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Determination of Strain Patterns Across the Root-Stem Transition Zone in Trees

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Determination of Strain Patterns Across the Root-Stem Transition Zone in Trees

Kenneth Edward Beezley

Thesis submitted

**To the Davis College of Agriculture, Natural Resources and Design
at West Virginia University**

in partial fulfillment of the requirement for the degree of

**Master of Science in Forestry
Forest Resource Management**

**Greg Dahle, Ph.D., Chair
David DeVallance, Ph.D.
William MacDonald, Ph.D.
Jason Miesbauer, Ph.D.**

Division of Forestry and Natural Resources

Morgantown, West Virginia

2016

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sampling, root-stem transition zone, static load test, tree stability**

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ABSTRACT

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Kenneth Edward Beezley

Trees are subjected to mechanical stressors, induced via dynamic (wind) and static (gravitational) forces, and must properly acclimate during their lifespan or face premature mortality. Resource allocation as a stress response is vital for tree survival, and can include the shedding of woody parts, adaptive growth, hormonal signaling cascades, and the initiation of energy transfer mechanisms. The strain resulting from stress intercepted by the canopy and transferred throughout the tree is of significant importance, not only for tree survival, but for the safety and well-being of the human population found in close proximity. As trees age and adapt to stressors and an ever changing environment, material properties also change that can influence tree stability, of which arborist and tree managers should account for. To test the function of tree orientation to an applied load, static load tests were conducted on 15 mature pin oak trees (*Quercus palustris* Muenchh.). Static load tests were applied to tilt the trees 0.1° from natural position to concentrate strain at the root-stem transition zone (RSTZ) and nondestructively mapped resulting strain patterns with an ARAMIS digital image correlation (DIC) system. Using bark as a surrogate for strain on the xylem, strain resulting from static loading was mapped with the DIC system from the main stem into the structural root system. Strain patterns were analyzed across the RSTZ in the leeward, tangential, and windward directions. Results indicate that mean maximum strain magnitudes are similar at the RSTZ on the leeward (0.088) and windward sides (0.090) and lower on the tangential direction (0.058). The leeward strain was comprised of 4% tensile strain and 96% compressive strain and windward strain was comprised of 95% tensile strain and 5% compressive strain. Mean maximum strain for the tangential orientation constituted 65% tensile strain and 35% compressive strain. The changes of proportional strains found on the tangential RTSZ orientation is poorly understood and often disregarded in tree biomechanical studies. This information could prove to be beneficial to the arboricultural and plant science communities to better understand how trees manage loading events and to further enhance tree risk assessment and root zone management protocols.

Table of Contents

Introduction	1
Methods	7
Results	62
Discussion	68
Implications	73
Literature Referenced	78
Appendix	83
Acknowledgements	89

List of Figures

Figure 1. Typical wood cell wall structure	6
Figure 2. Model of the mechanical forces distribution of longitudinal mechanical forces along the <i>Populus nigra</i> taproot	8
Figure 3. The balance of functions for tree survival of photosynthesis, mechanics, hydraulics, and reproduction	10
Figure 4. Elevated radial growth and increased diameter at the base of an elm tree	12
Figure 5. The root-stem transition zone (RSTZ)	13
Figure 6. The Triangle of Statics	14
Figure 7. Windward and leeward orientation in reference to loading on the upper stem	16
Figure 8. A typical stress/strain curve and associated properties	18
Figure 9. Wind velocity (α) increases with taller structures	22
Figure 10. Stem and root-plate tilt of <i>Pinus pinaster</i> in sandy soils	22
Figure 11. Anisotropic properties of wood	23
Figure 12. Schematic drawing representing strains in a tree bent under wind loads	24
Figure 13. Maximum bending moment of four different root systems in four theoretical soils	25
Figure 14. Root system architecture of trees	26
Figure 15. Typical static load test setup	28
Figure 16a and 16b. ARAMIS optical image correlation system image and graphical output	31
Figure 17. Stochastic paint speckling pattern utilized for RSTZ strain mapping with the ARAMIS optical image correlation system	31
Figure 18. Variables required for proper DIC strain determination	32
Figure 19. ARAMIS camera set up for strain measurement at the root-stem transition zone	33
Figure 20. Location map of survey trees, Evansdale Campus at West Virginia University, Morgantown, WV, USA	37

Figure 21. Typical landscape found in test area around survey trees	38
Figure 22. Numerated increment strips placed vertically on the main stem for each surveyed tree and root for diameter measurements	40
Figure 23. Directional schematic for static loading tests	41
Figure 24. Stochastic paint speckling pattern utilized for RSTZ strain mapping with the ARAMIS DIC system	42
Figure 25. RSTZ and root prepared for sampling, with painted surface, reference marks, scale bar and identification card	43
Figure 26. Incremental tic marks along a prepared surface and root reference labels	45
Figure 27. Soil moisture measurement at the “B” side of exposed root	46
Figure 28. Yellow lines indicate general path followed for diameter measurements across the RSTZ when no definable root was present	47
Figure 29. Typical anchor tree and winch attachment set up used in static loading trials	48
Figure 30. Typical rigging attachment and load cell setup for loading trials	49
Figure 31. Digital level and camera placement for loading trials	51
Figure 32. Root divergence from the main stem for the windward RSTZ orientation during static load test	52
Figure 33. Diagram of static pull test applied to induce a 0.1 degree inclination for strain measurement across the RSTZ and structural roots in the windward, leeward and tangential directions	53
Figure 34. Shade tent installed over RSTZ sampling area	54
Figure 35. Calibration board used during static load tests for DIC calibration	55
Figure 36. Sample image as used in determination of reference point R000 on the RSTZ	57
Figure 37. Magnified image used in the selection of R000, center of curvature on the RSTZ	57
Figure 38. Labeling schematic of typical RSTZ for static loading trial	58
Figure 39. Tree and root coding used for identification and post processing of RSTZ static loading trials and strain analysis	58

Figure 40. Subregions RA(above reference R000), R0(Center of R000), and RB (below reference R000) found in the RSTZ	59
Figure 41. 3D image produced by ARAMIS DIC software used for strain data processing and analysis for Tree 2 Root 1	60
Figure 42. Graphical image produced through by ARAMIS DIC software for Tree 2 Root 1	60
Figures 43a & 43b. Test trees prepared for DIC static load tests and trees post testing	61
Figure 44. Mean maximum strain found on the leeward, tangential, and windward RSTZ orientations, resulting from static load tests	70
Figure 45. Strain type (%) of major and minor strain contribution to maximum strain for each RSTZ orientation found during static load tests	71

List of Tables

Table 1. Tree and rigging measurements for surveyed trees	62
Table 2. Mean soil moisture percentage and P-Value for all tested trees and RSTZ orientation	63
Table 3. Mean strain and standard deviation for maximum, major and minor strain found at sampled RSTZ's and respective orientation to the pulling force found during static load tests	65
Table 4. Contribution of strain type to maximum strain at RSTZ's and respective orientation to the pulling force found during static load tests	65
Table 5. Means, P-Values, and Tukey Grouping from ANOVA test for RSTZ orientation by subregions	66
Table 6. R^2 and P-Values of each RSTZ orientation for maximum strain and all incremental reference locations	66
Table 7. Mean root divergence, P-Value and Tukey Grouping by RSTZ orientation	67

Introduction

Trees thrive in various ecosystems and localities, evolving a continuous balance of form and structure to cope with the forces of nature and the surrounding microclimate. From the highest branch tip to the deepest root, these meta-organisms attempt homeostasis through complex signaling pathways in order to efficiently allocate plant resources. A continuous cycle of plant resource exploration, acquisition, allocation and utilization requires the tree to perceive and anticipate stress, even in dormancy (Trupiano *et al.* 2012). Considering the complex hierarchy of tree form and function, the genetic coding has been written for the master plan of the tree: Live, Reproduce, Die.

Trees have the ability to manage strain (ϵ) induced from an array of naturally occurring environmental and man-made stresses (σ) placed upon both above ground parts (leaves, branches, woody tissue) and below ground in the structural root support system. Neild and Wood (1999) describe the two main principles of plant growth as the economy of nutrients for light competition and the plants' reaction to loading stress by forming reactive tissue material in areas where strain is greatest. The response of trees to external loading events, of which wind is the single most abiotic destructive mechanism (Niklas 1992, James 2006, Matheny and Clark 2009) in both individual trees and stands of forested trees (Jacobs 1936), initiate a cascade of energy transfer mechanisms. Trees are prone to failure as a result of elevated, sustaining winds and also to short, sporadic wind gusts (Coder 2008), although failure may not be instantaneous (Hale *et al.* 2010). Research has shown that trees manage σ and the resulting ϵ across various parts of their architecture using mass damping (James 2003, Moore 2014), shedding of woody parts (James *et al.* 2006), bending of stems and branches (Brudi and van Wassenae 2002, Dahle and Grabosky 2010), stem deflection and tilt (Neild and Wood 1999, James *et al.* 2013), root-plate

tilt (Jonsson *et al.* 2006, James *et al.* 2013), root anchorage (Dupuy *et al.* 2005) , soil-root interactions (Genet *et al.* 2005) and adaptive growth (Niklas 1992, James 2003). However, limited knowledge of how σ and resulting ε is transferred from the main stem and across the root-stem transition zone (RSTZ) into the structural roots and root plate is readily available in literature.

With the recent increase of catastrophic weather events in the US, Europe and Australia, (Moore 2004, Yang *et al.* 2014) liability concerns arising from the retention and preservation of large amenity trees is of increasing concern. As more mature managed trees are found in populated areas, arborist and tree practitioners are faced with sometimes daunting tasks of deciding whether a tree should be removed if an imbalance of benefit to liability is compromised based on current tree risk assessment methods (Mortimer and Kane 2004) and conservative tree risk assessments (Moore 2014). Predisposing factors can also increase the likelihood of tree failure during wind events even under mild wind and weather conditions (Kane 2004, Smiley 2014). These factors can include prior root damage from wind (James *et al.* 2013a), unstable soil conditions and compromised soil properties (Gibbs and Greig 1990, Genet *et al.* 2005), intrusion of the rooting zone resulting from construction (Moore 2014, Smiley 2014), forest stand thinning for silvicultural management (Krause *et al.* 2014), improper planting (Genet *et al.* 2005), poor arboricultural practices, and the mechanical properties of individual tree species (Neild and Wood 1999). There is a lack of empirical data (Kane 2008) on tree stability and one goal of this research is to improve the evaluation of the likelihood of failure so that we can better manage amenity trees, rather than simply erring on the side of caution by removing such trees.

The mechanical stability of trees and plant forms has been well documented, including the works of Galeo pertaining to plant allometry (Cited by Niklas 1992), da Vinci's writings on

fluid mechanics (Niklas 1992), as well as Charles Darwin's examination of thigmotropic responses of roots, shoots, and tendrils to external stimulation (Darwin and Darwin 1881). Tree biomechanics, more specifically, applies mathematical relationships to plant form and function to better understand plant processes to natural occurring events and man-made trials. Niklas *et al.* (2006) discussed past and current literature relevant to plant form and function and the relationships of structural engineering principles pertaining to the foundation of tree biomechanical research, including adaptive evolution. James *et al.* (2014) discussed tree biomechanical concepts, including basic wood structural properties, the effect of wind, dynamic and static loading testing methods and the application of tree biomechanics into various practices, including forestry and arboriculture.

Past forestry research primarily focused on the stand level approach of understanding tree biomechanics (Coutts 1983), initially inferring conclusions derived at the stand level applied to individual trees. As this research developed, it was theorized that not all trees behave in the same manner of their neighbor. Trees found in non-forested environments, on the forest edge and open grown trees exhibit dissimilar traits, such as morphological species variation (Niklas 1992), branch structure (Moore and Maguire 2004), root architecture (Fayle 1983, Moore and Maguire 2005, Dupuy *et al.* 2005), and nutritional demands (Stokes *et al.* 1995), all of which account for variation in individual tree responses to external loading events (James 2003). Trees found in forested conditions also rely heavily on neighboring trees to reduce wind interception, whereas open-grown trees have to deal with wind and loading on an individual basis (Coutts 1983, Moore 2014). Thus the field of plant biomechanics, specifically tree biomechanics, has evolved to adapt basic engineering principles related to σ and ϵ relationships, laws of motion, equilibrium, and energy transfer to tree form and function (Niklas 1992).

