Tree Risk Assessment & Tree Mechanics

By Ed Hayes

The art and science of tree risk assessment continues to evolve as we increase our knowledge base and with field experience. Trees do not fail at random. Tree failures are predictable over a broad time range. And tree assessment is not an exact science but a science nonetheless and one that is constantly advancing.

An arborist performing tree risk assessments must be well trained in biology, tree structure, and tree mechanics. The arborist should possess a high level of comfort and experience with the inspection process. It takes a trained eye to recognize the subtle signs of impending mechanical failure. The possible result of over-reading these signs is overreacting. Any existing signs of failure must be thoroughly evaluated to determine cause. Because every tree is different, performing tree risk assessments is a learning process. This article briefly reviews structural defects and basic tree mechanics.

The process for evaluating the risk of tree failure begins with visual inspection for defects (visual tree assessment, VTA), followed by sounding for suspected decay and probing, if necessary, with a portable drill, increment borer, or an advanced decay detection device. Formulating a decision involves considering several factors, including multiple defects, species characteristics, location and extent of decay, characteristics of decay organisms, crown size, crown ratio, stem taper, exposure, target considerations, tree value, and owner attitude.

Learning objectives—
The arborist will be able to

- explain the components of tree risk assessment.
- describe categories of structural defects.
- apply guidelines for evaluating decay above and below ground.
- discuss some basic principles of tree mechanics.

Components of Risk Assessment

The three components of tree risk assessment proposed by Matheny and Clark (1994) are the tree's failure potential, an environment conducive to tree failure, and a target.

Failure Potential

Although some trees without defects fail in major storms, the presence of any defect will increase the chances of failure. Each species has its own profile of defects. Some factors that must be considered include the species' growth habit, tree condition, branch attachments, resistance to decay, condition of anchoring roots, cultural or maintenance history, and previous damage. In addition, the severity of any defects found should be considered. Other factors related to the site such as intensity of use, soil condition, and prevailing winds must be considered in conjunction with the defects present when assessing the potential for failure. Any individual factor can directly impact tree safety (or, more often, multiple factors impact the tree's failure potential). The size of the tree or tree part that may fail is also important. Usually, the tallest, most exposed tree and tree parts are of greatest concern.

Environment Conducive to Failure

A weakened tree that is exposed to additional loads from wind, ice, or other factors obviously will have an increased likelihood of failure, especially if the load is unusual in direction or magnitude. Most tree failures occur during or as the result of storms, and exposure to rain, snow and ice loading, and lightning increases risk of branch and tree failures. Many site factors and past history can influence tree condition and the types and severity of the defects present.

Some examples of stress factors and the injuries or defects they can cause are listed in Table 1.

Table 1. Stress factors and the injuries or defects they can cause.

Stress Factor	Resulting Injury or Defect
Soil compaction, paving, and grade changes	Dieback and deadwood
Construction injury to stem and roots	Cankers, decay, cracks, leaning, and windthrow
Wounds, flush cuts, cavity fillings, and other mistreatments	Cankers, decay, and cracks
Planting too deeply	Dieback, deadwood, stem-girdling roots, and windthrow

Target

Theoretically, without a target there is no hazard. However, in urban settings, we rarely can completely discount target potential. Targets include facilities, people, and personal property. In various tree-rating approaches, targets may be prioritized by intensity of use or exposure to people.

Inspections and Documentation

Inspecting trees for defects must be a careful and systematic process. The entire tree must be inspected. Inspections should be done once a year and following storm events. Inspections are best conducted during the leaf-off season for temperate climate hardwood species to facilitate observation and inspection. Always document the evaluations, recommended actions, and actions taken. Keep permanent records.

Structural Defects

Identification and correction of structural defects such as weak branch attachments, leaning, cracks, wounds, deadwood, and decay may reduce the failure potential (and, therefore, reduce risk to property and injury to people).

