Final Report:

Assessing the Potential of Reduction Pruning in Mitigating the Risk of Branch Failure

Report of findings and recommendations

BioCompliance Consulting, Inc.

10/30/2012

Acknowledgements

BioCompliance Consulting, Inc. would like to acknowledge the support and involvement of several individuals and organizations that have been instrumental in the successful completion of this project:

Project team members:

Andreas Detter, Brudi & Partner TreeConsult, Gauting, Germany participated directly in the field work, in conducting analysis of the data, and in preparing this report.

Nelda Matheny, HortScience, Inc. Pleasanton, CA led the effort to review available literature pertaining to branch reduction pruning.

Arboricultural technicians John Siefer and Brian Jeffers with Davey Tree, as well as Ryan Lewis and T.J. Detton , provided capable support during the week of field testing.

Mark Hoenigman, Busy Bee Tree Service, Novelty OH provided access to equipment and shop during the week of field testing.

Project Sponsors:

Craig Allen, National Grid USA
Paul Sellers, NStar Electric
Sara Sankowitz, Unitil Corp.
Duane Dickenson, Central Vermont Public Service
Bill Van Cura, Public Service Electric & Gas
Ward Peterson, Davey Resources Group
Ray O'Sullivan, Consolidated Edison of New York

Special thanks to Greg Mazur and Ward Peterson, Davey Tree Expert Company, for generously providing access to, and use of trees at the Davey Research Farm.

Executive Summary

This research project provides quantitative evidence that branch reduction pruning reduces load induced stress, and in so doing decreases the likelihood of structural failure of a branch overhanging energized distribution lines. Reduction pruning is a descriptive term that describes pruning intended to reduce the profile of a branch.

Reduction pruning compliant with appropriate industry standards and best management practices resulted in an approximately 50% reduction in stress in the critical fracture zone where the branch would likely fail by. A qualitative assessment of branch reduction pruning demonstrates that it can be a cost-effective alternative to the removal of an entire branch.

An earlier project completed by the researchers characterized branch failures and recommended risk assessment criteria. This project is a follow-on effort focused on branch reduction pruning as a means of risk mitigation.

A review of the literature related to branch reduction pruning was conducted as part of this project. Limited published research on the topic of reduction pruning, particularly as a means of reducing the risk of branch failure, was identified. This lack of available information demonstrates a knowledge gap, heightening the importance of this project's findings.

The project involved loading a branch by simulating an accumulation of one-half inch of ice followed by progressively pruning to reduce its overall profile. Thirty-two branches representing four different species were tested. Field work was carried out in Ohio in March 2012 while the test trees were in full dormancy.

The work was sponsored by six utilities with service areas in the northeastern U.S., and by Davey Tree Expert Company, a provider of utility vegetation management services.

Recommended specifications for the inclusion of branch reduction pruning in distribution vegetation maintenance contracts were developed and are included in this report.

Table of Contents

Introduction

Arborists have become increasingly aware of the risks associated with hazard trees over the last several years. As a result, research has focused on the structural integrity of trees. More recently, the issue of branch failure within the crowns of trees has begun to receive attention. A gathering of some 200 practitioners in September 2012 at the Morton Arboretum[1] identified the failure of branches as a leading cause of damage and a significant concern shared by utility, commercial, and municipal arborists. Subsequently a gathering of tree biomechanics researchers identified crown and branch reduction as the third highest research priority. The need for research into the efficacy of reduction pruning as a means of reducing risks scored closely behind the need to improving our understanding of tree growth response to stress, and to improve visual condition assessment techniques focused on the potential for structural failures.

Small- to medium-diameter (2-8 cm) branches adjacent to and above energized conductors in the upper crowns of trees present a significant risk to electric system reliability. This is particularly true under ice and snow loading conditions. This point was clearly demonstrated in New England in late October 2011, when a Nor'easter brought significant accumulations of heavy wet snow across New England. As a result millions lost power, some for over a week.

These branches are also difficult to access and expensive to maintain during scheduled preventive vegetation maintenance activities. The traditional approach to reducing risk to reliability has been the attempted elimination of branches that overhang conductors. This is rarely practical or fully achievable, and generally occurs only on the most critical line segments where an interruption in service will result in an outage affecting a large number of customers. It should also be recognized that because the trees in question are in close proximity to energized conductors they likely have been repeatedly pruned and may exhibit asymmetrical form.

This project considered the possibility that selective reduction of high-risk branches may be an effective means of reducing the likelihood of their structural failure, thereby reducing associated risks. The industry standard[2] defines reduction pruning as pruning to decrease height and/or spread of a branch. The current industry Best Management Practice[3] uses the term "subordination" as a synonym for reduction (e.g., *"leaders may be subordinated or reduced in length"*). The focus of this investigation was reduction pruning as a means of reducing branch size (length, width, depth, and mass).

Ice and snow loads on branches create relatively static unidirectional force (gravity), which may be considered as a pre-stressed cantilevered beam. These assumptions simplified the

---

[1] *Tree Risk Assessment Symposium: The Biomechanics of Stability, Strength, and Structure,* Morton Arboretum, September 24-25, 2012

[2] ANSI A300 (Part 1) 2008 Pruning §4.34

[3] BMP: Utility Pruning of Trees

experimental design.   In contrast, the force applied by wind loading is dynamic and more difficult to simulate.

Wet snowstorms that adversely affect the overhead electric system typically occur in mid to late autumn when deciduous trees are still in leaf and temperatures are at or above freezing.   Large ice storms with freezing rain resulting in significant ice accumulations typically occur when surface temperatures are at or a few degrees below the freezing point of water. In either the case of wet snow or icing, one assumption is that the underlying branch tissue is not frozen.   The modulus of elasticity of frozen woody tissue can be expected to be much higher than that of unfrozen wood. However, this is not considered a significant factor for this experiment since the focus is load-induced stress within the range of elasticity for the branch. The experimental method did not include pulling branches to the point of structural failure.

Previous work[4] by the researchers that involved static loading of branches to the point of failure identified the potential of branch reduction pruning as an effective means of reducing stress where the branch was likely to break. An unexpected early season snow storm occurred while field work was being completed and presented a unique opportunity. An assessment method was improvised and limited data were gathered.   Two Norway maple (*Acer platanoides*) branches on each of two individual trees were selected for study. The trees were in full leaf and heavily loaded with snow. The length of each branch was reduced by 15% of its length, with a resulting reduction in stress on the order of 30-45%.   Subsequent work was carried out by the principal investigator during ISA tree biomechanics week in August 2010. That effort involved assessing approaches, equipment, and methods that resulted in the development of experimental protocols useful in quantifying the effect of branch reduction pruning in reducing the likelihood of structural failure.

The Hypotheses

There is predictable public outcry and regulatory attention given electric utility system performance and maintenance following severe damaging storms that result in extensive outages. Once an initial interest in undergrounding all distribution lines is deflected due the reality of cost, attention often turns to vegetation maintenance practices. It's not uncommon for consideration to be given to the removal of all overhanging branches, a practice known as “ground to sky” clearance.   This practice can be excessively expensive, has the potential to adversely affect the

[4] *“Development of Risk Assessment Criteria for Branch Failures within the Crowns of Trees',* Final Report July 12, 2009

health, long-term viability, and stability of the tree, and often results in a very significant aesthetic impact.

There was reason to believe that branch reduction pruning may be a suitable alternative to the elimination of all branches overhanging overhead distribution conductors. The project was intended to test the hypothesis that branch reduction pruning can be a cost-effective means of decreasing the risk of trees causing power outages.

There are several mechanisms at play when considering reduction pruning as a means of reducing risk. First, branch reduction effectively shortens the lever arm, thereby reducing leverage as a branch is loaded. Secondly, reduction pruning reduces the mass of the branch. Thirdly the surface area available for accumulation of ice and snow is reduced resulting in less loading. These first three points all act to reduce stress on the branch, and lower stress is expected to reduce the probability of branch failure. The reduction in the mass of a reduced branch reduces the force of impact should the branch fail and fall in to conductors. Finally, by reducing the size of the branch, its target area is also reduced making it less likely to adversely impact conductors should it fail.

Of course if the branch were entirely eliminated the associated risk would also be eliminated. This calls the obvious question: why consider reduction pruning if risk can be eliminated by removing the entire branch? As previously stated, “ground to sky” line clearance work is difficult and costly. By definition more material is being removed, which drives both the cost of pruning as well as generating more residue that must be disposed of. Proper branch removal also requires that the arborist be positioned close to the main stem, above and beyond conductors in order to properly remove the branch. This typically requires the use of extra-tall aerial lifts (a.k.a. bucket trucks) which cost more to own and operate, and due to large size are sometimes slower. Their large footprint may also impede traffic and result in greater traffic control cost. On the other hand, branch reduction may be accomplished with conventional equipment and involves the removal of less material.

While branch reduction pruning work may cost less, perhaps a greater benefit is the ability to perform line clearance maintenance pruning on more miles of line for the same outlay of maintenance dollars. In addition, beyond cost is the matter of the impact of pruning on trees. Excessive reduction in live crowns can result in loss of vigor, impeding wound response and potentially affecting viability. The net effect is a potential increase in future hazard trees and associated risks. There is also emerging research that suggests that lateral branches act as mass dampers and play a significant role in preserving structural integrity of trees during wind events. If this is true, then at least some lateral branches should be retained. Finally, the aesthetic impact of “ground-to-sky” pruning on individual trees and the canopy is often dramatic. When electrical service is restored and the storm forgotten, the public is likely to have a strong negative reaction to way in which this practice alters the appearance of a site.

While this project has been sponsored by the utility industry, findings that provide greater understanding of the benefits of branch reduction pruning have broader implications, and should be of interest to municipal and commercial arborists.

Literature Review

The literature review began with an electronic search for potentially useful articles. After reviewing cited abstracts, the most relevant articles were acquired and reviewed in detail. Subsequent revised electronic searches were conducted as additional insight was gained. Direct contact with authors of highly relevant work was initiated and the specifics of their projects discussed.

A general observation is that there is a surprising lack of published research on the topic of reduction pruning, particularly as a means of reducing the risk of branch failure. One of the outcomes from this literature review has been to identify a knowledge gap, heightening the impact of this project's findings. The authors intend to submit a technical paper to the *Journal of Arboriculture and Urban Forestry.*

General Texts

General texts were reviewed. Rather than repeatedly cite relevant material from each, the following books are recommended to the reader:

Gordon, J.E., 1978, *"Structures, Or Why Things Don't Fall Down"*. Da Capo Press. London.

