TREE RISK ASSESSMENT
What We Know (and What We Don't Know)

By Nelda Matheny and Jim Clark

We performed a literature search to identify and evaluate research that has been published related to tree risk assessment. The topic is quite broad because it considers aspects of biomechanics: architecture, structure, decay and other defects, root characteristics, wood properties; site conditions: topography, geomorphology, soils and hydrology; and weather conditions: endemic and catastrophic storms, wind, snow, ice, and rain. A variety of tools, equipment and techniques have been developed to evaluate tree stability. There are legal issues surrounding our duty, standard of care and liability. In addition, there are a host of topics addressing social, psychological and technical aspects of risk, particularly associated with how arborists quantify, rank and describe it.

What is a bibliography?

A bibliography is collection of published literature. Our task was to identify research publications that focus on arboriculture, excluding equipment and climbing methods except as it related to tree risk assessment. Literature from silviculture and pomology was included as secondary sources.

Our bibliography focused on articles from peer-reviewed journals (see sidebar at end). To a lesser extent, we included relevant book sections and conference proceedings, significant publications produced by government agencies, and a few magazine articles covering professional practice. Self-published manuscripts, conference hand-outs, posters, and web pages were excluded.

E. THOMAS SMILEY/BARTLETT TREE EXPERTSE. THOMAS SMILEY/BARTLETT TREE EXPERTS

An arborist uses a level to check the lean of a tree.

After we compiled the bibliography, we summarized key literature, assessed past and current trends of research and practice, and recommended needs for additional research and standards of practice.

What's in the bibliography?

This bibliography includes 700 citations. About half are from peer-reviewed journals; and a quarter from key scientific papers related to tree risk assessment. Citations are from over 100 journals published internationally and in 15 countries. Authors are from around the world: North America, United Kingdom, Europe, Canada, Australia, and Asia.

> Want access to tree risk assessment literature?
> A good place to start is the ISA's Portal to Research (http://www.isa-arbor.com/publications/arbResearch).

The full bibliography is available through the ISA's website. A literature review of key scientific papers will be published in *Arboriculture & Urban Forestry*, ISA's scientific journal.

There are four primary subject categories; the first two are briefly discussed in this article.

- tree biomechanics
- identification and assessment of structural defects
- risk assessment
- risk reduction or abatement

Tree biomechanics

Scientists have developed a large body of literature about tree biomechanics. Over a third of the scientific articles and books we collected related to that area. While many of the experiments were performed on individual trees, most of the trees were in stands where their structure and exposure to wind was affected by nearby trees.

Articles and books by Claus Mattheck, Lothar Wessolly and others in the 1990's introduced biomechanics to the arboricultural world. Arborists began to describe trees as engineered structures, using equations and terms such as modulus of rupture, applied bending moment, and lever arm.

> Biomechanics studies the way trees grow in specific environments to sustain both structural support and biological function. How does the tree manufacture and distribute food, absorb and transport water and mineral elements, while supporting a crown of leaves that buffeted by wind and weighed down by rain, snow and ice?

Biomechanics experiments are designed to quantify the forces imposed on trees and their ability to support the load or fail. Often models are developed to simplify complex computations and interactions. Those models must be tested for validity through scientific experimentation and replication. Few of the models used in arboriculture have undergone that scrutiny.

To apply mechanical and engineering formulas, certain material properties must be known. Forest researchers have measured a variety of wood properties for important lumber species. Key wood properties have been measured for some ornamental species, but not most, and it is unclear how those properties vary in different growing conditions, climates, and exposures.

Effect of wind on trees

Most tree failures occur during winds, so the biomechanics of wind and trees is an important area of research. Wind effects on trees have been extensively studied in conifer forests, but hardly at all for shade trees in urban environments. Cullen assembled a bibliography of wind and trees for tree care professionals (Cullen 2002).

> Trees are flexible, porous structures that change their shape as the wind blows.

Some models and experiments consider trees as non-porous, rigid structures intercepting a constant wind force (static modeling). Others think the dynamic movements caused by wind gusts are important to tree failure and must be considered in modeling tree response (dynamic modeling) (Baker and Bell 1992; James, Haritos, and Ades 2006). A recent wind literature review not only describes the effects of wind on trees, but also how plant movement in wind affects wind dynamics (de Langre 2008). There is a general trend among the literature to use fluid mechanics to describe wind and to model trees as flexible and porous rather than static, rigid structures.

