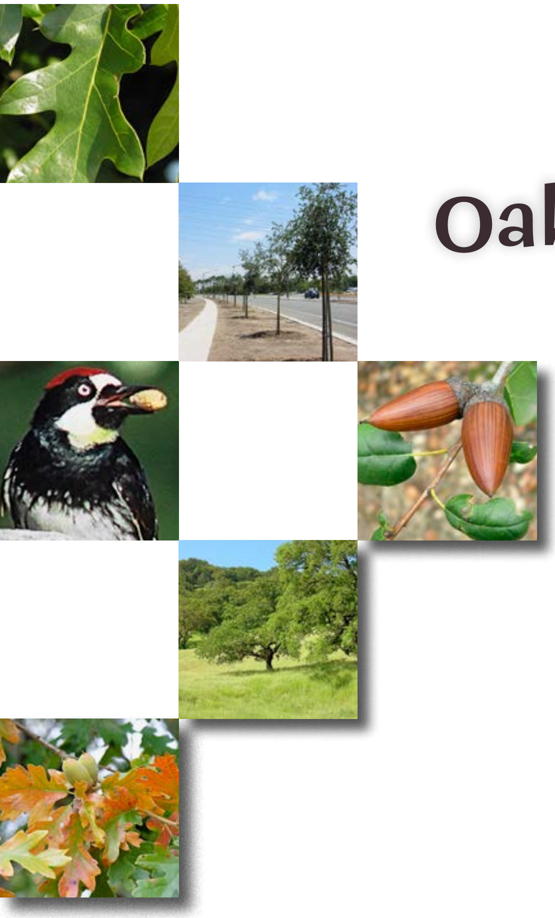

Oaks in the Urban Landscape
Selection, Care, and Preservation

Chapter 8

Structural Failures, Defects, and Risk Assessment

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Chapter 8

Structural Failures, Defects, and Risk Assessment

Oaks can drop branches, topple over, or otherwise break apart. When these structural failures occur in urban areas, unfortunate consequences can follow, such as personal injuries and damage to homes, vehicles, and utilities (fig. 8.1). These outcomes represent liability risks for tree owners and managers. Avoiding such consequences must be an integral part of all tree management programs. This is especially important for oaks because they can achieve a very large size and, when close to people and structures, can have a significant potential to cause injury and damage. For urban oaks, maintaining strong structure is just as important as maintaining good health (fig. 8.2).

To minimize the potential for failure in oaks, it is important to understand the types of failures that can occur, be able to recognize defects, know how to assess specific defects for their potential to cause or contribute to a failure, and be able to mitigate defects when possible. In addition, preventing failures by minimizing defect development in young trees must be an integral part of management programs. This chapter addresses these topics as they relate to oaks. Data from the California Tree Failure Database (CTFD) is included to provide a quantitative assessment of failure types and patterns for California native oaks (see sidebar). Keep in mind that it is not possible to eliminate the potential for failure in oaks, but it is possible to minimize it and thereby reduce risk.

Figure 8.1. As for other genera and species, oaks are subject to structural failure (branch breaks, uprooting, and trunk breaks) that can cause property damage, personal injury, and liability risks. Here, a large branch of valley oak caused considerable damage when it fell on a parked car.
B. Hagen

For more information, refer to the following:

- tree risk management: Matheny and Clark 2007a, b, and c.
- identification of structural defects: Matheny and Clark 1994.
- tree structure and development: Harris, Clark, and Matheny 2004.

Types of Failures

Structural failures can be classified as being one of three general types: trunk, branch, or root. In the CTFD, root failures constitute 36% of all reports for oaks, while 35% are trunk failures and 29% are branch failures. For each of these failure types, breaks can occur at different locations (e.g., at the base or midsection of a trunk); causal factors differ, and the general level of risk varies.

Figure 8.2. This coast live oak (A) was evaluated as being both healthy and structurally strong, while the southern live oaks shown in (B) are healthy but, with multistem architecture and weak branch attachments, were assessed as being structurally weak.
K. Jones

Summary of Oak Failures in the California Tree Failure Database (CTFD)

The California Tree Failure Report Program (CTFRP) is a University of California program that has documented over 4,900 tree failures in California since 1987 (fig. 8.3). Information identifying species, size, location, type of failure, causal factors, site conditions, and weather has been collected by a network of cooperators for individual trees and entered into the California Tree Failure Database (CTFD, http://ucanr.org/sites/treefail/). Data is used to describe characteristics of structural failures of common species and identify key factors that contribute to failures. With sufficient data, species profiles can be constructed that assist tree managers in assessing and managing species to minimize failure potential. Collectively, oaks are the largest group in the database. The following is a summary of reports for oaks as of July 2010.

- Total number of reports: 1,063
- Number of reports for California native species:

Q. agrifolia	coast live oak	530
Q. lobata	valley oak	243
Q. kelloggii	California black oak	119
Q. wislizeni	interior live oak	81
Q. douglasii	blue oak	42
Q. chrysolepis	canyon live oak	14
Q. garryana	Oregon white oak	5
Q. engelmannii	Engelmann oak	1

- Type of failure (% of total): root 36%, trunk 35%, branch 29%.
- Mean age: 110 years.
- Mean diameter at breast height (DBH): 35 inches.
- Mean height: 54 feet.
- Mean crown spread: 52 feet.
- Reports for age classes (% of total):

< 50 years old	19%
51–100 years	43%
101–150 years	19%
151–200 years	12%
> 200 years	7%

- Wind speed at time of failure (% of reports): 0 to 5 mph 43%, 5 to 25 mph 29%, over 25 mph 28%.
- Structural defects contributing to failures, excluding decay (for failures associated with decay, see p. 196)

heavy lateral limbs	15%
multiple trunks or codominant stems	14%
failed portion dead	13%
none	11%
unbalanced crown	10%
leaning trunk	9%
dense crown	7%
other	6%
girdling roots	2%

Figure 8.3. The California Tree Failure Database (CTFD) contains over 1,000 reports of oak failures. Included are branch breaks, trunk breaks, and uprootings. The large codominant stem that failed on this coast live oak fell across the adjacent roadway, and details of the failure were entered into the CTFD. L. Costello

Keep in mind that report numbers for species do not provide an assessment of the frequency of failure for the species (i.e., how often a species fails relative to its occurrence in a population of trees). Rather, it is likely the data reflect the relative abundance of a species in the areas from which reports are being received. To determine frequency of failure, the population size is needed. Since this information is not known for species in the CTFD, an assessment of the propensity of one species to fail relative to other species cannot be made.

In 2006, the CTFD merged with the International Tree Failure Database (ITFD). All data from the CTFD is now contained in the ITFD. For more information, see the ITFD Web site, http://svinetfc2.fs.fed.us/natfdb/.

Branch Failures

Branch failures can occur at the point of attachment or along the limb (fig. 8.4). Data from the CTFD indicates that 37% of branch failures occur at the point of attachment, while 63% occur along the branch. For breaks along the branch, 59% occur within 6 feet of the point of attachment, and 41% occur beyond 6 feet. Common causes include weak attachment (included bark), heavy end weight, decay, internal cracking, lack of taper, horizontal orientation of branch, and dieback (dead branch). Frequently, a combination of one or more of these factors in concert with adverse environmental conditions (principally wind and rain) leads to branch breaks. Nonetheless, oak branch failures do occur during low-wind conditions. In fact, 57% of oak branch failures in the CTFD occurred when wind was less than 5 mph, while 21% occurred when winds were between 5 and 25 mph, and the remaining 22% occurred under higher wind conditions (greater than 25 mph). Although a significant defect is typically associated with failures during low-wind conditions, oak branch breaks have been reported to occur during hot, calm conditions when no visible signs of defect are present (fig. 8.5). This type of failure has been termed sudden branch drop (SBD) and is not uncommon in oaks (see sidebar).

