Final Report:
Development of Risk Assessment Criteria for Branch Failures within the Crowns of Trees

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Prepared by:
BioCompliance Consulting, Inc.
Redmond, Washington

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Executive Summary

An investigation of branch failures having the potential to cause interruptions to electric service was completed in four phases. These included a review of the literature, interpretation of photos of tree-caused outages, a survey of the industry's experience, and destructive testing of branches of six species of tree. The small- and medium-sized branches included in this research ranged between two and eight centimeters (≈1-4 in.) in diameter. Qualitative and quantitative observations were analyzed and used in the development of recommendations intended to aid in the assessment and mitigation of the risk of branch failures to an overhead electric distribution system.

This research identified a critical zone of failure within twenty percent of the branch length to the union with the main stem. It also demonstrated the resiliency of small diameter branches in resisting failure under static loads. The role of irregularities in the branch form in concentrating load-generated forces of stress was identified and characterized. The study also found that a relatively small reduction in branch length resulted in a substantial reduction in load-induced stress in branches, and may be an effective means of mitigating the risk posed by branches adjacent to and, particularly, overhanging distribution conductors.

Opportunities to apply various risk assessment criteria were identified. Risk mitigation practices including hazard inspection and branch reduction are included as recommendations.

Introduction

Deflection and structural failure of individual branches within the crowns of trees in close proximity to, and sometimes overhanging, energized conductors represent an important risk to system reliability. Pruning these branches is time consuming, difficult, and costly work. In many cases it is not practical or feasible to remove all overhanging branches.

BioCompliance Consulting, Inc. completed an investigation into the manner in which individual branches within the crowns of trees fail. The project placed emphasis on understanding the risk to reliability posed by failure of branches adjacent to and overhanging conductors.

Findings from this research have the potential for practical application in risk assessment and mitigation practices. Improvements in the ability to identify and manage high risk branches can be expected to result in a reduction of tree-caused damage to the overhead electric system, to reduce interruptions, and to improve the cost-efficiency of vegetation maintenance expenditures by the utility.

Problem Statement

Tree failure adjacent to and sometimes well outside the maintained right-of-way corridor has been recognized as a dominant cause of electric service interruptions on well-managed overhead electric distribution systems. Considerable work has been done throughout the industry to develop hazard tree risk assessment and mitigation techniques. Vegetation managers focus on identification of individual trees adjacent to the cleared corridor that demonstrate readily apparent characteristics that would predispose them to failure. Techniques for assessing the potential for structural failure of individual trees are generally well understood.

The failure of individual small- and medium-sized branches within the crown of trees in close proximity to, and sometimes overhanging, energized distribution conductors should also be a major consideration. Like whole tree failure, individual branches failure has the potential to cause mechanical damage to energy delivery infrastructure. Individual branches can also provide a fault pathway between areas of unequal electrical potential such as two-phase conductors, resulting in the electrical mode of failure. In either case the structural failure of individual small- and medium-sized branches represents an important risk to system reliability.

Figure 1 Branch failure due to ice loading is a major cause of interruptions during ice storms.

Many of the defect-based criteria used in traditional hazard tree assessments can readily be adapted for application to crown inspection. However, less is known about the structural integrity and failure potential of seemingly healthy branches in the crown. Yet these kinds of branch failures can be a major contributor to damage sustained during severe weather. This is particularly true of branches high in the crown that overhang conductors.

Current vegetation management specifications establish a preliminary foundation for branch failure risk mitigation. The purpose of this research project was to establish a basis of understanding for development of risk assessment criteria and mitigation strategies that would focus on branch failure within the structural crowns of trees and the forest canopy. A new body of knowledge is developing regarding the structural integrity of tree crowns

Project Overview

The investigation was conducted over the course of a year and included the following tasks:

- **Literature Review:** A review of relevant literature was conducted. The literature review provided an overview of the current body of knowledge and supported development of an experimental protocol.
- **Qualitative Analysis:** The project included two methods of qualitative assessment of the industry's direct experience with branch failures as a threat to service reliability.
  - A structured review of post-interruption branch failure photographs provided by practicing arborists.
  - A survey of the membership of the Utility Arborists Association focusing on the experience of practicing utility arborists with branch failures.
- **Quantitative Analysis:** A field experiment involving the mechanical loading of individual branches to the point of failure.
- **Development of Risk Management Recommendations:** Development of recommendations for improved risk assessment and risk mitigation methods

This final report serves to document our findings, and is intended as a reference for considering improvements in distribution line clearance vegetation maintenance and management specifications.

Project Team

BioCompliance Consulting, Inc. assembled an expert team to complete the project. The team included:

Lead Consultant: John Goodfellow

Mr. Goodfellow has 30 years of experience in the electric utility industry, having held positions of responsibility for vegetation management, T&D operations, maintenance and engineering at three large investor-owned electric and gas utilities. He is recognized as a leading authority on utility vegetation management and reliability, and currently manages a portfolio of high voltage research and development projects focusing on tree-initiated faults and interruptions.

Technical Advisor: Andreas Detter

Mr. Detter holds an engineering degree in landscape design, is a court-appointed expert witness, and is co-founder of Brudi & Partner TreeConsult based in Munich, Germany. Mr. Detter is a member of SAG Baumstatik, an international association of consultants engaged in tree statics. Mr. Detter teaches at the University of Applied Sciences in Weihenstephan, Germany and conducts workshops and presentations in both North America and Europe.

Field Researcher: Phillip van Wassenaer

Mr. Van Wassenaer has been a practicing arborist for over fifteen years. He is principle consultant with Urban Forest Innovations Inc. in Mississauga, Ontario. Mr. VanWassenaer is a member of SAG Baumstatik, and has been instrumental in bringing European static testing methods to North America.

Research Technician: Michael Neiheimer

Mr. Neuheimer has been a practicing arborist for over eleven years, and is actively engaged in both consulting and practical arboriculture in Windsor, Ontario. He has worked extensively in Germany over the past 10 years in the field of tree statics. During this time, he has worked closely with Andreas Detter and Erk Brudi on various projects including investigations of branch failure as related to arborist safety and tree stability.

Review of Literature Related to Branch Failures

A literature review was conducted as the first step of the investigative process. The focus was to conduct a summary overview of the current body of knowledge related to tree and branch failure, and to gain insight as to experimental methods.

General References

Two general texts were reviewed. Rather than repeatedly cite relevant material from each, these 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.

- Niklas, K.J., 1992, *“Plant Biomechanics, An Engineering Approach to Plant Form and Function”*, University of Chicago Press, Chicago.

This is a scholarly text provides a detailed technical discussion of the principles of structural engineering as specifically related to plant materials. This would be a useful technical reference for those interested in an in-depth study of the topic.

Search Methods

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 some of the authors of highly relevant work was initiated and the specifics of their projects discussed.

Abstracts from the relevant articles that were reviewed in detail are included in Appendix A. The following narrative discussion is intended to give the reader a general sense of the findings from the literature review. Abstracts are numbered and presented in alphabetical order by author. The number in the summary below references the abstract within Appendix A.

Summary Finding from the Literature Review

A growing body of work in Europe is beginning to provide insight into the structural integrity of tree crowns. Several papers (2, 5, 21, 22) related to the emerging field of “tree statics” were identified as having direct application to this project. This was particularly true of a recent and as yet unpublished work (5) on the risk of larger structural branches that have the potential to be used as attachment points for climbing lines used by arborists. This body of work reporting on the efforts of European arborists was deemed sufficiently relevant to invite some of the authors cited (2, 5,16) in the literature review to become directly involved in this investigation.

The forces impressed on a branch differ. Loads due to accumulation of ice, wet snow, and wetted branch and leaf surfaces can be thought of as unidirectional static gravitational loads. These loads have been simulated experimentally in a number of studies (4, 5, 13, 16). One author noted that simple static loading models using one point of contact to apply loading break down with branch deflections greater than 25 degrees (15).

Measures of tree and branch strength based exclusively on static load tests have been shown to overstate the strength of trees. Dynamic loading caused by the force of turbulent wind, which can vary in direction and intensity, results in greater bending moments than have been considered in most static tests (1).

A limited number of studies intended to quantify actual wind loading (8, 20) are reported in the literature, and demonstrate the difficulty of simulating the force of wind. These studies point to the role of the force of wind acting on exposed branches high in the crown in creating the stress and strain that cause stem deflection. Wind speeds above 50 mph are reported to result in extensive branch and tree failure in the urban forest (14). This is consistent with the general experience of the utility industry. Branch failure was reported as being three times as likely to occur during the growing season (14). This is likely due to the presence of leaves on deciduous trees and the severity of summertime convective storms.

Traditional branch risk assessment has placed emphasis on the branch union with the main stem. This was therefore an area of interest during the literature review. Characteristics of the connective tissues between branch and stem vary by the angle of attachment (6), with smaller and horizontal branches reported as less conductive and being more likely to resist decay following removal of the branch. Smaller branches relative to main stem diameters were shown to be stronger than branches more similar in diameter to the main stem to which they were attached (9).

Physical characteristics of branches were reported to be an indicator of strength. Branches that developed as “waterspouts or “sucker” growth were reported to be half as strong as natural growth (4). The risk of branch failure was reported to vary with diameter. This is explained in part by the observation that smaller branches contain a higher percentage of flexible tissue than do larger branches (17). The fiber strength of woody tissues in branches was reported to be much stronger than woody fibers in the main stem (21). One author suggested that the diameter of the branch at the mid-point is a useful indicator of failure (3).

Published strength tables such as the “Stuttgart Table of Wood Strength” demonstrates variation in the strength characteristic between tree species (2). Several papers also clearly demonstrate that the strength of branches can vary significantly within an individual tree, depending on a number of factors (4, 9, 17, 21, 22). One author in particular suggests that traditional measures of wood strength such as specific gravity, modulus of rupture, and modulus of elasticity are poor indicators of risk of branch failures during ice storms (11). The important role of reaction wood in increasing branch strength and resistance to failure is cited by several authors (10, 12, 16, 17).

The failure processes of branches has been described in detail. Initial loading occurs in the range of elasticity. Primary failure occurs as cells in compression on the lower cross section of the branch are crushed, and a secondary failure occurs as fibers in tension on the upper cross section of the branch tear (5, 16, 22). The concept of a tree safety factor was presentation in two sources, reported to be in the range of between 2.5:1 (10) and 4:1[1].

Branch reduction pruning was suggested as a means to increase wind firmness and to reduce the likelihood of branch failures under wind loading conditions (8, 14, 17, 20).

Findings and insights gained in the literature review were used to develop a baseline of the current state of knowledge of branch failures. These insights were applied in designing the experimental phases of the project.

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

Branch Failures Photo Investigation

The first investigative phase of the project involved a systematic review of photos of tree failures that had caused interruptions. The purpose of this task was to refine the definition of the problem by focusing on branch failures that had resulted in interruptions to electric service. The task required the collection and analysis of photographic records of tree-caused interruptions.

Call for Photos

A call for post-interruption site photos was made to practicing utility arborists working in the northeastern, mid-Atlantic, midwestern USA and eastern Canada (Appendix B). The request for photos made to members of the Utility Arborist Association (UAA) included the following criteria:

- Photos of branch failures that resulted in interruptions on the overhead distribution system.
- Photos taken soon after the event were preferred.
- Photos that clearly showed the location of failure within the crown.
- Photos that showed the failure site along the branch.
- Photos take as part of a post-interruption investigation were of particular interest.

Photos that were received were initially screened using these same criteria. This screening step eliminated the majority of photos received from further considerations. Many of the photos received involved whole tree failures, and were deemed to be out of scope. Photos of branch failures where the mode and cause of failure were not clearly evident were also eliminated.

A sampling bias was also identified during the initial screening process. It became apparent that many of the photos being submitted were of tree and branch failures that had caused major damage to utility infrastructure. In retrospect this is to be expected. The practicing utility arborists were more likely to capture images of the most significant events, and less likely to record the more routine outages caused by the failure of small and medium diameter branches.

Figure 2 A typical example of a branch failure photo received from UAA members for use in the photo

Photo Interpretation

Forty-one photos were determined to meet the selection criteria and were subject to detailed analyses. A series of attributes related to branch failure were defined and used in an assessment of the branch failure depicted. These attributes are summarized in Table 1 below.

Table 1 - Attributes considered in evaluation of post-failure site photos.

Attribute	Rationale
Species	Did the risk of branch failure vary by species?
Site Factors	Did branch failure rates differ by land use site type?
Season	How did the risk of branch failure vary over the course of a year?
Crown Competition	What was the competitive position of the tree in the canopy? Traditional forestry constructs were used.
Crown Form	The question focused on the form or gestalt of the crown, defined in terms of crown symmetry.
Utility Forest Zone	The question evaluated the location of the tree with failed branch(es) relative to the overhead distribution line.
Prior Pruning Objective	Had been any previous pruning, and if so what type of line clearance?
Prior Pruning Type	The intent of this question was to characterize the type (quality) of prior pruning work
Location of Failure	What was the relative position of the site of failure along the branch?
Location of Branch	What was the position of branch origin within the crown where the branch failure occurred?
Class (Order) of Branch	The focus was on characterizing the branch in terms of hierarchy within the crown
Branch Angle	What was the angle of attachment of the branch union with the main stem?
Branch orientation	What was the general "slope" of the branch relative to a horizontal plane?
Branch Condition	Describe the condition of the branch at the time of failure.
Type of branch failure	What was the position of the branch once it failed?
Interruption Mode & Cause	What was the impact of branch failure on the reliability of overhead electrical distribution systems?

The number of photos that were determined to be useful was limited. Several of the attributes applied yielded inconclusive results. That was to be expected in this initial investigative task, the primary purpose of which was to support development of the field experiment. The other limitation of the submitted photos was that they tended to depict outages that had resulted from failures of branches with diameters larger than those that were the focus of this study.

Having acknowledged these two limitations, some useful trends are worth noting. They are summarized in the following section of this report.

Variation by Genus

Due to the small sample size and inherent uncertainty in conclusively determining tree species from the photos submitted, trees were identified only to the genus level, as presented in Figure 3.

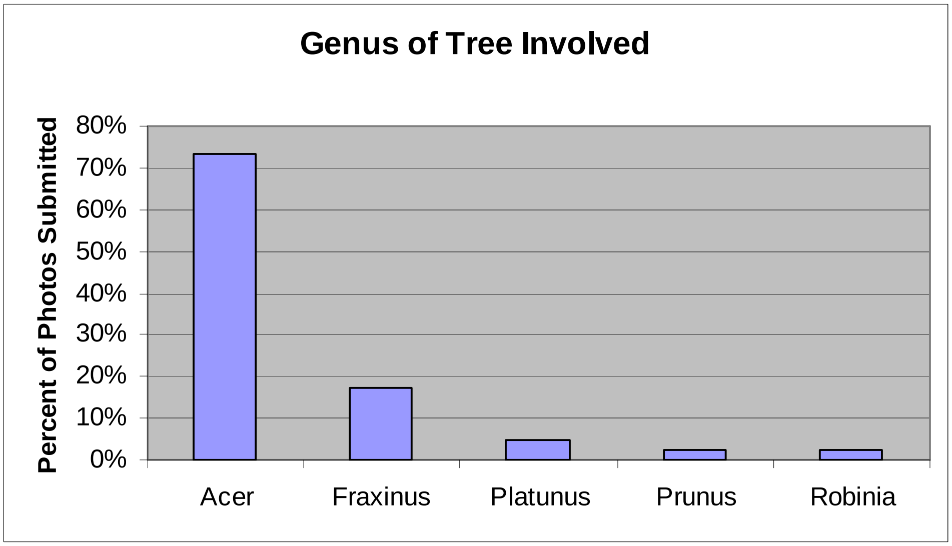

Figure 3. Frequency of occurrence of genera in post-interruption photos. Maples (genus *Acer*) were over-represented in the photos submitted for analysis.

Species of maples (genus *Acer*) were found to be clearly dominant within this limited sample. Over 80% of the photos subjected for detailed interpretation came from the Northeast USA. Other recent research undertaken by BioCompliance Consulting, Inc. in this region has found that maple species may represent more than 40% of the stems in the utility forest. In other words the number of photos involving maples was twice as great as the frequency of occurrence in the region.

Variation by Site Type

Figure 4 demonstrates that the majority of failures depicted in the photos involved trees in more formalized landscape settings where trees often occur as individuals. In this setting, trees typically exhibit full spreading crowns, and present a large sail area to intercept precipitation and storm winds.

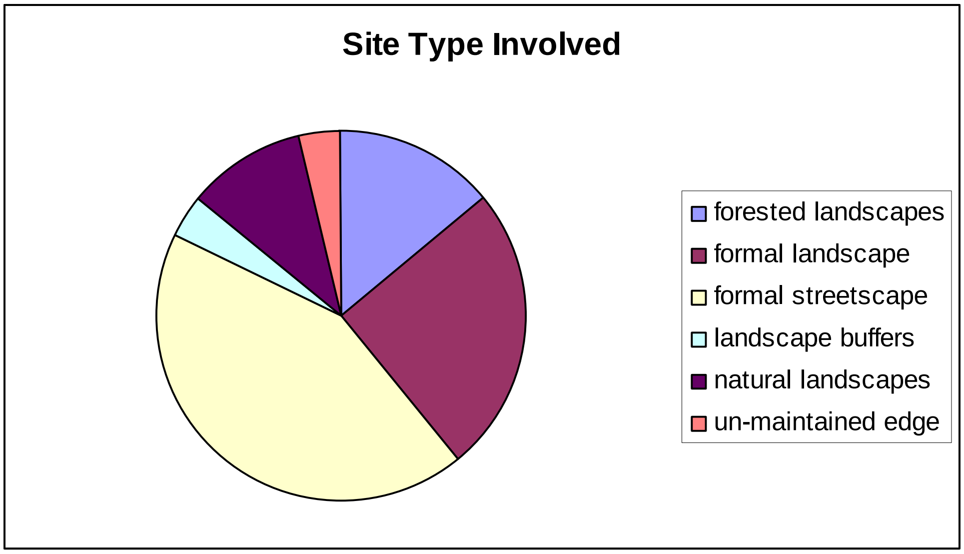

Figure 4. Frequency of occurrence of branch failures by site type in post-interruption photos. Trees in formal plantings (landscapes & streetscapes) were dominant.

Variation by Competitive Crown Position

Photo interpretation revealed differences due to crown type and position relative to neighboring trees. It is important to note that the definitions used in this criterion are based on those found in traditional forestry, and are used to define the competitive position of a tree's crown within the forest canopy. A co-dominant crown should not be confused with co-dominant stem architecture. It is also important to recall the aforementioned sampling bias. The photos that were submitted tended to feature extensive damage that would be expected to correlate with larger dominant stems.

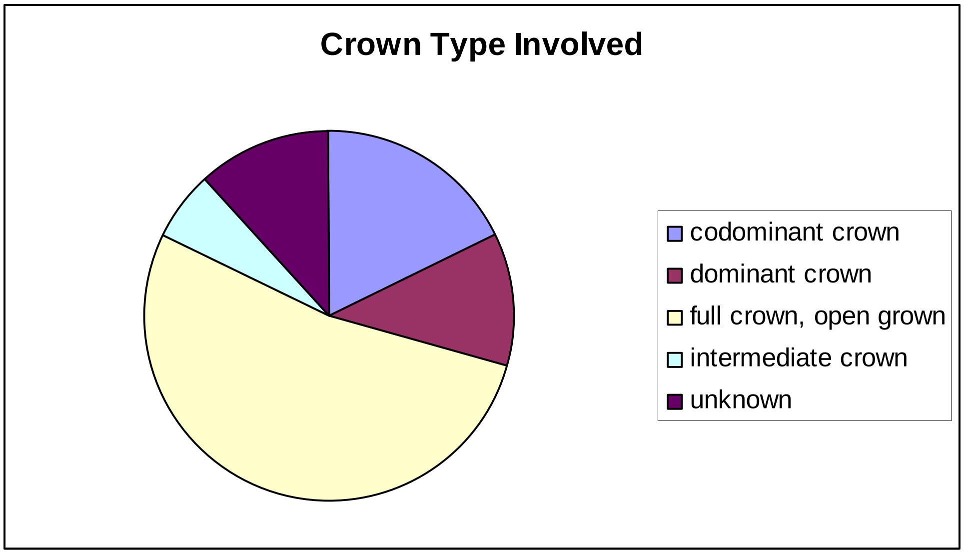

Figure 5. Competitive position of the crown of trees included in post-interruption branch failure photos. Many of the failure photos submitted by UAA members featured trees with large prominent crown forms (open grown and dominant).

