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WOOD BIODETERIORATION:

Causes, Processes, Prevention and Remediation

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SUMMARY

Many organisms see wood as an ideal food source. In order to use wood efficiently, we need to understand these organisms and devise ways to prevent them from deteriorating wood while we are using it. In Northern temperate climates certain fungi are the most economically important of these organisms. In subtropical and tropical climates, termites assume much greater importance. The fungi causing deterioration of wood include moulds, staining fungi, soft-rot fungi and wood-rotting basidiomycetes. The last group can be subdivided into white-rot fungi and brown-rot fungi and the latter are the most economically important. Once wood rotting basidiomycetes are established the rate of growth and strength loss is surprisingly rapid, consequently control of decay must focus on preventing these fungi from gaining a foothold. The primary consideration is to keep the wood dry and, where moisture cannot be avoided, durable wood products should be used, either naturally durable or pressure-treated. Eradication of established decay fungi is difficult, because the early stages of decay are difficult to detect and wood-rotting basidiomycetes can survive for long periods in dry wood and will revive if the wood re-wets. If it is not 100% certain that all the fungal infection has been removed and all moisture sources eliminated, it is advisable to use pressure-treated wood, to CSA O80 standards, to replace rotted members and treat, in situ, the remainder of the original wood.

1 INTRODUCTION

We see wood as an almost ideal construction material but a lot of organisms, specifically certain bacteria, fungi, insects, crustaceans and molluscs, see it as a conveniently oriented series of holes made of food.

These organisms are crucial to the breakdown of woody material on the forest floor or in water. Without certain fungi and, in warmer climates, termites, forest ecosystems could not function. These organisms live by consuming complex organic materials that form the structural and non-structural components of wood. However, they cannot use wood as food unless they also have their oxygen, water and temperature needs satisfied (see Section 3.2). The wood itself also has to be susceptible to attack, that is, it must not be naturally durable. The susceptibility of wood to biodeterioration is related to its chemical composition.

At the chemical level, the major component of wood cells is ligno-cellulose, composed of cellulose and hemicelluloses, long chain polymers of sugar units, encased in lignin. Fortunately, only a limited range of organisms are capable of breaking down cellulose which provides most of the mass and strength to wood. Lignin is a three dimensional resin of interlinked phenolic units which even fewer micro-organisms can degrade. Hardwoods generally have less lignin than softwoods and the lignin they contain is also more readily degraded making them particularly susceptible to attack by some types of fungi. The breakdown of ligno-cellulose by fungi is the process we call wood decay. More detail on wood as a substrate for biodeterioration may be found in the publications by Eriksson *et al* (1990), Eaton and Hale (1993) and Zabel and Morrell (1992).

2 WOOD-INHABITING ORGANISMS

A wide range of organisms can live in and degrade wood. In temperate climates, fungi cause the most damage to wood products. In the tropics, termites are the more serious problem. Carpenter ants can be a minor problem in southwestern BC and the Pacific Northwest of the USA. Wood-boring beetles are regarded as a serious concern in some regions of the world but have not proved to be a major problem in wood in service in Canada. Marine borers can cause problems for wood stored or used in the oceans.

2.1 Fungi

The filamentous fungi are a group of organisms which feed on organic matter and grow by extension and branching of tubular cells (hyphae), in a manner somewhat similar to the roots of plants. This form of growth is called mycelium. Unlike plants, fungi do not have the chlorophyll necessary to produce carbohydrates from sunlight and CO_2 but use enzymes to digest and assimilate organic materials. Fungal reproduction involves the production of microscopic spores that are smaller than the pollen grains of plants. These spores are spread by air currents, insects or by water splash. The amount and types present in the atmosphere vary with the season and the weather. For example, spore production of many fungi increases dramatically in the fall. A light rainfall can increase the spore load in the air but a heavy rainfall can wash most of the spores to the ground. The fungi that live in wood can be divided into moulds, staining fungi, soft-rot fungi, and wood-rotting basidiomycetes. These are listed in the order of increasing levels of damage of wood and in the order in which they commonly colonise wood in service.

2.1.1 Moulds and Staining Fungi

Mould and staining fungi live on non-structural components of wood and are thus more prevalent in sapwood. These fungi typically produce spores on structures that can only be identified under the microscope. They normally require a high relative humidity to produce these spores.