> "A tree without branches is not a tree."
> —Shigo (1986)

Relatively little data on the effects on wind on trees in urban areas are available. James and others (2006) measured the dynamic loads on single trees having different shapes and branch structures. They found that trees do not sway back and forth under dynamic loads, but rather they move in a complex looping pattern. As the branches move around in the wind, they dissipate wind energy, which reduces the load transferred to the trunk and increases the mechanical stability of the tree.

Trees in cities experience different wind patterns than trees in forests. The turbulent character of winds around building has been studied and described. We can assume that urban trees are exposed to greater turbulence that those in uniform forest stands or woodlands. Baker and Bell (1992) suggest that because "bending moment is reasonably dependent upon turbulence intensity," that trees in urban areas can be expected to experience greater moments (bending force) than those in rural areas for the same mean wind speed.

> "Each branch is a mass that sways in the wind and dynamically interacts with other branches and the trunk in a complex way. This interaction between the components of the crown can prevent the generation of natural harmonic sway frequencies and minimize extreme dynamic loads that would potentially cause mechanical failure."
> —James, Haritos, and Ades (2006)

Tree failure surveys

Much of what we know about how trees fail comes from post-storm tree damage surveys (see Duryea et al. 2007 for a summary; Cutler, Gasson, and Farmer 1990; Kane 2008). Ice accumulation causes damage to trees, and the degree of damage varies by species and location (Hauer, Weishen Wang, and Dawson 1993; Luley and Bond 2006). As an example, Norway maple (*Acer platanoides*) is relatively resistant to ice damage, while silver maple (*A. saccharinum*) is extensively damaged (Sisinni, Zipperer, and Pleninger 1995; Hauer, Weishen Wang, and Dawson 1993).

Another source of information about tree failures is the International Tree Failure Database (formerly the California Tree Failure Database). Summaries of reported failures have been used to develop tree failure profiles for only two species, however: coast live oak (*Quercus agrifolia*) (Edberg and Berry 1999), and Monterey pine (*Pinus radiata*) (Edberg, Berry, and Costello 1999).

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Forest-grown trees are protected from wind and have less taller, less tapered trunks than the open-grown tree that is exposed to wind; as is the case with this exposed Monterey cypress tree (*Cupressus macrocarpa*).

Identification and assessment of structural defects

Tree risk assessments rely on identifying and assessing structural condition to assess failure potential. 'Defect' is the term we commonly use to identify a condition or characteristic that is structurally weak or contributes to a structural weakness. Yet, there has been limited scientific study of what characteristics are important, or how to translate what we see into likelihood for failure.

Tree risk assessment procedures

There are many publications that describe how to perform a tree risk assessment. All have similar components: visually assess tree ►

structure, describe defects, evaluate the likelihood of failure, and note what would be damaged if the tree failed. There are no scientific publications, however, that evaluate, test or compare the procedures or methods. We do not know which, of the methods or procedures are most important or accurate.

In most tree inspection protocols, the arborist is instructed to systematically view the tree from top to bottom and move 360º around it. But are there other methods that give acceptable results? Rooney et al. (2005) compared walking and windshield inspections. During the windshield inspection, the arborist assessed trees as the vehicle was driven along the street at an average speed of 3.06 km/h (1.9 mph). Both sides of the trees were examined if there was vehicular access; if not, only one side was inspected. A comparison of the hazard ratings assigned trees during the windshield inspection with ratings of the same trees in a walking inspection indicated that the windshield inspection accuracy increased as the tree hazards become more severe (rated 10 and above on a 3-12 scale). The authors noted that, "If the trees are reasonably maintained, the windshield survey could be used just to locate quickly developing hazardous conditions such as hanging branches or recent storm damage, or for an annual update of streetside conditions."

Visual assessment

As long as arborists have been examining trees we have used external characteristics to give us clues about internal conditions and assess structural stability. Mattheck (1994) described this process as Visual Tree Assessment (VTA), which is widely used in tree risk assessment.

How accurately does a visual assessment represent internal conditions? Experiments to answer that question are limited. Nor do we have data identifying which characteristics are most likely to result in tree failure except under a few specific conditions.