Trees & Loading

External forces resulting in loading stress (σ) is induced upon trees via two primary mechanisms: dynamic and static forces (James *et al.* 2014). Dynamic forces, primarily wind, are dispersed through the tree via complex sway rhythms and damping mechanisms that enable the tree to disperse energy (James 2003) and are typically short in duration. The effects of wind on trees can vary significantly based on geographical situation, topographical situation and seasonal and meteorological influences (Brudi and van Wassenae 2002, James *et al.* 2014). Static loading may be more concentrated over longer durations on individual tree parts as a result gravity, as incurred by snow, ice, heavy mass/fruit production and increased canopy biomass over time (James 2003, Peltola 2006). Tree response to dynamic and static loading events varies according to spatial-temporal indices such as time of year, tree health and vigor, site history and soil conditions (James *et al.* 2006). Tree response to loading also vary by maturity level (Niklas 1992, Genet *et al.* 2005) at the time of loading, including more flexible wood properties found in juvenile wood compared with stiffer mature wood properties of the same species (Dahle and Grabosky 2010).

Plant tissue response

Physiological acclimation resulting from loading events enable trees to avoid extreme physical damage and catastrophic root failure (uprooting), including the shedding of woody parts and leaves during accelerated wind events (James *et al.* 2006), streamlining mechanisms of leaves to reduce drag (Milne 1991), stem deflection (Milne 1991), root-plate tilting (James *et al.* 2013, Coutts 1986, Stokes and Mattheck 1996) and root morphology (Fayle 1983, Genet *et al.* 2005). Milne (1991) also lists branch and canopy interference with neighboring trees as a form of

reducing interception, as these trees can effect responsive growth of their neighbor. Reactionary responses of the tree can be isolated in individual tree parts during static loading or constitutive with adjoining tree parts resulting from both static and dynamic loading (James 2003). James (2003) describes a tree as a “de-tuned system”, in which the tree can prevent large swaying in order to internally diminish intercepted forces and prevent damage or uprooting. In a dynamic event, the first force is intercepted by the tree in the canopy at various heights, while the second force is gravitational, as the tree sways away from its natural axis. Detuning has been reported to be a survival mechanism which allows the tree to minimize the amount of energy transfer into the main stem and roots (James *et al.* 2006). Stokes and Matheck (1996) also report that ϵ in the main tree stem is greater than ϵ found in roots of the same tree, as ϵ is transferred into the soil in order to avoid root failure and/or complete tree uprooting.

Cellular Responses

At the cellular level, the tree responds to bending stress through the alteration of cellular structural components, primarily by changes in secondary cell wall layers found in the secondary xylem of trees (Burgert 2006). Cell wall layers consist of the primary cell wall and secondary wall layers that encase the lumen with cellulose (Figure 1). Prior to and encompassing the secondary layers during development, the primary cell wall supports the cell during development. Secondary cell walls consist of three layers: the S1, S2, and S3 walls (Figure 1). Each secondary cell wall is composed of varying microfibril angles (MFA) attached to the respective wall, providing directionally orientated strength and rigidity to the cell (Burgert 2006). The outermost S1 wall is engineered to resist outward buckling, while the inner S3 wall is designed to resist inward buckling (Esau 1977; Niklas 1992). The S2 layer is thought to be the most crucial wall in determination of cell wall and tissue strength, through the alteration of MFA

in relation to the adjoining walls (Burgert 2006). MFA has been found to vary by morphological stage (Lindstrom *et al.* 1998). Differences in wood mechanical properties in relation to MFA found that in the same species of juvenile and adult wood, adult wood is much stiffer to resist wind loads as compared to the younger, more flexible stems (Groom *et al.* 2002; Mott *et al.* 2002).

Figure 1. Typical wood cell wall structure (nature.com)

The development of modified fibers held in tension, termed a gelatinous layer, may replace the S3 wall in some angiosperms and is composed of a sheath of cellulose microfibrils that are orientated about 5 degrees from the longitudinal axis of the cell structure (Panshin and Zeeuw 1967). This thick-walled gelatinous layer is composed of primarily cellulose and smaller amounts of lignin and can increase the specific gravity of reaction wood compared with normal wood (Panshin and Zeeuw 1967). However, Tsoumis (1968) found that in reaction wood held in tension, strength decreases in contrast to normal wood that increases strength with greater

density. Typically associated with eccentric cambial growth and variations in wood mechanical properties the formation of the gelatinous layer is termed reaction wood, since cell modification is occurring at the area of greatest stress (Almeras *et al.* 2005). The various combinations of MFA attachment and orientation vary by tree species and serves to aid in the selection of specific tree species for wood products (Telewski 2012).

In response to corrections of stem deflection and gravitational forces, reaction wood is formed that enables the tree to alter growth form and balance mechanical perturbations (alterations of function). This reactionary response by the tree occurs slowly and must be long-lasting (Almeras and Fournier 2009), as the tree promulgates nutrients to the stressed area and acclimates to a new position. Reaction wood formation varies by plant species and response to mechanically induced stress is found in two primary forms, compression and tension wood. In general, angiosperms produce tension wood whereas gymnosperms produce compression wood (Panshin and Zeeuw 1967, Trupiano *et al.* 2012) (Figure 2).

Trees manage bending stress through strain transfer and damping mechanisms in order to prevent and/or lessen tissue deformation, which may compromise trees stability. Angiosperms, such as deciduous forest trees, concentrate lignin formation on the upper or elongated side of the area under stress. Tension stress is an elongation of cell fibers and considered a positive strain, while compressive stress results in the shortening or compaction of cell fibers and considered a negative strain. Trupiano *et al.* (2012) surveyed the bending of 1-year old woody roots of *Populus nigra* saplings and measured the resulting strain, through lignin content and hormone analysis, at the beginning of vegetative growth (T1), active growth (T2), and dormancy (T0) at three sections below the root collar, above bending section (ABS), bending section (BS), and

below bending sections (BBS). Positive strain is found on the convex (elongated side) and negative strain found on the opposite side (negative strain) (Figure 2).

Figure 2. Model of the mechanical forces distribution. Distribution of longitudinal mechanical forces along the *Populus nigra* taproot at time T1 (left) and T2 (right). Average value of the mechanical force for the three defined sectors (ABS, BS, BBS) are indicated for both the areas being under tension-(positive values) and compression-condition (negative values) (Trupiano *et al.* 2012)

Hormone signaling stimulates the production of lignin in areas of greatest stress within most conifers, in reaction wood formed in compression. Lignin formation increases under compression while cellulose content decreases in bending tests of *Pinus radiata* (Schwerin 1956) and again from bending tests on *Populus nigra* taproots (Trupiano *et al.* 2012).

Molecular Response

As a result of mechanical stress, lignin formation in the areas of greatest stress is initiated by endogenous hormone concentrations. Trupiano *et al.* (2012) propose physiological and molecular associations for activation of specific mechanisms in woody poplar taproots. The activation and regulation of these hormones in response to stresses related to mechanical perturbation's are briefly described below.

Upon the induction of stress in woody poplar roots, 1-aminocyclopropane-1-carboxylate oxidase (ACCox), a catalyst in the production of ethylene, is shown in increased concentrations during the formation of ethylene. Ethylene is then involved in the biosynthesis of auxin and increases of cell division. The increase of auxin in the cell upregulates the concentration of gibberellins (GA) and stimulates the formation of lignin (Trupiano *et al.* 2012). Trupiano *et al.* (2012) also show that with the increased production of lignin on the concave side of bent woody taproots, an increase of lateral root formation on the convex portion is found. Lateral root formation was almost absent from the concave section of the root, primarily resulting from the increase of auxin on the concave surface and an increase in IAA on the convex surface. It has also been determined that woody plants respond to mechanical stress (bending) through up-regulation of ACCox and ethylene during the dormant season, initiating vegetative growth earlier in the active growing season, as compared to unstressed control plants (Trupiano *et al.* 2012).

This early “jump” on growth for the upcoming year is likely a survival mechanism of the plant in response to mechanical loading stress, initiated sooner in order to produce the required amounts of reactive tissue during active growth, once reproductive organs and vegetative growth has commenced. Throughout the active growing season, reaction wood formation continues, but little is known about how plant response and hormone signaling carries over into the second growing season. The chemical and physical properties of reaction wood formed by trees is just starting to be investigated, although the properties of reaction wood have been well researched in the wood products industry and wood science technology fields.

Tree Growth

Throughout the life of a tree, four primary functions are balanced to maintain plant survival and acclimation strategies to abiotic and biotic stress related events: photosynthesis, reproduction, mechanics, and hydraulics (Niklas 1992; Figure 3).

Figure 3. The balance of functions for tree survival of photosynthesis, mechanics, hydraulics, and reproduction, as proposed by Niklas (1992)

Beginning with seed germination, the first structure to emerge from a seed is the radical, from which the first taproot develops (Kozlowski and Pallardy 1997). Early expression of cells is undifferentiated and may take the form of root-apical or stem-apical meristematic tissue and differentiation occurs as hormonal signals attempt plant homeostasis (Sanchez *et al.* 2012). This differentiation produces one of the primary differences in root and stem tissue, being the organization of the central part of the root, the stele (Sanchez *et al.* 2012).

Root versus stem wood

Above ground and below ground woody plant tissues converge and differentiate in transition regions found throughout three primary tissue systems: vascular, ground, and dermal tissues (Esau 1977). Lyford and Wilson (1964) classify roots into one of two categories. Non-woody roots are thin, flexible roots that have not undergone secondary growth. These roots are found further from the main trunk and are primarily used for water and nutrient conductance, although the finer roots may account for up to 90% of the total root mass (Roberts 1976) and aid considerably in tree anchorage (Genet *et al.* 2005). Woody roots, also called structural roots, have undergone secondary growth, are typically found within six feet of the trunk in mature trees and are the primary structures responsible for tree anchorage and stability, although woody roots may extend further from the trunk in response to mechanical stresses and/or soil conditions (Stokes *et al.* 1995).

Tree tissues also differ greatly from root to stem depending on root age, tree species, and root physical properties (Yang *et al.* 2014.) Differences in tissue properties can be attributed to increased cellulose content and sugars found in the roots (Genet *et al.* 2005). Sanchez *et al.* (2012) discusses how the vascular arrangement within the root of dicot trees is centrally located within the stele (abaxially) and transitions laterally along the root into the adaxial position, found on the stem periphery. Cell microfibrils are strengthened by decreased cell size in the transition process, in anticipation of supporting vertical loading (Gardner 1997). James (2003) discusses that in areas of trees under stress, adaptive growth, such as reaction wood and asymmetric growth, is increased to relieve stress at that point. This could be the case in the area of the root-stem transition zone (RSTZ), as elevated radial growth can be seen in the cross sections of cut stump. This reasoning is in line with axiom of uniform stress proposed by Mattheck and Breloer

(1994), which states that trees are highly efficient organisms that optimize resources for long-term survival. Visually, adaptive growth to stress can be seen at the base of tree trunks where thickening occurs from supporting the greatest loads found in trees (James 2003). This area is also the oldest and strongest section of the tree. James (2003) also states that torsion is greatest in the base of the tree trunk, typically being circular in circumference, resulting from adaptive growth that is efficient at managing torsional strain (Figure 4).

Figure 4. Elevated radial growth and increased diameter at the base of an elm tree

Area of Interest

Little information is readily available in the literature that discusses the portion of the tree found between the area of convergence of roots and stem (at the root collar near ground level) and at the distal (vertical) point of the beginning of the trunk flare at the main stem. The Zone of Rapid Taper (ZRT), typically found within two meters horizontally at base of the tree, is where

the stem diverges into large structural roots and rapidly taper into smaller diameter roots (Layford and Wilson, 1964). Fayle (1983) defines a stem-root junction, found at the intersection of the main stem plate and structural roots, near the soil line, where a hinge point can be found after uprooting. After tissue convergence from root to stem, the base of trees experience increased radial growth (James 2003) from canopy stress, compared to the bole (main stem), as seen by an apparent swelling effect (Figure 4). This swelling phenomenon is thought to be the result of increased torsional strain at the base of tree (James 2003). Many terms describing this region exist and are used synonymously, sometimes applied incorrectly, throughout the various plant and tree science professions. For this study the term Root-Stem Transition Zone (RSTZ) will be applied to this area, which will include the root-collar, structural roots, and ZRT (Figure 5).

