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ORIGIN OF FROST CRACKS IN STEMS OF TREES

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Abstract. Frost cracks in the stem of living trees are separations along the radial plane. They occur at temperatures below the freezing point of water and result mainly from "frost shrinkage" due to internal drying, that is, freeze-out of cell wall moisture into lumens of wood cells. Wood frost-shrinks more as temperatures are falling. The shrinkage leads to frost cracks mainly because wood tends to shrink more along the growth rings than in the direction of stem diameter. Other factors which contribute to frost cracks are ice layers which grow in the cooling wood, relatively rapid cooling of the stem surface, and expansion of freezing water in waterlogged zones of the stem. The reason why some trees frost-crack while others do not appears to be the notch effect of earlier injuries in the first place, as well as pockets of unusually wet wood in the stem.

When the outdoor temperature drops far below the freezing point of water, some tree stems break open as shown in figures 1 and 2A. The resulting *frost crack* typically extends several feet up the stem, occasionally reaching into the crown area. The crack gapes open, as can be seen on the tree at right of Figure 1; the drawing of Figure 2A is exaggerated in this regard for the sake of clarity. When temperatures return to the freezing point or to somewhat higher degrees, the

Figure 1. Forest stands with frost-cracked oak trees (*Quercus* spp.). (Photographs courtesy of M. Schirp.)

crack—with some delay—gradually closes (Figure 2B).

The microscopically thin *cambial* sheath between the wood and bark cracks, too, but it heals early in the following growing season when its two fracture edges produce new, fusing cells. Wood beneath the healed cambial sheath remains cracked for the rest of the tree's life.

Another healing process develops in new wood. In all growing trees, *mother cells* of the cambial sheath divide to form new wood cells (xylem) at the wood side and bark cells (phloem) at the bark side. The new cells press against the jacket of bark and dilate it, causing the stem to become thicker. Along the frost crack, the cambial sheath produces callus tissue of unusually many and/or thick wood cells besides bark cells, so that outside the healed sheath the growth ring of wood becomes relatively thick and strong. Nevertheless, more often than not, the callus tissue breaks open again in the following winter, until in a relatively mild winter the new wood may have sufficient strength to resist recracking. The excessive annual growth along the crack leaves a *frost rib* (Figure 2C) which only gradually overgrows, and thus remains visible for many years after final crack-closing.

Open frost cracks facilitate entry of wood-damaging microorganisms and insects, which may continue to thrive under the healed crack. Hence, frost cracks are likely to shorten the tree's life; frost-cracked trees, on average, do not reach the age of others.

Misconceptions About the Cause of Frost Cracks

At first glance, frost cracks appear to result from *thermal contraction.* Wood molecules, like molecules of other materials, move closer together when the temperature decreases. The resulting contraction is presumed to lead to frost cracks, because with falling air temperature the stem surface cools faster than deeper layers. The core remains relatively warm and large, restraining the outer cylinder's contraction. If this explanation would be correct, frost cracks would be restricted to the surface cylinder, to sapwood for example, and could not extend to the stem center as most frost cracks do (Figure 2A).

The V-shape of the crack (Figure 2A) is well-known from observing drying checks in tree rounds and utility poles; it indicates relatively large *tangential* contraction (in the direction of tangents along the growth rings), compared with *radial* contraction (in the direction of the stem cylinder's radius). Thermal contraction of wood is indeed higher tangentially than radially. However, small *green* wood samples separated from living trees contract thermally very little (see the temperature range between 30 and 60 °F in Figure 3; the large "frost shrinkage" below 30 °F is explained later). Only dry wood contracts substantially during cooling. Therefore, thermal contraction, as such, cannot contribute to, or cause, the formation of frost

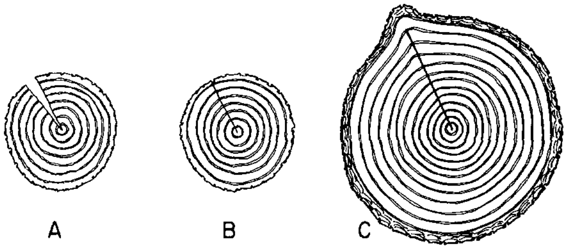

Figure 2. Cross section of a stem with a frost crack. A: at very low temperature in winter of formation. B: at the end of the winter of formation. C: one growth season after the first winter during which the crack did not break out again.

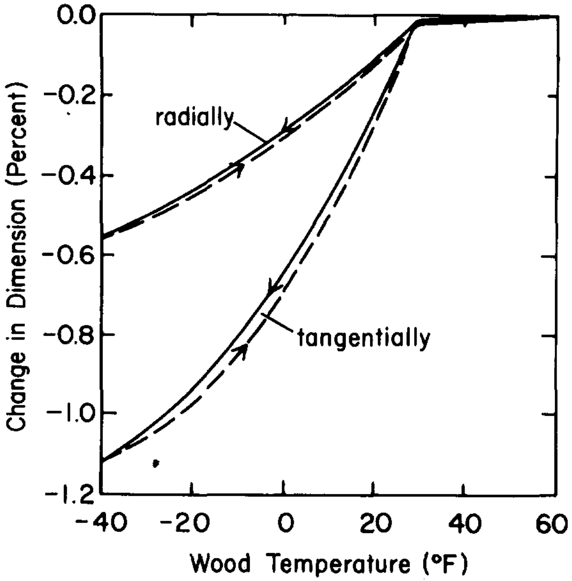

Figure 3. Dimension change during cooling and reheating of green oak wood samples.

cracks.

