Overview of techniques and procedures for assessing the probability of tree failure

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Assessment of the mechanical strength and integrity of trees is the main topic of this seminar. We can thereby estimate the probability of failure occurring within a given time, or decide whether a tree satisfies a chosen standard of safety. The concept of probability has been applied within various systems of hazard rating, notably that of Matheny & Clark (1994) and of quantified risk assessment, which is the subject of Mike Ellison's seminar (Ellison, 2003). The concept of a chosen standard is the basis for Static Integrated Assessment. Irrespective of whether we use probabilities or standards, we need to decide whether mechanical assessment of individual trees is justified on the basis of risk to people or property, as explained in Mike Ellison's presentation.

In the UK, there has been a long tradition of visually assessing trees for suspected 'defects', using subjective criteria to decide the need for possible remedial action, while also taking site usage into account. The contributions of Matheny & Clark (1994) in the USA and Mike Ellison in the UK have provided a basis for integrating site usage into the overall assessment and management of risk. In this context, the key requirement is to manage risk within acceptable limits, taking into account the probability of failure and the potential for consequent harm to people or property ('targets'). A fundamentally different approach is to test trees against a fixed standard for strength or stability. The potential for harm can be taken partly into account if such a test is applied, but only in the sense that the presence of targets can help to decide whether a particular tree should be tested.

The work of assessing trees visually has been very much aided by the contribution of Claus Mattheck in Germany, who has developed the concept of visual tree assessment ('VTA') so as to interpret the biomechanical significance of many visual signs (Mattheck & Breloer, 1995). Practitioners have thereby become better able to develop their observational skills and to apply a greater degree of objectivity. In particular, they have an enhanced opportunity to make visual assessments of various kinds of defect or potential defect, including the following: various categories of 'weak' union; excessively descending or protruding branches; branches with 'dog-legs'; various kinds of crack; inadequate taper; unstable ground conditions or unstable leaning of trees; large or numerous wounds; external signs of decay.

Through the work of Shigo and his co-workers in the USA, the internal development of development of decay and of structural defects has become better understood by practitioners. In particular, the 'CODIT' model (Shigo & Marx, 1977) has become widely known, although to some extent modified by later authors, notably by Boddy & Rayner (1983) and by Pearce (1996), working in the UK. Another important contribution has come from Francis Schwarze and his co-workers in Germany, who have elucidated the significance of the presence of various decay fungi within the context of assessing the current loss of strength of trees due to decay and the likely future loss of (or increase in) strength (Schwarze *et al*. 1997).

Among the various kinds of 'defect' that can be assessed visually, decay (and to some extent cracks) have increasingly been subjected to detailed tests with a range of devices, developed in the UK, the USA and, particularly, in Germany. These work on the basis that certain measurable properties of wood are affected by decay and in some cases by cracks. Such properties include mechanical penetrability, the transmission of sound waves and electrical resistance. Essentially, the aim of using devices is to make cross-sectional maps of the extent of decay or cracks, and to apply mechanical criteria in deciding whether the part of the tree concerned is significantly weakened. This approach seems to have been pioneered by Wagener in the USA (Wagener, 1963), and has been further developed by Claus Mattheck (Mattheck & Breloer, 1995).

It is essential to decide which part(s) of the tree should be subjected to any tests for the mapping of decay or internal defects. Unnecessary tests represent not only a waste of resources, but also increase the risk of harming the tree by the use of invasive methods. These include any form of boring or drilling into the wood, thus breaching the boundaries of decay columns and perhaps allowing decay to develop within previously sound wood. The large wounds created by the use of increment borers have in particular been a cause for concern, but more research is needed to compare the long-term effects of using different kinds of drills and borers in a variety of tree-fungus associations. The positions for mapping should be selected on the basis of adequate knowledge of decay patterns and of modes of failure. In the absence of such knowledge, there might be some justification for the criticism that internal tests would have to be made at many positions along the length of the tree in order to do the job properly.

The application of tree statics in assessing the strength of main stems using a height: diameter ratio is another important method, which has been refined in Germany by Lothar Wessolly and co-workers (Sinn & Wessolly, 1989). It can be used in conjunction with decay mapping, so as to assess whether the residual wall thickness around a decayed zone is sufficient to withstand a wind force of a given strength (Kolařik, 2003). It can also be used for the assessment of trees that are free from significant decay but whose stems are appear to be of small girth in relation to tree height (e.g. following exposure due to the removal of neighbouring trees).