Figure 5. The root-stem transition zone (RSTZ)

Biomechanics

Tree biomechanics is the science of applying engineering principles to tree form and function (Niklas 1992). Dahle *et al.* (In Review) further define the field as seeking “to understand how growth and development leads to a structurally stable plant that can withstand environmental and gravitational loading over its lifespan”. The triangle of statics has been applied to assist in quantifying forces placed upon trees and responses to loading events (Wessolly and Erb 1998). The principle factors consist of the parameters of load (external force), form (load bearing parts) and materials (properties of green wood) (Figure 6).

Figure 6. The Triangle of Statics (Wessolly and Erb 1998)

Most data for tree material properties are derived from green wood sampling of various wood species and can be found in the Wood Products Laboratory publication: *Wood as An Engineering Material* (USDA 2010). This wood handbook is internationally recognized among wood science professionals, including construction engineers and tree biomechanical researchers. Inferences are made from green wood and clear specimen data found in the Wood Product Database, because little data is available for large, open grown shade trees (Kane 2014), possessing irregularities and decay.

Relevant tree biomechanical research on the effects of wind and loading events on tree tissue(s) has been conducted in order to examine how trees manage stress and the resulting

strain. At the canopy level, James (2003) describes the effects of wind and the resulting energy that is intercepted by the tree, utilizing complex sway motion and the phenomenon of mass damping, although damping remains the most unknown parameter in dynamic loading of plants (de Langre 2008, Moore 2014). In an effort to resist tissue deformation or failure from wind entering the upper canopy, energy is dissipated throughout the tree via strain movement by leaf deflection (Milne 1991), through branches (James 2003) and limbs into the main stem (Milne 1991). Brudi and van Wassenaeer (2002) discuss how only roots near the trunk of the tree were subjected to pulling forces during load tests, while Stokes and Mattheck (1996) found strain to dissipate from the main stem into the root-soil complex. Tensile stress of fine roots, which aids in the trees resistance to uprooting, has been quantified (Genet *et al.* 2013) as a function of cellulose content and matrix structural analysis of root system architecture (Dupuy *et al.* 2005). However, there is little information readily available that discusses or quantifies strain movement from the main stem into the structural root system.

Stress and Strain

Force may be induced by an array of abiotic or biotic factors, including atmospheric phenomena, natural occurring events and anthropogenic intrusions. As a tree bends in response to an applied load, the windward side of the tree stem is placed in tension while the leeward side opposite the force is placed in compression (Coutts 1983, 1986) (Figure 7).

Figure 7. Windward and leeward orientation in reference to loading on the upper stem

Stress (σ) is a measure of force per unit area and strain (ϵ) is the displacement resulting from loading a material, in reference to its original shape (Burgert 2006). Wood strength properties are greater in tension than compression, and vary by wood species (USDA 2010) and morphological level, in relation to mature and juvenile wood (Niklas 1992, Genet *et al.* 2005, Dahle and Grabosky 2010). As a tree disperses and manages energy resulting from loading events, a concert of strain management is initiated (James 2003). Newton's Third Law of Motion states, "for every action there is an equal and opposite reaction" (Cited by Niklas 2002) and helps explain how the potential energy intercepted by the tree is converted to kinetic energy. For the ease of data manipulation and analysis, tensile strain, or major strain, is typically a positive number. Compression strain, or minor strain, is typically a negative number.

The ϵ resulting from loading σ on any given material may be minor and return to its original position within short period of time, staying within an elastic limit that does not result in

deformation (Niklas 2002). As strain increases and exceeds the materials elastic yield point, plastic deformation occurs and the material will not return to its original dimensions (Burgert 2006) and structural integrity can be compromised. It is noted that reaction wood formation in living wood (trees) leads to increased wood properties, including higher resistance to deformation. Once the material's breaking point is eclipsed, bending failure occurs at the Modulus of Rupture (MOR), also referred to maximum stress. A material's MOR is the amount of strength or force required to cause failure in bending (Peltola 2006) and should not be confused with modulus of elasticity, or MOE (Dahle and Grabosky 2010). The limit of the elastic domain (Y) of most green wood for lumber producing tree species can be determined as the ratio of MOR over MOE (Bonnesoeur *et al.* 2016), found in the following equation in reference to the tree species wood material properties (USDA 2010).

Equation 1: $Y = \text{MOR}/\text{MOE}$

Where:

Y = Limit of elastic domain

MOR = Modulus of Rupture

MOE = Modulus of Elasticity

The Modulus of Elasticity (MOE) or Young's Modulus, is calculated using the following equation:

Equation 2: $E = \sigma / \epsilon$

Where:

E= modulus of elasticity (MOE)

σ = stress

ϵ = strain

The slope of the stress/strain curve is a function of stiffness (resistance to displacement) of the material, with a steeper slope representing resistance of the material to displacement (Burgert 2006). The proportional range of a materials elastic range is found under the slope of

the MOE curve, up to the yield point (point at which material begins to deform plastically).

Displacement (deformation) may occur through the elongation or compression of the material subjected to stress, and recovery time can vary within the elastic range (Burgert 2006) (Figure 8).

Figure 8. A typical stress/strain curve and associated properties (mathalino.com)

Bending moment

The application of an external force (or moment) on a structure across any portion of the span, such as wind or static loading on a tree stem, produces a response referred to as the bending moment (Neild and Wood 1999, Peltola 2006). Bending stresses are compressive and tensile and found to be greater on the peripheral of material (Spatz and Pisterer 2013). Bending moment calculations are a critical factor in the evaluation of tree stability during static loading tests to determine stem breakage thresholds (Neild and Wood 1999, Brudi and van Wassenauer

2002). Bending moment determination in static pulling tests is also dependent on the height of the attachment to the main stem (Brudi and van Wassenae 2002, James *et al.* 2006), as some stem curvature along the main stem occurs since the attachment to below ground parts is rigid (Coutts 1983). Peltola (2006), in destructive sampling, utilizes a bending moment equation in static load tests, considering the force applied from both dynamic (wind) and static (gravity) loading:

$$\text{Equation 3: } BM_{\max}(z) = F_1(z) \cdot z + F_2 \cdot x(z)$$

Where:

F_1 = Wind-induced force

F_2 = Gravity-based force

z = the height on the stem (in meters) and

$x(z)$ = the horizontal displacement of the stem from the upright position (in meters).

Young's modulus (MOE) can be calculated from the initial linear part of the stress-strain curve and stress is obtained by dividing force (F) by cross-sectional area (CSA) of the load bearing structure (Bjurhager *et al.* 2008).

However, to ensure that the likelihood of tree failure and tissue deformation is minimized, a specific bending moment is needed that will be compatible with the wood materials' Y (proportional limit) and within elastic domain for the tree species. Since there are few published values available for Y for large, open grown trees, (Kane *et al.* 2014), bending moment and Y could be used in conjunction with root-plate tilt data to better quantify the movement of strain across the RSTZ. Brudi and van Wassenae (2002) have proposed the following stress equation for nondestructive pulling trials, using a bending moment calculation to account for the height of the attachment and the circumference of the cross section of attachment. Equation 4 can be utilized during nondestructive pulling trials to determine loading stress at a particular cross section, utilizing an elastometer for strain measurement.

Equation 4: $\sigma = M_b \text{ (bending moment)} / W \text{ (cross section modulus)}$

where: $M_b = F * (H - S) * \cos \alpha$

$W = d_1^2 * d_2 * \pi / 32$

with:

σ = stress in N/mm²

F = force in N (dynamometer)

H = height of cable attachment

S = height of elastometer, measuring plane

α = angle of steel cable

d₁ = trunk diameter, 1 m above ground

d₂ = trunk diameter perpendicular to d₁, 1 m above ground

Intercepted forces create a turning moment at the stem base that is resisted by stiffness in the root plate (James *et al.* 2013), also called the structural root zone. As tree inclination is altered by loading, the rotational angle (torsion) is approximately found where the trunk centerline intersects the ground plane (Neild and Wood 1999, James *et al.* 2013). Neild and Wood (1999) report that as a tree bends, roots flex because the attachment to the ground is rigid, but there is currently no supporting evidence into the amount or direction of strain across the RSTZ. It is also noted that torsion has been greatly omitted from literature in past studies (Moore 2014, and Dahle and Grabosky 2012).

A tree's resistance to uprooting (or catastrophic root failure) is the combination of the horizontal force of wind and the vertical force of gravity (including stem and canopy mass and/or snow) combined with the anchorage strength of the root system and weight of the root-soil plate (Peltola 2006). Stokes and Matheck (1996) determined that the tap roots of certain tree species and tree age also contribute to a tree's resistance to uprooting, although the species studied primarily consisted of plate like and tap-rooted species. Primary root system architectural types are discussed later in this report. One of the basic principles applied to this relationship of force (force and gravity) is Hooke's Law, which states that for an elastic material, such as wood, the

stress (σ) created is proportional to the strain (ϵ) within the materials elastic limit (Niklas 1994, Burgert 2006). Burgert (2006) further defines stress as a measure of force per unit area and strain as the displacement resulting from loading a material, in reference to its original shape. The mathematical computation of Hooke's Law is found in Equation 5:

Equation 5: $F = -k * x$

where:

F = the restoring force of the material

k = the force constant

x = the displacement from its equilibrium position

The maximum uprooting resistance for an individual tree can be estimated using the individual tree characteristics of biomass, diameter at breast height (dbh), and tree height, along with parameters associated with soil properties and root-plate characteristics (Peltola 2006, Neild and Wood 1999). Tree failure will occur if the uprooting moment exceeds the respective maximum resistive moment (Ray and Nicoll 1998). Bending moment can increase as the upper canopy produces more biomass, increases in height and the crown is exposed to greater wind velocities (α) (Niklas and Spatz 2000) (Figure 9).

Wind - the heavenly force

Figure 9. Wind velocity (α) increases with taller structures (Niklas and Spatz 2000)

Danjon and Fourcaud (2009) developed a model to examine the root-plate and stem tilt in *Pinus pinaster* in sandy soils found in south-western France. Although the image in Figure 10 may not be fully representative of large amenity trees found in North America, the visualization depicting possible stress/strain relationships, soil interactions and stem deflection is represented.

Figure 10. Stem and root-plate tilt of *Pinus pinaster* in sandy soils (Danjon and Fourcaud 2009)

Wood Properties

The anisotropic properties of wood allow for directionally dependent variations of wood strength within the material along three principle axes, in relation to grain orientation (Figure 11). The axial direction is found parallel to grain orientation, while the radial axis is perpendicular to the axial axis and the tangential axis is tangent to the growth rings. According to Spatz and Pisterer (2013), the most important mechanical property of trees related to stability are those in the axial direction.

Figure 11. Anisotropic properties of wood (materials.unsw.edu.au)

Strength properties are influenced by decay resulting from wounding occurring from insect and pathogens, or mechanical injury from environmental and/or human induced sources. Wood strength properties can vary from tree-to-tree of the same species as result of reaction wood formation and variations in annual growth rings due to changes in seasonal growth that alter moisture and density (Spatz and Pisterer 2013) and age of maturity in branches (Dahle and Grabosky 2010). As discussed earlier, reaction wood formation in areas of increased stress can possess greater material properties and increased resistance to bending forces (Figure 12).

Figure 12. Schematic drawing representing strains in a tree bent under wind loads (From Spatz and Pisterer 2013)

Soils

Soil structure, soil type, bulk density, cohesion (Genet *et al.* 2005) and soil moisture (Smiley 2014) play a key role in tree stability. Dupuy *et al.* (2005) determined that uprooting mechanisms vary by soil type, as predicted using Finite Element Modeling (FEM). Sampled trees in clay soils uprooted in manner that rotated on an axis directly below the stem while in sandy soils the rotational axis was shifted leeward (Dupuy *et al.* 2005). This study, although theoretical in nature, provides data that can be compared through field trials for further refinement to tree risk assessment standards. Figure 13 shows bending moments generated for the four root types and theoretical soils.