Figure 8.4. Branch failures can occur at the point of attachment or along the limb. The failure of a large branch on this valley oak (A, arrow) occurred at the point of attachment and was associated with a bark inclusion. The branches of this valley oak (B, arrows) failed along the limb. Likely, an upper branch failed first, causing the failure of the lower branches. B. Hagen (A); L. Costello (B)

Sudden Branch Drop

Sudden branch drop (SBD), or summer branch drop, is a term that has been used to describe the failure of branches during the summer months when days are hot and the air is calm (see fig. 8.5). By some accounts, branches seem to suddenly explode from the tree, sometimes accompanied by a very loud sound. This type of failure has been reported in Australia, England, South Africa, Canada, and the United States (Harris et al. 2004). At some locations, such as the Royal Botanic Gardens in Kew, England, signs have been posted warning visitors that large trees are liable to shed branches without warning.

Harris, Clark, and Matheny (2004) provide a review of some of the characteristics that have been ascribed to SBD failures:

- failure of apparently sound limbs
- hot, calm summer afternoons
- branches more horizontal than vertical and extending beyond the crown
- break most often occurring along the limb some distance from the attachment
- wood at break may appear sound or the branch center may be decayed
- more common in overmature and senescent trees than in young or juvenile trees
- occurs on deciduous trees, broadleaf evergreens, and conifers

Genera and species reported to experience sudden branch drop include *Acer saccarhinum*, *Aesculus*, *Ailanthus altissima*, *Castanea sativa*, *Cedrus*, *Eucalyptus*, *Fagus*, *Ficus microcarpa*, *Fraxinus*, *Grevillea*, *Liquidambar styraciflua*, *Olea europaea*, *Pinus*, *Platanus*, *Populus*, *Quercus*, *Salix*, *Sequoiadendron giganteum*, *Sophora japonica*, and *Ulmus* (Harris et al. 2004).

Figure 8.5. Of the California native oaks, sudden branch drop is most common in valley oak. The branch failure shown in the upper crown of this valley oak (arrow) was considered to be a case of sudden branch drop because it occurred during a hot (> 90ºF), calm day, and wood at the break appeared to be sound (inset). L. Costello

In California, SBD appears to be most common in the Central Valley, but it also occurs elsewhere. Failures occur in urban and rural sites and in irrigated and nonirrigated settings. Oaks in particular are noted for being susceptible. In the California Tree Failure Database (CTFD), 78 cases of SBD were found when data was sorted for branch breaks occurring during hot (> 70ºF) and calm (wind < 5 mph) days, along the branch, and without visible defects. When compared with other genera, oaks were found to have the greatest number of cases (27% of all SBD failures). For oak species, the majority of SBD reports were for valley oak (57%), followed by coast live oak (29%), black oak (9%), and Oregon white oak (5%).

Even though there are many reports of sudden branch drop, surprisingly little technical information exists that contributes to an understanding of this phenomenon (Costello 2005a). Ostensibly, something unique about hot, calm weather causes branch wood to become less resistant to loading. Shigo (1989) suggested that SBD may develop from internal cracks in large branches caused by wounds and flush cuts. During hot, dry conditions, changes in wood properties in the cracked section may lead to failure. Others suggest that the position and orientation of the branch are key factors. Perhaps it is a combination of factors: some defect (as yet undetermined) in branch wood is exacerbated by hot, calm conditions and, in concert with a critical end weight and perhaps a certain branch orientation, the branch is shed when the load-bearing capacity of the wood is exceeded. Certainly, further research and close inspection of failed branches is needed to provide a definitive assessment. In the interim, pruning to lighten branches with heavy end weights or to reduce overextended branches may be a useful practice to reduce the potential for SBD failures.

Both small- and large-diameter branches have been reported to fail, either at the point of attachment or along the branch. Branches with a diameter of less than 12 inches at the point of breakage account for 34% of failure reports, while 44% are for branches from 13 to 24 inches, 16% for 25 to 36 inches, and 6% for branches larger than 37 inches. Although small-diameter branches (less than 2 inches) represent a lower risk than larger branches, damage can result from branches in all diameter classes. (For a definition of risk as it applies to trees, see sidebar.)

Trunk Failure

Trunk failures can occur anywhere along the main stem (fig. 8.6). In the CTFD, 37% of oak trunk failures occurred at the ground line, while 33% occurred between ground line and 5 feet, and the remainder (30%) occurred above 5 feet. Trunk diameter at the point of failure ranges from 13 to 36 inches for the majority of cases (72%), while smaller diameters (less than 12 inches) represent 12% of all cases and larger diameters (greater than 36 inches) account for 16%. In cases where more than one main stem exists (multiple trunks or codominant stems), failures occur principally at the point of attachment.

Common causes of trunk breaks include weak attachment of codominant stems (the stems split apart), decay, internal cracking, unbalanced crown distribution (top heavy), and girdling roots. As noted for branch failures, a combination of one or more structural defects and adverse environmental conditions usually leads to trunk failure. Generally, trunk breaks occurring in the lower half of the stem (basal section) are of greater concern (higher risk) than those occurring in the upper half, largely because lower trunk failures constitute whole-tree failures, while only part of the tree is involved in upper trunk failures. Both can cause severe damage or injuries, however.

Figure 8.6. An extensive amount of decay (brown rot) developed in the trunk of this oak (A) and led to its failure. Upon inspection of the trunk of this valley oak (B), no evidence of decay was apparent, but an internal crack was found. B. Kempf (A); B. Hagen (B)

Tree Risk Terms

- Risk: the potential for injury or damage due to tree failure.
- Risk assessment: The process of evaluating the likelihood that a tree or tree part will fail and cause injury or damage.
- Hazard: the presence of a condition that is likely to cause injury. In a risk assessment, a tree is considered to be hazardous if the potential for injury or damage due to tree failure exceeds a threshold that is defined by the tree owner or managing agency.

Source: Matheny and Clark 2007b.

Root Failure

Typically, root failures result either from breakage of anchoring roots or lifting or rotation of all or part of the root plate. In some cases, a combination of root breakage and root plate lifting is involved. In all cases, anchorage is lost and the entire tree fails (fig. 8.7).

Root breakage

Whole-tree failures are not uncommon following the breakage of relatively large-diameter roots. In many cases, heavy wind loads and decay contribute to breakage. In some cases, wind loads alone simply exceed the capacity of sound roots to tolerate the load. When root decay occurs, however, wood strength is compromised and the capacity of roots to tolerate wind loading is reduced. In other cases, decay alone can diminish the capacity of roots to support the tree to the point where it fails.

Similar to breakage, root injury caused by cutting (root pruning) or mechanical damage (e.g., trenching) compromises anchorage and can lead to failure. Root pruning that

Figure 8.7. This valley oak (A) failed as a result of extensive root cutting on one side of the tree. During a winter storm, saturated soil and shallow root development led to a loss of anchorage and uplifting of the root plate of this coast live oak (B). Extensive decay in the lateral and oblique roots of this valley oak (C) was considered to be a key factor leading to failure. B. Hagen

removes lateral roots close to the trunk can substantially destabilize a tree, particularly if the roots are cut on the windward side of the trunk (Fraedrich and Smiley 2001). Wounding from root pruning and mechanical injury can lead to decay, which further reduces the capacity of injured roots to tolerate loads.