Branch Attachments and Branch Failures

Weak branch attachments include unions with included bark and branches formed from epicormic buds. A weak union with included bark has bark present inside the branch union. There is little wood tissue attachment between the codominant stems or branch union with included bark. Weak unions are common in species with an opposite bud set. Examples include maple *(Acer)* and ash *(Fraxinus)* species. Weak unions are often easy to evaluate. Weak unions with open cracks or decay are obvious hazards. The propagating rib on opposite sides of the weak union can be an indicator of an internal crack and, in some cases, decay.

When trees are topped, overpruned, or stressed, they produce epicormic buds. Branches from epicormic buds are weakly attached, especially if there is internal decay below the attachment, which is often the case below old topping cuts. Weak unions are one of the most common causes of branch and stem failures during storm events and one of the easiest defects to prevent. Guidelines call for subordination or removal of all competing leaders beginning the second year after planting. This practice should continue over several years to produce one central leader.

Leaning Trees

Most trees lean to some extent. Phototropism (growing toward light) can cause a natural lean, which may or may not be a problem in later years. The key question is, is the lean natural or is the tree failing? When leaning trees have preliminary signs of failure, further inspection is essential because failure may be imminent (Figure 1). Arborists should be familiar with these signs.

- At ground level, look for soil lifting, movement, or mounding associated with root or root plate disruption, or cracks in the soil near the base. Leaning trees with recent soil lifting, movement, or mounding could indicate the tree is failing.
- At the base, look for compressed or buckling fibers on the lower or compression side and horizontal tension cracks (perpendicular to the stem) on the upper or tension side. Tension cracks are rare and require immediate action—tree removal.
- When roots are severed, there can be a significant loss of root anchoring support, especially for leaning trees. It is the small-diameter, lateral roots under tension that provide the greatest anchoring support for the tree. The tensile (tension-pulling strength) of a 2-inch-diameter root is dramatic and equivalent to as much as 4 tons of holding power.

Cracks

The most common cracks observed in trees are radial cracks. Radial cracks are wood fiber separations along the rays in the axial plane (up and down). Open cracks are physical separations of the wood fibers. Open cracks indicate that part of the tree has failed or is failing. All cracks arise from load imbalances (mechanical stress) and are in most instances predisposed by natural flaws in tree anatomy (natural weak points). Internal cracks may or may not be visible from the outside. Cracks are evaluated for the extent of compromise to the branch or stem cross section, as well as their location and their association with other defects.

Wounds and Cankers

Wounds can lead to cankers, which are localized diseased areas on stem tissue that may be shrunken and discolored. Wounds associated with canker tissue usually fail to compartmentalize completely and often become more serious defects. Wounds must be evaluated for the extent to which they compromise the strength and integrity of a branch or stem. If decay is present, the severity of the defect is greater.

Figure 1. This sugar maple *(Acer saccharum)* has a lean that is not natural, and the tree is failing. Internal decay has reduced the remaining wall to under 20 percent. Note the root flare delamination. There are opposing shear cracks perpendicular to the lean and an obvious tension crack. Immediate removal was necessary.

Deadwood

Dead trees and dead branches can fail at any time. Dead and decayed wood fail at different rates depending on species, material size and weight, and resistance to decay. Dead branches or dead tops that have already broken off and lodged (hangers) are especially high risk.

Decay

Understanding the process of tree decay is vital to evaluating trees for decay. The symptoms and signs of decay include cavities, holes, cankers, branch stubs, fruiting structures (mushrooms and conks) of decay organisms, stem bulge, and stem swelling (Figure 2). Tree roots typically decay from the bottom up.

The key to understanding compartmentalization is that decay is confined to the wood present at the time of wounding unless it breaks through the barrier zone. The extent of the internal decay is *not* the primary issue. Most important is the amount of sound wood present in the stem or remaining wall. (Periodic reinspection is required because some decay organisms can cross the barrier zone into wood tissue that was laid down after initial wounding.)

