Static Load Tests in Arboriculture

1 Basics of the method

For many years, winching tests or pulling test have been used during research in tree biomechanics as a means to determine the resistance of trees against rupture and uprooting. Usually, the tests are designed to cause ultimate failure and therefore lead to the destruction of the subject trees.

In practical arboriculture, a non-destructive assessment of tree risk is required in order to identify hazard trees and to be able to retain mature valuable trees. Often, veteran trees will be sufficiently stable despite obvious defects in their wooden body. Therefore, static load tests were developed in the mid 80's at the University of Stuttgart in Germany and were applied on more than 10.000 trees so far in Europe and North America.

Basically, a static load test consists of three distinct steps:

Pulling test: measurement of the subject tree's reaction to static loads

Wind load analysis: assessment of loads generated from a defined wind event

Evaluation: definition of safety factors against rupture and uprooting

These three steps indicate that the Static Load Test as currently applied in arboriculture is strictly speaking more than a test of the tree's mechanical properties. It also comprises extrapolations of strength based on guideline values, specific analysis on the exposure of the subject tree to wind and a numeric measure for the current reserves against failure.

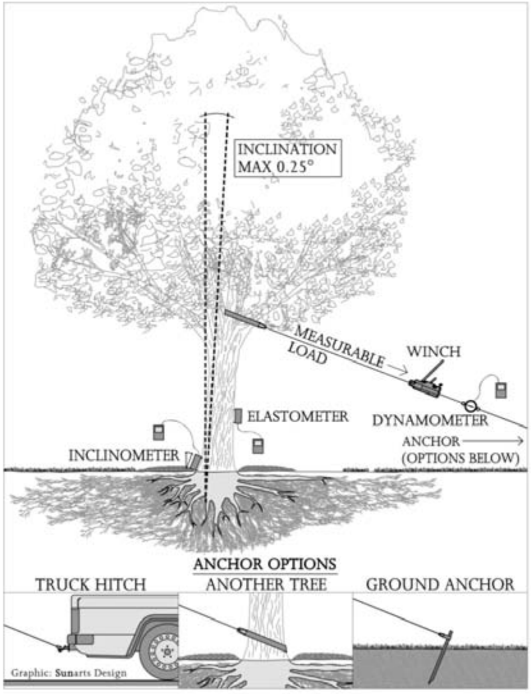
The actual measurements draw a very accurate picture of the trees reaction to loads. But the aim of every investigation is to determine the level of risk involved in retaining the subject tree or to reliable prove the need for its removal. Like it is true for any other devices used in tree risk assessment, this cannot be accomplished without a number of further evaluations, judgments and estimates.

Due to the heterogeneity of trees and the natural variability of several parameters used during the evaluation, the results represent a lower extreme of a bandwidth. Yet, the Static Load Test examines properties of the tree that would also initiate its failure in case over overloading: tilt of the root plate and compression of marginal fibers in the stem.

2 Pulling test

Using this methodology to assess the likelihood of failure (stem breakage or uprooting), the subject tree is pulled to simulate moderate wind loading and the resultant changes in fibre length and root plate inclination are measured. The experiment is designed to determine how the tree responds to defined loads. Using a grip hoist or rope winch, small quasi-static forces will be applied to the tree through a rope fixed in the crown and measured with an in-line dynamometer.

While the tree is exposed to increasing load, its stem bends and its root plate tilts to a miniscule degree that is invisible to the human eye. High sensitivity instrumentation continuously monitors the tree reaction and links it to the applied load. Data is logged via radio into a computer and is being stored electronically for later evaluation.



The pulling force is monitored using an electronic forcemeter (Dynamometer) with a resolution of 0.01 kN (roughly 2.2 lbf). The bending of the tree stem is detected via high-resolution displacement transducers (*Elastometer*) that monitor fibre strain at an accuracy of 0.001 mm (1/25,000 in). At the same time, the inclination root crown just above ground is detected by highly sensitive inclinometers (resolution 0.001°).