Seasonal Variation

Approximately 75% of the photos received depicted branch failures that had occurred during the growing season. This is consistent with findings[2] in the literature review that branch failures were three times as likely to occur during the growing season when deciduous trees are in full leaf.

Variation in Branch Orientation

Figure 6 presents findings from the photo interpretations that suggest that upswept and upright branches are more likely to fail and cause interruptions.

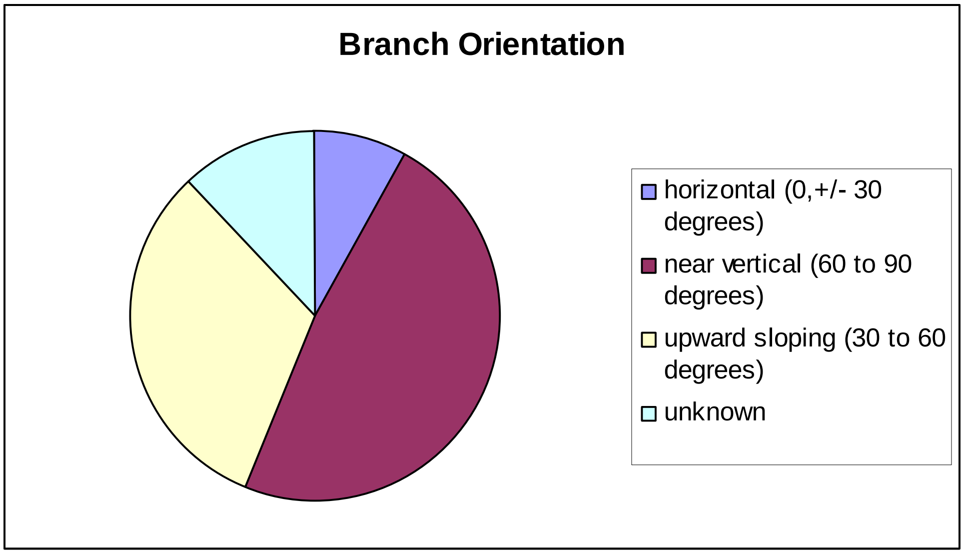

Figure 6. Apparent original orientation of failed branch depicted in post-interruption photos. Photos of upward and nearly vertical branches accounted for three of four post-interruption branch failure photos.

Location of Failure

Two-thirds of the branch failures recorded in the post-interruption photos that were reviewed in detail were found to occur within the first third of the length of the branch, as depicted in Figure 7.

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[2] Luley, et. al.

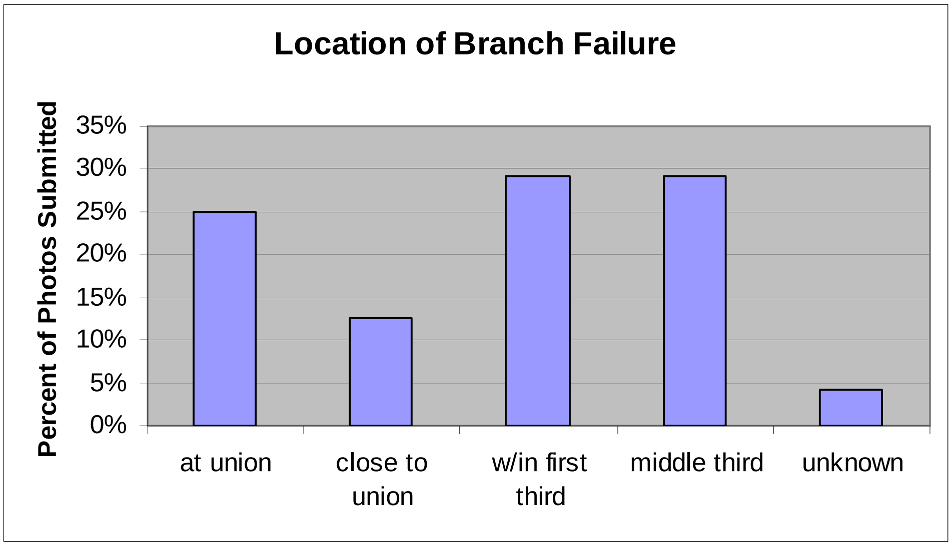

Figure 7 Location of the fracture location along the failed branch, as depicted in post-interruption photos. Nearly three-quarters of the branch failures occurred within the first third of the branch.

As previously stated, the intent of the photo interpretation exercise was to frame a wide range of potentially useful risk assessment criteria. Findings from this task were used to define expectations, and to develop and refine the investigative methods used in the field experiment involving static load testing of branches to failure.

Survey of Industry Experience with Branch Failures

The second phase of the qualitative investigation involved conducting an industry survey. A fifteen-question survey was designed using expert knowledge and findings from the literature review and photo-interpretation work previously discussed. The survey was sent to the approximately 2000 members of the UAA, and was conducted electronically over the Internet. One hundred sixty responses were recorded, resulting in a participation rate of ~8%. The purpose of the survey was to gain insight by tapping into the wealth of experience found among practicing utility arborists who deal after-the-fact with branch failures that have resulted in interruptions. As with the photo-interpretation task, the intent of this task was to further refine a list of potentially useful risk assessment criteria for testing in the quantitative experiment.

Survey Findings

The intent of the following sections of this report is to provide a high-level narrative summary of results from the survey of the UAA members. A copy of survey questions and results of this survey is included as Appendix B.

Effect of Prior Pruning

Survey respondents indicated that branches of trees that had been properly pruned using cuts placed at natural branch nodes were much less likely to fail than those that had been pruned using inter-nodal heading cuts (questions 1 and 13). This is consistent with findings[3] in the literature review. Respondents also indicated that the benefit of reduced risk of branch failure is relatively short-lived, and in the experience of respondents, is significantly diminished after two growing seasons (question 2).

Branch Form

Survey respondents indicated that in their experience smaller diameter branches are much less likely to fail, and that large co-dominant stems represented elevated risk. Branches with small diameters were reported to be low risk (question 14). Branches with diameters approaching that of the main stem were rated as higher risk (question 9). These statements[4] are consistent with findings from the literature review. Respondents also indicated that branch failures were more likely to occur in the zone from branch union with the main stem up to a distance of one-third the branch length (question 4).

Respondents noted an elevated risk of failure for branches in a upward sloping through nearly vertical orientation (question 5). The same trend is reported for branch angle of attachment at the union with the main stem, with a smaller angle (generally found in more upright branches), perceived as presenting an elevated risk of failure (question 10). Branches with either an upswept or downward drooping form were perceived as higher risk than branches that were generally straight (question 11). Similarly, branches with atypical form including sharp bends, twists, and defects were ranked as higher risk than

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[3] Dable et al

[4] Gilman

those that demonstrated a typical form for the species (question 12). The presence of defects was rated as particularly high risk.

Seasonal Variation

The survey results identified elevated risk of branch failure during the growing season. The risk of branch failure causing interruptions was lower in the dormant season (question 7). While this trend is consistent with findings[5] in both the literature review and photo-interpretation work associated with this project, it was not as strongly expressed by survey respondents than these other references would have suggested.

Crown Position

Edge trees were reported to present the greatest risk of branch failure (question 6). Not surprisingly, survey respondents indicated that branches in the mid and upper portion of the crown, adjacent and above conductors represented the greatest risk (question 8).

Wind Speed

The force created by wind acting on an object is known to increase by the square of its velocity. As such, the forces increase dramatically with increasing wind speeds. Survey respondents confirmed a marked increase in branch failures at wind speeds in excess of 50 mph (question 15). This is consistent with observations reported[6] in the literature.

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[5] Luley, et. al.
[6] Ibid

Static Testing of Branches in the Field

Static load testing of branches to the point of failure was conducted in an effort to gather empirical data on branch failures under simulated precipitation events such as wet snow or ice loading conditions. These can be thought of as unidirectional gravitational loads. The dynamic loads that are created under high wind conditions are more complex, varying in direction and magnitude, and create additional torsional stresses. It was not practical to simulate the complexity of dynamic wind loading in the field experiment, and as such wind loads were not directly considered in this project. However, while not a direct surrogate for wind loading, it is believed that static testing does provide useful information on the relative risks of branch failure under wind loading conditions.

Failure modes of interest

The failures modes of interest are defined in terms of their potential impact on the reliability of an overhead electric distribution system. In this case the electric conductors are the “target”, and the potential for an interruption is the risk of concern.

Table 2. Branch failure modes with the potential to result in an interruption.

Type of Failure	Failure Mode	Risk Implications
Temporary Branch Deflection	Branch returns to original position when the load is removed.	Risk of electrical fault on 3Ø lines if branch provides fault pathway between energized phases. Transient condition.
Permanent Branch Deflection	Branch suffers primary compression yield failure, and does not return to original position when load is removed.	Risk of electrical fault on 3Ø lines if branch provides fault pathway between energized phases.
Branch Fracture, Hinge Break, Branch Retained	Branch suffers secondary tension fracture, but remains attached.	Risk of electrical fault, as well as mechanical damage with larger branches.
Branch Fracture, Falls Clear	Branch suffers secondary tension fracture, and tears away and falls clear.	Risk of electrical fault, as well as mechanical damage with larger branches.

The areas of risk for three of the failure types occur within the arc of branch sweep as it moves from its normal position through deflection, failure and retention. The area of risk associated with the fourth failure type involving a branch failing and falling away is larger and includes any conductors in the potential fall zone.

All four failure modes present a potential risk of causing an electrical fault, as can be seen in Table 2 above. The potential risk is created by the possibility that the failed branch would provide a short circuit fault pathway between areas of unequal electrical potential (voltage). The greatest risk occurs in areas of high voltage stress gradient such as between energized phases of a multi-phase line. Risk can also be present between an energized phase and system neutral.

Branch failures that have the potential to create continuous contact with conductors present higher risk. Permanent branch deflection and the two types of failure involving branch fracture have the potential to result in continuous contacts. The elevated risk associate with continuous contact is due to the high initial impedance of the fault pathway provided by the branch between areas of differing voltage. At typical distribution system voltages a tree-initiated fault is unlikely to occur immediately. The initial low level of fault current first dries, and then creates a carbon track across the surface of the branch. Once established, the carbon path provides a conductive low-impedance pathway and a high current fault occurs. Continuous contact allows the alteration of the branch creating a conductive fault pathway.

The risk that the failed branch contains enough kinetic energy to cause structural damage to energy deliver infrastructure is more likely to occur due to failure of larger branches, and for failures where the failed branch tears away and falls clear.

Test Site

The field investigation was conducted during the week of October 27 – 31, 2008. Most of the test trees were entering the period of seasonal leaf senescence and abscission, and were exhibiting autumn coloration. The test location was the Davey Tree Company's research arboretum in Shalersville, Portage County, Ohio. 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 were anticipated. This presented the project with a population of trees scheduled for removal that were available for destructive testing.

Figure 8. Site of static testing work, Davey research arboretum, Shalersville, OH.

The trees selected for static testing typically were edge trees that occurred along an access road or border between planting blocks. As such they are similar to edge trees found along maintained utility rights-of-way.

Species Tested

Six species of tree were selected for testing based on their occurrence on utility rights-of-way in the Northeastern United States, and their availability at the Shalersville research arboretum. The species tested are presented below in Table 3.

Table 3. Species of trees used in static load testing.

Common Name	Botanical Name	Static tests completed
Norway maple	*Acer platanoides*	13
Red maple	*Acer rubrum*	13
Silver maple	*Acer saccharinum*	15
Sugar maple	*Acer saccharum*	9
Eastern white pine	*Pinus strobus*	10
Northern red oak	*Quercus rubra*	4

Static Testing Methods

The experimental protocol used in the static load test phase of this research project made use of concepts found in the European Statics Integrated Methods[7] (SIM) testing methodology. Similar equipment and instrumentation was used, and several of the research team members had direct experience with SIM. The SIM method is used to evaluate the structural integrity of large legacy trees, and involves the application of nondestructive static loads.

The method used in this research project differed from SIM in that it involved destructive testing by intentionally overloading branches to the point of failure. The test is conceptually described as application of a vertical load to a branch at its approximate center of gravity. The load was increased incrementally and measures of load and deflection were recorded to the point at which the branch failed. Deflection and loading data were gathered as the load on the branch was increased until the point of failure.

Selection and Preparation of Branches

Branches were selected based on species of interest and whether there form was representative of edge trees found adjacent to utility lines. Individual branches were representative of those that, should they fail, could result in an interruption on the electric distribution system. The small and medium branches tested ranged from approximately 2-8cm (1-4 inches) in diameter beyond the union with the main stem.

Once selected, each individual branch was prepared for testing. This included estimating the approximate center of gravity, which was used as the point at which the static load was applied. Measures of the physical dimensions and orientation of the branch and main stem were recorded as well as any apparent defect.
Measures included:

- Angle of branch attachment

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[7] Brundi and van Wassenaer.

- Horizontal distance from main stem to load point (estimated center of gravity)
- Diameter of main stem – immediately above branch union
- Diameter of branch – immediate beyond branch collar
- Branch orientation (degrees from horizontal)
- Branch order defined by hierarchy within the crown.
- Evidence of visually observable defect

Static Load Testing

A pulling bridle was attached to the branch at its approximate center of gravity. A load line was attached and run vertically down below the point of attachment. A load cell was placed in the pulling line in a position that allowed access for reading applied tensions. Both electronic dynomometers and mechanical tensiometers were used, based on the magnitude of the force being applied. The load line continued vertically down to ground level, through a turning block and then horizontally to a mechanical winch.

The mechanical winch was used to draw in the pulling line, applying a vertical downward force. Measures of the force being applied and the distance of deflection expressed as the amount of pulling line recovered were recorded periodically. The force applied to the branch was increased incrementally by manual operation of the winch to the point of branch failure.

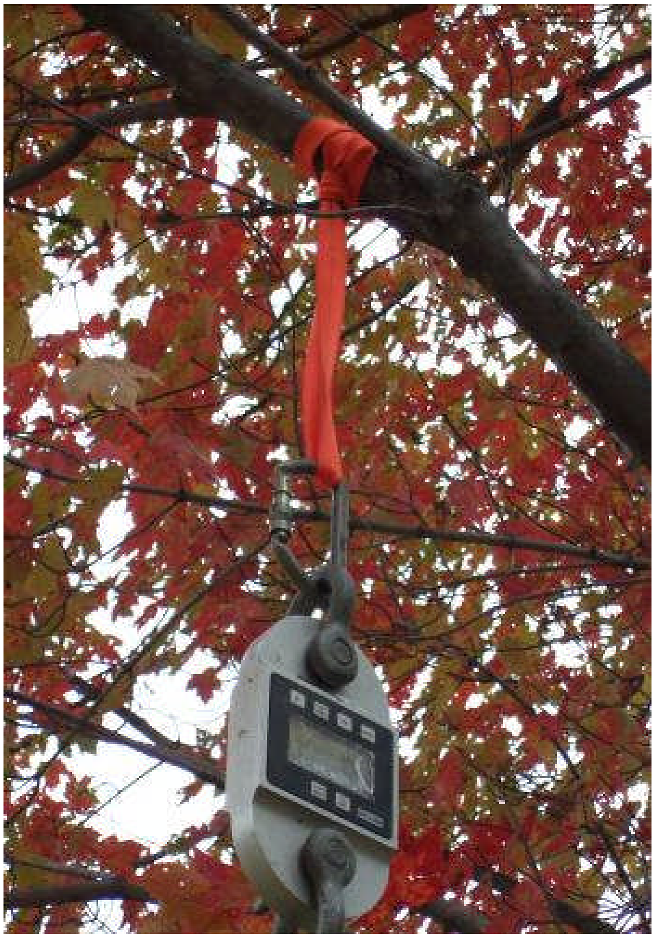

Figure 9. Pulling bridle and load cell in place on test branch.

Evaluation of Failed Branches

Characteristics of each failed branch were recorded. The distance from main stem to the point of failure was recorded. A photographic record was created and the branch was pruned from the main stem.

Several additional measurements of the failed branch were made once on the ground. These included:

- The overall length of the branch
- Distance along the branch to the point of load (estimated center of gravity)

- Distance along the branch to the actual center of gravity
- Measures of branch diameter in horizontal and vertical planes at incremental distances from union to load point
- Weight of the branch
- A close inspection of the fracture areas for evidence of external and internal defects

A small portion of the failed branch was cut from the branch and weighed green. These samples were then kiln dried and reweighed, and the percent moisture at the time of testing was calculated.

Figure 10. Examples of stem dissection in the failure zone. Evidence of fracture can be seen as wood fibers were torn in the upper portion of the branch's cross-section.

The area of fracture of each the failed branches was severed and reviewed in greater detail in the lab. A qualitative assessment of each specimen was conducted and a photographic record created. The close inspection of each fracture provided insight into the failure mechanism and aided in interpretation of the static test data.

Limitations of the Experimental Method

Several limitations were identified during the course of the fieldwork and subsequently during the data analysis. None are considered to be serious flaws, but they should be recognized and acknowledged:

- When branch and stem orientation were measured prior to attaching the load line, initial measures of tensions and deflection included the added weight of the pulling line and load cell preloading the branch. This effect was most pronounced with the smallest branches.
- The extreme deflections created by loading small branches created difficulty in applying a vertical force. As the branches deflected, the point of attachment moved inward toward the main stem. The turning block was readjusted in an effort to keep the load line in vertical orientation directly below the point of attachment. It is also worth noting that the literature had identified a related limitation, as one author advised that a simple static loading model using a single point of contact tends to break down with branch deflections greater than 25 degrees[8].
- Some error was likely introduced due to inconsistency in the data being recorded in the field. Minor changes were made to the field data sheet based on direct experience during the first day of work. Use of two teams working concurrently resulted in some inconsistencies. Some data omissions were noted between the field records completed by both teams as the data were analyzed. However, these were considered to be relatively minor concerns.

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[8] Morgan et al.

Basic Mechanical Principle of Branch Failure

Basic principles of mechanical engineering were applied in designing the static load testing protocol and in the analysis of data. It should also be noted that the project was designed and conducted as applied, rather than basic research. An effort was therefore made to simplify analysis with a bias to the development of findings that could be readily applied by practicing utility arborists.

The mechanical engineering construct referred to as the “Statics Triangle” is useful in introducing the variables of interest in considering the risk of branch failure. Simply stated, the resistance of the branch to failure, or conversely its risk of failure, is due to the interplay of three factors: the material properties of branch, the load being applied, and branch geometry.

The material of concern is the woody tissue of the branch and the properties of primary concern are its resistance to failure in both compression and tension. The strength of wood is known to vary between species. Branches of six different species were included in this investigation. Stratifying the data set by species controlled for the material variable. As noted in the literature review, the strength of branches can vary significantly within an individual tree, depending on a number of factors[9]. An effort was made to select branches for testing within the crown of individual test trees that would be in a position to be in conflict with an overhead distribution conductor, had one been present on site.