Tree statics has been applied relatively little in the UK, perhaps because it was not included in "The Body Language of Trees" (Mattheck & Breloer, 1995), nor in "Principles of Tree Hazard Assessment and Management" (Lonsdale, 1999). More recently Claus Mattheck has, however, adopted the use of the height: diameter ratio as a criterion for hazard assessment (Mattheck, 2002). This may help to address the criticism that the VTA 'system' did not previously incorporate any formulae for the estimation of loading, based on the length of the lever arm and the stem diameter. The VTA 'system' still includes no prediction of the fracture load at a given wind speed, but perhaps this is not essential as trees tend to grow adaptively and thus to self-optimise their loading patterns enough to withstand all but the most exceptionally strong winds. Instances where such optimisation has not occurred or has been impaired by decay are evidently betrayed by visual signs. Moreover, the accuracy of predictions of loading can be questioned, as current methods do not take account of factors such as dynamic loading (James, 2003) and growth stresses.

The use of tree pulling in the UK has largely been confined to forest trees, for which it has been employed destructively so as to assess wind-firmness in relation to site conditions. In an arboricultural context, tree pulling has been developed mainly by Lothar Wessolly. His technique, which is a key topic in this seminar, is covered in detail by Jarek Kolařik's demonstration and is explained by Petr Horáček (Horáček, 2003) in relation to the underlying mechanical principles. Essentially, a modest bending load is applied by means of a cable and winch and the resulting strain is measured by means of a strain gauge (Sinn and Wessolly, 1989). The strain measurements can be made at successive points along the length of the stem. At the same time, instability of the root-plate can be detected by a similar pulling test, in which a device near the base of the tree measures any tilt during application of the load.

The tree pulling technique has not been adopted by arboricultural practitioners in the UK, partly because detailed descriptions of the technique in English have not been widely available. Also, there have been a number of concerns expressed about the validity of the method. In particular, it has been suggested that different kinds of decay may result in misleading readings. For example, selective white-rots reduce stiffness long before they affect tensile strength. A tree affected by this form of decay might show abnormal bending in a pulling test, even if its overall strength is not seriously compromised. Conversely, brittle decay (e.g. in the case of a brown rot) appears not to reduce the stiffness of the stem very much until an advanced stage, when there has been considerable shrinkage and cubical cracking of the affected zone. It seems, at least at first sight, that the earlier stages of such decay might not be detected by a pulling test, even if the decayed zone is extensive enough to have caused serious weakening.

It has been possible during the discussion sessions of this seminar to examine the justification for some of the criticisms that have been levelled at the pulling technique. Generally, Petr Hor**áč**ek has argued that, regardless of the kind of decay, its presence within a stem will affect the overall modulus of elasticity of the stem within the affected height-zone and will thus influence the strain gauge (Elastometer) reading. Decay on one side of the stem would cause a displacement of the neutral plane (i.e. the plane in between compressive and tensile stresses during pulling). It was, however, acknowledged that misleading results could occur (especially in cases of one-sided decay) if there was any failure to fulfil the correct procedure whereby the test is conducted by pulling in two opposite directions. In this context, Ken James mentioned that his tests in Australia involve pulling in four directions.

The presence of compression wood in conifers or of tension wood in broadleaved trees, like one-sided decay, seems to be of potential concern in relation to the reliability of the pulling test. Similarly, a one-sided impairment of root anchorage might seem to be detectable only when pulling is done in an appropriate direction. In the discussions, however, the same solution was suggested; i.e. that the test should always be applied from two different directions of pull. From the perspective of practitioners without specialist knowledge of physics or engineering, there is probably still a need for an explanation as to why the proponents and opponents of the pulling technique both cite theoretical arguments to support their case. Perhaps there is a need for research on real trees with different kinds of decay and reaction wood.