This text is an excellent primer for the non-mechanical engineer, presenting concepts such as elasticity, compression, and tension in simplified terms that an arborist would find both useful and entertaining. The author has another text as well that may be helpful: *"The New Science of Strong Materials"*.

Niklas, K.J., 1992, "Plant Biomechanics, An Engineering Approach to Plant Form and Function", University of Chicago Press, Chicago.

This scholarly text provides a detailed technical discussion of the principles of structural engineering as specifically related to plant materials. This would be a helpful technical reference for those interested in an in-depth study of the topic. A new volume titled *"Plant Physics"* (Niklas & Spatz, 2012) has recently been published.

Gilman, Edward F. 2012. An Illustrated Guide to Pruning, 3rd Edition. Delmar: Clifton Park, NY.

This is a very approachable text providing the practitioner with the latest information on contemporary tree pruning practices. As the title suggests, this text provides complete information on how, when, where, and why to prune trees. It includes sections on tree structure and strength, pruning methods and tree responses, and pruning mature trees to minimize risk. It is an important guide for those who prune trees.

Technical Articles

The following narrative discussion is intended to give the reader a general sense of the findings from the literature review. Abstracts were developed for the relevant articles that were reviewed in detail, and are included in Appendix A.

The literature review from a previous work by the researchers served as a starting point for this investigation. That earlier investigation identified four papers that referenced branch reduction pruning as a means of increasing wind firmness and reducing the likelihood of branch failures under wind loading conditions (Gilman 2008, Luley 2002, Niklas 2001, Smiley 2006). While not related to static loads created by ice or snow accumulations, they are referenced here as they do address reduction pruning as a risk mitigation strategy.

In this study we were primarily interested in literature regarding the effect of reduction pruning on the degree of branch deflection and the likelihood of failure. Unfortunately, we found no experimental research on these topics. There are a few experiments testing the effects of pruning treatments on trunk movement and failure (Pavlis, et al. 2008, Kane and James 2011), as well as experiments on the strength of branch attachments (Kane 2007, Kane et al. 2008).

The most helpful publication was Gilman (2012), which noted that, "reduction cuts are commonly used to correct defective structure of trees of all ages." A reduction cut reduces the length and weight of a branch by cutting to a lateral branch, preferably one that is one-third to one-half the diameter of the cut stem. Gilman notes that reduction of branch length, "immediately improves the taper of the parent branch, preventing it from drooping excessively."

Some caveats to branch reduction are noted, especially if the cut is made to a small lateral branch: (1) Excessive sprouting can occur in some species, requiring more pruning. (2) Bark death or decay can occur at the cut. Gilman recommends that for species that are weak compartmentalizers, cuts less than 2 inches in diameter are best to minimize future decay; cuts of 4 inches are recommended for strong compartmentalizers.

An interesting series of experiments by Ennos and van Casteren (2009) and van Casteren et al. (2012) examined how small branches fail. Stating that "Living tree branches are almost impossible to snap", they described three failure modes: In "clean fracture" the branch breaks through the top of the branch, and then splits laterally along the neutral plane. This type of failure occurs in higher density wood such as *Fraxinus*. In "diffuse fracture" the branch breaks with multiple fractures across the branch cross section and on small longitudinal cracks. This is how very dense wood fails. In "transverse buckling" no tensile fracture occurs and the branch fails by buckling. This response is typical of low density wood such as *Salix*. These differences are explained by the anatomy and mechanical properties of wood. By observing how small branches fail on a particular type of tree, we can better predict their likely response under bending loads.

Experimental Design

The researcher's earlier work on the structural failure of branches had identified the potential of branch reduction pruning as an effective means of reducing bending moment stress. Subsequent developmental work on experimental methods and instrumentation served to guide the design of this investigation.

Test Site

The field investigation was conducted during the week of March 26-30, 2011, when test trees were in a dormant condition.

The test location was the Davey Tree Company's research arboretum in Shalersville, Portage County, Ohio. This is the same site as was used in the previously referenced branch failure investigation. It is also the site that hosted ISA Tree Biomechanics Week in August 2010.

Figure 1. Trees on Davey's Shalersville, OH test site

Several species of trees commonly found as street trees were established at this location in the 1960's for the purpose of developing and testing new arboriculture practices. The crowns of individual trees in each of the planting blocks had closed to create a continuous canopy. The management objective for the research blocks was to create full crowns similar to those of street and landscape trees. Thinning operations to open up the stands of test trees are anticipated. This presented the project with a population of trees scheduled for removal that were available for destructive testing.

Trees Tested

The trees selected for branch reduction pruning were located along the edge of the planting blocks adjacent to an access road, and were typical of edge trees found along maintained utility rights-of-way. The branches selected for reduction were located in mid to upper crown positions, and ranged in orientation from near horizontal to an upright orientation.

Thirty-two branches from four different species of tree were selected for testing. The species tested are presented in Table 1.

Table 1. Species of tree branches that were subject to reduction pruning during this investigation.

Common Name	Botanical Name	Reduction Tests Completed
Red Maple	*Acer rubrum*	18
Pin Oak	*Quercus palustris*	8
Norway Maple	*Acer platanoides*	3
White ash	*Fraxinus americana*	3

Defining Reduction Pruning Dose

This project was intended to determine if branch reduction pruning was a reasonable alternative to the removal of entire branches, and if so, to develop a means of specifying the work in a practical and intuitive manner that could be easily adopted by line clearance tree crews. The first decision that was made was that branch reduction pruning should be compliant with relevant industry standards and BMP's. This was to provide a degree of uniformity and structure to the manner in which reduction pruning would be conducted.

The second consideration was how best to quantify the extent to which a branch was to be reduced (a.k.a. pruning "dose"). This proved to be the greater challenge. A number of alternatives were considered as potential means of specifying dose. Once again the bias was to develop an intuitive means of defining dose that would be useful to qualified line clearance arborists in the field. An initial list of possible approaches is presented in Table 2.

Table 2. Attributes of a branch considered as intuitive measures useful to field practitioners as a means of conveying the amount of branch reduction required.

Potential Means of Conveying Pruning Dose	Attribute
% reduction in the length of the branch	Dimension
% reduction in the estimated weight of the branch	Mass
% reduction in live foliage	Energy
% reduction in the shadow projected by the branch	Area (2D)
% reduction in the three-dimensional space occupied by the branch	Volume (3D)
% reduction based on cross-sectional area of the pruning cut as compared to the diameter of the "parent" branch, or at the union with the main stem.	Pipe theory

Several experienced line clearance supervisors were consulted in evaluating these options. In the end, most felt that crew personnel could reasonably visualize the concept of space occupied by a branch. Volume had the advantage of including length, spread, and depth of space occupied by a branch, each a potential dimension where reduction could occur. Supervisors also supported the notion that pruning dose be based on current industry standards and BMP's, as qualified line clearance arborists are already familiar with these references.

For the purpose of this investigation two levels of pruning dose were evaluated during each test:

1. A preliminary light pruning dose was described as approximately half of what the full dose would require. This light dose was an intermediary step that took place during each test and was used to gain insight on branch performance.
2. A full pruning dose was defined as branch reduction to the full extent possible and still remain compliant with industry standards and best practices. A utility industry default guideline[5] of 1/3 reduction was assumed.

Important note: ANSI A300 (2008) Part 1 §6.1.4 states:

> *"Not more than 25% of the foliage should be removed within an annual growing season. The percentage and distribution of followers to be removed shall be adjusted according to the plant species age, health and site."*

On first reading, a guideline of 1/3 reduction would appear to be in direct conflict with the Standard. However, this standard reference applies more correctly to a reduction in the total foliar area of a tree rather than individual branch. Secondly, the proper interpretation of this statement is to recognize that the first sentence contains the word 'should', and is therefore

[5] The "1/3 rule" is widely used in the utility industry. It has traditionally been applied to selection of an appropriate lateral to prune back to as well as in terms of foliar reduction.

advisory. The second sentence containing the word *shall* and is a mandatory requirement. This requires the utility to consider the site, which includes consideration of the proximity of the branch to energized conductors.

ANSI A300 (2008) Part 1 §9.3.1.4 states:

> *"Trees growing next to, and into or toward, facility/utility spaces should be pruned by reducing branches to laterals (5.3.3) to direct growth away from the utility space"*

This advisory statement clearly establishes the need to consider the site and potential conflicts when considering the amount of reduction to prescribe.

If the alternative to reduction is to completely remove a branch, then reduction pruning clearly retains more foliage.

Estimating Weight of Ice Accumulation

The purpose of this investigation was to evaluate the efficacy of branch reduction pruning in reducing stress in the location branches would likely fail under static loading due to accumulation of ice or heavy wet snow. Ice accretion was more easily simulated, so was selected as the loading condition. An accumulation of 1/2 inch (1.2 cm) was selected as a likely loading scenario. Damaging ice storms typically occur during the dormant season and result in ice buildup on main stems, branches and twigs. In contrast, the most damaging snowstorms occur in late fall when many trees are still in leaf. Loading due to heavy wet snow accumulation may be distributed differently than with ice. However, in either case a higher percentage of the load would tend to be biased to the outer ends of branches on small twigs (ice) or foliage (snow).

The volume of ice was calculated based on the dimensions of the branch segments targeted for removal. Lengths and diameters of each segment were recorded, and the volume of the branch cylinder was calculated. The branch cylinder for each portion to be removed was assumed to have a constant diameter. Branching form, taper, and the greater surface area of small branches were modeled by this simple cylinder.

An inch was added to the measured diameters of each segment to account for one-half inch of ice accumulation over the entire circumference of the branch. The volume of the ice laden-branch segment was calculated, and the volume of the branch alone subtracted, resulting in the weight of ice using Equation 1.

Equation 1

$$M = Di*(Di+Db)*pi*Lb/1000$$

Where:

M = mass of ice layer

Di = Diameter of ice layer

Db = Diameter of branch

Pi = 3.1415

Lb = Branch length

Test protocol

Previous work[6] by the researches on static loading of branches to the point of failure identified a Critical Fracture Zone (CFZ) typically located within 5-10% of total branch length to the main stem. Other researchers[7, 8] have also reported similar anecdotal observations suggest that the failure point is often located at a distance of two to four times the branch or stem base diameter, and is related to the transition from a relatively flexible branch or stem into a relatively stiff branch or stem base. The compressive and tensile stresses relative to the branch's ability to resist are critical in this CFZ. In effect, the branch is a lever arm, and bending moment-induced stress can be reduced by shortening and lightening the outer end of the lever arm.

Figure 2. The CFZ is close, but not at, the branch union with main stem or parent branch.