The static test itself involved incrementally increasing branch loading in a controlled manner. This was the determinant variable in the testing.

The variable of greatest interest to this project is that of branch (and stem) geometry. As defined here, the geometry of the branch included a variety of characteristics including angles, lengths, and diameters, as they are potential indictors of relative risk. A wide range of measures of branch and stem geometries were recorded. The various characteristics of branch geometry represent the major potential risk assessment criteria that were evaluated in this project.

Properties of the Branch

In simple terms, the physical form of a tree branch can be thought of as a tapered beam. It is light in weight, and relatively rigid yet flexible. At steady state the branch is at equilibrium, having grown in such a way that it can be considered as ‘pre-stressed’. The upward supporting forces are in equilibrium with the downward force of gravity.

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[9] Morgan (4), Gilman (9), Niklas (17), Wessoly (21, 22)

From a mechanical engineering standpoint, the branch is a cantilever beam, fixed at one end to the main stem. Tissue on the upper side of branch is subject to tensile stress[10], and is under strain[11] tension (elongation). Tissue on the underside of the branch experiences compressive stress forces and the material is shortening due to compressive strain. An engineered cantilever beam is designed to distribute these forces effectively along its length. Stress is critical in sustaining loads, just as deflection is positive in relieving loads. Both reactions have the same significance with regard to load-bearing capacity.

The distribution of stress and the resulting strain are perpendicular to the surface of the branch, and are greatest at the outer surface. Within the branch they diminish to a neutral axis at or near the branch center, where they are zero.

Branches, of course, are not uniformly manufactured beams. They contain a variety of tissue types and typically include irregularities such as rapid changes in diameter, crooks and bends, and defects. Irregularities along the branch cause a localized increase in stress (force). These irregularities act as stress force concentrators. The elevated stress gradients associated with irregularities can be much higher than those distributed along the remaining portions of the branch.

The flexibility of the branch is an important consideration. Flexibility is a measure of deflection as force is applied. It is proportional to load being applied. Within the range of elasticity, a branch returns to its original position when load is removed. Flexibility is affected both by size and geometry of the branch, and the material properties of the branch tissue. Any area that is elastically different from the rest of the branch will create a stress concentration.

> *"Anything which is, so to speak, elastically out of step with the rest of the structure will cause a stress concentration and may therefore be dangerous"*[12]

Finally, it is very important to note that woody tissue is weaker in compression than in tension. The same force that results in the crushing of fibers in compression will not damage fibers in tension.

Conceptual Model of the Mechanics of Branch Failure

Observations made during the static load to failure testing supported the development of a conceptual model of branch failure. The three stages of branch failure are:

- ***Deflection:*** During the initial phase, the branch is able to resist structural failure by deflection. The degree of deflection is proportional to the load being added.

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[10] Stress is a measure of the forces at work within the branch, either placing the wood fibers under tension or compression.

[11] Strain is a measure of deformation resulting from these forces, either lengthen or compressing the wood fibers.

[12] Gordon, J.E., 1978, *"Structures, Or Why Things Don't Fall* Down". Page 69, Da Capo Press. London.

This initial phase can be though of as a period of elasticity. If the load is removed, the branch recovers to its original position.

- ***Primary Yield Failure in Compression:*** Primary failure occurs when the woody tissue on the concave underside of the branch is crushed in compression. The compression failure begins as fiber buckling in the outermost annual rings. External evidence of the crushed tissue includes the formation of ridges or compression creases on the underside of the branch. The branch remains attached, and a small tear on the topside of the branch may be visible. The branch's ability to resist additional loading is altered and is typically diminished. When the load is removed the branch will not return to its original position. Once the fibers buckle they have very little tensile strength, and they represent an elevated risk of failure if load is applied in another direction.

- ***Secondary (or Ultimate) Fracture Failure in Tension:*** The second stage of the branch failure occurs when the fibers in woody tissue on the convex upper side of the branch tear in tension. This typically occurs on the upper surface of the branch above the area of compression failure. Secondary failure of fibers in tension results in a visible fracture.

Figure 11. A failed silver maple branch following static load test. Note the compression bands on the underside of the branch, and the torn wood fibers on the upper surface in the fracture zone.

Following fracture, the broken portion of the branch may fall clear or may remain attached to the remaining portion of branch and stem as shown in Figure 11.

Figure 12 depicts the failure process in terms of the deflection due to loading. Initially the branch resists failure by flexing. As load increases the branch deflects. If the load is removed from the branch during this period of elasticity it will return to its original position. The point of yield is reached when the forces of stress due to loading exceed the ability of the branch to adjust by flexing. This is can be see in Figure 12 at the point where the branch loses much of its ability to resist and the rate of deflection increases. As the load continues to increase, the stress of tension in the upper portions of the branch exceeds the strength of the wood fibers and the fibers tear. The graph ends at the point of fracture.

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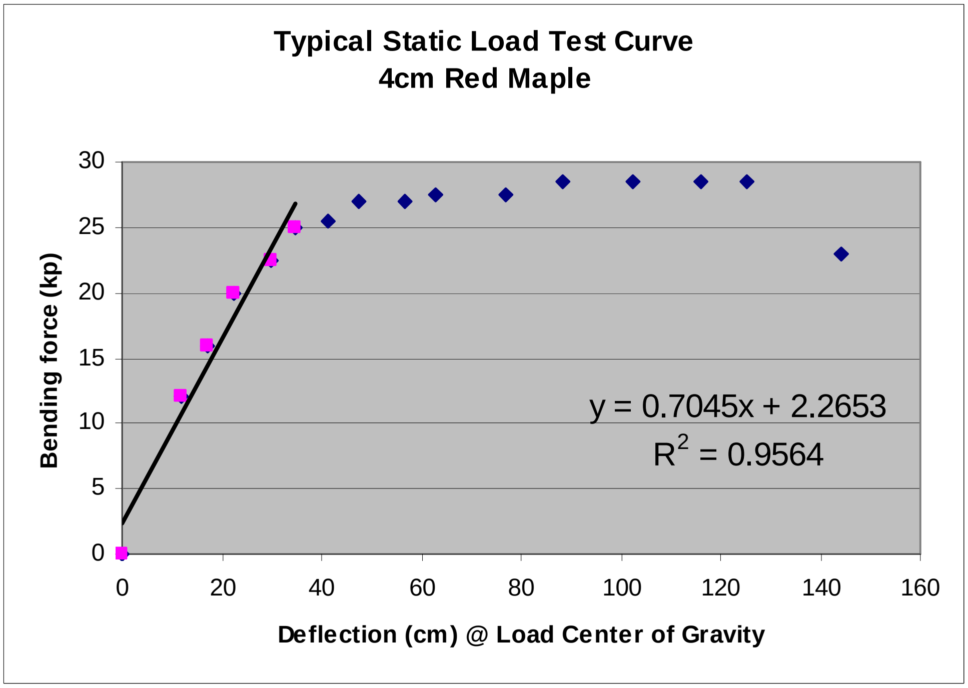

Figure 12. Reaction of a red maple branch to applied load. The solid line depicts elastic deflection. Compression yield occurred at the upper end of the line. Tension fracture occurred after the last observation.

Evidence of the failure process can also be seen on close inspection of the branch in cross section of the failed branch, as shown in Figure 13 below. It is also readily apparent in Figure 10 showing dissection of a failed branch.

Figure 13. Cross section of failed red maple branch. Wood-staining fungi have colonized the area of crushed cells on the lower portion of the branch, discoloring the area of compression failure. The area of torn fibers is also evident in the upper portion of the branch.

The failure process observed in Eastern white pine is similar to that observed in the deciduous trees that were tested, with one important exception. Reaction wood in conifers occurs as compression wood. Compression wood is reported to be 50% stronger than other wood in conifer branches. The compressive stress appeared to result in cracking on the undersurface of the branch (Figure 14). This crack temporarily relieves stress.

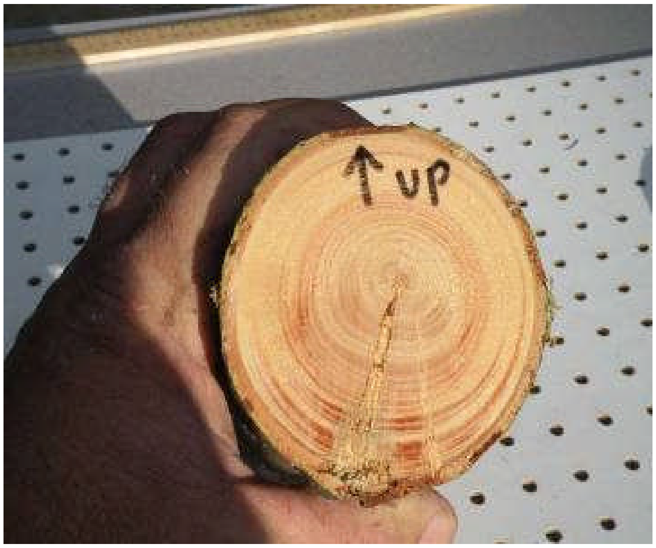

Figure 14. Cross section of failed Eastern white pine branch showing compression crack on the underside of the failed branch section.

As load increases, further failure in tension occurs, often resulting in a wedge of wood being forces out of the break from the underside of the branch, as can be seen in the photo in Figure 15.

Figure 15. Underside of failed Eastern white pine branch with compression wedge evident.

In order for the failure process to proceed in the case of either deciduous or coniferous branches, the stored energy in the deflected branch must be great enough to be converted to fracture energy. The likelihood that a fracture occurs is largely influenced by the presence and location of the worst areas of stress concentration. This may be associated with irregularities in branch form such as pre-existing cracks, holes, sharp bends, and rapid changes in diameter.

Analysis and Discussion

The purpose of this research project was to establish a basis for understanding branch failures. Once characterized, the intent was to identify critical characteristics that could be used to develop risk assessment criteria and risk mitigation strategies that would aid the practicing utility arborist in reducing the risk of branch failure resulting in interruptions to electric service.

The project began with a broad list of potential risk assessment criteria, described in Table 1. These were initially developed by the research team and refined based on findings from the literature review, photo-interpretation, and industry survey phases of this project.

The field experiment involving the static load testing of branches to the point of failure was carried out over the course of five days. This enabled the research team to make a number of general qualitative observations that proved to be useful in analyzing the data. Data gathered in the static testing phase of the project were used to test the utility of the refined and shortened list of potential risk assessment criteria.

Critical Zone of Failure

Very few branches failed at the union with the main stem. Failures typically occurred beyond any area of swelling associate with the union with main stem or larger branch, out to a distance of approximately ten percent of the total length of the failed branch.

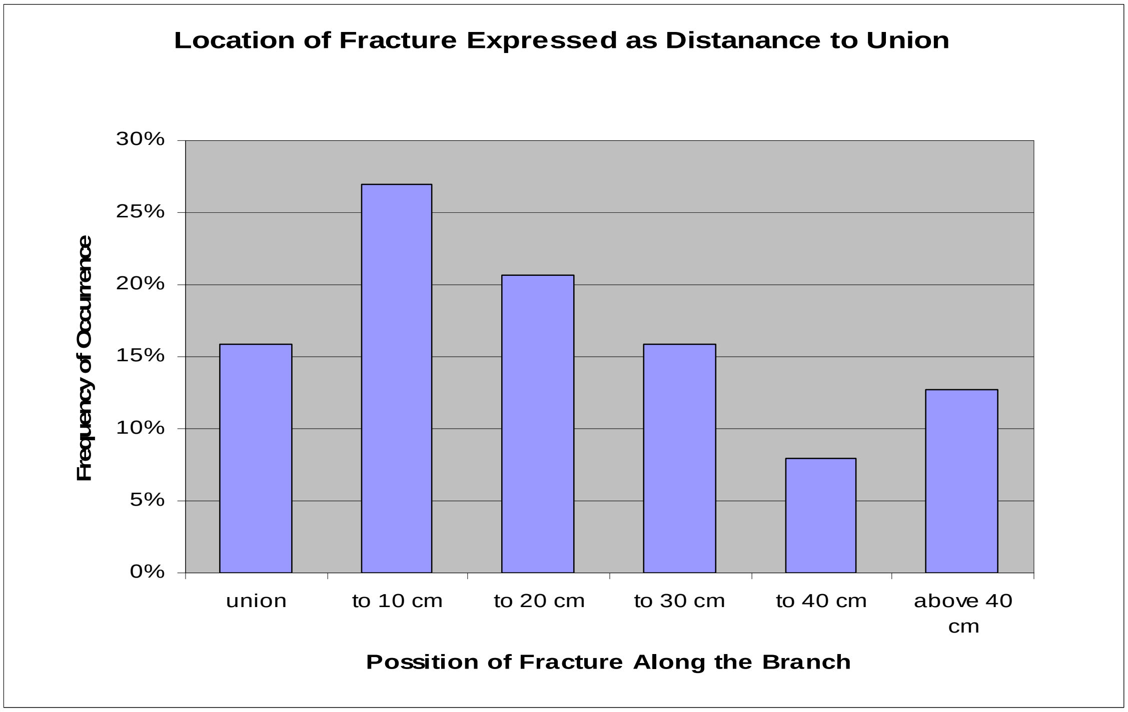

Figure 16. Location of fracture as measured from union with main stem. More than three quarters of the failures occurred within 30cm (≈12 inches) of the main stem.

Figure 17. The typical location of branch failure was beyond, but close to the branch union with the main stem.

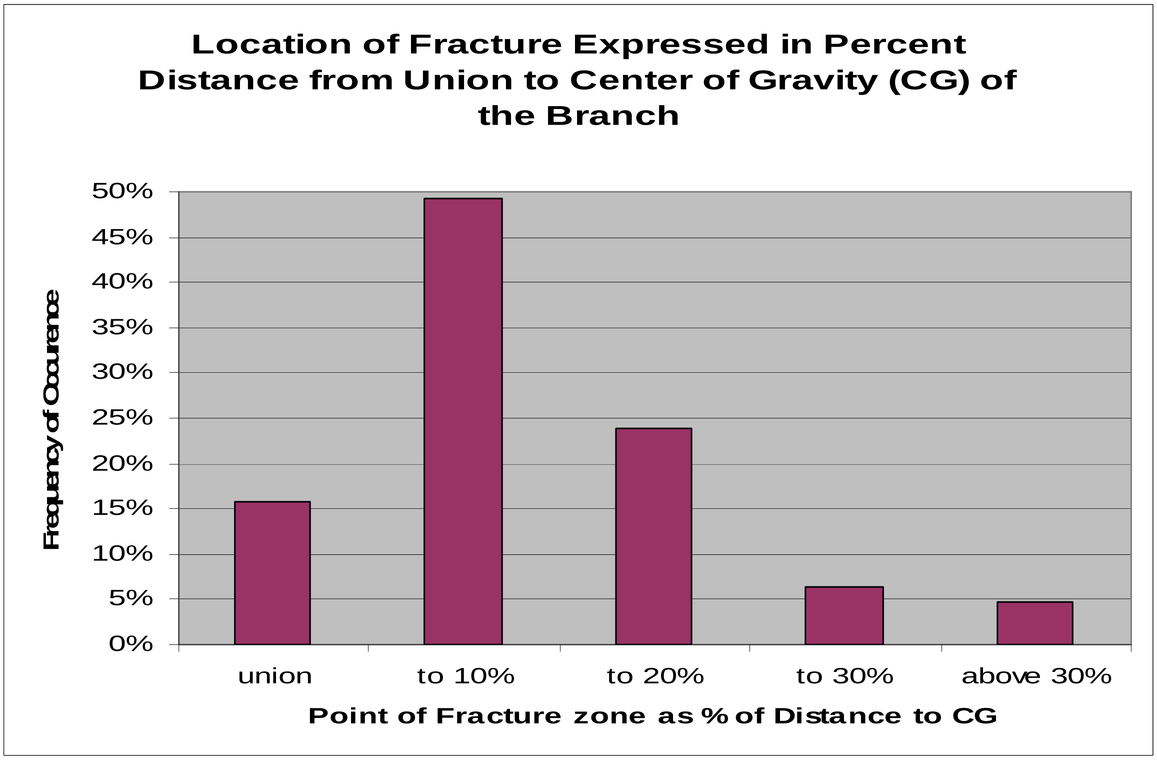

Figure 18. Location of branch fracture expressed as percentage of the distance from union with main stem to the CG of the branch. The CG or balance point of a branch is typically within the first half of the branch.

Traditionally, emphasis has been placed on a close inspection of the branch union with the main stem. A simplified model of the branch would describe it as a flexible member attached at one end to a ridged, unmoving structure. In this simple model, forces are assumed to be distributed along the branch as it flexes until the connection to the main stem, which is fixed. This condition would create a localized concentration of stress. But in fact the main stem also flexes, acting to disperse and redistribute the forces at work. Branch unions also tend to be buttressed, adding strength in the areas immediately adjacent to the union. Live branches in the size range tested (2-8cm) are rarely sheared off at the main stem. This finding is in conflict with the results of the survey of UAA membership, where 75% of the respondents believed that branch failure was “more likely” and “much more likely” to occur at the union with the main stem.

While in most cases the branch union is not the “weak link”, there are notable exceptions. Larger co-dominant stems in upright orientation with included bark comprising the unions are well known to create hazardous conditions. Additionally, dead branches may be shed at the union as the living stem tissues compartmentalize the dead and decaying branch tissue at the point of union.

Elastic Durability of Small Branches

Small branches were found to be much more flexible that larger branch specimens. They were able to sustain a very high degree of deflection. This was true both in the range of elasticity, and as they experienced yield failure due to compression. This is likely due to several factors.

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 a great deal of the flexibility of smaller branches and their ability to deflect to the extreme. Smaller diameter structural members are able to deflect to a much greater degree before material in the concave portion of the bend experiences a yield failure in compression as depicted in Figure 19.

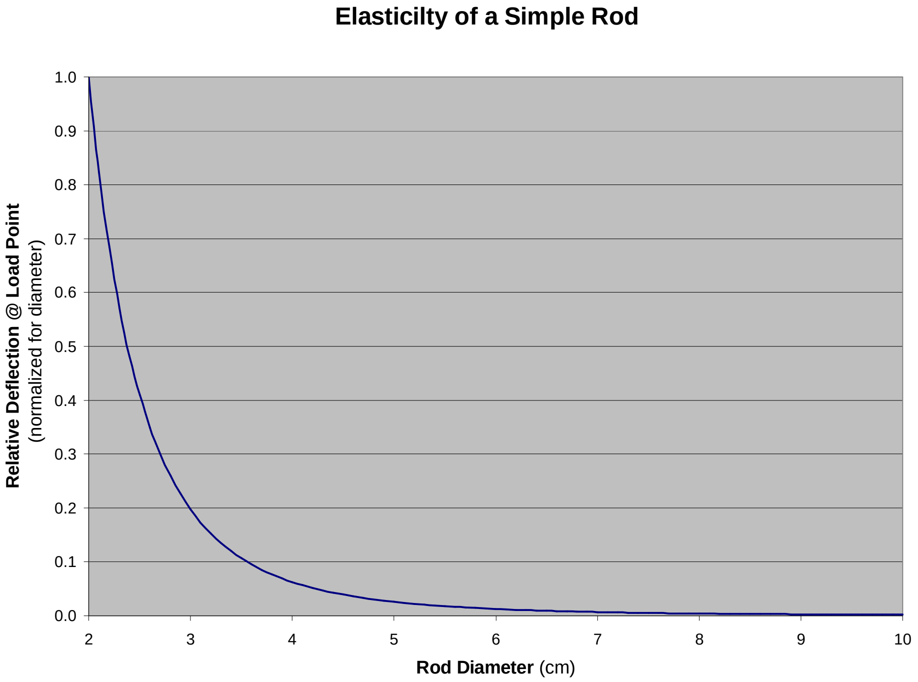

Figure 19. Theoretical range of relative flexibility of a rod of between 2-8cm in diameter, as determined by mechanical engineering formula.