The discussions revealed the interesting and reassuring fact that practitioners of tree pulling rely primarily on the visual assessment of trees, just like their counterparts who employ techniques for the mapping of defects. Both groups of practitioner thus assess the majority of trees by visual methods alone, with only a small percentage requiring the use of diagnostic devices. Both groups also make equal use of visual information and of their knowledge and experience in deciding where on the tree to make their measurements. It is also important to realise that there are some kinds of defect (e.g. weak forks) that cannot be assessed (at least currently) by means of mathematically-based criteria.

Another concern regarding the root-plate tilting test is that it might not account for the temporarily impaired anchorage that occurs when the soil is very wet. This is, however, a problem, which is common to all systems of assessment and thus always needs to be taken into account within reason.

The contribution of Ken James on tree dynamics raises the very important point that formulae and tests based on tree statics do not take account of the ways in which trees move in the wind. Similarly, the various models that have been used in the estimation of the bending moment of trees do not take account of complex aerodynamic effects. In the visual assessment of trees, practitioners are to some extent able to recognise crown shapes that differ in the way that the wind flows over or through them. For example rounded and dense crowns sometimes withstand severe winds very well, perhaps due to smooth air-flow over the crown. When, however, crown shape is used as a factor in the SIA system, rounded crowns are given a worse rating than the three other notional shapes recognised under this system.

Another interesting point of comparison between methods is the reliance placed on standard values of wood strength in different tree species. UK practitioners have made little use of such values, partly because the system proposed by Claus Mattheck (Mattheck & Breloer, 1995.) involves the (undesired) use of the increment borer for extracting test cores. Also, the values available for 'green' wood are based on continental data, which may reflect differences in growing conditions and provenance, compared with various parts of the UK. As far as Claus Mattheck's 'VTA system' is concerned, trees can be assessed without recourse to the standard wood strength values that he has provided. In contrast, however, the static integrated system and the tree pulling criteria depend on the use of standard values for the species concerned. In discussions, Petr Horáček considered that variations of wood strength within species were, however, relatively unimportant compared with the between-species differences.

The safety factor of trees is another concept that is used both in the measurement of residual wall thickness and in the use of tree statics. It should, however, be noted that different concepts of the safety factor are set out by the proponents of tree pulling on the one hand and by Claus Mattheck on the other. In engineering, the safety factor of a structure is its breaking stress divided by its maximum estimated working stress. In the use of SIA for trees, the safety factor is taken to mean the breaking stress divided by the bending stress that would (as calculated) be exerted by the strongest predictable wind at the site concerned. In contrast, Claus Mattheck (Mattheck and Breloer, 1995) defines the safety factor of a tree as the breaking stress divided by the average stress during the life of the tree.

The safety factor is of especial interest in relation to partly decayed cross-sections. Building on the work of Wagener (Wagener, 1963), Claus Mattheck has shown that failure is rare in hollow stems with an outer ('residual') wall thickness of at least one-third the stem diameter. He has stated that cross-sections that do not satisfy the 'one-third rule' tend to become flattened when bent, eventually failing by buckling, rather than by bending. However, if principles of tree statics are applied, much thinner walls are 'permissible', provided that the stem radius is great enough in relation to the lever arm (as in the case of a cooling tower).

Even disregarding the beneficial effect of very large-girth stems, other workers (e.g. Hanns-Christof Spatz in Germany) have argued that the wall thickness would have to be less than one-tenth of the radius before buckling failure replaces bending failure. A similar argument was expressed in these seminar discussions by Petr Horáček. Indeed, Claus Mattheck (Mattheck 2002) has provided data to show that axial compression stress is affected little by hollowing, until the wall thickness is less than 20% of the stem radius. On the other hand, he has shown that tangential tensile stress (which contributes to buckling) is much more affected by hollowing, especially when the wall is less than 50% of the radius.

Finally, any practitioner who may be concerned about apparently conflicting theoretical arguments may be reassured by information provided about the 'track record' of the pulling test; i.e. that, except in one case where roots of a tree were severed after a pulling test, that no tree that has passed a pulling test has subsequently undergone either a root-plate or a stem failure. On balance, it seems that the pulling test (like other methods that are used) probably errs on the side of caution. This may be evident from the natural 'safety features' of trees (e.g. mechanical damping, aerodynamic re-modelling in the wind and the 'pre-stressing' influence of the growth stresses), which are too complex for current models and which have a very real effect in preventing failures. The main concern is perhaps that erring on the side of caution may lead to unnecessary remedial work.

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