

Tree load: Concept

By Jerry Bond



LEARNING OBJECTIVES

The arborist will be able to

- describe the central concept of load and differentiate among various load categories
- explain how load movement may affect stress versus strength in various areas of a tree
- define “stress raiser” and describe visible, outer conditions that may indicate the presence of a stress raiser within a tree

CEUs for this article apply to Certified Arborist, Utility Specialist, Municipal Specialist, Tree/Worker Climber, and the BCMA science category.

As arborists, we are expected to judge tree failure probability, yet recent advances have made it increasingly clear that limiting our focus to the presence and severity of defects can no longer be considered adequate. In addition, risk assessment research has proposed biomechanical considerations that underscore the centrality of load analysis (Matheny and Clark 2009). There thus seems to be a practical need for a basic exploration of load, as well as a field method of estimating its potential magnitude and distribution.

In this first installment of a two-part treatment of this topic, I want to examine the concept of load in detail and explore its importance for the daily work of arboriculture. I do not write as an engineer, but as someone who is familiar with the biomechanical 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 to non-specialists.

Basic Load

Let's start with a definition of 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 simple forces exerted on homogeneous and rigid beams as used in mechanical theory (Niklas 2002). We cannot simply equate external force and internal 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 species differences that show up in catalogs of storm damage (e.g., Hauer et al. 1993). In the world of arboriculture, load is perhaps best understood as the resulting internal force of the interaction of all the individual traits of the energy (such as speed, quality, duration, temperature) and the structure (for a tree: wood elasticity and density, leaf characteristics, crown architecture).

Such forces derive from a 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. The closest a tree comes to this is with the above-ground wood that increases

slowly throughout a tree's life.

Healthy trees typically 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—and the weight that comes with it—where not needed (Niklas 1992).

Live loads can be further broken down into 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 in arboriculture to address the critical issue of the loading from climbers and their rigging operations (see Kane et al. 2009).

Environmental load derives from natural phenomena and includes



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Eucalyptus (*Eucalyptus* sp.), height: 92 ft. (28 m), dbh: 29 in. (74 cm). An estimate of the tree's failure potential would be highly dependent on analysis of wind load magnitude and distribution.

in engineering discussions of tree structure and failure. Yet the shear strength of green wood varies almost five-fold among species (Wessolly and Erb 1998; Forest Products Laboratory 2010), and defects such as cracks in long leaders, suggest that torsion might reward closer attention.

Load Transference

Now that we have looked at load, we need to consider its movement, for it is not restricted to a motionless combination of forces at equilibrium. As recently noted, for nearly all trees the greatest load is from the wind that comes as gusts of rapid, periodic, dynamic events (James et al. 2006). If we consider the actual movements of a tree or branch under wind loading, we can imagine load pulsing as an internal force wave through the tree. Because of the apoplastic continuum, that is, the fact that cell walls are interconnected (Shigo 1994), this load is efficiently transferred. 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

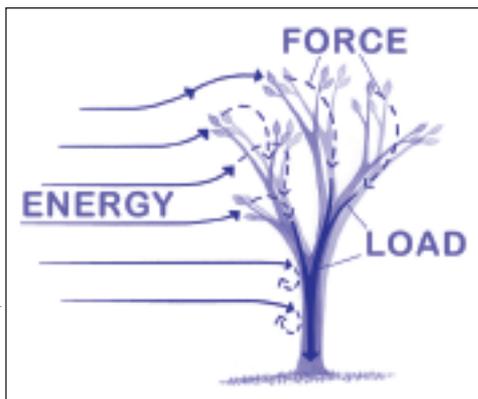
As load moves through the tree, it produces different stress levels that depend upon the local mechanics, the local material, and the local supporting area (see for instance, Niklas 1999). This key concept of stress (in the U.S., pounds per square inch) is defined by a simple formula:

$$\text{Stress} = \frac{\text{Force}}{\text{Area}}$$

As this formula makes clear, stress is increased at a given location when either the force increases or the area to which it is applied decreases. The moving load tests for weakness by forcing the material to match stress with strength as it proceeds.

Strength = ability to withstand an applied stress without failure

The first time it encounters a location where stress is greater than strength, permanent deformation (=strain) will



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.



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.

the application of vertical (e.g., ice), lateral (e.g., horizontal wind), and/or rotational (e.g., twisting wind) forces. This load category includes many widespread catastrophic failures of trees and tree parts.

Static load describes external, non-varying forces that are exerted over a relatively long period. This load can be analyzed during tree risk analysis, as notably promoted by the Statics Integrated Method (Wessolly and Erb 1998; Brudi and Van Wassenae 2002).

Dynamic load comes from forces that rise and fall rapidly, as with earthquakes and wind gusts, but also with vehicular impacts and even top removal during tree takedowns. Dynamic loads are dominated by the effects of motion and change, and tend to be very complex, particularly in organic structures under real-world loading events. For this reason, they are extremely difficult to analyze (James et al 2006).