E. THOMAS SMILEY/BARTLETT TREE EXPERTISE. THOMAS SMILEY/BARTLETT TREE EXPERTS

A couple of arborists perform a pre-climb inspection of a tree's health and stability.

Hickman and others (1995) evaluated and rated 695 oaks (*Quercus wislizneii* and *Q. lobata*) for eleven components including site factors, tree structure and vigor, and target value. Seven years later they reexamined the trees to identify which had failed or died. They found that three factors - decline (leaf cover and color), trunk condition and lean – were most closely related to failure, and decline was the most important predictive characteristic.

Internal decay testing equipment

Sometimes visual assessments are not enough and we need to know more about the internal condition of trees to assess risk. Forestry and wood-in-service scientists have studied ways to identify and quantify wood defects for decades, and there are volumes of literature reporting those results. Comprehensive experiments have evaluated time-of-flight stress wave techniques, micro-drilling resistance, stress-wave tomography, electrical resistivity, radar, and other techniques (Wang et al. 2005; Socco et al. 2003; Sambuelli et al. 2003; Bucur 2003; Tomikawa et al. 1986).

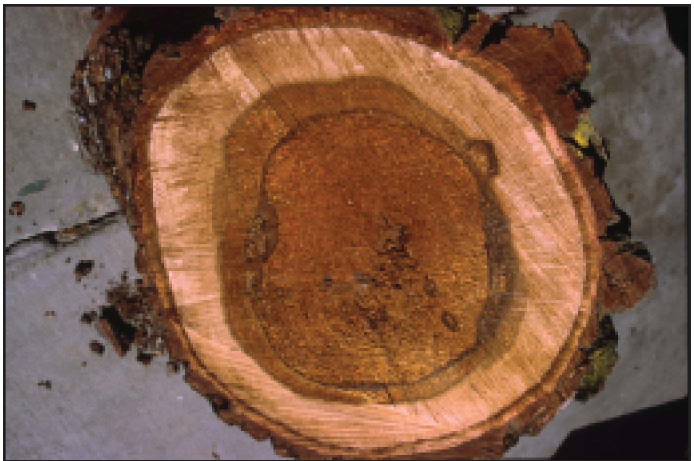
> Currently arborists apply a small set of experimental data to assess and evaluate a large, diverse and complex tree population.

Several internal defect detection technologies have been adapted for arboriculture and tested on urban shade trees. Most of the literature describes use of the equipment and compares test results on a few intact trees. Usually the tree is dissected and the test results compared to the decay pattern. A more rigorous assessment is to subject the wood samples to laboratory tests (Costello and Quarles 1999). Studies have been performed with only a few tree species, types of decay, management histories, growing conditions and environments. Because of the small sample size, statistical analysis often is not possible. We do not know the extent to which these variables affect equipment performance and interpretation of their data output.

No one piece of equipment provides a complete assessment. An example of using a combination of techniques and technologies is described in an experiment on two red oaks (*Quercus rubra*) (Wang et al. 2007; Wang and Allison 2008). The trees were visually assessed and then tested with a single-path stress wave equipment (Fakopp Microsecond Timer), acoustic tomography (Picus Sonic Tomograph), and a resistance microdrill (IML Resistograph). After testing, the trees were felled and samples were analyzed at a wood products laboratory. The authors concluded that the visual inspection and single-path stress wave equipment identified that there was a defect. The tomography confirmed that internal defect was present, although the defect area was larger than the actual decay and did not distinguish between decay and cracks. They recommended additional testing with a resistance microdrill to accurately locate and evaluate the defects.

Assessing structural strength

Trees may become structurally unstable and identified as hazardous for a variety of reasons. Terho and Hallaksela (2008) examined 181 park and street trees in Helsinki that were identified as hazardous and were removed. Most of the *Tilia* and *Betula* had extensive internal decay. For *Acer*, however, internal cracks resulting from codominant attachments were the primary defect.



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Several "strength loss" formulae are in common use that model trees with decay as circular trunks with a central circular decay (Figure 4). The formulae cannot be applied to trees with non-circular trunks or asymmetric decay (Figure 5).

Strength loss due to decay

While tools and techniques are available to identify and quantify conditions that can reduce structural stability, we have almost no research information to help us quantify the loss in stability.

