Professional Affairs

HOW TO KEEP YOUR AWARD-WINNING BUILDING FROM ROTTING[1]

Allen F. Rosenberg
Overstreet and Rosenberg, Architects and Planners, San Francisco, CA 94105

and

W. Wayne Wilcox
Forest Products Pathologist and Professor of Forestry
University of California, Forest Products Laboratory, 47th and Hoffman Blvd.
Richmond, CA 94804

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ABSTRACT

The subject is introduced with a review of the types and extent of deterioration that can occur in wooden buildings with moisture problems, along with a discussion of the biology of decay fungi and the effects of decay on wood. Actual case histories of failures or damage due to water infiltration are presented representing problems in design or construction involving aluminum windows, plastering, flashing, roofs, membranes, etc. The importance of determining and designing for pressure differentials is stressed. Both the basis and results of problems associated with use of green wood in construction are examined. The dangers of soil contact and the necessity for controls on designs to establish proper finish grades are dealt with. Finally, design details and procedures for keeping water out of buildings are specified for such problem areas as: wall penetration and roof flashing, membranes, sealants, cement plaster and "miracle" materials.

Keywords: decay, water infiltration, building failure, design, construction.

THE PROBLEM

There is a high-rise building in Boston, for which the architect was given a gold medal by the AIA, that has been shedding glass for several years. The Kemper Auditorium won the highest honor the AIA has to confer, and its roof collapsed. Many similar examples can be cited. The point is, in recognizing excellence in design, the architectural profession appears to assign little priority to the workability and structural integrity of the building after it is built. Of course, it shouldn't be absolutely necessary to make your building fail, collapse or decay in order to get an award; it's preferable if none of those things happen—except the award, of course.

Unfortunately, few people ever hear about the hundreds and hundreds of low-rise wooden units, many of which also win awards, that have reached moderate to advanced stages of decay because of leaks or other moisture problems caused by inadequate design or construction. One example is an award-winning college complex in Santa Cruz, California, consisting of wood-frame buildings with cement plaster exteriors. They look beautiful from the outside, but when we opened them up, we found that the plaster appeared to be supporting the buildings be-

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cause the wood frames were so decayed after only eight years that they couldn't do it alone. We encountered similar problems in a group of condominiums in Diamond Heights, San Francisco. There, a wood deck was integrally connected with the main structure and allowed to extend well beyond the roof line without adequate moisture protection. The balcony rotted and carried water and decay back into major support beams holding up the entire structure. Of course, it is not only wood that is attacked by water infiltration. Water infiltration in reinforced concrete buildings can set up an oxidizing process in the reinforcing steel causing the concrete to spall off. Most people don't realize how prevalent this problem is. Frequently buildings are covered by exterior coatings such as cement plaster, and one doesn't see the deterioration until there is a failure making it necessary to tear into the building. We encountered a serious problem of this nature in a fairly new building at the University of California's Medical Center in San Francisco, where trimmer bars on eyebrows were placed with insufficient concrete covering. The United Airlines maintenance facility in San Francisco looked great from the outside when we went to inspect it, but when we got inside we found that inadequate provisions for thermal movement had caused such massive cracking that the building flooded when it rained. Fortunately, unlike residential structures, this building had no interior finish that could have made detection and diagnosis considerably more difficult.

WHAT HAPPENS WHEN WOOD GETS WET?

Wood is a biological material. It is our only construction material that comes from a renewable natural resource. Trees grow and when used replace themselves. As a biological material, wood is also subject to biodegradation or decay. When this process occurs in the forest, we think of it as "good" because it prevents excessive buildup of fuel for uncontrolled wild fires and miscellaneous garbage that would make the forest floor unsightly and impenetrable to us; it also functions in the nutrient cycle that keeps the forest healthy and growing. However, when this same process occurs in a structure that we have built from this wood, we label the process "bad" because it is destroying what we have built. It does no good to ignore the process of decay, for it will go on whether we ignore it or not; therefore, in order to use wood adequately in structures, we must understand the nature of decay and how to prevent or control it.

A number of woods have what is called natural decay resistance, that is, their heartwoods have some native ability to withstand the attack of decay fungi (Table 1). Redwood and the cedars among our domestic woods used in buildings are good examples of this. Note that it is only the heartwood, and not the sapwood, that may possess decay resistance and that there are a number of species we use frequently in construction that have little or no decay resistance. For these species to be used effectively in structures, decay must be prevented by some source other than the natural properties of the wood itself. Decay is caused by fungi in the group called Basidiomycetes, related to the common mushroom, and they have four requirements for carrying out decay: air, water, favorable temperature, and a food source. Of course, in this case, the food source is the wood itself. Decay fungi invade their substrate in the form of hyphae that grow at the tip, branching and ramifying through the wood. They secrete enzymes that actually dissolve the wood substance, resulting in total destruction of the wood cell

TABLE 1. *Relative grouping of some U.S. domestic woods according to heartwood decay resistance based upon laboratory tests and field performance. (From USDA Agriculture Handbook No. 72, Wood handbook: wood as an engineering material, 1974, Table 3-10; by permission.)*