Figure 13. Maximum bending moment of four different root systems in four theoretical soils. (Dupuy *et al.* 2005)

Roots System Architecture

The mechanical properties of roots have been found to vary greatly depending on the architecture of the root system and location of roots within the soil horizon. Four principle root architectural systems are presented by Dupuy *et al.* (2005), generated by Finite Element Modeling (Yang *et.al.* 2014). The heart root system (Kostler *et al.* 1968), tap root system, herringbone root system (Fitter 1990, Stokes *et al.* 1996) and the plate like root system constitute the majority of tree root architecture systems, with the heart root system most typically found in the temperate Appalachian region for angiosperm species (Dupuy *et al.* 2005) (Figure 14). Stokes *et al.* (2000, 2005, & 2006) determined the most resistant species to overturning were those possessing a heart root system, including many branched, oblique, horizontal and lateral roots.

Figure 14. The heart root system (a); (b) tap root system; (c) herringbone system; (d) plate like root system. (Dupuy *et al.* 2005)

Descending roots are concentrated mainly around the base of the trunk (Moore 2008).

The tap root is considered a first order root and the second order roots are the main lateral roots that arise from the first and progress in order to the fine, absorbing roots (Fayle 1983, Moore 2014, Stokes and Mattheck 1996). Genet *et al.* (2005) found that these fine absorbing roots have increased tensile strength and cellulose content compared to thicker roots. This finding suggests that finer roots held in tension are comparable to other findings and assist in the support role of managing load from the root plate and structural roots.

Tree Stability

Undetected tissue deformation can occur from loading stress that may predispose the tree to failure at a later time. Internal shear stress, structural root damage and fine root slippage in contact with the soil can alter tree stability and can go undetected during normal tree inspections (James *et al.* 2013a). Coutts (1983, 1986) reported that windward roots held in tension are the most important component of root anchorage, followed by the weight of the root-soil plate, soil cohesion and bending strength of leeward roots.

A nondestructive dynamic wind survey conducted by James *et al.* (2013a) on mature tree species representative of specimens found in Victoria, Australia (minimum tree height 15 meters) to determine tilt (inclination) of the root-plate during dynamic and static loading events. Utilizing tilt sensors placed on the test trees, researchers found that after 2 weeks of monitoring, maximum tilt values at the base of the trees were between 0.09 and 0.44 degrees, with a maximum wind speed of just under 48 kph (30 mph). Maximum root plate tilt in a second group of trees ranged between 0.09 and 0.88 degrees, with maximum wind speeds recorded at 54 mph. James *et al.* (2013a) also measured maximum root plate tilt in ten Eucalyptus trees by nondestructive static pulling and reported that none of the trees exceeded 0.6 degrees in maximum tilt. Average DBH(m) and height(m) were 0.535m (21.06 in) and 22.22m (72.9 ft) respectively with an average maximum tilt of 0.3 degrees and maximum applied moment ranges from 47.2 to 84.8 kNm. They concluded that the peak tilt of 0.90 degrees is below the threshold for root damage and over-turning moment for the selected trees.

Mechanical Loading (Static load test)

Static load testing has been used to simulate natural loading events and can be conducted without compromising tree health and stability (Brudi and van Wassenae 2002). Loading stress is applied on selected trees through the use of a static loading protocol, a research method that originally was used in forestry research (Coutts 1983). Static pull tests have been implemented into tree biomechanics and open-grown trees to measure the amount of force required to pull trees to failure (Peltola 2006, James *et al.* 2013a, Smiley 2014), and to test the effects of root loss on short term tree stability (Smiley 2014). Static pulling trials are implemented to test trees nondestructively, (Brudi and van Wassener 2002, James 2013a, Sebera *et al.* 2014) to estimate overall tree stability during formal tree risk assessments (Figure 15).

Figure 15. Typical static load test setup. (Brudi and van Wassener 2002)

Although it is documented that static loading on tress does not fully consider all the dynamic parameters of wind loading (Moore 2004, Peltola 2006, Kane and Clouston 2008), for our research static loading should provide meaningful results used to determine a baseline for strain movement in a concentrated location. James *et al.* (2006 and 2013a) discusses the effectiveness of static pull tests in order to establish baseline data and validate field tests, although these tests are designed to simulate dynamic wind loading. The main draw-back to static loading trials is the pulling force is concentrated in one specific area and the tension applied does not allow for natural tree sway. Results from static loading trails have been published, with most trials destructively pulling trees to failure. Kane and Clouston (2008) tested the likelihood of failure in large shade trees of the genus *Acer*, comparing stem failures of single stemmed and codominant stemmed trees. Moore (2014) reviews methods for static pulling by multiple researchers and the progression of using static loading trials in an effort to quantify the dynamics of wind and tree response, with the primary goal of providing diagnosis for tree stability assessment.

Tosi (2007) suggested that static tree pulling has been known to overestimate the force required to uproot trees, while Kane (2006) comments that most tree pulling trials have been performed on trees exhibiting little or no visible structural defects, while the amenity trees of most concern are rarely found in pristine condition. James *et al.* (2013) also concluded that a relaxation effect in the roots can sometimes occur during static loading trials, creating a stair-step effect in data analysis, which is not common under dynamic conditions. Ow *et al.* (2010) states static pull tests allow for testing in a consistent manner, in regards to root plate strength determination. To avoid root damage during nondestructive static pulling trials, Brudi and van Wassenauer (2002) recommend that an inclination of 0.25 degrees should not be exceeded, however, James *et al.* (2013a) concluded that a higher threshold of 0.90 degrees will not compromise tree stability or result in root damage. The 0.25 inclination to the trees natural lean is sufficient to 40% of gale force (wind force) enacted on a tree (Brudi and van Wassenauer 2002). Sebera *et al.* (2014) successfully demonstrate static load trials and resulting strain patterns did not result in tissue deformation while testing a twenty-year old walnut tree (*Juglans regia* L.). However, as a result of static loading trials carried out on Norway spruce (*Picea abies* L.) trees, Jonsson *et al.* (2006) suggested that an elastic range of the root plate is very small or may not exist at all because of repeated loading

Torsion in static tree pull testing is often disregarded during strain analysis of the stem (Moore 2014) and branches (Dahle and Grabosky 2012). As torsion is likely induced during dynamic loading and a factor related to tree stability, an estimation of torsion induced during static load tests (Dahle and Grabosky 2012) can be examined during this research.

Strain measurement

Equipment and devices are being continuously developed to measure strain on various materials. James and Kane (2008) have utilized strain gauges attached to the trunks of trees to calculate MOE during wind events over long periods of time. In their paper, James *et al.* (2013) discuss various tools used in measure tree tilt, including displacement transducers, strain sensors, prism based systems, tilt sensors, inclinometers, lasers, and video based technology, while Brudi and van Wassenaeer (2002) utilized an elastometer to measure alterations in length of tree tissues during static loading trials.

Strain can be determined utilizing digital image correlation (DIC) techniques, which is widely are used to nondestructively test two and three dimensional surface deformation (Godara *et al.* 2009, Guan *et al.* 2014, Johansson *et al.* 2013, Tyson *et al.* 2002, Sebera *et al.* 2014) on material such as wood (Bjurhager *et al.* 2008). Dahle (2015 Under Review) has found the application of DIC strain mapping can be successfully used to nondestructively observe strain movement in trees, using bark as a surrogate for strain in the xylem.

Digital Image Correlation (DIC)

Strain patterns can be measured with digital image correlation (DIC) software to calculate deformation of 2 and 3 dimensional surfaces (Tyson *et al.* 2003, Serbera 2014). Optical focal sensors map the movement of pixilated speckling (strain) that result from the applied load (stress) and surface deformation. Predefined reference points located on the surface tissue are used to calculate the displacement of speckling, to an accuracy of .001 mm. The resulting data can be visually enhanced to show color-coordinated compression and tensile strain (Figure 16a), coverage areas (Figure 16b) as well as vector displacements to show strain movement across the

sampled tissue surface (Tyson *et al.* 2002). To detect surface strain, a white base coat (water based latex paint) is applied to the bark surface, followed by black speckling to cover roughly 50% of the surface (Figure 17).

Figure 16a and 16b. ARAMIS optical image correlation system image (right) and graphical output (left)

Figure 17. Stochastic paint speckling pattern utilized for RSTZ strain mapping with the ARAMIS optical image correlation system

Cintron and Saouma (2008) discuss the underlying principles required for correct calculation of strain using DIC software and published step-by-step procedures for initiating, conducting and interpreting DIC strain related research. The primary components for accurate

strain determination with DIC consists of calculation of digital image resolution (pixel columns(c) $\times$ pixel rows(r)), width(w) and height(h) of test specimen, distance between camera and specimen(d), focal length of camera lens(f) (Figure 15) and the characteristic stochastic speckling paint pattern (Figure 18)

Figure 18. Variables required for proper DIC strain determination. Digital image resolution (pixel columns(c) $\times$ pixel rows(r)), width(w) and height(h) of test specimen, distance between camera and specimen(d), focal length of camera lens(f). (Cintron and Saouma, 2008)

The speckling pattern is critical for proper measurement of strain across the tested surface and DIC prefers three primary diameters of speckling that encompass various pixel sizes: small (10 pixels), medium (20 pixels) and large (30 pixels) (Cintron and Saouma, 2008). The speckling pattern can be applied with black spray paint, holding the paint can over the object and spraying a mist on the object. Larger diameter speckling is applied by depressing the paint nozzle in a 45 degree angle from the normal direction, to provide contrasts between the speckled diameters and to achieve optimal pixel coverage.

Utilizing DIC strain mapping techniques on biological plant organisms, such as trees, repeated testing can occur over a period of time, leaving the tree and associated components in their natural environment (Figure 19). One advantage of utilizing a nondestructive method for sampling wood and surface strain data from full field measurements is that Finite Element Models data can be directly compared (Tyson *et al.* 2002) and empirical data established by the research community effectively compared (Sebera *et al.* 2014). It is noted in the literature that because of differences in the properties between the white, contrasting base paint layer and the upper surface of the bark, these differences could affect the accuracy of strain mapping and resulting analysis (Cintron and Saouma 2008).

Figure 19. ARAMIS camera set up for strain measurement at the root-stem transition zone

Bark

As the transfer of strain patterns during static pulling trials will be examined on living trees, DIC can be utilized to map strain by applying the paint speckling directly on the bark of mature trees. Dahle (In Review) found no difference in the measured strain with bark in place

compared to directly on the xylem after removal of the bark. While this work was on thin bark samples of 2-4 year old *Quercus rubra* (L.) stump sprouts, Dahle *et al.* (In Review) believes that with the minimal loading taking place during our sampling, strain measurement with bark intact will be sufficient. Kane (2014) found in pulling tests that bark thickness may not be accounted for. However, Coutts (1983) reports that bark contributed little strength in roots. Although current and past research seems to differ on the exact physical properties and mechanical contribution of strain transfer in trees (Sebera *et al.* 2014, Dahle In Review), this research did not aim to directly measure strain on the bark surface, but in fact determine patterns of strain movement within selected tree architectural parts. The geometry of tree bark is complex and not well understood. Further research will be required to determine the extent and nature of tree barks' contribution to tree biomechanics.

Root excavation

Excavation of the rooting zone adjacent to the base of each tree was required in order to expose the root tissue surface that is in contact with soil and organic matter. Danjon *et al.* (2005, 2008) discusses root evacuation methods, including uprooting and hydraulic excavation that tend to damage and kill structural and absorbing roots. For nondestructive testing, root excavation can be completed utilizing a supersonic air tool as described by Smiley *et al.* (2014) and Danjon *et al.* (2005). Our methodology only exposed the root-stem transition zone and the first order roots for up to 1 meter from the trunk. We exposed the top half of the root system only, and as such we did not alter tree stability. Root excavation and/or invigoration is used to decrease tree decline associated with compacted or compromised soils (Fite 2008) and appears not to alter tree stability.

Research Questions

This research utilized static pull tests to map how load is transferred from the stem, across the RSTZ into the structural roots. We used the DIC to measure strain, using bark as surrogate for load distribution. As load enters the root system it will likely be spread into the first order roots resulting in compressive strain on the leeward side and tensile strain on the windward side. Additionally, roots in the tangential direction will likely exhibit tensile strain.

H1_o: Leeward strain (ϵ_L) will be compressive

H1_a: ϵ_L will not be compressive

H2_o: Windward strain (ϵ_W) will be tensile

H2_a: ϵ_W will not be tensile

H3_o: Tangential strain (ϵ_T) will be tensile

H3_a: ϵ_T will not be tensile

As the ARAMIS system can map the magnitude as well as direction we will determine if the strain is the same in each of the direction of the root system.

