Structural Features Related to Tree Crotch Strength

by

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Abstract

Crotches were cut out of red maple (Acer rubrum), callery pear (Pyrus calleryana), and sawtooth oak (*Quercus acutissima*) trees (2.5"-7" d.b.h.) and then pulled apart in an engineering testing machine to identify physical parameters correlated with crotch strength. Parameters measured included the diameter of the branch and of the trunk above and below the crotch, angle of the branch and branch bark ridge, and the length of the crotch and the branch bark ridge. The force required to break each sample was used to calculate breaking strength based on the formula for bending stress. Each parameter was tested for correlation with crotch strength within the individual species and for the three species combined. The ratio of branch diameter over crotch width had the highest correlation coefficient for crotch strength. Branch angle was also correlated with crotch strength but not as highly as the ratio of the diameters. V-shaped crotches (those with included bark) were significantly weaker than U-shaped crotches for all species. The ratio of the two stem diameters greatly influenced the manner in which the crotches broke. In crotches where the branch diameter was 2/3 the size of the trunk or smaller, the crotch broke by being pulled directly out of the trunk. Crotches with branches more than 2/3 the diameter of the trunk broke when the trunk split longitudinally and had significantly lower strength values. These results indicate that increased crotch strength results from a small branch diameter relative to that of the trunk.

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Table of Contents

List of Tables

List of Figures

List of Figures (cont.)

CHAPTER ONE

INTRODUCTION AND JUSTIFICATION

Trees are an integral and conspicuous part of our environment. From city streets to primitive recreation areas, trees provide numerous environmental, economic, and social benefits. In urban areas, trees trap airborne pollutants, provide a buffer against noise and lights, help to moderate temperatures and improve aesthetics (McPherson, et al. 1999, Dwyer et al. 1992). Trees on residential properties have been shown to increase property values over comparable non-wooded lots (Anderson and Cordell 1985). In outdoor recreation areas, visitors are drawn to wooded areas or to the shelter of lone trees.

However, trees near people pose an inherent risk due to their size and the fact that they are living organisms that grow, decline, and eventually die. Trees are also routinely subjected to extreme forces due to weather. Successful management of trees near people involves maximizing the benefits while minimizing the risks given the level of knowledge and resources available for maintenance at a particular time.

Since the primary risk from trees involves their failure, one way of reducing risk is to reduce the potential for failure. This involves identifying factors that increase a tree's potential for failure, establishing some threshold for when the potential is too high and remedial steps are needed, and then applying effective treatments.

The goal of this study was to identify features related to structural strength in tree crotches. This will help to identify trees that are prone to failure due to structural weakness. The annual growth of trees combined with the routine occurrence of extreme weather means that trees need to be assessed repeatedly throughout their lifetimes. Defining the gross morphology of stronger tree crotches would lead to better methods to visually assess trees quickly from the ground.

Reducing the risk of tree failure can reduce personal injury, property damage, and reduce expenses related to emergency maintenance of failed trees. Prolonging the life of individual trees would help to reduce replacement costs, and may help to protect individual trees of significant cultural or monetary value.

This research may also lead to improved application of maintenance activities such as pruning and cabling intended to lengthen the functional life of trees. Quantifying the evaluation of structural integrity in trees will help to improve maintenance prescriptions by tree care professionals. This would reduce the expenses associated with unnecessary tree maintenance including pruning, cabling and removal. Better information among arborists may also help to educate the public about tree safety.

Defining desirable tree forms would help to guide selection programs for new tree varieties and aid in selecting better quality nursery stock for installation in the landscape. This may also lead to improved guidelines for pruning young trees to help develop strong structure and reduce future problems.

This study was intended to compare the strength of a large number of tree crotches in several species in hopes of finding strength characteristics common to a range of landscape species. The specific objective was to determine how well crotch strength is correlated with branch angle, branch diameter, and the presence of included bark. The study also sought to identify threshold values for those parameters that showed significant correlation. Several external parameters such as the length and angle of the branch bark ridge and the change in trunk diameter above and below the crotch were tested for correlation also. These tests may lead to better field indicators of relative crotch strength.

The tests were conducted in an engineering laboratory to reduce variability and to allow for more accurate measurements. The test was designed to break the crotches and not the branches so that the strength of the crotches could be compared between all samples.

CHAPTER TWO
LITERATURE REVIEW

Modes of Tree Failure

Tree failure can involve the entire tree or just a portion of the crown. Failure of the entire tree results from uprooting or breakage of the main trunk. In mature trees, failure of the main trunk is usually due to extreme winds, extensive decay or a combination of the two.

Several methods have been developed to detect or predict the severity of decay within trees and then to determine the associated loss of strength in the tree. Each method begins with some measurement of the size of the decay column in the tree and then uses the ratio of decayed wood to solid wood to estimate the strength loss in the trunk (Nicolotti and Miglietta 1998, Kennard et al. 1996). Threshold values have been established for the different methods to determine when strength loss exceeds a reasonable limit and the tree should be removed. Most of these thresholds have been based on measurements of failed and standing trees with cavities (Smiley and Fraedrich 1992, Mattheck et al. 1993, Mattheck et al. 1994, Kane et al. 2001).

Failure of a portion of the crown usually results from weak structure, excessive stresses from wind, ice load, or fruit set, localized decay, or most commonly from a combination of these factors (Matheny and Clark 1994).

Forestry research into wind damage has dealt primarily with the relationship between reduced stocking levels and increased wind exposure in intensively managed stands (Smith et al. 1987). Fredericksen et al. (1993) measured the wind firmness of loblolly pines by pulling over individual trees. In this study, wind firmness was positively correlated with stem taper and tree size. Niklas (2002) studied the safety factor in various parts of individual open-grown trees by measuring wind speeds at various heights in the canopy as well as the bending strength of stems throughout the canopy. Results of this study showed that smaller stems were more resistant to breaking due to greater flexibility and that the safety factor decreases with increasing size and age of the stem. However, for the largest tree in this study, (approx. 40’ in height) failure was predicted to occur either at the base or in the small stems at the periphery of the crown.

Shedding small stems during high winds may help to reduce stress on the trunk and prevent failure of the whole tree.

The impact of major ice (glaze) storms on forest trees has been observed for decades. Most forest researchers have compared the susceptibility to damage for various species and the effect this may have on forest ecology (Croxton 1939, Bennett 1959, Lemon 1961, Seischab et al. 1993, and Whitney and Johnson 1984). It is difficult to draw broad conclusions on the susceptibility of various species from these studies because the results are often contradictory. In a review of fourteen studies that rated the glaze damage susceptibility of North American tree species, yellow-poplar, sugar maple, eastern white pine, black locust, beech, and white ash were each classified as strong, moderate and weak in resistance to glaze damage by different authors (Bennett 1959). Only 13 of the 53 tree species in this review were classified in just one category by multiple authors. White oak, hickory, and catalpa were consistently rated as resistant to damage, while American elm, black cherry, basswood, cottonwood and willow were rated susceptible. Forest researchers have also looked at the effect of plant spacing and density on ice damage in intensively managed stands (Amateis and Burkhart 1996, and Guo 1999).

Ice storm damage in the urban forest has also been studied to determine relative susceptibilities of landscape tree species. These studies have been aided by the existence of new street tree inventories, which facilitate damage summaries and before-and-after comparisons. Tree species with excurrent growth form such as conifers and young sweetgum trees, and species with low surface area (few stout branches as opposed to many fine branches) such as walnut, ginkgo, and white oak are more resistant to ice storm damage (Hauer et al. 1993). Alternately, fine twigged species such as Siberian elm, hackberry, and pin oak sustained greater damage. Species with multiple stems or large branches such as Bradford pear, honeylocust, and Norway maple were more susceptible, especially when included bark was present (Sisinni et al. 1995). These effects increase with tree age due to increased incidence of decay and the spreading growth habit of mature trees.

Few studies have been conducted to study the relative strengths of trees within an individual species or branches within individual trees. Failures within the crown can occur in three ways, breakage of the trunk, failure of individual branch attachments, or breaking of the branches themselves.

Cannell and Morgan (1989) tested *Picea sitchensis* branch sections to determine the effect of lateral branch design on the load bearing capacity of branch stems under snow and ice loads. Computer models were used to calculate the bending moment of branch stems covered with typical snow or ice accumulations as the number of lateral branches was increased. They found that the branch design that required the least amount of wood to support the maximum amount of foliage increased the branch's susceptibility to fail under normal snow and ice loads. These results agree with other studies that identified branch surface area as a key component in susceptibility to ice damage.

This research project focuses on trunk-branch unions and trunk-trunk unions in hopes of identifying external features of these unions (crotches) that can be used to assess their relative strength.

Structure of Tree Crotches

Crotches, the structural attachment of branches to trunks, have received relatively little attention in research as distinct entities in woody plants. Much of the terminology related to crotches that is used in arboriculture today was described less than twenty years ago.

Crotches have unique anatomical features that help to limit the movement of water and some pathogens between the trunk and branch. The branch base serves as a protection zone to stop the spread of pathogens from infected or decaying limbs into the trunk (Shigo 1985). Decay-resistant substances are concentrated in the swollen areas at the base and sides of the limb (branch collar) where it joins the trunk. Differentiation in the vascular system within the crotch reduces hydraulic conductivity and again acts to limit transport between the branch and the trunk (Lev-Yadun and Aloni 1990). It is the combination of decay-resistant materials and the unique vessel anatomy at the branch base that increases the ability of the crotch to resist the spread of decay pathogens into the trunk (Eisner et al. 2002). This protection zone exists in branch-trunk unions but not in the junction of codominant stems. Codominant stem junctions lack both the restricted conductivity and the swollen branch collar found at the junction of subordinate branches and the trunk.

The crotch can be viewed as the intersection of two expanding cylinders, one the branch and one the trunk. From dissections of thousands of tree crotches and studies of the orientation of wood fibers within, Shigo (1985) found that the trunk is connected to the limb only at the base and sides of the branch attachment. Fibers do not extend from the top of the branch to the trunk above the crotch or vice versa; rather the fibers turn to either side and grow around the base of the branch (Figure 2.1). Studies using dye injected into the base of tree branches performed by Shigo (1985) and Neely (1991) showed there to be no transport between the branch and the trunk above the crotch.

The zone above the crotch where branch fibers and trunk fibers turn perpendicular to their respective stems was described by Shigo (1985) as the compaction zone (Figure 2.1). This refers to the fact that the two expanding cylinders have little room to expand on the inside of a crotch that is less than ninety-degrees. The compaction zone is the weakest point of the crotch because the fibers are oriented perpendicular to the stem and parallel to each other.

The annual expansion of the two cylinders also causes the bark to be compacted above the crotch. The bark however, has room to expand outward and this growth forms the branch bark ridge (Figure 2.2). As the trunk grows in diameter, the branch bark ridge extends down and outward from the crotch at approximately the same angle as the branch core wood within the trunk.

In crotches that have very narrow angles of attachment the branch bark ridge sometimes fails to expand outward and is swallowed by the growth of the branch and trunk (Figure 2.2). Each year thereafter, more bark is enclosed within the crotch. This condition is referred to as included bark (Shigo 1985). The process by which included bark first forms has not been identified. Included bark has long been associated with weakness in tree crotches since it is frequently seen in failed tree forks. It is easy to assume that the included bark prevents the formation of connecting wood between two stems and therefore reduces crotch strength. The actual significance of included bark in reducing the strength of tree crotches has yet to be established over a broad range of species and types of crotches.

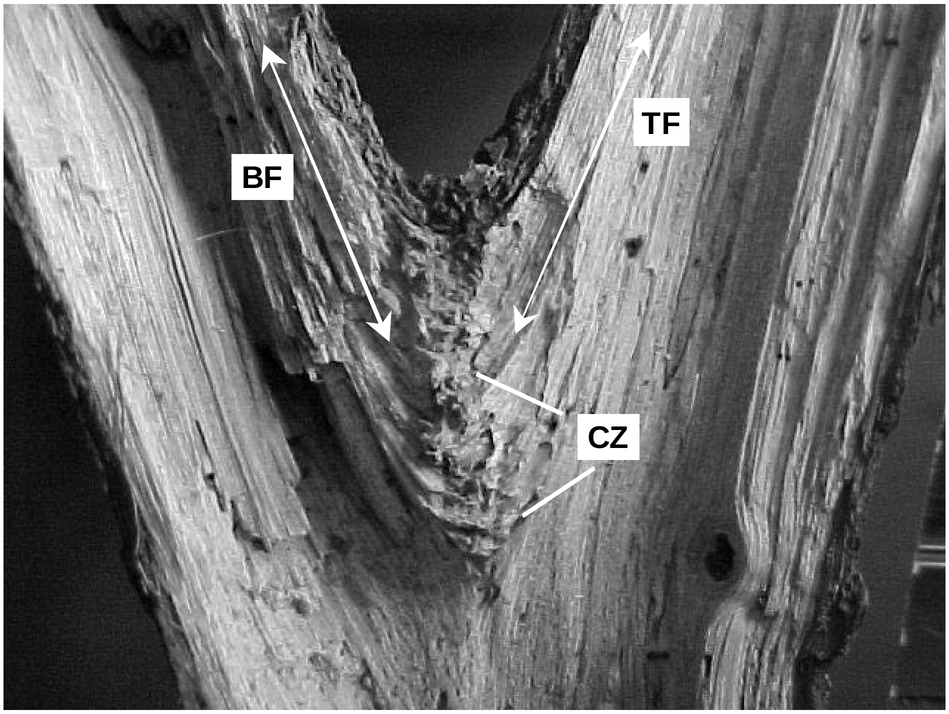


Figure 2.1. Red oak crotch (not used in this study) showing the intersection of a branch and trunk and the resulting compaction zone. At arrows, trunk fibers (TF), and branch fibers (BF) entering the crotch are oriented longitudinally to their respective stems. In the compaction zone (CZ), the branch and trunk fibers are oriented tangential to both stems as they turn to pass around the branch base
.