Resistant or very resistant	Moderately resistant	Slightly or nonresistant
Baldcypress (old growth)[1]	Baldcypress (young growth)[1]	Alder
Catalpa	Douglas-fir	Ashes
Cedars	Honeylocust	Aspens
Cherry, black	Larch, western	Basswood
Chestnut	Oak, swamp chestnut	Beech
Cypress, Arizona	Pine, eastern white[1]	Birches
Junipers	Southern pine:	Buckeye
Locust, black[2]	Longleaf[1]	Butternut
Mesquite	Slash[1]	Cottonwood
Mulberry, red[2]	Tamarack	Elms
Oak:		Hackberry
Bur		Hemlocks
Chestnut		Hickories
Gambel		Magnolia
Oregon white		Maples
Post		Oak (red and black species)
White		Pines (other than longleaf, slash, and eastern white)
Osage orange[2]		Poplars
Redwood		Spruces
Sassafras		Sweetgum
Walnut, black		True firs (western and eastern)
Yew, Pacific[2]		Willows
		Yellow-poplar

[1] The southern and eastern pines and baldcypress are now largely second growth with a large proportion of sapwood. Consequently, substantial quantities of heartwood lumber of these species are not available.
[2] These woods have exceptionally high decay resistance.

walls. No one who can reach into his wall and pull out a piece of wood that crumbles between his fingers needs technical assistance in diagnosing the fact that he has a decay problem. However, the frightening thing about decay in structures is that most of the strength of the wood is lost in such early stages of decay that the decay can only be diagnosed with accuracy under the microscope. For this reason, the difficulty of detection of loss in strength in early stages of decay—as well as the waste of wood and labor involved—decay must be prevented from occurring in buildings.

SOURCES OF WATER INFILTRATION

One of the most important considerations in keeping water from infiltrating wooden buildings is the detailing of areas where horizontal and vertical surfaces meet. Flashing must be properly laid out and shingled and the joints soldered if metal. The common treatment for an inadequate flashing job is just to smear it up with some kind of miracle goop. Such substances will usually dry out within a year and provide a perfect conduit for water directly into the structure. Some of the best examples we've seen of the disastrous results of improper flashing were found in those award-winning campus buildings in Santa Cruz. Flashing simply cannot be detailed without turning the corner. If the flashing is allowed to terminate flush with an adjoining structure, the inevitable result is decay beneath. Flashing around masonry, such as chimneys, should be installed raked into the brick grout joints and stepped down the slope in shingle fashion. An unfortunately frequent alternative to proper flashing detail is reliance on a tube of something. One of the least understood mistakes in modern construction is improper use of sealants. There are many kinds of sealants and most make all sorts of claims. But in addition to the properties of the sealant, one must take into account the materials to which it is going to try to adhere, whether it is polysulfide, urethane, silicone, acrylic, or whatever. Important properties include elasticity, hardness, curing time, and "memory" characteristics. Frequently, when dissimilar materials come together, there is a difference in their characteristics either in terms of their thermal interaction or their shrinkage and curing properties.

Another common source of water infiltration is the design concept of the window wall and wide expanses of glass. A common source of problems is that glass will migrate out of its frame. Glass, if not installed properly with setting blocks and side blocks, will tend to migrate because the difference in thermal coefficients between the aluminium and glass is approximately 2.65 to 1. To stabilize the whole assembly, one must wedge the glass in thoroughly.

Water can also migrate on the underside of an overhanging projection back into the frame of the building. This particular condition requires exceptionally good attention to the detailing and flashing conditions. Indoor/outdoor carpeting has made living on balconies a great pleasure for many people who live in condominiums and apartments. But it acts as a sponge. When the rain hits, it absorbs the water and holds it. If there's any source of infiltration available, you can be sure it is going to get in if it is retained long enough.

Roof membranes are the first line of defense against rain water. The whole idea of a roof is to shed water. This, of course, doesn't say much for flat roofs; all that's needed for failure in these is one pinhole. But built-up roofs aren't the only kind with problems; we find failures in some of the more traditional types too. Very often buildings are designed with dead-flat roofs for reasons of economy. The problem is that at the center of the span of the structural members some deflection undoubtedly will occur. This will cause ponding of the water, and as the water ponds, the deflection will increase because of the greater weight. This deflection also will flex the membrane and have a tendency to rupture it.