Tests branches were selected as being representative of branches typically found growing above and overhanging electric distribution conductors. An experienced arboricultural technician identified the location of the intended reduction cuts, which were verified by the

[6] *"Development of Risk Assessment Criteria for Branch Failures within the Crowns of Trees",* Final Report July 12, 2009

[7] Albers, J., and E. Hayes. 1993. *"How to detect, assess and correct hazard trees in recreational areas"*. Minnesota Department of Natural Resources, St Paul, MN

[8] Ellis Ellison, M., *"The Hot Spot – or why trees and branches fail beyond their point of attachment"*. Presented at International Society of Arboriculture Conference, Providence, RI, July 2009.

researchers. The centers of gravity (CG) of the entire branch and each of the portions to be removed were estimated and distances to the branch union at the stem were measured in a horizontal plane. The physical dimensions (diameter, length) of each branch and branch segment were also recorded.

A digital fiber strain gauge (TreeQinetic Elastometer by Argus Electronic, Rostock, Germany) with accuracy to 1µm was attached to the dorsal [9]surface of the branch bridging the CFZ. A load line with digital load cell (iLoad Series Integrated Load Sensor, by Loadstar Sensors, Fremont, CA) with accuracy to 0.3kg was attached at the branch's estimated position of the CG, and used to manually apply force through a redirect on the ground located vertically below the estimated CG.

Field Testing

Prior[10] work by the researchers had developed regression equations that correlated branch diameter to failure loading. This information was used to estimate the expected load that would cause each test branch to fail in compression. The first phase of the test was intended to characterize the elastic behavior of the branch as it was progressively loaded. Each branch was loaded to 25%, 50%, and 75% of its theoretical maximum. Measures of fiber strain, applied force, and deflection were recorded.

The second phase of the test involved loading and reduction pruning of the branch. The branch was preloaded to 75% of its estimated maximum. The theoretical load added by one-half inch of ice to each pruning segment was calculated as previously described. Water bottles containing water with the ice-equivalent weights for each segment were attached at each segment's CG.

The fully loaded branch subject to forces being applied both by the load line and the weight of ice (water equivalent) was then progressively reduced using the two pruning doses that have been previously described. The second dose reduced the branch to the full extent possible while still remaining

Figure 3. A branch subjected to load line tension and simulated weight of ice added to segments to be removed, prior to pruning.

[9] There was one exception, the fiber strain gauge was placed on the ventral surface of test branch 31.
[10] *"Development of Risk Assessment Criteria for Branch Failures within the Crowns of Trees"*, Final Report July 12, 2009

compliant with industry standards and BMPs. Once reduction pruning was completed, load in the load line was released and the entire branch was removed. Fiber strain, force applied by the load line, and branch deflection were recorded at each step in this process.

Once removed from the tree, the weight of the residual branch and the weights of the segments that had been pruned away with each reduction dose were recorded. The branch was then laid out on a grid, placing the residual branch and the segments removed in the approximate orientation that they occupied in the tree prior to pruning. A sketch[11] of each branch was created and a series of photographs[12] were taken to illustrate the extent of each reduction dose.

Figure 4. An example of a series of progressive branch reductions. Full branch on left, first order reduction in center, and full reduction on right.

[11] Sketches were made for test 8-32.
[12] Photos for test 26-32 were not successfully retained.

Analysis and Findings

Direct observations of the force being applied, branch deflection, and fiber strain were used to confirm the validity of the test protocol.

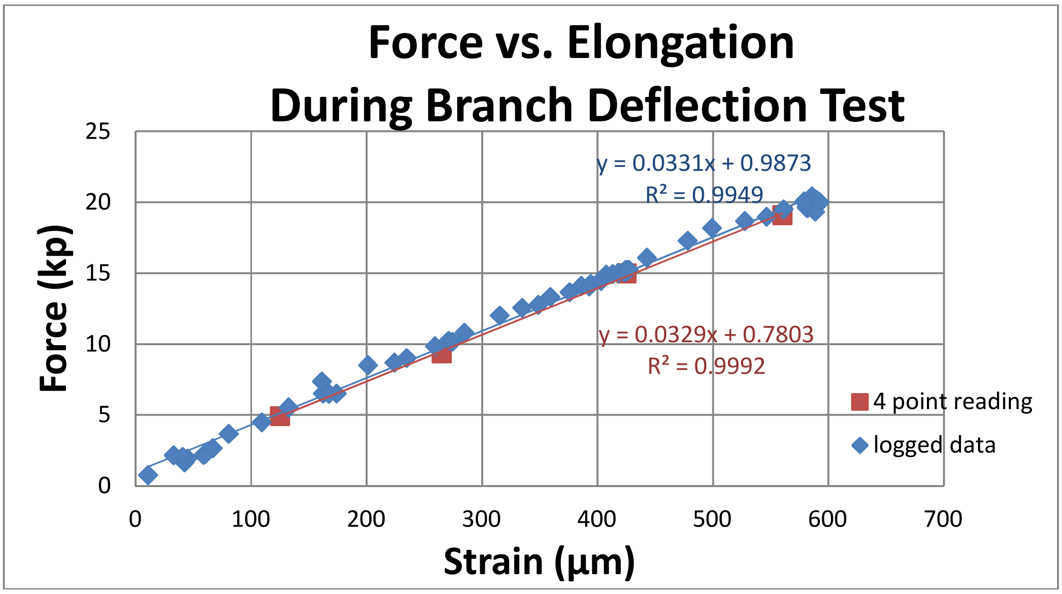

Figure 5. High correlation between deflection, fiber strain, and force indicating that tests were made in the range of elasticity of the branches.

The high correlation between the applied force and fiber strain observations presented in Figure 5 demonstrates that the tests were carried out within the range of elasticity of test branches[13]. These results also demonstrate that there is a direct relationship between fiber strain and the applied force. Loads were deduced from the strain measurements after the load line was released and used in a calculation of the stress being created.

The readings taken in four subsequent steps (0%, 25%, 50% and 75% maximum load) during initial deflection testing exactly display the branch behavior under load. The data logged from strain gauge and dynamometer matches the four points, and the gradient of the line (which is an indicator of the flexural stiffness of the branch) is practically identical. Therefore, flexural stiffness could be derived from the four load points.

[13] This was true for 31 of 32 tests. Test branch 7 failed during initial loading.

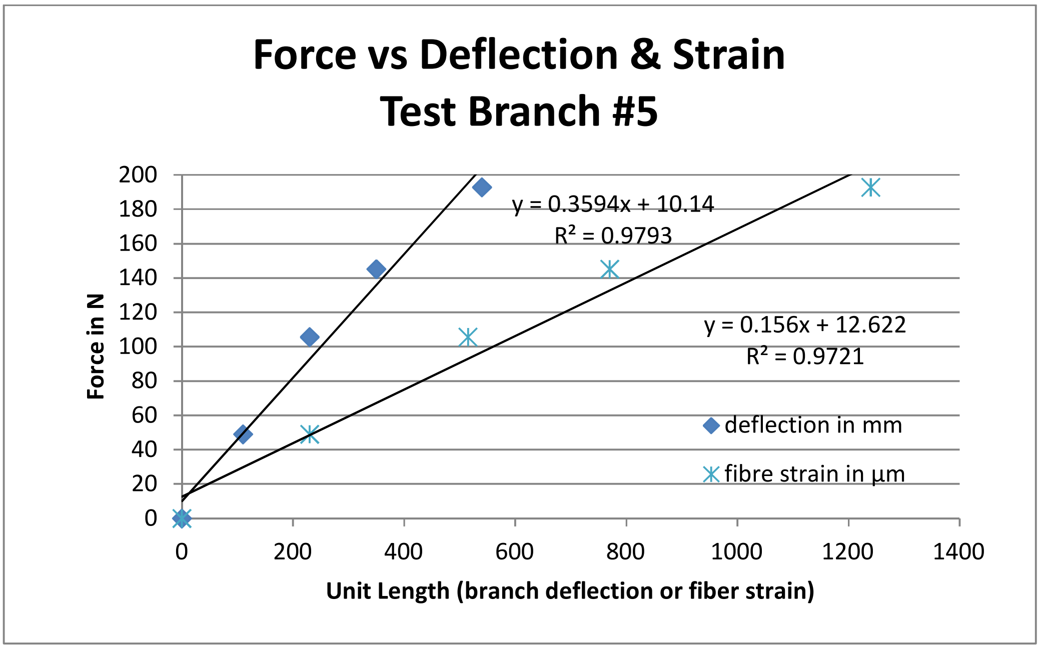

Figure 6. The relationship between force and both deflection and fiber strain indicate elastic limit may have been reached.

Fiber strain and deflection would be expected to be proportional to force within the range of elasticity. Analyst of test results for branch #5 (Figure 6) suggest that the force with the weight of ice and 75% maximum exerted by the load line caused the branch to reach the upper limit of elasticity. The upper values for both variables appear to the right of the regression line. This suggests that the specimen had transitioned from elasticity to plasticity, which is an indication of initial failure in compression. This is also a general indication that the experimental protocol was successful in assuring that reduction work took place when test branches were in the upper range of elasticity, which was the intent.

The bending moment at the base of the branch (CFZ) is calculated by multiplying the force that is applied vertically by the horizontal length of the lever arm using Equation 2.

Equation 2

$$\mathrm{BBM} = Dh * Fv$$

Where:

BBM is base bending moment

Dh is the horizontal distance between load line and the CFZ at the base of the branch

Fv is the vertical force being applied (in this case by load line and simulated ice measured in kg)

Equation 2 was used to calculate bending moments induced by loading. The length of the lever arm is defined as the horizontal distance between the load application point and a projection of the reference point, which for this project was defined as within the CFZ at the base of the branch. In this case, the force was applied vertically by load line to a point on the branch that was estimated to be the CG, and by simulated ice loads attached to the estimated CG's of branch segments to be removed. The horizontal distance between these CG's and the CFZ describes the lengths of the lever arms used in the calculation of Base Bending Moment (BBM) of the branch at several steps within each test.

Once BBM's were calculated, a number of statistical tests were used to identify any significant relationships. As expected, a correlation was identified between pruning dose and BBM. However statistical analyses indicate that only 30% of the variability observed can be explained by this relationship alone. Therefore other factors must play an important role as well. Other factors such as the effects of branch diameter, length, orientation, and flexual stiffness (modulus of elasticity) were tested, and found to have no meaningful correlation with stress release in the CFZ at the branch base following reduction pruning.

The researchers suspect that the greatest source of variability is related to inconsistency in achieving a uniform reduction dose. This is likely due to experimental design and natural variability between branches. The visual portrayal of this point is presented in Figure 8.