Figure 2.2. Branch bark ridge on a U-shaped red maple crotch (left) and on a V-shaped red maple crotch (right). In the V-crotch, the branch bark ridge has rolled in at the top, leading to the formation of included bark.

Based on dissections of tree-branch unions, Shigo (1985) concluded that the strength of tree crotches is due to the annual formation of overlaying trunk and branch tissues at the base and sides of the crotch. As the tree grows, the trunk-branch union is buried more deeply within the trunk and the strength of the attachment increases. Based on dissections throughout the growing season, Shigo (1985) concluded that the growth of branch tissue in the spring formed a branch collar. This was then overlapped by a trunk collar that formed in the summer. Neely (1991) studied this growth pattern by injecting dye into the trunks of various species below branches at different times during the growing season. The patterns of dye movement around the crotch did not change throughout the season. He concluded that the branch was not overgrown seasonally in layers as proposed by Shigo, but was overgrown annually. Neely (1991) also proposed that the swollen tissue around the base of the branch, Shigo's branch collar, was the result of trunk tissues increasing growth around a dying limb. He concluded that on healthy limbs a swollen area develops below the limb due to the tissues there receiving nutrients from both the trunk and branch. He termed this area the branch shoulder.

Both authors agree that the annual growth of the trunk encloses the branch base deeper inside the trunk. The branch is held "like a dowel in a chair leg" no matter how the layers are formed. This is important because the only way this can happen is if the trunk is sufficiently larger than the branch (Harris 1992).

The angle of the branch and therefore the crotch is determined by the branch's reaction to the opposing effects of geotropism and epinasty. The inherent form of the tree species rules this reaction but it is also affected by the age of the tree, location of the limb in the crown, and by environmental conditions. Young trees in most species will develop an excurrent growth habit if they must compete for sunlight. However, once freed from this competition most deciduous species will develop a decurrent form to intercept available sunlight. Even pines and baldcypress, species that typically have an excurrent form, will develop broad flat crowns when mature. Moisture stress may also cause trees to develop shorter, more rounded outlines than is typical for their species (Zimmerman and Brown 1971). Individual branches can also change their inclination as the tree matures and their position relative to the crown changes. This is seen in pin oak, which typically has narrow branch angles in the young branches at the top of the crown, perpendicular branches in the middle of the crown and drooping branches near the base.

Features Related to Crotch Strength

In arboriculture, there are several long-standing and widely accepted beliefs regarding the strength or weakness of tree crotches. Many of the structural features associated with strength and weakness in trees have received limited formal testing.

Narrow branch angles are widely associated with decreased strength in crotches, particularly when associated with included bark (Matheny and Clark 1994) (Harris 1992). However, MacDaniels' (1932) early study of 225 crotches from 20-year-old apple trees indicated that branch angle is not an important factor in breaking strength unless included bark is present.

Miller (1959) tested the relationship between branch angle and strength by pulling 1,081 apple tree limbs down until they broke and calculating the maximum stress each branch withstood. In this study, the pulling force was applied some distance out on the branch resulting in failure either at the crotch or on the branch. The branch broke in just over half the cases. There was strong correlation between crotch angle and the location of the break. Branches with narrow-angled crotches were more likely to break at the crotch than on the branch. Miller found that the correlation between strength and angle was weaker than the correlation between relative branch size and strength. Because the narrow-angled branches were consistently larger than the wide-angled branches, he concluded that relative branch size led to the weak correlation between decreasing strength and narrow angles. When Miller compared the strength of similar–sized branches with differing angles there was no correlation between strength and angle. All of the trees in this study were the same age so the author concluded that the larger branches had grown faster and had lower wood density and this accounted for the decrease in strength.

In a more recent study, Lilly and Sydnor (1995) broke forty branches from Norway and silver maple trees. These authors found that wider crotches were "less stable than" narrow crotches in silver maple but that Norway maple branches with narrow angles broke more frequently at the crotch rather than on the branch. However, in this study the force was applied perpendicular to the ground rather than perpendicular to the limb. This may have affected the manner in which the force was transferred to the crotch.

Two summaries of ice storm damage in urban trees found conflicting results in regard to branch angle and susceptibility to ice damage. Sisinni et al. (1995) concluded that horizontal branches collected more ice and were therefore more susceptible. Hauer et al. (1993) found that horizontal branches were less susceptible to damage. These results are based on species comparisons rather than looking at individual broken limbs. It could be assumed that horizontal branches have wider crotch angles but it was not indicated in these studies if that was the case.

Current hazard tree assessment guides state that for a branch to have a strong attachment, the branch angle must be broad enough to permit formation of a branch-bark-ridge, and there must be no included bark (Matheny and Clark 1994). Harris' (1992) textbook of arboriculture summarizes that "branch angle is not a problem unless there is included bark." However, branch attachments with included bark are inherently weak and should be removed. This assumed weakness of crotches with included bark has only recently been proven for codominant stems (Smiley 2003). This study compared the force required to break codominant stems with included bark versus those without included bark utilizing samples taken from red maple trees. Results indicated a significant decrease in strength attributed to included bark. However, the reduction was only in the range of 14-20% and the study was limited to codominant stems.

Both MacDaniels (1932) and Miller (1959) concluded that the relative size of the branch to the trunk was the most important factor in determining the strength of the crotch in apple trees. Harris (1992) states that a strong branch attachment requires that the branch be smaller than the stem from which it arises. Specifically, the diameter of lateral branches should be less than ¾ that of the trunk. However, no basis is provided for selecting this threshold value. The same general information is included in the photo guide to hazard tree evaluation, which states that; "strong branch attachment only occurs if the two components are unequal in size" (Matheny and Clark 1994).

Branch size relative to the trunk, termed aspect ratio, plays a significant role in determining the crotch's ability to resist the spread of decay (Eisner et al. 2002). Aspect ratio is equal to the branch diameter ÷ trunk diameter. Eisner et al. (2002) found that junctions with an aspect ratio above 0.59 for red maple and 0.39 for live oak were associated with an increased amount of trunk decay four months after pruning to remove the branch.

None of the studies cited have shown a significant relationship between wood strength and crotch strength. In their summary of ice damage to urban trees (Hauer et al. 1993) found that tree form was more important than wood strength when rating species susceptibility to damage. Similar results were found in the comparison of breaking strength in Norway and silver maples (Lilly and Sydnor 1995). While these species have different wood densities, no difference in strength (resistance to breaking) was demonstrated in that study. Smiley et al. (2000) found that red oak and red maple crotches of the same diameter required the same amount of force to break. However, it is difficult to draw conclusions based on wood strength comparisons between species because the most common wood strength values are based on tests of clear-grained boards. Limb and crotch wood may vary significantly from these test conditions. Also, there is considerable variability in wood strength values for an individual species so comparisons of species averages may be misleading.

Pruning and Cabling Standards

Industry standards have been established for the practice of tree maintenance activities such as pruning and installing cables (Smiley and Lilly 2002). However, published standards do not address specifically when these maintenance activities are needed.

Pruning is the most common remedial work and is used to remove weak branches and secondary trunks, reduce weight and wind resistance in weak branches, and guide development of stronger structure in young plants (Matheny and Clark 1994, and ANSI A300-2001). Harris (1992) recommends that branches with included bark should be removed as early as possible and the growth of scaffold branches (main branches that attach to the trunk) should be slowed so that these branches maintain a smaller diameter than the trunk.

The one study of the effectiveness of preventative pruning to reduce storm damage found, however, that branch failures were not reduced in pruned versus un-pruned trees (Luley et al. 2002). This study looked at storm-related service requests for pruning from eight years of street tree inventory data. The pruning standards involved in this study included the removal of branches with angles of less than forty-five degrees. The authors suggest that pruning can reduce hazards by removing particular weak limbs but not by reducing the overall susceptibility of the urban forest to storm damage.

The installation of brace rods and cables is used to support weak structures in trees. Installation of hardware is almost always accompanied by pruning to reduce weight and wind resistance (Lilly 1993). Proper cable installation requires that appropriate size hardware be used, that it be well placed within the tree, properly tensioned, and then monitored and maintained over the life of the tree. Several studies have been conducted to determine the necessary cable size to support branches over various diameters. However, few guidelines exist that quantify the proper cable tension. Since very few cables fail (except due to age), it would seem that generally accepted cabling guidelines encompass a sufficient margin of safety (Harris 1992). This may also indicate that hardware is being installed in trees where it is not needed. Little or no scientific data exists to identify relatively weak crotches that would benefit from the installation of hardware.

The tree care industry has recently developed installation standards that establish specifications for hardware installation in trees. These standards are based on consensus from professional arborists rather than field-testing of the impact of hardware in trees. Brace rods are similar to cables in that standards exist for the size and type of hardware to install but guidance for when to install and where is limited. Smiley et al. (2000) tested the strength of brace rods in trees in order to compare two methods of installation. Their tests showed that installing brace rods just above the crotch increased crotch breaking strength compared to the typical installation just below the crotch.

Branch Strength Experiments

Miller's (1959) study of apple tree crotches was one of the earliest to combine a large number of sample crotches, a consistent method of pulling, and a breaking stress calculation based on the branch section modulus. In Miller's study, the branches were pulled while still attached to the tree but the ends of the branches had been cut off to reduce variability due to weight. The force was applied at a point eighteen inches from the graft union on all limbs and the graft unions were located from twelve to eighteen inches from the trunk. Applying the force at this distance from the trunk enabled them to test whether the branch would break or the crotch.

Miller calculated the maximum bending stress using the following formula (simplified to exclude the weight and length of the beam used to pull the limbs):

$$S = \frac{P * L}{.09818D^3}$$

Where: S = s = maximum stress at breaking (psi)
s = bending moment / beam section modulus = $\frac{32 * M}{pd^3}$
M = (P * L) = bending moment
P = maximum pulling force measured
L = distance from the break to the point of attachment
0.09818 = $p \div 32$
D = diameter of the branch at the break

Miller observed that in this formula, small variations in measured diameter would have a large impact on calculated stress values. Miller's results showed that branch diameter was better correlated with strength than crotch angle (the only other variable tested).

More recently, Lilly and Sydnor (1995) pulled limbs from silver and Norway maple trees to compare the relative breaking strengths of the two species. These tests were also performed on limbs still in the tree but in this case the pull was maintained perpendicular to the ground rather than to the limb. Applying the force perpendicular to the ground rather than the limb increases the compressive force parallel to the branch in branches that are not horizontal. The proportion of the force acting in compression increases as the branch angle increases relative to horizontal. This would seemingly alter the manner in which branches of differing angles react to the force as applied in this study. This may be suitable for a comparison between species but it would limit the ability to measure strength differences related to branch angle.

The distances from the crotch to the point of attachment of the load are not mentioned in the article but the distance was far enough to allow either the crotch or branch to break. The bending stress was calculated using basically the same formula as Miller.

$$S = \frac{4(F * L)}{p * r^3}$$

Where:S = bending stress (psi)
F = P = force applied
L = horizontal distance from the breaking point to the loading point
(F * L) = M = bending moment
r = branch radius at the breaking point
$\frac{4}{r^3} = \frac{32}{d^3}$

Smiley et al. (2000) removed 63 sample crotches from red maple and red oak trees before breaking them in their study of brace rod installations. The crotches were pulled apart by a tractor moving at a constant rate of speed. The tractor was attached to each sample by a cable attached at a point 30 cm above the crotch. The force required to break each crotch was measured with a dynamometer and those values were used to compare several brace rod installation methods. No strength values were calculated because the treatment comparisons were between branches of the same diameter and the moment arm was the same for all samples. Similar methods were used in a second study testing codominant stems with and without included bark (Smiley 2003). No strength calculation was utilized in this study either.

Cannell & Morgan (1989) studied the strength of spruce branches in resistance to snow and ice loads. The branches were removed from the trees and tested in engineering rigs that applied force at a constant rate to the center of branch segments, which were supported at both ends. The force required to break the branch was measured and used to calculate bending moment at the end of the branch. Bending moment was found to be linearly related to the cube of the branch diameter.