Resonance is when the period of load application coincides with the structure's natural (or "modal") frequency, where 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 of load are not just of academic interest, but also serve to signal the pervasiveness of load factors in tree work of all kinds.

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)
- 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 most tree risk analysis. Of the two forces, compression is considered the critical limit because wood is weaker under compression than under tension. The circumferential load of torsion (twisting) is routinely ignored

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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.

begin, and complete failure will result if that process does not stop. So when we ask about the structural integrity (stability) of a limb or tree, we are really asking whether the strength of the material can match the stress at all locations for a given load.

In the Real World

But how can we actually reach a decision about whether strength can match stress? Except by destructive testing, strength itself can't be measured reliably in a single location, much less in a thousand. Attempts have been made to do that (with the fractometer, for instance, Mattheck et al. 1996), but have not gained wide acceptance.

It may be helpful to visualize stress flow by thinking of the imaginary force lines commonly used in drawings of

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Close-up 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*). The damage was likely caused by large rotational stress.

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.

We also need to search for locations that will be subjected to unusually high stress levels. In a basic field approach, our best strategy within the limits we have would be to identify where the smooth flow of load that marks stability is significantly altered. Such localizations of high stress (Pilkey and Pilkey 2008) concentrate stress lines, and for this reason are often referred to as “stress raisers”:

A stress raiser is an internal condition that leads to high localized stress.

Such raisers may not be discernible, such as “bark occlusions” that significantly lower strength (Kane and Clouston 2008), but they can take a number of visible forms in trees:

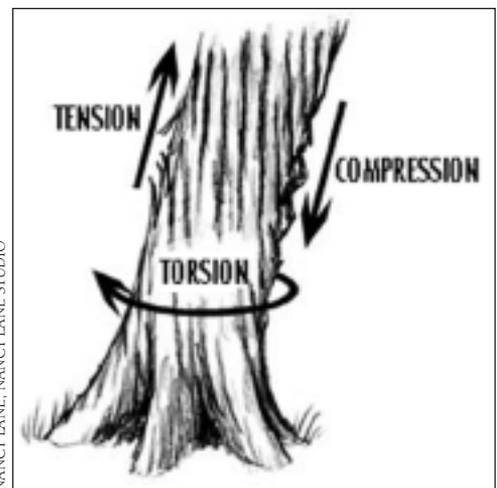
- an abrupt change in shape (such as a dogleg)
- a sudden reduction in cross-sectional area (such as at a large decay location)
- “notches” (Mattheck 1998) of all kinds (such as cankers, cracks and holes without sufficient adaptive growth)

Stress is several times greater where such raisers are present. Healthy trees are able to reinforce areas of high stress by altering the quantity and/or quality of new wood, a fact that underscores the importance of including an estimate of tree health (Bond 2010) during risk assessment.

Our task, then, involves four steps:

1. Visualize and assess load flow from the tips of the shoots to the tips of the roots.
2. Search for stress raisers by examining external structural changes [as described for instance by Mattheck and Breloer (1994)].

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Representation of the three dimensions in which load is exerted. Most risk assessments concentrate implicitly on the axial component, where compression strength is the critical limit.



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.

3. Evaluate tree health in order to estimate the tree's ability to compensate for high stress.
4. Assess the likely interaction of load and stress raisers within the limits (wind speed, time period) of the scope of work.

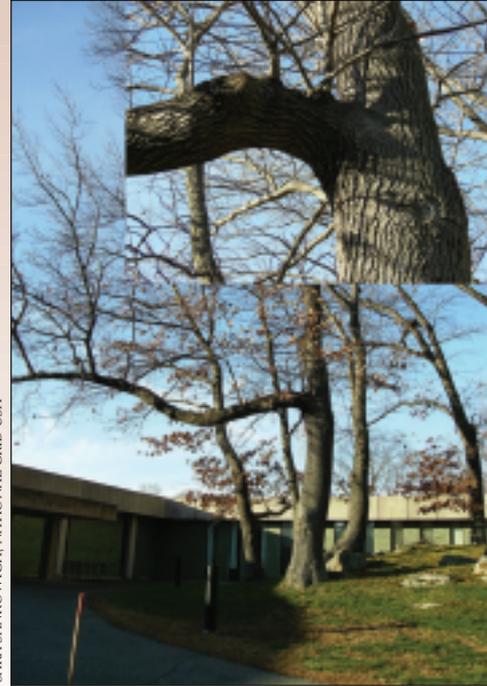
Such a procedure will help the arborist bring some of the more recent research results into daily practice, as well as widen the observer's traditional field of view during risk assessment.