One of our newer architectural idioms is the tight eave or clipped eave detail. There should be nothing wrong with such a detail if the architect pays attention to what's happening at the edge. However, if the roofing material inadequately overhangs the edge, water can curl under and enter the roof decking or stud cavity. Membranes under raised decks must be properly terminated. In one case the membrane of a balcony stopped abruptly at the facia and there was no consideration for flashing to direct the water away from the structure. The result was severe decay of the beam supporting the balcony. One of the poorly understood phenomena of water infiltration is that under wind-driven rain conditions, there is a pressure differential buildup with positive pressure building up outside the building and negative pressure inside. While it is frequently thought that water is blown in whereas in many cases it is, in fact, sucked in by the negative pressure. When we test buildings to locate the points of infiltration, we simulate these conditions. This involves destructive testing in which the interior finish is peeled away from around the window or other suspect locations. Often it is difficult to tell whether the water is infiltrating through the window assembly itself or through the connection between the window and the structural frame of the building. Storm conditions are simulated by using a 5-hp exhaust blower to draw the room down to the negative pressure. Prior to doing this the room is sealed off, and a door to a corridor is removed to allow installation of a plywood template cut out for the exhaust hose. The room then is drawn down to various degrees of negative pressure while water is sprayed from hoses on the outside. In one case, a low-rise wooden condominium group in Tiburon, California, there was infiltration below the aluminum window frame assembly adjoining the structural frame as well as through the glazing in the aluminum frame itself. Fortunately, such a combination is unusual. In this instance we were in the process of setting up our equipment and testing to see if we could draw the room down to negative pressure for a water infiltration test, when, to our surprise, water started coming in everywhere. It had rained the night before and there was a thin film of water on the balcony, but that was sufficient to thoroughly flood the interior just in the process of testing our equipment. The structure was so loose that water not only came in under the sliding door to the balcony but also directly through the wood frame adjacent to the door. Interestingly, despite these severe moisture problems, the last of these condominiums sold for $295,000.

Clearly, there are a number of ways in which water may enter a building. Water is the key to wood decay in structures! Normally the other of the four factors (air, temperature, and food source) are not limiting to decay fungi in a structure. One of the major criteria involved in the designing of structures built by man throughout history is the shedding of water. If water can be kept from wetting wood in a structure, the wood will simply never decay. However, once water has infiltrated, particularly if it is trapped and not allowed to leave the structure, decay is the inevitable result. Frequently the coverings we put on the outsides of buildings (for example, stucco) are so concealing that we are not aware that serious decay problems may exist in the structure beneath. Decay caused by water infiltration from rainwater is probably most likely to occur in roofs and walls. And again, the most likely site for advanced deterioration is where water moving within the wall structure becomes trapped and cannot go any further. If the foundation and sill are not sufficiently higher than the outside grade, rainwater that puddles on outside surfaces may run into the interior of the structure and cause interior decay problems.

Roofs, of course, are the first line of defense against the infiltration of water into a structure. Roofs, and the roof covering material, must be adequate to the task and always kept intact so that they may shed water adequately. If the roof of a structure leaks, there may be little hope for the remainder of the building. Placing vapor barriers in structures, particularly in the roof, may be hazardous in locations where there is substantial flow of water vapor from the inside of the building to the outside. Such a barrier will prevent exchange of water vapor causing the water to condense on wooden members in the interior of the structure leading to decay and structural failure. Wood exposed to weather requires special protection. If not adequately covered and separated from the main structure, decay that starts in the exposed portion may extend to major structural elements of the building and constitute a life hazard.

IMPORTANCE OF CONSIDERING WOOD PROPERTIES IN DESIGN

Beside the fact that it decays, wood has other properties affecting its performance in structures of which the architect must be fully aware in order to avoid designing a disaster. Even architects who work frequently with wood must be constantly on the alert. To prove this, as well as the fact that mistakes can happen to anyone, let's look at an example close to home. Our office designed a very elaborate houseboat to be built on the shores of Sausalito, California. We knew we had a very adverse climate to deal with—severe wind and water exposure and also salt in the air—so we took every precaution possible, such as calling for pressure-treated exterior siding. We knew that the siding we received was pressure-treated because it was covered with very apparent, and ugly, sticker marks. The treater insisted that it was impossible to dry the salt-treated wood below 19% moisture content. So, we reluctantly accepted the wet product. Once installed, however, the wood dried to its surroundings with the result that the siding cupped, warped and split in place. We also made the mistake of specifying Douglas-fir, which we found out later has the highest shrinkage of any West Coast wood, and we accepted flat grain which, it appears, is most subject to distortion upon drying. Our friendly supplier neglected to tell us these things. All the siding had to be removed and redone.

This serves to emphasize the fact that another feature of wood that is unique among structural materials is that it is hygroscopic. Furthermore, when wood changes moisture content, it changes dimensions; this is called shrinking and swelling. A knowledge of these properties is essential for proper use of wood in structures. In order to understand better some of these related properties in wood, let's first look at how wood is put together.

Wood is, of course, produced by trees and as trees grow they lay down a very narrow cone of wood each year of their growth. Because the tissue differs with the season in which it's produced, these growth surges, or annual growth increments, are visible in the wood as annual rings or grain. One can actually determine the age of a tree at a given height by counting the number of annual rings. Trees may produce definable heartwood at their center and have what is called sapwood at the outside. Only the heartwood of certain trees possesses natural decay resistance. Sapwood of all of our commercial species is decay-susceptible. Looking at a cross section of wood under the microscope, we can see that it not only consists of annual rings, but the annual rings are made up of cells. It is this cellular structure of wood that makes it so strong for its weight. Most woods actually tend to be more air space than cell-wall substance, which also makes them an excellent insulating material. Wood in the standing tree is very wet, often over 200% based on the oven-dry weight of the wood. As wood dries, it loses this moisture down to a point called the fiber saturation point, which is at approximately a moisture content of 25%. Down to this point from the green condition, or the moisture condition present in the tree, to the fiber saturation point no dimensional changes are encountered. However, as wood loses moisture below 25%, it begins to shrink because the water is being removed from within the