The amount of sound wood is determined based on stem and branch diameters or cross-sections. Trees can have decay and still be stable; in fact, most large trees do contain decay. Generally, a full-crown tree without a lean can be up to 70 percent hollow—a level of risk that can be tolerated (in the absence of cavities or other factors). Trees such as this may be within safety margins but must be fully evaluated for possible mitigation.

Anything above this amount of decay (70 percent), or defects in addition to the decay, increase risk factors (Figure 3). Current guidelines in the United States recommend a minimum 30 percent of the stem and branch wood diameters be sound. The amount of sound wood remaining is calculated as the ratio of remaining wall-to-stem radius (t/R), or 15 percent of stem or branch diameter (remaining wall on each side of the stem or branch), excluding the bark. The guidelines apply to full-crown trees.

Figure 3. This failed bur oak had a 15 percent remaining wall for most of 75 percent of the stem circumference. It was in the open with a full crown, which is why it failed in an average storm event.

Where large cavity openings exist, guidelines call for increasing the sound wood requirement (Figure 4). The size, location, and extent of the cavity must be considered in assessing the risk potential. If a tree has less than 20 percent residual wood, the Bartlett Tree Research Laboratory (Fraedrich and Smiley 1999) recommends that it be removed without climbing. Instead, it should be removed using an aerial lift or crane.

Figure 2. This bur oak *(Quercus macrocarpa)* has a sign of decay, yet there is no symptom of swelling. Further examination is needed, first by sounding, then by invasive or advanced techniques. The stem may have an asymmetrical column of decay, the decay may be extensive, or both. Check through the opening first.

Another way to approach estimating whether sufficient sound wood remains is using a guideline that calls for 1 inch of sound wood to be present in the remaining wall for each 6 inches of stem or branch diameter. This guideline is a starting point, a way to quickly estimate the sound wood requirement. The actual remaining wall thickness must be calculated as previously described, based on the results of the inspection at the drilling site, as well as the cavity opening percentage. For asymmetrical decay columns, the risk of failure increases when the areas of decay are large and the remaining wall on the decayed side is thin. Ultimately it may be possible to use wind load analysis to predict tree failure factoring in stem form, geometry, and average material wood fiber strength. More research is needed to provide base information that can be applied to this form of analysis.

A guideline suggested by the Bartlett Tree Research Laboratory (Fraedrich and Smiley 1999) for major buttress root flares is a sound wood requirement of 15 percent of dbh for every two out of three roots present. The Bartlett Tree Research Laboratory recommends that trees with more than a third of the buttress roots significantly decayed, missing, or severed be recommended for removal. They define "significantly decayed" as having less sound wood on the top of the buttress root than dbh times 0.15. For a 30-inch tree, if the buttress root has less than 4.5 inches

Figure 4. This red maple *(Acer rubrum)* has a 20 percent cavity opening from mid-opening to the ground line relative to the increasing circumference. A consistent, 20 percent remaining wall exists around the cone-shaped base. Although the maple is 80 feet tall, it is protected by its downslope position by some large white pines above. There is no immediate target.

of sound wood, it would be considered significantly decayed.

Diagnostic Tools to Evaluate Tree Defects

Fortunately, arborists now have a number of tools at their disposal for evaluating tree defects. The basic equipment includes, but is not limited to, a mallet for sounding; diameter tape; logger's tape (or suitable distance tape); an increment borer; a portable drill (preferably 18 volt or higher); drill bits (brad point), 1/8-inch by 8 to 12; clinometer; calculator; soil excavation tools; and any of the advanced decay detection devices such as the Resistograph. Invasive techniques (drilling or boring) are used where needed to confirm or alleviate suspicions of decay. The wounds made by the drills may or may not impact the ultimate extent of decay depending on the decay organism involved and the tree's ability to compartmentalize the wounds. One noninvasive piece of equipment available is the PICUS sonic tomograph, which produces a graphic representation of a tree's cross section based on the speed of sound among multiple points around the circumference of the tree (Figure 5). In the future, ground-penetrating radar adapted to use for decay detection may be possible.