> Research has yet to confirm that any formula accurately represents trunk strength loss, nor has a critical load threshold been determined.

Formulas to estimate the loss in strength due to decay are in common use. Although we use the term 'strength loss' these formulae actually calculate the moment of inertia of the trunk. An excellent review of the limitations of the formulae and comparison of their accuracy in estimating different trunk and decay geometries is provided by Kane and Ryan (2003, 2004).

As Kane and Ryan point out, there has been relatively little quantitative testing to establish thresholds for failure. Tree failure thresholds that are in use have been established by examining trees that failed and trees that remained standing following storms, and comparing the 'strength loss' of each (Smiley and Fraedrich 1992; Mattheck, Bethge, and West 1994; Mattheck, Bethge, and D. Erb 1993).

A static load test (pull test) is used by some arborists to evaluate the risk of root and trunk failure (Sinn and Wessolly 1989; Wessolly 1995; Wessolly and Erb 1998). As the load is applied, trunk elastic deformation and root collar inclination are analyzed by a proprietary computer program, and a safety factor determined. The supporting data have not been published under peer-review. James and Kane (2008) cautioned that wind forces are dynamic rather than static and trees have been shown to fail under less wind force than predicted under static pull tests.

Pull tests have been used experimentally to assess effect of root pruning (Smiley 2008), root barriers (Smiley, Key, and Greco 2000), and to establish baseline data to assess tree failure (Kane and Clouston 2008).

Codominant stems and branch attachments

In performing tree risk assessments the presence of codominant stems and how branches are arranged and attached to the stem are considered. Recent research on the strength of those attachments has provided helpful guidance for tree risk assessments.

Arborists have considered u-shaped branch attachments stronger than v-shaped. However, several studies have concluded that the relative size of the branch to trunk is more important to strength than the angle of attachment (Lilly and Sydnor 1995; Gilman 2003; Kane and Farrell 2008). The strength of branch attachments is reduced by presence of included bark (Smiley 2003; Farrell 2003).

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Codominant trunks are weaker than single-trunked trees. The strength of branch attachments is reduced by presence of included bark. Angle of attachment (u or v) does not affect strength. Branches that are half or less the diameter than the trunk are stronger than those that are similar in size.

►

These results are from experiments on young trees; mature trees have yet to be tested.

Kane and Clouston (2008) confirmed that trees with codominant trunks are weaker than single trunk trees. They subjected 30 Norway maple (*Acer platanoides*), red maple (*A. rubrum*) and sugar maple (*A. saccharum*) to pulling tests. Trees with codominant trunks failed at 45% of wood strength, while single trunked trees failed at 79%.

Summary

Tree risk assessment is a broad area of expertise that combines many disciplines. There is a large body of scientific literature about biomechanics, wind in trees, soils, wood decay, and other topics that relate to tree risk assessment. However, there are major gaps in research that is directly applicable to our professional practice. Arborists need to stay current in the scientific literature related to tree risk assessment, and use that knowledge to help make sound professional judgments.

What is Peer-Review?

Scientific journals rely on the peer review process to test the validity and quality of the work. Work submitted to peer reviewed journals (also known as refereed journals) undergoes an impartial scrutiny by scientists knowledgeable in the subject matter. The process is intended to ensure that published work has appropriate experimental design, execution and statistical analysis, and that results, interpretations or conclusions are supported by the data. Peer review is, in short, the method scientists use to assure quality in the literature.

As an example of how the peer review process operates, consider, *Arboriculture & Urban Forestry (AUF)*. *AUF* adheres to a double-blind process. The editor-in-chief assigns each manuscript to an associate editor who then sends it to others for review. Reviewers do not know the author names, and authors do not know the reviewers name. Reviewers review the paper, make comments and suggestions for improvement, and either recommend the paper for publications, require changes to be made, or reject the paper as inappropriate or inadequate for the *AUF*.

In general, literature prepared by research scientists in governmental agencies such as the USDA Forest Service undergoes a similar review process. Most technical books are reviewed in a similar fashion. These situation differ from traditional peer review in that the author selects the reviewers and determines how to incorporate the comments. It is not considered as rigorous as the double-blind review.