Moulds are particularly prevalent in exterior air in late summer and fall when diurnal temperature variations favour the formation of fog and dew. This is also the season when plants are dropping overripe fruit and dying back. Inside the home, under the right conditions, this type of fungi will grow on drywall, paint, wallpaper, insulation, acoustic tiles, wood products and other building materials. It will also grow on carpets, curtains, furniture, clothes, paper, cardboard boxes and other home contents. It will grow on grout, paint, metal window frames, shower curtains, and other dirty surfaces. It thrives on soil, compost, straw and dead plants. However the most likely place to encounter moulds is in the far corner of your refrigerator on cheese, fruit and other foods. The mould many people are concerned about these days, *Stachybotrys chartarum* is most commonly found in buildings on the paper surface of drywall, usually in very wet conditions.

Many moulds have colourless or pale coloured mycelium and coloured spores. En mass, these spores may appear white, black, grey, green, olive, brown, yellow or other colours, depending on the fungus species. Mould spore production and the associated discolouration, is often confined to the surface and can be washed or planed off. However, some moulds are known to cause respiratory problems in sensitive individuals.

Staining fungi have brown- or black-coloured mycelium, giving the wood a characteristic black or blue appearance (Figure 1). To the naked eye, they may look like black fuzz or whiskers. These fungi, while unsightly, generally cause very little damage. If the wood dries out, they die or go dormant. If it does not they are normally replaced by wood rotting fungi. The major economic impact of staining fungi is in the disfigurement of the appearance of wood products. This can reduce the value of raw lumber and require costly refinishing on wood in exterior exposure. In some heavily stained wood there are reported reductions in impact strength.

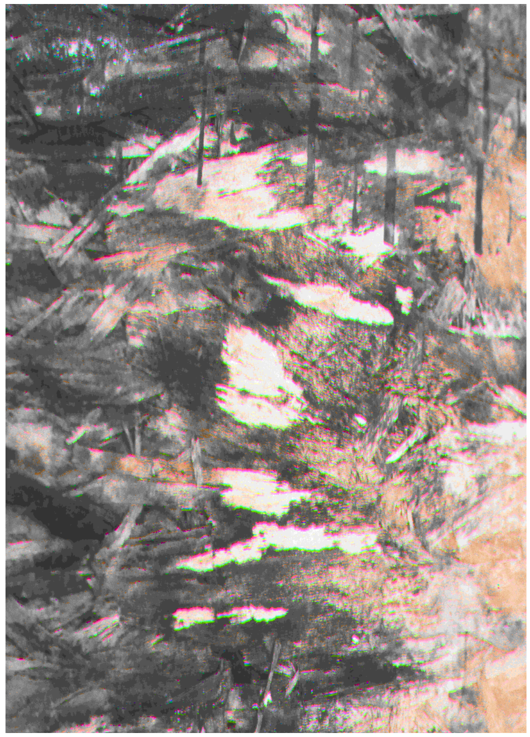

Figure 1: Bluestain (black) and white rot (bleached patches) on OSB

Some stain fungi are early colonisers of freshly felled logs and they rapidly penetrate deep into the sapwood. Other stain fungi tend to grow mainly near the surface of the wood. Some have the capability to penetrate through paint films and their pigment protects them from ultraviolet (UV) light. Some can also live on the products produced by the breakdown of wood by UV. Consequently, they are a particular challenge to transparent film-forming finishes which do not block UV light and/or crack when wood expands in response to humidity. Stain fungi grow particularly well on surfaces that are kept moist by a partially intact surface film but remain exposed to UV light. If wood is left unfinished, UV light, in combination with water, causes the breakdown of the lignin that is then washed away by rain. The exposed cellulose reflects light giving a silvered appearance but staining fungi darken this to a grey "weathered" look.

2.1.2 Soft-Rot Fungi

Closely related to the mould and stain fungi, the soft-rot fungi are capable of breaking down ligno-cellulose and therefore of causing severe strength loss. Some types erode the cell wall, others tunnel within it. Confirmation of soft-rot must be made using the light microscope. These fungi typically attack wood in permanently moist conditions such as soil or cooling towers. They attack relatively slowly from the surface inwards and some are tolerant of heartwood extractives and wood preservatives. They can cause severe damage to preservative-treated wood in ground contact if insufficient preservative is used. However, in untreated wood above ground they are normally succeeded very quickly by wood-rotting basidiomycetes. Hardwoods such as oak and maple are particularly susceptible to soft rot. Since we primarily use softwood in construction, soft rot causes problems only insofar as it places limits on the service life of preservative-treated wood in ground contact.