H4_o: $\epsilon_L = \epsilon_W = \epsilon_T$

H4_a: $\epsilon_L \neq \epsilon_W \neq \epsilon_T$

The expected outcomes of this study will include: 1) a determination of how sampled trees distribute applied load and resulting strain across the root-stem transition zone; and, 2) how

strain is transferred into first order roots in the windward, leeward, & tangential directions in relationship to the pull.

The basis of this research is to determine baseline data concerning how strain ε from static loading trials moves from the main stem, across the RSTZ and into the first order roots. This research may afford arborists, foresters and urban forest managers further insight into how trees manage σ through ε transfer mechanisms.

Methods

Site & Tree selection

Fifteen mature pin oak (*Quercus palustris* Muenchh.) trees located on the Evansdale Campus of West Virginia University in Morgantown, West Virginia, USA were sampled during late spring-early summer 2015 to measure the stress required during static load tests for stem deflection to 0.1 degree from natural lean and mapping of the resulting strain. Sampled trees were located in a lawn type setting in close proximity to other pin oak trees and structures. The pin oak tree population found on this section of the Evansdale Campus range in age from approximately 35 to 45 years. The test site was chosen as it provides a uniform selection of trees growing in an altered/built up environment, typical of urban development (Figure 20). Static loading tests were conducted on dates starting on May 28, 2015 through June 24, 2015.

Figure 20. Location map of survey trees, Evansdale Campus at West Virginia University, Morgantown, WV, USA

Incorporating the Level 2 Basic inspection for the Best Management Practices for Tree Risk Assessment protocol (Matheny and Clark 2009), individual trees were selected based on physical attributes that would minimize risk to the general public during and after static load testing. Desired characteristics included lateral distance between trees to reduce crown deflection with neighboring trees during static load tests and minimal site disturbance under the drip line of the canopy that may influence root architecture and tree stability. Such undesired disturbances include permanent/impermeable surfaces (sidewalks, paved access) in close proximity to the structural root zone and past construction related activities (trenching, construction) that could influence the tree(s) during loading trials. Consultation with WVU's campus arborist regarding maintenance history of the trees, general tree health, and previous site modifications were considered during tree selection. The selected trees were growing in a maintained lawn type setting, with most of the root-stem transition zone exposed for a majority of the trees (Figure 21). To facilitate the static pulling line, anchor trees were chosen for each sampled tree, with multiple test trees being assigned the same anchor tree. Anchor trees were also selected using similar criteria for use of cable attachments to facilitate loading trials.

Figure 21. Typical landscape found in test area around survey trees

Prior to conducting loading trials on each tree, lower crown cleaning was performed to remove dead and/or hanging limbs that could interfere with rigging lines and sampling

equipment or elevate the risk of tree parts falling during testing. Selected limbs were also removed on a few sample trees to provide clearance for pulling line and/or rigging attachment(s). The removal of aerial parts prior to preparing the trees for testing also insured that tree limbs and debris did not scar the prepared surfaces on the area of interest.

Tree Measurement & Preparation

Above ground tree measurement data was collected, including diameter at breast height (dbh, 1.4 m above the base of the tree) (mean = 51 ± 7 cm), stem diameters at 3cm increments, total tree height (mean = 18.5 ± 4.2 m), crown spread (mean = 13.1 ± 2.7 m) and the horizontal distance between the main stem of the test trees and their neighbors. Incremental stem diameters were measured starting at dbh to within 15 cm (6 inches) of ground level using a Criterion RD 1000 laser measuring device (Laser Technology Inc., Centennial, Colorado. USA). To ensure proper incremental diameter measurements along the main stem, thin strips of cut plywood with increment numeration were attached vertically near each RSTZ orientation (Figure 22). The Criterion RD 1000 was limited to a maximum diameter measure of 104 cm (41 inches), therefore in some cases trunk flare exceeding 104 cm (41 inches) near the ground level was not collected. Tree height measurements were collected with a TruePulse 200B laser hypsometer (Laser Technology Inc, Centennial, Colorado. USA). Average crown spread was determined using a measuring tape, averaging the longest side of the canopy from the main stem with the measurement of the crown found perpendicular to the longest side.

Figure 22. Numerated increment strips placed vertically on the main stem for each surveyed tree and root for diameter measurements

Surveyed root divergence at the respective RSTZ orientation from the main stem and azimuth of crown spread were collected using a hand held compass and entered on a data collection form (Appendix A). First order root divergence from the main stem was defined as the direction the sampled root departed from the orientation of the RSTZ on the main stem, found by the surveyor standing over the respective RSTZ, with back against the test trees, and aligning the handheld compass with the direction of the main root, using the center of the main stem as a reference.

Three roots per test tree were examined and RSTZ orientation labeled as follows: The number 1 root in the direction of the pulling force (leeward), the number 3 root opposite the direction of the pull (windward), and the number 2 or 4 root found tangential to the direction of the pull, although the tangential root was could found on either side of the pulling direction, as depicted by root morphology or physical limitation (Figure 23).

Figure 23. Directional schematic for static loading tests

Excavation of the rooting zone adjacent to the base of each tree using a supersonic Air Knife (Allison Park, PA. USA) exposed the first order roots for one meter distally from the base of each tree trunk. The average depth of soil excavation for each root was approximately 15 cm below grade. Soil excavation was required in order to expose the root tissue surface that was in contact with soil and organic matter. Danjon *et al.* (2005 and 2008) discuss root evacuation methods, including uprooting and hydraulic excavation that tend to damage and kill structural and absorbing roots. For nondestructive testing, root excavation can be completed utilizing a supersonic air tool as described by Smiley *et al.* (2014) and Danjon *et al.* (2005). Our methodology exposed the root-stem transition zone and the top half of first order roots for up to 1 meter from the trunk. Root excavation and/or invigoration is used to decrease tree decline associated with compacted or compromised soils (Fite 2008) and appears not to alter tree stability.

Fine woody roots were removed with small hand pruners to provide a direct line of site of the exposed structural roots. DIC imagery requires a moderately smooth surface, as thick ridges, deep furrows and sharp angles found on surfaces can create a shadowing effect and

obstruct the view from one or both cameras. On some larger roots and deeply furrowed areas on the RSTZ, thick bark ridges (secondary phloem) were reduced by means of a draw knife and care was taken to avoid damaging the primary phloem. Areas of moss or organic matter were removed with a wire brush. A final pass with the Air Knife provided a clean surface for paint application and adhesion. After initial surface preparation, a white background was applied using a flat, non-glossy paint, followed by a stochastic black speckling pattern (Sebera *et al.* 2014, Dahle In Review) and was allowed to sufficiently dry, typically for a minimum of 6 hours prior to testing (Figure 24).

Figure 24. Stochastic paint speckling pattern utilized for RSTZ strain mapping with the ARAMIS DIC system

After the paint was allowed to dry, reference marks were placed with a permanent marker at 3 cm increments along the main axis of the root, starting near the top edge of the painted RSTZ and continuing distally along the main root. An identification card and scale bar was also created for each sampled root to assist in post processing and cataloging of data (Figure 25). A digital image of each prepared root was captured prior to sampling. Once roots were prepared for sampling, testing of the respective survey tree occurred within 24 hours.

Figure 25. RSTZ and root prepared for sampling, with painted surface, reference marks, scale bar and identification card

Root mapping was conducted in order to record quantifiable data related to exposed tree root architecture. Survey trees and roots were classified for sampling purposes using the following alphanumeric nomenclature:

Tree number: A tree identification number was predetermined for each potential survey tree and recorded on a survey map. Fifteen surveyed trees are included in this report. Although 17 trees total were sampled, tree numbering does not correspond with the order trees were sampled, due to the disqualification of certain trees that did not meet initial protocol requirements.

Root identifier: Tree roots were assigned a number 1 through 4 according to the location of the root on the tree in relation to the pulling force., with 1 = leeward root, 2 and 4 = tangential roots, 3 = windward root (Figure 23).

Root reference to side: A, B, and C notation was applied to the side of the root, in reference to the main stem when facing the tree. A is in reference the top of the root, while B

and C were applied to the right and left sides of the root, respectively (Figure 26). For this specific project, only the A, or top side, of the root will be examined.

Camera location: The location of the DIC camera system was notated by the designated Root reference to side notation described previously, however numerals were added after the A,B,or C notation in reference to the number of times DIC imagery was captured. The additional numeration was required if an error occurred or if additional trials were required during the loading trial of the sampled root.

Incremental reference marks: Incremental tick marks were located at 3cm and marked starting at from the top most tick mark within the painted region and proceeded down the RSTZ and distally along the roots (Figure 26).

Figure 26. Incremental tic marks along a prepared surface and root reference labels. “A” refers to the top of the root when facing the tree, “B” the right side, and “C” the left side

Root profile data was mapped and recorded in reference to the tic mark identification described above, which included the steepness of the RSTZ, total tic marks found above and below ground, total sampled root length, and the point(s) at which the ground line intersected the sampled root. Data was recorded on a root profile data collection sheet for each tree (Appendix B). Also noted were any irregularities, such as callous tissue from lawn maintenance, shallow roots, cavities and/or decay, and if all of the sampled root was not completely subterranean.

Soil moisture was recorded the same day of sampling for each tree and respective root. Using a Campbell Scientific HydroSense soil moisture probe (Campbell Scientific. Logan, UT,

USA) soil moisture was recorded at three locations for each root. Using the same root reference as in Figure 26, location A was found at the point distally from the root, just past the excavated soil. Location B was found on the right side of the root and location C on the left side of the root (Figure 27).

Figure 27. Soil moisture measurement at the “B” side of exposed root

Root diameters were measured and recorded across the width of the exposed surface at the corresponding incremental tic mark of the root at using a twelve inch digital caliper (Model CD-12”C, Mitutoyo Corp., Kawasaki, Japan). Where the root adjoined the main stem past the root-stem junction, caliper readings followed the edge of the root seam until no definable root demarcation was found on the main stem. At this point on the root or RSTZ, caliper readings were taken along two vertical paths, using the last definable root edge, to the top of the last tic mark on the painted RSTZ (Figure 28, unpainted for reference). The root diameters recorded are

only for the horizontal diameters and do not account for changes in root symmetry since the entire root was not exposed.

Figure 28. Yellow lines indicate general path followed for diameter measurements across the RSTZ when no definable root was present

A 44 kN capacity electric winch (Warn Industries, Inc., Clackamas, Oregon, USA) was attached to the base of the anchor tree using a webbed sling (LiftAll, Landisville, PA, USA) with a 52 kN capacity and two 44 kN capacity steel shackles. Amsteel Blue metal fiber rigging line (Samson Rope Technologies, Ferndale, WA, USA) was attached to the winch cable and steel shackle (Figure 29).

Figure 29. Typical anchor tree and winch attachment set up used in static loading trials

To concentrate the static load and produce a measureable bending moment at the base of the tree, the attachment height on the test tree was selected based on tree architecture. A second webbed sling was placed on the main stem using a basket hitch, below any codominant branching or lateral limbs that would affect the pulling process or cause damage to the test tree. The pulling force was recorded using a 44 kN capacity load cell (Interface, Scottsdale, AZ, USA), which recorded pulling force at 20 frames per second (fps). The load cell was attached on both ends via steel shackles at the end of the pulling line nearest to the sample tree and to the webbed sling on the sample tree (Figure 30). The height of the pulling line attachment and the diameter of the stem at the point of attachment were recorded.

Figure 30. Typical rigging attachment and load cell setup for loading trials

The pulling line angle (θ) was calculated using the measurements of attachment height (Height_A) and horizontal pulling distance ($\text{Dist}_{\text{Pull}}$) from the base of the sample tree to the base of the anchor tree, using Equation 5. Three sides of a triangle are required to determine the angle of the pulling line, thus the pulling line distance ($\text{Dist}_{\text{PullLine}}$) was calculated using Equation 6. Comprehensive data is found in the Results section of this report.

Equation 5. $\theta = \cos(A) = (b^2 + c^2 - a^2) / 2bc$

Where

θ = pulling line angle

A = the resultant of the fraction equation

Equation 6. $a^2 + b^2 = c^2$

Where

a = $\text{Height}_A(\text{m})$

$$b = \text{Dist}_{\text{Pull}}(\text{m})$$

$$c = \text{Dist}_{\text{PullLine}}(\text{m})$$

The recorded measurements of force (F) and pulling line angle (θ) were used to calculate the applied bending load (P) (Equation 7), and carried into equation 8 along with pulling line attachment height (Height_A) to calculate the bending moment (M_{Bend}).