On the basis of experience with bursting water pipes in winter, one may suspect that frost cracks result from the *expansion of freezing water,* which amounts to 9% in volume and almost 3% in any one direction. This freeze expansion, however, is only a minor secondary cause of frost cracks. Most cavities of wood fibers (Figure 4) and of other wood cells contain not only water but also some air. The freezing cell-cavity water expands into the air space without stretching the cell in girth. Only the few cells whose cavities are completely filled with water expand during freezing. The freeze expansion may contribute to frost cracks in abnormal trees in which waterlogged *wetwood* heartwood is encircled by less-wet sapwood. Trees with this kind of bacteria-infested heartwood, indeed, suffer more frost cracks than healthy trees whose heartwood holds no more or less water than sapwood. Freeze expansion may also contribute to frost cracks in other stems with waterlogged zones, whose expansion tension-stresses the adjoining less-wet tissue.

Freeze-Out of Moisture

During cooling of moist substances below the freezing point of water (32°F), ice often segregates. Arborists know about this segregation from the Native Americans' way of making maple syrup: when sugar maple sap "froze," a layer of pure ice formed at the surface, while the remaining sugar solution underneath became more concentrated. How much water froze out of the sap depended on temperature: the colder the solution became, the more water froze out. In porous solids such as soil, bricks, fruits, and meat, some of the segregating ice accumulates at the surface, but most remains within the solid material in the form of lenses and layers.

In green, cooling wood at slightly below 32°F, all the water in the cell cavities freezes. Moisture in the cell walls remains unaffected at this freezing temperature; being bound to the essentially porous cell wall substance, this moisture is already above 32°F temperature in a sort of solid (*frozen*) state. As the temperature drops farther and farther below 32°F, the cell cavity ice seems to progressively pull moisture out of the cell walls. The apparent pull is explained with the reduced vapor pressure of ice (Kubler 1983), as the higher vapor pressure of some of the bound water drives the diffusion of cell wall moisture to the ice in the cell cavities. How much water freezes out, again depends on temperature; lower temperatures being associated with more freeze-out, since at dropping temperatures the vapor pressure of ice decreases faster than that of bound moisture.

Migration of water out of moist cell walls to ice in the cell lumens appears to be the main cause of frost cracks. The *internally-drying* cell walls become thinner, as do the entire cells; the wood *frost-shrinks.* Note that this frost shrinkage is much larger than the thermal contraction discussed earlier, and has a different cause. Before cracking, stems shrink percentagewise as much tangentially as radially, since the circumference (c) of a circle is proportional to the radius (r; $c = 2\pi r$). Small wood samples which do not contain the stem center, by contrast, shrink independently in the two directions; on average of our tree species, their tangential shrinkage exceeds radial shrinkage by a factor of two. This anisotropy applies to frost shrinkage as well as to shrinkage from evaporation of moisture into the surrounding air (Figure 3). In stems and other wood products with enclosed stem centers, the imposed uniform shrinkage causes tangential tension stress, which may be sufficiently high to break the stem and cause a V-shape crack (Figure 2A).

To understand the cracking resulting from the

Figure 4. Transverse section of Douglas-fir wood, magnified 675x to show cell cavities and cell walls. (Courtesy of U.S. Forest Products Laboratory.)

high tangential frost shrinkage, consider a theoretical stem which does not shrink, neither in diameter (radially) nor in circumference (tangentially), except the last growth ring which tangentially tends to shrink excessively, and to become much shorter. Around the theoretical, dimensionally stable stem the shrinking outer ring stretches itself and breaks when stretched only about 1%.

According to Figure 3, frost shrinkage progresses as the temperature decreases. At the same time, the gap between tangential and radial shrinkage widens. Consequently, in intact stems the tangential tension increases, and the stem may finally crack. The colder the stem, the more likely is frost-cracking, and the wider the crack.

The amount of water frozen out, as well as frost shrinkage, reaches an equilibrium at each temperature. When the wood temperatures rise again, ice moisture diffuses back into the cell wall in proportion to the rising temperature. The walls re-swell to their original dimension at the particular higher temperature, and the frost crack narrows, finally closing when the wood temperature approaches the freezing point of 32°F.