2.1.3 Wood-Rotting Basidiomycetes

These are the fungi that cause most of the damage found in buildings. Given time, basidiomycetes typically produce large fruiting structures, toadstools, brackets or conks, which are obvious to the naked eye. A good example of a fruiting body of a wood-rotting basidiomycete is the oyster mushroom now sold in an increasing number of produce stores. Although many basidiomycetes in temperate regions produce annual fruiting bodies in late summer and fall, spore production may continue through a mild winter. When moisture and temperature conditions are favourable, some wood-rotting basidiomycetes will produce fruiting bodies in winter, spring or early summer. Yet others, particularly those which grow on live trees, have perennial fruit bodies which grow larger each year. The mycelium of most of the economically important wood-rotting basidiomycetes is white, pale yellow or buff. Several of them produce mycelial cords, consisting of bundles of hyphae that extend by growing at the tip. These cords are capable of growing considerable distances over inert materials and, in some cases, transporting moisture with them. They are more resistant to drying out and competition than a loose web of mycelium. They also concentrate the energies of the fungus facilitating the invasion of new substrates. The power to invade new substrates is termed inoculum potential. Mycelial cords have more inoculum potential than mycelium, which, in turn, has much more inoculum potential than a spore. Infection of wood structures above ground probably occurs mainly through spore germination, though subsequent spread from component to component can be by mycelium or mycelial cords. In or near the ground, infection by mycelium or mycelial cords is much more likely.

The term wood-rotting basidiomycetes (WRB for short), although cumbersome, is at least precise. Many wood-rotting fungi (for example the soft-rot fungi) are not basidiomycetes and many basidiomycetes do not decay wood. The WRB decay wood at a much faster rate than the soft-rot fungi. Their destructive effects can be readily distinguished with the naked eye and they can be divided into white-rot fungi and brown-rot fungi on the basis of the colour change they cause on wood.

White-rot fungi: These fungi tend to attack hardwoods such as aspen and maple. They degrade both lignin and cellulose leaving the wood bleached to a paler colour (Figure 1). Decay may start in small pockets and may result in a stringy texture to the wood. Strength loss is comparatively slow to occur.

Brown-rot fungi: These fungi tend to attack softwoods such as pines, spruces, hemlocks and firs. They degrade primarily the cellulose but they do modify the lignin leaving a brown, almost charred appearance (Figure 2). As the first step in the decay process, the cellulose is chopped into short lengths by a non-enzymic process resulting in rapid early strength loss. This also allows the wood to crack across the grain as it shrinks in response to the breakdown and removal of the cellulose. The cross-grain cracks and longitudinal cracks combine to give the characteristic cubical cracking pattern. In some cases the wood may appear charred. Brown-rot fungi are the most economically important agent of destruction in wood buildings in temperate climates.