Every test will be terminated at very low reaction levels in order to ensure that deformations are fully reversible and the subject tree remains structurally undamaged.

Pulling test (from WASSENAER & RICHARDSON 2009 by kind permission)

The degree of compression or extension exerted in the marginal fibres by the applied load is used as an indicator of the resistance to fracture. The initial resistance of the root plate against tipping serves to mathematically establish the anchoring strength of the root system. In order to accomplish this without damaging the tree, extrapolations from low force levels to the expected wind load during a storm event are required.

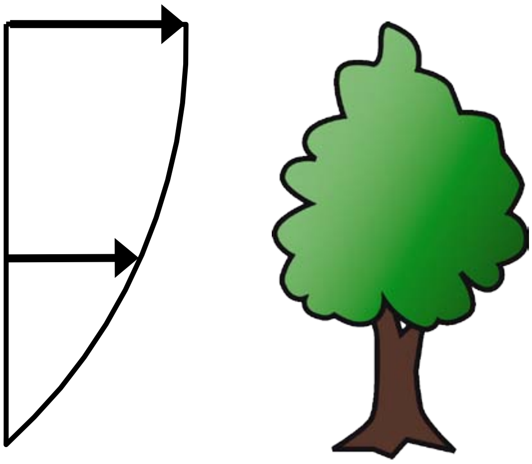
3 Wind load analysis

All methods for wind load assessment are designed to give an estimate of the expected wind load at a given location during a defined wind event. A sufficiently safe tree will have to withstand the effects of wind, snow and ice, among which the wind is the dominant load as long as the stem is more or less vertical.

Wind loads required for the evaluation of tree risk generally depend on:

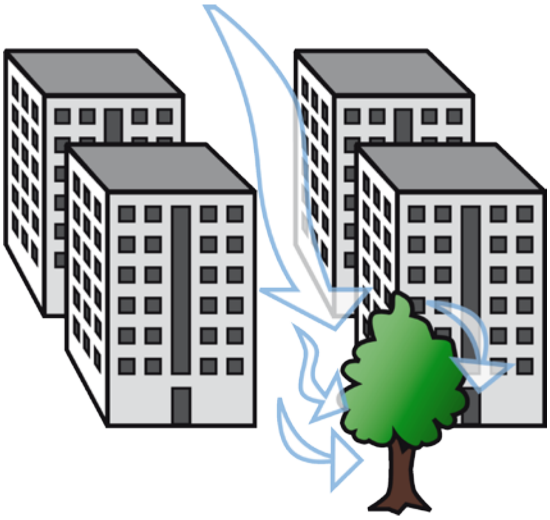
- the expected wind speed and wind structure at the specific location and
- the trees resistance to streaming air, i.e. its static surface area (like a wind sail) and its dynamic reaction (i.e. its nature as a flexible, porous, swaying structure).

The surface area exposed to the wind is determined from the vertical projection of all above ground tree parts (crown in leaf and stem) in the chosen load direction. During the wind load analysis, the crown outline is extracted from a digital picture. The crown outline is continuously scanned over its height in order to determine distinct components of the surface areas at different heights. Those segments are correlated with the wind speed that is known to increase with greater height above ground. This method is used to determine the theoretical static wind pressure and drag on the crown.



Wind speed increasing with height (logarithmic profile)

Reference wind speeds are generally chosen from specific national wind zone maps. In many cases, the analysis refers to a wind event where gusts reach a speed of 33 m/s (roughly 120 km/h or 75 mph) at 10 m height above ground (30 ft). This is the case because healthy trees are reported to fail when exposed to gust of this speed. The wind speed for the chosen wind event is only valid in an undisturbed environment. The reference wind speed must be altered according to the specific type of terrain the tree is located in. For trees in the urban environment, an additional factor must be applied in order to adapt the wind speed to near ground flow properties. Within the rough layer of a city for example, the adjacent buildings may cause tunnel or blast pipe effects as the air passes narrow street canyons or is forced to flow around high rise buildings.