The interaction between compressive stress and tensile stress on opposite sides of a rod causes resistance to bending. Between the two extremes is a transition zone where compression changes into tension – the so-called "neutral plane". If the rod diameter is small, the distance between the two areas of stress is short. The mechanical metric for the distribution of forces within a cross section is called the *moment of inertia*. It describes the capability of a cross section to resist deformation. The greater the distance to the neutral plane, the greater the resistance. Because both the cross sectional area and the distance to the neutral plane play an important role, the *moment of inertia* is expressed as cm^4. Expressed another way, it is a quadratic function, and it works with the fourth power of the diameter. For a round-shaped rod, the moment of inertia is defined as

$$diameter^{4} * \pi / 64$$

That is, in essence, why doubling the diameter increases the resistance to deflection by a factor of 16 (e.g., $2^4 = 16$).

The same mechanical engineering analysis was applied to an assessment of conceptual branches. Using data from the population of test branches, two additional factors were incorporated into the analysis. First, the effect of increasing dead weight as branch diameter increases was considered. Second, the change in the horizontal distance from load point to union (lever arm) at various levels of deflection was factored in to the analysis. The result of this analysis appear in Figure 20.

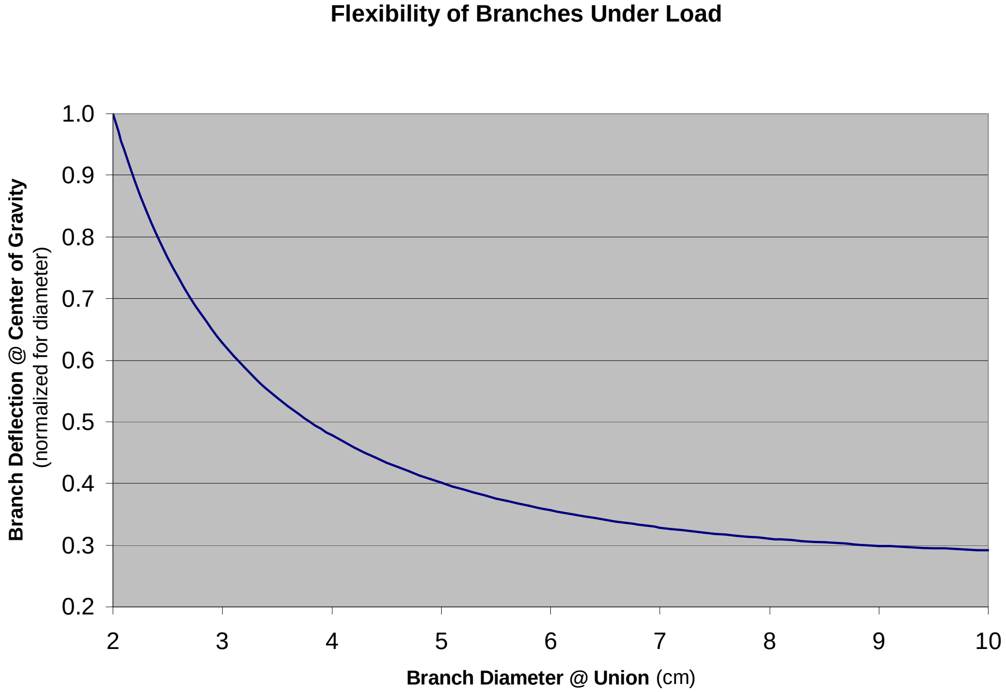

Figure 20. Projected change in branch elasticity based on application of mechanical engineering principles. Results adjusted for changes in branch mass with diameter, and changing length of lever arm.

Clearly, the mechanical engineering approach to analysis explains a great deal of the high level of elasticity observes in small branches.

Another reason why smaller branches demonstrate high elasticity is because they are composed of a higher percentage of flexible plant tissues and consequently have a higher stress capability than larger branches[13].

Finally, the orientation of force vectors account for some of the resistance of small branches to fracture. This relates to the geometry of the branch and direction of the static load change, especially in branches in extreme deflection. As the branch deflects, it is pulled into approximate alignment with the static load being applied. This results in a higher percentage of the tensile force being applied in alignment with the wood fibers in the branch cross-section. More fibers in tension mean more strength (in tension). This effect can be seen in Figure 21.

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[13] Niklas

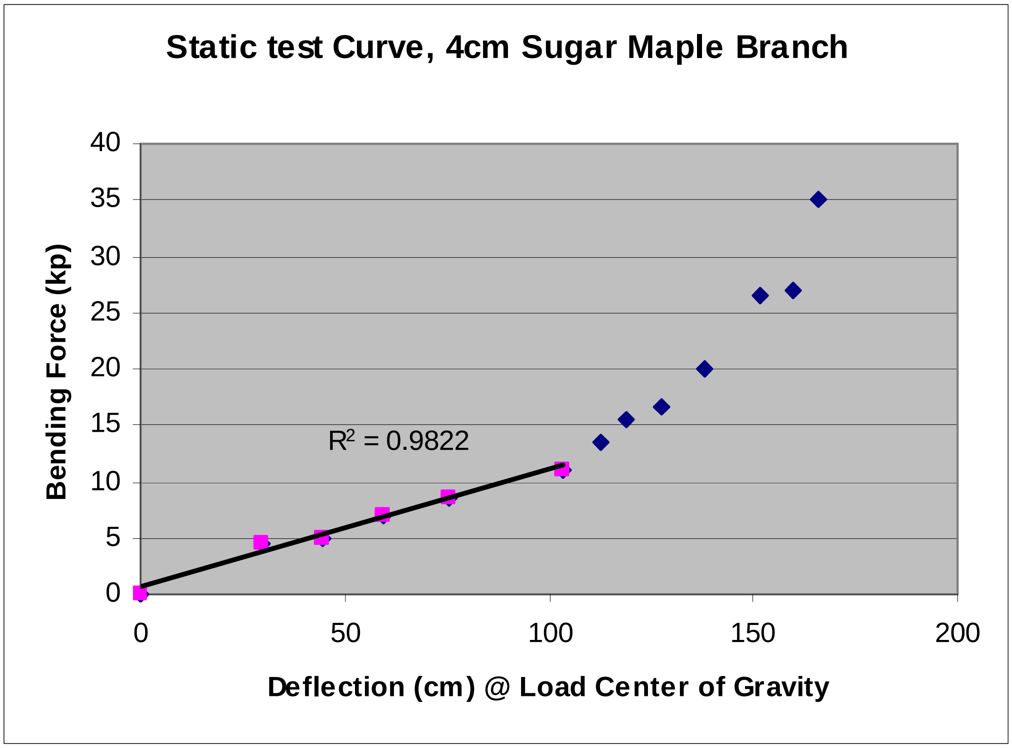

Figure 21. A reduction in rate of deflection loading following Primary Yield Failure in Compression is evident in the trajectory of the blue points. The amount of force required to cause additional deflection increases.

The figure pattern shown in Figure 21 is typical of many of the force vs. deflection graphs for small diameter branches. The depressed slope of the elasticity line indicates a high rate of deflection. The steepening slope of the curve after the yield point is reached indicates increasing resistance to further deflection, as the force applied is becoming aligned with the axis of the branch.

As previously noted, wood is stronger in tension than in compression. This effect was most pronounced in small sugar maple branches.

The net result of these factors explains the high degree of elasticity of small diameter branches.

Branch Safety Factor Defined

The concept of a branch Safety Factor was used extensively in the analysis of static testing data. The ratio of the maximum sustainable load-generated force to the steady state load force describes the safety factor of the branch. The safety factor of trees is generally reported to be in the range of 2.5-3:1[14] and 4:1[15].

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[14] Gilman (10)

15Niklas, K.J., 1992, “Plant Biomechanics, An Engineering Approach to Plant Form and Function”, Page 63. University of Chicago Press, Chicago.

This report makes use of two levels of branch Safety Factors, defined in terms of yield and fracture.

Safety Factor (yield)

A branch at rest experiences a downward force equal to its mass. As previously described, the branch deflects in response to additional load. At some point the branch will experience an initial yield failure due to the compressive stress. The Safety Factor defined by yield is the upper limit of the range of elasticity, above which it sustains primary yield failure in compression. In other words, the Safety Factor (yield) describes how much load a tree or branch can safely carry and from which it can recover.

Safety Factor (fracture)

As load increases beyond the point of yield, the forces on the branch continue to increase. At some point load-generated forces exceed the ability of the wood fibers in tension to resist, and branch fracture occurs. The Safety Factor defined by fracture is the point above which load-generated forces result in final failure of the branch. That is, the Safety Factor (yield) describes how much load a tree or branch will support before the branch fails completely.

Effect of Diameter on Safety Factor

Safety Factors for individual branches were found to vary by branch size. Since Safety Factor is an expression of forces on the branch due to loading, the first approach to consider is branch weight. Figure 22 presents the results of analyses of the relationship between the branch weight and the calculated Safety Factor.

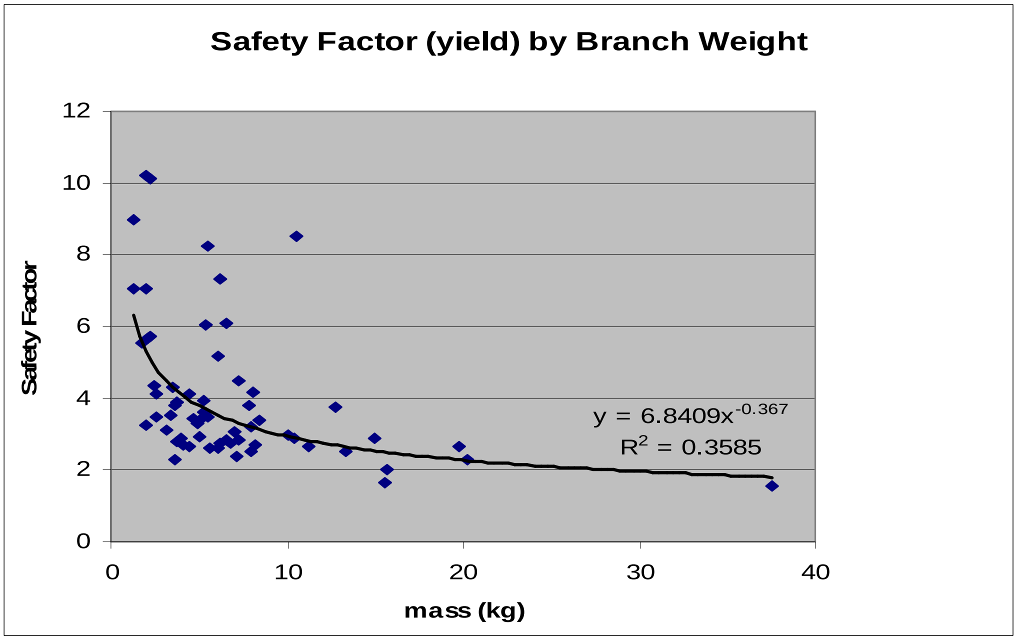

Figure 22. Safety Factor for compression yield resistance for branches expressed in terms of branch mass, for the range of branch sizes tested.

Branch weight is difficult to estimate in the field. Since the focus of this investigation was to test potentially useful risk assessment criteria, branch diameter was considered. It is reasonable to assume that there is an implied relationship between the weight and diameter of individual branches. Figure 23 presents the findings from the static test using branch diameter at the point of failure, rather than mass, on the x-axis.

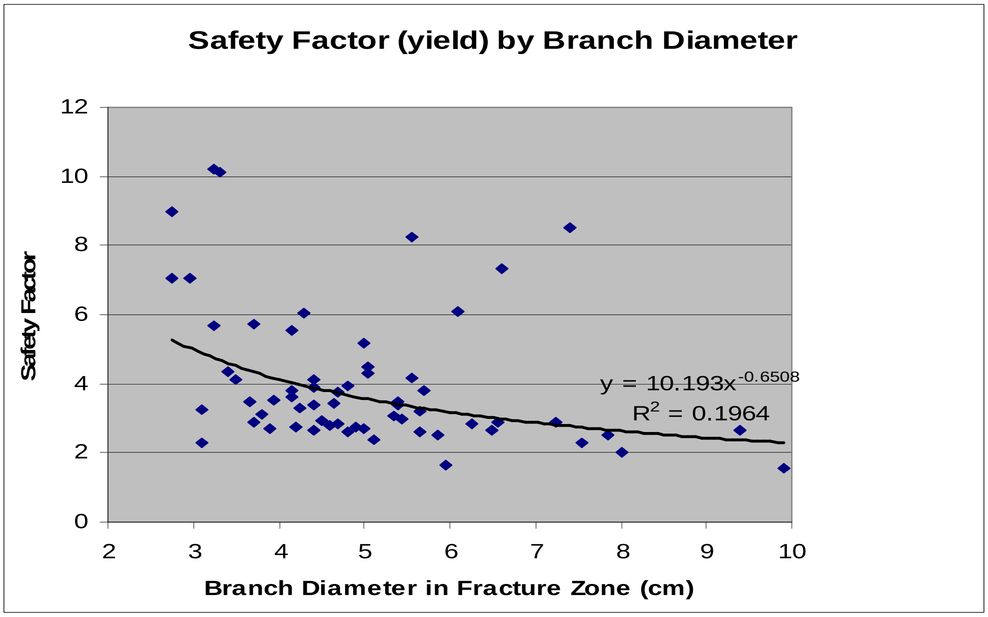

Figure 23. Safety Factor for compression yield resistance for branches expressed in terms of branch diameter at the point of fracture.

The results for diameter vs. Safety Factor are statistically weaker than for mass vs. Safety Factor, however both figures demonstrate that the safety factor of small branches tends to be much higher than that of larger branches.

Figures 22 and 23 made use of the Safety Factor in terms of resistance to primary failure in compression. However, the more operationally important consideration may be the Safety Factor for secondary fracture failure in tension. This is when the branch breaks and may fall into conductors.

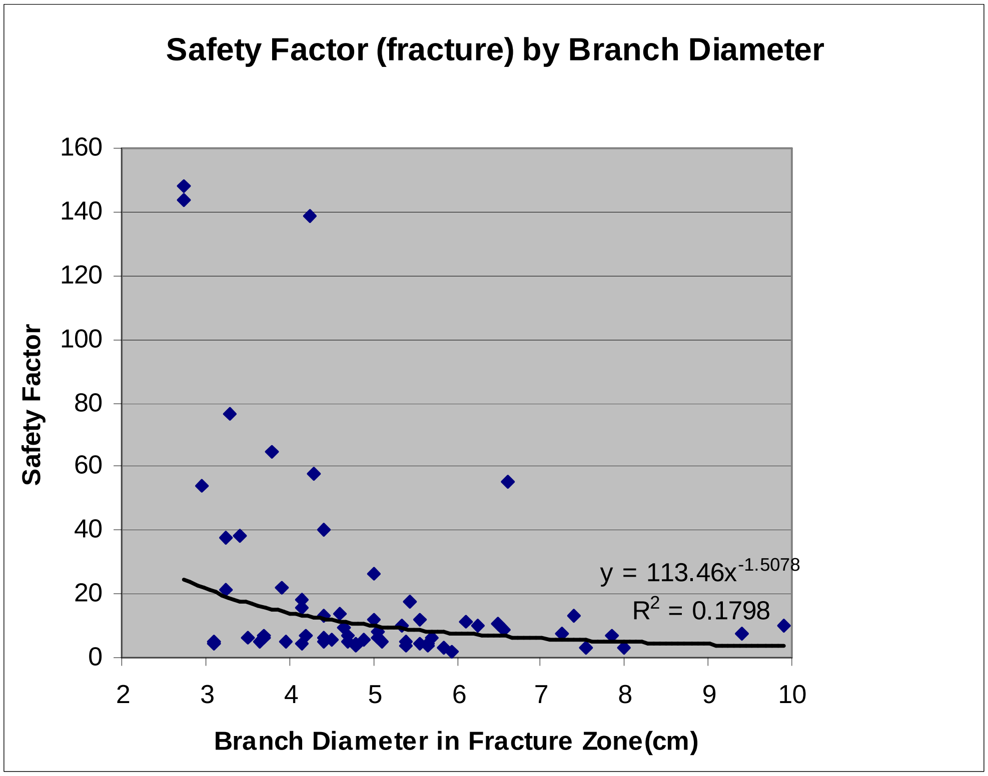

Figure 24. Relationship between branch diameter at the point of failure and Safety Factor defined as the point of tension fracture.

The relationship between branch size and resistance to structural failure is also evident when load at the point of secondary tension fracture is substituted in place of compression yield, as depicted in Figure 24. In this case, the resistance of small diameter branches to breaking, expressed in terms of Safety Factor at fracture, is much greater than that of larger branches. It is also higher than what has been reported for whole trees. In many cases the difference between the safety factors for fracture was an order of magnitude (10X) greater than the yield safety factor.

The elasticity of small branches and their resistance to fracture, as previously described, is clearly reflected in the high Safety Factor values observed in the population of test branches. Since Safety Factor is defined in terms of force, another factor related to geometry offers some additional explanation as to why the Safety Factor for fractures is much higher than that for yield. The horizontal length of the lever arm (perpendicular to the load) is effectively shortened under high deflection, reducing the rate of increase in force as load is applied.

The absolute (rather than relative) strength of branches should also be considered. The cross-sectional area of a round branch increases geometrically ($A= \pi r^2$) with diameter. The result is that the amount of branch tissues available to resist a static load increases much faster than branch diameter. The other consideration is the fact that the ratio of outer fleshy flexible tissue and bark to relatively ridged interior woody fibers is highest in small diameter branches. Considering these two factors together, it is clear that there is a much higher proportion of woody tissue available in larger diameter branches. As such, it is not surprising that the resistance to deflection in large diameter branches is higher than that of small branches.

When the elasticity of small diameters and the inherent strength of large branches are considered together, they describe what is commonly known as a “bathtub” curve, as depicted in Figure 25 below.

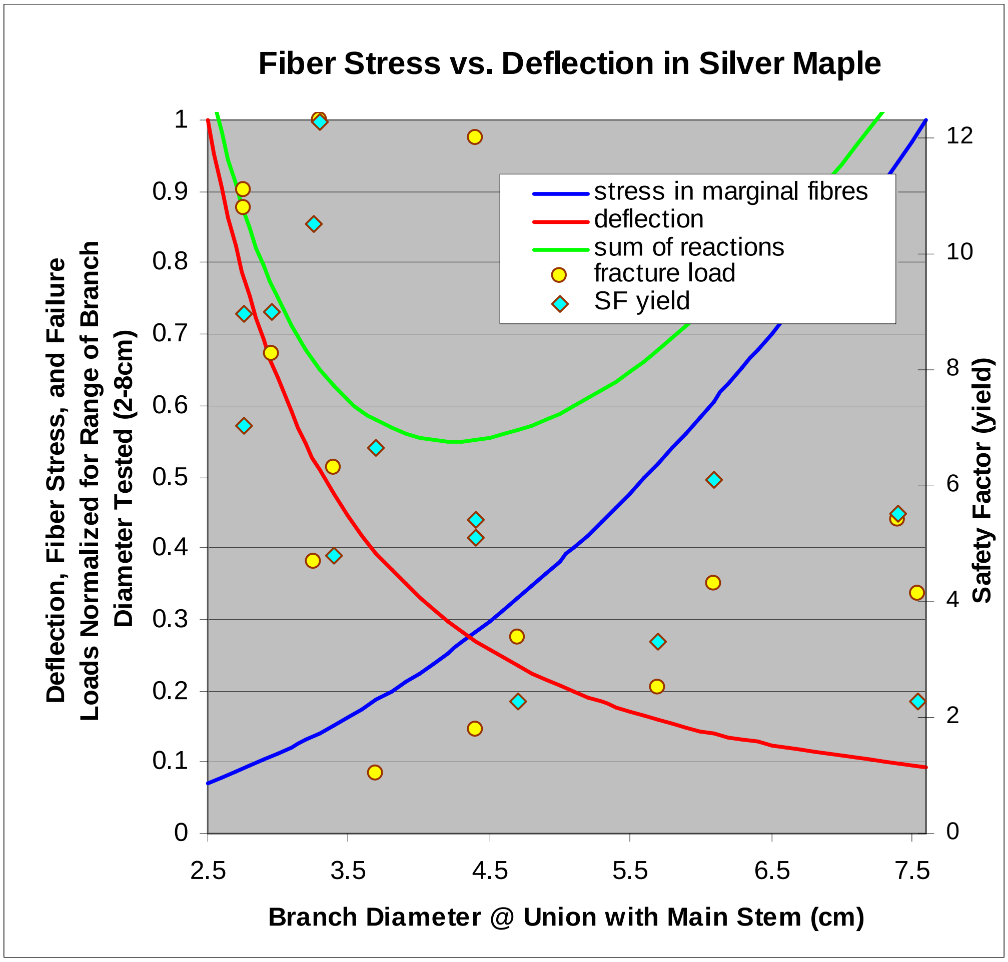

Figure 25. Comparison of elasticity vs. Safety Factors found in silver maple (*A. saccharinum)* over the range of branch diameters included in the static tests.