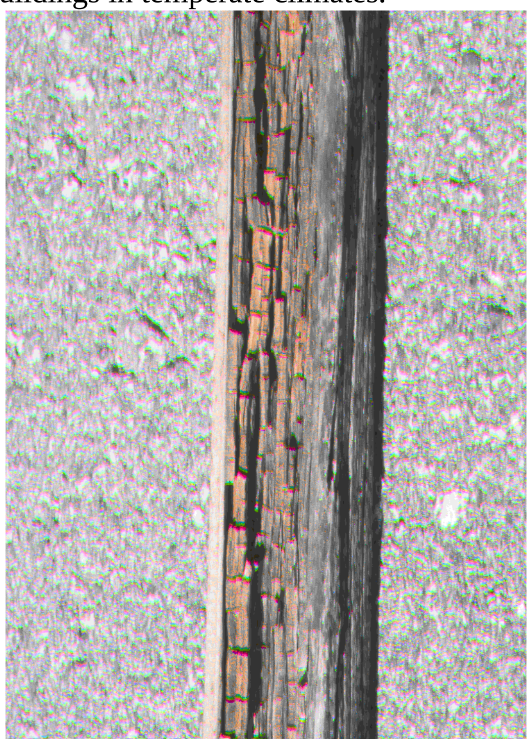

Figure 2: Brown rot showing the typical darkening and cubical cracking

No extensive studies have been done to determine which wood-rotting basidiomycetes cause the most damage in Canada but the list is likely to have much in common with the list developed for the United States (Duncan and Lombard 1965). The basidiomycetes most often identified with decay in buildings in the USA were *Meruliporia incrassata, Gloeophyllum trabeum, Tapinella panuoides, Antrodia vaillantii, Coniophora puteana, Serpula lacrymans, Postia placenta and Antrodia serialis.* In Canada, *Gloeophyllum* *trabeum*, a species with a more northerly range, can probably be substituted for *Gloeophyllum sepiarium.*

All of these are brown-rot fungi, two of them, *M. incrassata* and *S. lacrymans*, have the capability to transport water from wet wood to relatively dry wood over inert surfaces. This allows them to spread more rapidly under conditions that are marginally favorable for decay.

Although these agents of biodeterioration are a nuisance to us in our attempts to use wood for our own purposes, they also have the potential to recycle wood at the molecular level when wood products reach the end of their useful service lives.

Wood-rotting-basidiomycetes are generally more sensitive to wood preservatives than soft-rot fungi or bacteria. There are, however, a number of brown-rot fungi which are tolerant of moderate amounts of copper, and some which are tolerant of arsenic. Many of the white-rot fungi and a few of the brown-rot fungi are tolerant of organic preservatives, possibly through the action of the enzyme or non-enzymic systems they use to break down lignin.

2.2 Bacteria

Bacteria tend to colonise wood with high moisture content, either fresh from the tree, water sprinkled for long-term storage prior to sawing, submerged in lakes or wet soil. Some bacteria simply live on the non-structural components in sapwood and may increase the permeability of wood by destroying pit membranes. Other bacteria are capable of degrading ligno-cellulose but the rate of decay is very slow. They can, however, cause considerable strength loss over the course of many decades. They can also attack preservative-treated wood, but again, this is a very slow process. Many archeological artifacts recovered from lake sediments have been attacked by bacteria. Bacterial attack can be seen under the light microscope but electron microscopy is required for detailed diagnosis of the various types of bacterial decay. Bacterial decay is not regarded as of great economic significance.

2.3 Termites

Termites are primitive social insects related to cockroaches. Though often called “white ants”, they are not closely related to ants. They do, however, superficially resemble ants and live in large colonies with a variety of specialised castes including a Queen (and King). Based on their effect on wood in construction, termites can be divided into three groups: damp-wood termites, subterranean termites and dry-wood termites. Damp-wood termites live in damp and decaying wood, and the damage they cause is of relatively little economic significance. Prevention of decay is the main problem here. Subterranean termites cause the majority of the economically important damage to wood products throughout the world. They typically require some connection to moist soil through a system of galleries. In order to cross inert substrates to access wood, they will build shelter tubes from earth, wood fragments, faecal excretions and salivary excretions. Formosan subterranean termites have, however, been known to start colonies out of ground contact, for example, around water tanks in high-rises in Hawaii. This particularly voracious species has also been introduced into the continental United States via several Gulf Coast ports. It is also the species that is prevalent in southern Japan. Dry-wood termites attack dry sound wood and do not colonise via the soil. A mated pair of winged reproductives can fly in and start a new colony directly in wood in buildings. In North America, dry-wood termites are confined to the extreme southern United States and Mexico.

In Canada, subterranean termites are only considered a serious pest in some southern Ontario cities (particularly downtown Toronto) and in some of the drier areas of British Columbia (Eastern Vancouver Island, the Gulf Islands, the Sunshine Coast and the Okanagan).

2.4 Wood-boring Insects

There are a large number of types of wood-boring beetles, weevils, wasps and bees (Bravery *et al* 1987; Levy (undated, 1979?). For the species that cause most structural damage in buildings, it is only the grubs that feed on the wood. After pupation, the adults emerge by biting their way out of the wood. Since they do not consume wood at this stage, they are not killed by surface application of preservatives, many of which are stomach poisons. Such preservatives will however prevent re-infestation by the next generation. Some beetles and wood wasps lay their eggs only through bark and are only problematic in their unexpected emergence from wood products. Wood wasps are particularly large and alarming in appearance. Typically such species do not re-infest wood in service.