Equation 7. $P = [\cos(\theta) * F]$

Where

P = Bending load

θ = Pulling line angle

F = Force

Equation 8. $M_{\text{Bend}} = P * \text{Height}_A$

Where

M_{Bend} = Bending moment

P = Bending load

Height_A = attachment height

To measure tree tilt/inclination at the stem base, a 22.9 cm long digital level (Husky, Atlanta, GA, USA) was mounted on the tree, with the center of the level 42.5 cm above the ground, 180 degrees opposite of the pulling direction. Two flat-topped aluminum nails were affixed to the tree to attach the digital level, at distances 35.5 cm and 49.5 cm above the ground. A digital video recorder was positioned to record the measurement of the digital level and to capture audio during each pulling trial for use in post processing (Figure 31).

Figure 31. Digital level and camera placement for loading trials

The pulling azimuth (direction of the winching line from the test tree to the anchor tree) was determined by use of a hand held compass and recorded.

The root divergence was calculated for each sample root in respect to RSTZ orientation found by difference in angle of departure from the main stem in relation to the pulling direction. For the leeward and windward RSTZ roots, root divergence was calculated as the departure from the pulling line direction (azimuth degrees). Tangential root divergence was calculated by the angle of departure from the plane found 90 degrees from the pulling direction (Figure 32).

Figure 32. Root divergence from the main stem for the windward RSTZ orientation during static load test. The level and orange string are placed opposite of the pulling direction, 180 degrees from the anchor tree

Once the load cell and all rigging devices and pulling lines were properly installed on the tree for loading, the ARAMIS DIC camera system (GOM, Braunschweig, Germany) was positioned over the respective RSTZ and root, similar to the protocol described in Sebera *et al.* (2014). Refer to Figure 29 for typical static loading setup used for this research.

Figure 33. Diagram of static pull test applied to induce a 0.1 degree inclination for strain measurement across the RSTZ and structural roots in the windward, leeward and tangential directions. Electric winch (A), load cell (B), ARAMIS camera system (C), digital level (D), digital audio/video recorder (E), and data acquisition and processing station (F)

To reduce the occurrence of sun and shading effects on images captured through DIC data collection, a portable shade tent was installed over the sampling area, or a small tarp was positioned over the sampling area and camera system (Figure 34).

Figure 34. Shade tent installed over RSTZ sampling area

Initial setup and calibration of the ARAMIS DIC camera system was carried out using a working distance (d) of 180 cm between the center of the test root and the camera. Focal length of camera lens (f) was 60cm and found by dividing the working distance (f) of 180cm by 3. Each camera was placed 30cm along the support arm from center of the arm. The aperture for each camera was set fully open to allow the maximum amount of natural light into the focal area and then adjusted accordingly to display proper coverage of the prepared sampling area. Each camera was focused to properly display the selected area on the DIC computer screen. The DIC system was calibrated using a $350 \times 180\text{mm}^2$ calibration panel (Model P04063, GOM, Braunschweig, Germany) (Figure 35), held at the correct working distance from the camera. Calibration deviations were below the recommended 0.03mm during all tests.

Figure 35. Calibration board (Model P04063, GOM, Braunschweig, Germany) used during static load tests for DIC calibration

Occasionally the camera system and DIC software required recalibration to meet deviation requirements because of moving the camera system between respective RSTZ orientations or unpacking of DIC equipment from the previous days' sampling. Following recalibration prompts from the DIC software, either a full calibration or “quick” calibration protocol was executed in order to resolve deviation errors. In some instances, paint speckling was applied to meet deviation requirements or the focus adjusted on the camera(s).

Active pulling process

Once the DIC camera system was initialized and the initial reference point on the RSTZ was found for image correlation and calibration deviations met, the pulling line was attached to the winching device and line adjusted to allow for about three to four feet of slack. The digital level and load cell were then calibrated and the digital camera began to record. To synchronize the load cell measurements with the DIC image recordings, a manual force was applied to the line for a period of approximately 5 seconds and then released, causing a distinct sudden drop in

load cell measurement that coincided with the initiation of DIC image collection. The winching technician immediately started operation of the electric winch. The winch line was retracted until the digital level reached 0.1 degrees inclination. The winch line was relaxed and the digital camera was stopped. The specific loading trial and DIC project was saved on the hard drive and initial processing was carried out to confirm coverage of the sampled area met correlation requirements. Finally, the load cell data was saved and archived for post processing. A total of three roots per tree were sampled for a total of 6 pulls per tree. Post processing of field data was completed by combining the time signatures of the load cell data (recorded at 20 readings per second (Hz)), and DIC strain stages (collected at 2 frames per second (fps)) with the audio/visual cues from camera collection.

Digital Image Correlation Processing

The reference tic marks (3cm apart along the RSTZ) were used to establish a reference point for analysis within the RSTZ. R000 was assigned to the center of the concave point along the curvature (inflection point) of the RSTZ. This point was the center of concave transition curve, near the tapering swelling effect of lower stem and was found by placing straight edges along the top edge of the structural root and main stem. The resulting intersection in the center of the concave region found was designated as the reference point, R000 (Figure 36). Since trees and roots are curved surfaces and limit the application of straight edged tools for this task, the contoured images produced in the ARAMIS system were utilized for determining the reference point R000, as seen in Figure 32. Resulting images were uploaded into MS Paint and adjustable straight edged rectangles were laid over to the respective surface. The reference point found nearest the intersection of the two planes was labeled the point of reference, or R000 (center of

concave transition). Points found above R000 were numbered sequentially R001, R002, etc., while points found below R000 were numbered R-01, R-02, etc. (Figure 37).

Figure 36. Sample image as used in determination of reference point R000 on the RSTZ

Figure 37. Magnified image used in the selection of R000, center of curvature on the RSTZ

Intersection of root with top of soil grade was noted during field trials for each root and recorded. This intersection at the groundline will be referred to as G000 and points found above G000 are positive while points found below G000 are negative (Figure 38).

Figure 38. Labeling schematic of typical RSTZ for static loading trials. Red lines indicate reference points in relation to inflection point, R000. Green lines indicate reference points found either above or below ground level of G000. White numerals within the thick black line indicate reference location, starting at 1 on the top edge of the RSTZ and increasing distally along the root

A typical coded tree and root used for this thesis project is described below in Figure 39.

T02R1A0S401R007G022

T02	R1	A0	S4	01	R007	G022
Tree	Root	Root side	Stage	Tic	In	In
number	Number	Camera	interval	mark	reference	reference
		Shot			to R000	to G000

Figure 39. Tree and root coding used for identification and post processing of RSTZ static loading trials and strain analysis

Stage intervals for loading time were selected as follows: 0 (Start) and 4 (Finish at 0.1 degree) stages, along with the time stages of 1, 2, and 3, corresponding with the ends of the first quarter, midpoint and third quarters of time, respectively.

As post processing commenced, it was determined that a more distinguished RSTZ region be defined in order to concentrate strain analysis near the inflection point. The RSTZ was further classified into three subregions, based on tic mark proximity to the inflection point of R000. Subregion R0 (centered at R000) consists of the tic marks R001, R000, and R-001. Subregion RA (Region Above R000) consists of tic marks R002, R003, and R004. Subregion RB (Region Below R000) consists of tic marks R-02, R-03, and R-04. Each subregion spans 6 cm in length and covers approximately 24 cm linearly along the RSTZ (Figure 40).

Figure 40. Subregions RA(above reference R000), R0(Center of R000), and RB (below reference R000) found in the RSTZ

Figures 41 and 42 show a 3D image produced by ARAMIS DIC software used for strain data processing and analysis. The first example is at 0.1 degrees tilt for Tree 2, Root 1 and displays round, multi-colored points assigned to the incremental tic marks (Figure 41).

Figure 41. 3D image produced by ARAMIS DIC software used for strain data processing and analysis for Tree 2 Root 1. Multi-colored points are the incremental tic marks and color patterns show areas of varying strain magnitudes

Figure 42. Graphical image produced through by ARAMIS DIC software for Tree 2 Root 1

After all static load tests were completed, the exposed painted RSTZ and first order roots were lightly concealed with a battleship gray non-metallic spray paint application (Figures 43a

& 43b). WVU Facilities Maintenance personnel applied a top dressing of top soil to all excavated roots to establish turf grass and provide a level grade for pedestrian traffic.

Figures 43a & 43b. Test trees prepared for DIC static load tests (left) and same trees post testing, with concealed paint application (right)

All data collected and processed was combined into a master spreadsheet for data analysis and analyzed in an RStudio statistical package (Version 3.2.2). All data was checked for normality and transformed when necessary. Alpha was set to 0.05.

Maximum strain was analyzed from each sampled location on the RSTZ, by means of selecting the absolute value of strain (major or minor) at each location. For example, at a given location on the RSTZ, both major (tensile, positive) and minor (compressive, negative) strains are present. The highest absolute value was called maximum strain, although the values for major and minor strains will also be referred to.

Results

Forty five static load tests were examined on the 15 sampled trees. Mean ($\pm$ SD) tree dbh was 51 ± 7 cm and mean tree height (Height_T) was 19 ± 4 m. Pulling line height (Height_A) was 5.5 ± 1.0 m and Diam_A was 42 ± 7 cm. The maximum pulling force for sampled trees at 0.1 degrees from natural lean was $18,537 \pm 5600$ N and ranged from 6436 to 30234 N. The M_{Bending} (bending moment) for all pulls averaged $99,105 \pm 40,435$ Nm and ranged from 31,009 to 210,968 Nm. Table 1 shows the characteristics of sample trees with respect to diameter dbh, total tree height (Height_T), diameter of the tree at point of attachment (Diam_A), pulling line attachment height (Height_A) and the pulling distance ($\text{Dist}_{\text{Pull}}$) (Table 1). See Appendix C for complete loading results, by tree and RSTZ orientation.

Table 1. Tree and rigging measurements, mean and standard deviation (SD) of each tree for diameter breast height (dbh), total tree height (Height_T), diameter of the tree at point of attachment (Diam_A), pulling line attachment height (Height_A), pulling distance ($\text{Dist}_{\text{Pull}}$) and angle of pulling line (θ)

Tree	dbh(cm)	Height_T (m)	Diam_A (cm)	Height_A (m)	$\text{Dist}_{\text{Pull}}$ (m)	θ
2	56	18.4	42	6.1	36.9	9.4
6	56	19.2	48	4.9	19.7	17.1
8	49	19.3	40	6.1	11.0	27.2
9	59	21.2	52	4.7	16.6	20.8
10	62	21.7	52	5.6	23.3	15.3
12	51	23.3	42	6.3	19.0	18.8
13	61	24.5	54	6.4	23.6	17.3
14	50	19.9	38	6.5	29.3	9.6
17	59	25.3	49	7.3	16.5	17.5
21	52	14.6	36	4.9	21.1	12.6
22	44	13.6	31	5.2	12.2	17.5
23	48	16.2	40	4.7	14.4	16.3
24	43	15.1	33	3.8	11.2	27.1
25	41	13.0	40	4.2	10.5	12.1
26	39	12.6	33	5.7	17.8	12.8
mean	51	18.5	42	5.5	18.9	16.8
SD	7	4.2	7	1.0	7.3	5.3

A weak linear relationship was found between the pulling force and dbh ($r^2=0.30$, $n=45$). A weak linear relationship was found between the pulling force and Height_A ($r^2=0.32$, $n=45$). A slightly stronger linear relationship was found between M_{bending} and dbh ($r^2=0.37$, $n=45$) and M_{Bending} and Height_A ($r^2=0.52$, $n=45$). As expected, a significantly higher relationship was found between dbh and Height_T ($r^2=0.75$, $n=45$). Also refer to Beezley *et al.* (2016 In Print).

Within the sampled region of the defined RSTZ, 405 strain locations were designated on fifteen tested trees. Nine strain locations were omitted, due to poor coverage or no coverage within the ARAMIS DIC software, bringing the total amount of strain points analyzed to 396. A total of 133 strain points were located within in the defined RSTZ on the leeward orientation, 132 on the tangential orientation and 131 on the windward orientation. Subregion RA (above reference R000) contained 128 points, R0 (at reference R000) contained 135 points, and RB (below R000) contained 133 points.