Root plate lifting

Strong winds and saturated soil conditions can cause the root plate (roots and adjacent soil) to lift, resulting in whole-tree failure. Lateral wind forces acting on the trunk transfers stress to the roots. Roots on the windward side of a tree are pulled upward under tension, while those on the leeward side are pushed downward by compressive forces. If the wind is strong enough, tension forces applied to the roots on the windward side cause roots (and soil) to lift. Roots under compression may crack and buckle downward. The root plate appears to tilt, so that the windward side roots are lifted and exposed, while leeward side roots push downward. Moisture plays a major role in root plate lifting because the cohesive properties of a soil are reduced under saturated conditions, permitting roots to lift more readily than they do in drier soil.

In addition to strong winds and saturated soil conditions, restrictions in root distribution can contribute to root plate lifting. Physical barriers (curbs, concrete footings, foundations) or restrictive soil conditions (compaction, hardpan, shallow soil over rock, high water table) can limit the radial and vertical distribution of roots, leading to diminished anchorage across certain parts of the root plate. If both conditions exist (radial and depth limitations), an increase in the potential for root plate lifting is likely.

Factors associated with oak root failure

Most root failures in oaks occur in relatively large-diameter trees. Trees with DBH ranging from 18 to 60 inches account for 80% of all root failure cases in the CTFD, while those less than 18 inches represent 16%, and those greater than 60 inches account for 4%.

Although many root failures occur during wind and rain events, it is important to note that some occur during dry, calm conditions. In the CTFD, 28% of all oak root failures occurred during dry conditions, and 32% occurred during low-wind conditions (< 5 mph). Conversely, 67% of root failures were associated with rain events, and 68% with winds greater than 5 mph.

A key defect associated with root failures is decay. In the CTFD, 74% of all oak root failure reports identified decay as a primary contributing factor. In 35% of these cases, the extent of decay was greater than 50% of the root cross-sectional area (at the break), while 23% of cases reported decay affecting 26 to 50% of the cross-sectional area, and 13% with less than 25%. Of cases where decay and wind were reported to be associated with the failure, 67% occurred when winds were greater than 5 mph and decay was greater than 25% of the cross-sectional area. Only 9% of root failure cases occurred when winds were less than 5 mph and decay was less than 25% of cross-sectional area, while 24% occurred when winds were low and decay was greater than 25% of the cross-sectional area. Although wind is an important factor in many oak root failures, CTFD data indicate that some root failures occur as a result of decay alone.

Structural Defects and Contributing Factors

To reduce the potential for structural failure in oaks, it is important to be able to recognize key defects (e.g., decay) and be aware of contributing factors (e.g., improper pruning). Here, brief descriptions of common defects and contributing factors are presented as they relate to oaks. Keep in mind that these are not the only defects and factors that can lead to failure in oaks; certainly, others do occur, but these are defects most commonly reported in the CTFD.

Decay and Canker Rots

Decay is a major defect that contributes to branch, trunk, and root failures in oaks (fig. 8.8). Of the 1,063 failure reports for oaks in the CTFD, 74% identified decay as a primary factor contributing to failure. For the different failure types, decay was reported as a primary factor in 80% of all trunk failures, 75% of root failures, and 65% of branch failures. For trunk, branch, and root failures combined, over 50% of the cross-sectional area of the wood at the point of failure was decayed in 52% of all decay-related failures. In an earlier report, Edberg and Berry (1999) indicated that decay was associated with 83% of all trunk failures in coast live oak.

Some level of decay occurs in most oaks, with the amount varying with age, species, health, wounding, and environmental conditions. Older, declining trees with large pruning wounds are likely to have greater levels of decay than younger, vigorous trees that have experienced little wounding. In the CTFD, only 16% of failures associated with decay were less than 50 years old, while 63% of cases were 50 to 150 years old, and 21% older than 150.

Wood decay fungi digest cell wall materials, diminishing the load-bearing capacity of the wood. The two principal types of decay are white rots and brown rots, which are distinguished by the cell wall materials they digest. White rot fungi degrade cellulose, hemicellulose, and lignin, producing a moist, soft, stringy, or spongy decay that becomes lighter in color than sound wood. Brown rot fungi degrade cellulose and hemicellulose, leaving lignin largely unaffected. Wood becomes brown, dry, and crumbly, with both longitudinal and transverse cracks (see figs. 7.96 and 7.97).

Canker rots are perhaps the most serious of the wood-decaying pathogens of oaks (Swiecki et al. 1990). Generally, canker rots enter through wounds, dying branches, or branch stubs and decay underlying heartwood. Spreading into sapwood and cambium tissues, they cause cankers to form in bark tissues (see sidebar). By decaying both heartwood and sapwood, canker rots can substantially diminish the load-bearing capacity of wood, leading to branch and trunk failures. For complete descriptions of common wood decay fungi and canker rots occurring in California native oaks, refer to Swiecki and Bernhardt 2006; for a general discussion of tree decay, refer to Hickman and Perry 2003.

Figure 8.8. Extensive decay in the trunk of this valley oak (A) led to its failure. The failure of this large coast live oak (B) was caused by extensive decay in the root collar. B. Hagen (A); L. Costello (B)

Locating and Measuring Decay

Methods currently used to locate and measure decay in trees include the portable drill, resistance microdrilling, and sonic tomography (fig. 8.9). Brief descriptions of each approach are given here, while more detailed information can be found in the references.

- For evaluations and comparisons of these and other techniques, refer to Nicolotti and Miglietta 1998; Nicolotti et al. 2003; and Harris et al. 2004.
- For an evaluation of sonic tomography for decay detection in red oak, refer to Wang and Allison 2008; in white oak, refer to Gilbert and Smiley 2004.
- For an assessment of the IML-Resistograph for decay detection in eucalypts, refer to Johnstone et al. 2007.
- For a comparison of portable drilling and resistance microdrilling in eucalypts and elms, refer to Costello and Quarles 1999.

Figure 8.9. Portable drill (A), resistance microdrilling (B), and sonic tomography (C) can be used to determine the extent of decay in oaks. K. Jones

Portable Drill

This simple and relatively inexpensive technique has been used by arborists for a number of years. A brad-point drill bit is driven into the tree using a battery-operated drill, with typical drill bits being 12 inches long and having a diameter of ⅛ inch. Changes in drilling torque indicate changes in wood resistance: resistance diminishes when passing from sound wood into decayed wood. The operator notes wood resistance changes along the drill path and evaluates the condition of wood drillings (chips and shavings) removed from the hole. Based on torque changes and wood evaluations, an assessment of decay presence or absence is made for each drilling location and depth. Although this method has been found to be useful in detecting decay (Costello and Quarles 1999), it is invasive, and drill holes may serve as avenues for subsequent fungal development.

Resistance Microdrilling

This relatively new technique (Bethge et al. 1996) uses a specialized tool called the IML-Resistograph. A battery-operated motor drives a specially engineered drill bit (referred to as a "needle" by the manufacturer) into the wood at a constant feed rate. The drill bit varies in length (currently 5 inches to 19 inches) and has a diameter of ⅛ inch at the cutting tip and ¹⁄₁₆ inch along the shaft. Similar to the portable drill, changes in wood resistance are used to determine decay presence or absence. Unlike the portable drill, however, the resistograph plots resistance measurements on a chart that corresponds to drill bit depth in the wood. Changes in resistance patterns are used to assess decay location and extent. Although this technique has been found to reliably detect decay in *Eucalyptus* spp. and elms (Costello and Quarles 1999), it is also invasive and may create avenues for fungal development (Johnstone et al. 2007).