Through frost shrinkage (not through thermal contraction), temperature differences within the stem affect the occurrence of frost cracks. In cooling stems, the still warm, hardly shrunken core restricts shrinkage at the surface and augments the tangential tension. Whether stems in the state of cooling are more likely to crack than

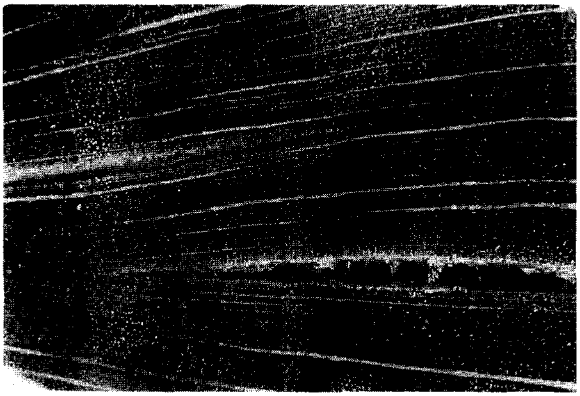

Figure 5. Transverse section of beech wood (*Fagus sylvatica*) magnified 15x. The two radial splits result from formation of ice lenses. The split at left in the upper half is still filled with ice, while in the split in the lower half at right most of the ice has melted. (Courtesy of M. Schirp.)

stems which are cold throughout, depends on the wood's tendency to shrink tangentially more than radially. In some tree species—such as black walnut (*Juglans nigra*), whose small wood samples shrink (and frost-shrink) only a little more tangentially than radially—the temperature difference contributes more to the formation of frost cracks than does the slight shrinkage anisotropy.

Water-logged wood whose cell cavities are completely filled with ice does not frost-shrink, of course; any cell wall moisture migrating to the cavity ice would squeeze the cell wall out and stretch the cell to the original pre-freeze-out size.

Ice may attract water from the adjoining tissue, causing the cell to burst. The ice may grow to a layer many times larger than the cell diameters. Ice layers in the radial plane of wood rays (Figure 5) pry the wood apart as they grow. The resulting fractures are oriented like frost cracks and may develop into frost cracks through their *notch effect* (as we know from cloth, any fracture tends to spread when the material is stressed by some force, such as tangential tension from frost shrinkage in our case). Ice layers press the adjoining wood aside, but they compress the wood less than one may think, because water loss from the adjoining tissue is associated with frost shrinkage. To some extent, the ice grows at the expense of wood volume.

Why some stems frost-crack, while others do not. In most forest stands, only a few trees suffer frost cracks, although all are exposed to the same temperature. Before failing, cracked stems seem to be identical with many others. Likewise, in laboratory trials with short sections of 1 ft thick stems cooled to −40°F, some stems suffered small cracks, while others did not. One probable reason for the different susceptibility may be different moisture contents, particularly pockets of very wet wood whose freeze expansion stretches the adjoining wood.

The main reason why some stems crack, while others do not, appears to be the notch effect of earlier faults. Butin and Shigo (1981) dissected 25 frost-cracked oaks (*Quercus* spp.) and found all frost cracks associated with other wounds, branch stubs, or basal sprout stubs. They concluded: "frost *does* play a role but only as the factor responsible for the *continuation* of the crack;"

therefore they wrote "frost crack" in quotation marks.

People frequently tear off or scrape off patches of bark from the stem. The exposed cambial sheath dies as it dries, so that neither new wood cells nor new bark cells develop on the patch. Fortunately the edge of the surrounding live cambial sheath responds with excessive growth of callus, as explained above for healing of frost cracks. The callus overgrows the patch from all sides and completely covers it during following years, but it does not intergrow with the patch surface and leaves a fissure along the original patch surface. Callus growing from opposite sides over the patch does not intergrow either, and leaves a radial separation. This separation, due to its notch effect, may spread and develop into the frost crack when frost shrinkage generates tangential tension. Hence, we should realize that healed wounds still remain a potential danger for the tree.

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Abstract

Shigo, A. A. 1986. **Journey to the center of a tree.** Am. Forests 92 (6): 18-22, 46-47.

Trees are so common that we often forget how extraordinary they really are. They live on all continents except Anarctica and in an astonishing variety of environments, from tropical to subarctic, rainforest to desert fringe. How have trees been able to survive and thrive? The answers lie within that tree out your window. As we journey to the center of that tree—or any tree—we'll find that the answers lie more specifically in the structural properties and growth processes of a tree. You'll also see that a better understanding of these can have practical applications, such as helping you prune your trees to their advantage and prevent unnecessary wounds. But a journey to the center of a tree will require you to visualize and think about trees in a way that you probably never have before. Trees can adapt to changes in the environment, when change occurs too quickly, they may not be able to respond fast enough. Two species, American chestnut and American elm, were driven to near extinction when people imported other species of chestnut and elm infected with diseases that indigenous trees were not adapted to resist. A journey to the center of these trees would have revealed that they were not able to compartmentalize quickly enough to fight off the unexpected foreign invaders. Our journey has shown us that trees are far more complex than what appears when we look out our window. We have also found that trees rely on structures and processes that no other organisms possess. Perhaps this is how they have survived all these eons and have watched dinosaurs come and go.