Summary

The high value of trees as assets and potentially high cost of trees as liabilities make it important that arborists and urban foresters reduce the risk of tree failures. To do this they must be able to identify weaknesses, and perform remedial work with confidence in their assessment. Limited resources for tree maintenance require that remedial work be limited to that which is needed and effective.

Tree removal, pruning, and the installation of cables and brace rods are routinely performed to prevent hazards. Standards have been developed to guide pruning and the installation of hardware. However, scant scientific evidence is available to guide the assessment of trees and the prescription of these remedial activities. Scientific studies are needed to support or refute the anecdotal evidence that has long been the basis of arborictural recommendations regarding tree safety and maintenance.

Much work is being done to improve the assessment of the strength of tree trunks and roots. However, the attachment of branches to the trunk and of multiple trunks has received less attention. Past studies have focused on the breaking strength of individual species and even specific cultivars. The applicability of this information to other landscape species is unknown. Recent studies have compared the breaking strength between two species of maple and compared the strength before and after hardware installation. But in these studies, the structure of the crotch itself is secondary. Most of the previous studies of branch strength involved pulling on the branch some distance away from the crotch. This allows for failure to occur either at the crotch or along the branch, making it impossible to compare between all samples. None of these studies attempts to find correlations between the external features of the crotch and the breaking strength for multiple landscape species.

Only by measuring the strength of a large number of crotches from common landscape species will it be possible to prove or refute many of the commonly held beliefs in arboriculture. This research may enable more accurate diagnosis; thereby reducing hazards, prolonging tree life spans, and improving the allocation of limited resources.

CHAPTER 3
METHODS & ANALYSIS

Sample Collection

On July 22, 1996, crotches were cut from 31 red maple (*Acer rubrum*), 22 callery pear (*Pyrus calleryana),* and 25 sawtooth oak (*Quercus acutissima*) trees located at Watkins Nursery in Midlothian, Virginia. All of the trees were approximately 15 years old. Trunk diameters ranged from 2.5 to 7 inches and heights ranged from 15 to 30 feet. All of the sampled trees had developed narrow, upright crowns due to close spacing. All the crotches sampled came from upright stems rather than from horizontal branches.

All the trees within each species were cut at the same time; red maples first, then the pears, and the sawtooth oaks last. Felling the trees and cutting the samples took from 10:30 AM until 5:30 PM. Weather in the morning was overcast with occasional light rain and temperatures rising from the mid-seventies into the lower-eighties. The weather in the afternoon was partly sunny and humid with temperatures in the mid-eighties.

Trees were felled with a chainsaw and all suitable crotches cut out, one tree at a time. Suitable crotches were composed of two stems, each with sufficient diameter to be held in the testing machine and no signs of decay or decline in either stem. The number of samples taken from an individual tree ranged from one to seven per tree (Table 3.1). Each sample was marked with a letter indicating the species, and the tree number. Within each species, trees were numbered sequentially starting from one. After removal, the cut ends of the samples were coated with a wax emulsion end-sealer ("Anchorseal" by U-C Coatings Corp. Buffalo, NY). This was used to prevent the samples from drying out and to maintain them in as close to the "green" condition as possible. The end-sealer was applied either by using a brush or by dipping the cut ends into the sealer. Ends were sealed immediately after cutting where possible but always within thirty minutes after cutting. The samples were then transported to Blacksburg, Virginia.

In Blacksburg, the samples were placed in a pile in a shaded location and covered with plastic and a tarp. The samples were uncovered and sprayed with water daily. To ensure adequate coverage the samples were re-coated with end-sealer. The red

Table 3.1: The number of trees in each species, listed by category for the number of samples obtained from individual trees. Total number of red maple trees equals 29 because samples from two of the thirty-one trees were not tested. Total number of sawtooth oaks equals 24, because samples from one tree were not tested.

Number of samples from one tree	Red maple	Callery pear	Sawtooth oak
1	4	0	3
2	10	1	2
3	4	3	5
4	7	3	7
5	2	9	5
6	2	4	2
7	0	2	0
Total # of Samples	86	106	87

maple samples were repainted on July 23rd, the pears on July 23rd and July 24th, and the sawtooth oaks on July 26th and July 27th.

Because of difficulties in scheduling the testing machine and the time involved in measuring and breaking the samples, it was determined that the pear samples, the last to be tested, would be stored in water tubs while the oaks and maples were tested. All the pear samples were placed into water tubs located outdoors on July 30th and covered with a tarp. From this point on, the oak and maple samples were kept in shaded piles covered with wet blankets and plastic.

Data Collection

Prior to measuring, each crotch was classified as one of three types: the union of a branch and the trunk; the union of two codominant stems; or the union of two branches (Figure 3.1). A stem was classified as a trunk when it met the following criteria: 1) the diameter was nearly the same as the diameter of the trunk below the crotch; 2) the stem continued roughly in the same direction as the trunk below (still vertical); 3) the stem was still large enough to support more main branches higher up in the tree. A stem was classified as a branch when: 1) it was clearly subordinate to the other stem (the trunk) in size; 2) the stem was not oriented in the same direction as the trunk below the crotch; 3) the stem was not large enough to support more main branches. When both stems could be classified as trunks, the crotch type was recorded as the union of codominant stems. When both stems were classified as branches the crotch type was recorded as the union of two branches.

Crotch form, V-shaped versus U-shaped, was determined using two criteria. In V-shaped crotches the bark ridge rolls in at the crotch, and the inner surfaces of the two stems come into contact at the crotch (Figure 2.2, right). By this definition, a V-shaped crotch will have included bark at least at the very top. Presence of included bark deeper within the crotch could not be determined prior to breaking and was not used a criteria for determining crotch form. In U-shaped crotches the bark ridge is raised in the crotch and the inner surfaces of the two stems do not touch (Figure 2.2, left) (Shigo 1991).

Branch angle was measured by establishing the centerline of both stems and then measuring the angle of the intersection of these two lines (Figure 3.2).

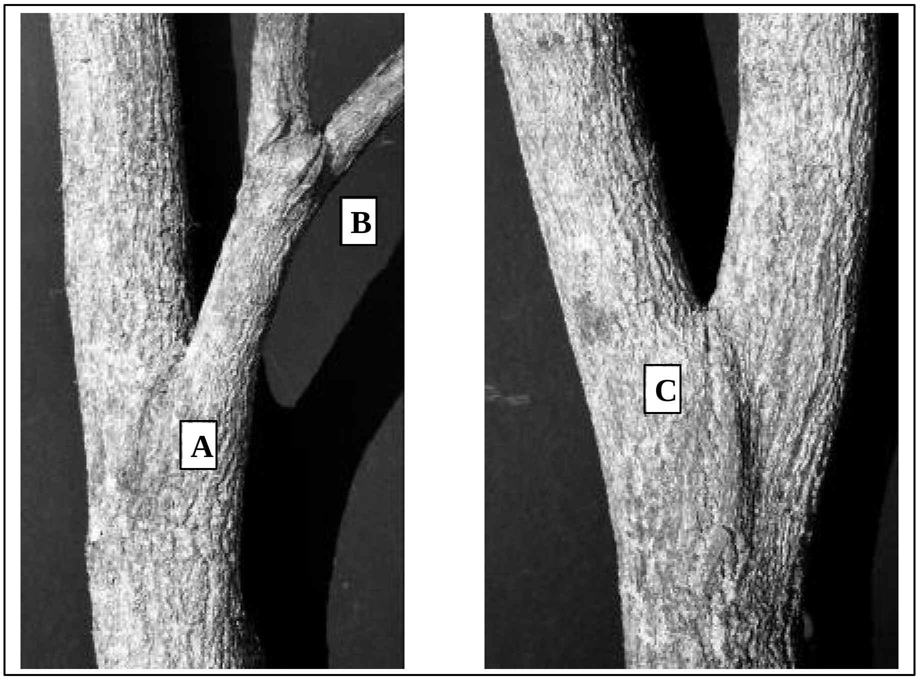


Figure 3.1. Examples of the three crotch types; trunk-branch (A), branch-branch (B), and codominant stems (C).

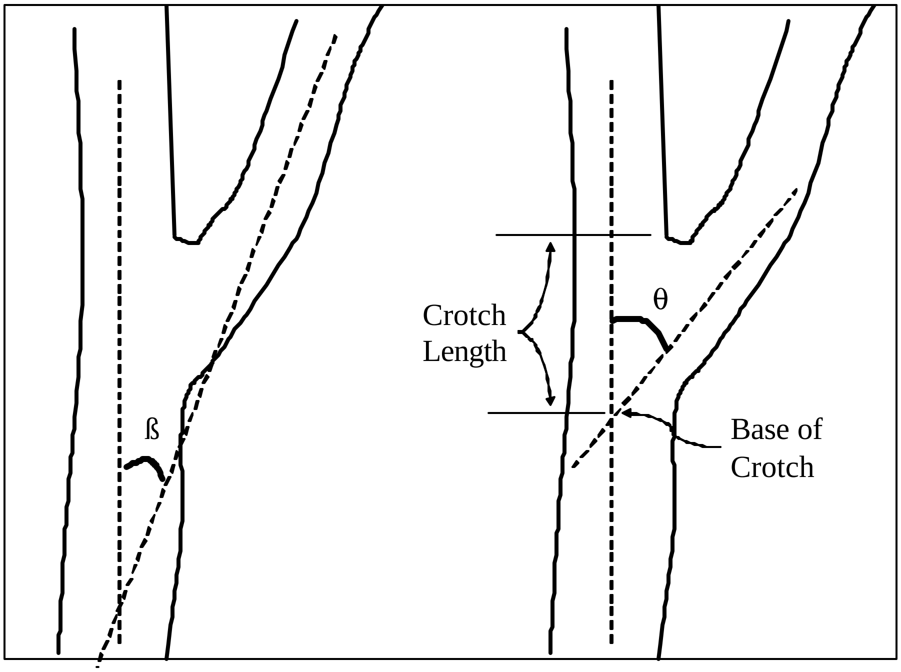


Figure 3.2. Measurement of the branch angle (ß) and crotch angle (θ), the location of the crotch base, and the measurement of crotch length.

Because many branches curve up after growing out from the trunk, the angle of the branch where it joins the trunk was also measured. This angle was termed the crotch angle and was measured by establishing the centerline of the branch where it attached to the trunk and measuring the angle of the intersection of this line with the trunk centerline. For branches that did not curve, branch angle and crotch angle were equal.

The point of intersection of the crotch and trunk centerlines was established as the base of the crotch (Figure 3.2). This was based on dissections of crotches that showed this point corresponded with the origin of the branch pith at the trunk pith. The length of the crotch was measured as the distance from the inside of the crotch to the base of the crotch (Figure 3.2).

The diameter of both stems was measured parallel to the crotch as near on the stem to the crotch as possible using a caliper. The diameter of the trunk below the crotch was also measured at the point established as the base of the crotch. Trunk diameter below the crotch was measured both perpendicular and parallel to the crotch and the values averaged.

Crotch width was measured perpendicular to the crotch at its widest point using a caliper (Figure 3.3). The widest point was found by measuring the distance between the branch bark ridges on either side of the crotch.

Length of the branch bark ridge was measured as a straight line from the inside of the crotch to the endpoint of the ridge on one side of the crotch only (Figure 3.4). The angle of the branch bark ridge was measured as the angle of intersection of the centerline of the ridge and the trunk centerline.

The distance to nearby branches was measured from the inside of the crotch of the study branch to the inside of the crotch of the proximal branch. The horizontal angle between the study branch and the nearby branch was also recorded. The diameter of proximal branches was measured at the point of attachment to the trunk. This data was collected but not analyzed.

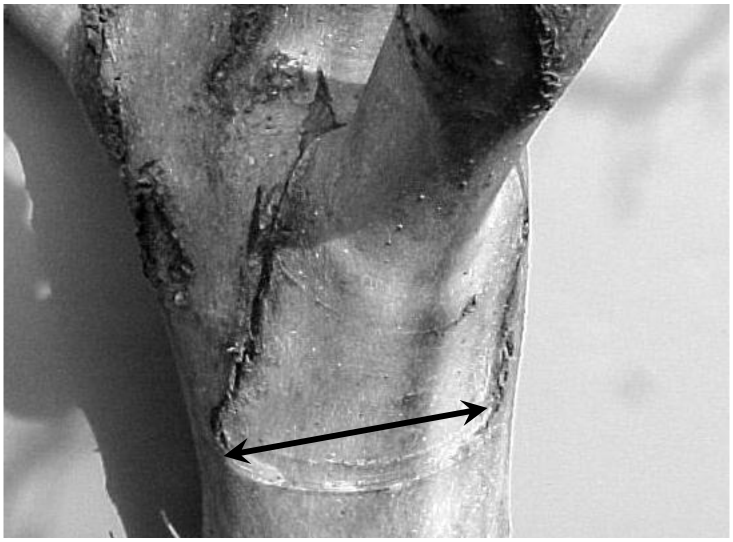


Figure 3.3. Location of the measurement of crotch width between the two farthest extents of the branch bark ridge on either side of the crotch.