Sonic Tomography

Unlike the drilling methods, this minimally invasive technique uses sound waves to detect decay. A specialized instrument called the Picus sonic tomograph (Argus Electronics GmbH, Rostock, Germany) generates decay images using a set of sensors attached to pins (nails) that are hammered into the trunk (through the bark and into the outermost wood). By tapping on each of 10 or more sensor pins that are evenly spaced around the trunk, sound waves are propagated through the wood, and sensors measure the relative speed of transmission. Because sound waves passing through decayed wood move more slowly than through solid wood, differences in sound wave transmission can be used to identify areas of decay. Using Picus software, measurements are processed with a computer to create a 2-dimensional image (tomogram) of the trunk or branch cross-section. The location and extent of decay can be determined by interpreting color-coded tomograms. Although this technique has been found to identify decay location and extent in oaks, it can have difficulty distinguishing decay from wood cracks (Wang and Allison 2008).

Figure 8.10. Cankers are typically caused by a pathogen (fungi and bacteria), but can they can also be caused by abiotic agents, such as sunburn. Both the cankers shown here (A, B) likely resulted from fungal infections. B. Hagen

Decay development is largely a function of three factors: host, pathogen, and environment. The age, health, and inherent capacity of a host to limit (compartmentalize) decay affect the extent of decay. Old trees are less likely to limit decay than are young trees (Rudman 1964). Certain species compartmentalize decay readily, while others do not (Shigo 1986). Although response differences have been found for certain oak species (Grabosky and Gilman 2007), these differences have not been established for California native species.

Wood decay fungi vary in their capacity to infect and develop in trees (Schwarze et al. 2004). Some infect a wide array of species, while others are limited. Some develop aggressively in hosts, while others progress slowly. Since host and pathogen interactions vary substantially, it is important to identify the specific pathogen causing decay and collect information regarding its virulence. Typically, sporophores and laboratory cultures are used for the identification of decay fungi (Swiecki and Bernhardt 2006; Luley 2005). Recently, however, DNA isolation techniques have been used to identify these fungi from samples of decayed wood (Garbelotto 2008; Guglielmo et al. 2007). This technique takes relatively little time (compared with laboratory cultures) and can be used to identify multiple species of fungi that may be present.

Decay development is also affected by environmental conditions. Temperature, moisture content, and oxygen concentration influence the activity of wood decay fungi. Generally, relatively low temperature, dry environments, and low oxygen levels are less favorable for fungal development than warm, moist, well-aerated conditions. Although these factors are difficult to monitor in trees, some consideration of how they may affect fungal activity will help when formulating assessments of decay development (Hagen 2007).

Cankers: What Are They?

Cankers are localized areas of dead, sunken, or missing bark tissue on the trunk or branches (fig. 8.10). They can be caused by fungi, bacteria, mistletoe, sunburn, or mechanical injury. Cankers allow the entry of decay-causing pathogens that can affect both heartwood and sapwood, decreasing the load-bearing capacity of wood. Hayes (2005) indicates that cankers affecting more than 40% of the circumference of a trunk or branch can be considered hazardous, while Fraedrich and Smiley (1999) note that branch cankers affecting more than 33% of the circumference are of concern.

Figure 8.11. Leaning oaks (A) must be carefully inspected and monitored, particularly when they occur in high-use areas. Soil plate lifting on the side opposite the lean (B, arrow) is a strong indicator that this valley oak has shifted position and should be considered to have a very high failure potential. A simple method of determining a change in trunk position (lean) is to place a digital level at one location on the trunk and measure changes in position over time (C). B. Hagen (A, B); K. Jones (C)

How much trunk decay is too much?

A number of formulas have been developed to assess the potential trunk failure from cavities and decay (see Mattheck and Breloer 1998; Kane et al. 2001). Most of the formulas use a ratio of the thickness of the sound wood (or decay column) and the trunk diameter. An assessment of the accuracy of the formulas was reported by Kane and Ryan (2004) and further assessed by Bond (2006). As noted in these reports, significant limitations exist to the application of the formulas. The best approach is to consider the formulas along with other data, such as failure profiles for the species, tree characteristics (height, live crown ratio, etc.), degree of risk assumed by owner, and how well mitigation measures can reduce failure potential or risk.

Lean

Under certain circumstances, oaks can partially tip over or develop an uncorrected lean (see sidebar). Typically, this happens when loads in the crown exceed the capacity of the root system to hold the tree in a vertical position (fig. 8.11). Either crown loads increase (e.g., from wind) or the anchorage of the root system diminishes (e.g., root breakage). A combination of the two conditions likely causes many leans.

Aside from wind and root decay, a number of other factors can contribute to uncorrected leans, including root severance, soil erosion, saturated soil, and asymmetric or unbalanced crown (Harris et al. 2004). Depending on the number and severity of factors involved, the degree of lean (deviation from the vertical position) can range from relatively small (less than 10 degrees) to increasingly more severe (greater than 10 degrees) (see Trummer and Hennon 2007).

Trees that have a relatively large degree of uncorrected lean can be considered to have a high failure potential. If the failure of such a tree is likely to cause personal injury or property damage, corrective action should be taken immediately. In cases where the deviation is small, however, trees should be monitored for further movement and treated with caution. Unfortunately, there is little information available to assess the potential for failure based on the degree of lean. Consequently, lean should be considered to be a significant defect in most cases.

Keep in mind that the trunks of many oaks are not naturally straight or vertical. Trees that have grown in a dense forest stand, at the edge of a stand, or under shady conditions often develop a trunk with a curvature or sweep (corrected lean). Such trees do not necessarily have a high failure potential, as they likely have developed support wood to compensate for the lean. A deviation from the "natural" position of the trunk can indicate the development of an uncorrected lean, however.

Types of Lean

Two terms have been used to describe types of lean: corrected and uncorrected. Trees that have grown in a nonvertical position and remain in that position (no shift or tilt) are considered to have a corrected lean. A tree that leaned at one time but has stabilized, often developing an upward sweep due to reaction wood, is considered to have a corrected lean. Trees that have grown in one position (vertical or nonvertical) but then change position (shift or tilt) are considered to have an uncorrected lean. Although trees with a corrected lean can be unstable, of greatest concern with regard to failure potential are trees with an uncorrected lean.

Figure 8.12. Multiple stems can develop in oaks after fire injury, tree cutting (A), or from the loss of the main stem (central leader) during crown development (B). Loss of the main stem can be caused by poor pruning practice, wildlife injury, and lightning strikes, among other factors. Multiple stems is commonly reported in the California Tree Failure Database as a structural defect. B. Hagen (A); L. Costello (B)

Multiple Stems or Branches

In many parts of California, oaks have regenerated from stump sprouts following tree cutting for cordwood (or wood products), land clearing, and fire. In some areas, oak stands have developed primarily from sprouts, with few cases of trees originating from seed (McDonald and Tappeiner 1996). As a result, many oaks have become multistemmed and can be structurally deficient (fig. 8.12).

Stems of multistem trees initially grow with sufficient space for development, but they eventually become crowded with age. In many cases, stems fuse together near the base, so that they resemble a single-trunk tree. Bark may become embedded between stems (included bark), limiting the development of attachment wood and reducing the strength of attachment. As stems grow larger, develop greater end weights, and begin to lean away from each other, their failure potential increases and splits can occur. If decay develops near the point of attachment, a further increase in failure potential is likely.

In addition to stump sprouts, oaks that regenerate from acorns can develop as multistem trees. In some cases, individual acorns can produce dual shoot and root systems (fig. 8.13), or acorns germinating in close proximity to one another can develop side by side. In either case, stems compete for space, eventually creating one-sided, unbalanced crowns. In addition, root development may be restricted on one side (limiting support for the tree) or girdling roots may develop. As such trees develop, the combination of an unbalanced crown, restricted root support, and possible girdling roots increases the potential for failure.

Similar to multiple stems, multiple scaffold branches can arise from one point on the trunk. Generally, these branches are weakly attached and prone to failure. Often, included bark develops in the union between the branches and the trunk.