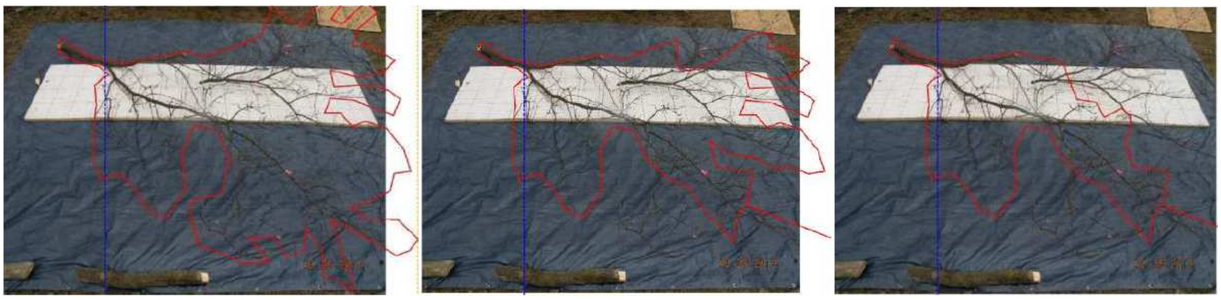

Figure 7. Example of photographic analysis of changes in areas with each reduction cut. Un-pruned branch on left, first reduction in center, and full reduction on right.

Two-dimensional photography was used to calculate the changes in area with each reduction cut. Because intact branches occupy a three-dimensional space, some error was introduced to this analysis as a result.

The definition of pruning dose used was intentionally worded to be operationally practical and easily adopted by working line clearance crew personnel. A full pruning dose was defined as branch reduction to the full extent possible, while still maintaining compliance with industry standards and practices. In actual practice the amount of reduction in area achieved by the arboricultural technicians varied considerably, as can be seen in Figure 8. Branch allometry naturally varies and pruning cuts were placed at appropriate nodes rather than at fixed distances. As a result, the amount of reduction achieved by experienced arboriculture technicians was variable.

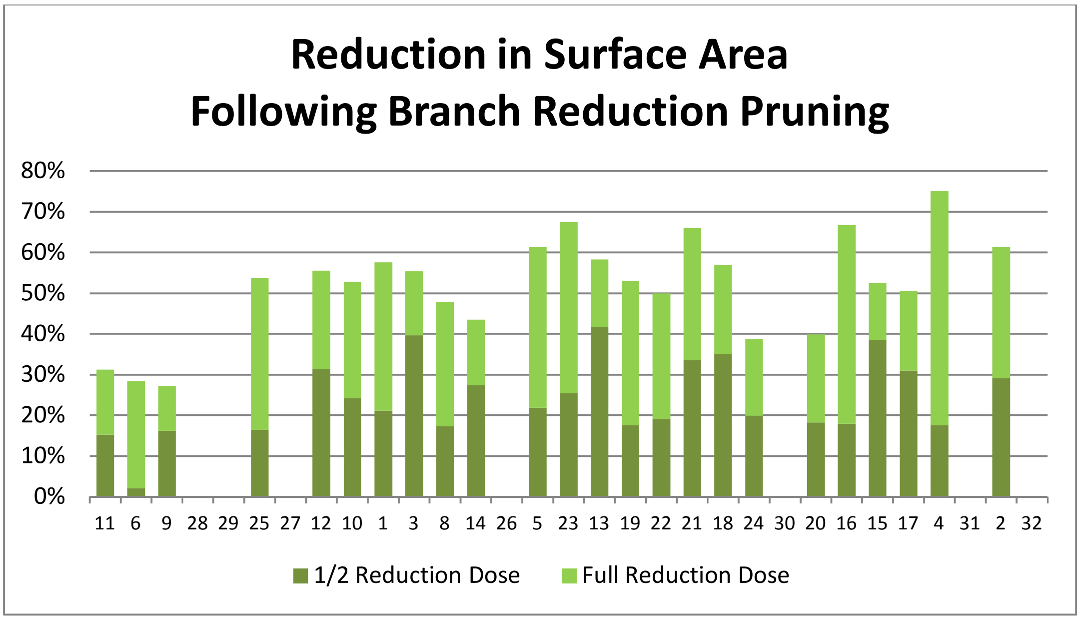

Figure 8. Relationship between pruning dose, described in terms of two-dimensional area and BBM. Numbers on x-axis indicate test number. Missing data were due to lack of photographic details.

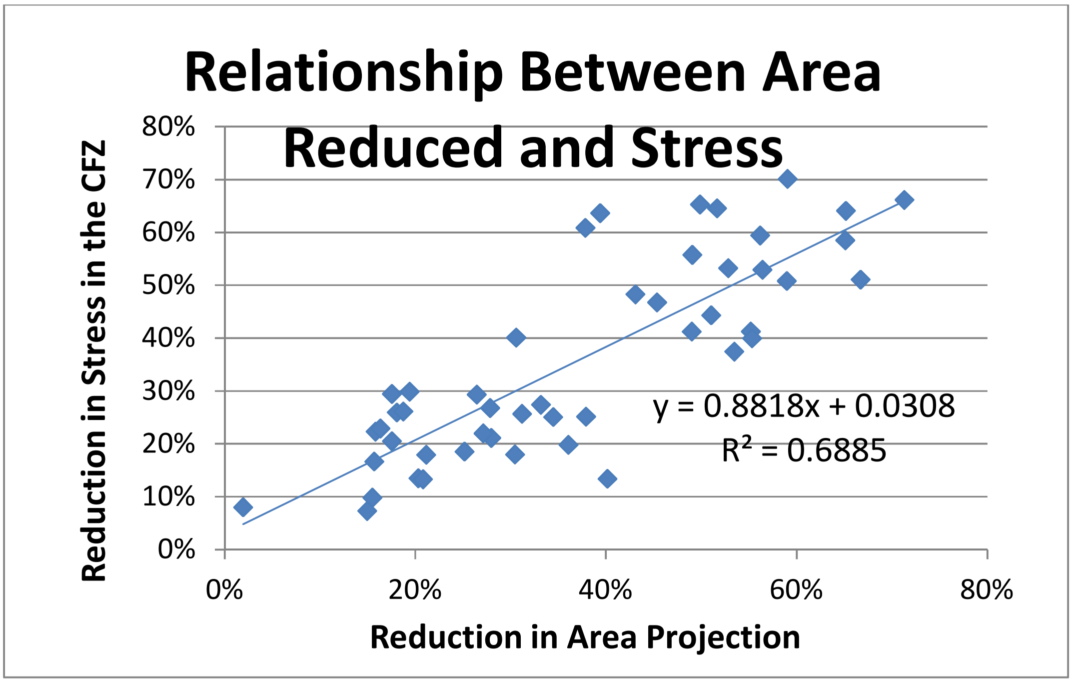

Figure 9. Reduction in a two dimensional area projection is related to dose and correlates with reduction in BBM.

Figure 9 confirms that when dose in quantified in terms of area it correlates reasonably well with the resulting reduction in stress.

Efficacy of Branch Reduction Pruning

The results presented in Figure 10 demonstrate that reduction pruning is an effective means of reducing stress in the CFZ and therefore the probability of branch failure. Branch reduction pruning reduced stress (defined as bending moment) exerted in the area where a branch is most likely to break.

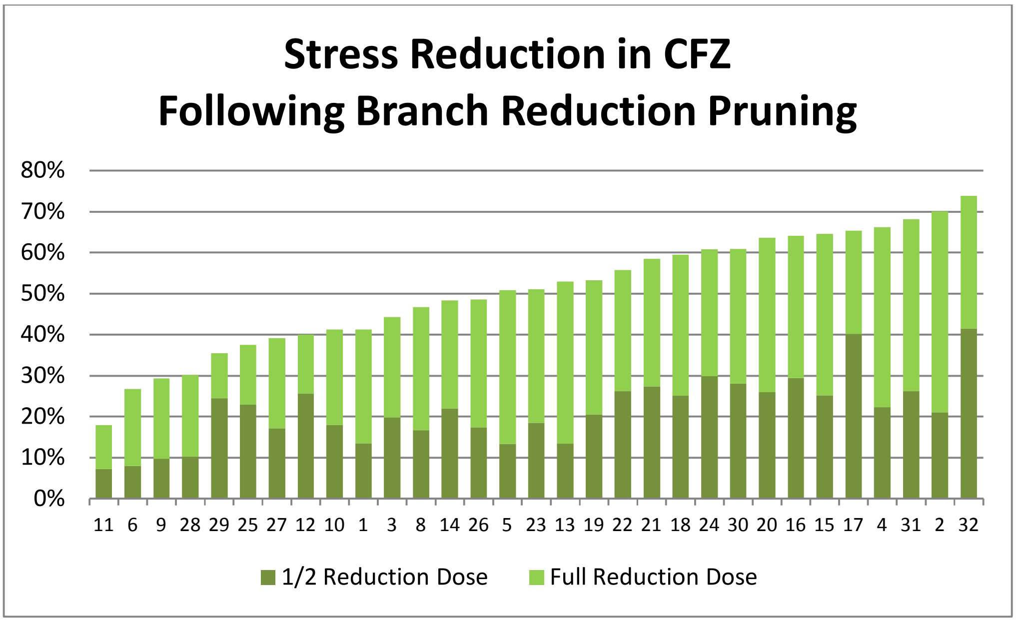

Figure 10. Reduction in bending moment following branch reduction pruning in the region where the branch is most likely to fail structurally. Numbers on x-axis indicate test number.

An average reduction in BBM (stress) in the CFZ of 50.54% was achieved with the full reduction dose. While Figure 10Figure 10 reports the results of both steps of the reduction applied to each test branch, the operationally important level to utility arborists is the full dose. This is because the cost of completing the pruning work is largely a matter of getting into position to place the cuts in the first place. The lighter reduction dose achieved an average 21.53% reduction in stress and may be an appropriate alternative for commercial and municipal arborist in application where greater risk of branch failure can be tolerated.

Factors Affecting Efficacy

The importance of both the length of lever arm and the mass used in calculating BBM (Equation 2) provides important insight. Reducing the branch by removing those portions of greatest mass that are the furthest from the CFZ will result in the greatest reduction in BBM. This is both quantifiable and intuitive.

The effect of branch deflection on stress reduction was analyzed. A branch changes shape (bowing) as it is loaded. As a result, the length of the horizontal lever arm can also change. A branch will also change position, deflecting downward as it is loaded. This too may result in a change to the length of horizontal lever arm. It is import to note that these changes can either shorten or lengthen the horizontal lever arm, depending on the initial orientation of the branch.