These results suggest that the smallest branches are highly resistant to fracture due to their inherent flexibility. On the other end of the spectrum, the inherent strength of the largest branches allows them to successfully resist very high static loads.

Species-specific Variation

Branches of six different common tree species (Table 3) were pulled to failure during the static testing phase of the project. Figure 26 graphically presents the results of this analysis. As expected, the ability of a branch to resist static loads varies by species, with Northern red oak (*Q. rubra*) branches able to safely carry more load than those of Eastern white pine (*P. strobes*). Perhaps the more interesting observation relates to maples (genus *Acer*).

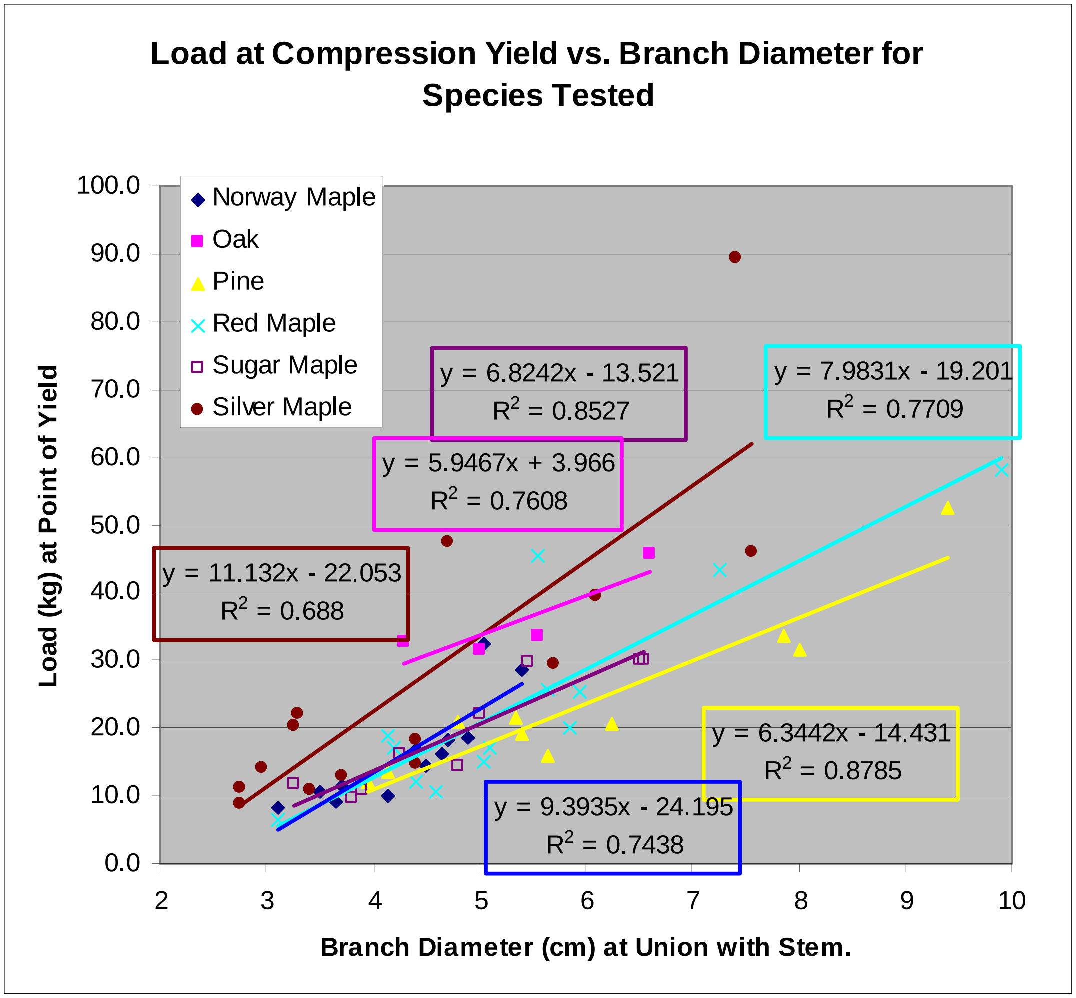

Figure 26. Relative differences in branch strengths by species, expressed in term of resistance to primary yield failure in compression.

Three of four species of maples maple have very similar trend lines. However, silver maple (*A. saccharinum)* surprisingly demonstrates greater initial load-carrying ability (before yielding) than the other maples. This is contrary to silver maple's reputation among utility arborists as being weak-wooded.

Further insight can be gained by reviewing the magnitude of the stress forces on wood fibers at primary yield failure in compression (Figure 27), and at secondary fracture failure in tension (Figure 28).

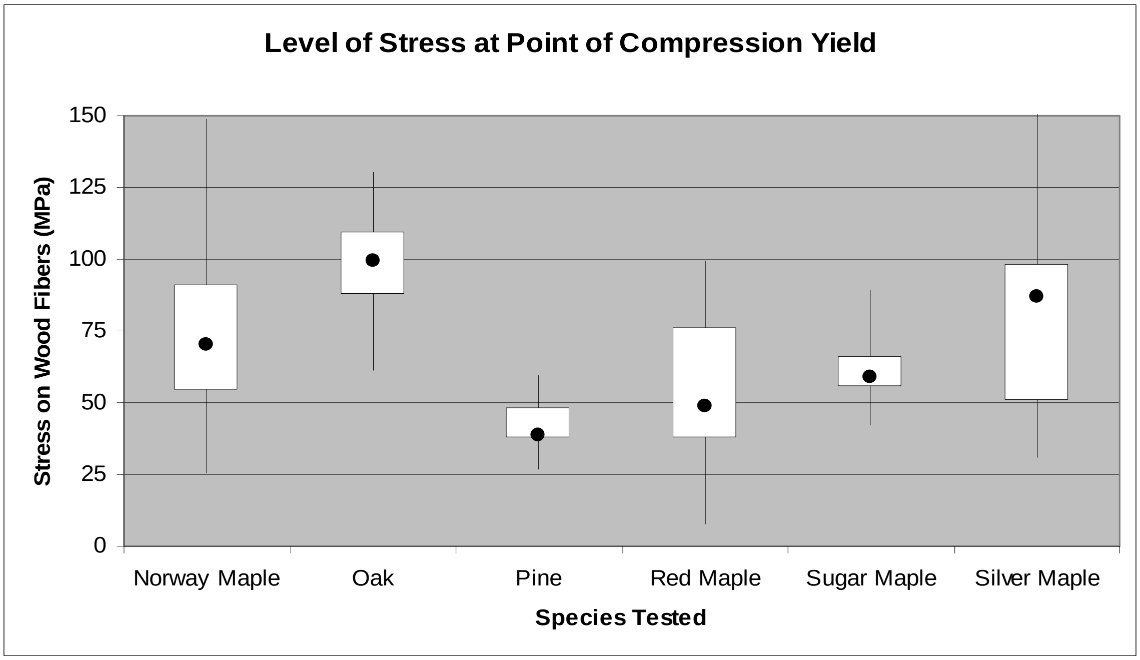

Figure 27. Force of stress experienced by wood fibers at primary yield failure in compression. Mega Pascal (MPa) is a measure of the forces of stress acting on a cross-sectional area of marginal fibers.

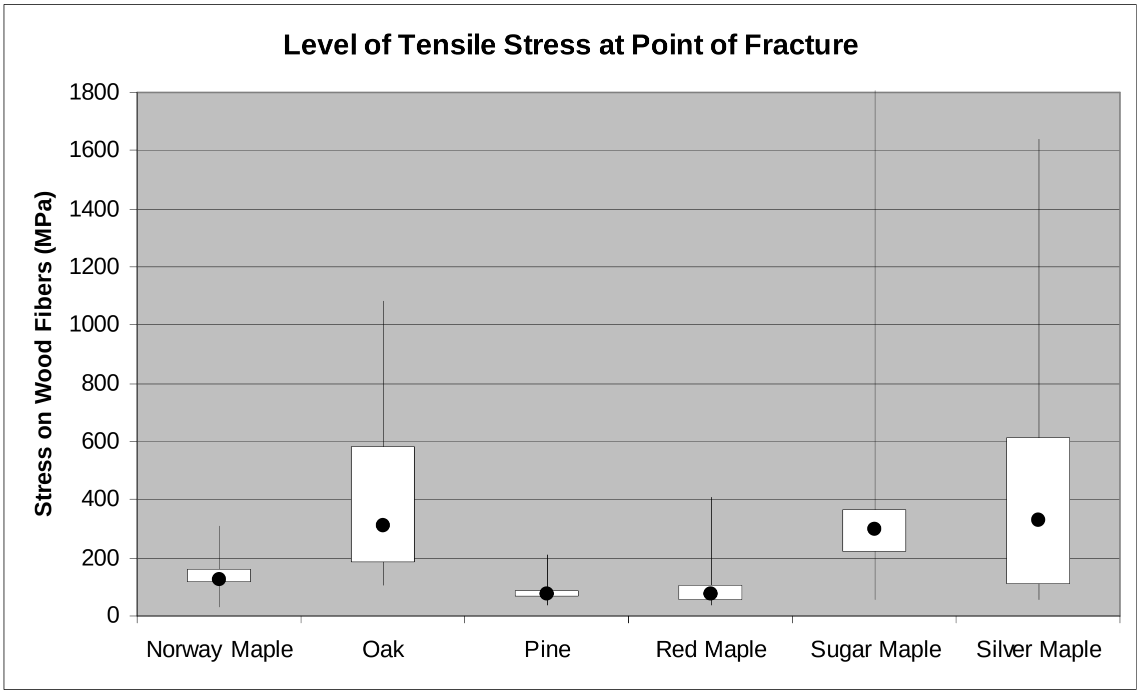

Figure 28. Force of stress experienced by wood fibers at secondary fracture failure in tension.

A comparison of silver maple with sugar maple (*A. saccharum*), a species considered to be relatively strong-wooded, reveals that silver maple is initially resistant to compression failure. However its resistance to fracture is similar to that of sugar maple, at least for branches in the range of diameters tested. This suggests that other factors are the cause of silver maple's reputation as a "problem species". Silver maple crowns often occupy a dominant position in the urban forest, spreading widely and extending above the adjacent canopy. The force of wind acting on this large and exposed sail area may be a significant contributor to silver maple limb failures. Another factor to consider is that silver maple has a propensity to produce weakly attached "water sprouts" or "sucker" growth.

In summary, the tree species appears to be a useful risk assessment criteria. This is consistent with findings from the photo interpretation and industry survey phases of this project.

Branch Diameter to Length Ratio

Measurements of branch diameter adjacent to attachment with the main stem and the length of each branch were recorded. These measures were used to define taper in terms of a diameter-to-length ratio. Simple physics establishes that a longer lever arms results in greater force. However, natural growth tends to produce an inherently resilient form through processes that include compensatory growth of branch tissues. The net effect is that long thin branches often appear to have the necessary strength to survive expected loading..

Analysis of the data failed to reveal any potentially useful trend regarding taper and/or diameter-to-length ratio that could be used as a risk assessment criterion. In summary, branch taper did not prove to be a significant indicator of risk.

Branch Diameter to Stem Diameter Ratio

Measurements of branch diameter adjacent to the union, and at the point of fracture zone, were considered. The ratio of branch diameter at the point of failure to the diameter of the main stem immediately above the attached branch proved a more useful indicator. These measures were used to define a branch-to-stem diameter ratio. Safety factors for each of the branches were also calculated and compared to the branch- to-stem diameter ratio. The results of this analysis are presented in Figure 29 below.

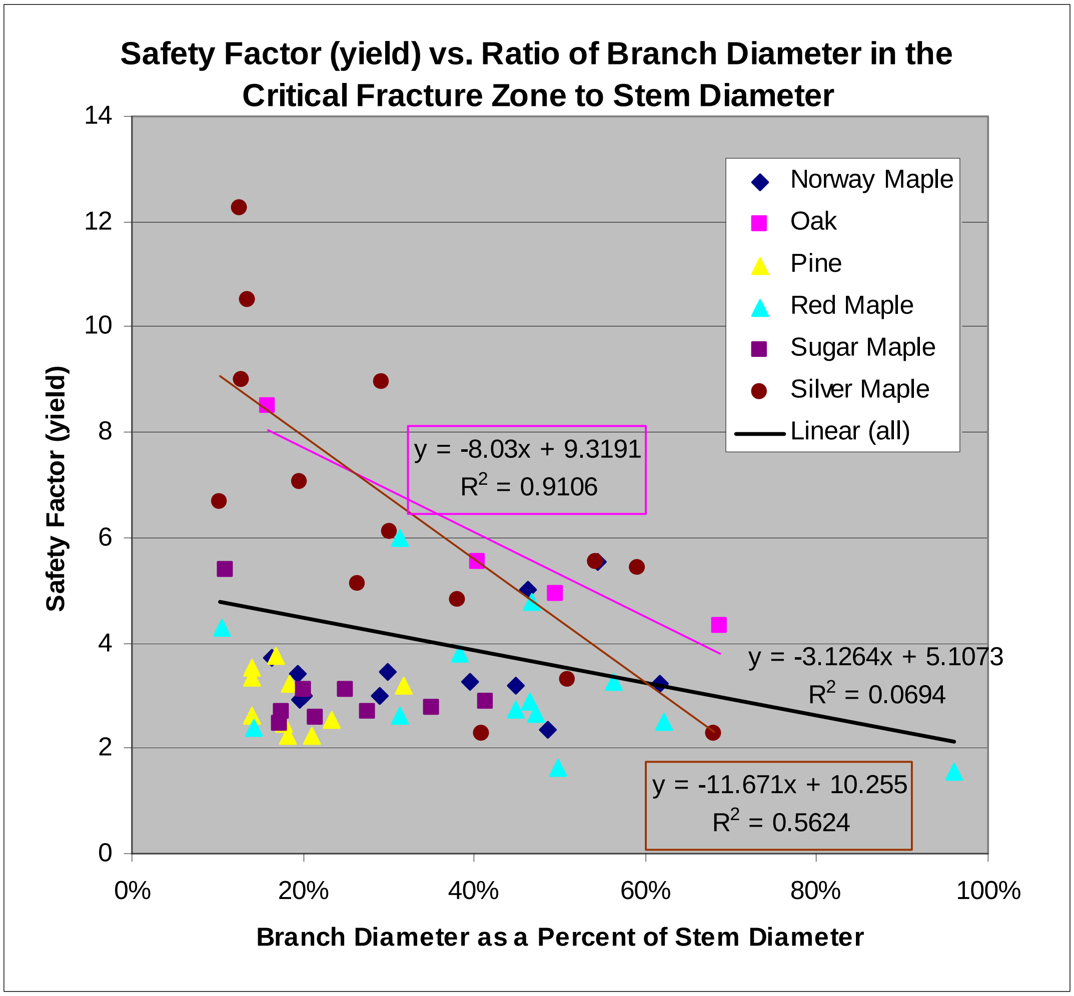

Figure 29. Effect of the ratio of branch diameter at the point fracture to stem diameter on Safety Factor (yield).

The safety factor drops as the diameter of the branch approaches that of the main stem. This is consistent with literature reports. It is also supported by anecdotal evidence from the survey of industry experience. The ratio of branch diameter in the fracture zone to stem diameter appears to be a useful risk assessment criteria.

Branch Roundness

Conventional wisdom suggests that branches that assume an ovoid form in cross section with elongation in the vertical axis will be stronger due to the reaction wood. Branch diameters in the horizontal and vertical axes were recorded in the area of fracture. The degree of roundness was calculated and compared to the safety factors for each of the branches in the test populations.

Results from this analysis suggest a slight trend but were considered inconclusive. Field observations made during static testing support the notion that compensatory growth of branch tissue in reaction to stress returns the branch to a “normal” level of load-carrying capacity.

As noted in the literature review, “tension wood” develops in deciduous trees as a growth response that enhances the strength of the upper portion of a branch under tension stress. “Compression wood” develops in coniferous trees, as a growth response that enhances the strength of the lower portion of a branch under compressive stress[16]. There are physiological differences in both tissue types. The lignin content of tension wood is lower and the cellulose content higher. Compression wood can be as much as 50% denser than wood from areas of the same tree that are not under compression.

This reactive growth response makes sense in terms of the branch as a biological organ of the tree. Individual branches need sufficient strength to resist normal loads. There is no biological advantage for an individual branch to be notably stronger than others within the crown. The most durable form is one where stresses are distributed along the branch, and reaction wood serves this purpose.

The degree of roundness did not appear to be particularly useful risk assessment criteria.

Branch order

As originally envisioned, the static test phase of the project would have included pulling a wide range of branches to failure. The industry survey included four levels of branch:

- Fine branch
- Lateral branch
- Scaffold branch
- Co-dominant stem

However, the stated focus of this investigation was small- and medium-diameter branches. As such, no data were acquired on scaffolding branches and co-dominant stems. This potential risk assessment criterion was excluded from further consideration.

Branch Orientation

Branch orientation was defined in terms its general alignment to a horizontal plane. The at-rest orientation of each branch was recorded prior to static testing. The following four classifications were used to define the orientation of each branch:

- Near vertical (60 to 90 degrees)
- Upward sloping (30 to 60 degrees)
- Horizontal (0, ±30 degrees)
- Downward sloping (30 to 60 degrees)

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[16] Kramer and Kozlowski

The effect of branch orientation on branch safety factors was evaluated, using the compression yield and tension fracture Safety Factors. No useful trends related to initial yield failure were identified. However, branch resistance to fractures in tension provides some additional insight.