Some wood-inhabiting beetles, such as *Lyctus* sp. and *Anobium* sp., can cause considerable damage particularly where, over many decades, generation after generation can re-infest the same piece of wood unnoticed. A typical example would be trusses and enclosed wooden staircases in older European houses. The rate of growth of many species is controlled by the nitrogen and starch content of the wood. The sapwood of hardwoods is particularly susceptible to beetle damage. A number of beetles (eg *Buprestis* sp) and weevils preferentially attack rotted wood. Sometimes their emergence holes, bitten through an otherwise sound surface, are the first signs of decay. Wood boring beetles have not been known to cause economically important damage in wood structures in Canada.

2.5 Carpenter Ants

Carpenter ants (*Camponotus* species.) are easy to identify because they are large (workers 6 - 10mm) and completely black. They are very common in B.C. They do not eat wood, they merely excavate it to live in. They emerge from the wood to forage for vegetation and any sugary household foods. They prefer softer woods or those that have been softened by decay and other soft building materials, such as insulation. Unchecked, carpenter ants can cause serious structural damage. The noise of their excavation can be highly irritating particularly in buildings with expanded polystyrene insulation. Removal of woody debris, adequate soil/wood separation (or use of treated wood in ground contact) and general sanitation of buildings is normally adequate to discourage carpenter ants. A mixture of sugar and borax has been used as a home made poison bait to reduce infestation.

2.6 Marine Borers

Two types of marine borers are important in the coastal waters of Canada, shipworms (*Bankia setacea* and *Teredo navalis*) and gribble (*Limnoria quadripunctata* and *Limnoria tripunctata*). The damage from these organisms is unlikely to be found in buildings unless the lumber has been cut from logs which have been stored too long in sea water. Shipworm damaged wood has occasionally been used as decorative panelling. Shipworms are molluscs that settle on the wood as larvae and tunnel deep into it by rasping with their serrated shells. They leave tunnels up to 12 mm in diameter and a major infestation can destroy untreated piling in less than a year. Gribbles are crustaceans which leave very small tunnels (1mm) seldom extending more than 12 mm from the surface of the wood. Severe damage can occur over several years as the weakened surfaces are continually abraded by the action of waves and flotsam. Both types of borer are controlled by good quality preservative treatment. Bramhall (1966) provided an excellent review of the situation on the West coast of Canada.

More detail on the organisms involved in biodeterioration of wood can be found in the textbooks written by Cartwright and Findlay (1950), Eaton and Hale (1993), and Zabel and Morrell (1992). Two other texts, Bravery *et al* (1987), and Levy (undated, 1979?) are very useful for identifying which organism is causing a particular problem.

3 MICROBIAL BIODETERIORATION PROCESSES

Of all the organisms that use wood as a food source, the most important, in the temperate regions, are the wood-rotting basidiomycetes. In structural softwoods, the brown-rot fungi are particularly important. Wood that is recognisably rotten is the product of a sequence of events with the participation of a succession of microorganisms.

3.1 The Colonisation Sequence Leading to Decay

Although they can decay fresh, previously sterile wood, WRB are commonly prevented from colonising by competition from a sequence of organisms, including: bacteria, mould fungi, staining fungi and soft-rot fungi. This sequence can take weeks or months to complete, depending on the conditions prevailing in the wood. As discussed above, the bacteria, mould fungi and staining fungi live on non-structural components of the wood and cannot break down ligno-cellulose. They are, however, adapted to rapidly colonising and exploiting readily digestible carbohydrates, lipids and proteins in sapwood. To prevent other fungi from competing with them, many fungi produce antibiotics. When the bacteria, moulds and staining fungi have used up all the non-structural components, they stop growing and the soft-rot fungi and WRB can take over. The wood-rotting fungi can compete at this stage because the only remaining carbon source is ligno-cellulose and only they can use it. Unless the WRB are excluded by unfavourable conditions, such as high moisture content or wood preservative, they will out compete the soft-rot fungi. (Note: most of the research on the colonisation sequence has been done on sapwood. Heartwood which has relatively little readily digestible component and some natural toxins may have a different sequence)

If wood becomes stained and stays at the right moisture content, it will almost certainly be colonised by wood-rotting fungi some time later. It is difficult to predict how long this stage will take. It depends on the chances of a WRB arriving on the wood when the wood is in the right conditions for colonisation and also on the ability of the WRB to compete with the fungi already present. The cellar fungus, *Coniophora puteana* is one of the most aggressive in overcoming the resistance of the mould and staining fungi. *Gloeophyllum sepiarium*, the most common decayer of millwork and decking, is relatively weak.