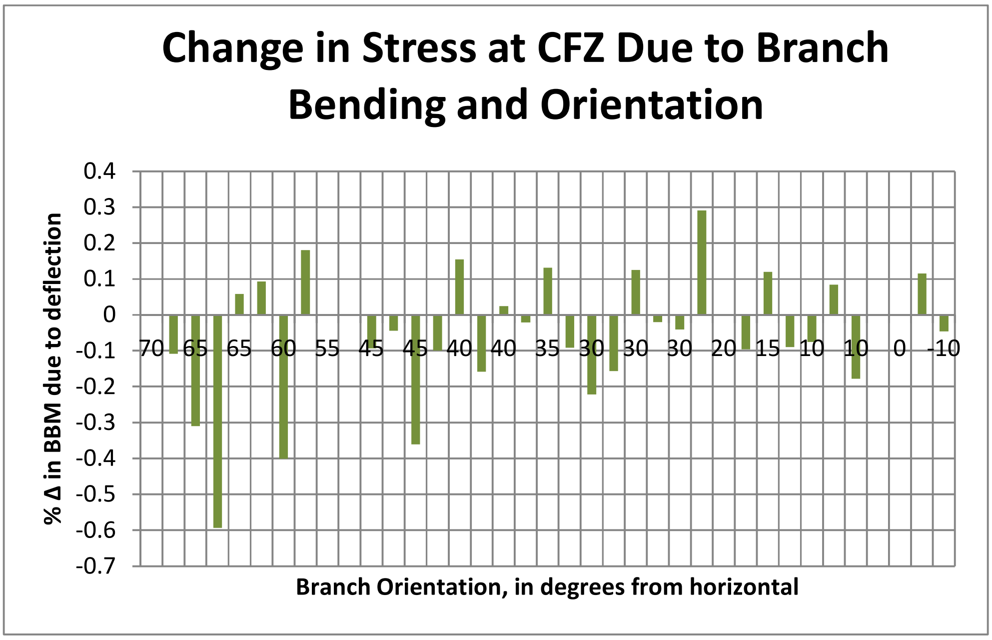

Figure 11. Contribution of the physical deflection of a branch to overall changes in bending moment in the CFZ.

The analyses of the effects of branch bending and branch orientation, presented in Figure 11, are inconclusive. The effect of bowing is shown to both increase and decrease BBM across a range of branch orientation from upright (+65 degrees) to approximately horizontal. The researchers believe that these inconclusive results can be attributed in large part to the previously discussed variability in pruning dose achieved. The other likely factor is that the CFZ for upright stems and branches is less well defined. Critical compression stress may focus on a point well above the union. If this is the case the placement of fiber strain gauges and the calculation of bending moment would be different.

Regardless of these results, simple physics would suggest that as upright branches deflect the rate of increase in bending moment would be much higher than in horizontal branches due to changes in the horizontal lever arm length. As upright branches deflect, the CG moves further away horizontally from the CFZ, increasing BBM. In contrast, deflection of horizontal branches results in the CG moving closer horizontally to the CFZ, and should reduce stress One implication of this observation is that upright branches tend to be at greater risk of failure under loading conditions.

The researcher's earlier work[14] identified this concern. It is also supported by observations by others[15,16] working the field of biomechanics. Finally, anecdotal observations following the late October 2011 Nor'easter snowstorm confirm the high incidence of damage to upright branches and leaders of deciduous trees which were still in leaf when subjected to heavy snow-loading conditions.

Figure 12 Failure of upright branches during 2011 heavy wet snostorm in CT.

The effect of branch flexibility on BBM was also considered. The elastic behavior of a branch would be expected to vary with diameter, form, and composition.   First, the inherent elasticity of a simple rod or pole is known to vary significantly with diameter. Although a branch is not a uniform pole, a mechanical engineering principle helps explain some of the flexibility of smaller branches and their ability to deflect to the extreme. Smaller diameter structural members of uniform composition are able to deflect to a much greater degree before material in the concave portion of the bend experiences a yield failure in compression. The engineering principle describing the relationship between diameter and deflection is a quadratic equation where doubling the diameter increases the resistance to deflection by a factor of 16. Clearly, this mechanical engineering approach to analysis explains a great deal of the high level of elasticity of small branches as evident in Figure 13.

[14] *"Development of Risk Assessment Criteria for Branch Failures within the Crowns of Trees",* Final Report July 12, 2009

[15] Correspondence with E. Gilman and J. Miesbauer, University of Florida

[16] Conversation with M. Rudnicki, University of Connecticut

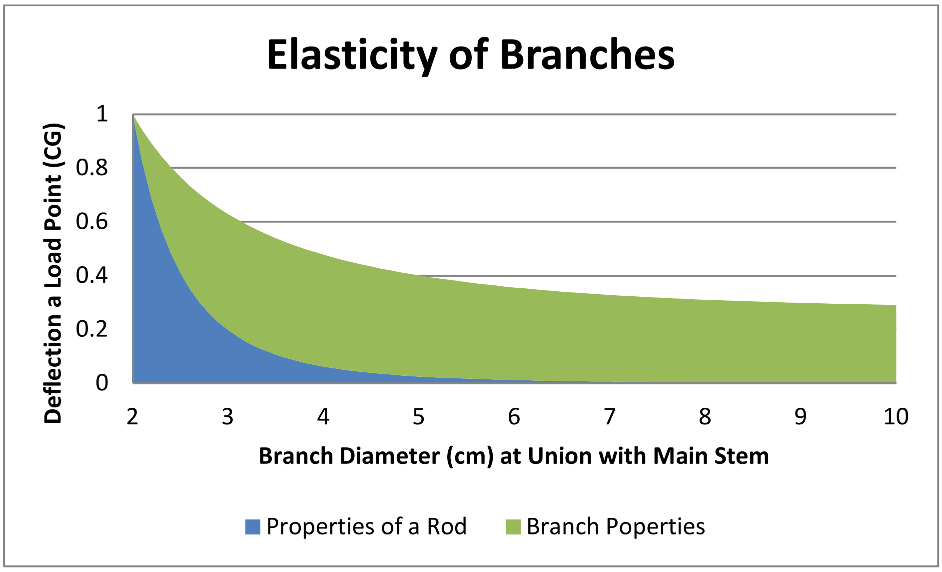

Figure 13. Influence of branch properties such as form and composition on flexibility.

The y-axis in Figure 13 is an expression of relative elasticity. The most flexible branch, defined as the branch that experienced the greatest deflection, was given a value of 1, and was used to rate the relative flexibility of all other branches. As expected, large diameter branches are less flexible than small diameter branches, although they are considerably more flexible than the engineering formula predicts. This is due to at least two factors: the physical form (e.g., taper, branching habit, etc.) and the material properties of the branch itself.

The flexual stiffness of the test branches was analyzed, as reported in Figure 14. The Modulus of Elasticity (MOE) describes the elastic properties of a material and is applied here as a structural value as if the branch was made of homogenous material.

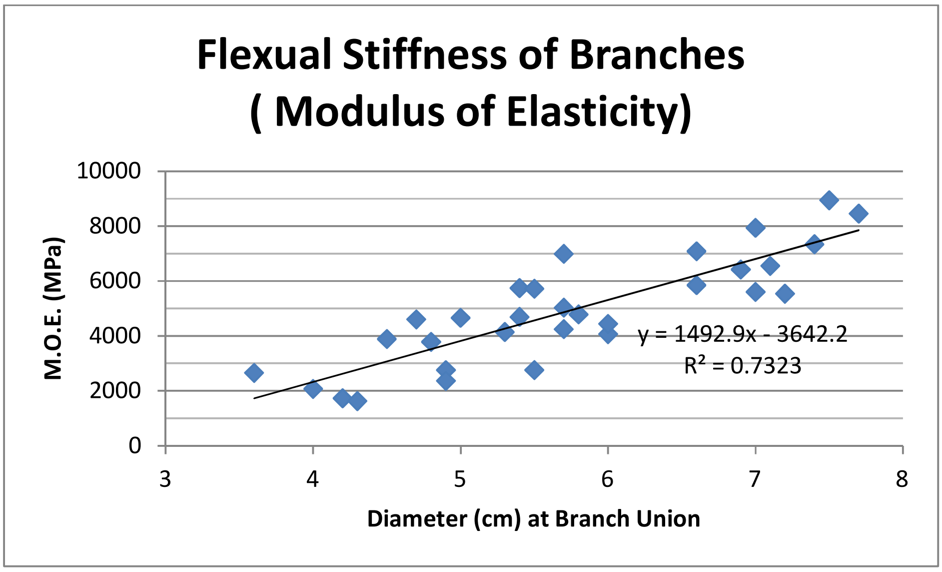

Figure 14. Correlation between branch diameter and elasticity.

If the MOE were constant across all branches, the slope of the line would be zero, i.e., horizontal. The upward sloping line in Figure 14 indicates that the MOE of small branches is low, indicating a higher degree of elasticity, than for larger branches. This is likely due to changes in the relative composition of branches with diameter. Small branches have a much greater percentage of juvenile tissues which are known to be less rigid. A greater portion of the cross section of larger branches is composed of fully developed woody fibers and xylem tissues which may include rigid "heart" or "core" wood.

Reduction Pruning and Torsion

The potential of reduction pruning to increase imbalance was considered. This effect may occur when the removal of a portion of a branch increases asymmetry in the residual branch. This could create a temporary imbalance and subject the pruned branch to increased torsional stress. Other tree biomechanics researchers[17,18] have identified this possibility and are working to quantify the potential for pruning-induced torsion to increase the likelihood of branch failure.