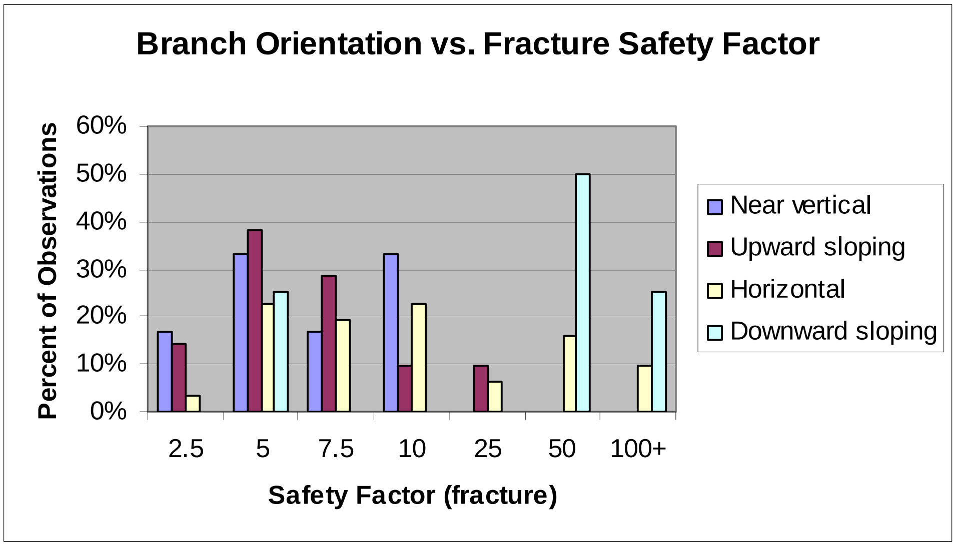

Figure 30. Effect of branch orientation on Safety Factor for tension fractures.

Figure 30 shows the Safety Factor for the final failure of a branch by fracture in tension. Here horizontal and downward sloping branches are shown to have much higher resistance to fracture. Conversely, the more upright classes of branches tend to have lower safety factors.

There are at least two explanations for this observation. The first is related to a matter of geometry and physics. Initially, as load is applied to an upright branch, the dominant force vector is aligned with the branch. At some point the load begins to result in deflection. The results of deflection are two-fold: the force vector perpendicular to the branch increases dramatically, and the arc of deflection increases rapidly. Secondly, as the branch deflects, the center of gravity of the loaded branch moves horizontally further away from the fracture zone. The effect of this is that the force generated by the branch increases as the length of the lever arm increases.

An upright branch is initially resistant to deflection, but yields in compression soon thereafter. In contract, a horizontal branch deflects easily and has a higher resistance to compression yields. The force vectors shift into alignment as the branch deflects past horizontal.

These findings are consistent with the literature review and results from the survey of industry experience. Large upright branches (60-90 degrees) were found to be a dominant cause of outages in the photos submitted by UAA members.

Branch orientation appears to have potential as a risk assessment criterion.

Branch Location Within the Crown

The location of the branch within the crown was determined while the branch was at rest, prior to static testing. The crown was divided into three locations generally defined by the typical height of distribution conductors. Both the origin and general position occupied by each branch was considered in making this qualitative determination. The three locations of interest included:

- Upper crown, above height of conductors
- Mid-crown, at approximate height of conductors
- Lower crown, originating below height of conductors

The relationship between branch location and branch safety factor was considered in evaluating this potential criterion. The results of this analysis are graphically portrayed in Figure 31 below.

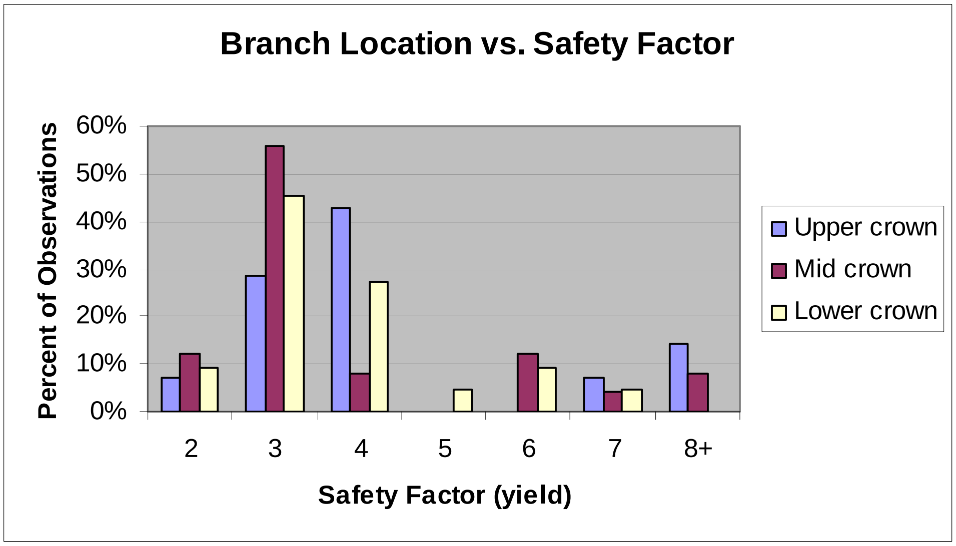

Figure 31. Effect of branch location within the crown on Safety Factor (yield)

There appears to be two different groups of branches in the upper and mid crown positions, one with Safety Factors in the 2-4 range, and another in 6-4 range. In both cases a second group of branches was to found to have Safety Factors twice as high as the majority of the population.

Obviously branches located in the lower crown, at or below the level of conductors, present a lower risk to electric reliability than branches high in the crown and above the conductors. Branch orientation is also likely to vary to some extent by a branch's location within the crown. For example it would be reasonable to expect branches in the upper crown to have a more up-right orientation than that of branches in the lower crown, which are more likely to be horizontal, or directed in downward orientation.

Findings from this analysis, and those of the literature review and survey of industry experience, suggest that branch location should be given some consideration as a risk assessment criterion.

Branch Competitive Position

The crown classification system used in traditional forestry to describe the competitive position of the crowns of individual trees in the forest canopy was adapted for classification of the relative competitive position of individual branches tested within the crown of each test tree. The classifications used were:

- Dominant competitive position
- Co-dominant competitive position
- Intermediate competitive position
- Suppressed competitive position

The relationship between branch competitive position and branch safety factor was considered in evaluating this potential criterion. The results of this analysis are presented in Figure 32. There is an important limitation to the analysis of this attribute. There were too few branches rated as having a dominant competitive position to support a definitive conclusion across all four classes. However, the relatively high safety factors attributed to some intermediate and suppressed branches is worth noting. This suggests that the risk of failure associated with these lesser branches is lower than one might assume.

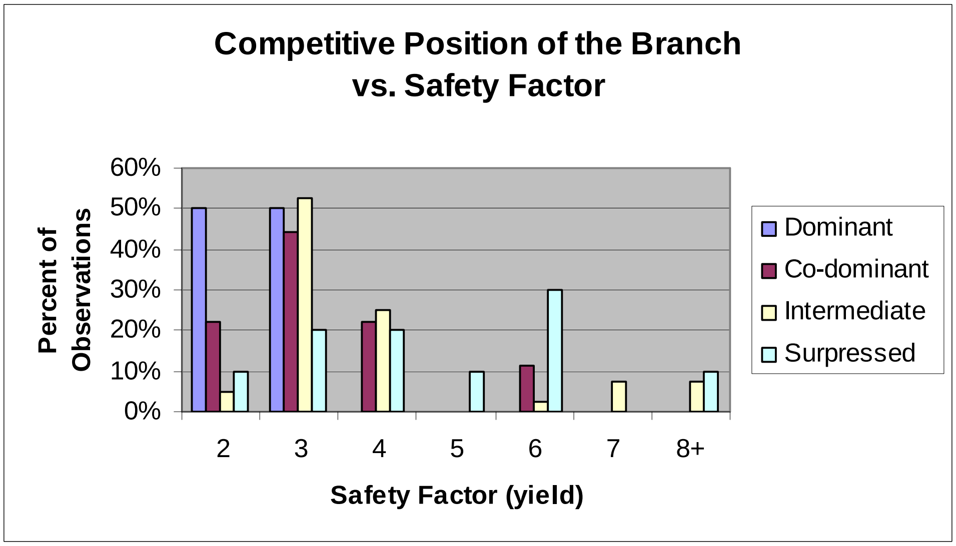

Figure 32. Comparison of Safety Factor at the point of compressive yield to the competitive position of the branch. Note that a co-dominant rating refers to the competitive success of the branch and is not an indication of co-dominant stems.

The lack of observations for dominant branches tends to limit this criterion's use as a risk assessment criterion. However this information may have application in developing risk mitigation actions. That is, it may be possible to reduce risk (by increasing the safety factor) of dominant and co-dominant branches through pruning, reducing their dominance to a lower competitive stature.

Branch Form

The at-rest form of each branch was characterized using a qualitative scale based on the alignment of branch axis to a uniform plane. The following three branch forms were used:

- Up-swept bow
- Generally straight along the length of the branch
- Downward-swept bow

The range of safety factors associated with the up-swept form was found to be lower than either of the other two forms. The down-swept bow appears to have the highest resistance to fracture failures. This may be due in part to what had previously been described as a limitation to the experimental design. As branches with the downward bow are subject to loading they deflect, becoming increasingly aligned with the force vector. This has the effect of greater percentage of branch fibers being subject to tensile stress, and fewer fibers in compressive stress. Since wood fibers are stronger in tension this would increase branch resistance to fracture.

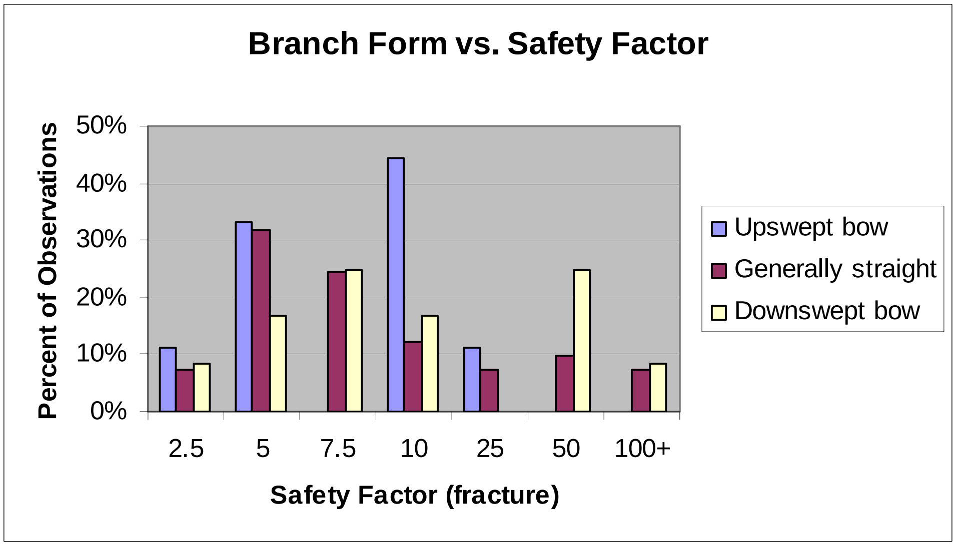

Figure 33. The form of the branch influences its ability to resist structural failure.

It should also be noted that branch form is likely to vary to some extent by a branch's location within the crown. This is similar to the observation offered in the discussion of branch orientation. It is likely that branches in the upper crown exhibit an upswept form, while branches in the lower crown may be more likely to have a down-swept form.

The tendencies appear strong enough to consider branch form as a potential risk assessment criterion.

Branch Uniformity

Branch uniformity was envisioned as a means of rating the degree to which the branch exhibited characteristics consistent with what would be considered “normal” for the species. The classification system used included the following condition definitions:

- Typical growth form and structure for the species
- Atypical form and structure for the species
- Presence of sharp angles and bends
- Presence of defects and wounds
- Crooked or twisted branches

The results of the analysis were inconclusive due to the lack of observations in all but the “typical growth form and structure for the species” category. Eighty-two percent of the branches fell in this category.

Branch Defect

The presence of external defects such as old wounds and cavities has been traditionally used as an indicator of weakness. As such it was natural to include this concept in an assessment of potential risk assessment criteria. The types of defect considered are listed as follows:

- Old wounds
- Branch node stubs
- Cross-grain cracks
- Longitudinal splits
- No apparent defect

Only one case each of cross-grain cracks and longitudinal splits were encountered. These two defect categories were subsequently eliminated from analysis. The effect of the presence (or absence) of an observable defect on branch safety factors was evaluated, and presented in the two figures below.

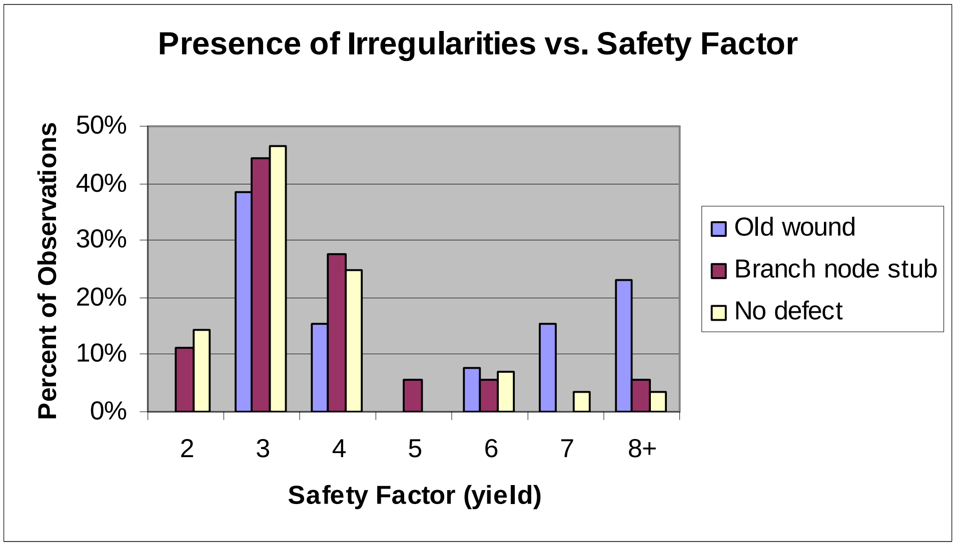

Figure 34. Effect of observable branch defects on Safety Factor (yield)

Assuming that branches with no observable defects represent “normal” typical distributions for Safety Factors expressed in terms of both compression yield and tension fracture, some interesting observations can be made. Figure 34 reveals that branches with evidence of old wounds appear to resist failure as well as, and in some cases better than branches with no observable defects. This finding from analysis of the data is consistent with what the research team had previously observed during field-testing of branches to failure. Detailed assessments of the point of fracture made post-failure revealed an apparent role for callous tissue and compensatory growth in returning the branch to an efficient form that was able to distribute loads evenly.

The other notable observation based on the results of analysis, as presented in Figure 34. is the relatively low Safety Factors associated with some of the branches that contained old branch stub nodes. This too is consistent with field observations made during static load tests, as well as insight gained during dissection and close inspection of the areas of fracture for failed branches. This appears to be related to the pronounced change in diameter, which commonly occurs at branch nodes.

Both observations appear to be important. Old callused wounds are not necessarily fatally flawed. Rapidly changing diameters associate with swollen branch nodes and the evidence of old branch stubs appear to have potential as a risk indicators.

Effect of Reduction Pruning on Snow Loading

Northeastern Ohio experienced an early season “lake effect” heavy wet snowstorm on October 29, in the middle of the week in which the static load testing was being conducted. Although this made for difficult field conditions, the accumulation of wet snow on branches, many still in leaf, afforded a unique opportunity for the research team to make a variety of direct observations related to snow loading of branches. Three separate investigations were conducted during the snowstorm.

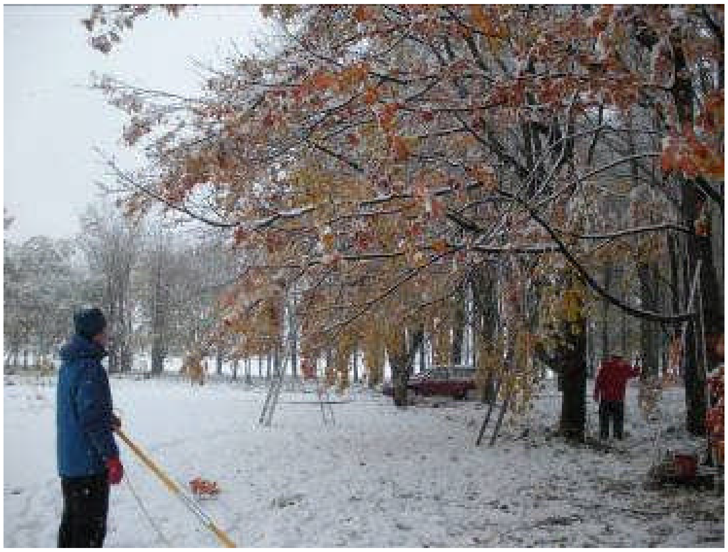

Figure 35. Testing continued during an early season snowstorm.

Accumulated Weight of Snow

Ten heavily loaded silver maple branches were selected and carefully cut from the trees. These silver maple trees were in full leaf at the time of the snowstorm. A concerted effort was made to retain as much of the snow load accumulated on the foliage as possible during the removal and weighing process. These branches were smaller than most of the branches being tested in the static load tests. Each branch was weighed and the combined weight of the branch and accumulated snow was recorded. The branches were then set aside and reweighed two days later after the snow had melted and the foliage was dry.

Figure 36. Weighing a small silver maple branch heavily loaded with snow. The branch being weighed is suspended horizontally from the tree from which it was removed.

The weight of accumulated snow was calculated by comparing the snow-covered and unloaded branch weights. The weight of accumulated snow averaged 165% of branch weight, and ranged from 100% to nearly 300%.

Effect of Branch Reduction on Snow Loading

Two Norway maple (*Acer platanoides*) branches on each of two individual trees were selected for study. The trees were also in full leaf and heavily loaded with snow. A number of measures defining branch form and dimension were recorded. The location of the center of gravity was estimated and marked, and its distance above ground was measured. The length of each branch was then reduced by 15% of its length, and measurements repeated. Care was taken to minimize loss of snow on the un-pruned portion of the branch as they were measures and pruned..

Two days later, after the snow had long since melted, several measures were repeated including recreating the deflection of the previously snow loaded branch. This was done by reattaching the load line at the same point as was used previously used, and loading the branch until the correct measure of deflection was reached. Data related to the level of static load necessary to recreate the levels of deflection experienced by each branch was used to calculate the corresponding bending moment stress at the union. The results are presented in Table 4 below.

Table 4. Reduction in bending moment stress due following 15% branch reduction pruning of Norway maple.

Branch Test Number	1	2	3	4
Calculated Reduction in Bending Moment	49%	31%	44%	39%

An as yet unpublished German study[17] involving an investigation of the effect of branch reductions on oak found that a reduction of branch length resulted in a correspondingly greater reduction in the total mass of leaves attached to the branch. Table 5 generally characterizes summary findings from this study.

Table 5 Effect of reduction pruning of oak branches on foliage and bending moment stress, as reported in unpublished thesis.

Amount Branch Length Reduction	Corresponding Reduction in Mass of Foliage	Corresponding Reduction in Bending Moment Stress
10%	>20%.	22%
20%	45%	43%.
30%	65%	60%

Of course the significant loss of leaves associated with the higher levels of stem reduction pruning will have a direct impact on photosynthetic capacity of the branch and would likely effect branch vigour. On the other hand, a reduction of 10% of the branch length results in 22% stress relief at the branch base with regard to bending moments resulting from the dead weight of the branch. This would increase branch resistance to load-induced failure.

Effect of Crown Reduction on Snow Loading Induced Stress In Main Stems

Some limited work involving the pruning of whole trees under loaded condition was conducted during the snowstorm. The crowns of three pin oak (*Q. palustris*) trees had heavy accumulations of wet snow.. Elastometers were attached to the lower trunks of the trees at heights of 0.5 and 1.5 meters, and were used to record changes in strain in the main stems of the trees as they were pruned. The upper crown of each tree was reduced by approximately 15% in stature. It should be noted that some of the snow that had accumulated on the lower crowns was lost during the pruning operation.