The mean soil moisture (%) ($\pm$ SD) for all tested trees ($n=15$) was 36 ± 10 and for RSTZ orientation's ($n=396$) was 35 ± 6 for leeward ($n=133$), tangential was 37 ± 11 ($n=132$), and windward was 36 ± 11 ($n=131$). ANOVA tests returned a P-value of 0.250 for mean soil moisture and all RSTZ orientations ($n=45$) against the response of Maximum Strain (Table 2).

Table 2. Mean soil moisture percentage and P-Value for all tested trees and RSTZ orientation

Orientation	n	Soil Moisture(%)
Leeward	133	35.2
Tangential	132	37.1
Windward	131	36.1
P-Value		0.250

Soil textural analysis found undeveloped, compacted soils near each sampled RSTZ orientation, with minimal O horizon formation (less than 0.5cm) for all sampled trees. Initial soil ribbon tests found high percentages of clay (clay-loam and silty-clay) content within the undeveloped horizon, at depths from 1cm to 20cm. These undeveloped soil horizons are indicative of soil found areas that have been subjected to site modification for development purposes. Results from additional soil analysis were not completed by the time of this publication.

During the initial stages of statistical analysis, it was determined that the response variable maximum strain did not appear to have a normal distribution or equal variances, and data transformation was required. Using the Box-Cox method for power transformation analysis (Box and Cox, 1964), a lambda value of -0.24 was identified for the Maximum Strain response data. Although a lambda value of -0.24 determined from the Box-Cox procedure indicated a natural logarithmic transformation; this value was previously attempted for data transformation and failed to produce normality and confounded means during analysis. Subsequently, the lambda value of -0.5 was used, applying the reciprocal square root to the original value, and produced satisfactory data normality. For ease of presentation purposes, the back transformed values of maximum strain will be presented. Refer to Appendix D-F for normality plots, residual plots and Box-Cox transformation plots of original and transformed maximum strain data.

The mean maximum strain and SD (mean $\pm$ SD) for the leeward RSTZ orientation was 0.088 ± 0.132 , the tangential RSTZ was 0.058 ± 0.101 and the windward RSTZ was 0.090 ± 0.115 . Mean major strain for all orientations was 0.068 ± 0.062 and individual mean major strains found on the leeward side were 0.030 ± 0.040 , tangential 0.072 ± 0.070 and windward of 0.103 ± 0.047 . Mean minor strain for all orientations was -0.069 ± 0.119 and individual mean

minor strains found on the leeward side were -0.110 ± 0.030 , tangential -0.055 ± 0.070 and windward of -0.043 ± 0.121 (Table 3).

Table 3. Mean strain and standard deviation for maximum, major and minor strain found at sampled RSTZ's and respective orientation to the pulling force found during static load tests (Means with same letter are not significantly different)

Orientation	n	Maximum Strain	Major Strain	Minor Strain
Leeward	133	0.088 ± 0.132 b	0.030 ± 0.040 a	$(0.110) \pm 0.130$ b
Tangential	132	0.058 ± 0.101 b	0.072 ± 0.070 b	$(0.055) \pm 0.091$ a
Windward	131	0.090 ± 0.115 a	0.103 ± 0.047 b	$(0.043) \pm 0.121$ a
P-Values	396	<0.001	<0.001	<0.001

The contribution of strain type (major and minor) to maximum strain were found for all RSTZ orientations, with leeward contributing 3.8% major and 96.2% minor, tangential contributing 65.2% major and 34.8% minor, and windward contributing 95.4% major and 4.6% minor. Overall, the contribution to maximum strain from all static load tests represented 54.7% major strain and 43.3% minor strain (Table 4).

Table 4. Contribution of strain type to maximum strain at RSTZ's and respective orientation to the pulling force found during static load tests

Orientation	n	<u>Strain Type(%)</u>	
		Major	Minor
Leeward	133	3.8	96.2
Tangential	132	65.2	34.8
Windward	131	95.4	4.6

Analysis of Variance (ANOVA) testing was conducted to determine if significant differences existed between the means of maximum strain values (response variable) and the selected factors (predictors) of RSTZ orientation (leeward, tangential and windward) and the factors of subregion (RA, RO and RB).

ANOVA results for maximum strain by RSTZ orientation found an overall P-value of <0.0001 , Mean maximum strain for each RSTZ root orientation was 0.088 for the leeward side, 0.058 for the tangential side and 0.090 for the windward side. Post Hoc testing was performed using the Tukey Grouping method. Mean values with the same letter are not significantly different. (Table 5)

Table 5. Means, P-Values, and Tukeys Grouping from ANOVA test for RSTZ orientation by subregions (Means with same letter are not significantly different)

RSTZ orientation	N	Mean Maximum Strain			Pvalue
		RA	RO	RB	
Leeward	45	0.095 a	0.096 a	0.077 b	0.036
Tangential	45	0.065 a	0.056 a	0.054 a	0.293
Windward	45	0.095 a	0.095 a	0.082 a	0.435

Regression analysis found overall R^2 and P-Values for each RSTZ orientation for maximum strain and all incremental reference locations. (Table 6) The mean root divergence (degrees) ($\pm$ SD, $n=45$) for all tested trees was 18.7 ± 15.0 and for each RSTZ orientation ($n=396$) was 19.5 ± 15.7 for leeward ($n=133$), 18.7 ± 13.4 tangential ($n=132$) and 17.8 ± 15.9 windward ($n=131$). ANOVA did not find a significant difference of overall RSTZ orientation for mean root divergence ($p=0.649$, Table 7).

Table 6. R^2 and P-Values of each RSTZ orientation for maximum strain and all incremental reference locations

Orientation	n	R^2	P-Value
Leeward	133	0.04	0.022
Tangential	132	0.01	0.217
Windward	131	0.17	0.167

Post Hoc testing was performed using the Tukey Grouping method to determine if significant differences exist between the mean angle of divergence from the main stem, in relation to the pulling direction, across all three RSTZ orientations (excluding strain). Mean values with the same letter are not significantly different. ANOVA testing found a P-Value of 0.649 (Table 7).

Table 7. Mean root divergence, P-Value and Tukey Grouping by RSTZ orientation (Means with same letter are not significantly different)

Orientation	Mean Root Divergence	n
Leeward	19.6 a	133
Tangential	18.7 a	132
Windward	17.8 a	131
P-Value	0.649	

Discussion

Our static load trials subjected trees to a bending force that caused a minor 0.1 degree deflection. Yet only a weak relationship ($r^2 = 0.30$) between the applied force and the diameter of the tree was determined. This weak regression is not surprising as the placement along the stem of the pulling rope varied for each tree. M_{Bend} is a function of the applied bending force and the moment or distance along the trunk that force acted. A stronger relationship was found between the bending moment and diameter ($r^2=0.37$). The stronger relationship between bending moment and diameter compared to applied force and diameter demonstrates that researchers are not restricted to a fixed tie in location during field trials. While the relationship between M_{Bend} and Height_A is stronger than dbh, this is in part because Height_A is one of the factors involved in calculation M_{Bend} . Additionally, this regression suggests that attaching the rigging rope higher in the tree can be advantageous, yet this could lead to curvature of the stem during loading which would require a different calculation for M_{Bend} .

One concern during whole tree static tree pulls is that the pull will lead to tree instability. Our study stayed well below the threshold of 0.25° (Brudi and van Wassenae 2002) where instability may be induced or the 0.9° for root damage (James *et al.* 2013a). An additional concern is staying below the estimated maximum elastic limit for the pin oak species (0.62), as found using data from the Wood Handbook (USDA 2010) with ratio of MOR/MOE. In very few instances, “hot spots” of increased strain magnitude were found within the DIC coverage area, but not within the area of the defined RSTZ and require further investigation. Since we pulled multiple times per tree, each tree may need to relax between pulls to return to the original state. At least 10 minutes elapsed between subsequent pulls on the same root and at least 20 minutes between pulls on roots when moving to the next sampled root. We feel that the strong

relationship between bending moment and dbh suggests that the trees relaxed between pulls. Future analysis will further explore this potential issue.

Complicating the analysis of bending moment on the tested trees and the corresponding lower r^2 values found thus far in this study could be the result of the root-soil plate complex, as little data is available for incorporation into our current methodology. Further analysis of the root-soil plate interaction with the structural root zone and RSTZ could provide valuable information in the area of tree stability and structural soil and root interaction. Consideration of root morphology and rooting architecture was evaluated only for the exposed rooting parts, which was limited to one meter distally from the base of the tree and approximately to a depth of 15.2 cm. Additional analysis will be conducted on data collected concerning if root branching architecture contributes in the depletion of strain transfer. Further analysis can also examine if a relaxation effect occurs in sampled tree parts that may influence strain magnitude.

Our static load tests on the selected pin oak tree population confirm that mean maximum strain was similar for the leeward and windward RSTZ orientations (0.088 and 0.090, respectively) for the tested trees. The mean maximum strain of the tangential RSTZ orientation (0.058) was found to significantly differ from the other tested orientations, a decrease in mean maximum strain of approximately 35% (Figure 44).

Figure 44. Mean maximum strain found on the leeward, tangential, and windward RSTZ orientations, resulting from static load tests

The results of static load tests also confirm that strain patterns on the leeward RSTZ orientation were primarily comprised of compressive (minor) strains, of which maximum strain was comprised of 96% minor strain and 4% tensile (major) strain, as found in Table 4. The opposite effect was found on the windward RSTZ orientation, where tensile (major) strain comprised 95% of maximum strain and compressive (minor) strain comprised 5%. These strain concentrations are comparable to relevant research that indicates leeward wood fibers of trees subjected to loading are held in compression, while windward wood fibers are more tensile under loading (Stokes 1999). Maximum strain patterns resulting from our static load tests found on the tangential RSTZ orientation were 65% tensile (major) and 35% compressive (minor) (Figure 45). These strain patterns found on the tangential RSTZ orientation could indicate torsional strain. Torsional strain analysis is often disregarded during loading trials and are little understood in tree biomechanics and structural tree stability research and warrant further investigation.

Figure 45. Strain type (%) of major and minor strain contribution to maximum strain for each RSTZ orientation found during static load tests

Similar strain patterns were present when comparing the three RSTZ orientations among each subregion. The changes in strain magnitude down the RSTZ, across the three subregions, in both the leeward and windward orientations, were found to change in similar fashion. The change in strain magnitude was greater for the tangential orientation from the subregions RA to R0, and then found to be more similar to the other orientation, in magnitude from RA to RB. This also could signal torsional strains on the tangential RSTZ orientation, and further research could be conducted to evaluate torsional strain patterns during load trials.

The decrease and dissipation of strain found in this study is comparable to Stokes (1999) research, of which states that strain is higher in the main tree stem compared to roots, as strain is transferred into the soil and the soil-root plate complex. Fayle (1983) also alludes to the root-stem junction, found further distally from the RSTZ, which acts as a bridge for tree to soil strain transfer and a hinge point during tree/root failure found in mature trees. Rapid root tapering (the Zone of Rapid Taper) near the stem base, at the stem-root junction, likely plays a crucial role in tree stability and mechanics, and these results can help strengthen conceptions of the overall role of strain transfer within trees, although more research is warranted.

Results also indicate that the mean root divergence from the main stem, in relation to the pulling force, does not significantly vary between the sampled RSTZ orientations. Further analysis of the data collected will provide insight into the complexities of quantifying root system architecture and how strain is managed from the stem into the root structural root system.

The geometry of tree bark is complex and diverse (Rossell and Olson 2014). It is thought the primary function of bark is for insulation purposes, however the mechanical roles of bark have been investigated (Niklas 1999) and well as investigations of strain transfer from xylem to bark (Dahle *et al.* In Review) and bark pattern modeling (Dale *et al.* 2014). Also to add the complexity of bark geometry, one must consider the hydro-elastic swelling or shrinkage and the day-night expansion or shrinkage of bark (Bonnesoeur *et al.* 2016), of which little information is readily available. Questions currently arise about the use of bark for direct strain measurement found on the xylem of trees, however for this research, we are primarily concerned with mapping strain patterns along a relatively concentrated portion of the tree (the RSTZ), and not determining direct strain values for xylem, while Sebera *et al.* (2014) showed that strain was different as measured on the bark and xylem.