Basic Tree Mechanics

Tension is pulling or lengthening; compression is pushing or shortening. A tree is loaded by tension on the outside and by compression on the inside. Shear is slippage. Claus Mattheck lectures about how trees "react" over time to mechanical stress by adding more wood where the loading is greater and less wood where the load forces are lesser (adaptive growth). Adaptive growth is uniform (mechanical) stress distribution. Leaning trees, for example, can put down wood tissue to adapt to the added load of the lean. Conifers (gymnosperms) "push themselves up" on the lower compression side with compression wood (reaction wood). Hardwoods (angiosperms) "pull themselves up" on the upper tension side with tension wood.

Stems and branches must be supported with adequate taper (slenderness ratio, also called the height-to-diameter ratio). Taper serves as defense against stem and branch failure. Typically, mature hardwoods in the upper midwestern United States have slenderness ratios of 20 while conifers are 30. Lack of taper is a risk factor for solitary trees, trees from stands that become edge trees, and for branches with taper problems (lion tailing).

Trees evolved with excess capacity both biologically and mechanically. In engineering, this is referred to as the *safety factor* or *design factor*. That is, if a structure is designed to handle loads that are double the expected working loads, they are said to have a safety factor of two. The safety factor for trees has been estimated to be about four times their working load. The concepts of safety and reliability are linked. A safe structure performs reliably under the normal working conditions it experiences. The connection here is that most trees perform reliably when structurally sound. As tree defects take their toll, the safety margin is reduced. A tree with a structural defect can fail at less than normal working conditions (average storm events).

The goal of risk assessment is to predict potential failure in trees. Typically, normal weather conditions are factored in. In most geographic areas, wind forces up to 50 mph are considered normal. At wind forces in excess of 70 mph, even structurally sound trees can be overpowered.

Treatment and Prevention

Mitigation is the process of reducing tree failure potential. A level of zero risk does not exist unless the tree is removed. Sometimes the risk of failure is unacceptable and cannot be mitigated. Once a tree is condemned, its removal should take place as soon as possible or the target area should be closed. Short of removal, treatment options include moving the target, removing dangerous branches, cabling and bracing, propping, reducing the crown, and closing the area. Treatment options for cavities are limited. No scientific or experimental evidence exists to support cavity treatments; more often, cavities are filled for aesthetic or maintenance reasons.

Prevention of tree defects involves focusing on all of the best management practices: selecting quality planting stock; matching species to site; planting properly; pruning to establish a strong structure; and avoiding wounds, injuries, and construction damage.

Managing Veteran Trees

Old trees are sometimes called veteran trees. Arborists in Europe have been focusing on techniques to preserve veteran trees for decades or even centuries. The steps to consider include

- predicting the failure pattern that is to be expected.
- outlining the options that would need to be taken to prevent the failure.
- evaluating the outcomes of those treatments over time.