In the absence of experimental data, we must assume that colonisation and decay processes start where they left off when lumber is dried and re-wetted.

3.2 Conditions Required for Decay

Wood-rotting fungi have the same basic needs as other organisms: a food source, an equable temperature, oxygen and water. As discussed above, the wood provides almost everything a fungus needs for food. However, the heartwood of some species is less susceptible than others. Furthermore, wood can be made non susceptible to decay through chemical treatment.

The temperatures that we regard as ideal for comfort are also perfect for the growth of wood-rotting fungi. Such fungi do vary in their temperature optima, but these commonly lie between 20^{o}C and 30^{o}C. A few WRB grow fastest at 34 - 36^{o}C and these are typically the species (*Gloeophyllum* species) that are dominant on exterior wood products exposed to full sunlight. All WRB are stopped by temperatures higher than 46^{o}C but they may not be killed until the temperature reaches 60^{0}C. As with many biological systems, a ten degree drop in temperature results in a halving of the growth rate. Growth and decay does not cease until the temperature is very close to 0^oC.

Oxygen is ubiquitous and is not normally a limiting factor. Painting or otherwise sealing the wood surface will not exclude oxygen from the wood. Although decay is an oxidative process, WRB are relatively tolerant of very low oxygen levels. A normal atmosphere contains 21% oxygen and reduction in growth of WRB does not occur until the concentration drops below 1 - 2%. When buried in anaerobic lake sediments, wood is not attacked by WRB or soft-rot fungi, but it can still be degraded very slowly by some bacteria.

Water is the key limiting factor in decay of wood in structures and, in temperate climates, moisture control is key to the durability of wood systems. While some moulds can colonise wood at moisture contents between 15 and 20% little or no sporulation occurs. Most moulds require moisture contents above 20% for growth and sporulation. Infection by spores of WRB probably does not occur at wood moisture contents below about 27%. At typical interior temperatures, this corresponds to a relative humidity (RH) around 96%. In order to germinate, spores need to absorb moisture from the wood and below the fibre saturation point, the wood exerts too much suction on the water. The mycelium and mycelial cords of WRB can colonise wood below the fibre saturation point, possibly down to 20% mc, provided they are growing from a substrate at a higher moisture content. Certain WRB, such as the true dry rot fungus, are capable of transporting water through mycelial cords over inert surfaces and depositing it into dry wood. The true dry rot fungus (*Serpula lacrymans*) is very rare in Western North America but common in the East and in Europe. It shows a distinct preference for wood in contact with bricks and mortar. In Western North America there is another water-conducting fungus (*Meruliporia incrassata*) with more limited capabilities for water conduction.

Once WRB are established, the optimum moisture contents for decay of wood lie between 40 and 80% mc. The upper limits vary between 100 and 250% mc depending on the wood density. Once water fills more than 80% of the space in the wood, diffusion of gas is slowed to the point that CO_2 builds up to inhibitory levels and oxygen is limiting. WRB may stop growing under these conditions but they are not necessarily killed.

Once WRB are established, the minimum moisture content for decay to proceed is around 22 - 24%, so 20% is frequently quoted as a maximum safe moisture content for wood. The National Building Code requires the moisture content of wood to be below 19% when the building is closed in. Drying the wood to below 15% will stop the decay process but will not necessarily kill the decay fungus inside the wood unless a sufficiently high temperature has been used in the drying process. WRB can survive for up to nine years in wood at moisture contents around 12%. If the wood wets up again, the decay process can restart.

3.3 Growth and Decay Rates of Brown-Rot Fungi

While their growth rates in the laboratory on artificial media or sterile wood are well known, the growth rates of brown-rot fungi under field conditions have not been extensively studied. Some reports suggest that, under ideal temperature, moisture and nutrient conditions, WRB will grow between 1 and 10mm per day over the surface of wood (Thornton and Johnson 1986) and at a somewhat slower rate within solid wood (Dobry and Rypacek 1991) in the longitudinal direction (parallel with the majority of cells). The rate of growth within solid wood across the grain will be slower still.

