Field tree load analysis: A basic method for arborists

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I. Introduction

As arborists, we are expected to judge tree failure probability, but we lack a well-founded method to make such estimations. In addition, risk assessment research has proposed biomechanical considerations that underscore the centrality of load analysis (Matheny and Clark 2009). Time being limited in the workday, any method would need to be quick and easy, or it simply wouldn't be used. There seems to be a need for a basic method of estimating potential load magnitude and distribution.

Eucalyptus (*Eucalyptus* sp.), height: 92ft (28m), DBH: 29" (74cm). An estimate of the tree's failure potential would be highly dependent on analysis of wind load magnitude and distribution. (*Photo by Brian Sullivan, Descanso Gardens*)

One promising source for such a method comes from tree load analysis techniques that have been around for well over a decade now. Introduced by Lothar Wessolly and his colleagues as a means of estimating safety that does not rely on invasive measurements or ignore basic mechanics (Wessolly and Erb 1998), it is practiced under the name of SIA in many areas of Europe, the United Kingdom and parts of Canada and the United States (Brudi and Van Wassenaer 2002).

Despite important limitations (e.g., Lonsdale 2003, James and Kane 2008) to such an approach, it nonetheless offers much potential service to practicing arborists. It asks interesting and important questions, offers an alternative approach to common problems, and reaches the logical conclusion that simply quantifying defect severity is insufficient for risk assessment. Also, its attention to tree-specific factors such as crown shape, tree height and strength help to persuade the practitioner that more than an abstract engineering formula is being promoted.

Yet most arborists and tree managers are unable to utilize this research in their daily work. The procedures are highly technical and time-consuming, and the equipment and personnel required for field testing require financial resources beyond those available for most jobs.

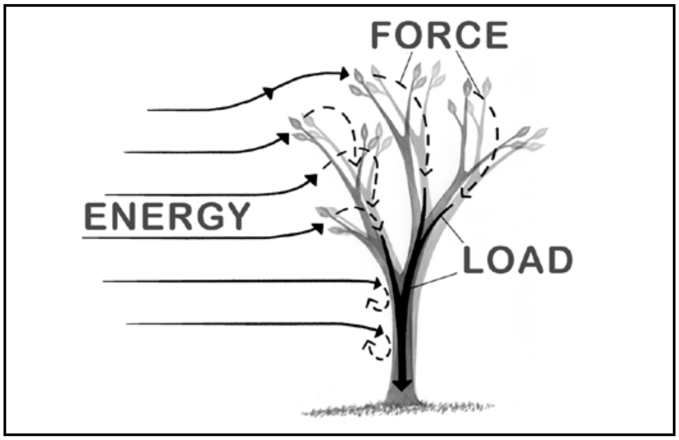
For these reasons, it seems to me critical that we get basic load analysis into the hands of arborists and tree managers as a standard practice for everyday work. This would require three steps:

- Develop a field protocol
- Create good documentation
- Get industry agreement on use

In this article I address the first step only, and hope thereby to attract serious attention to the topic from arborists who don't have engineering training. I do not write as an engineer, but as someone who is familiar with the research in English and German and who has been writing (e.g., Bond 2006) and speaking on this topic for the last five years in an attempt to make it more accessible.

Such a basic field protocol would not be a substitute for a detailed scientific analysis, and it could never be relied on for high-risk situations, for which a trained professional is required. The objective of creating it would be to make simple load analysis a standard field tool for gaining a 'first approximation' of load potential. Employing it would be analogous to the use of a sounding hammer to detect the ***presence*** of significant decay, where a positive result points to the need for advanced techniques to measure the decay's ***extent*** and ***failure potential***. Ultimately, basic

Failure of Norway spruces (*Picea abies*) in a late winter storm. Excurrent species efficiently transfer the wind load down the tree and out into the roots, where failure occurs when a saturated soil is unable to match the resulting stress. *(Photo by Chris Luley, Urban Forestry LLC)*



Simplified diagram of the relation of energy (here: kinetic), force and load. The dashed lines represent the interaction of the air and the tree that produces the external force that, in turn, induces load. *(Diagram by Nancy Lane, Nancy Lane Studio)*

load analysis should be incorporated into standard Visual Tree Assessment (VTA) techniques.