Codominant Stems

Although many oaks develop a single dominant trunk, some develop two stems of relatively equal size called codominant stems (fig. 8.14). In oaks, as well as many other genera, this condition frequently leads to the failure of one or both stems.

For trees with codominant stems, crown development largely occurs on the outer side of each stem, and the uneven distribution of weight tends to pull the stems apart, similar to multiple stems. Furthermore, bark can become embedded between the stems (included bark) preventing the formation of a strong union. Codominant stems with a narrow angle of attachment (V-shaped) are more likely to develop included bark than those that are more widely separated (U-shaped). In cases where included bark occurs and crown development on each stem is largely on one side, the potential that codominant stems will split is relatively high. If other contributing factors occur, such as wood decay and wind loading, the failure potential increases further

Figure 8.13. Occasionally, codominant trees can develop directly from acorns. After germination, dual root and shoot systems grew from this acorn. L. Costello

Figure 8.14. Codominant stems that developed low on the trunk of this coast live oak (A) have included bark at their attachment (arrow) and have a relatively high potential for failure. After the failure of a codominant stem of this coast live oak, a substantial amount of included bark was exposed (B, arrow). L. Costello (A); B. Hagen (B)

Figure 8.15. With codominant stems, included bark, and extensive decay at the stem union, this coast live oak has a high potential for failure (A, B). Being located next to a pedestrian path, it can be assigned a high risk rating as well. L. Costello

(fig. 8.15). For oaks with codominant stems, it is very important to inspect stem unions carefully (looking for included bark), assess weight distribution, and consider all contributing factors. Keep in mind, however, that not all codominant stem attachments are inherently weak, and mitigating measures will not be needed in all cases (Gilman 2002).

Branches with Included Bark

Included bark between a branch and trunk compromises the strength of the attachment and increases the potential for branch failure (see sidebar). Indicated by a furrowed or V-shaped seam between the branch and parent stem, included bark often occurs between branches of similar size and where the angle of attachment is narrow. When this develops, the branch and parent stem are separated by bark where they appear to join one another. Although there is contact between the branch and trunk, there is no actual union. This condition occurs when the cambium of the branch and trunk turns inward (downward) rather than upward (outward) with growth (Shigo 1986). Rather than a raised ridge of bark occurring on the upper side of the attachment (branch bark ridge), a seam or depression can be found. The capacity of a branch with included bark to withstand loading (e.g., from branch weight, wind, or snow) is lower than that of a branch with a branch collar or branch bark ridge (Gilman and Lilly 2002) (see sidebar).

What Constitutes a Strong or Weak Branch Attachment?

Most branches that are less than half the diameter of a parent stem develop a distinct, somewhat swollen branch base called the branch collar (Shigo 1986) (fig. 8.16). This collar delineates the actual union between the branch and its parent stem. It is a transition zone where branch wood overlaps and connects with that of the parent stem. With the onset of growth in the spring, wood produced by branch cambium envelops the entire branch but turns abruptly at the stem base, growing laterally around it, coalescing with wood tissue of the parent stem below. As branch growth slows, the parent stem cambium begins to produce wood that grows down, around, and over the stem base, forming an outer "collar." This overlapping of tissue within the branch collar forms a strong attachment.

Branches with included bark do not develop normal branch collars (figs. 8.14b and 8.16b). As a result, wood development characteristics associated with a strong attachment are lacking, and such branches are deemed to have weak attachments (Gilman and Lilly 2002). The branches have little connection to the parent stem on the upper side of the attachment, with only a few outer annual rings of "fused" wood to either side of where the stems make contact, binding them to the parent stem. Pronounced bulging or ribs on either side of branch attachments with included bark indicates a propagating crack in the fused rings and is often a precursor to failure (Mattheck 1991).

Figure 8.16. Features of a strong attachment include the presence of a branch bark ridge or branch collar, or both (A, arrow), a relatively wide angle of attachment, and branch diameter of one-half (or less) of that of the trunk at the point of attachment. Weakly attached branches (B) generally have a relatively narrow angle of attachment and included bark (arrows) at the point of attachment (no branch bark ridge), and the branch diameter is larger than one-half that of the trunk at the point of attachment.
B. Hagen

Trunk and Branch Cracks

A crack is a split that develops in wood, sometimes extending all the way through a trunk or branch (fig. 8.17). Cracks indicate that a separation of wood fibers has occurred and the load-bearing capacity of the branch or trunk is diminished (Mattheck and Breloer 1998). Cracks that go completely through a stem or branch, or two or more cracks in the same general area of the stem, are of substantial concern. Internal cracks are abundant in many trees—particularly oaks—and may contribute to many branch and trunk failures (Phillips 2008).

A number of factors can cause cracks, such as wind loading, heavy end weights, wounds, flush cuts, decay, lightning, and cold temperatures. In some cases, high or low temperatures, drought, and wind can extend cracks that were initiated by other factors, leading to trunk and branch breaks. Depending on species and environmental conditions, these factors (or combinations of factors) can produce different types of cracks, such as radial, shear, and circumferential.

"Frost cracks" that result from internal shrinkage of wood during freezing temperatures have been reported in oaks (Kubler 1987). These radial cracks, which may extend to the center of the tree, usually callus over. However, freezing weather can cause woundwood tissue that forms during the growing season to rupture each winter, causing a prominent ridgelike seam (sometimes referred to as "ribs") to form over the crack. New wood that forms over the crack makes it less distinct with time, and frost cracks eventually close.

Shear cracks form in the middle of a stem or branch where compression forces change to tension forces (Mattheck and Breloer 1998). If they extend through the middle of the stem or branch, failure potential increases. McNeil (pers. comm.) notes that small horizontal shear cracks are relatively common in the middle of horizontal scaffold limbs of oaks.

Circumferential cracks (ring shake and wind shake) result from wood separation along growth rings, producing a concentric pattern. Typically, they are initiated as a result of wounding and subsequent barrier zone formation (Shigo 1993). These cracks can extend relatively large distances up and down a stem, exacerbated by movement during wind events (Phillips 2008).

Note that cracks may appear in bark tissue but they may not extend into the wood. These shallow fissures are called "bark cracks" or "growth cracks" and, being limited to the bark, are not considered to compromise the structural strength of a branch or trunk. Cracks in bark that extend into the wood are of concern, however.

Girdling Roots

Relatively large-diameter roots growing around the lower trunk or root collar of a tree are referred to as girdling roots (fig. 8.18a). These roots can interfere with vascular transport, restrict stem development, and contribute to trunk failure (Watson and Himelick 1997; Watson et al. 1990). In addition, girdling roots can restrict the development of buttress tissue at the union between lateral roots and the trunk. This restriction interferes with the load-bearing and stress-distributing function of buttresses (Harris et al. 2004). Restricting stem and buttress tissue development can increase the potential of trunk failure in oaks, particularly in windy environments.