The rate of strength loss and weight loss caused by brown-rot fungi has been much more extensively studied. As discussed above, the ligno-cellulose breakdown mechanism used by the brown rot fungi causes rapid strength loss before decay is obvious to the naked eye. Some strength properties are more sensitive than others. Compression perpendicular to the grain, important for the bearing strength of plates and beams may be reduced by up to 60% in one week under ideal conditions in sapwood. Under the same conditions, Douglas fir heartwood, which is moderately durable, might only lose 25% of compression perpendicular to grain in a week. For compression parallel, important for studs, sapwood might lose up to 40% and Douglas fir heartwood up to 15% in one week. Zabel and Morrell (1992) provide a detailed discussion of the effect of white-rot and brown-rot fungi on all the strength properties of softwoods and hardwoods.

Wood-rotting fungi break down the carbohydrates in wood to carbon dioxide and water, thus the moisture content of wood increases by tens of percentage points as decay progresses. This makes it somewhat more difficult to stop the decay process by drying out the wood. Some form of accelerated drying is normally needed. Interestingly, the WRB (*Gloeophyllum* species) commonly found attacking wood in exterior applications (decking, windows, shakes, etc.) cause a greater increase in moisture content than predicted from the breakdown of carbohydrate alone (Viitanen and Ritschkoff 1991). This suggests that they are capable of extracting additional moisture from the air. These fungi are also particularly tolerant of drying out and high temperatures (Cartwright and Findlay 1950; Zabel and Morrell 1992).

The figures quoted in this section were all taken from Cartwright and Findlay (1950), or Zabel and Morrell (1992). These textbooks provide references to the original publication from which these data are taken. More specific details on the wood breakdown mechanisms of fungi are provided by Eriksson *et al.* (1990).

4 FUNGI OR INSECTS CARRIED OVER FROM THE LIVING TREE

Green lumber may contain decay fungi that infected the standing tree (Eades 1932). These may remain viable and spread during storage if the wood is not treated with a prophylactic anti-sapstain treatment (Clark and Smith 1987). Such treatments are designed to provide short-term protection against mould, stain and decay fungi. Untreated green lumber is also susceptible to colonisation by fungi. Fungi which colonised in the standing tree or the lumberyard can remain active if green lumber does not dry out once it is built into a structure. The effects of this can be seen in the fact that almost all of the fungi causing serious problems in buildings in California were also found in green Douglas fir in lumberyards (Dietz and Wilcox 1997).

Live larvae or pupae of wood-boring beetles, bark beetles or wood wasps that attack weakened living trees may also be found in green lumber. They do not tend to re-infest cut lumber so the infestation does not spread. In most cases, however, organisms that attack standing trees do not survive the process of manufacturing into wood products. The initial wet heat involved in conventional and higher temperature kiln drying are effective at killing all fungi and insects. Even the most resistant wood-rotting fungi can be killed by 75 minutes at 65^{o} C, 20 minutes at 80^{o} C, or 5 minutes at 100^{o} C in the centre of the product, provided the atmosphere is close to saturated with moisture (Cartwright and Findlay 1950). Increasingly complex life forms die at lower time/temperature combinations. Pinewood nematodes are killed at a temperature of 56^{o} C for 30 minutes or if heated to 70^{o} C. Wood-boring beetles can be killed if the wood is heated to 50^{o} C. Being a good insulator the wood will remain at these target temperatures for some time. The temperatures typically generated in the manufacturing of structural panels and engineered wood products are normally adequate for sterilisation. Air drying and lower temperature kiln drying methods, such as dehumidification, may not kill these organisms.

5 SOME CONSIDERATIONS FOR PREVENTION AND REMEDIATION OF DECAY AND TERMITE DAMAGE

5.1 Protection by Design

In the cool temperate zones, where insects which attack dry wood are of little significance, wood products and systems can last indefinitely, provided they are kept dry. There are numerous examples of historic wooden structures that are thousands of years old. Most often quoted are the temples of Japan and the stave churches of Norway (Figure 3).