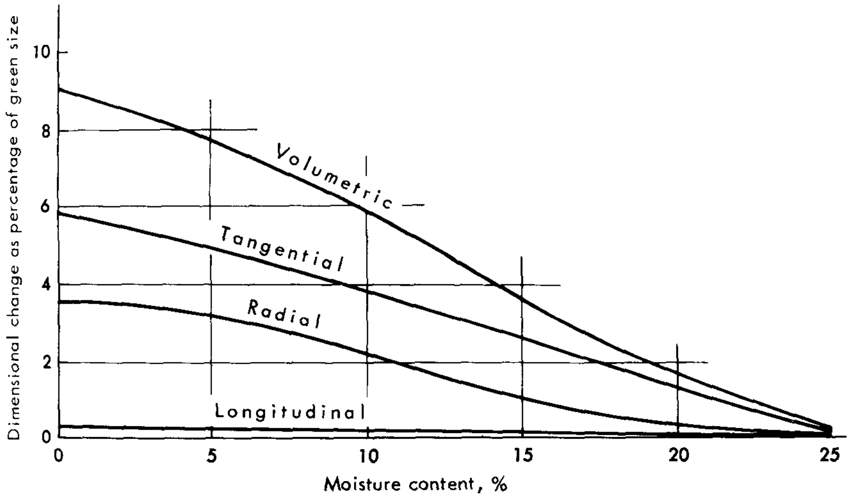

FIG. 1. Shrinkage curves for wood. (Reprinted from Panshin, A. J. and C. deZeeuw. 1980. Textbook of wood technology, 4th ed., McGraw-Hill Book Company; Figure 6-3; by permission.)

cell walls themselves. Wood shrinks differently in its three cardinal directions. It has very little shrinkage along the grain (the longitudinal direction), about 4% total shrinkage across the annual rings (in the radial direction), and approximately 6% total shrinkage parallel to the annual rings (in the tangential direction). This total shrinkage would involve drying the wood to 0% moisture content or the oven-dry condition. Between 25% and 0% moisture content, various proportions of the total shrinkage may be encountered as demonstrated in Fig. 1.

Because wood shrinks differently in its different directions, distortion of wood pieces with varying grain patterns may be encountered as indicated in Fig. 2. Note that a flat-grained piece of wood, as noted at the top of the diagram, will tend to cup severely when it dries; and a vertical-grained piece, as indicated at the far left of the diagram, will remain essentially in its original shape. This is why vertical-grain lumber is normally specified for exterior exposure such as siding. Wood produced near the center of the tree when the tree is young, perhaps 10 to 15 years of age, is subject to abnormal amounts of longitudinal shrinkage, which may cause severe distortion upon drying of these boards, as shown in Fig. 3. The shrinkage of wood and the distortion that accompanies such shrinkage constitute another excellent reason why wood should be put into a structure in the dry condition, that is to the degree of dryness the board will eventually reach in service, and kept dry throughout the life of the structure.

GROUND CONTACT AND FINISH GRADING

Another common problem in structures is a lack of coordination between the finish grade on the exterior and the wood framing. Indicative of this problem we have found foundation vents, a major source of moisture control in the substructure, bricked over to allow higher-than-design exterior grades. Untreated wood carried below grade is highly susceptible to decay, especially if in soil contact or if the membrane fails.

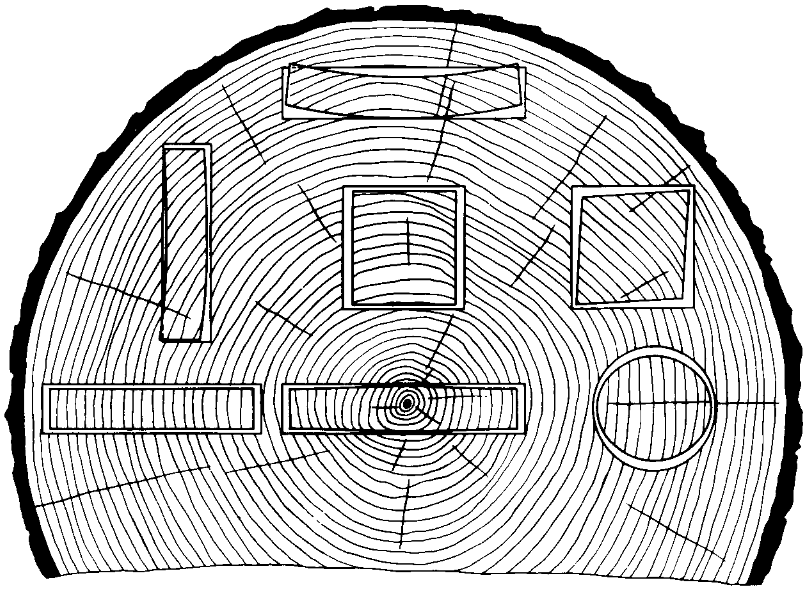

FIG. 2. Characteristic distortion of sawn boards to be expected upon drying depending upon annual ring orientation. (From USDA Agriculture Handbook No. 72, Wood handbook: wood as an engineering material, 1974, Figure 3-2; by permission.)