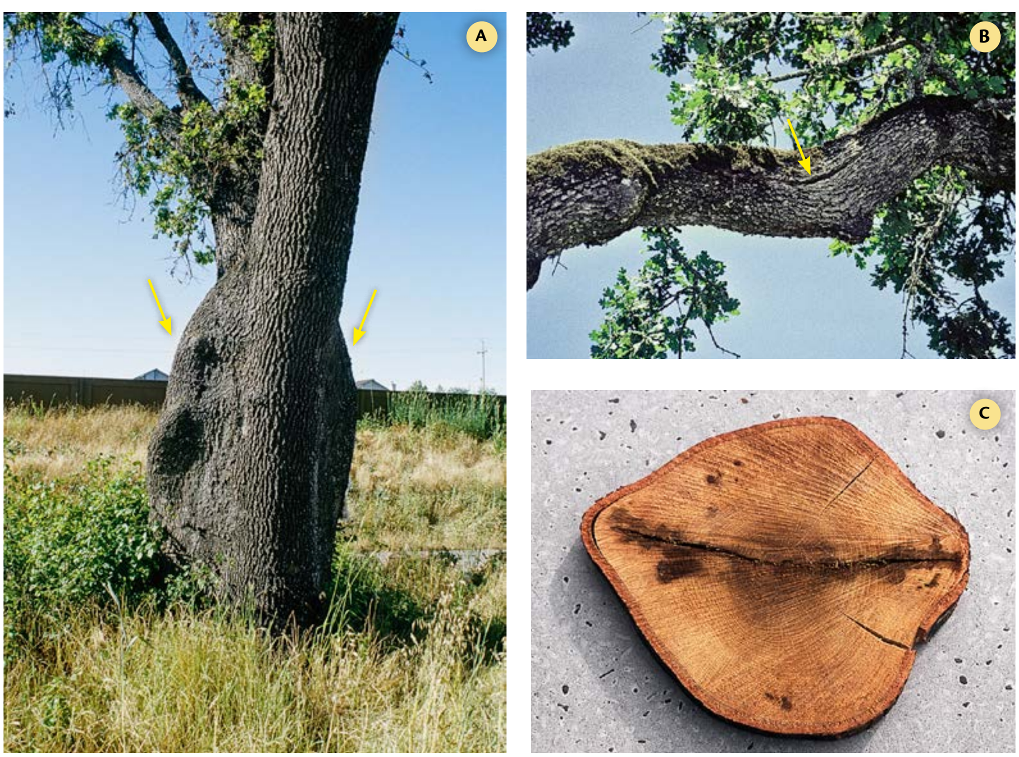


Figure 8.17. Bulges ("elephant ears") that formed on the trunk of this valley oak (A) indicate that an internal crack exists (arrows). Cracks can extend through the bark, as seen on this branch of valley oak (B, arrow). Cracks can be limited to wood tissue that is not visible from the outside; these internal cracks can cause irregular growth patterns, resulting in abnormal shapes (C). B. Hagen

Figure 8.18. A large girdling root (A, arrow) on this coast live oak has restricted trunk development on one side of the tree. Inspect the crown for hanging or lodged branches, as shown here on this coast live oak (B). K. Jones

Girdling roots can occur at the ground line or just above or below the ground line. They may partially or completely encircle the trunk. Flat spots on the root collar or a constricted appearance in the trunk can indicate girdling roots below the ground line.

Dead Branches

Dead branches eventually break off and can cause property damage or injuries. The crown of an oak should be inspected for larger branches (greater than 2 inches in diameter) that have died, and remedial action should be taken as is consistent with risk level. Inspect deciduous oaks when they are in leaf (late spring through early fall) and evergreen oaks at any time of the year.

Hanging Branches

In some cases, branches break but remain partially attached to a parent branch or stem. These are called "hangers." In other cases, a branch breaks completely but remains lodged in the crown (fig. 8.18b). The crown of an oak should be inspected carefully for both cases, because hangers and lodged branches have a relatively high potential to fall, particularly during wind and rain, and may cause damage or personal injury (Costello et al. 1999).

Risk Assessment

Tree risk assessment has been defined as the process of evaluating the likelihood that a tree or tree part will fail and cause injury or damage (Matheny and Clark 2007b). Risk assessment is a complex process that requires both a thorough understanding of tree structure and a substantial amount of field experience. Even for the most knowledgeable and experienced tree care professionals, tree risk assessment is a challenge and should not be undertaken without adequate training and preparation. Matheny and Clark (2007b) identify three components of risk assessment:

- inspection of the tree and evaluating its potential to fail
- evaluation of site conditions as factors that may contribute to a failure
- determination of the likelihood that a person or object would be injured or damaged by the failure

Inspection

Prior to a systematic examination of tree parts, collect basic information regarding species, age, size, and general health. Typically, this is entered onto a standardized form used for risk assessments (see Matheny and Clark 1994). Next, carefully examine all tree parts (root collar, trunk, scaffold branches, and crown), looking for structural defects that may increase failure potential. For descriptions of common defects, see the previous section; for an extensive discussion of tree failure mechanics and inspection guidelines, see Mattheck and Breloer 1998.

Root collar

Remove vegetation (turf, weeds, etc.) and organic debris that may obscure the root collar. In some cases, soil may need to be removed to expose the root collar and lateral roots (see Britton 1990). This can be accomplished using pneumatic or hydraulic excavation methods (see Harris et al. 2004). Since a root collar excavation is not needed in all cases, the inspector will need to make a determination as to its value. Keep in mind that in cases where the trunk flare is not evident, an excavation is likely warranted. During a root collar inspection (fig. 8.19), look for

- a root collar clearly visible at the ground line
- girdling roots (partially or entirely encircling the trunk or root collar)

Figure 8.19. To facilitate a root collar inspection, soil should be removed from around the base of the tree using hand tools or a pneumatic excavation tool. B. Hagen; L. Costello (inset)

- wounds, decay, or cavities (see sidebar)
- conks or mushrooms (fungal fruiting structures)
- loose and cracked bark
- bark cracks between lateral roots (as indicators of root decay)
- dead, sunken areas (cankers) extending below the soil line
- exudation of sap (bleeding) from collar or lateral roots
- callus tissue (woundwood) near the soil line
- adventitious root formation (as an indicator of root injury or grade change)
- evidence of root cutting or other root injury
- roots exposed by soil erosion

Fraedrich and Smiley (2001) note that trees with more than one-third of their roots dead, decayed, or severed should be considered to have a high potential for failure. This threshold should be reduced for leaning trees, particularly when damaged roots are on the opposite side of the lean or on the uphill side of a slope.

Trunk

Stand back from the tree and examine the overall structure and orientation of the trunk. Examine crown symmetry relative to the trunk, noting the arrangement and distribution of branches. Determine whether the live crown ratio and crown density (area of crown with leaves and leaf-bearing branches that block sunlight) is normal for a tree of that species, size, age, and location. Photographs of existing conditions are useful for future inspections, particularly when assessing or documenting a lean. Look for

- signs of lean (change in trunk orientation, roots lifting out of soil, soil mounding, sponginess of soil around trunk)
- codominant stems (or multiple-stem structure)
- bowed or curved trunks
- included bark in union of codominant stems or main scaffold branches
- signs of decay such as wounds, cavities, conks or mushrooms, loose or missing bark, swellings or bulges, bleeding, nesting holes, beehives, carpenter ants, or termites
- wood cracks and splits
- vertical seams that develop from woundwood formation over a cavity, canker, crack, or decay pocket (fig. 8.21)
- signs of buckling (accordionlike wrinkling) on the bottom side of a leaning stem (see Mattheck 1991) and lifting or loosening of bark plates on the tension side of the lean

Scaffold branches

Carefully examine scaffold branches (large branches arising from the trunk) for structural characteristics such as size and orientation (angle of attachment) relative to the trunk, foliar distribution, and defects. Look for

- multiple scaffolds arising from a common point along the trunk
- included bark at a scaffold branch attachment

Root Decay*: *Symptoms and Signs in Oaks

Symptoms and signs of decay in roots or lower trunk include branch dieback, sparse and undersize foliage, sudden and perceptible lean, loose or missing bark, basal wounds, cankers with callused margins, adventitious roots, cavities, and soft wood (fig. 8.20). Generally, roots decay from the tips back toward the root collar and from the underside upward. The upper side of affected roots can appear sound while the underside is decayed. Cone-shaped columns of decay extending from the underside of roots into the trunk base may develop (basal rots). Exaggerated swelling of the root collar beyond what is normal for oaks and seams originating between large buttress roots are indicators of root decay and basal rot (Matheny and Clark 1994). White mycelial fans developing under the bark with black rhizomorphs on the bark surface or under loose bark are indicators of infection by oak root fungus (*Armillaria mellea*). Periodically, clusters of mushrooms may be found near the base of the trunk as well. Granular boring dust (frass) accumulating on the trunk or soil surface can indicate the presence of termites or carpenter ants nesting in decayed wood.