[17] Presentation by G. Dahl, University of West Virginia, at Tree Biomechanics Symposium, September 2012
[18] Conversation with J. Grabosky, Rutgers University

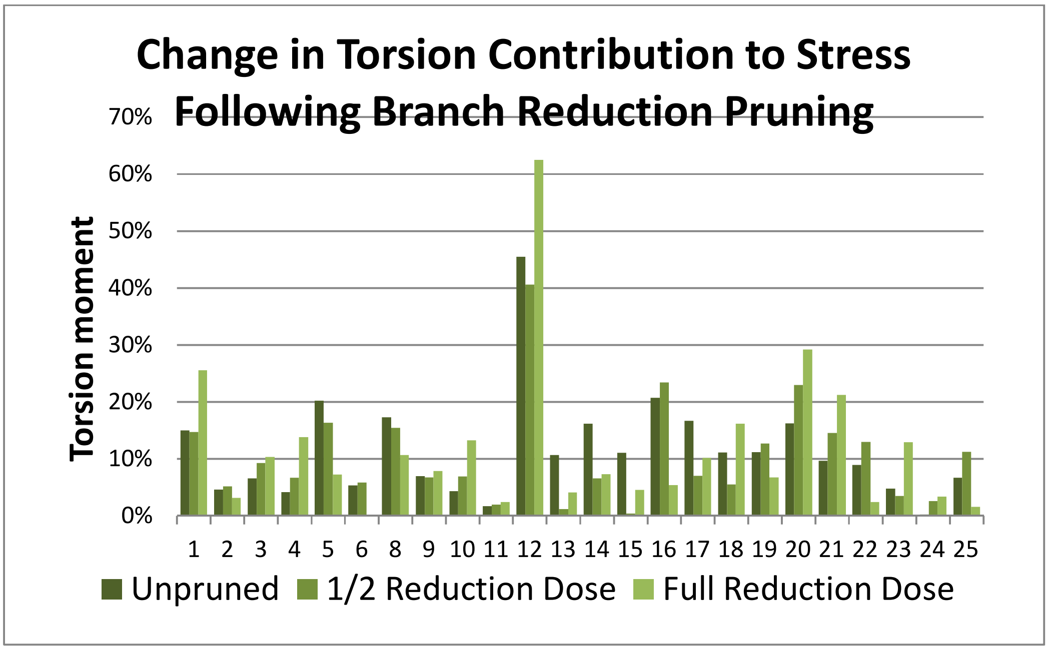

Figure 15. Relationship between reduction pruning and torsion moment as a percentage of bending moment. Numbers on x-axis indicate test number.

Our analysis, as shown in Figure 15, indicates that in almost every case the natural form of the un-pruned branch creates torsion. The average amount of pre-existing torsion amounted to 12% of BBM. Both levels of reduction pruning resulted in similar changes in torsion as a percent of BBM: 1/2 dose 11%, and full dose 12%. The data indicate that, in several cases, reduction pruning actually reduced the percent of torsion moment a compared to bending momnet in the CFZ, restoring some balance to the branch. The implication is that at least in the case of this investigation reduction pruning did not results in dramatic change in torsion moment acting on the branch which would have been a concern in terms of branch stability.

Cost-efficiency of Branch Reduction Pruning

Findings from this research demonstrate that branch reduction pruning can reduce load-induced stress in the CFZ by one half. A reduction in stress reduces the likelihood of structural failure under comparable loading scenarios. A reduced branch is also presents less surface area for interception of ice and snow loads. A pruned branch overhanging conductors also has less mass and a smaller target area should it fail. These factors result in a reduced branch presenting less risk to overhead distribution lines. On the other hand, completely eliminating a branch that overhangs conductors reduces the risk to zero, so the obvious question is whether branch reduction is cost-effective as compared to branch removal. A note of caution is also warranted: under extreme weather conditions such as high wind or substantial accumulations of ice or wet snow, line clearance pruning will not eliminate the risk of branch and whole tree failures causing major damage to an overhead electric distribution system.

The project did not include any quantification of the cost of branch reduction work in a production environment, nor did it seek to quantify the benefits, other than to define the decrease in breaking stress in the CFZ as a result of branch reduction pruning. The approach taken therefore in assessing the costs and benefits of branch reduction pruning is therefore largely qualitative in this study, and compares branch reduction to the removal of an entire branch.

Three qualitative assessment criteria were used to characterize the costs and benefits of reduction pruning of branches overhanging energized primary conductors. They include qualifications of costs, risks, and a third category of miscellaneous considerations. In each case, branch reduction is compared to the total elimination of branches overhanging conductors.

Cost Factors

Table 3 presents a summary of a qualitative assessment of the cost factors associated with the maintenance of branches above and overhanging electric distribution lines. Four broad themes are considered. The first two factors, working positions and equipment, are related. Working positions aloft explores the differences in the position of a qualified line clearance arborist in making the pruning cut. The total removal of a branch requires a cut close to the main stem or parent branch and edge trees along the corridor can be at a considerable distance horizontally from conductors. Whereas branch reduction pruning cuts are not made at the main stem but at a suitable node on the outer end of the branch some distance from the edge of the corridor.

Table 3. Factors considered in a qualitative comparison of the relative costs of managing branches overhanging energized conductors.

Cost Factor	Reduction of overhanging branch	Removal of overhanging branch
Working positions aloft	Pruning position at outer end of the branch is accessible from above and on the "road side" of energized phases.	Pruning position is in proximity to main stem on "field side" of line requiring arborist to boom up, over, and beyond energized phases.
Aerial equipment	Pruning position should be accessible by standard (55ft) platform.	Pruning position may require extended reach (70ft) aerial platform. (billing rate ~30% cost premium)
Slash disposal	One third reduction result in 1/3rd accumulated slash.	Three times more slash to handle and dispose of.
Production rate	Expected to be equivalent to routine line clearance work.	Estimated reduction in production rate by ⅓ to ½.

The second factor considers access to these locations. Branch removal typically requires an aerial platform to be extended above and to cross over the top of energized conductors. The working height of a conventional (±55 ft) line clearance "bucket truck" parked on the side of a road can quickly become a limitation. The elimination of overhanging branches well above the height of the conductors typically requires taller aerial equipment which comes at a cost premium, estimated at approximately 30% more than the cost of conventional equipment. The larger equipment also takes up more space and may increase the need for traffic control (an additional expense), and is sometimes slower. Branch reduction, on the other hand, generally should be possible using conventional aerial lifts.

The third cost factor is relatively straightforward. If branch reduction involves an approximate one-third reduction in branch volume, then only one-third the volume of pruning residue is generated as compared to total branch removal. The cut material must make its way safely from aloft to the ground, and then be processed for disposal.

Finally, these three cost factors are considered together as one, expressed in term of productivity. This qualitative comparison of productivity is subjective, based on conversations with experienced line clearance supervisors and professionals. Quantitative data are available comparing the cost of routine line clearance maintenance to "enhanced" clearances including basic widening of the corridor, the elimination of all overhanging branches, and targeting hazard trees on three-phase backbone lines. These data suggest a cost premium on the order of three to five times for such work, as compared to conventional line clearance work. "Ground to sky" branch elimination is only part of this cost premium.

This assessment of relevant costs suggests that mitigation of a portion (but not all) risks associated with overhanging branches can be accomplished cost-effectively by branch reduction. The key point is not that the work costs less, but that preventive maintenance can be performed on more branches, trees, and miles of line for the same investment of O&M resources. This is an important consideration given that circuit and system reliability improvements may accrue more quickly using branch reduction pruning.

Risk factors

Qualitative factors focusing on relative risks were considered, and are summarized in Table 4. These risks factors are defined in terms of potential impacts on the power system. The first factor considered is the risk of a branch failing and causing an interruption. Clearly if the branch is eliminated there is no risk of an interruption. However, a reduced branch is less likely to cause an interruption for the reasons already stated, including reduced likelihood of failure, reduced areas to experience loading, reduced force of impact, and reduced target area.

The likelihood of tree failure was also considered. Here the results may be somewhat surprising to the reader. Work[19] in the field of biomechanics has identified the importance of lateral branches as mass dampers, reducing harmonic oscillation induced in a tree stem during wind events. While the current study explicitly considered static loads associated with ice and snow, dynamic wind loading is also a concern. High-amplitude oscillation can overwhelm a tree stem's structural strength, resulting in stem failure. Branches that are retained through reduction pruning may help to mitigate this risk.

[19] K James, *Dynamic Loading of Trees*, Journal of Arboriculture and Urban Forestry 29(3), May 2003

Table 4. Factors considered in a qualitative comparison of relative risks associated with branches overhanging energized conductors.

Risk Factor	Reduction of overhanging branch	Removal of overhanging branch
Branch-caused electrical faults	Less likely to occur than un-pruned branch, due to <BBM, mass, and target, but more than with total removal.	Risk is eliminated
Tree-caused electrical faults	Reduced branches act as mass dampers, reducing oscillations and thus risk of stem failure	Total elimination of side branches may increase risk of harmonic oscillation and stem failure
Arborist-caused electrical faults	Average risk, similar to routine line clearance operations. Less than with branch removal.	Elevated risk due to working position, as well as size and volume of material being removed.
Mechanical damage due to branch failure	Reduced due to less mass of residual branch and smaller profile, reducing target zone.	Greater during pruning operations, but risk of subsequent failure during cycle period is eliminated
Catchment and support of branches from above.	Enhanced ability of reduced branches to support deflection of branches from above, reducing likelihood of failure.	None, no support of branches above.

The likelihood of vegetation management activities causing an interruption was also a consideration. Although the likelihood of this occurring under either scenario is typically very low, line clearance crews do occasionally cause outages, particularly during pruning operations above energized lines. The removal of an entire overhanging branch presents greater risk. The overall length and weight of the branch makes it more difficult to control as it is removed. The branch itself is also longer, increasing the possibility of it providing a fault pathway between energized phases should it fall into contact with conductors. In contrast, branch reduction by definition results in smaller and lighter portions of an entire branch being removed, which presumably are then more easily controlled.

The force of impact of a branch or branch segment was another consideration. This factor is relevant either in the case of loss of control during pruning operations, or over the course of the preventive maintenance cycle. Entire branches have greater mass and therefore would generate greater force of impact. However, if a branch is eliminated during line clearance pruning operations, then subsequent failure is irrelevant.

The final risk factor considered was the influence the branch may have in mitigating risks associated with the deflection or failure of other branches located above its location. A reduced branch may provide some support to branches above as they deflect under loading conditions. This condition is often seen in conifers. Removal of these supporting branches eliminates this protective effect.

Other Factors

The third type of qualitative assessment criteria does not have a common focus. They are however important considerations, and there are differences between the two techniques, as summarized in Table 5.

The first of these factors relates to operational feasibility. The elimination of all overhanging branches (a.k.a. "ground-to-sky clearance") is difficult to achieve on many sites. This is due to the canopy height of adjacent trees and forest; in the eastern hardwood forest, canopy heights are routinely 70 feet and can approach 90 feet in mature stands. The cost implications of working well above electrical utility lines have already been discussed. Rather, this factor questions whether it is operationally feasible to work at these heights. In this case, branch reduction represents an alternative to standard pruning practices.

Table 5. Other factors considered in a qualitative assessment of reduction pruning versus removal of branches overhanging conductors.

