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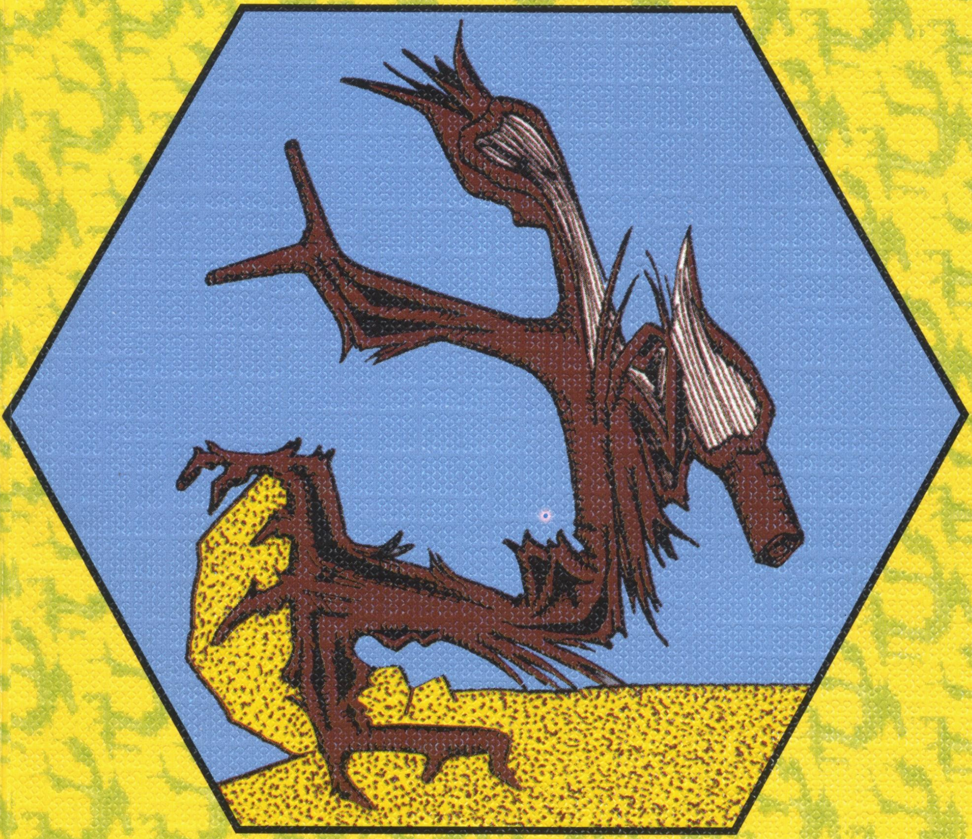

The body language of trees

A handbook for failure analysis

by Claus Mattheck and Helge Breloer

Edited by David Lonsdale
from a translation by Robert Strouts

No. 4 • Research for Amenity Trees No. 4 • Research for Amenity Trees

The Body Language of Trees

A handbook for failure analysis

Claus Mattheck/Helge Breloer

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The original work was translated into English by Mr Robert Strouts and technically edited for the Office of the Deputy Prime Minister by Dr David Lonsdale of the Forestry Authority Research Division

The tale of the tree warrior
is not silenced
with the giant's fall.
E'en when hostile life
has long feasted on his bole and bough
his lifeless frame
yet tells of battles past
with storm and tribulation
and to the understanding eye tells silently
where bold Achilles' heel lay waiting
till death's arrow
met its mark

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FOREWORD BY THE OFFICE OF THE DEPUTY PRIME MINISTER

The Office of the Deputy Prime Minister is grateful to Claus Mattheck, Helge Breloer and the Karlsruhe Research Centre for their co-operation in the production of this new English edition of the authors' book 'Handbuch der Schadenskunde von Bäumen'.

By providing a scientific basis for defining and recognising the various types of defect that can occur in trees, this book should help all those concerned with the care and management of amenity trees towards more soundly based judgements and decisions. It is fitting, therefore, that it should be published in the Department's series 'Research for Amenity Trees' which aims to promote high standards of amenity tree care by ensuring that research results are readily available to practitioners.

This book is a companion volume to 'Diagnosis of Ill Health in Trees' (number 2 in the series) and to a further manual, being produced for the Department by the Forestry Commission, which addresses the assessment and management of hazardous trees.