II. Basic load

Before we get to the field protocol, it seems to me that we must make sure that we are all using the same words in the same way—and understanding their implications. Let's start with the central concept of load:

Load is the internal force created by the interaction of energy with a structure or one of its parts.

I specify ***internal*** force here (contrast Chen and Lui 2005) because the phenomenon is much more complex with organic structures in natural settings than it is with the homogeneous and rigid beams in mechanical theory (Niklas 2002). That we cannot simply equate force and load results from the observation that the same amount of energy can produce loads that vary greatly depending on the details of the energy's interaction with the structure—as illustrated by the species differences that show up in catalogs of storm damage (e.g., Hauer et al 1993). In the world of arboriculture, then, load is perhaps best understood as the ***resulting internal force*** of the interaction of all the individual traits of the energy (speed, quality, duration, temperature, etc.) and the structure (for a tree: wood elasticity and density, leaf characteristics, crown architecture, etc.).

It is instructive to consider the full range of loading sources. The standard division separates out the following:

- **Dead load** designates the internal force created by the weight of material that is relatively constant. This applies to the above-ground wood that increases slowly throughout a tree's life. Healthy trees account for this load during growth.
- **Live load** (wide sense) refers to all temporary forces. The tree's ability to tolerate such forces depends to a large extent on what it has experienced during its life, since biological organisms do not add strength where stress is not experienced (Niklas 1992).

Live loads can be broken down into further categories, which overlap to some extent:

- **Live load** (narrow sense) is sometimes restricted to the load from vertical and non-environmental forces, and is a useful concept to address the critical issue of the loading from climbers and their rigging operations (Kane et al 2009).
- **Environmental load** derives from natural phenomena, and includes the application of vertical (snow and ice), lateral (horizontal wind) and/or rotational (twisting wind) forces. This load source accounts for many widespread catastrophic failures of trees and tree parts.
- **Dynamic load** comes from forces that rise and fall rapidly, such as happens with earthquakes and wind gusts, but also with vehicular impacts and even top removal during tree takedowns. When the period of load application coincides with the structure's natural (or 'modal') frequency, it can cause ***resonance***, where even small forces can lead to large oscillations and a dangerously increased chance of failure (James 2003). Even when failure does not occur, oscillation can result in repetitive stresses that induce structural fatigue (Niklas 1992).

These different types are not just of academic interest, but serve to signal the pervasiveness of load factors in tree work of all kinds.

Finally, structural load on trees can also be categorized by the direction of its effect:

- Axial (parallel to the dimension of length, i.e., with the grain)

Large limb of a Norway maple (*Acer platanoides*) dropped by the remnant of hurricane Gustav. As load moved down, it encountered this union as the first place where—thanks to reduced area from advanced decay—wood strength fell below the stress level being applied. *(Photo by Jerry Bond)*

- Radial (at right angles to the dimension of length, i.e., across the grain)
- Circumferential (around the dimension of length)

Tension and compression dominate the axial dimension, the focus of tree failure analysis, where compression is considered the critical limit because wood is weaker under compression than under tension (USDA 1999). The circumferential load of torsion (twisting) and the shear forces that it can produce are routinely ignored in engineering discussions of tree structure and failure, though the appearance of vertical cracks in long leaders, for instance, suggests that it might reward closer attention.

Closeup of a long exposed leader of a silver maple (*Acer saccharinum*), showing a large spiraling crack with an associated fungal fruiting body (prob. *Polyporus squamosus*). This damage was likely caused by large rotational stress. *(Photo by Jerry Bond)*

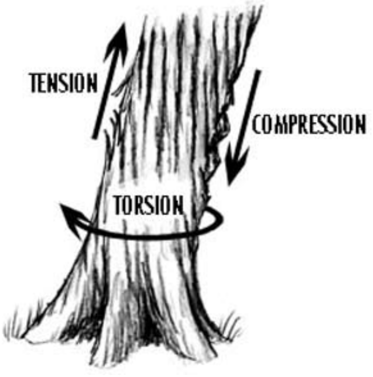
III. Load transference

Now that we have looked at load, we need to consider its motion through the tree. Because of the apoplastic continuum, that is, the fact that cell walls are interconnected (Shigo 1994), and because living cells are turgid and press tightly against each other, load is easily transferred through the tree. This transference occurs typically from:

- the outside of the crown inwards toward a main stem
- the top of the stem downwards toward the butt
- the butt of the tree outwards into the soil

As load moves through the tree, it produces different stress levels that depend upon the local mechanics, the local material and the local supporting area.