Factor	Reduction of overhanging branch	Removal of overhanging branch
Feasibility, practicality	Branch reduction can be accomplished even in the case of very tall canopy heights.	Tall canopy heights make the elimination of all overhanging branches technically challenging and costly.
Impact on the tree	Minimal if pruning is compliant with industry standards and BMPs	Depends on number of branches removed. Could be very significant with "ground to sky" work.
Aesthetic impact	Similar to routine line clearance operations. Less than with total branch removal.	Greater, depending on number of branches removed.
Risk of failure of upright branch	Reduction pruning practices can be applied to upright branches and stems, which are at greater risks of failure under loading conditions.	Generally would not address upright branches and stems that are not overhanging conductors.

The next factor considered is the impact of branch reduction versus branch elimination on the tree being pruned. Neither technique will result in serious adverse effects provided that the pruning is performed in a manner consistent with industry standards and BMPs. The more important question is the extent to which either technique is applied to a tree. The total elimination of all overhanging branches has the potential to significantly reduce the live crown area of the tree, and adversely affect its ability to produce energy needed for its survival. The retention of branches that have been reduced mitigates this concern. The tree uses energy produced in the leaves to sustain growth processes including wound closure and defense against decay.

The aesthetic impact resulting from removal of overhanging branches has the potential to be severe. The visual change to the site will be less dramatic following branch reduction pruning as compared to removal of all overhanging branches.

Finally, branch reduction pruning can be applied to upright branches and leaders that may not be overhanging conductors. An upright orientation may increase the risk of structural failure under loading conditions. Although upright branches are initially structurally stable, as loads increase the branches begin to deflect and are subjected to rapid increases in stress which increases likelihood of fracture. Height reduction pruning techniques used in maintaining trees located directly under overhead lines already involve branch reduction. These same ideas may apply to upright branches and leaders high in the crown of trees adjacent to distribution lines.

Recommendations

Branch reduction pruning has been shown to reduce risks to overhead distribution lines, and can be a cost-effective alternative to branch removal. Reduction pruning should be included in distribution line clearance vegetation management plans and preventive maintenance specifications.

Contemporary approaches to distribution system vegetation management typically include establishing an area clear of all vegetation in proximity to energize conductors. Specified clearances below, beside, and above conductors may vary. Branch reduction pruning may occur in each of these locations. These recommendations also pertain to branches that directly overhang conductors.

Recommended technical requirements suitable for inclusion in contract specifications are included at the conclusion of this report.

Branch Reduction Pruning and Routine Line Clearance Vegetation Maintenance

Distribution vegetation maintenance specifications typically allow overhanging branches to remain at some specified height above conductors. This is common industry practice, and recognizes the height limitations of convention aerial lifts. Branch reduction pruning should be considered as a means of maintaining overhanging branches in a transitional zone between conductors and the upper limits of the pre-defined clearance zone, above which un-pruned viable overhanging branches are allowed to remain.

Branch Reduction Alternative to "Ground to Sky" Pruning

The removal of all branches overhanging conductors is occasionally specified, particularly as applied to the three-phase segment of a circuit from the substation breaker to first line reclosing device (a.k.a. "feeder" or "backbone"). This practice also tends to come as a reaction to damage sustained during major storms. As previously discussed, this practice can be prohibitively expensive. Branch reduction pruning should be included in enhanced clearance specifications focusing on reducing the risk of all overhanging branches. This recommendation is intended as a means of complementing rather than replacing all overhang removal. It will always be appropriate to remove high-risk branches. However, the risk to overhead lines can be reduced or eliminated by simply reducing an overhanging branch.

These recommendations can be considered as alternatives to the complete removal of all branches overhanging conductors, in cases where enhanced "ground to sky" clearances are being advocated.

Branch Reduction and Upright Branches and Stems

Branches with an upright orientation and near-vertical stems and leaders are at elevated risk of failure under loading conditions. It is also important to note that the CFZ may be further from that union as compared to more horizontally oriented branches. Branch reduction pruning techniques would apply to upright branches and stems, as would existing specifications for height reduction pruning of trees directly under lines. It is possible that upright branches in close proximity to lines present greater risk exposure than do many horizontal overhanging branches.

Branch Reduction and Small Diameter Branches

Small diameter branches are flexible and more likely to deflect to the extreme, rather than fail. As such, the implications in terms of impact on the target are different. Reduction of small diameter branches can be justified on the basis of "training" future branch development. It could also be prescribed to reduce the arc of sweep described by small branches as they deflect, reducing the chance of intercepting an energized phase should they fail. The origin of the small branch is an important consideration. This recommendation applies to branches that develop naturally. Branches that grow at exaggerated rates from adventitious buds (a.k.a. "suckers" or "water sprouts") are typically weakly attached and should be removed.

Technical Specifications for Branch Reduction Pruning

The following specifications are based on a two-tiered line vegetation maintenance clearance zone above conductors:

> **Clearance Zone:** an area immediately above conductors to a height of X feet. All branches within the clearance zone are removed or reduced to parent or lateral branches outside the clearance zone, as necessary to achieve required clearance. No branches are allowed within the clearance zone.

> **Reduction Zone:** an area above the clearance zone extending from X feet above conductors to a height of Y (may be "ground-to-sky" or a set distance). Upright branches beyond the Clearance Zone that are in close proximity but may not directly overhang conductors are included in the branch reduction zone. The size and extent of the Reduction Zone shall be adjusted based on line voltage, number of customers potentially affected by an interruption, the location and/or presence of protective devices, and other factors as specified. Branches within the Reduction Zone are subject to reduction pruning as specified below.

Note: *Several of the technical requirements specified below would apply equally to all types of line clearance pruning, and are not unique to branch reduction work. They may be included elsewhere in a set of technical specifications, and simply cross-referenced. They could also be incorporated by referencing ANSI A 300 Part 1. They are included here in an effort to create a complete stand-alone set of requirements for branch reduction pruning.*

1. Technical Requirements - Reduction Pruning of Limbs Overhanging Conductors

   Branch reduction pruning involves decreasing the length and/or spread of branches overhanging conductors. The purpose is to reduce the chance of failure by shortening, rather than removing, entire overhanging branches that may interfere with conductors, should the branches fail. A reduced branch will experience less stress under loading condition and will be less likely to fail.

   1.1. Branches that overhang conductors and extend into the Clearance Zone immediately above conductors shall be removed or reduced to parent branches or laterals outside the Clearance Zone.

   1.2. Overhanging branches in the Reduction Zone that meet specified conditions and are of a size that could cause an interruption shall be removed or reduced to parent branches or laterals inside or outside the reduction zone as necessary.

   1.3. The branch being reduced shall be inspected for obvious structural defect and/or decay.

      1.3.1. The branch union with main stem or parent branch shall be included in the inspection.

1.3.2. Branches with defects and/or poor attachments that increase the risk of structural failure shall not be reduced but removed.[20]

1.3.3. Branches with defects close to the union with stem or parent branch (within 20% of total branch length) are of particular concern.

1.4. Branches with poor taper should be critically evaluated, and may be good candidates for reduction if pruning can improve taper.

1.5. The branch selected for reduction shall be pruned by removing a portion of the branch with the most mass at the greatest distance from the union with main stem of parent branch.

1.6. The branch should be reduced by approximately one-third[21] of the volume of space it occupies.[22]

1.7. The extent of reduction in live foliage should not compromise viability of the residual branch.[23]

1.7.1. Where reduction may result in a branch of uncertain viability, the branch shall be removed rather than pruned.

1.7.2. Branches of excessive length, especially those with areas of foliage at their extremity (a.k.a. "lion's tailing") should be critically evaluated, and may not be good candidates for reduction if reduction required excessive removal of foliage.

1.8. In conifer species with regular whorls of branches (e.g., Eastern white pine), a progressive series of increasing percent reductions over two or three whorls of branches is preferred.

1.9. Branch reduction should be accomplished using a minimum[24] number of pruning cuts. It may be possible to effectively reduce a branch with one well-placed cut.

1.10. Smaller diameter reduction cuts are preferred.

1.11. Care shall be taken during pruning to minimize damage to the residual branch.[25]

1.12. Reduction pruning cuts should be made to a lateral(s) large enough to assume the terminal role of dominance[26].

1.12.1. This requires the preservation of terminal buds on the selected lateral.

1.12.2. The lateral should be at least 1/3 the diameter of the cut, however it may be necessary to select laterals of less than recommended size.

1.12.3. Reduction pruning cuts should be made to a lateral(s) that will direct future growth in a direction that will not further overhang conductors.

---

[20] ANSI A300 Part I § 6.2.5
[21] ANSI A300 Part I § 6.1.4
[22] ANSI A300 Part I § 7.4.2
[23] ANSI A300 Part I § 6.1.4

[24] ANSI A300 Part I § 9.3.1.2
[25] ANSI A300 Part 1 § 5.3.7
[26] ANSI A300 Part I § 5.3.4 and § 9.3.1.1.4

1.13. Pruning small branches in the Reduction Zone should serve to train and direct future growth away from conductors.

1.14. Reduction pruning cuts shall be made at a slight downward angle[27] relative to the remaining stem.

1.15. Reduction pruning should not create severe imbalance in the residual branch, such as all remaining lateral branches concentrated on one side of the residual branch. Imbalance may create excess twist and create torsion stress that can lead to failure. Further reduction may be necessary to reduce imbalance.

1.16. The natural structure and growth habit of the tree should be taken into account, including expected re-growth response of the species following reduction.

1.17. Branches with upright growth orientation should be considered for reducing pruning if they do not directly overhang conductors, but would as they deflect under loading.

[27] ANSI A300 Part I § 5.3.3 and § 9.3.1.1.2

Summary & Conclusions

This research project provides quantitative evidence that branch reduction pruning reduces load-induced stress, thereby the likelihood of structural failure. The recommended branch reduction pruning practices of interest to utility arborist will reduce stress on average by one half. A lighter reduction while less effective, was shown also to reduce stress by one quarter, and may be of interest to other arborists and applicable to situations with greater risk tolerance. A qualitative assessment of branch reduction pruning demonstrates that it can be a cost-effective alternative to the removal of an entire branch.

The research was intended to be operationally relevant. A practical definition of reduction dose was selected, which in retrospect introduced variability. Ice loading was modeled and assumptions have made that stress imposed on a branch will be similar under snow loading. Tests were carried out on four species which are assumed to be representative of the utility forest.

Regardless of these limitations, the practical bias reflected in this project supported development of recommendation that should be easily incorporated into distribution vegetation maintenance specification.

Appendix A: Review of Branch Reduction Literature

A review of the literature related to reduction pruning to as a means of mitigating the risk of branch failure was completed as part of this project. The abstracts below describe the relevant articles that were identified.

Croxton, W. C. "A Study of the tolerance of trees to breakage by ice accumulation." *Ecology* 20, no. 1 (1939): 71–73.