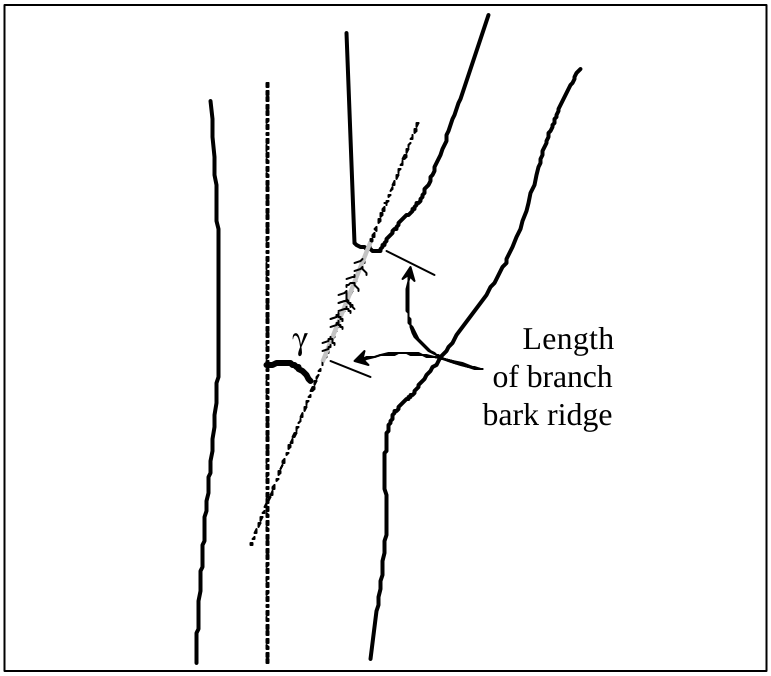


Figure 3.4. Measurement of the branch bark ridge angle (γ) and length of the branch bark ridge.

Testing

Sample crotches were pulled apart using a 20,000 lb. capacity servo-hydraulic testing machine (MTS Systems Corp., Minneapolis, MN) located at the Thomas Brooks Forest Products Center in Blacksburg, VA. The testing machine utilizes an overhead-mounted hydraulic ram to apply vertical compression or tensile force on a sample while recording applied load and deformation of the sample.

Sample crotches were placed on the testing machine table horizontally with the branch attached to the hydraulic ram and the stem to the table surface (Figure 3.5). Chains with slip-hooks were used to attach the samples to the hydraulic ram and to the table surface.

All crotch samples were pulled apart at a constant rate and the testing machine measured the force of the crotch resisting this pull. The maximum force measured was used to calculate the maximum breaking strength of the crotch. Force was recorded by the testing machine, displayed on a digital readout, and recorded on a chart-recorder.

The rate of pull for the machine is established by setting the rate of travel of the hydraulic ram. For this study, the ram was set to travel its full available distance of five inches in 150 seconds, a displacement rate of 2"/minute. This rate was chosen to provide a short breaking time while still allowing time to make measurements during the test. This rate also simulates a steady increase in force as would occur with ice loading on a branch, albeit for a shorter duration. This test was not meant to simulate the dynamic loading applied to crotches during windstorms.

The chains were attached to the stem and trunk approximately two inches from the inside of the crotch. After the samples were attached to the machine, slack was taken up by tightening the threaded rod that attached the chain the to machine table.

When the hydraulic ram was actuated, the sample's angle relative to the attachment chains sometimes changed as the load increased. To determine the perpendicular component of the pulling force acting on the branch, the angle between the branch and the chain was measured in five-degree increments using a protractor (Figure 3.6, angle = α). The angle measured when the load peaked, as evidenced by a sudden drop in load displayed on the digital readout, was recorded as the angle of the pulling force at the point of maximum stress. Samples were then pulled completely apart.

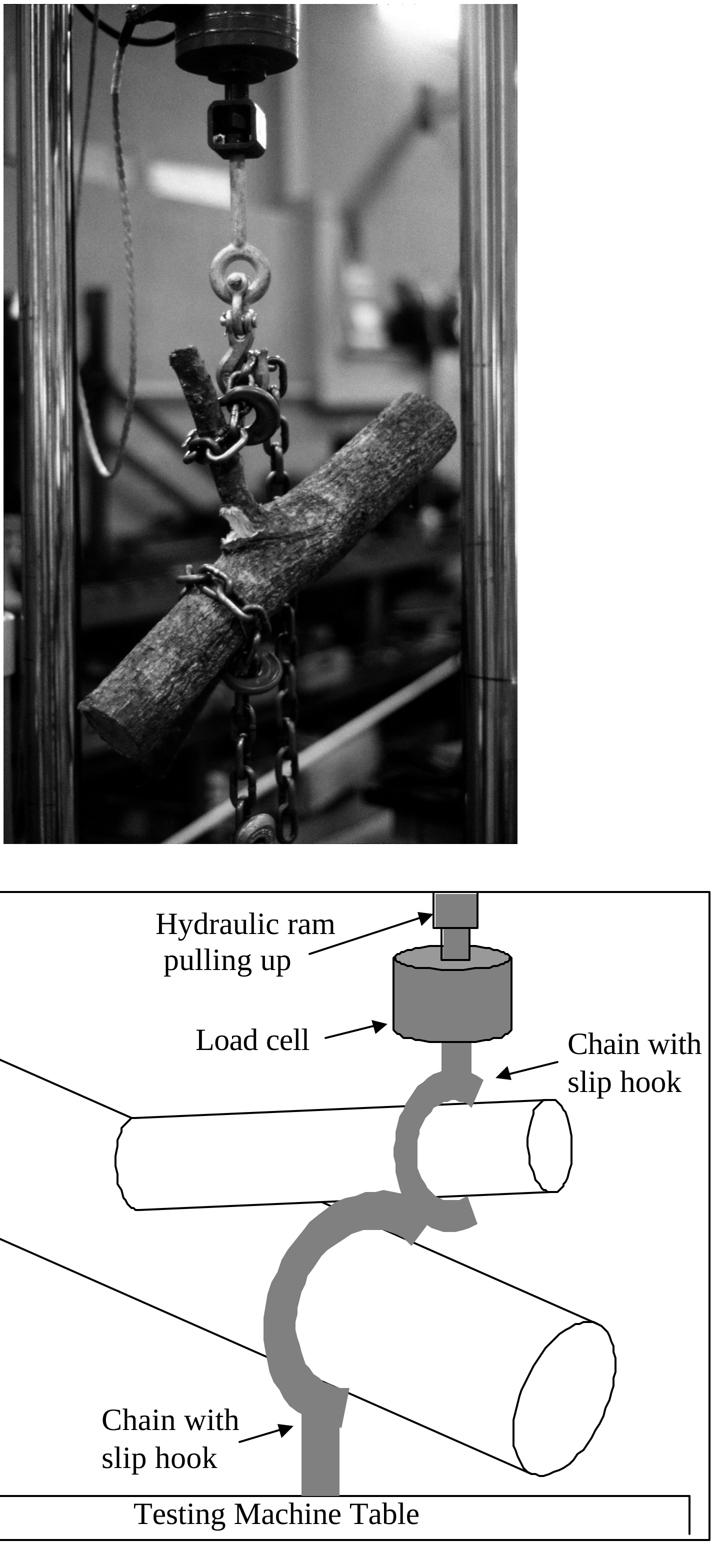
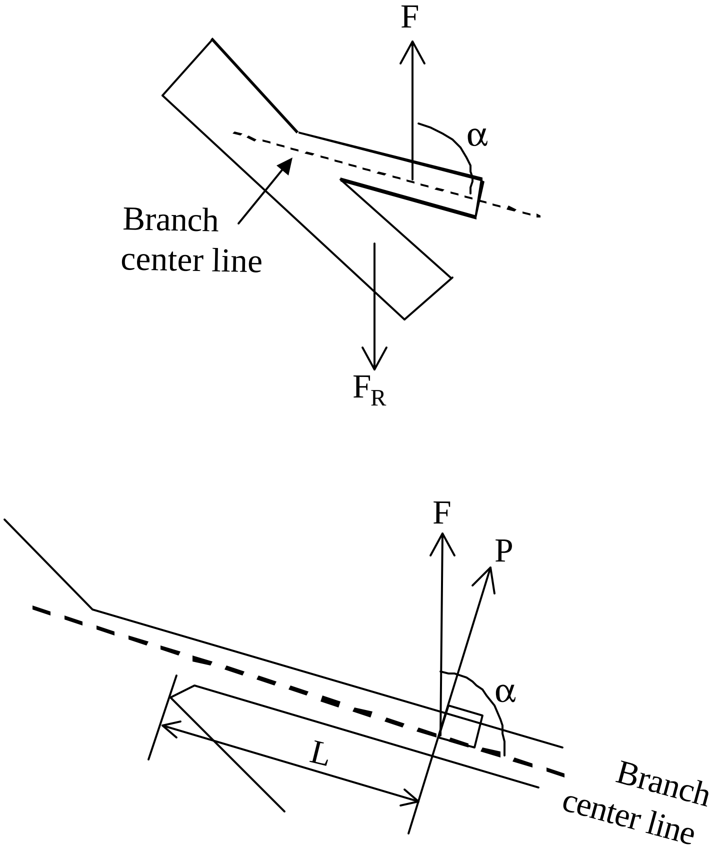


Figure 3.5. Photograph of a sawtooth oak sample after breaking (top) and a diagram of the testing machine set-up.



F = Applied force (max. value recorded by load cell)
F_R = resulting force from attachment to table
α = angle between branch centerline and chain
P = F cos (α-90)
L = distance from chain attachment to inside of crotch
M = P*L

Figure 3.6. Free body diagram showing all forces acting on the crotch sample during testing (top). Close-up of the branch showing values used to calculate maximum bending stress (bottom).

The distance from the inside of the crotch to the attachment point of the chains on both stems was measured to the nearest 0.1 inch. Since all samples failed at the crotch, these distances were recorded as the moment arms for the trunk and branch. The maximum load recorded by the testing machine was also recorded.

Post-Breaking Data Collection

After all crotches were tested in each session, usually thirty crotches per day, wood samples were cut from each crotch to use for measuring the moisture content and specific gravity of the wood. One-inch thick wood samples were cut from the branch or trunk as near to the crotch as possible. Sample diameters varied depending on the size of the branch or trunk from which they were cut. Immediately after cutting each sample was weighed to the nearest 0.1g to determine the green weight. After weighing, samples were dried for 24 hours at a temperature of 104° (F).

After 24 hours, oven-dry weight was measured to the nearest 0.1g. Percent moisture content was calculated by dividing the weight of water removed from the sample by the oven dry weight of the sample, and multiplying the result by 100.

The volume of each wood sample was measured by coating the sample in wax and suspending it in a container of water so that the sample was just immersed. Because one cm^3 of water weighs one gram, the weight of the displaced water equals the volume in cm^3 of the immersed sample. Specific gravity (oven dry basis) was then calculated by dividing the oven dry weight of the sample by its oven-dry volume, and then dividing this result by the density of water.

The inside-bark diameter was measured for each branch by cutting the branch directly above the crotch and measuring two perpendicular diameters of the wood surface to the nearest 0.01-inch using calipers. The average of the two measurements was recorded as the branch inside-bark diameter.