Tunnel effects may increase wind loads on urban sites

In order to assess a tree's reaction to wind, species dependent parameters and structural guideline values are being used. Streamlining of the crown, causing a reduction of tree height and surface area by bending of thin branches, increasing crown porosity and reducing leaf area, is usually assessed based on proposals by WESSOLLY & ERB (1998) and SINN (2003). The effect is expressed in the form of an aerodynamic drag factor.

Dynamic effects are generated from the interaction of wind gusts and a tree's natural sway behavior. Parameters like the natural frequency of the tree and damping properties can be used in a probabilistic approach according to DIN 1055-4 or Eurocode 1. The models used in the current wind load analysis for trees are also consistent with recent research results on responses of trees to natural wind (cf. JAMES 2010).

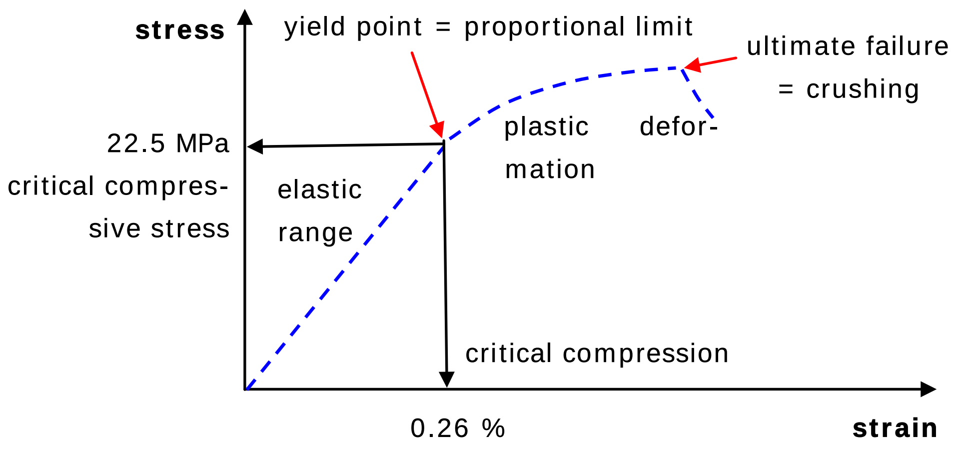
The algorithm based evaluation analyzes the expected reaction of a tree to typical dynamic sequence of wind gust at the specific site. The resulting base bending moments represent equivalent static wind loads that generate in the same maximum deformation of the tree stem as the gust would exert during a storm event. Because dynamic elements are incorporated in the assessment process, equivalent static wind loads may be directly compared to static loads applied during a pulling test.

4 Evaluation

Data acquired during the pulling test will be extrapolated to specific thresholds in order to determine critical loads. Those may be weighed against the expected wind load at the tree site. All algorithms required for the evaluation are available from specialist software (e.g. *Arbostat*, see www.arbosafe.com).