A sleet storm in Missouri and Illinois on January 7, 1937 caused widespread tree damage. An examination of 979 trees of 52 species found strong species variation in damage. *Fagus grandiflora, Carpinus caroliniana, Prunus serotina, Gymnocladus dioica, Magnolia acuminate, Acer rubrum, Maculura pomifera,* and *Picea pungens* had little damage. *Cornus florida* and *Celtis occidentalis* were moderately injured. T*illia Americana, Ulmus fulva, Quercus velutina,* and *Prunus persica* were badly broken.

Dahle, Gregory A. and Jason Grabosky. 2009. "Review of literature on the function and allometric relationships of tree stems and branches". *Arboriculture & Urban Forestry* 35(6):311-320.

Pruning trees is a common practice for managing trees and reducing their likelihood for failure. this paper reviews three models of branch form – pipe model theory, fractal dimensioning, and power laws. How these models influence pruning research, particularly as it relates to wind loading, is discussed.

Dahle, Gregory A. and Jason Grabosky. 2012. Determining if lateral imbalance exists in first-order branches leading to a potential development of torsional stress. *Arboriculture & Urban Forestry* 38(4):141-145.

The purpose of this experiment was to determine if first-order branches on open grown trees are laterally balanced. An imbalance in mass could lead to torsional stress under wind or gravity loading. Using mass and center of gravity measurements for second-order branches, loads on first order branches were estimated. Measurements for 15 first-order branches and 110 second-order Tilia cordata branches revealed that 60% off the first-order branches were imbalanced, and 80% had more loading to the left side of the branch.

Ennos, A. R., and A. van Casteren. “Transverse stresses and modes of failure in tree branches and other beams.” *Proceedings of the Royal Society B: Biological Sciences* 277, no. 1685 (December 16, 2009): 1253–1258.

This paper describes the stresses that occur in branches under loads that cause bending and how the branches facture. Curved branches that are straightened split down the middle along the neutral plane. Straight branches of low density wood such as *Salix alba* buckle rather than break when bent because of low transverse compressive strength. In contrast, branches of higher density wood, such as *Fraxinus excelsior*, experience ‘greenstick fracture’ in which the top of the branch breaks first, then splits along the neutral plane. In very dense wood, the branch might break across the branch without splitting.

Gilman, Edward F., F. Masters, and J. Grabosky, “Pruning Affects Tree Movement in Hurricane Force Wind,” *Arboriculture and Urban Forestry, January* 2008, pp. 20-28

This reports on an assessment of the effects of pruning on dynamic wind loads and branch movement under extreme winds. The study involved pruning live oak (*Q. virginiana*) trees and subjecting them to high velocity winds in situ. The trees were all clones growing at the University of Florida and averaging 4.8” in diameter and 19.8’ in height. The pruning methods used were defined by ANSI A300 pruning standards and included crown raised, reduced, and thinned trees, as well as un-pruned control trees. Instruments were placed on the trunk and branches of test trees to measure movement. Following pruning, artificially induced hurricane force winds (up to 110 mph) were applied to each tree. Thinning and reducing significantly reduced upper trunk movement, whereas crowning rising did not. Foliage and branches toward the top of trees appear to cause greater trunk movement. Trees that are reduced or thinned could receive less damage in windstorms.

Gilman, Edward F. 2012. *An Illustrated Guide to Pruning*, 3rd Edition. Delmar: Clifton Park, NY.

This text provides thorough information on how, when, where, and why to prune trees. It includes sections on tree structure and strength, pruning methods and tree responses, and pruning mature trees to minimize risk. It is an important guide for those who prune trees.

Guggenmoos, Siegfried. “Tree-related electric outages due to wind loading.” *Arboriculture & Urban Forestry* 37, no. 4 (2011): 147–151.

Ten years of tree-caused electric outages at Puget Sound Energy were correlated with wind data during the same time period. Most of the unplanned service interruptions were caused by trees, 95% of which were due branch, trunk, or whole tree failure. Only 32% of these had visible defects or conditions that would have been identified in a visual inspection. The author concludes that tree-related service interruptions due to wind loading can be modeled. Because wind loading is exponential to wind speed, tree-related service interruptions also should be exponential to wind speed. The frequency of outages can be projected for various wind speeds.

Kane, Brian, R. Farrell, S. M. Zedaker, J. R. Loferski, and D. W. Smith. "Failure mode and prediction of the strength of branch attachments." *Arboriculture and Urban Forestry* 34 (2008): 308–316.

Branches 2.4 to 17.8 cm (2.6 to 7.1 in) and 1.8 to 8.4 cm (0.7 to 3.4 in) from 75 15-year-old trees (*Acer rubrum*, *Quercus acutissima*, and *Pyrus calleryana*) were removed from trees below and above the point of attachment with the main stem. In the laboratory, the branch was pulled from the stem with a known load, and the breaking stress calculated. Breaking stress varied with the shape of the attachment ('u' or 'v'), failure mode (flat surface, embedded branch, ball and socket), and presence of included bark. The best predictor of breaking stress was the ratio of branch to trunk diameters. Codominant stems where the branch diameter was 70% of the trunks diameter were 50% as strong as attachments were the branch is smaller than the trunk.

Kane, Brian R., and Kenneth R. James. 2011. "Dynamic properties of open-grown deciduous trees". *Canadian Journal of Forestry Research* 41:321-330.

Pull-and-release tests were performed on12 19.9 cm (2.9 in) diameter *Pyrus calleryana* 'Bradford' and 12 6.9 cm (1.0 in) diameter *Quercus prinus*, vibrations measured, and natural frequency and damping ratio were calculated. The trees were then pruned by either raising or reducing the *Quercus*, and reducing or thinning the *Pyrus*. Half of the trees were tested again when in leaf, and 10 were tested following a surprise storm that left 1-2mm ice on the trees. The other half of the trees were tested after leaf fall. Drag-induced bending moments were much less when trees were leafless, and less than when trees were pruned or had ice loading. Pruning may not reduce likelihood of failure in wind if wind events typically occur when the tree is out of leaf.

Luley, Christopher J., S. Sisinni, and A. Pleninger. "The Effect of Pruning on Service Requests, Branch Failures, and Priority Maintenance in the City of Rochester, New York, U.S". *Journal of Arboriculture May 2002, pp. 137-143*

This paper reports on an assessment of the efficacy of tree pruning in reducing tree damage and the need for corrective maintenance pruning. The study involved an assessment of records of preventive maintenance of street trees, the need for corrective repairs, and meteorological records of wind speed. The study site was City of Rochester, NY, which had been routinely pruning street trees on a 5-year cycle. This preventive maintenance pruning was completed to appropriate industry standards and was intended to reduce hazards and improve structure.

Key findings:

- Branch failures, as measured in terms of the need to respond to damage in the urban forest, increased significantly with wind speeds over 50 mph.
- The need for corrective pruning of street trees due to branch failures was significantly reduced in areas that had been pruned as compared to un-pruned areas, as measured by "service requests".
- The effect of preventive maintenance pruning did not reduce requests from the public for site cleanup following windstorms
- The authors reported that branch failures were three times more likely to occur during the growing season when deciduous trees were foliated. The presence of leaves increases the probability of branch failure.

Niklas, Karl J. "Wind, Size, and Tree Safety", Tree Structure and Mechanics Conference Proceedings, International Society of Arboriculture, October 2001

This paper offers a broad summary of the subject of tree failures. While its stated focus is wind-related failures, there is a wealth of information related to the mechanical strengths of trees.

The mechanical capabilities of trees are known to vary even among the same general size and appearance. The load-bearing capacities of trees and branches within the same canopy can vary due to thigmomorphogenetic responses. Tissues within the branch vary in accordance to the degree of mechanical perturbation they experience. Removal of neighboring stems and branches exposes remaining branches to mechanical stress that can lead to deformation or failure under otherwise manageable conditions.

In general, smaller stems are composed of more flexible plant tissue and thus have a higher stress capability than larger stems. Susceptibility to damage increases with the age and height of the tree. Different sized branches on the same tree can vary in terms of the risk of mechanical failure.

Pavlis, Michael, Brian Kane, J. Roger Harris, and John R. Seiler. "The effects of pruning on drag and bending moment of shade trees." *Arboriculture and Urban Forestry* 34, no. 4 (2008):207-215.

The effects of simulated wind on drag-induced bending moment was measured on 47 young *Acer* x *freemanii*, *Quercus bicolor*, and *Q. imbricaria* before and after pruning to raise, reduce, or thin tree canopies. The effectiveness of pruning to reduce bending moment varied with pruning type and tree species. In general, reduction pruning was more effective than thinning or raising, and strongly correlated with how much mass was removed.

Smiley, E. Thomas, and Brian Kane, "The Effects of Pruning Type on Wind Loading of Acer rubrum," *Arboriculture & Urban Forestry*, January 2006, pp. 33-40

This paper reports on an investigation of the effect of various pruning methods on wind loading. The study used relatively small red maples (*Acer rubrum*) with an average diameter of 3". Pruning methods evaluated thinning, reduction, lions-tailing, and leaf stripping. Pruned trees were subject to high-speed winds prior to and following pruning and measures of dynamic wind loading were recorded. The authors determined that all pruning methods evaluated reduced wind load significantly, suggesting that trees pruned regularly may be less susceptible to failure.

Sterck, F. J., H. A. van Gelder, and L. Poorter. "Mechanical branch constraints contribute to life-history variation across tree species in a Bolivian forest." *Journal of Ecology* 94, no. 6 (2006): 1192–1200.

This paper examined the differences between branch development and strength for 20 shade-tolerant and 10 shade-intolerant species in a lowland tropical moist forest. For each species, 5 branch samples were collected from low light conditions and five growing in high light conditions, and the modulus of rupture, among other characteristics, was measured. Branches growing in shaded locations had denser and stronger branches; those in higher light conditions had lighter and weaker branches and allocated more resources to height growth.

van Casteren, A., W. Sellers, S. Thorpe, S. Coward, R. Crompton, and A. Ennos. "Why don't branches snap? The mechanics of bending failure in three temperate angiosperm trees." *Trees - Structure and Function* 26, no. 3 (2012): 789–797.

"Living tree branches are almost impossible to snap." Branches of different species fail in different ways under bending loads. In "greenstick fracture" or "clean fracture" the branch breaks through the top of the branch, and the splits laterally along the neutral plane. In "diffuse fracture" the branch breaks with multiple fractures across the branch cross section and on small longitudinal cracking. In “transverse buckling” no tensile fracture occurs and the branch fails by buckling. These differences are explained by the anatomy and mechanical properties of wood.