These were built with only the best of materials using the true wood (heartwood) of the most durable local trees (Malmfuru in Norway). When those structures were built, the sapwood was normally cut off and discarded. Such temples and churches were designed with pitched roofs to shed the rain and they were constructed with great attention to detail. Being places of worship, they have almost certainly been well maintained over the years. They will also have undergone periodic repairs. With all these factors taken into consideration, it seems we can build wooden structures to last as long as we like. The primary consideration is to keep the wood dry and, where moisture can not be avoided, use durable wood products: naturally durable or pressure-treated (Hazleden and Morris 1999). Where termites are a problem, specific design elements must be included to exclude them from the structure (Morris 2000).

More detail on construction of wood buildings for durability can be found in publications by the Canadian Wood Council (1995), Dost and Botsai (1990), Lstiburek and Carmody (1991), the National Forest Products Association (1988), Scott (1968), Trechsel (1994), Wilcox *et al.* (1991) and the Wood Protection Council (1993). More detail on protecting wood from termite damage can be found in publications by the UK Building Research Establishment (1976), the National Forest Products Association (1988), and the Wood Protection Council (1993).

Figure 3: The stave church built in 1150 at Borgund in Norway

Most wood products used in full exterior exposure should be constructed from naturally durable or pressure-treated wood if they are to provide a service life, safety and maintenance requirement acceptable to the end user.

5.2 Considerations for Repair and Remediation

Since decay and termite damage are usually far advanced when they are discovered, the primary consideration is normally the restoration of the required strength to the structure. The second consideration is the restoration of the appearance. The third, and often overlooked, consideration is the prevention of recurrence of the problem. This requires an understanding of the causes of the problem in the first place. This should include the search for primary and secondary sources of moisture. Since fungi need moisture contents at or above the fibre saturation point, the initiation of decay may have been associated with a water leak which has since been eliminated. However, once established, decay can progress at moisture contents as low as 22% so it can be maintained by a moist atmosphere. All sources of moisture must be eliminated. It is also critical to remove all infected wood, not only that which is obviously decayed but 60cm beyond the end of the visible decay along the length of the damaged member. As discussed above, visibly rotten wood is the last stage in the decay process, thus WRB may be present in wood which is not apparently affected. Normally decay in part of the cross-section of a wood member means that the entire cross-section has to be replaced.

Eradication of infection by WRB is made more difficult in buildings with brick, block or masonry construction where the true dry-rot fungus can survive in wood concealed within solid walls. In a study by Bricknell (1984) of incidences of the true dry-rot fungus in UK buildings, 52% had a history of dry rot and had undergone previous attempts to eradicate it.

If it is not 100% certain that all the fungal infection has been removed and all moisture sources eliminated, use pressure-treated wood, to CSA O80 standards, to replace rotted members and treat, in situ, the remainder of the original wood. A diffusible, borate-based, preservative is recommended for in-situ treatment either in the form of soluble rods placed in drilled holes or as a brush or spray application to exposed surfaces. Soluble rods are best used where it is expected that the wood will stay wet for some time. Where the moisture source is known, the rods should be placed as close as possible to the point where the water will enter the wood. Soluble rods can provide enough preservative to halt existing infections but a surface application can only hope to prevent WRB and insects from transferring out of infected wood onto new wood.

In the case of subterranean termites, their means of entry to the building should be eliminated by redesign and/or repair. Restoration of other elements of the original termite management system may also be necessary. Where reinfestation seems likely, pressure-treated wood to CSA O80 standards should be used for any repairs.

Where the structure being restored has some historic importance, the historic qualities should not be compromised by the restoration process. It is often desired to retain as much as possible of the original material, thus new wood or other materials may be attached to existing decayed structures. Attempts may be made to restore the strength of rotted wood and fill rot pockets. As a result, existing infections may not be completely eradicated and intensive remedial treatment may be needed. Ideally, nothing should be done to a historic structure that cannot, in future be reversed if more appropriate conservation technology is developed.

For further reading on remediation and repair of decay in buildings refer to Freas (1982) and the publications of the US National Pest Control Association, Dunn Loring VA. Some additional information is provided by Eaton and Hale (1993), Bravery *et al.* (1987), and Levy (undated, 1979?). The recommendations provided by Scott (1968) are designed for British housing and are somewhat out of date. Design and construction principles for primary construction which are also valid for repair can be found in booklets by the Wood Protection Council (1993) and the National Forest Products Association (1988).

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