Figure 8.20. Decay at the base of the trunk (A, arrow) of this Oregon white oak may have progressed up from lateral roots into the root collar. Basal decay in the trunk of this valley oak (B) suggests that structural roots may be decayed as well.
B. Hagen

Figure 8.21. The vertical seam on the trunk of this valley oak suggests that a cavity may exist behind the seam.
B. Hagen

- signs of decay such as wounds, cavities, conks, bleeding, loose or missing bark, bulges or swellings, nesting holes, beehives, carpenter ants, or termites
- past scaffold branch failures
- wood cracks and splits
- cankers
- lack of branch taper
- uneven distribution of branches and foliage along the scaffold (unbalanced weight distribution or heavy end weights; branches with heavy end-weight—foliage concentrated near the branch tip—and poor taper are prone to breakage; see Mattheck 1991)
- evidence of prior inappropriate pruning (heading cuts or lion-tailing) and subsequent development of weakly attached shoots (epicormic shoots)
- horizontal orientation of scaffold
- scaffolds with diameter equivalent to that of the trunk
- overextended scaffolds (branch end extends well beyond the outer part of the crown)
- large branches with a bow or sweep (long branches with distinct downward bows due to a concentration of foliage near their distal ends indicate stress loading and are more likely to split and fail; heavy branches that arc or sweep upward, particularly those that originate low in the tree, are also more likely to split as the branch weight causes them to flex downward)

Crown

From a distance, examine the crown to evaluate overall health, growth, and distribution of branches and foliage. Determine whether the live crown ratio (or the surface area with leaves and leaf-bearing branches) is normal for the species, size, and location, and is adequate to sustain reasonable health. Within the crown, examine branch attachments and inspect for defects. In some cases, an aerial inspection will be needed to closely evaluate suspected defects. Look for

- included bark in the attachment of second- and third-order branches along a scaffold
- dead, hanging, or lodged branches (see fig. 8.18b)
- asymmetric distribution of branches
- an abnormally dense crown, particularly in windy locations

Oaks that are large, mature, or declining should be inspected routinely, particularly if they are close to targets. Simply because of their size and weight, large trees can have a substantial potential to cause injury or damage. Mature and declining trees are more likely to have more significant defects than young and vigorous trees (Schwarze et al. 2004).

Site Conditions

In addition to a careful and systematic inspection of structural characteristics, an evaluation of site conditions must be included in risk assessments. Failure potential can be strongly affected by a number of site factors, such as climatic conditions, topography, and soils. Keep in mind that certain factors affect only specific types of failures, while others affect all types (root, trunk, and branch). In addition, more than one site factor can contribute to failure potential. For instance, an oak that grows in a windy location with shallow soil and has experienced significant root loss will have a higher failure potential than the same species in a protected location in deep soil without root disturbances. The potential contribution of each factor and combination of factors must be carefully considered when conducting a risk assessment.

Climate

Wind and precipitation contribute to many oak failures (CTFD 2008). Regional and local climate information is available for many locations from a number of sources. Wind speeds (average and maximum), prevailing wind direction, and wind patterns (steady, gusty, channeled, or turbulent) should be evaluated. Keep in mind that wind exposure can vary with terrain. For instance, trees on ridges, hilltops, or knolls will be exposed to wind patterns that differ from those located on flat terrain, in protected canyons, or behind tall buildings. In addition, trees at the edge of a clearing or forest stand are exposed to greater wind loads and turbulence than are protected trees.

Site precipitation is important to consider, particularly when assessing the potential for root failure. As noted previously, saturated soil conditions contribute to a number of root plate failures. An understanding of rainfall amounts, soil depth, and drainage characteristics helps determine whether soils are prone to saturation. In addition, precipitation can contribute to weight loads on branches and stems, particularly when trees are in leaf and rain occurs in conjunction with wind. Snow loads must be considered in cold-winter locations.

Figure 8.22. For some oaks growing on slopes, crown development is not balanced, and root development can be more extensive on the uphill side. As a result, trees on slopes can be less stable than those on flat terrain, particularly when the slope is saturated and soil erosion has occurred, as shown here. K. Jones

Topography

Oaks growing on slopes develop structural characteristics that differ from those growing on flat terrain. Root distribution, wood development patterns, and branch distribution are affected by topography, with additional variation related to the degree of slope (fig. 8.22). As a result, failure potential and risk assessments must consider whether the terrain is flat, gently sloped, moderately sloped, or severely sloped. For example, cutting of roots on the uphill side of an oak growing on a gentle slope will have less of an impact than cutting of roots on the uphill side of an oak growing on a severe slope.

Soils

Root development and distribution is markedly affected by soil conditions such as depth, moisture content, density, volume, drainage characteristics, and grade changes (see chapter 4). The capacity of a root system to provide anchorage and structural support for the aboveground parts is strongly affected by soils. The following conditions affect root system stability.

- Saturated soils have been noted to contribute to root failures in oaks (CTFD 2008).
- Shallow soils limit the development of heart and sinker roots, which likely compromises anchorage.
- Soils with physical barriers (such as foundations, footings, and basements) limit the development of lateral roots, with adverse effects on anchorage being likely.

Numerous other soil conditions, such as a high water table, surface compaction, hardpan, and grade changes (fills), affect root development and anchorage function and should be considered in risk assessments.

Understory

The composition of an oak understory can affect root development, health, and structural stability, particularly in urban areas. As noted previously, natural leaf litter and native vegetation are considered most favorable for oak root development (see chapter 5). In many urban locations, however, vegetation that requires seasonal irrigation may be installed beneath oaks, such as turf, groundcovers, and annuals. Frequently, root disease and decay develop as a result of irrigation, which in turn compromises oak health and structural stability. Where hardscapes such as pavements occur under oaks, an assessment of installation impacts on root stability should be included.

Site history

During site development, changes in conditions can increase the potential for oak tree failure. Excavations for foundations, trenching for utilities, soil compaction, and changes in hydrology can have adverse effects on the structural stability of root systems. Cutting of lateral, heart, and sinker roots, injury to fine roots, and restrictions to the development of all root types are not uncommon occurrences during development. Following development, maintenance practices such as irrigation, fertilization, and pruning may be unfavorable for oaks. In particular, the pruning history should be considered carefully: the removal of large lower branches, creation of pruning wounds, and changes in branch and foliage distribution can severely affect structural stability (see the section "Structural Defects," above). Prior pest management practices should be considered as well, particularly if trunk injections have been made over an extended period of time.

Tree failure history in the area should be integrated into evaluations of site conditions. Trees with a history of branch failures are likely to experience additional branch failures (Matheny and Clark 1994). Similarly, sites with a history of root failure caused by decay fungi such as *Phellinus* spp. and *Fomes* spp. are likely to be locations for future failures (Smith et al. 1984).

Stand characteristics

For oaks growing in groups or stands, their location in the stand (on the edge or in the middle) and crown position (dominant or subdominant) affects their structural stability. Oaks at the edge of a natural grove or along a road often develop trunks with sweeps and asymmetrical crowns. These conditions can increase failure potential, particularly when other structural defects occur, such as root decay.

