get under the finish. Over the last 30 years, these papers have gone through several generations, with mixed results. Sold variously as air, moisture and vapor barriers and retarders, at times their use has proved problematic, ironically in part because of their effectiveness. Water, in liquid or vapor form, may flow into a wall or roof from inside or outside. An effective barrier against these inflows, if breached in one spot, can limit outflow elsewhere. In such a circumstance, water accumulates and, if in sufficient anounts, leads to degradation and decay, often unseen.

If a vapor barrier on the inside surface of gypsum wallboard is installed imperfectly, airborne moisture flows into wall cavities around tears or breaches, condensing and creating potential for decay. Reversal of the expected vapor flows, such as during summer cooling, also traps water inside cavities on the backsides of barriers. Likewise, vapor barrier wraps installed on the exterior walls capture moisture driven through breaches or from interior moisture-laden air flows, and hold the water against the sheathing, promoting decay. Effective barriers to vapor flow do not allow the underlying components to dry.

Some manufacturers produce and sell vapor *retarders*, as opposed to vapor barriers, recognizing the need to allow vapor to pass albeit slowly. However, in cold climates and in some wall assemblies, there may not be enough solar gain to evaporate the moisture under the retarder or drive it through, particularly on elevations of buildings facing away from the sun. Standard building papers like No. 30 (formerly 30#) felt possess higher permeability, which actually increases the wetter they get, raising their drying potential above that of more-recent products. Used in two layers, the wrinkling of the paper after moisture cycling can actually create drainage planes on its own. —MACK MAGEE

Mack Magee (m@ftet.com) is a principal at Fire Tower Engineered Timber in Providence, Rhode Island. This is the second of two articles. It appears in original, unedited form, with many additional illustrations, at www.tfguild.org/woodprotection.html.

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