FOREWORD CONCERNING TREE BIOLOGY

TIMING AND THE REST OF THE STORY

Claus Mattheck and Helge Breloer have published their book on failure analysis of trees at the perfect time. During the last decade, concerns over hazard trees have been increasing greatly. Information on tree biology and tree care also has been increasing greatly over the last few decades. Missing during these times was the rest of the story, a look at the tree from the view of its mechanical design.

TREES ARE UNIQUE ORGANISMS

Trees are the tallest free-standing organisms in the world. Trees live longer, and become more massive than any other organism ever to live on earth. How do they do it? Trees bring together a unique biological system that compartmentalizes infections and a structural form that resists heavy loading.

CONNECTIONS: BIOLOGICAL AND MECHANICAL DESIGNS

To understand the way a tree survives, both its biological and its mechanical design must be understood. Claus Mattheck and Helge Breloer not only give us new and needed information about the mechanical design of trees but they do it in a clear and fascinating way. When I see faces in the trees, I know the authors are in close touch with reality. Why not? Their diagrams are crisp and clear. They leave no room for misunderstanding.

LIMITS TO ALL SYSTEMS

Yes, trees are big and tough. Yet they do have their limits for maintaining the biological integrity and structural integrity of all of their parts. Insects and diseases do injure and kill trees. Branches do break. Trunks do split. And roots do release their grip on the soil. When loading increases beyond the intrinsic strength of any structure, failure of the structure is inevitable. Or when one portion of the structure is weakened, that weakened portion then will be the new position where failure is most likely to occur after heavy loading.

Trees have branches that sway in the wind and bend when loaded with ice or snow. The branch is well designed for swaying to the sides and for bending downward. But bending or swaying upward often brings on serious problems – internal cracks.

CRACKS, THE BEGINNING OF SERIOUS PROBLEMS

Trees have 'learned' to deal with wounds and with rot very effectively. After wounding, microorganisms usually infect and invade the newly exposed wood. The tree responds against the forces of invasion by 'building walls'- chemical and structural – that compartmentalize the infection. The ability to compartmentalize infections effectively is under moderate to strong genetic control.

Radial cracks start much more serious structural problems than those caused by the invasion of microorganisms. The cracks form rapidly. They threaten the mechanical support system of the tree. The probability of mechanical failure then increases greatly. Claus Mattheck gives a clear account of crack development and shows in diagrams the many ways the failures usually occur.

TWIST, TURN, BEND, BREAK

As a tree grows bigger it becomes an easier target for all loading forces. Branches and trunks twist, turn, bend and sometimes they break during storms. Claus Mattheck explains in great detail how all of these twists and turns follow well-known concepts of mechanical engineering.

The real beauty of this book is in the way Claus Mattheck connects many basic principles of mechanical design failures with the living tree. This is new and needed now.

RESISTANCE AND REPAIR

For any system to survive it must be able to adjust and to adapt rapidly to forces and conditions that could destroy it. Trees do have the capacity to resist many types of biological and mechanical forces that could destroy them. An example is the way branches are attached to trunks. One of the marvels of natural design is the pattern of tissues that wind, twist and turn at the branch base. And within the branch base there is a biological defence system ready to start after injury.

After wounding, soft callus tissues form about the margins of the wound. Later, much stronger ribs of woundwood tissues form. The woundwood ribs are much stronger than the normal, healthy wood of the tree. The woundwood acts to repair the weakened mechanical support system.

Claus Mattheck shows and explains the ways the repair systems develop to maintain the mechanical support of the tree. He shows in clear diagrams how the repair processes follow basic principles of mechanical engineering.

PRACTICAL APPLICATIONS

The information given by Claus Mattheck and Helge Breloer is needed now to help clarify many points about risk potentials of trees. Because of the increasing fear of litigation, more and more people are ready to cut their trees at the first sight of any slight problem. 'Hazard tree experts' are everywhere!

The woundwood ribs that may or may not close wounds have a primary function to repair the mechanical support system, not to stop decay. The tree responds to decay by compartmentalizing infections on the inside. The woundwood ribs on the outside strengthen the trunk or branch.

Why is it important to know this? Because we are told over and over again that we must add all types of material to wounds to stop decay. And one sure way to stop decay, we are told, is to close the wound rapidly. When wounds do close rapidly, the woundwood usually curls inwards and internal cracks start.

The better we understand the biological AND mechanical designs of trees, the better the chances are that treatments will be done that heal rather than hurt.

Claus Mattheck and Helge Breloer do give us a clear account of the rest of the story. When scientists from one discipline focus on another discipline, the results are bound to be exciting. They have given us an exciting book!