Diagram of the three dimensions in which load is exerted. Most risk assessment concentrates implicitly on the axial component, where compression strength is the critical limit, but torsion can also be important. *(Nancy Lane, Nancy Lane Studio)*



Stress = force per unit area

This moving load tests for weakness by forcing the material to match it as it proceeds. The first time it encounters a location where stress (in the US: pounds per square inch) is greater than strength, local breakage and deformation (=strain) will begin, and complete failure will result if those processes do not stop.

Strength = ability to withstand an applied stress without failure

White oak (*Quercus alba*) felled by a thunderstorm. Butt decay had been found previously on the underside, suggesting that the tree failed initially under compression and finally under tension. *(Photo by Chris Luley, Urban Forestry LLC)*

So when we ask about the structural integrity (stability) of a limb or tree, we are really asking whether strength can match stress at all locations for a given load.

But how in the world can we make a decision about that? Strength itself can't be measured reliably in a single location, much less in a thousand, except by destructive testing; attempts to do that (with the fractometer, for instance, Mattheck et al 1996) have not gained wide acceptance.

In a basic field approach, then, our best strategy within the limits we have seems to be to identify locations where the smooth flow of stress that marks structural stability is significantly altered. Such locations produce stress concentration or 'localization of high stress' (Pilkey and Pilkey 2008), and are sometimes called 'raisers':

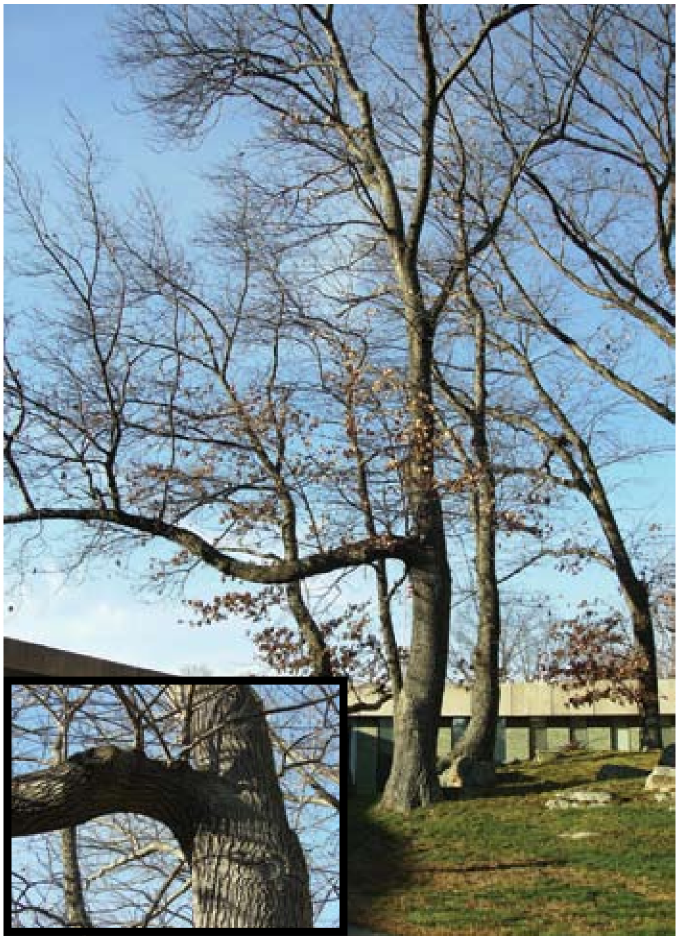
A stress raiser is a material condition that leads to high localized stress.

Such raisers can take a number of forms in trees:

- an abrupt change in shape (such as a dogleg)
- a sudden reduction in surface area (such as a large decay area)
- 'notches' (Mattheck 1998) of all kinds (such as holes, cankers, and cracks)

At such locations—not all of which may be discernible—stress is several times greater than where these raisers are not present.