Contact with the soil is the most hazardous terrestrial exposure to which wood can be put. The soil provides both an adequate source of moisture and the source of the decay fungi themselves. In order to survive for an adequate service life in contact with the ground, wood must be protected by pressure treatment with a preservative. Subterranean termites are also a significant hazard to wood placed on or near the ground. Separating the wood from the soil forces the termites to form soil tubes over the inhospitable environment allowing one to detect their presence and to undertake control measures. Decay from contact with the ground and from subterranean termites can cause substantial losses in structures if not prevented or controlled. Control can be achieved by treating the wood under pressure in a large retort and forcing a toxic chemical deep into the wood. One hazard to keep in mind in placing wood in a highly decay-susceptible environment, even if pressure treated, is that the treatment must have been effective. In one case we have observed recently, a large 80-unit condominium project was constructed on more than 300 treated pilings that turned out to be inadequately treated and not to have met industry quality control standards. They are now suffering decay only six years after being placed in service. In this case, since the pilings are the foundation of the buildings, their failure puts the entire structure in jeopardy.

EXPECTED CHANGES IN THE WOOD WE USE

The wood resource of the future will tend to be considerably different from the wood we have been used to in the past. For one thing, when the lumber comes

FIG. 3. Severe distortion of boards upon drying resulting from abnormal longitudinal shrinkage associated with both juvenile wood and compression wood.

from smaller, younger trees it will tend to have more knots, because more of the tree is involved in branch formation, and it will have smaller pieces. This means that the grades of clear lumber we have been used to will be in very short supply, and in order to make large members, we will have to glue smaller members together rather than using solid timbers. Available on the market before very long may be machine-stress-rated lumber where the bearing capacity of each piece of lumber placed in service in a certain manner may be predicted for the designer and builder, reducing the necessity for over-building to provide for safety factors. Trees from the highly managed forests of the future will be more rapidly grown and therefore have wider rings. They will also have less heartwood available, which means that a larger proportion of the wood available will have no decay resistance whatsoever and will require protection by preservation methods. On the West Coast we are moving from an era in which hydraulic jacks may be required to fell a large tree to one where a machine with essentially an overgrown

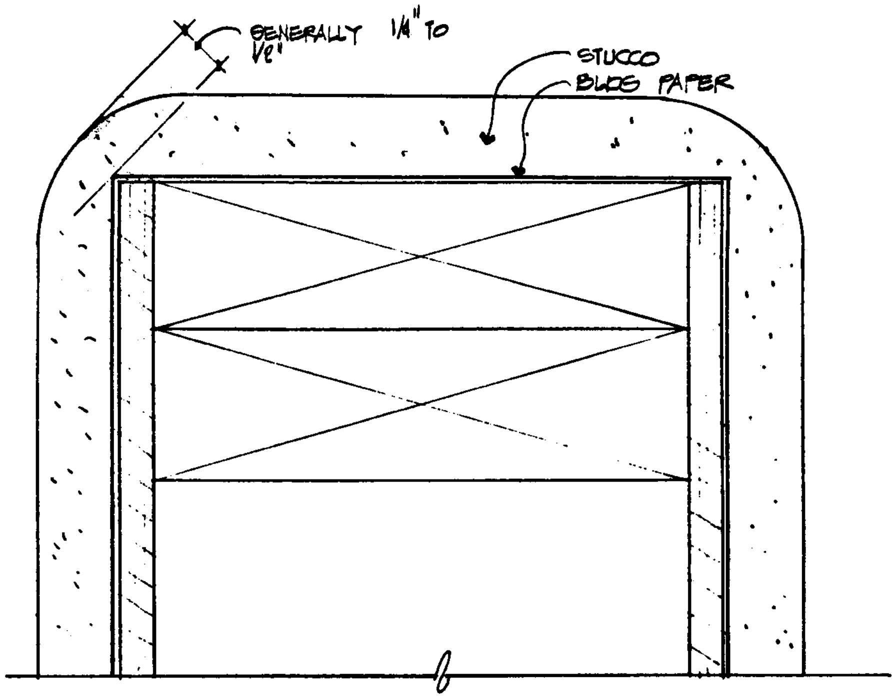

FIG. 4. Parapet cap as built leading to water infiltration when stucco cracked at corners.