Articles published in trade magazines like *Arborist News* and *TCI Magazine* generally undergo technical and editorial review, but not to the same degree as peer review. Trade magazine articles focus on education and professional practice and do not necessarily meet the standard of scientific rigor.

Compilations of conference proceedings (e.g. Landscape Below Ground I and II) typically undergo editorial review but not peer review.

Literature Cited

Baker, C. J., and H. J. Bell. 1992. The aerodynamics of urban trees. *Journal of Wind Engineering and Industrial Aerodynamics* 44: 2655-2666.

Bucur, Voichita. 2003. *Nondestructive characterization and imaging of wood*. Berlin, Germany: Springer Verlag .

Costello, L. R., and S. L. Quarles. 1999. Detection of wood decay in blue gum and elm: an evaluation of the Resistograph® and the portable drill. *Journal of Arboriculture* 25, no. 6: 311-317.

Cullen, s. 2002. Trees and wind: a bibliography for tree care professionals. *Journal of Arboriculture* 28: 1

Cutler, D. F., P. E. Gasson, and M. C. Farmer. 1990. The wind blow tree survey: analysis of results. *Arboricultural Journal* 14: 265-286.

Duryea, Mary L., Eliana Kampf, Ramon C. Littel, and Carlos D. Rodriguez-Pedraza. 2007. Hurricanes and the urban forest: II effects on tropical and subtropical tree species . *Arboriculture & Urban Forestry* 33, no. 2: 98-112.

E. F. Gilman. 2003. Branch-to-stem diameter ratio affects strength of attachment. *Journal of Arboriculture* 29, no. 5: 291-294.

Edberg, R., and A. Berry. 1999. Patterns of structural failures in urban trees: Coast live oak (Quercus agrifolia). *Journal of Arboriculture* 25, no. 1: 48-55.

Edberg, R., A. Berry, and L. R. Costello. 1999. Patterns of structural failure in Monterey pine. *Journal of Arboriculture* 20, no. 6: 297-304.

Farrell, Robert W. 2003. Structural features related to tree crotch strength. MS Thesis, Virginia Polytechnic Institute and State University, June 11. http://scholar.lib.vt.edu/theses/available/etd-05122003-124617/.

Gilman, E. F. 2003. Branch-to-stem diameter ratio affects strength of attachment. *Journal of Arboriculture* 29, no. 5: 291-294.

Hauer, Richard J., Weishen Wang, and Jeffrey O. Dawson. 1993. Ice storm damage to urban trees. *Journal of Arboriculture* 19, no. 4: 184-194.

Hickman, G. W., E. J. Perry, and Richard Evans. 1995. Validation of a tree failure evaluation system. *Journal of Arboriculture* 21, no. 5: 23-34.

James, Kenneth R., Nicholas Haritos, and Peter K. Ades. 2006. Mechanical stability of trees under dynamic loads. *American Journal of Botany* 93, no. 10 (October 1): 1522-1530.

James, K. and B. Kane. 2008. Precision digital instruments to measure dynamic wind loads on trees during storms. *Agricultural and Forest Meterology* 148(6-7):1005-10-61.

Kane, B. C. P., and H. D. P. Ryan. 2003. Examining formulas that assess strength loss due to decay in trees: woundwood toughness improvement in red maple (Acer rubrum). *Journal of Arboriculture* 29, no. 4: 207-217.

Kane, B., and H. D. P. Ryan. 2004. The accuracy of formula used to assess strength loss due to decay in trees. *Journal of Arboriculture* 30, no. 6: 347-356.

Kane, Brian, and Peggi Clouston. 2008. Tree pulling tests of large shade trees in the genus Acer. *Arboriculture & Urban Forestry* 34, no. 2: 101-109.

Kane, Brian, and Robert Farrell. 2008. Failure mode and prediction of the strength of branch attachments. *Arboriculture and Urban Forestry* 34, no. 5: 308-316.

de Langre, Emmanuel. 2008. Effects of wind on plants. *Annual Review of Fluid Mechanics* 40 (January 3): 141-168. doi:10.1146/annurev.fluid.40.111406.102135.

Lilly, S., and T. D. Sydnor. 1995. Comparison of branch failure during static loading of silver and norway maples. *Journal of Arboriculture* 21: 302-305.