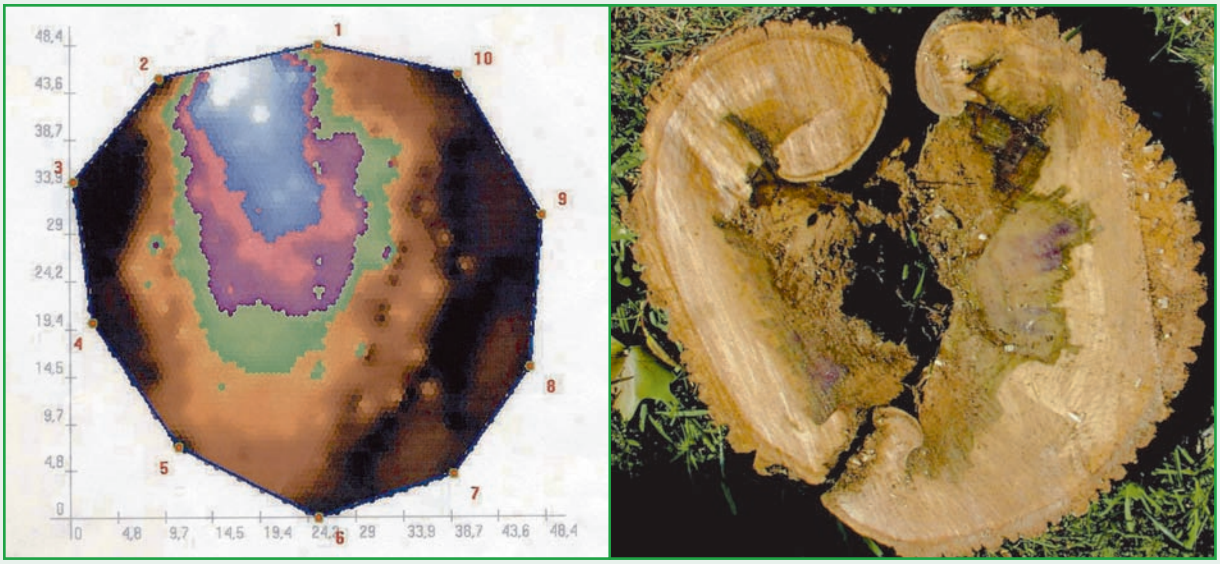

Figure 5. A tomograph taken of a cross section of a tulip poplar *(Liriodendron tulipifera)* (left) with the dissected comparison (right).

If mechanical means are to be used, how will they be dimensioned? Static cabling over time can suppress secondary thickening or diminish the positive effects of adaptive growth. Should more dynamic cabling techniques be considered? Sometimes cable installation is accompanied by crown reduction. Many European arborists advocate progressive crown reduction over a period of many years to reduce failure potential. While this practice certainly can be effective in reducing the likelihood of failure, other arborists would argue that the aesthetic value of the tree is also reduced, perhaps unacceptably.

The great Wye Oak failed in June 2002 after a long, distinguished life in Maryland. Its fate may have been sealed many years ago when the decision to cable was followed by the decision to add more cable. It still took an enormous force to topple the Wye Oak, but, judging from the pictures of the amount of sound wood in the remaining wall, the tree had few safety reserves left. The wind force merely had to challenge the aboveground mass. Members of the Society of Commercial Arboriculture visited the Wye Oak in 2000 during ISA's Baltimore conference. At that time, a small debate arose between some European and some American arborists. The Americans advocated preserving the tree in its full majesty by employing judicious pruning to minimize removal of live tissue, installing cables, and taking measures to improve and maintain tree vitality. The Europeans suggested a gradual and systematic reduction of the crown to reduce failure potential. The latter measures likely would have saved the Wye Oak, yet many arborists would question what would be left to save.

Managing Risk

Two important strategies should be used for managing the potential liability associated with performing risk assessments. The first is expert tree assessment (training), and the second is limiting liability. Consulting arborists should consider using a disclosure statement. A disclosure statement does not remove the arborist from all potential liability, but it can limit liability. Ultimately, the decision of how much risk to accept lies with the client. The goal of the assessment is to determine the risk and convey it to the client in an easy-to-understand way and in writing. The arborist may make recommendations and suggestions, but the client decides the best course to take.

All trees have a risk of failure. As trees increase in size, mass, and maturity, the risk of failure increases. Eventual failure is inevitable. Arborists must learn from tree inspections and tree failures. The most important and reliable field information is obtained from a tree or branch failure that does not strike an important target. Perform the dissections, take the measurements, and do the math. A tree failure without a loss is a valuable piece of information. Education in tree biology and structural mechanics is important, and training in risk assessment is essential. Even with thorough education and training, however, nothing can substitute for experience and good judgment.

References

Fraedrich, B.R., and E.T. Smiley. 1999. *Guidelines for Qualifying and Evaluating Wood Decay in Stems and Branches.* Bartlett Research Technical Report, Bartlett Tree Research Laboratory, Charlotte, NC.

Matheny, N.P., and J.R. Clark. 1994. *A Photographic Guide to the Evaluation of Hazard Trees in Urban Areas.* International Society of Arboriculture, Champaign, IL.

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