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[17] Florin, Olaf (2009). Unpublished Bachelors thesis. “Untersuchungen zur Nachhaltigkeit von Asteinkürzungen” (investigations on the sustainability/lastingness of branch reductions). HAWK, Göttingen, Germany. Formal results are currently being prepared for publication in a scientific journal.

Figure 37. Assessment of the effect of crown reduction pruning on snow loading. Changes in stem deflection were recorded as the tree was pruned.

Strain data from the elastometers were used to calculate the corresponding bending moment stresses experienced in the main stems of the test trees. The reduction in stress following 15% crown reduction is reported in Table 6 below.

Table 6. Reduction in bending moment in the main stem following 15% crown reduction under heavy snow-loaded conditions.

Height of Elastometer	Tree 1	Tree 2	Tree 3
@ 0.5 meters	49%	64%	59%
@ 1.5 meters	50%	70%	68%

These levels are generally consistent with those reported above for branch reduction, particularly when considering the unintentional loss of snow on the lower portion of the crown due to pruning work above.

Conclusions and Recommendations

The preceding sections of this report presented results from the four phases of this investigation. These four phases included:

1. A review of the relevant literature.
2. Interpretation of photos of branch failures that had caused interruptions.
3. A survey of the experience of practicing utility arborists with branch failures that have caused interruptions.
4. Static load testing of branches to the point of failure.

The purpose of these investigative efforts was to establish a basis of understanding of the manner in which branches fail under static loads, and to identify readily observable characteristics that could be used in an assessment of the relative risk individual branches pose to adjacent distribution lines. An understanding of the branch failure processes also was used in the development of risk mitigation practices.

The frame of reference used in developing the recommendations presented in the remainder of this report was by choice decidedly biased to what could be practically applied to distribution line clearance maintenance pruning operations. The recommendations are also framed in a manner that relies on the experience of the practitioner to make the final determination of risk. They are based on technical analysis (science), but in application require professional judgment (art) based on experience. It is the combination of art and science that will create value in the application of these recommendations to distribution system vegetation management work.

The reader is also reminded of the relative size of the branches in this study (2-8 cm or ~1-4”). As such these recommendations pertain to the assessment and mitigation of risks related to small- and medium-sized branches. Large scaffolding branches and dominant stems are more likely to fail in a manner consistent with that of hazard trees. Hazard tree assessment criteria should be applied to inspection of major structural elements of the crown.

It is important to restate that the focus of this work has been branch response to unidirectional static loads. This loading is consistent with the gravitational loads created by wetting of foliage such as the accumulation of wet snow and ice. Forces generated by the wind are dynamic in nature. Though developed through static testing, the recommendations have general application for managing the risks of wind-related loads as well.

Recommendation #1: Visually Inspect the Critical Failure Zone

This project has demonstrated that branch failure is much more likely to occur beyond the union with the main stem than at the union itself. The Critical Failure Zone was found to be within the first 20% of branch length from union with main stem or larger scaffolding branch. As such it is recommended that line clearance tree workers make a close inspection of this Critical Failure Zone. This recommendation is easily incorporated in to routine distribution vegetation maintenance pruning work. Practically stated, the Critical Failure Zone is generally within arm's reach of the main stem or scaffolding branch to which the smaller branch is attached

The forces of stress generated by loading along the lever arm that is the branch are greatest in the Critical Failure Zone.

Contrary to popular opinion, branches are less likely to fail at the union with the main stem. There are two important exceptions to this observation:

- ☐ Branch unions involving co-dominant stems *with included bark* represent a higher risk of failure. Narrow branch attachment angles are not necessarily a problem unless true included bark is present.
- ☐ Dead branches are often shed at the union with the main stem. This is a natural process involving wound compartmentalization.

Important Note: The intent of this recommendation is not to focus attention exclusively on the Critical Failure Zone. It is intended to complement current practices such as assessing the integrity of the branch union with the main stem and a hazard inspection of the main stem and major branches.

Recommendation #2: Identify Areas of Irregularity That Concentrate Stress

Branches fail in response to forces associated with load-induced stress. A structurally efficient branch distributes these forces of stress smoothly along its length. However, branches often are irregular in form and function, and in their response to stress. Like a chain, a branch is only as strong as its weakest section. The size and shape of the worst irregularity in the critical failure zone is what counts.

The key is to identify irregularities that cause a concentration of stress forces. These areas are elastically different; they are more or less flexible than adjacent sections.

There are a variety of reasons why bending stress could be concentrated along a localized area of branch. Note that the concept being described is that of branch *irregularity* rather than the more common reference to "defect". Defects involving decay fungi that weaken woody fibers are always a concern. While a number of the defects traditionally considered in hazard assessment of whole trees would apply to branches, that list is inadequate.

Examples of areas that might result in sharp changes in flexibility and thereby cause a concentration of stress include:

- Areas of pronounced changes in diameter. In particular those that occur at old branch stub nodes.
- Sharp crooks and bends.
- Large wounds.
- Areas of decay.

This is where the art and craft of the practicing arborist and line clearance tree worker must complement science, using the arborist’s experience to identify areas along a branch that could act as a stress concentrator.

Recommendation #3: Recognized Nature’s Elegant Design

The previous recommendation focused on the importance of identifying areas that might be elastically out of step with the rest of the branch. This recommendation deals with areas that may appear as irregularities in terms of their physical appearance and form but are not necessarily different in terms of strength and flexibility.

It is well known that trees have the capability to mount a growth response to physical and biological stress. As previously stated, a structurally efficient branch distributes the forces of stress created by loads smoothly along its length. Compensatory growth in the form of reaction wood serves to strengthen areas along the branch in response to stress. In this manner the branch is responding to the distribution of stress along its length.

Irregular physical form does not necessarily imply that the elastic properties of the branch are irregular.   Given time, the tree’s growth response to stress or wounding often serves to return the stressed area of a branch to a point where it is generally elastically consistent with that of adjacent sections of the branch.

Relatively new areas of wounding or stress-induced damage are a concern. In these cases the strength to the branch has been compromised. However, areas where a growth response to the damage has occurred in subsequent growing seasons do not necessarily represent elevated risk even if they are irregular in appearance. This is the branch’s response and is an attempt to restore strength and flexibility.

Here too, the experience of the practicing arborist and line clearance tree worker needs to guide the determination of actual risk. The test criterion isn’t how uniform the branch is in physical appearance, but should be based on branch strength and how the branch performs elastically.

Recommendation #4: Retain Some Small Diameter Branches

Small diameter branches represent relatively low risk. They are highly elastic and typically have high Safety Factors. They do not need to be removed “ground-to-sky”.

The risk created by small branches is generally within the arc of sweep of their length in deflection. They are much less likely to fracture and fall clear. And even if they do, they are less likely to cause mechanical damage to energy delivery infrastructure. They can however create an electrical short circuit if their failure provides a fault pathway between two conductors or other areas of unequal electrical potential.

Retention of small branches also serves two additional purposes:

- The terminal buds on these branches produce growth hormones that help inhibit sucker growth that is sometimes stimulated by line clearance pruning elsewhere in the crown.
- The role of branches in harmonic dampening is an emerging area of research. The harmonic oscillation of trees under wind loading is beginning to be recognized as a cause of structural failure. It has been suggested that these branches counteract this effect.

Recommendation #5: Consider Branch Competition for Dominance In Initial Risk Assessment

The concept of competition among branches in the crown appears to be a useful construct in assessing the potential risk of branch failure. It is recommended that branches that are competitively dominant or co-dominant in terms of their competitive position be carefully considered.

Branches in direct competition with one another tend to exhibit the following characteristics:

- They are more likely to have an upright orientation, which has been shown to represent elevated risk.
- They tend to have larger diameters relative to the main stem. Smaller branch-to-stem diameter ratios have been shown to be stronger.
- Intermediate and suppressed branches had relatively high Safety Factors. Some competitively dominant and co-dominant branches were found to have relatively low Safety Factors.
- Branch sucker growth can be thought of as uncontrolled competition; it is recognized as being relatively weak and presents an elevated risk of failure.

Branches in the upper crown were found to have an elevated risk of failure. These branches are often in dominant competitive positions and have a upright orientation. Their form is more often that of an upswept bow which was found to have a lower safety factor than branches in the form of a down swept bow. Branches in the upper crown also have greater exposure to precipitation and wind loading, and as such may experience greater levels of stress. Their position high in the crown obviously can represent an elevated risk to conductors. Hazard assessment includes consideration of both the likelihood of failure and the target. A higher percentage of branches in the upper crown may impact conductors (the target) upon failure due to their wider target zone.

Co-dominant stems are the quintessential example of branch competition. They tend to be upright in form and by definition have similar diameters. When the union is compromised by included bark, they represent a relatively high risk of failure.

To be clear: the concept of branch competition is being recommended as a means of focusing attention, and not as an absolute indicator of risk. Many branches that are competitively dominant and co-dominant will surely be found to be structurally sound. The intent is that the construct of branch competition that is being recommended will lead to a closer inspection by an experienced arborist or line clearance tree worker who will then consider other factors in making a determination of risk.

Recommendation #6: Recognize Species-specific Risks

Branch response to the stress created by loading was shown to vary by species. This is due to factors such as the material properties of branch tissue and the branching form and habit of each species of tree. Branches of six species were evaluated in this investigation. Not surprisingly, Northern red oak had the highest Safety Factors, and Eastern white pine the lowest. Three of four species of maple all were relatively similar in terms of Safety Factor. The data indicated that the resistance of branches to failure varies by species.

It is also likely that the exposure of branches to adverse loads varies by species. This would be the case for example with silver maple. As noted previously the crowns of silver maple often occupy a dominant canopy position in the urban forest and have greater exposure to wind loading. Another example can be found in species like Norway maple, which tend to retain their leaves longer in to the fall, creating greater exposure to early season heavy wet snowfall.

It is recommended that a species-specific branch hazard ranking metric be developed. This may be as simple as the development of a three-tier rating system that considers both the structural properties of the branch and likely exposures. Table 7 provides a high-level example of a matrix that could be used to develop species-specific ranking of the relative risk of branch failure.

Table 7. Conceptual matrix used to develop species-specific ranking of the relative risk of branch failure.

Combined risk rating	Structural Strength Factor	Exposure Factor
High	Based on performance (e.g., Safety Factor) of individual branches	Based on the nature of a species form and exposure to loading
Medium		
Low		

The other advantage of developing risk rankings for common species is that it could include consideration of species-specific irregularities in branch forms and defects that may create unique risks.

Recommendation #7: Be a Careful Observer

Utility arborists are increasingly recognizing the value of performing post-interruption investigations. It is recommended that the risk assessment criteria identified in this report be field validated. A simple scoring checklist could be developed and used in evaluating branch failures as part of routine post-interruption investigations.

Successful application of the recommendations made in this report involves both the art and science of branch performance under loading conditions. Much can be gained by being a careful observer of actual branch failures in the field under operational conditions.

Recommendation #8: Incorporate Branch Reduction Pruning into Distribution Vegetation Maintenance Specifications

The risk of branch failures resulting in interruptions can be managed. This does not have to be accomplished exclusively through removal of the branch in question. Risk mitigation in the form of branch reduction pruning should be included in routine distribution line clearance maintenance work practices.

This report has compared a branch to a long tapered cantilevered beam. The long lever arm of the branch creates high levels of stress in the Critical Failure Zone. The transfer of the forces of stress through the lever arm is further compounded by the presence of foliage on the outer end of the branch. In addition to its weight, foliage provides additional surface area for forces related to precipitation and wind to act on.

Branch reduction can significantly reduce stress in the Critical Failure Zone, thereby increasing branch stability. The effects are two-fold. A reduction in the length of the lever arm reduces the force applied in the Critical Failure Zone. Secondly, a reduction in foliage reduces the surface area available for loading, whether it is precipitation-related static loads or dynamic loading caused by wind.

There are other reasons why branch reduction rather than branch elimination should be considered. Recommendation #4 advocates the retention of small diameter branches, and mentions their potential role in dampening harmonic oscillation. The same would be true of branches that are reduced by pruning. Perhaps more important is the matter of cost. The removal of entire branches well above and overhanging conductors is a slow and expensive process. It can also lead to crew-caused interruptions when control of the branch being pruned is lost and it falls into energized conductors. Branch reduction in the outer portion of these same branches will take less time, and the small lengths of branch ends being removed are more easily controlled and made to fall clear of conductors.

Said another way, this recommendation is to avoid attempts to achieve “ground-to-sky” clearance in distribution corridors.

The amount of branch reduction necessary is relatively small. The results of the test of branch reduction under snow loading indicate that a reduction of 15% will reduce load-induced stress in the Critical Fracture Zone by approximately 40%. This is significant. However, the branch reduction testing done in this project was limited in scope. Simple rules of thumb for branch reduction should be developed through an application of some basic principles of mechanical engineering, and then validated by field-testing. It appears very likely that a limited amount of reduction pruning of overhanging branches could significantly reduce the risk of failure and subsequently the threat to reliability.

Summary

This investigation has focused on the failure of small- and medium-sized branches capable of causing interruptions to electric service. It was carried out over the course of a year and involved four phases including destructive testing of branches of six species of tree.

The research identified the importance of making a careful inspection of the critical zone of failure. It also highlights the elasticity of small diameter branches and the importance of deflection as a means of their resisting failure under static loading.

The project identified the importance of identifying area of change in branch elasticity. The potential for areas of irregularities in branch form were shown to acts to concentrate forces of stress within the branch, and identified as an important risk assessment consideration.

Opportunities to apply risk various risk assessment criteria were identified. Risk of branch failure can be eliminated with removal of high-risk branches. Risk mitigation practices such as branch reduction pruning should also be considered.

Appendix A. Review of Branch Failure Literature

1. **Baker, C.J. and H.J. Bell. "The Aerodynamics of Urban Trees". Journal of Wind Engineering and Industrial Aerodynamics, 41-44 (1992)**

Abstract: The study reports on an evaluation of wind-related failures of non-forest trees from an engineering perspective. The authors concluded that many of the published studies using static loading overstate the ability of the tree to resist wind loads. They concluded that the dynamic nature of wind is a factor of considerable importance that should be considered. They also note that tree failure is very species-specific. They demonstrate the bending moment (force) is reasonably dependent on the intensity of turbulence, with greater turbulence resulting in greater bending moment. Because of this, the authors suggest that urban trees will experience greater bending moment than rural forest trees.

2. **Brundi, Erk. and P. van Wassenaer. "Trees and Statics: Nondestructive Failure Analysis." Tree Structure and Mechanics Conference Proceedings, International Society of Arboriculture, October 2001**

Abstract: The authors discuss a nondestructive technique for assessing the structural integrity of large mature trees based on biomechanical engineering principles. The article includes a discussion on the physical characteristics of wood including its strength when "green", as presented in the "Stuttgart Table of Wood Strengths". The method includes an assessment of the load potential based on a two-dimensional silhouette of crown area.

3. **Cannell, M.G.R.; Morgan, J. (1989): *Branch breakage under snow and ice loads*. In: Tree Physiology 5: 307-317.**

Abstract: This paper reports on an investigation of the mechanics of branch failure under gravitational load, and provides a useful discussion of the relationship between the mid-point diameter of a branch and its likelihood of failure.

4. **Dahle, Gregory A., H. Holt, W. Chaney, T. Whalen, D. Cassens, R. Gazo, and R. McKenzie; "Branch Strength Loss Implications for Silver Maple (Acer saccharinum) Converted from Round-Over to V-Trim," Arboriculture & Urban Forestry, July 2006 pp. 148-154.**

Abstract: This study reports on an assessment of the breaking strength of silver maple (*Acer sacharinnum*) branches that had grown in response to prior line clearance pruning. The investigation compared the breaking strength of branches that had grown back as water sprouts (suckers) following heading (round over) pruning, to the breaking strength of branches that had naturally arisen from lateral buds.

Branches were mechanically loaded to failure and pulled from trees using a system of winches and pulleys, and breaking strength was determined using a dynamometer. The presence of decay was noted, and the percentage of decayed wood was measured.

Key findings:

- Trees converted from “round-over” to “V-trim” have an increased likelihood of branch failure.
- On average, water sprouts were found to be 49% weaker than naturally occurring branches.
- Water sprouts are more likely to have internal decay at or near the branch union
- Larger water sprouts were more likely to have greater amounts of decay, and to be relatively weaker as their diameter increased, and therefore more prone to failure.
- The decay was not always confined to the water sprouts, and often caused weakening of the parent leader

5. **Detter, Andreas *“Arborist Safety and Tree Stability”*. Active research project undertaken for British Health and Safety Executive (HSE) and UK Forestry Commission focusing on integrity of branches used as anchor points for climbing lines. Unpublished manuscript. March 2008.**

Abstract: Forty branches of four different tree species were pulled until they fractured in the course of this research project. Seven mature trees were used in the course of the study, including three roadside and four park trees. Tests were carried out at two locations in three different seasons. The diameters of tested branches ranged from 7 to almost 30 cm at the trunk. The dataset contains seven branches classified as re-growth and 10 leaders from the top of an un-pruned crown. The other 23 branches were growing laterally from stems or main leaders rising from the bottom, or the middle third, of the crown.

Loads were measured with two Dynafor load cells at resolutions of 2 and 5 kg units and a custom-built dynamometer indicating 100 N units. Stiffness was derived from readings of elastometers placed on the upside and/or downside of the branch during the load tests in a manner consistent with the Elasto-Inclino method. Over-bark diameters were measured, as well as effective lever arms and line angles. Bark thickness was measured later, at several points along the fracture surface, after the destructive tests had been completed. By incrementally recording the applied force, stress in the marginal fibers was derived from the cross-section modulus and the applied bending moment. The test was interrupted at low loads, where recorded fiber deformation was well below the expected critical degree (usually less than 0.1% elongation). By correlating the generated stress to fiber elongation, measured at the marginal fibers (by placing Elastometers at the top and bottom side of the perimeter of the branch), values for fiber stiffness were derived.

In the subsequent destructive part of the pull test, to avoid damaging the instruments, only load cells were set up, and the deformation of the branch was filmed with digital video. Deflection was recorded by counting the number of pulls and pushes of the cable winch, each shortening the cable by 22 mm in length. Loads were recorded after specific numbers of pulls and pushes of the cable winch. The load steps were selected in smaller increments as the presumed yield point was approached.

6. Eisner, Nathan J., E. Gilman, J. Grabosky, and R. Beeson, Jr., "Branch Junction Characteristics Affect Hydraulic Segmentation in Red Maple," Journal of Arboriculture, November, 2002, pp. 245-251

Abstract: This paper reports findings from an investigation intended to characterize the branch/trunk union. The specific attribute of interest was the relative hydraulic conductivity of branches. Branches of varying sizes and angles of attachment were evaluated. Measures of the ease of flow of internal fluids between branch and main stem were recorded and analyzed.

Key findings:

- Greater hydraulic conductivity was found in branches with narrow angles of attachment and branches closer in size to parent branches.
- Greater hydraulic conductivity between branch and main stem correlated positively with an increase in discolored wood in the main stem following branch removal.
- A tree's ability to resist decay following branch removal may be estimated by taking into account the size of the branch being removed and its angle of attachment. There is less likelihood of decay with relatively smaller branches and wider angles of attachment.

7. Ellison, Michael J. , "Quantified Tree Risk Assessment used in the Management of Amenity Trees," *Journal of Arboriculture*, March 2005, pp.57-65

***Abstract**:* The author proposes a quantitative model for objectively assessing the relative risk of tree failure. The system referred to as " Quantitative Tree Risk Management" involves making numeric estimates of a number of factors including hazard potential, probability of failure, risk, the concept of acceptable risk, and cost-benefit analysis. The model considers the components of tree failure analysis and assigns numeric values and probabilities. The result of this assessment is a numerical estimate of risk. The system provides a means of identifying unacceptable risks and insight into the elements of the risk. While the paper focuses on high value amenity trees in public spaces, the basic model may be adapted to other applications such as utility vegetation management.