Our goal, then, is to be able to visualize and assess this load flow from the tips of the shoots to the tips of the roots, using external structural changes (Mattheck and Breloer 1994) to aid us in the search for stress raisers. It may be helpful to think of the imaginary force lines commonly used in drawings of magnets, even though in this case the lines are more real since the load actually flows through rows and columns of cells. This visualization requires that we consider the magnitude of the forces that one can typically expect on the whole tree or one of its parts, and identify and prioritize unstable locations that will be subjected to high stress levels as the load moves through the tree. We can make this process easier by structuring it in the form of questions organized into a field protocol, which is what I try to do in the rest of this article.



Scarlet oak (*Quercus coccinea*) in a forest remnant incorporated into the landscape. Despite the presence of significant lower stem decay, the long limb toward the north has a severe stress raiser (inset) and is likely to fail under high stress before the main stem. *(Photos by Sara Sankowich, National Grid USA)*

IV. Six questions toward a protocol

I will argue now that six questions can lead the field arborist to a functional appreciation of potential load magnitude and distribution. The questions aid the arborist to follow load from its origin in the application of a force to its dispersion in the soil. Only categorical responses are required: high, medium, and low. Such responses are not measurements, and they are barely estimates. Yet the set of answers are sufficient to provide a 'fuzzy portrait' of potential load that will help identify and prioritize instability.

Large limb of a 64 in (163 cm) DBH white oak (*Quercus alba*) extended over 3-phase wires and completely exposed to the prevailing winds from the west. *(Photo by Jerry Bond)*

Q1: What is actual exposure potential to high levels of wind, ice, etc?

Factors:

- Weather exposure:
  - Average (10-year?) high wind speed and direction in tree's leaf-on season
  - Frequency, type and severity of disastrous events (e.g., a 'Pineapple Express')
- Site exposure:
  - Protection from neighboring vegetation
  - Presence of nearby human structures
- Individual exposure:
  - Leaning edge tree, overextended limb, etc.

Failure of a red oak (*Quercus rubra*) during an early spring storm with a large amount of rain and wind. Despite the absence of leaves, the load resulting from the wind on the crown and trunk was enough to exceed the strength of the small root mass in a saturated soil. The failure mode suggests possible root decay on the curb side as well. *(Photo by National Grid USA)*

  - Recent loss of protection through removal of trees, limbs, structures, etc.

Q2: How much surface area is available to capture the force?

Factors:

- Foliage surface area—size and density of foliage on the tree or branch
- Wood surface area—generally only a significant factor in leaf-off periods or during extreme events that escape prediction
- Leaf and twig (roughness, stiffness, etc.) play a decreasing role as larger forces are applied
- Lopsided foliage distribution increases torsion

Q3: How severe are the stress raisers present?

Factors:

70ft (21 m) tall black cherry (*Prunus serotina*) with a DBH of 17 in (43 cm), newly exposed on the edge of recent construction. The load descending from the small crown is magnified by leverage, producing very high stress at the obvious stress raiser about half way up and at the base. *(Photo by Chris Luley, Urban Forestry LLC)*