Alex L. Shigo
Chief Scientist, U. S. Forest Service, retired
Durham, New Hampshire, USA

FOREWORD CONCERNING THE MECHANICS OF TREES

The *'Body Language of Trees'* originates from two authors from completely different disciplines. Claus Mattheck is a scientist, Helge Breloer a lawyer.

Because of her thorough understanding of arboriculture, tree valuation and the relevant law, Helge Breloer counts as *the* German expert in all questions of public safety where trees are concerned. She has successfully incorporated aspects of biomechanical knowledge into a presentation of the existing legal position, while considering all aspects of the problem including ethical questions. This is a significant contribution to this book which usefully complements the rest of the text.

Claus Mattheck wrote the mechanical sections – the larger part of the book – which was extraordinary in itself, as his university education had nothing to do with trees. His original specialist field, theoretical physics, could hardly have been further removed from trees. The author came via the biomechanics of bones and other parts of the body of man and animals to trees. Early in his career he compared trees with mechanically optimal structures and found that trees are perfectly fashioned. So Mattheck learnt to marvel at and to love trees, which are the biggest and amongst the longest-lived of organisms; they fascinated him and in this way became the subject of his research and his uncompromising working style.

Within a few years Mattheck had established himself as a world renowned expert in tree mechanics with his particular studies of branch junctions, root stability, wound occlusion and other areas of tree science in which his most far reaching discovery was undoubtedly the *axiom of uniform stress*. A hint of this principle, as applied to tree stems, had been put forward in 1893 by the Münden Forestry Officer, K. Metzger. Mattheck confirmed it in a more precise formulation and was able to apply it not only to branch junctions, double stems and tree roots, but also to bony structures.

By growing so as to distribute mechanical stresses uniformly over their surfaces, trees attain stability with minimal outlay of material. However, the fact that some individuals, even sound ones, can nevertheless fail is not convincing proof of sufficient strength and an optimal structure. Mattheck explains this apparent contradiction convincingly by emphasising the compromise that Nature makes between absolute safety and minimum expenditure on materials, the result being an economical, lightweight structure.

Mattheck the physicist discovered a whole series of tree characteristics that for long had remained unrecognized. Gifted with a colourful turn of phrase and an unusual talent for putting over his knowledge and observations with simple, characteristic 'Mattheck style' sketches, he has succeeded in producing a fascinating, instructive book with straightforward examples from everyday life that illuminate both the structure and the weaknesses of trees. Inattentive readers may doubt Mattheck's interpretations and observations; but after looking more closely and thinking more deeply, they will probably agree with the author. For his new observations, Mattheck coined expressions such as *discarding collar* round dead branches, *devil's ears* on broken stems, *hazard beams* for split branches and *branch tails* at branch junctions.

Claus Mattheck uses many anthropomorphic metaphors such as 'the tree exposed to the wind lays its ears back' which in scientific publications are unusual but which vividly illustrate the fact. Many readers may bridle when the author writes of "trees' clever reactions and solutions", especially as trees have no organs with which to think. It is my opinion that in such cases the author has a deeper insight than biologists, who are inclined to underestimate the abilities of living things if the mechanism of the reaction is not or not yet understood. Take as an example the dying of shaded branches: this is often explained by saying that the branch can assimilate insufficient carbohydrate for it to remain alive and for its growth. In contrast, Mattheck thinks that it does not pay the tree to keep the branch alive because the branch is not worth the necessary nutriment. That is to say, trees could just as well supply the shaded branch with carbohydrates as the roots and cambium. In this case botanists look for hormones that are synthesised somewhere in the tree and which regulate growth in distant parts of the tree. Mattheck sees only the phenomenological success of the tree and leaves it to the botanists to discover how the success comes about. His version presents botanists with new problems.

As an outsider in tree science it was important for Mattheck to find the right tree literature for his research and this he quickly succeeded in doing amazingly well. From the overwhelming number of available books and journal papers he recognized what was important and valid. Apart from this he was clever enough to keep away from those things which were only peripheral to his way of looking at problems. So the authors, as a team, have succeeded in producing a book on which readers can rely. It will contribute a great deal to the accurate assessment of tree safety and so lead to the retention of those trees that should be left standing while others that are liable to break, and that anyway have no future, will be felled promptly before they – as Mattheck might say – crack somebody's nut.

Hans Kübler,
Professor in the Department of Forestry,
University of Wisconsin, Madison, USA.

