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...
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.

\[ \text{Strength} = \text{ability to withstand an applied stress without failure} \]

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

Additional Reading
Forest Products Laboratory. 2010. Wood handbook - Wood as an engineering material. General Technical Report FPL-GTR-190. Madison, WI. Forest Products Laboratory.


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

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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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