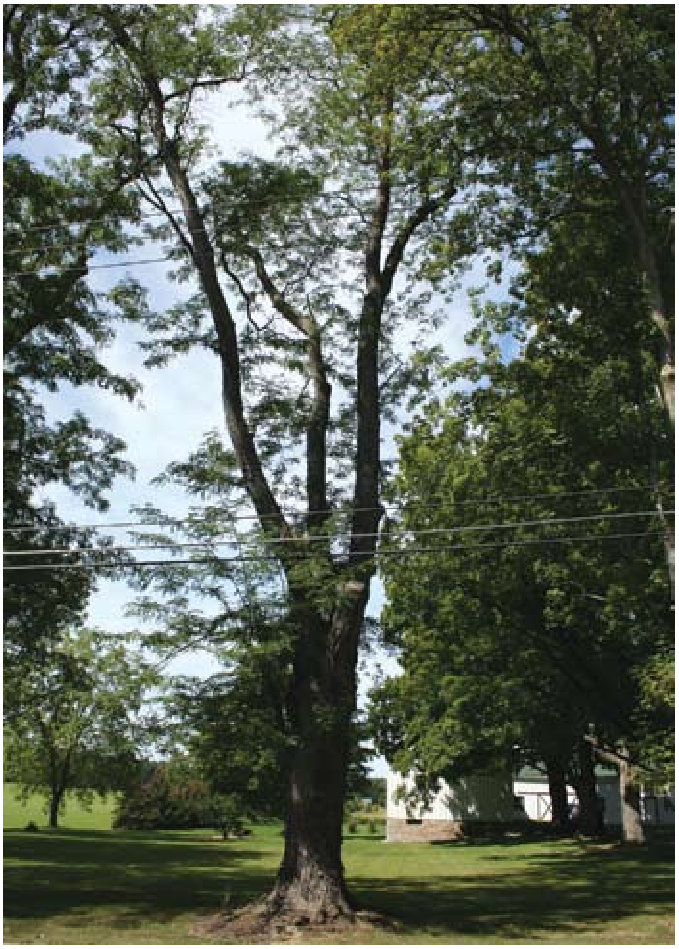
- Stress raisers concentrate load moving through the tree
- Types:
  - Sharp bends such as doglegs
  - Cankers, cracks and other material defects
  - Sharp reduction in load-bearing surface area such as produced by decay
- Severity level judged with standard VTA techniques

Q4: How long is the lever arm to magnify the force?

Factors:

- Lever is the distance from center of gravity to the nearest susceptible stress raiser or base
  - Center of gravity—here, the approximate center of the foliage mass
  - Most susceptible stress raiser—select from responses to Q3 or use termination point

A honeylocust (*Gelditsia triacanthos* var. inermis) with limbs repeatedly pruned up to clear utility wires. This common procedure actually increases the stress felt at the limb's base by constantly lengthening the lever arm and raising the foliage into faster winds (here partially blocked by other vegetation). *(Photo by Jerry Bond)*



Bur oak (*Quercus macrocarpa*) with 75 ft (23 m) height and 43 in (114 cm) DBH. The many large limbs radiating from the top of the main stem are capable of absorbing a great deal of energy, relieving the stress on the lower stem and roots. *(Photo by Jerry Bond)*

Work = Force x Distance

Q5: What is the degree of excurrent architecture?

Factors:

- Excurrent limbs and trees have a single dominant central axis
- They tend to maximize load transference through tree
- They are also more likely to resonate to dynamic loading
- More decurrent architecture has large lateral branches that absorb force

Old pruning wound on a cottonwood (*Populus deltoides*) over 3-phase wires. The combination of a weak-wooded species with a large decayed wound on the upper load-bearing surface would be a serious threat if the limb were exposed. This particular one is on the lee side of the crown and surrounded by other limbs, so subject to low external loading. *(Photo by Jerry Bond)*

Q6: How weak is the material along the critical axis?

Factor:

- Species differ in strength by a factor of about 4 (compression) to about 8 (torsion) in standard tests
- Actual individual trees deviate from laboratory values due to genetics and environment
- Species anatomy, such as fiber structure in the elm family, is also important to consider

V. Conclusions

My persuasion is that this basic field method provides a convenient tool for creating a legitimate basis for judgments about likelihood of failure that we make every day about individual trees as well as populations. But that persuasion needs to be tested by arborists, and their feedback used to modify and improve the method. A simple data form can be created for data collection (Bond 2010), and the procedure adapts easily to electronic format. Once we have good field testing behind us, we can turn to the questions of documentation and industry acceptance.

Basic Tree Load Analysis Data Sheet

		Q1	Q2	Q3	Q4	Q5	Q6
ID	High		x				x
	Medium	x				x	
	Low			x	x		

Example of a possible data form, illustrating the useful output of this basic method of basic load analysis.

It is important to repeat what this proposal does not claim to be. It does not offer a magic bullet for risk assessment, it is not a substitute for formal scientific analysis, it does not provide easy answers, and it does not eliminate the need for experienced and knowledgeable interpretation of its data. But these six questions are one effective means of estimating load analysis in the field, and they also constitute a useful pedagogical tool for workshops, crew training, etc. With luck, such an approach may bring load analysis into everyday work situations for us non-engineers doing risk analysis with limited time and resources.

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