PREFACE

The gnarled oak into whose bark you whispered your childhood secrets can kill you. The lime tree whose soft leaves you laid on your beloved's lips can today be the tree of your misfortune, and the poplar whose rustling you enjoy in your latter years can destroy your snug retirement home or your last retreat even before natural death has overtaken you.

This book is dedicated to the potential hazards of trees. It should show you how a tree breaks, why it breaks, why perhaps it breaks too soon and how it gives you warning. Yes, it is quite true that in most cases the tree gives you a silent sign in its body language. It draws your attention to many types of potential fracture points by producing symptoms. This book introduces you to this body language, and teaches you to interpret and evaluate these symptoms biomechanically. It is therefore a book for everyone who lives with and beneath trees and a book especially for all those who have responsibility for the safety or care of trees, or who have to pass judgement on them. It is also a book for any observant naturalist who would like to improve his or her understanding of the signals given out by trees.

The body language of trees does not tell lies. This is another reason why it is a language worth learning.

The book contains all the information needed to understand this subject both generally and in depth, but other sources must be consulted for details of some of the theories and techniques which the authors have applied. These include the most modern of computerized methods, which have been used at the Karlsruhe Research Centre in Germany (Forschungszentrum Karlsruhe, Technik und Umwelt) for confirmation of the concepts presented in the book. In particular, new mathematical methods developed there for modelling biological growth have caused a stir and aroused interest worldwide. Any reader interested in further reading on mechanical theory will find theoretical works cited in the list of references.

The text is presented in a somewhat narrative, descriptive style. It is the fruit of years of scientific labour in a light wrapper which you should still be able to undo even after a long day's work.

After studying this book you will be able to understand the trees around you better, to recognize their warnings and to assess their safety more reliably. All this will bind you more closely to your trees; you will be able to trust them more readily, and you will have made a more soundly based decision when you replace the tree that has become dangerous with a younger, less dangerous one.

The authors thank all their friends and co-workers in their specialist field and in the forest, especially Jörg Sigmund, and also their colleagues at the Karlsruhe Research Centre and the students who have been involved in this work through their studies or while writing their dissertations. They also thank the management of the Karlsruhe Research Centre for their unreserved support of this research on trees and thus for demonstrating faith that we would succeed. Frau Heidi Knierim and Frau Dagmar Graebe prepared the German manuscript in their usual reliable way.

The authors would like to extend their thanks to the translator Mr. Robert Strouts and the editor Dr. David Lonsdale for the excellent production of this English version. They also greatly appreciate the helpful comments of Mrs. Caroline Davis (Department of the Environment) which have contributed considerably to the value and clarity of numerous passages in the text. Her efforts to promote the understanding of the body language of trees amongst arboriculturists in the English-speaking world are also highly valued.

Ass. jur. Helge Breloer
Prof. Dr. Claus Mattheck

CONTENTS

PART 1:

TREES, PEOPLE AND BIOMECHANICS

1.0 PEOPLE ENDANGER TREES – DO TREES ENDANGER PEOPLE?

Trees are sadly much more easily endangered than many people might imagine, without knowing at least a little about their structure and function. That subject could, on its own, occupy a larger book than this one; indeed a number of books have been devoted to it (e.g., see references [7,10,75]). This book deals mainly with the mechanical failure