The manner in which the crotches broke was recorded as “Breaking Mode” (Figure 3.7). Crotches that broke parallel to the trunk grain with the trunk splitting roughly in half longitudinally were termed “Flat-Surface” breaks. Other crotches broke parallel to the grain but the trunk did not split down the middle. Instead, only the trunk-

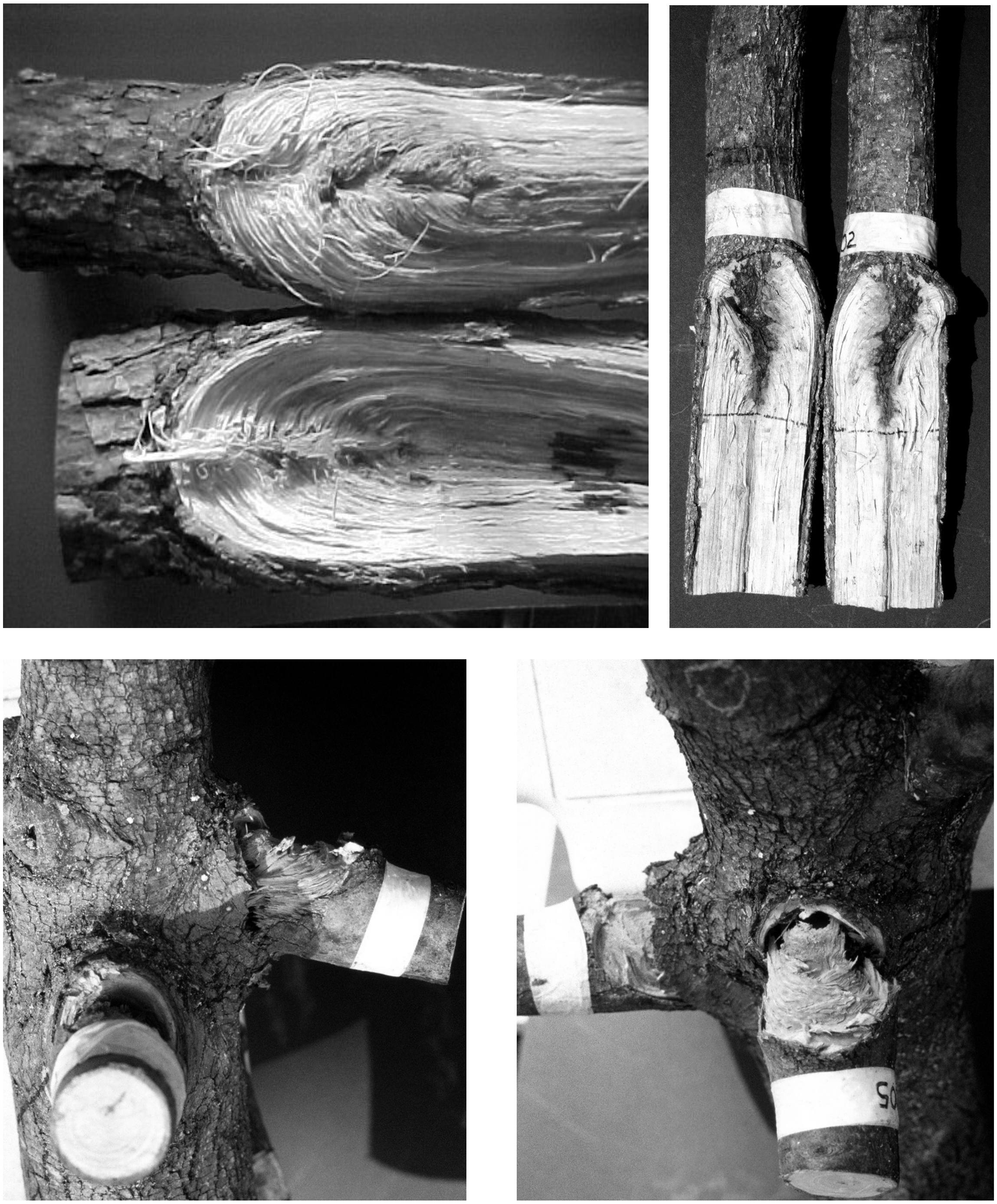


Figure 3.7. Examples of the three breaking modes. Flat-Surface break on a sawtooth oak sample with included bark (upper right). Example of an Imbedded-Branch break on a white oak (sample not broken in this study)(upper left). Side view and top view of a Ball-in-Socket break on a pear sample (bottom).

wood associated with the branch split out, leaving a groove in the trunk. This type of splitting was termed an “Imbedded-Branch” break. The rest of the samples broke at the crotch only. In these, the branch broke from within the trunk without tearing the trunk below the crotch. This was termed a “Ball-and-Socket” break because of the arrangement of the branch attachment. This same breaking mode is described by Shigo (1985) for branches that were slowly pulled apart from the trunk.

The surface area of included-bark was measured where present. To measure the area of included-bark, all of the branch wood was removed from the crotch down to the included-bark using a wood chisel. This exposed a flat surface the full width and length of the crotch, at the center of which was the area of included-bark. A sheet of transparency film was tacked down onto this surface. The outside edge of the crotch, inside the bark, and the perimeter of the included-bark area were then traced onto the transparency.

Calculation of Breaking Strength

It is beyond the scope of this research project to calculate the actual strength (stress per unit area) of a tree crotch. Due to the variation of fiber orientation within an individual crotch and the variation in form between crotches, no existing strength calculation would provide comparable results over a range of crotches. The three breaking modes observed in this study apparently resulted from very different fiber orientations within the crotch and therefore had different reactions to the stress applied.

For this study, crotch breaking strength was calculated as being equal to the maximum bending stress measured in the branch section proximal to the crotch at the moment of crotch failure (Miller 1959). Maximum bending stress ($s_{\max}$) for circular sections is defined by the formula:

$$s_{\max} = \frac{Md}{2I} = \frac{32M}{pd^3}$$

Where:M = (P*L) = bending moment
P = the maximum force applied to the branch
L = the distance between the point of attachment and the break
I = the second moment of area for a circular section
d = the branch diameter

(Cannell & Morgan 1989). *M* is equal to *P* x *L*, where *P* is the maximum force applied to the branch and *L* is the perpendicular distance between the line of action of that force and the crotch (Jensen & Chenoweth 1983). The force *P* was recorded from the testing machine as the peak load for each sample. *L* was measured as the distance between the point of attachment of the hydraulic ram and the breaking point at the crotch (Figure 3.5).

When the bending stress formula is used to test wooden beams it is assumed that the test material is relatively homogeneous. Test samples are obtained from trunk wood and are determined to be clear and straight-grained (USDA 1974). The presence of defects such as knots or splits would likely lead to failure at the location of the defect and at a smaller load than a homogenous sample would be able to bear without failing.

In this crotch-strength study the test samples are not homogenous, from a wood-testing standpoint, the entire crotch is a defect. However, it is precisely this defect that is the focus of the test. This study assumes that the short section of branch wood is homogenous and the only defect present is the crotch itself, the compaction zone to be precise. The fact that all samples broke at the compaction zone supports this assumption. No branches with decay or other obvious defects were used in the tests.

This formula also assumes that the test sample is circular in cross-section. All of the branches tested were approximately round, the difference between the two perpendicular diameter measurements of the branch was 10% or less for most samples (100% of the pears samples, 93% of the maples, and 84% of the oaks).

Shear stress (τ) was calculated for all samples using the formula below:

$$(\tau) = \frac{VQ}{Ib} = \frac{Vay}{Ib} = \frac{4}{3} * \frac{P}{p * r^2}$$

Where: $V = P$ = maximum shear force
a = area from the neutral axis to the outer edge
y = distance from the neutral axis to the centroid of the of the area “a”
I = moment of inertia = $\frac{pd^4}{64}$
$b = d$ = diameter of the branch
$r = \frac{d}{2}$

Shear stress values were small relative to bending strength, 10% to 15% for most samples. Shear stress is linearly related to bending stress $R^2 = .99$. Regressions of (bending strength + shear strength) with crotch parameters provided the same R^2 values as regressions with bending strength alone. Based on this, all results utilize bending strength alone.

Data Analysis

Duncan's multiple range test was used to test for significant differences ($\alpha = 0.05$) between the average strengths for crotch type, crotch form, and breaking mode within each species. Crotch form was not analyzed for the pears because there was only one pear sample with a V-shaped crotch.

Each of the variables related to the size and structure of crotches was tested for correlation with strength in the individual species using linear regression equations in SAS (SAS Institute, Cary, NC). Based on examination of scatter plots, no other models were apparent. The variables with R^2-values above 0.25 for at least two of the species were then tested for correlation with all species combined.

The variables with R^2-values above 0.25 included branch angle, branch diameter / crotch width (Table 3.2), trunk diameter above the crotch / crotch width (Table 3.3), branch inside-bark-diameter, branch inside-bark-diameter / crotch width, and diameter ratio. The diameter ratio of each crotch was calculated by dividing the branch diameter (smaller stem) by the trunk diameter (larger stem). For this variable both diameters were measured parallel to the crotch, outside of the bark using a caliper. Diameter ratio in this study is similar to "aspect ratio" as described by Eisner et al. (2002).

The following variables had R^2-values below the 0.25 threshold: crotch angle, crotch length, crotch width / trunk diameter below the crotch, length of the branch-bark-ridge, angle of the branch-bark-ridge, and branch angle / branch-bark-ridge angle. Each of the variables, moisture content, specific gravity, and number of days between harvest and testing also showed very low correlation with crotch strength.

Six of the oak samples were damaged during the strength test so that the inside-bark diameter on the branches could not be measured. A regression formula was

Table 3.2: Range of values for branch diameters, crotch widths, and the ratios of branch diameter over crotch width for all three species.

Species	Range of Branch Diameters (in.)	Range of Crotch Widths (in.)	Range of Ratios (a)
Sawtooth oak	0.9 - 2.7	1.3 - 4.6	0.31 - 0.83
Red maple	0.7 - 2.9	1.5 - 4.9	0.29 - 0.87
Callery pear	0.9 - 3.3	1.3 - 4.9	0.46 - 1.0

(a) Ratio = branch diameter/crotch width

Table 3.3: Range of values for trunk diameters above the crotch, crotch widths, and the ratios of trunk diameter over crotch width for all three species.

Species	Range of Trunk Diameters (in.)	Range of Crotch Widths (in.)	Range of Ratios
Sawtooth oak	1.1 - 4.1	1.3 - 4.6	0.67 - 1.30
Red maple	1.0 - 5.1	1.5 - 4.9	0.61 - 1.58
Callery pear	1.2 - 3.9	1.3 - 4.9	0.65 - 1.85

calculated relating inside bark diameter to total diameter of the branch for all other oak samples. This formula was used to generate values for the six damaged samples.

Data was gathered on proximal branches for each sample but the data was not tested. During the break tests, proximal branches did not have any apparent effect on crotch strength. For these samples, the proximal branches were much smaller than the test crotches in most cases. Proximal branches may have more effect when they are larger in relation to the crotch.

Crotches that were found to contain included-bark were traced onto transparencies for measuring the area of included bark relative to the total area of the crotch. Prior to tracing, the wood was chiseled away from the split surface as needed to expose all of the included bark area and to create a flat surface for tracing. The outline of the crotch and of the included bark area was traced. A dot grid was used to measure the total surface area of the crotch first and then the area covered by include bark.

The included bark area was divided by the total area of the crotch to determine the percent-included-bark-area for each sample. The percent-included-bark-area was tested for correlation with strength for the maples and oaks.

Samples Dropped from Analysis

Sawtooth oak sample number 303 was measured but never tested. Samples 501, 1501, 1701, and 2201 were broken using the initial clamp setup that proved ineffective. These samples were dropped from analysis because all subsequent samples were broken using chains. Sample 801 was dropped because the MTS machine ran out of travel on the ram before breaking the crotch. Crotch width was not measured for sample 504. This sample was dropped only for the three variables based on crotch width.

Callery pear sample number 303 was measured but never tested. Sample 1104 was dropped because the branch broke instead of the crotch. Sample 1106 was dropped because the moment arm measurement could not be made. On sample 1503 the trunk broke instead of the crotch. Sample 1606 was the only pear sample that contained included-bark and the only one that was V-shaped. This sample was dropped from all regression tests. R-values did not change after dropping this sample. Sample 2205 shows up as an outlier on the graph of strength versus crotch width and the crotch width measurement is smaller than the branch diameter. This may indicate an error in data recording. This sample was dropped only for the three variables based on crotch width.

Red maple sample number 1002 was dropped because the breaking angle was not recorded. On sample number 1504 a small branch was growing out of the center of the crotch. Decay was present inside the crotch on sample number 1601.

The following red maple samples were measured but not broken: 1305, 1404, 1405, 2201, 2302, and 2602. Some trunk sections contained more than one sample crotch and some crotches were damaged during the breaking of the first crotch on the same trunk section. Other samples from the red maples were too small to be held effectively in the breaking machine.

The following samples were not measured for crotch width due to the growth habit of the branches on the trunk: 101, 401, 502, 702, 804, 1202, 1301, 1502, 1701, 1902, 2101, 2303, 2502, 2901, 3101, and 3104. These 16 samples were dropped from the analysis of the three variables relating to crotch width.

Samples 2303 and 3104 were not measured for branch bark ridge angle. These two samples were dropped from that analysis.

CHAPTER 4

RESULTS AND DISCUSSION

Crotch Type

Trunk-branch was the most common crotch type in each species followed by co-dominant stems and a small number of the branch-branch type (Table 4.1). Breaking strength was significantly different between all crotch types for each species except for the branch-branch and co-dominant stem types in the oaks. The trunk-branch crotch type was the strongest, followed by branch-branch and co-dominant stems for all three species. These results are consistent with the literature in that a strong branch attachment results from the branch being smaller than the trunk from which it arises (Harris 1992 and Matheny and Clark 1994).

Crotch Form

U-shaped crotches were significantly stronger than V-shaped crotches on average for the maples and oaks. Only one pear sample was classified as V-shaped. Oak samples had an average strength of 14,513 psi for U-shaped crotches and an average of 8,136 psi for V-shaped ($p < 0.001$). Maple U-shaped crotches had an average strength of 7,622 psi compared to 4,874 psi for the V-shaped ($p < 0.001$). These results were anticipated since "V" crotches are commonly associated with structural weakness (Smiley and Lilly 2002).

In V-shaped crotches, the branch bark ridge fails to form between the branch and trunk allowing the branch and trunk surfaces to come into contact. Continued growth in this manner causes the bark of both surfaces to be buried inside the crotch. All 31 of the V-shaped oak crotches and 17 of the 18 V-shaped red maple crotches contained included bark. (It may be that the lone V-shaped red maple sample without included bark was incorrectly classified as V-shaped, or that the included bark area was small enough to avoid detection). This evidence would support the commonly held belief that V-shaped crotches are synonymous with included-bark (Shigo 1991).