The application of DIC for the purpose of determining strain patterns is relatively new to the of plant and tree biomechanics, although previous work has been conducted. Serbera *et al.* (2014) tested one walnut tree and found that DIC strain measurement is an acceptable alternative to using strain gauges directly on the xylem of trees. While the authors found a difference between xylem and bark strain, they used different tools, DIC on the bark and elastometers in the xylem), Dahle *et al.* (In Review) found that there was no difference between strain measured in red oak (*Quercus rubra*) stump sprouts using DIC when bark in place and after it was removed. The stump sprouts had relatively thin bark in comparison to the trees in this study. While the

total magnitude of strain may be slightly different in our thicker bark RTSZ tests, we believe the overall patterns are accurate. These studies indicate the potential application of DIC into the biological research and arboricultural management fields to non-destructively tests and monitor trees in their natural environment.

Implications

This study was primarily designed to establish baseline data for mapping strain patterns in trees across the RSTZ, which has not yet been fully examined in past research. The data presented could guide future research in concerning tree stress and resulting strain management and help define the overall function of strain management as it relates tree stability.

We found during static loading tests of the surveyed pin oak trees that predicted strain patterns across the tests RSTZ orientations to hold true. Leeward is compressive, windward is tensile, yet the tangential orientation indicates a torsional effect and as of yet fully defined. This finding does not diminish the importance of the tangential side of the tree and the effects of torsion within the structural root system have yet to be investigated. Also the leeward and windward RSTZ orientations were of the same magnitude and tangential may be less, yet again further research needs to fully explore what types of strain were occurring in the tangential roots. Our analysis also found “hot spots” of strain outside of the sampled RSTZ and further analysis of the DIC data may assist in painting a clearer picture of how trees manage strain transfer and role of strain transfer to tree stability.

Mechanical stress is induced upon trees in landscape during dynamic (wind) and static (gravitational) loading events (Niklas 1992, James 2006, Matheny and Clark 2009). This loading can cause failure in both above ground and below ground portions of a tree and result in

increased property loss in developed and urban areas (Yang *et al.* 2014, Moore 2004), while elevating the occurrence of human injury. Understanding how the load is transferred through the RSTZ and if it is evenly displaced throughout the root zone can be an important consideration, especially if damage occurs to a specific section of the roots. The transfer of strain throughout the entire tree system is a coordinated mechanism designed to minimize damage to plant tissue and resist deformation. The tree manages increased strain by forming reaction wood or sacrifices woody parts in order to resist catastrophic root failure (uprooting) or large tissue failures (shedding of woody parts) resulting from mechanical loading events.

Our initial soil analysis found the soil structure highly composed of clay within the structural rooting zone of the sampled trees. As Dupuy *et al.* (2005) discusses, root system architecture greatly contributes to tree stability, and in the case of our sampled trees, the heart root system possesses the greatest resistance to overturning (Stokes 1999, Dupuy *et al.* 2005). These factors must be taken into consideration when establishing thresholds to determine tree stability during loading tests, especially when dealing with built-up and/or altered soils. The variability of soil structure from one to its neighbor can vary greatly and can influence the opportunistic rooting morphology of trees and this tree stability.

The contributions of the root-soil plate complex to overall tree stability is little understood, however individual factors within the root-soil complex plate have been examined. As described by Danjon and Fourcaud (2009), the interaction of the soil matrix plays a crucial role in flexibility of the root-soil plate during loading, while Coutts (1983, 1986) found the most important component to tree stability was the anchorage strength of the windward roots held in tension, followed the contribution of the root-soil plate. Tree root architecture also plays a key role in overall tree stability, and as Dupuy *et al.* (2005) models, trees located in clayey soils

should be able to withstand greater bending moments. (It is noted that Dupuy *et al.* (2005) survey trees were of a tap rooted pine species). The fact that little information is readily available to researchers and practitioners related to soil structure and tree stability signals an area of interest for further exploration to model strain patterns in trees.

Through the complex process of plant signaling and acclimation, trees manage stress and the resulting strain through mechanisms of varying levels of plant hierarchy. In order to assimilate and allocate vital plant resources in an efficient manner while maintaining plant homeostasis, trees continually produce new wood tissue, increasing both above ground and subterranean biomass. The balance of nutrient allocation in the competition for light and the opportunistic savaging of required plant nutrients, reaction wood is formed in response to alterations in plant form and can alter mechanical functions (Almeras and Fournier 2009). Signaling cascades in response to mechanical stresses attempt to rectify the orientation of the plant in an efficient manner. Short term activation of selected endogenous plant hormones are activated to form long lasting reaction wood without compromising plant use efficient of vital resources. One avenue in woody plants response to stress is lignin formation in areas of greatest stress, but little is known of the long term effects of reaction wood formation and tree stability. Reaction wood formation occurs naturally as the plant attempts to self-correct to gather light and nutrients, and the wood mechanical properties in regards to tree stability are of rising concern. Research has shown that wood properties differ from branch, stem, and root tissues (Gurau *et al.* 2008, Dahle and Grabosky 2010) and is it assumed that the molecular composition of the tree at various parts locations differ. However, the research of the physiological response of tree experiencing mechanical perturbations at differing molecular and cellular combinations is in its infancy.

Efforts to quantify the structural stability of trees are actively being pursued, although research is primarily directed to individual plant tissues or conditions that do not fully consider the tree as a megaorganism. Current tree risk assessments may not be fully considering the long term responses of trees to mechanical stress and thus many large amenity trees have been prematurely felled in hopes of diverting litigious citations and compromising public safety. On the contrary, in order to bring the science of tree stability awareness to stakeholders, we may need to try and work up from the molecular level and establish a holistic approach to tree care and management, incorporating reasonable and sustainable practices.

The relevance of DIC combined with static loading trials will increase our understanding of how trees manage strain and the resulting stress from loading events, such as weather related events and manmade intrusions. DIC can be implemented to nondestructively test and monitor trees over a period of time and this technology will assist in developing models to predict responses to loading events and strengthen current tree management protocols. As analysis of this research study continues, we will be able to help further understand tree stability and the likelihood of failure of trees in an ever expanding urban environment and drastic alterations in regional and global climatic patterns.

One implication for future research can be relevant to the public sector, as an increasing global human population is relying heavily on affordable and reliable energy delivery. The growing urban population is placing increased demand on human safety, as well as securing safe and reliable utility transmission corridors. The potential for research on tree stability in the utility arboriculture sector is increasing with the rise of severe weather outbreaks and the reliance on cheap and reliable energy distribution, regardless of the energy source.

Arborist and tree care practitioners should fully consider how changes in material properties of trees over time effect tree stability. Tree species, tree health, and the local environment should all be considered when assessing tree stability for both immediate tree care and long term planning and adhere to the adage “Right tree. Right place. Right function”.

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Appendix A. Field data collection sheet for root divergence, crown spread and tree height

<div>Tree #</div>	
<div></div> <div>Root Azimuth</div>	<div></div> <div>Crown Spread</div>
<div> </div> <div>Tree height</div>	

Appendix B. Field data collection sheet for root profile

Root and Soil Depths																		Tree #																	
																		Root 1																	
																		Root 2																	
																		Root 3																	
																		Root 4																	

Appendix C. Tree measurements, force applied and bending moment at 0.1° inclination

Tree	RSTZ	dbh(m)	TreeH(m)	AttachD(m)	AttachH(m)	PullDist(m)	PullAngle	PullAzimuth	AdjustRootDiv	Force(N)	BmomentMax(Nm)
2	Leeward	0.56	18.38	0.42	6.13	36.88	9.40	280	7	19,842	119,927
2	Tangential	0.56	18.38	0.42	6.13	36.88	9.40	280	268	16,713	101,018
2	Windward	0.56	18.38	0.42	6.13	36.88	9.40	280	173	21,493	129,909
6	Leeward	0.56	19.17	0.48	4.88	19.66	17.14	290	20	16,039	74,747
6	Windward	0.56	19.17	0.48	4.88	19.66	17.14	290	200	13,835	64,474
6	Tangential	0.56	19.17	0.48	4.88	19.66	17.14	290	104	17,505	81,575
8	Leeward	0.49	19.32	0.40	6.07	10.97	27.20	170	12	17,037	91,911
8	Tangential	0.49	19.32	0.40	6.07	10.97	27.20	170	122	21,549	116,251
8	Windward	0.49	19.32	0.40	6.07	10.97	27.20	170	160	15,003	80,938
9	Leeward	0.59	21.21	0.52	4.72	16.58	20.75	163	7	26,201	115,755
9	Tangential	0.59	21.21	0.52	4.72	16.58	20.75	163	97	24,989	110,402
9	Windward	0.59	21.21	0.52	4.72	16.58	20.75	163	193	21,387	94,486
10	Leeward	0.62	21.70	0.52	5.64	23.35	15.30	10	3	21,073	114,617
10	Tangential	0.62	21.70	0.52	5.64	23.35	15.30	10	92	22,134	120,385
10	Windward	0.62	21.70	0.52	5.64	23.35	15.30	10	164	25,255	137,363
12	Leeward	0.51	14.63	0.42	6.28	19.02	18.80	172	17	17,433	103,618
12	Windward	0.51	14.63	0.42	6.28	19.02	18.80	172	168	25,539	151,803
12	Tangential	0.51	14.63	0.42	6.28	19.02	18.80	172	102	17,409	103,479
13	Leeward	0.61	24.54	0.54	6.40	23.56	17.25	186	9	26,920	164,560
13	Tangential	0.61	24.54	0.54	6.40	23.56	17.25	186	63	23,269	142,238
13	Windward	0.61	24.54	0.54	6.40	23.56	17.25	186	172	19,317	118,085
14	Leeward	0.50	19.87	0.38	6.49	29.26	9.57	194	34	12,120	77,592
14	Tangential	0.50	19.87	0.38	6.49	29.26	9.57	194	76	16,734	107,129
14	Windward	0.50	19.87	0.38	6.49	29.26	9.57	194	166	9,132	58,461
17	Leeward	0.59	25.33	0.49	7.32	16.46	17.47	44	51	24,946	174,070
17	Windward	0.59	25.33	0.49	7.32	16.46	17.47	44	175	28,903	201,676
17	Tangential	0.59	25.33	0.49	7.32	16.46	17.47	44	246	30,234	210,969
21	Leeward	0.52	14.63	0.36	4.94	21.06	12.64	320	16	6,436	31,009
21	Windward	0.52	14.63	0.36	4.94	21.06	12.64	320	180	16,289	78,483
21	Tangential	0.52	14.63	0.36	4.94	21.06	12.64	320	110	14,166	68,254
22	Leeward	0.44	13.59	0.31	5.18	12.16	17.52	38	240	19,138	94,565
22	Tangential	0.44	13.59	0.31	5.18	12.16	17.52	38	48	19,204	94,892
22	Windward	0.44	13.59	0.31	5.18	12.16	17.52	38	140	25,464	125,824
23	Leeward	0.48	16.22	0.40	4.72	14.42	16.26	304	18	15,530	70,436
23	Windward	0.48	16.22	0.40	4.72	14.42	16.26	304	192	23,995	108,826
23	Tangential	0.48	16.22	0.40	4.72	14.42	16.26	304	124	19,847	90,016
24	Leeward	0.43	15.12	0.33	3.84	11.22	27.06	258	38	15,073	51,551
24	Tangential	0.43	15.12	0.33	3.84	11.22	27.06	258	62	17,152	58,662
24	Windward	0.43	15.12	0.33	3.84	11.22	27.06	258	238	17,031	58,247
25	Leeward	0.41	12.98	0.40	4.21	10.52	12.08	352	342	8,338	34,297
25	Tangential	0.41	12.98	0.40	4.21	10.52	12.08	352	256	17,411	71,615
25	Windward	0.41	12.98	0.40	4.21	10.52	12.08	352	176	7,610	31,299
26	Leeward	0.39	12.65	0.33	5.73	17.80	12.83	20	2	17,967	100,385
26	Tangential	0.39	12.65	0.33	5.73	17.80	12.83	20	100	9,098	50,833
26	Windward	0.39	12.65	0.33	5.73	17.80	12.83	20	130	15,752	88,007

Appendix D

Appendix E

Appendix F

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