Trees in stands can be dominant (crown higher than the others), codominant (crown position about the same), intermediate (somewhat lower) or suppressed (well below). During wind events, crown loading varies with crown position. For instance, dominant and codominant trees are likely to be exposed to greater wind forces than intermediate or suppressed trees.

Evaluating Targets

People and property potentially affected by a tree failure are considered to be "targets." As noted previously, risk assessment evaluates the likelihood that a tree or tree part will fail

Figure 8.23. Targets of falling trees or branches include people, pets, and property (houses, vehicles, structures, etc.). In urban areas, targets are abundant, and oaks close to targets should be carefully inspected for structural defects on a regular basis. Shown here, targets include people, houses, cars, picnic tables, and playground structures.
B. HAGEN

and cause injury or damage, that is, hit a target (fig. 8.23). Tree failures that have little potential to cause injury or damage (such as those in wildland areas) represent little- or no-risk situations, even though failure potential may be very high. Conversely, many targets (people, buildings, vehicles, etc.) exist in urban areas, and the potential for a target to be hit by a failed tree is often high. An important part of risk assessment is to evaluate the potential that personal injury or property damage may result from an oak failure.

When evaluating targets, consider site use as well as occupancy (Matheny and Clark 2007b). Site use identifies how the area within striking distance of the tree is used, such as for parking, picnicking, recreation, or vehicle or pedestrian traffic. When considering use, identify all potential targets, such as homes and residents, cars, garages, pedestrians, pets, buildings, and landscape elements (fountains, statues, decks, etc.). In many cases, multiple targets exist.

Site occupancy identifies the level of use: whether it is frequent (e.g., a busy city street) or infrequent (e.g., a sparsely used county road), and whether targets are stationary (e.g., house or school) or mobile (e.g., bikes and cars). In a low-occupancy site, such as a rural residence, stationary targets (houses) generally constitute a greater risk than mobile targets because there is a constant potential for damage or injury to result from a tree failure. For some site uses (e.g., schools), occupancy is generally high and both stationary and mobile targets can constitute high-risk situations. Note that site use and occupancy can change with time (daily and seasonally).

Risk levels

With a careful inspection of the tree, an evaluation of site conditions that may contribute to failure, and a determination of the likelihood that a person or object would be injured or damaged by the failure, risk levels can be assigned for individual trees (e.g., high, moderate, or low) and a plan for abatement action can be developed. In cases where multiple trees are assessed, abatement work can be prioritized based on risk level. A number of rating systems have been developed to help determine risk level: see Paine (1971), Hickman et al. (1989), Schomaker (1990), Smiley and Fraedrich (1990), and Matheny and Clark (1994). In selecting a rating system, an assessment of industry or professional acceptability should be included. Regardless of the system used, however, recognize that professional training and substantial field practice are needed to become a competent tree risk assessor.

Abatement of Tree Hazards

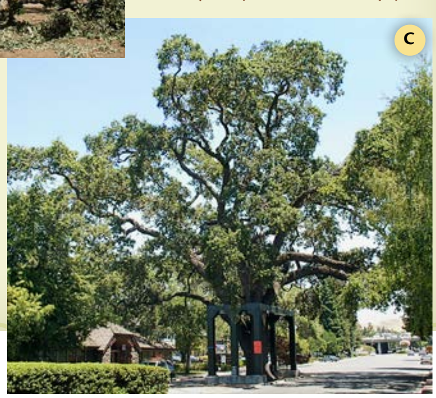
If an oak has been determined to have an unacceptable level of risk, various abatement options can be considered, such as moving the target, restricting access, pruning to reduce failure potential, installation of support systems (see sidebar), site modification, and tree removal. The best option depends largely on the type and severity of defects present. For instance, reducing the length of a scaffold branch with a moderate level of decay may be sufficient to reduce the risk of failure to an acceptable level, while a support system may be needed for a scaffold branch with a higher level of decay. In cases where decay is extensive, the branch may need to be removed. Frequently, combinations of actions are needed. For instance, a scaffold branch that has been assessed as a high risk because of extensive decay may need to be reduced, supported, and have targets moved. For abatement actions that may be considered for different defects, see table 8.1.

In some cases, further testing or inspection, including decay measurements and aerial inspections, will be needed

Supplemental Support Systems

Support systems include cables (rigid or flexible), guy wires, props, bolts, and threaded rods that can reduce the failure potential of a tree part or an entire tree (Smiley and Lilly 2001). Frequently, these systems are used to prevent splitting of codominant stems and weakly attached branches, to support branches and stems with substantial end weights and structural defects (such as decay or cracks), and to minimize the potential of a tree or tree part from striking a target (fig. 8.24). The effectiveness of support systems depends on the size and weight of limbs, the distribution of foliage, size of hardware, structure of the tree, the soundness of the wood, and the placement of the support system. Support systems have a fixed lifetime and must be inspected annually and adjusted or repositioned as needed. Keep in mind that it is possible to increase failure potential when support system design or installation is not appropriate for the structural defect being addressed. Consulting a well-qualified professional is highly recommended when considering the use of a supplemental support system.

Figure 8.24. Cables and props were installed to provide supplemental support for the limbs of this valley oak (A). Branches can still fail even though they have been cabled, as shown on this blue oak (B). Cables can fail as well. In the event of root or trunk failure of this large valley oak, a steel frame was installed to reduce the potential of property damage or personal injury (C). K. Jones (A, C); L. Costello (B)



to assess defects and prescribe abatement strategies. Keep in mind that if a tree failure is determined to be imminent, immediate action must be taken. This may entail moving targets or restricting access to the area while preparations are made for removal or other abatement action.

Obtaining Professional Advice and Services

When seeking professional advice and quality tree work, contact an arborist certified by the International Society of Arboriculture (www.isa-arbor.com) or a consulting arborist. Many consulting arborists are licensed by the American Society of Consulting Arborists (www.asca-consultants.org). Although certification or licensing does not guarantee quality performance, it does assure that a demonstrated level of knowledge and technical proficiency has been achieved by the arborist or consultant.

Table 8.1. Abatement options for specific tree defects

Type of defect	Action
trunk or root decay	With low to moderate decay, prune to reduce the weight and extension of the crown; this reduces the stress placed on the weak area. Where decay is extensive, removal may be reasonable. Cabling typically does not abate this defect. Propping may be feasible if the tree is leaning strongly.
branch crack or decay	For low to moderate decay, prune to reduce the weight and extension of the branch. Where damage is extensive, cable into solid wood or remove the branch. Cabling in decayed wood is not advised.
horizontal branch with poor taper and excessive end weight	The first choice is to prune to reduce the weight and extension of the branch. If pruning is inadequate to reduce stress on the branch, propping or cabling could be considered for high-value trees.
poorly tapered trunk with high height to diameter ratio and low live crown ratio, recently exposed	Remove the tree or move the target. Thinning seldom abates this condition. Over time, vigorous trees will develop taper and branching suitable for edge conditions, and the risk will decrease.
leaning tree	Where the top has grown vertically (self-correcting) no treatment may be needed. For moderate leans, prune to reduce weight and extension. For recent leans with mounded or cracked soil behind the lean, removal usually is warranted. For high-value trees, propping or guying could be coupled with pruning to reduce weight and extension.
weak branch attachment due to included bark	Prune to reduce weight on weakly attached branches, subordinate one of the stems, or remove one of the stems. Consider installing a cable or brace system.
previously topped tree with regrowth weakly attached	Prune to reduce weight and extension of regrowth. Subordinate and thin regrowth to provide spacing; retain shoots with the best attachments.
roots severed near trunk	Prune to reduce weight and extension in crown (crown reduce). If root loss is significant and tree is exposed to strong winds, consider removal.
dead branches or hangers	Prune to clean the crown.

Source: Reprinted with permission from Matheny and Clark 2007b.