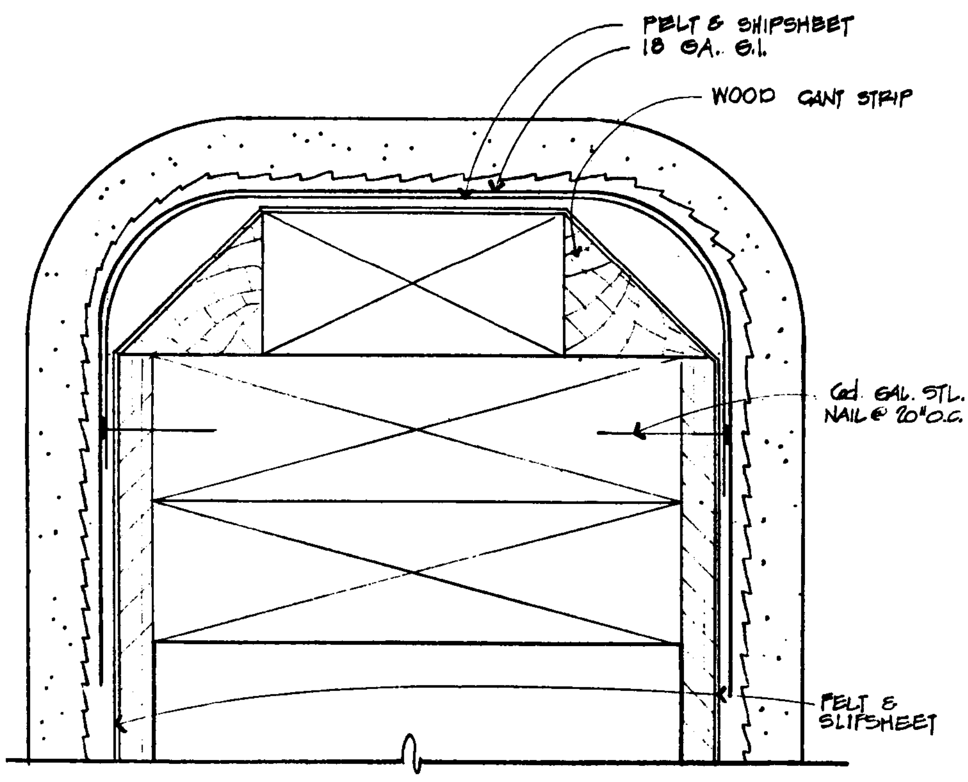

FIG. 5. Parapet cap as corrected.

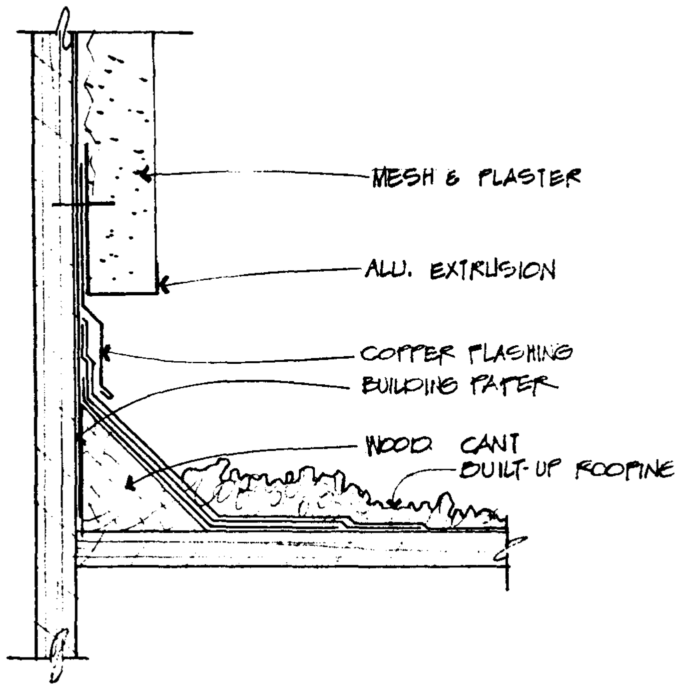

FIG. 6. Detail of vertical/horizontal intersection as built showing reverse shingling of building paper and flashing.

pair of shears will sever the tree, lay it down, and cut it into pieces. We are going from an era in which six-foot-diameter logs may commonly be seen entering sawmills to the point where log sizes will be more in the neighborhood of 24 to 30 inches in diameter. Again this means that a larger proportion of the product will consist of sapwood, and more juvenile wood. Because of the greater amount of residue generated in converting small round members to rectangular members, we will see more use of material such as particleboard and plywood. We will have more glued products that can use smaller portions of the raw material to produce the large, final product. All of these features of the raw material of the future must be considered so that the designer and builder can continue using wood effectively in structures.

SOME CRITICAL DETAILS TO HELP KEEP WATER OUT OF YOUR BUILDINGS

The exterior stairways of the award-winning college buildings provide our first example. Figure 4 shows the parapet cap as designed. You will notice that the cement plaster was carried vertically up and over the top of the frame and down the other side. Although the detail shows a relatively uniform thickness of cement plaster, as it was actually built, the plaster was applied with no control over thickness. The plaster was mounded at the center of the top of the rail and tapered down to a very minute dimension at the corner, which invariably cracked. This