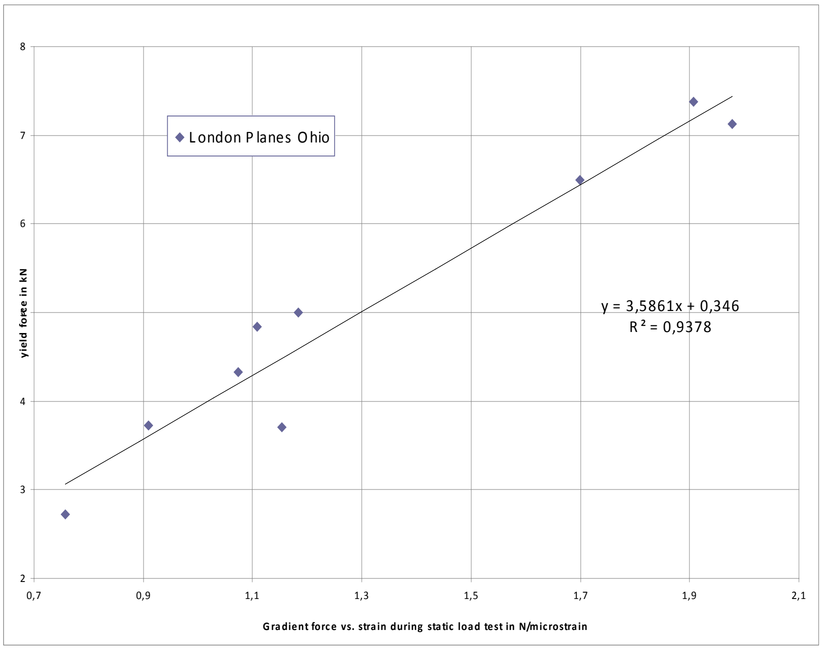
4.1 Stem resistance against fracture

The assessment of resistance against fracture uses a threshold which is called the proportional limit. Below this point, the deformation of wood fibers in the stem is fully recoverable, i.e. the wooden structure is not damaged and returns to its original state as soon as load is released. Beyond this so-called elastic range, primary failure of the trunk would initiate the fracture process by the occurrence of plastic changes in the wood fibers. In that case, the trunk will be irreversibly damaged and start to yield.



Stress vs. strain diagram for green wood in compression (data for *European Beech*)

Guidelines for critical strain in marginal fibres at the yield point have originally been derived from lab tests (WESSOLLY & ERB 1998). These material properties strongly depend on the species of the subject tree and wood density (LAVERS 1983, NIKLAS & SPATZ 2010).



During the evaluation process, the flexural stiffness of the stem is derived from the data measured in the pulling test. It serves as an indicator for yield strength in bending.

A good correlation (R^2=0.94) between flexural stiffness (horizontal axis) and yield strength (vertical) was confirmed e.g. for 9 *London Planes*, some with severe defects, in field tests in Ohio.

Results from destructive tests: stem fracture on full-sized trees

4.2 Anchoring strength of the root system

Root plate stability is assessed from extrapolations based on the typical tipping behavior of trees (cf. COUTTS 1983, WESSOLLY 1996). In a first step, the values measured during the pulling test are extrapolated along an exponential function. Thus, the load that would be required to reach an inclination of 0.25 ° at the root crown is determined. Up to this point, the tipping behaviour is rather congruent for all trees studied to date.

For higher degrees of inclination, the studies show a strong scatter in the data. Therefore, in a second step the tipping load is assessed conservatively from the moment required to arrive at 0.25 ° inclination. A factor is used to estimate the peak load during the tipping process. This approach is supported by other studies that indicate a close correlation between loads at low inclination and the tipping load (e.g. SMILEY 2008).

4.3 Factors of Safety

The results of the analysis are presented in the form of factors of safety. If the resistance against failure matches exactly the expected wind load, the factor of safety of the tree would be 1. But according to engineering standards any structure must have sufficient strength reserves beyond the expected loads. Due to the level of uncertainty involved in any numeric approach, a factor of safety of 1.5 is required in the Static Load Test.

Trees are able to compensate for strength loss by adaptive growth. Judging the subject tree's ability to form additional wood fibres in areas of excessive strain is part of any tree risk assessment and usually based on visual inspection. Correlating the results of any technical inspection with the visual assessments carried out by an experienced arborist is essential to deduct purposeful and sensible recommendations.

5 Limitations

In current research projects carried out in Germany, the Czech Republic and Austria, the effects of tree species, extensive decay, soil type, temperature and moisture on the results of Static Load Tests are being examined under the scrutiny of scientific experiments. In the near future, the magnitude of those influences will be known and may be counterweighed against the currently desired safety margin of 1.5.

The applicability of the method outside Europe still is limited by lack of material properties and drag factors for many tree species. The evaluation cannot be applied to forest trees or single branches until an adequate methodology for wind load assessment is established. Wind effects in climates that experience strong seasonal winds may have to be adapted according to local standards for the assessment of wind effects on structures.

6 References to the literature

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