Conclusion

A good basic understanding of how trees are loaded by external forces and how this load explores strength as it moves through the tree can be of great aid to any arborist in the field. Whether doing maintenance, climbing, or assessing risk, the arborist can use this understanding to raise the level of his or her everyday work.

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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.

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Jerry Bond is an urban forestry consultant with Urban Forestry, LLC (www.UrbanForestryLLC.com).

The author appreciates the editors' permission to revise this article for publication here. The author wishes to express his gratitude for critical readings by Andreas Detter, Chris Luley, and Philip Van Wassenaer, whose questions and comments greatly improved the article.

This article is a revised and expanded version of the original, which appeared in Western Arborist last year.



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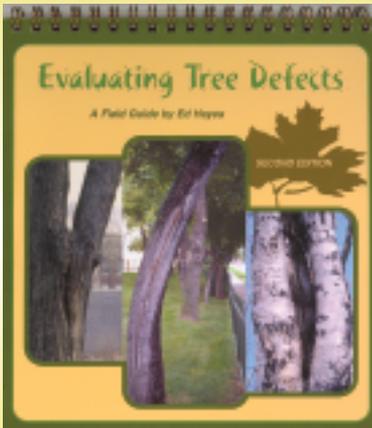
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1. What is tree load?
 - a. an external force
 - b. an internal force
 - c. a consequence of defects
 - d. a consequence of maintenance
2. What affects the tree load produced by a particular force?
 - a. air properties
 - b. leaf characteristics
 - c. crown architecture
 - d. all of the above
3. Why is the applied external force not identical to the tree load?
 - a. There is no relationship between the two.
 - b. Not enough is known about such a force to measure it.
 - c. It acts outside the tree.
 - d. The force interacts with the tree in a complicated fashion.
4. What term is applied to the load produced by a tree's wood?
 - a. dead load
 - b. live load
 - c. static load
 - d. dynamic load
5. When a climber is in a tree, the tree experiences
 - a. increased dead load
 - b. increased live load
 - c. decreased static load
 - d. decreased dynamic load
6. Why isn't dynamic load evaluated during risk assessment?
 - a. It has only a minor effect.
 - b. It is too complex.
 - c. It doesn't contribute to most failures.
 - d. It is overwhelmed in importance by dead load.
7. What direction of external natural force produces environmental load?
 - a. lateral
 - b. vertical
 - c. rotational
 - d. any of the above
8. Why are the effects of resonance important to consider during tree operations?
 - a. Small forces can produce large reactions that are potentially dangerous.
 - b. It makes it difficult to make correct cuts.
 - c. It increases the cost to the client.
 - d. It can lead to equipment failure.
9. Which load direction typically receives the **most** attention during risk assessment?
 - a. along the grain (axial)
 - b. across the grain (radial)
 - c. around the grain (circumferential)
 - d. they receive equal attention
10. Which load direction typically receives the **least** attention during risk assessment?
 - a. along the grain (axial)
 - b. across the grain (radial)
 - c. around the grain (circumferential)
 - d. they receive equal attention
11. When does a tree typically experience the greatest load?
 - a. in the growth period
 - b. in the dormant period
 - c. when it is at rest
 - d. when it is set into motion by wind
12. How is load transmitted through the tree?
 - a. through the xylem
 - b. through the phloem
 - c. through the plasmodesmata
 - d. through the linked cell walls
13. What happens to load once it descends to the tree butt?
 - a. It returns to its source.
 - b. It moves out into the roots and soil.
 - c. It is absorbed.
 - d. The load dies off.
14. Which two elements are needed to define stress?
 - a. force and area
 - b. force and hydration
 - c. species and site
 - d. species and size

15. Which of the following units could be used to measure stress?
 - a. tons/tonnes per second
 - b. feet/meters per diameter
 - c. acres/hectares per root zone
 - d. pounds per square inch/kg per square centimeter
16. When does failure start?
 - a. when stress is greater than strength
 - b. when strength is greater than stress
 - c. when the tree is growing weakly
 - d. when the tree is growing strongly
17. Why isn't strength directly measured during risk assessment?
 - a. There is no practical method for doing that.
 - b. Any measurement would only be valid for the location where it is taken.
 - c. The wood must be destroyed by the measurement.
 - d. all of the above
18. What is a tree stress raiser?
 - a. A material condition that leads to high localized stress.
 - b. A biological organism that attacks weak trees.
 - c. A chemical reaction in the cells of certain species.
 - d. A symbiotic relationship that most trees have.
19. Can stress raisers be recognized?
 - a. Yes, by trained observers.
 - b. No.
 - c. Still unknown to science at this point.
 - d. Many, but not all.
20. Why is a dogleg considered to be a stress raiser?
 - a. Because it is not straight.
 - b. Because the load flow suddenly changes direction.
 - c. Because a branch has been removed.
 - d. Because it can be found over utility lines.

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