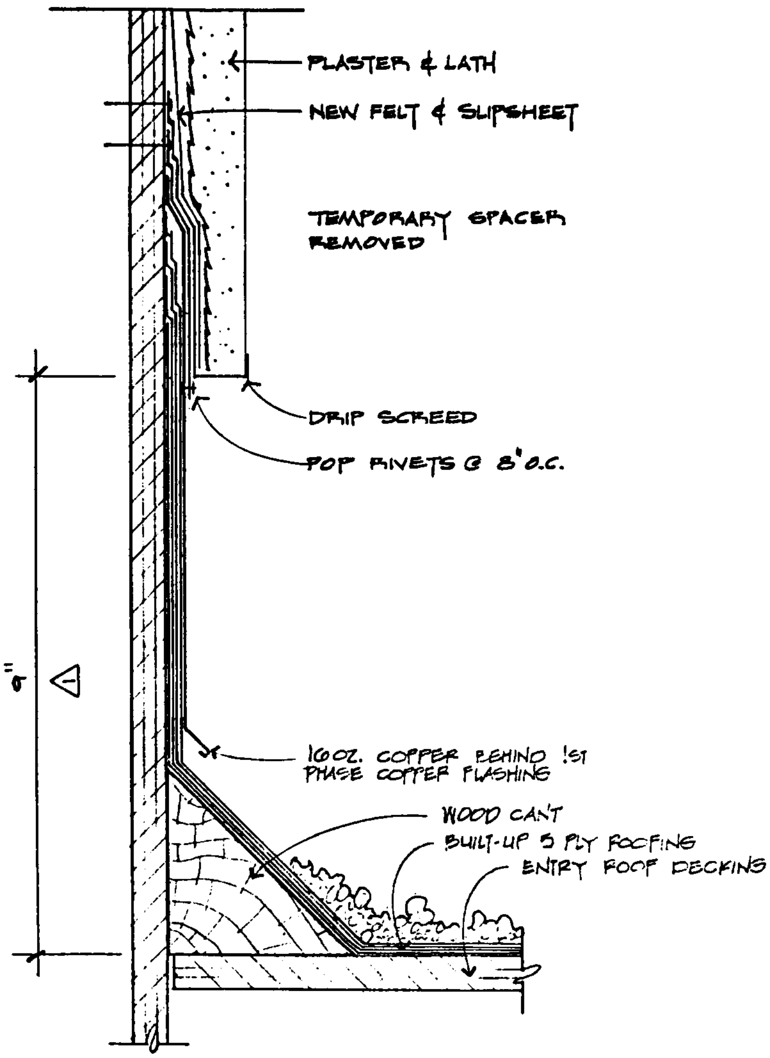

FIG. 7. Detail of vertical/horizontal intersection as corrected.

is a result of unequal shrinkage during the curing process due to the different dimensions in the material itself. Figure 5 shows this detail as corrected. In this particular case, the detail employed was to put sheet metal flashing over the top of the railing lapping, shingle-fashion, over the building paper membrane. The plaster was very carefully hand-applied, not gun-applied as before, to get a uniform thickness.

Another common error that will direct water into a structure is to ignore the principle of shingle lapping in terms of the contact between flashing and building paper. This mistake was also found in the college buildings. The building paper

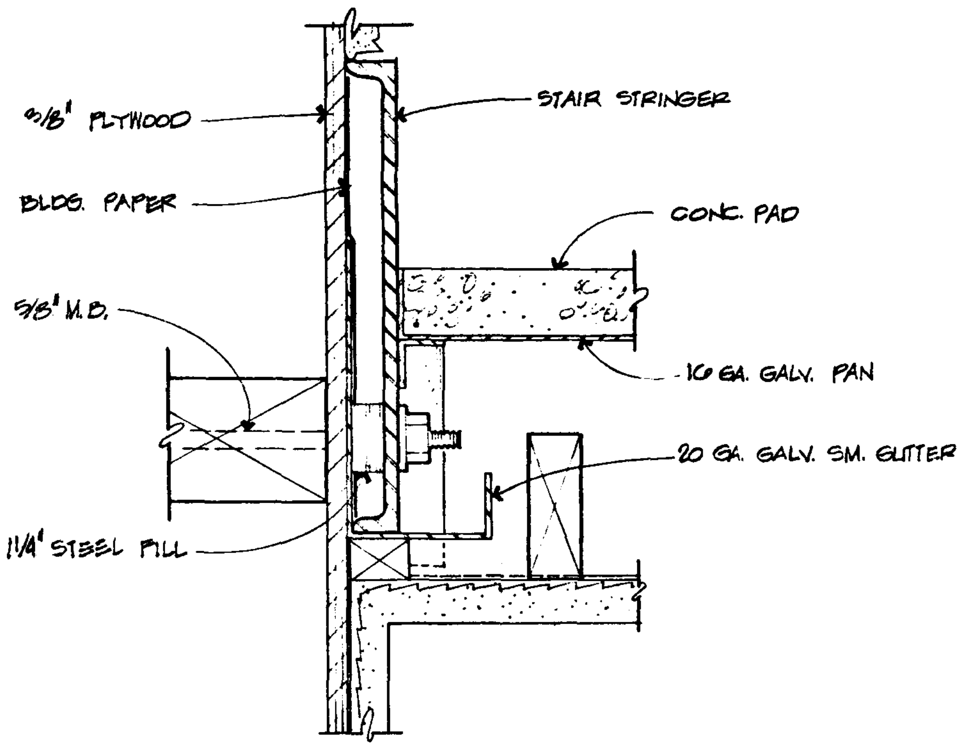

FIG. 8. Stair stringer detail as designed showing sheetmetal gutter.