8. 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

Abstract: 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.

9. Gilman, Edward F., "Branch to Stem Diameter Affects Strength of Attachment," Journal of Arboriculture, September 2003, pp. 291-293

Abstract: The paper reports on an investigation into the relative strength of branch attachments in red maple (*A. rubrum).* Branches were mechanically loaded to failure, and breaking strength was determined using a dynamometer. The author concludes that the strength of branch attachment is related to the ratio of the diameter of the branch to the diameter of the stem to which the branch was attached. Smaller diameter branches relative to the main stem were stronger. Branch unions where the two structural members involved were similar in relative size (co-dominant) were much weaker, and failed more easily as compared to branch unions where the branch was smaller in relation to the parent branch. Branch failure is less likely when branches are smaller in proportion to the leader or parent branch.

10. Gilman, Edward. "Pruning Methods: New Research Evaluates Failure, Growth, and Decay", unpublished presentation at Trees & Utilities National Conference, April 2008.

Abstract: Dr. Gilman's presentation was a wide-ranging survey of current research into the effects of pruning on trees. Several points were relevant to the structural integrity of branches and the proposed branch failure project.

- Reaffirmed the importance of reaction wood as a growth response and a matter of structural integrity. This confirms the notion that cross-sectional branch asymmetry may be a useful risk assessment criterion.
- Vertical branches have less reaction wood than horizontal branches. Horizontal branches may therefore be better able to support loads and resist failure.
- In general trees have a safety factor of 2.5-3 to 1 safety factor.

- When a horizontal branch breaks, the union with the main stem generally remains intact and failure occurs out along the branch. Vertical “co-dominant” branches often fail at the union.
- “If you want to minimize storm damage, minimize the number of vertical branches.”
- The diameter of a branch-to-stem ratio is a good indicator of strength of the union. Small branches connected to large stems tend to be strongly attached.
- Advocates the use of “reduction cuts” back to laterals to slow growth (which has the potential to increase instability) and to reduce mechanical loading.

11. Hauer, Richard J., W. Wang1, and J. Dawson. “ Ice Storm Damage to Urban Trees”, Journal of Arboriculture, July 1993, pp. 187-194

Abstract: The paper reports on the findings of a study that was undertaken to assess patterns of damage to urban trees following a severe ice storm in Urbana, Illinois in February of 1990. The study found that larger trees were more likely to sustain severe damage than smaller trees. A high proportion of deciduous trees with large stem diameter and broad spreading crowns suffered severe damage. The authors suspect that the crowns of these mature trees often have structural weakness. Other factors that contributed to the high level of damage to large deciduous trees are reported to include crown architecture, crown imbalances, included bark, and pre-existing dead wood in the crown. The authors suggest that these factors may predispose a tree to ice damage.

Trees that exhibited an excurrent branching habit experienced less damage. Trees with reduced branch surface area showed the least damage. The authors also conclude that there are no apparent relationships between ice storm damage susceptibility and the specific gravity of the wood, the modulus of rupture, or the modulus of elasticity of a tree species. Tables showing ice storm tolerance and damage rates related to wood strength were provided.

12. Kramer, P., J., and Kozlowski, T, T. Textbook: Physiology of Woody Plants. Academic Press: New York. 18-30, 1979

Abstract: This is a standard reference text. It includes a complete discussion of the formation and properties of the ‘reaction wood’ that develops in response to mechanical stress; this is the tree’s normal response to preserve structural form and integrity. Reaction wood in deciduous and coniferous trees differs in form, function, and location.

- “Tension wood” develops in deciduous trees as a growth response that enhances the strength of the portion of the stem or branch under tension, which is typically the upper portion of an inclined structural element. There are physiological differences in tension wood as compared to wood from areas that are not under tensional stresses. The lignin content of tension wood is lower and the cellulose content higher.

- Compression wood develops in coniferous trees, as a growth response that enhances the strength of the portion of the stem or branch under compression, which is typically the lower portion of an inclined structural element. There are physiological differences in compression wood. Compression wood may be as much as 50% denser than wood from areas that are not under compression.

The authors also note that there are species-specific differences in the characteristics of reaction wood.

13. Lilly, Sharon and T. Sydnor, "Comparison of Branch Failure During Static Loading of Silver and Norway Maples," Journal of Arboriculture, November 1995, pp.

Abstract: This paper reports on an investigation into the strength of silver maple *(A saccharinum*) and Norway maple (*A. platanoides*) branches. Branches were mechanically loaded to failure using a system of winches and pulleys, and breaking strength was determined using a dynamometer. Variables evaluated included the angle of branch attachment, tree/crown form, and specific gravity of the wood involved.

Key findings:

- The branches of Norway maple and silver maples do not exhibit significantly different breaking strengths.
- Narrow branch angle attachments were neither more nor less likely to fail unless they had bark inclusions.

14. 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

Abstract: 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.

15. Morgan, J. and M Cannell, “Structural analysis of tree trunks and branches: tapered cantilever beams subject to large deflections under complex loading”, Tree Physiology 3, 365-374 (1987)

Abstract: The paper discusses a quantitative approach to evaluating loading of tree branches based on modeling the branch as a series of segments. Simple models break down at deflections >25%. The problem is complicated by the irregular nature of branches as compared to engineered structures.

The authors discuss the complexity of distributed loads as opposed to single point loads. Of importance to the branch failure experiment is a discussion of loading direction. By maintaining a vertical load the effect of gravity is accounted for. The authors suggest that the method makes it possible to mathematically model the deflection of branches of known taper under loads such as snow, wind, and self-weighting.

16. Neuheimer, Michael, 2005, “Response of Urban Norway Maple Trees to Mechanical Stress”, Unpublished Honours Thesis, May 2005.

Abstract: This study explored the material properties of Norway maple (*A. platanoides*), a common urban street tree in this area. Properties investigated include: the elastic modulus, stress and strain proportional limit, stress at ultimate strength, and density. Five trees similar in size and age were tested. The test involved mechanically loading (pulling) the trees and recording the deflection along the main stem as force was applied. The trees were subsequently removed and the physical characteristics of the wood in compression tests were evaluated.

The report describes the complexity of the dynamic loads created by wind. It discusses factors such wind changes with elevation and surface characteristics. The author also recognizes factors such as crown form, branch structure and deformation with increasing wind velocity. The experimental design addresses this complexity by arguing that the force of wind on branches is transferred to the main trunk, thus this is where measurements of deflection are made. The risk being evaluated is that of whole tree failure rather than the failure of individual branches.

This document includes a summary of the basic physiology of the stems and branches of deciduous trees. It also includes a discussion of “reaction wood” which is part of a tree’s natural response physical stress and loading. Importantly, the author recognizes that deciduous and coniferous trees differ. Deciduous trees have “tension wood” that develops on the upper portion of an inclined branch and is under tension. Reaction wood develops in conifers as “compression wood” and is located on the underside of inclined branches and is under compression.

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

Abstract: 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.

18. Simpson, Peter, and R. Van Bossuyt, “Tree-Caused Electric Outages,” Journal of Arboriculture, May 1996, pp. 117-121

Abstract: The paper reports on the findings from a study of tree-caused interruptions. That study, entitled “Tree-Caused Interruption Research Project”, was conducted by Environmental Consultants, Inc., and involved the participation of 14 utilities in the United States and Canada. The study analyzed post-interruption data provided by the cooperating utilities. Data analyzed included tree characteristics, orientation of the tree to the conductor, weather conditions and other factors.

The authors report that preventable (predictable) tree or limb failures were responsible for 25% of tree-caused interruptions for all participants. The paper discussed study findings and implications for Eastern Utilities (EU) in greater detail. The structural failure of a limb or tree accounted for 40% of preventable tree-caused outages at EU. The authors also note that 73% of the customer hours interrupted occurred during storm events.

As a result of the study, EU surveyed its lines and categorized trees based on their characteristics and likelihood of failure. EU subsequently developed and implemented a “danger tree mitigation program” and modified their line clearance specification. The authors report that these changes resulted in a significant reduction in tree-caused service interruptions.

19. Sharon, E. Michael, "Tree Health Management: Evaluating Trees for Hazard," Journal of Arboriculture, December 1987, pp. 285-293.

Abstract: This paper describes the need for a systematic approach to managing tree hazards to enhance safety and reduce liability. The author opines that more failures occur in the crown of broadleaf trees than anywhere else on a tree. Entire crowns must be observed and potential hazards noted. Past failure patterns can be useful in predicting future failure patterns.

20. 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

Abstract: 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.

21. Wessolly, Lothar (1989): *Materialwerte grüner Hölzer, Stuttgarter Festigkeitskatalog*. In: Anonymus (ed.): Tagungsband des 12. Bad Godesberger Gehölzseminares.

Abstract: This paper describes the change of material properties with height of a mature beech tree, estimated at 85 years old. The author reports that the strength of the wood fibers in scaffold branches was 75% greater than stem fiber. Branch wood fibers were also reported as being 85% stiffer than stem wood fibers. The values of fiber strength and stiffness were determined by testing green wood extracted from the felled tree. This translation is credited to A. Detter.

22. Wessolly, Lother. "Fracture Diagnosis in Trees, The Expert Method". (1995) Stadt und Grun, No 6. pp416-422.

Abstract: This paper is one in a series of four that discuss the basis of the European "Statics" method of evaluating the risk of tree failure. It contains a complete discussion of the manner in which trees and branches progress with increased loading through failure.

As the load increases, at some point the elastic limit of the wood is exceeded, and creep failure begins in the compression zone. In this first stage of failure, compression of wood fibers occur from the periphery, without longitudinal delamination. Initially the fiber compressions can only be observed microscopically or measured with an elastometer.

With further increase in load, macroscopic compression lines develop, which spread out increasingly in the direction of the tension side. This fiber compression “absorbs” the compressive stresses until the fracture load is reached on the tension side and the stem breaks.

The author offers a narrative example: “*Under high wind load the wood fibers on the windward side are pulled, and those on the lee side compressed. They are deformed in the longitudinal direction. The stiffer they are, i.e. the higher the E- modulus, the less they give. Up to a certain stretch limit they do this without sustaining lasting damage. As the fibers withstand compression less well than tension (1:2), the compression load capacity is the valid measurement limit. The start of the plastic deformation is called the elasticity limit. This means: the maximum compression of the fibers lying immediately below the bark is the decisive criterion for assessing fracture resistance.*”

The deformation behavior of the wood under compression is divided into two zones: elastic and plastic. The elastic limit is the point when primary compression failure occurs. It is the point at which the wood starts to incur lasting damage with further load increases. It is referred to as primary failure. The fracture of trees occurring later is the result of secondary failure. The “statics” method focuses on the behavior of wood prior to it reaching primary failure (the elastic limit).

Appendix B, UAA Survey of Industry Experience With Branch Failures

Branch Failure Project, Q1

Based on your experience score the relative risk of branch failure within the crowns of trees that have been pruned in each of the following manners:

Answer Options	Much less likely	Less likely	“average” likelihood	More likely	Much more likely	No obvious correlation, not a relevant factor	Response Count
Trees that have been directionally side pruned	28	70	45	13	2	2	160
Trees that have received height reduction pruning	19	51	27	40	15	7	159
Trees that have received crown raising (lower	9	24	68	28	9	18	156
Trees that have been “through pruned, a.k.a. “V”	5	45	48	48	9	3	158
Trees that have been rounded over with heading cuts	2	17	21	43	66	8	157
						Additional Comments	27
						answered question	160
						skipped question	3

Branch Failure Project, Q2

Based on your experience, score the relative risk of branch failure associated with the elapsed time since the tree was last pruned, as listed below:

Answer Options	Much less likely	Less likely	Neutral, “average” likelihood	More likely	Much more likely	No obvious correlation, not a relevant factor.	Response Count
Recently pruned branch, within the current growing	54	52	26	8	6	5	151
One growing season since pruning	9	63	56	16	0	5	149
More than one growing season since pruning	3	22	44	63	14	5	151
						Additional Comments	16
						answered question	151
						skipped question	12

Branch Failure Project, Q3

Based on your experience, rank the relative likelihood of branch failure for each of the classes of branches listed below:

Answer Options	Much less likely	Less likely	Neutral, “average” likelihood	More likely	Much more likely	No obvious correlation, not a relevant factor.	Response Count
Fine branch	35	50	36	18	8	2	149
Lateral branch	3	36	62	43	6	0	150
Scaffold branch	4	37	60	44	4	0	149
Co-dominant stem	1	2	11	38	94	3	149
						Additional Comments	13
						answered question	150
						skipped question	13

Branch Failure Project, Q4

With regard to branches that have failed, rank the likelihood that a failure typically occurs in each of the locations indicated below:

Answer Options	Much less likely	Less likely	Neutral, “average” likelihood	More likely	Much more likely	obvious correlation, not a relevant factor.	Response Count
Failure at the branch union	0	15	22	60	48	0	145
Failure in first third of length from union	2	23	51	58	8	2	144
Failure in middle third of length from union	5	43	65	27	1	2	143
Failure in outer third of length from union	23	53	36	20	10	2	144
						Additional Comments	10
						answered question	145
						skipped question	18

Branch Failure Project Q5

Based on your experience, rank the relative risk of failure of each the following branch orientations:

Answer Options	Much less likely	Less likely	Neutral, "average" likelihood	More likely	Much more likely	obvious correlation, not a relevant factor.	Response Count
Near vertical (60 to 90 degrees)	12	33	35	33	25	1	139
Upward sloping (30 to 60 degrees)	2	15	49	62	9	1	138
Horizontal (0, +/- 30 degrees)	1	20	41	49	26	0	137
Downward sloping (30 to 60 degrees)	8	40	33	31	20	4	136
Additional Comments							10
answered question							139
skipped question							24

Branch Failure Project Q6

Rank the relative likelihood of branch failure for trees growing on each of the following site types:

Answer Options	Much less likely	Less likely	Neutral, "average" likelihood	More likely	Much more likely	obvious correlation, not a relevant factor.	Response Count
Individual street trees	2	13	50	48	18	3	134
Individual lawn and landscape trees	3	16	59	44	9	4	135
Trees in landscape buffers and screens	2	18	72	39	1	3	135
Edge trees associated with a stand of trees	2	14	29	61	26	3	135
Trees within a stand of trees	21	49	31	23	8	3	135
Additional Comments							9
answered question							135
skipped question							28

Branch Failure Project, Q7

Rank the relative risk of branch failure in each of the following stages of life in the year of a tree:

Answer Options	Much less likely	Less likely	Neutral, "average" likelihood	More likely	Much more likely	No obvious correlation, not a relevant factor.	Response Count
Late dormant season	15	38	38	22	7	10	130
Bud break	6	39	54	21	0	10	130
Active leaf development	1	25	45	43	6	8	128
Period of stem elongation	1	9	49	54	9	8	130
Period of radial growth	3	10	45	49	14	8	129
Senescence, leaf drop	4	42	59	12	2	11	130
Early dormant season	7	48	44	18	1	11	129
Additional Comments							17
answered question							130
skipped question							33

Branch Failure Project, Q8

Rank the relative risk of branch failure for branches within each of the crown positions described below:

Answer Options	Much less likely	Less likely	Neutral, "average" likelihood	More likely	Much more likely	No obvious correlation, not a relevant factor.	Response Count
Upper crown, above height of conductors	1	4	25	71	22	7	130
Mid crown, at approximate height to conductors	1	7	63	46	6	7	130
Lower crown, originating below height of conductors.	12	44	43	17	4	9	129
Additional Comments							10
answered question							130
skipped question							33

Branch Failure Project, Q9

Rank the likelihood of branch failures associated with the stem diameters listed below:

Answer Options	Much less likely	Less likely	Neutral, “average” likelihood	More likely	Much more likely	No obvious correlation, not a relevant factor.	Response Count
Branches that are less than 1/3 the diameter of the	7	35	45	21	12	8	128
Branches that are between 1/3 –2/3 diameter of the	0	13	65	39	3	8	128
Branches with diameters more than 2/3 the diameter	7	15	28	42	26	8	126
						Additional Comments	8
						answered question	128
						skipped question	35

Branch Failure Project, Q10

In your experience, is the branch attachment a factor in considering the risk of failure? Please rank the risk of branch failure for the range of attachment angles listed below:

Answer Options	Much less likely	Less likely	Neutral, “average” likelihood	More likely	Much more likely	No obvious correlation, not a relevant factor.	Response Count
Near vertical (60 to 90 degrees)	4	22	35	33	32	2	128
Upward sloping (30 to 60 degrees)	0	14	39	68	5	2	128
Horizontal (0, ±30 degrees)	1	16	48	46	15	2	128
Downward sloping (30 to 60 degrees)	5	40	34	34	9	4	126
						Additional Comments	8
						answered question	128
						skipped question	35

Branch Failure Project, Q11

In your experience, is the form of the branch a factor in considering the risk of failure? Please rank the risk of branch failure for each of the following branch forms:

Answer Options	Much less likely	Less likely	“average” likelihood	More likely	more likely	obvious correlatio	Response Count
Up-swept bow	0	16	44	45	5	16	126
Generally straight along the length of the branch	0	10	62	37	3	15	127
Drooping downward bow	2	30	30	41	10	14	127
						Additional Comments	5
						answered question	127
						skipped question	36

Branch Failure Project, Q12

In your experience is the uniformity of the branch a factor in considering the risk of failure? Please rank the risk of branch failure for each of the following branches:

Answer Options	Much less likely	Less likely	Neutral, “average” likelihood	More likely	Much more likely	No obvious correlation, not a relevant factor.	Response Count
Typical growth form and structure for the species	8	31	78	3	1	5	126
Atypical form and structure for the species	0	6	42	65	8	4	125
Presence of sharp angles and bends	0	0	21	75	28	3	127
Presence of defects and wound	0	0	2	25	99	1	127
Crooked or twisted branch	0	1	21	64	38	2	126
						Additional Comments	2
						answered question	127
						skipped question	36

Branch Failure Project, Q13

In your experience, is the type of growth a factor in considering the risk of failure? Please rank the relative risk of branch failure for each of the following types of growth:

Answer Options	Much less likely	Less likely	“average” likelihood	More likely	more likely	obvious correlatio	Response Count
Natural growth	9	41	64	6	1	3	124
Stimulated “natural growth”, stimulated by proper	10	28	60	20	2	3	123
“Sucker growth” originating from epicormic buds	0	3	11	50	58	2	124
“Sucker growth” originating from epicormic buds	0	8	12	56	47	1	124
						Additional Comments	1
						answered question	124
						skipped question	39

Branch Failure Project, Q14

Based on your experience rank the relative risk to reliability due to the failure of each of the following classes of branches:

Answer Options	Much less likely	Less likely	Neutral, “average” likelihood	More likely	Much more likely	No obvious correlation, not a relevant factor.	Response Count
Fine branches	30	46	33	13	3	1	126
Lateral branches	1	21	62	35	7	0	126
Scaffold branches	2	17	48	53	6	0	126
Co-dominant stems	0	2	10	39	73	1	125
						Additional Comments	4
						answered question	126
						skipped question	37

Branch Failure Project, Q15

In your experience, at what wind speed does the failure of individual branches within the crown become a significant cause of interruptions?

Answer Options	Much less likely	Less likely	Neutral, “average” likelihood	More likely	Much more likely	No obvious correlation, not a relevant factor	Response Count
<25mph	28	34	45	13	3	2	125
<35 mph	2	29	41	40	13	1	126
<45 mph	0	4	24	59	37	1	125
<55 mph	0	0	5	41	77	1	124
>55 mph	0	0	1	6	114	3	124
						Additional Comments	11
						answered question	126
						skipped question	37