The branch bark ridge is formed by the branch and trunk fibers bending to grow around the base of the branch. This bending is most pronounced at the top of the crotch since the fibers on the trunk and branch surfaces directly above the crotch must bend at a

Table 4.1. Number of samples and mean breaking strength of samples within each of the three crotch types for the three species.

Species	Crotch Type	Number of Samples	Mean Strength (psi)	Standard Error
Pear	Trunk-branch	71	10,336 a[1]	352
	Branch-branch	6	6,662 b	913
	Codom. stems	29	4,650 c	307
Maple	Trunk-branch	58	8,785 a	303
	Branch-branch	8	5,583 b	624
	Codom. stems	23	3,248 c	324
Oak	Trunk-branch	59	15,074 a	618
	Branch-branch	10	7,980 b	1020
	Codom. stems	18	5,320 b	409

[1] Within each species, means with the same letter are not significantly different based on Duncan's multiple range comparison ($\alpha = .05$).

ninety-degree angle to go around the branch base.

A reduction in the amount of fibers growing around the branch base would likely result in a reduction in the size of the branch bark ridge. Since there is no vascular connection between the trunk and branch above the crotch, all of the branch fibers must turn at the crotch and grow around the branch base. The trunk fibers however, can follow two alternative paths; some trunk fibers grow from the trunk to the branch while other trunk fibers grow around the base of the branch and continue up the trunk above the crotch. Any growth pattern that causes more trunk fibers to be dedicated to the branch would reduce the proportion of trunk fibers growing around the base of the branch and then continuing up the trunk. This would tend to shrink the branch bark ridge while increasing the diameter growth of the branch, creating a V-shaped crotch, and eventually, included bark.

Factors that could cause the tree to dedicate more fibers to a branch include, large branch size relative to the trunk, increased branch growth rate, or a very narrow branch angle. Most likely, a combination of these factors is involved. Altering these growth patterns then could prevent the formation of V-shaped crotches.

Included bark

All of the samples were inspected for included bark after breaking. Forty-eight of the oaks (55%) and twenty-one of the maples (24%)contained included bark. Only one pear sample in this study had included bark. The average strength of the samples with included bark was lower than that of the normal samples for the oaks and the maples. Oak samples with included bark had an average strength of 9,934 psi compared to 15,080 psi for those without ($p < 0.001$). Maple samples with included bark had an average strength of 4,951 psi compared to 7,719 psi for those without ($p < 0.001$). These results agree with those of Smiley (2003) in his study of codominant stems with and without included bark.

The percent-included-bark-area values ranged from 2% to 37% for the maples and 17% to 39% for the oaks. The average area value was 18% for the maples and 20% for the oaks. The relative size of the included bark area was poorly correlated with breaking strength, an R^2 value of 0.07 for the maples and 0.08 for the oaks. These low values may be due to the young age of the samples tested; the included bark areas were all small relative to the crotch. If this study had included older trees, some of the samples would likely have included larger relative included bark areas. It may be that included bark does not begin to significantly influence crotch strength until it reaches some threshold value. Also, very few of the included bark areas in these samples extended fully across the crotch, the crotch typically retained some connecting wood on both sides of the included bark (Figures 4.1a & b). In codominant stems from mature trees, the included bark area often does extend across the full width of the crotch; this is especially evident in trees that have split apart at a large V-crotch. It may be that the included bark area must attain some threshold width relative to the entire crotch before it begins to significantly reduce crotch strength.

Of the 48 oak samples with included bark, only 16 (33%) broke cleanly along the included bark interface. The majority of the samples separated wood from wood with the included bark remaining partially covered by wood on either the trunk or the branch part of the broken sample (Figure 4.1). This indicates that the included bark interface was not the weakest area in these crotches.

After exposing the full extent of the included bark, most samples contained a narrow wedge of included bark with an irregular margin. The included bark area usually extended from the top of the crotch to the point where the branch and trunk pith joined. This area corresponds with the weakest part of the tree crotch, the center where trunk and branch fibers turn parallel to each other year after year. These observations suggest that the presence of included bark in and of itself may not greatly weaken the crotch, at least in young trees. However, the presence of included bark is a reliable indicator of a weak structure.

In several of the samples, the included bark did not extend all the way to the top of the crotch (Figure 4.1.b). This may indicate that the tree was able to grow around the included bark over time and establish a stronger structure in spite of the included bark formed in earlier years. This transition was likely facilitated by the young age of the trees and the small size of the branches involved. The same may not be possible for large codominant stems in mature trees. However, this does indicate that in young trees at least, it is possible to manipulate crotch form and “repair” crotches with included bark.

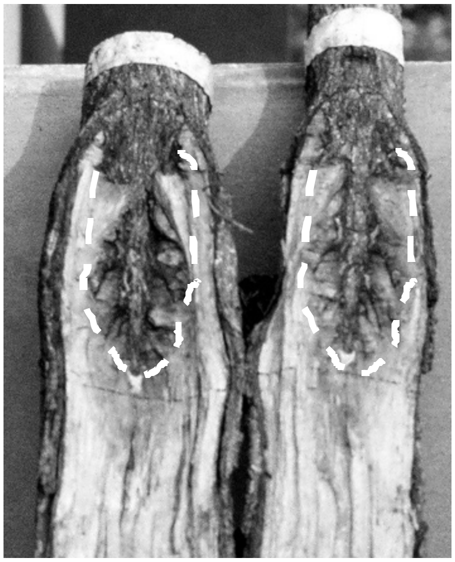


Figure 4.1.a. Sawtooth oak sample that did not break apart cleanly along the included bark interface. The dashed white line shows the outline of the included bark area, partially covered by wood on the trunk section (left) with the corresponding wood missing from the branch section (right).

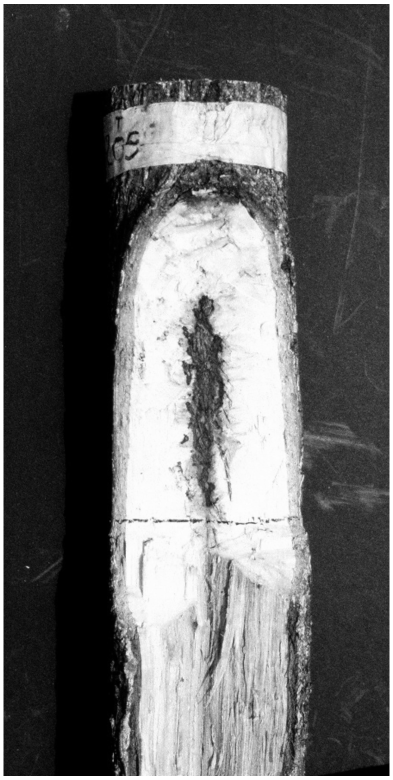


Figure 4.1.b. U-shaped oak crotch with included bark exposed after breaking. The included bark was buried inside the crotch indicating that this was a V-shaped crotch some years before and that it has since developed into a U-shaped crotch.

Environmental Variables

The sawtooth oak samples were broken on six different days ranging from 14 to 25 days following harvest (Table 4.2a). There were no significant differences between the average moisture contents and average strengths of the samples broken on each day. The percent moisture content was well above the fiber saturation point for all samples in all three species. The percent moisture content must drop below the fiber saturation point for the mechanical properties of wood to change due to drying (USDA 1974).

Red maple samples were broken during four sessions ranging from 36 to 50 days following harvesting (Table 4.2b). There were no significant differences in average sample strength for the four days. Average percent moisture contents were statistically similar on the first three days and also between the first, third, and fourth days.

There were significant differences between the average strengths of pears over the five testing dates (Table 4.2c). The average strength on the first day was significantly higher than that of the fourth day. Average moisture content was similar for all five days except the fourth day was significantly higher than the other four.

Wood specific gravity measurements showed very low correlation with strength for all three species in the individual tests. This finding agrees with results from previous studies that found specific gravity was not correlated with crotch strength when comparing two species (Lilly and Sydnor 1995)(Smiley et al 2000).

Table 4.2a. Mean percent moisture content, breaking strength, and specific gravity for sawtooth oak samples by testing date.

Days Past Harvest	No. of Samples	Mean Moisture Content	Std. Err.	Mean Strength (x 1000)	Std. Err. (x 1000)	Specific gravity	Std. Err.
14	1	64% ab[1]	--	11.4(psi) a	--	81 ab	--
15	12	63 ab	1.4	11.6 a	1.7	82 ab	1.4
17	13	62 a	1.2	13.2 a	1.6	86 a	1.1
21	21	65 ab	1.6	13.0 a	1.7	84 a	1.0
23	22	66 ab	1.2	11.7 a	1.1	83 ab	1.2
25	18	68 b	1.3	11.8 a	1.2	81 b	1.2

[1] Means within each column with the same letter are not significantly different ($\alpha = .05$).

Table 4.2b. Mean percent moisture content, breaking strength, and specific gravity for red maple samples by testing date.

Days Past Harvest	No. of Samples	Mean Moisture Content	Std. Err.	Mean Strength (x 1000)	Std. Err. (x 1000)	Specific gravity	Std. Err.
36	19	63% ab	1.5	7.5(psi) a	0.8	55 a	1.1
43	24	67 a	1.2	7.5 a	0.6	57 ab	0.7
44	19	63 ab	1.4	7.5 a	0.7	58 bc	0.9
50	27	61 b	1.3	6.1 a	0.6	60 c	0.8

Table 4.2c. Mean percent moisture content, breaking strength, and specific gravity for callery pear samples by testing date.

Days Past Harvest	No. of Samples	Mean Moisture Content	Std. Err.	Mean Strength (x 1000)	Std. Err. (x 1000)	Specific gravity	Std. Err.
64	25	90% a	1.3	9.8(psi) a	0.7	65 ab	0.3
65	19	92 a	1.1	9.3 ab	0.9	66 ab	0.4
71	26	90 a	2.2	8.5 ab	0.6	67 ab	0.6
72	14	101 b	1.7	7.3 ab	0.6	65 b	0.6
78	22	92 a	1.4	7.5 b	0.8	67 a	0.7

Correlation with Strength

The six variables that showed the best correlation with crotch strength in the individual species were diameter ratio, branch inside-bark diameter/crotch width, branch inside-bark diameter, trunk diameter/crotch width, rough branch diameter/crotch width, and branch angle (Table 4.3). These six variables were tested for correlation with all three species combined (Table 4.4).

Branch inside-bark diameter/crotch width ranked highest for the oaks and pears and was third highest for the maples in the individual species tests. This variable represents the most precise comparison of the size of the branch versus the trunk at the crotch and was ranked highest for the three species combined. This ratio is inversely related to crotch strength so these results support conventional wisdom that crotch strength is the result of the trunk being larger than the branch.

Branch inside-bark diameter ranked highest for the maples, third highest for the pears and sixth for the oaks in individual testing but ranked second for the combined species. Branch diameter is negatively correlated with breaking strength so crotches with larger branches were weaker in this test. This result is similar to that reported by Miller (1959) who attributed the lower breaking strength of larger branches in his study to their faster growth rate. Like Miller's study, all of the trees in this current research were approximately the same age. However, no data was collected on growth rate of samples.

Miller also points out the strong influence that branch diameter has on the formula used to calculate breaking strength in these experiments. Having the cube of the branch diameter in the denominator results in significant reductions in calculated strength for small increases in branch size. This alone may account for the strong correlation between crotch strength and branch diameter. The strong correlation of branch diameter with strength may also be related to the ratio of the sizes of the two stems. Due to the size of the trees studied, there were no samples that combined large branches with even larger trunks. This resulted in the larger branches also having higher diameter ratios.

Table 4.3. R^2 values and ranking for each crotch parameter tested individually for each species. Variables are listed in order of the average ranknig for the three species.

Variables	Species			Rank			
	Pear	Maple	Oak	P	M	O	Av.
Diameter Ratio	0.59 (105)[1]	0.56 (88)	0.56 (86)	2	2	1	1.67
Branch IB Diam. / Crotch Width	0.65 (104)	0.51 (72)	0.56 (85)	1	3	2	2
Branch Inside-Bark Diameter	0.56 (105)	0.58 (88)	0.36 (86)	3	1	6	3.33
Trunk Diam. Above the Crotch / Crotch Width	0.53 (104)	0.36 (72)	0.49 (85)	4	5	3	4
Rough Branch Diam. / Crotch Width	0.4 (104)	0.37 (72)	0.38 (85)	6	4	5	5
Branch Angle	0.35 (105)	0.17 (88)	0.47 (86)	8	8	4	6.67
Branch-Bark-Ridge Angle	0.31 (105)	0.15 (86)	0.36 (86)	9	9	7	8.33
Crotch Width / Average Lower Trunk Diam.	0.02 (102)	0.24 (70)	0.34 (82)	12	6	8	8.67
Crotch Length	0.41(105)	0.11(85)	0.15 (86)	5	10	12	9
Crotch Angle	0.31 (105)	0.06 (88)	0.27 (86)	10	12	9	10.33
Crotch Width / Perp. Trunk Diam.	0.008 (93)	0.25 (66)	0.23 (82)	15	7	10	10.67
Branch-Bark-Ridge Length	0.38 (105)	0.11 (86)	0.13 (86)	7	11	14	10.67
Number of Days Past Harvest	0.06 (105)	0.03 (88)	0.001 (86)	11	13	16	13.33
Specific Gravity	0.003 (105)	0.008 (87)	0.18 (85)	14	15	11	13.33
Moisture Content	0.001 (105)	0.01 (87)	0.14 (86)	16	14	13	14.33
Branch Angle / Branch-Bark-Ridge Angle	0.01 (103)	0.001 (85)	0.03 (85)	13	16	15	14.67

[1] Sample size for each linear regression test.