was installed in joints between vertical walls and horizontal roofs in reverse shingle fashion, thereby guaranteeing entry of water into the structure (Fig. 6). As corrected (Fig. 7) note that proper shingling of building paper and flashing was applied. A curious feature of the exterior stair detail of the college buildings is that the designer apparently knew it was going to leak, so sheet metal gutters were detailed underneath it (Fig. 8). As it was corrected (Fig. 9), a cap flashing was installed over the top of the stringer, and at the bottom side of the stringer a backer rod and a good grade of sealant were installed. Actually, the gutter system might not have contributed so greatly to decay if the joints had been soldered and if it had not termintated at the bottom into a ⅜-inch diameter copper tube. A tube of that dimension clogs up so quickly with dirt and debris that it ceases to function almost instantaneously. This clogging backed water up into the gutter, through the open joints and into the stud cavity, causing extensive decay of the wood frame.

The excessive cracking of the cement plaster observed in the college buildings can be dealt with also. We provided a double layer of mesh at the corners, where the stress builds up during the curing process because of shrinkage. We terminated the mesh at the bottom with a ventilated drip screed held 4–6 inches above finish grade. The building paper membrane behind the mesh consisted of a double layer, the first a grade B paper, the second anything at all because it simply acts

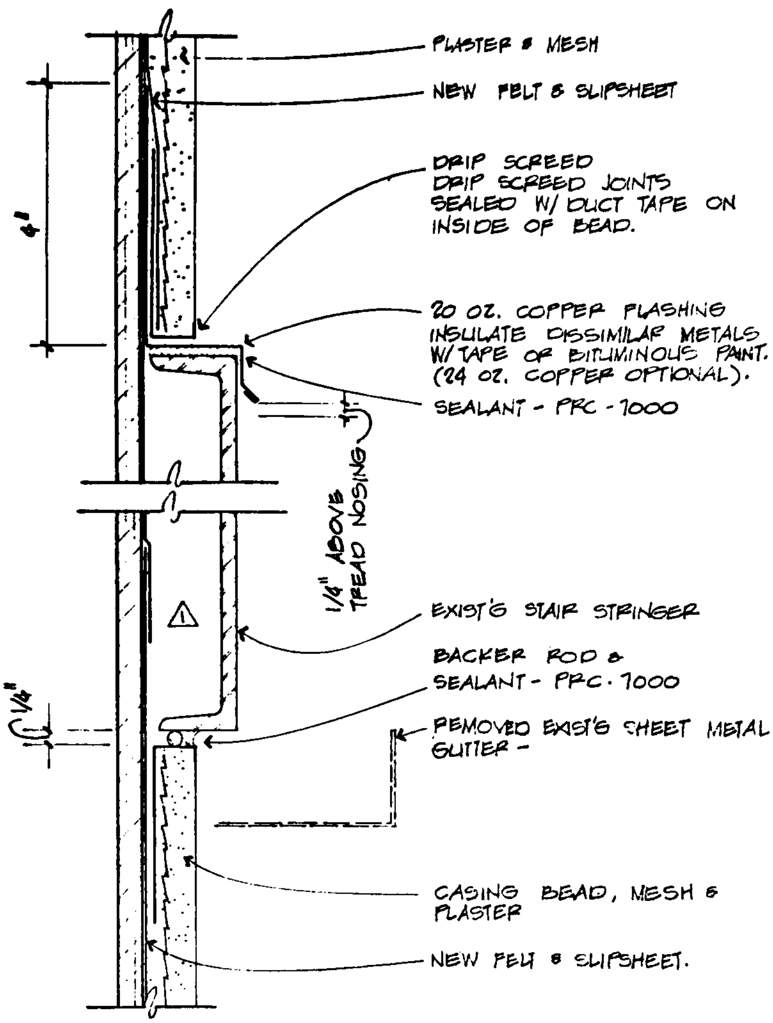

FIG. 9. Stair stringer detail as corrected.

as a slip sheet and can be sacrificed to keep the first membrane intact. Another technique employed was used years and years ago—that of reinforcing the plaster with animal hair. Though we called for animal hair in our specifications, animal hair is not as prevalent these days as it once was; we had to settle for shredded fiber glass instead. The plaster was applied in a three coat process—scratch, brown and white coat.

We encountered another problem with cement plaster in another award winner. We found that it was built with a lapping system employing the use of line wire behind the mesh to reinforce it and that grade D paper was the backing. Horizontal cracks developed where the mesh overlapped, with the double layer of line wire causing a stress point and failure of the cement plaster at this point. We were totally puzzled to find vertical cracks in the cement plaster columns until we opened them up and found the mesh had been installed vertically; here again the vertical cracks were following the line wire in the mesh.

CONCLUSION

The properties of wood that make it unique among materials present both opportunities and challenges for the designer and builder. These must be well known to use wood safely and effectively. Particularly with decay, to ignore properties that may present problems in use is to invite disaster. It is the responsibility of the wood-producing community to supply wood property information and counsel to those using wood to design and build structures. It is the responsibility of these designers and builders to seek out this information and to learn when it is needed. Mankind has known for centuries how to build structures of wood capable of lasting forever. The "secret" is *WATER*! The challenge is, through proper information exchange, to do right by our only renewable material.