Luley, C. J., and Jerry Bond. 2006. Evaluation of the fate of ice storm-damaged urban maple (Acer) trees. *Arboriculture & Urban Forestry* 32, no. 5: 214-220.

Mattheck, C., K. Bethge, and D. Erb. 1993. Failure criteria for trees. *Arboricultural Journal* 17: 201-209.

Mattheck, C., K. Bethge, and P. W. West. 1994. Breakage of hollow tree stems. *Trees - Structure and Function* 9, no. 1 (November 1): 47-50. doi:10.1007/BF00197869.

Rooney, C. J., H. D. P. Ryan, D. V. Bloniarz, and B. C. P. Kane. 2005. The reliability of a windshield survey to locate hazards in roadside trees. *Journal of Arboriculture* 31, no. 2: 89-94.

Sambuelli, L., LV Socco, A. Godio, G. Nicolotti, and R. Martinis. 2003. Ultrasonic, electric and radar measurements for living trees assessment. *Bollettino di Geofisica Teorica ed Applicata (Bulletin of Theoretical and Applied Geophysicist)* 44, no. 3-4: 253-279.

Sinn, Gunter, and Lothar Wessolly. 1989. A contribution to the proper assessment of the strength and stability of trees. *Arboricultural Journal* 13: 45-65.

Sisinni, S. M., W. C. Zipperer, and A. G. Pleninger. 1995. Impacts from a major ice storm: street-tree damage in Rochester, New York. *Journal of Arboriculture* 21: 156-167.

Smiley, E. T. 2003. Does included bark reduce the strength of codominant stems? *Journal of Arboriculture* 29, no. 2: 104-106.

Smiley. 2008. Root pruning and stability of young willow oak . *Arboriculture & Urban Forestry* 34, no. 2: 123-128.

Smiley, E. T., and Bruce Fraedrich. 1992. Determining strength loss from decay. *Journal of Arboriculture* 18, no. 4: 201-204.

Smiley, E. T., A. Key, and C. Greco. 2000. Root barriers and windthrow potential. *Journal of Arboriculture* 26, no. 4: 213–217.

Socco, L. V., L. Sambuelli, R. Martinis, and G. Nicolotti. 2003. Feasibility of ultrasonic tomography for nondestructive testing of decay on living trees. *Research in Nondestructive Evaluation* 15, no. 1: 31-54.

Terho, M., and A-M. Hallaksela. 2008. Decay characteristics of hazardous Tilia, Betula, and Acer trees felled by municipal urban tree managers in the Helsinki city area. *Forestry* 81(2):151-159. doi: cpn002. doi:10.1093/forestry/cpn002.

Tomikawa, Y., Y. Iwase, K. Arita, and H. Yamada. 1986. Nondestructive inspection of a wooden pole using ultrasonic computed tomography. *Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions* 33, no. 4: 354-358.

Wang, Xiping, and R. Bruce Allison. 2008. Decay detection in red oak trees using a combination of visual inspection, acoustic testing, and resistance microdrilling. *Arboriculture & Urban Forestry* 31, no. 1: 1-4.

Wang, Xiping, R. Bruce Allison, Lihai Wang, and Robert J. Ross. 2007. *Acoustic tomography for decay detection in red oak trees*. Research Paper. Madison, WI: U.S. Dept. of Agriculture Forest Service, Forest Products Laboratory. www.fpl.fs.fed.us/documnts/fplrp/fpl_rp642.pdf.

Wang, Xiping, Jan Wiedenbeck, Robert J. Ross, et al. 2005. *Nondestructive evaluation of incipient decay in hardwood logs*. General Technical Report. Madison, WI: U.S. Dept. of Agriculture, Forest Service, Forest Products Laboratory. http://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr162.pdf.

Wessolly, L., and M. Erb. 1998. *Handbuch der Baumstatik und Baumkontrolle (Manual of tree statics and tree control)*. Vol. 270. Berlin, Germany: Patzer-Verlag.

Wessolly, Lothar. 1995. Bruchdiagnose von Bäumen, Teil 1 : Statisch integrierte Verfahren - Messung mittels Zugversuch (Fracture diagnosis of trees Part 1: Statics-integrated methods - measurement with tension test, the expert's method. *Stadt und Grün* 6: 416-422.

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