Table 4.4. R^2 values and ranking for the top six crotch parameters tested for all three species combined.

Rank	Variable	R^2 Value
1	Branch Inside-Bark Diam. / Crotch Width	0.46
2	Branch Inside-Bark Diameter	0.41
3	Diameter Ratio	0.39
4	Branch Angle	0.38
5	Trunk Diam. Above the Crotch / Crotch Width	0.31
6	Rough Branch Diam. / Crotch Width	0.23

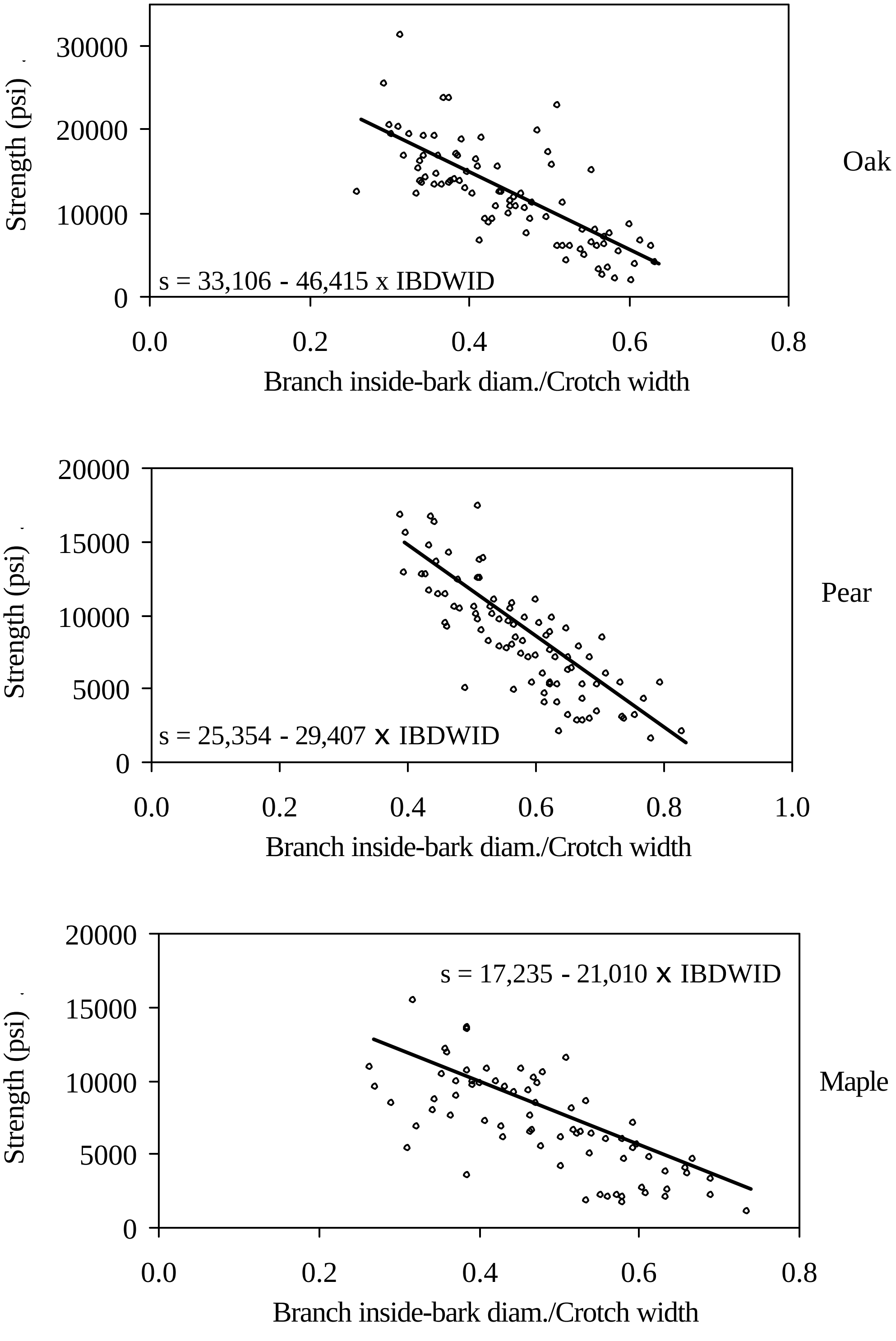


Figure 4.2. Relation of crotch breaking strength (s) to branch inside-bark diameter/crotch width (IBDWID) for each of the species tested.

Diameter ratio ranked second for each of the individual species and ranked third for the combined species. Diameter ratio values ranged from 0.28 to 1.0 for the oaks, 0.21 to 1.0 for the maples, and 0.38 to 1.0 for the pears. This variable represents a less precise measurement of the ratio between the branch and trunk because the diameters were measured outside the bark. Also, the trunk diameter was measured above the crotch rather than at the crotch. However, this variable is the easiest to estimate in the field so it may be the best variable for predicting crotch strength during tree structure assessments.

Branch angle ranked sixth for red maple and for pear but fourth for oak and for the three species combined. Branch angles among the samples that were tested ranged from 7 to 42 degrees in the maples, 7 to 55 degrees in the oaks, and 2 to 54 degrees in the pears. There was a positive correlation between branch angle and breaking strength but it was less important in predicting crotch strength than the diameter ratio between the stems. These data support the view shared by most authors that angle is less important than diameter ratio. However, these results do not support the idea that branch angle is unimportant unless included bark is present, as stated by MacDaniels (1932). None of the branches included in this study had angles greater than 55 degrees, testing branches with angles between 60 and ninety degrees give a better indication of the relative importance of branch angle.

Trunk diameter/crotch width ranked third for the oaks, fourth for the pears and maples, and fifth for the three species combined. This variable also represents the size of the branch compared to the size of the trunk since the crotch width is largely determined by the diameter of the branch attachment to the trunk (Figure 3.3). A higher value here indicates that the branch is smaller than the trunk to which it is attached. A value of less than one indicates a branch that is similar in size to the trunk or codominant stems. This variable has a positive correlation with strength, again supporting the conclusion that larger trunk size in relation to the branch makes for a stronger attachment.

Rough branch diameter/crotch width ranked fifth for each of the individual species and sixth for the combined species. This variable represents another measurement of the ratio between the two stems. This variable is negatively correlated with strength.

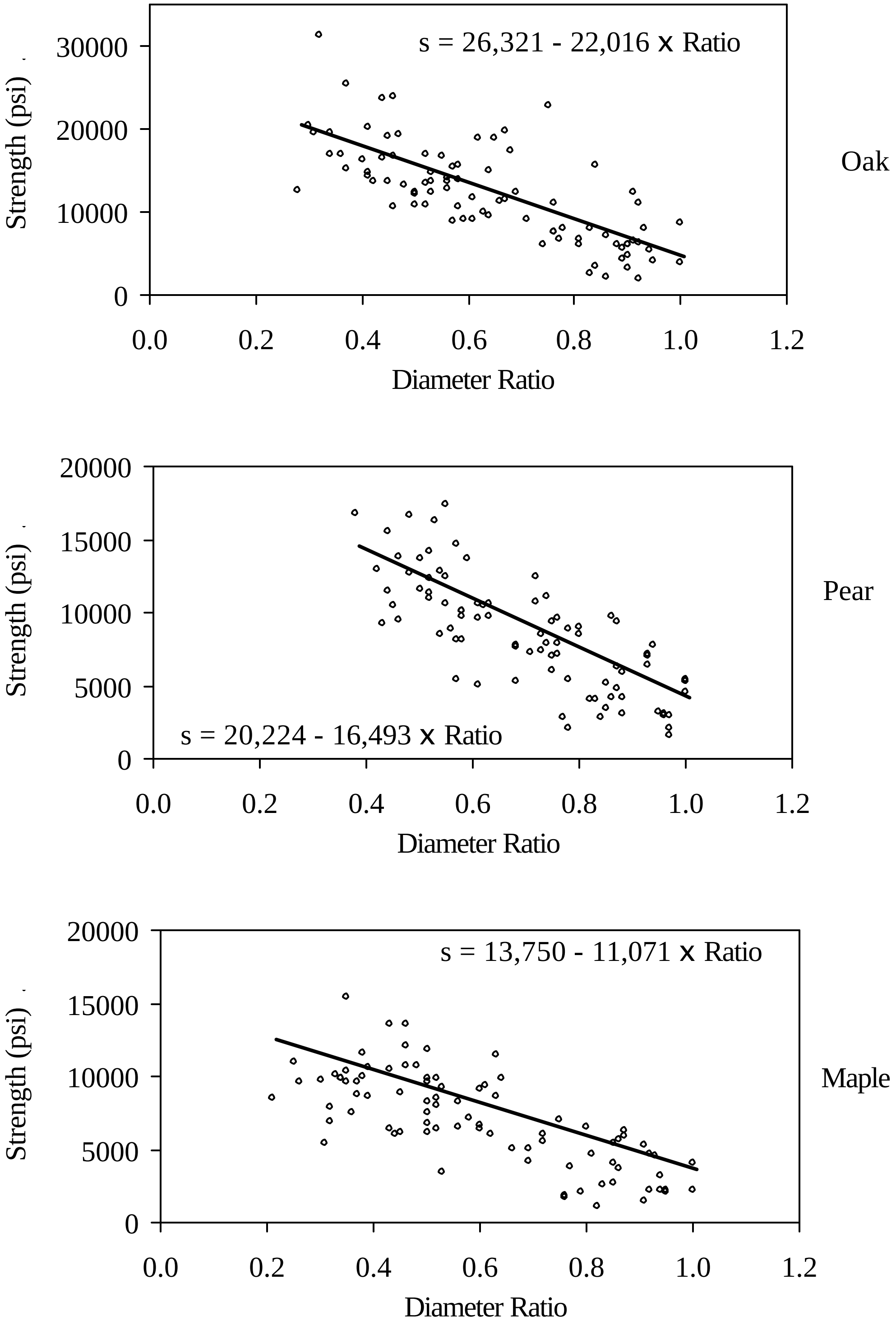


Figure 4.3. Relation of crotch breaking strength (s) to diameter ratio (Ratio) for each of the species tested.

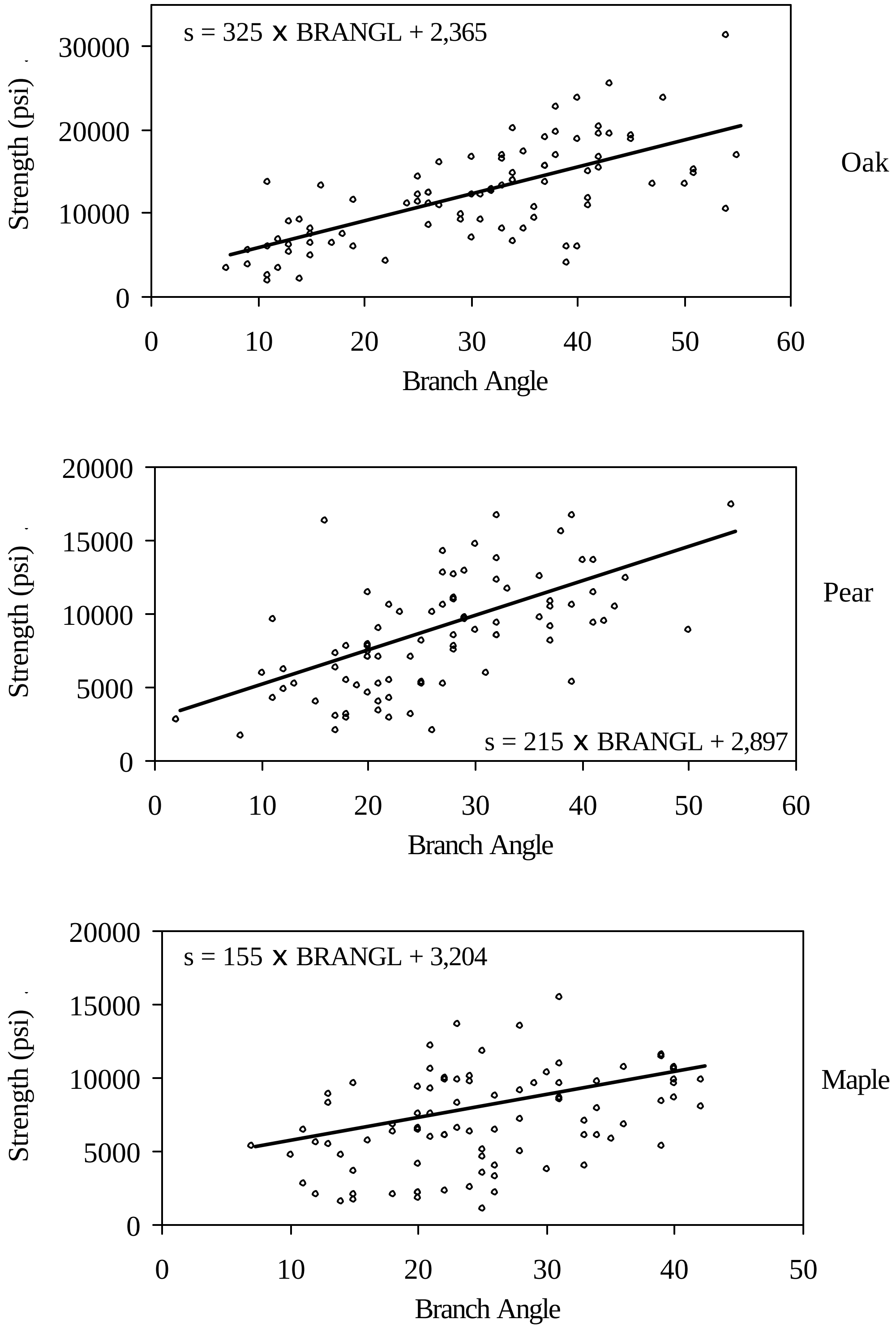


Figure 4.4. Relation of crotch breaking strength (s) to branch angle (BRANGL) for each of the species tested.

The following variables had R^2-values below the 0.25 threshold for the individual species: crotch angle, crotch length, crotch width / trunk diameter below the crotch, length of the branch-bark-ridge, angle of the branch-bark-ridge, and branch angle / branch-bark-ridge angle.

Breaking Mode

Average strength for all samples in each breaking mode was significantly different within each species. Crotches that broke in the ball-in-socket manner were the strongest, followed by the imbedded-branches and then the flat-surface breaks for all species.

In the case of flat-surface and imbedded-branch breaks, it may be more accurate to say that the trunk failed at the crotch rather than the crotch itself failed. In each of these breaking modes the branch remained attached to the trunk wood below the crotch but the trunk wood separated by splitting longitudinally. These results indicate that in the case of flat-surface and imbedded-branch breaks the trunks were not wide enough relative to the branch to grow around the branches. If the trunk cannot grow around the branch, the base of the branch will not become buried deeper in the trunk year after year. This annual overlap of trunk fibers around the branch base is widely thought to be the key component of strong crotches.

Tree crotches have three areas of fiber orientation; the trunk wood around the crotch where the fibers are all parallel to the trunk, the branch wood that is radial to the trunk and surrounded by trunk wood at its base, and the crossover zone where the trunk and branch fibers turn to join the branch to the trunk. The crossover zone lies beneath the branch bark ridge.

When downward force is applied to the branch, the crotch can fail in one of two ways, either the branch wood gets pulled out of the trunk (failure in tension perpendicular to the grain), or the trunk wood around the crotch separates (failure in splitting) allowing the branch to peel away from the trunk. Because wood is much weaker in splitting than in tension it would seem that crotch strength is most closely related to the amount of trunk wood around the crotch. The results of this study support this conclusion since the strongest crotches were those that involved a relatively small branch attached to a larger trunk.

Weakness in crotches, then, is related to factors that encourage more trunk wood to join the branch rather than growing around the branch and up the trunk. The size of the branch is the most important factor, but very narrow branch angles may also influence more trunk fibers to be dedicated to the branch. The proximity of other branches would also seem to reduce the amount of trunk wood available to secure an individual branch. Branch growth rate may be important early on in the life of the crotch to determine the proportion of resources that are dedicated to the branch rather than the trunk.

Diameter ratio influence on breaking mode

The combined data for all three species shows a consistent diameter ratio threshold for predicting how the crotch will break. Eighty-nine percent of the samples that broke in the ball-in-socket manner had diameter ratio values below 0.65 (Table 4.5). Correspondingly, only twelve percent of the imbedded-branch samples had diameter ratios below 0.65. There is a second diameter ratio threshold for predicting a flat-surface break at approximately 0.76 (Table 4.6).

These results indicate that there is a reliable threshold value for diameter ratio to determine the type of break. Personal field observations indicate that most storm-related breaks in hardwood trees in the Mid-Atlantic states are either imbedded-branch or flat-surface. In strong crotches the branch breaks before the crotch gets pulled out of the trunk, represented in this study as ball-in-socket breaks. Only in weak crotches does the trunk fail by splitting, as in flat-surface or imbedded-branch, before the branch fails due to bending stress. Having the branch break instead of the crotch pulling out of the trunk enables the tree to preserve the wound-healing structures that have been identified in the branch collar and branch-bark-ridge. A strong crotch effectively sacrifices the branch to prevent damage to the main stem.

Since both flat-surface and imbedded-branch failures represent a weak crotch, the diameter ratio of 0.65 represents the proper threshold for predicting crotch strength. In other words, branches should be less than ? the size of the trunk from which they arise. This is slightly lower than the ¾ stated by Harris (1992).

Table 4.5. Number of crotch samples in each breaking mode, broken down by diameter ratio classes for all species combined.

Diameter Ratio	Breaking Mode		
	Ball-in-socket	Imbedded-branch	Flat-surface
0.2 - 0.29	4	0	0
0.3 - 0.39	26	0	0
0.4 - 0.49	32	0	0
0.5 - 0.59	55	5	0
0.6 - 0.64	22	3	0
0.65 - 0.69	7	6	0
0.7 - 0.79	9	21	6
0.8 - 0.89	0	18	19
0.9 - 0.99	2	8	23
1.0	0	5	5

Table 4.6. Range of diameter ratio values for all samples within each breaking mode for each of the species tested.

	Breaking Mode		
Species	Ball-in-socket	Imbedded-branch	Flat-surface
Maple	0.21 - 0.69	0.5 - 0.94	0.76 - 1.0
Oak	0.28 - 0.74	0.57 - 1.0	0.76 - 1.0
Pear	0.38 - 0.95	0.67 - 1.0	0.78 - 1.0

CHAPTER 5

CONCLUSION & SUMMARY

The goal of this study was to identify features of tree crotches that could be used in the field to gauge the relative strength of branch attachments. Unlike previous studies, this project was designed to assess external features of crotches among several species and to concentrate the force on the crotch rather than the branch. It was hoped that the results would identify one or more external features that are best correlated with crotch strength in hardwood trees.

This study achieved its original objectives and provided useful insights into the development and maintenance of strong tree crotches. Lessons learned will aid in assessment of tree structure and help to guide urban forest management. Significant conclusions include:

Strength is best correlated with diameter ratio.

The variables that demonstrated the strongest correlation with crotch strength were related to the ratio of the branch diameter to the trunk diameter. This outcome supports the commonly held belief that strong crotches result from the branch being smaller than the trunk that supports it. Also, crotches comprised of a trunk and a branch were 2.2 to 2.8 times as strong as the union of codominant stems.

Branch angle is also correlated.

The angle of the branch relative to the trunk was also correlated with crotch strength but not as strongly as the diameter ratio. These results do not support the assertion that branch angle is unimportant unless included bark is present.

No other features showed significant correlation.

Many of the parameters that were tested, branch-bark-ridge angle and crotch length for example, failed to show a significant correlation with crotch strength.

This study identified a diameter ratio threshold of 0.65.

Results from all three species showed a consistent diameter ratio threshold to predict the manner in which the crotch would fail. In almost ninety percent of crotches where the branch diameter was 2/3 the size of the trunk or smaller, the crotch broke by being pulled directly out of the trunk. Over ninety percent of the crotches where the branch was more than 2/3 the diameter of the trunk, broke when the trunk split. This is important since the force required to pull the crotch out of the trunk is much greater than the force required to split the trunk longitudinally.

This effect can be observed in storm-damaged trees. Branches that are broken by wind or ice loads seldom if ever fail by pulling the crotch out of the trunk as described as a ball-in-socket brake in this study. This would indicate that these crotches are stronger than the branches they support since the branches must be breaking before the crotch is pulled apart. However, branches that fail because of splitting of the trunk are quite common. This means that crotches that fail by splitting are weaker than the branches that they support.

Results are consistent for multiple landscape species.

Many of the commonly held beliefs about crotch strength proved reliable for three different landscape tree species. Unlike previous studies, this research attempted to compare structural features rather than to compare between species. Results were consistent between all three species for most of the variables measured. This indicates that features related to crotch strength are likely consistent for many hardwood tree species.

Presence of included bark weakens the crotch.

U-shaped crotches were 1.6 to 1.8 times as strong as V-shaped crotches for maples and oaks respectively. V-shaped crotches, as defined in this study, have or are beginning to form included bark. None of the callery pear samples studied had included bark.

Many of the U-shaped samples had included bark buried within the crotch. The average strength for all samples with included bark was ? that of the normal samples for oak and maple. The size of the included bark area within the crotches was not well correlated with strength. However, none of the samples had more than 40% of the crotch covered by included bark.

Crotches with included bark can develop stronger structure.

Several samples had included bark that had been enclosed inside the crotch by the subsequent growth of normal crotch wood. This indicates that crotches have the ability to resume normal growth if the conditions that are causing the formation of included bark can be corrected early on.

Management Implications

The results of this study indicate that crotch strength is largely determined by the size of the branch relative to the parent trunk. A relatively large trunk is able to anchor the branch more securely. Any condition that reduces the trunks ability to grow around the branch and anchor it will reduce the strength of the crotch. Wider branch angles are also associated with increased crotch strength.

These results provide a scientific basis for recommending that branches should be less than 2/3 the size of the trunk from which they arise. This 2/3-diameter threshold can then be used to identify crotches that may not be able to withstand as much stress as the branches they support. These branches may be candidates for preventative maintenance such as cabling or pruning.

The observation of included bark buried within U-shaped crotches indicates that young trees have the capacity to correct this defect. This may provide another option for arborists that would normally remove a V-crotch during training pruning as has been recommended (Fraedrich, 1999).

The incidence of V-shaped crotches that leads to the formation of included bark could be reduced by preventing the development of branches with greater growth rates or larger diameters relative to the trunk, or with narrow angles of attachment. This has implications for the nursery trade as well as for arborists. When selecting new tree varieties, emphasis should be placed on trees that display wider branch angles and smaller branches relative to the main stem. Young trees can be trained to develop better structure by reducing the growth rate of branches that have narrow crotch angles or a similar diameter to the main stem. This can be accomplished by either thinning the foliage at the end of the target branch or by reducing the size of the branch through drop-crotch pruning cuts. This “subordination pruning” (Gilman 1997) will reduce branch diameter growth since the amount of sapwood is proportional to the amount of transport in the branch (Wilson 1990).

Limitations of this Study and Recommendations for Further Study.

The trees in this study were young with narrow, upright crowns. Repeating the experiment on mature trees in the landscape may provide a better range of some variables. Active timber harvests may also provide a ready source of large samples for testing. Including samples with larger, broader included bark areas may provide a more accurate test of the correlation of strength with included bark area.

Results were similar between the three species in this study; tests are needed on other common urban tree species, particularly the multi-stemmed conifers such as Leyland cypress.

The bending strength formula heavily weights the diameter of the branch relative to the resulting strength value. Interactions between diameter and the primary variables may be significant. Repeating this study with many branches of the same diameter on trunks of differing diameters may reduce the impact of the formula on the strength values.

The crotch strength value calculated in this study is based on the maximum bending stress for a round beam, the same method employed in several previous crotch strength studies (Miller 1959) (Lilly 1995) (Cannell & Morgan 1989). This current research focused on the strength of the crotch, not the branch. Branch bending strength does not represent the strength of the crotch itself but it did provide a relative strength for the crotches in this study. Measuring the stress (force per unit area) in the crotch was beyond the scope of this project. The three breaking modes may provide the starting point for developing accurate crotch strength calculations.

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Community Forester (November 1989 – December 1990)
Montgomery Village Foundation, Inc. Montgomery Village, Maryland.

Arborist (December 1990 – April 1992)
Tree King Professional Care, Inc. Gaithersburg, Maryland.

Surveyor (May 1992 - December 1992)
Anderson & Associates, Inc. Blacksburg, Virginia.

Research Specialist (January 1993 – December 1996)
Forestry Department, College of Forestry and Wildlife Resources, Virginia Tech.

Project Developer (January 1997 – March 1998)
Davey Resource Group, a division of the Davey Tree Expert Co. Kent, Ohio

Sales Representative (March 1998 – October 2000)
The F.A. Bartlett Tree Expert Company. Newport News, Virginia.

Area Forester (October 2000 – Present)
Virginia Department of Forestry. Gloucester, Virginia.