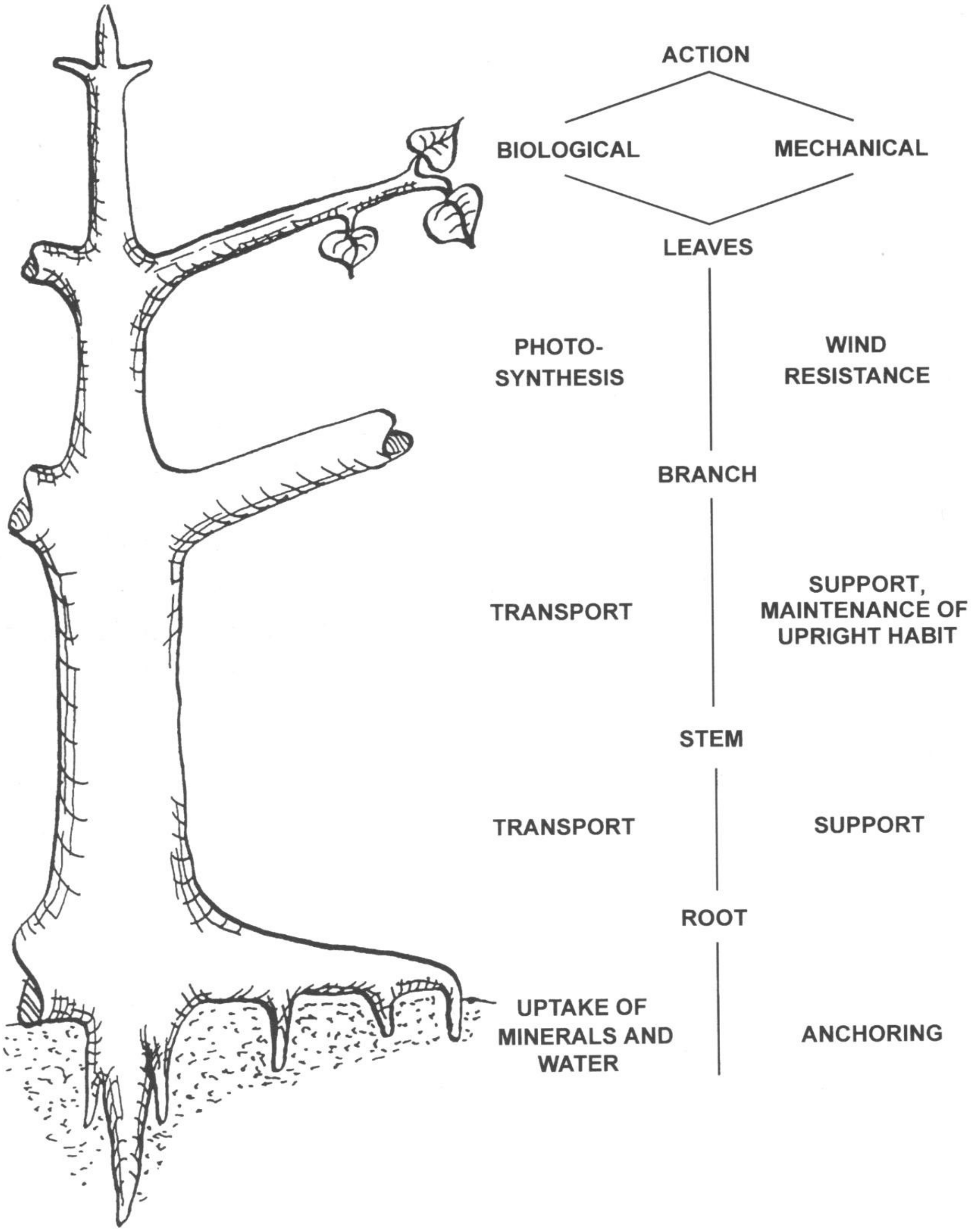


Fig 1. The principal structural parts of a tree and their function [37].

of trees, and so we can only touch upon their biology, while strongly recommending that anyone who has a general interest in the subject and would like to go into it thoroughly should consult reference [72].

A very simplified representation of the structure of a tree is shown in Fig. 1. Water, together with dissolved mineral nutrients, is taken up from the soil by the roots, and then passes into the water-transporting cells (xylem vessels or tracheids) within the wood of the tree. These cells are microscopically narrow pipes which connect the fine roots with the twigs and leaves, via the stem and branches. Much of this transportation takes place in the most recently formed annual ring of the wood, although some also occurs in older rings. The upward movement of water is largely the result of the suction created by its evaporation from the leaf surfaces. It is through the cooling effect of this evaporation that trees help to keep our towns pleasantly cool in summer.

The main function of the leaves is to capture energy from sunlight, and this is stored in the form of sugars and starches ('assimilates') which are built up from water and from carbon dioxide absorbed from the atmosphere. The sugars are transported in solution to the parts of the tree where they are needed for growth or for storage; downwards and inwards through the stem and roots, and a short distance upwards into the growing shoots. The downward flow takes place mainly in a narrow layer of tissue, the bast or phloem, which is just beneath the outer bark. For this reason a tree usually dies or declines if it is 'ring-barked', that is to say a ring of bark is cut away right around the tree.

The vascular cambium, a narrow layer of cells between the bast and the wood, also plays an important role. During every growing season its cells divide repeatedly to form a new layer of bast to the outside and an annual ring of new wood to the inside. The wood laid down in the early part of the growing season (early-wood) contains more space for water conduction than the denser late-wood which supplies more mechanical strength. The annual rings laid down by the cambium are not of uniform width or wood quality over the entire tree; instead the cambium responds to the prevailing load at any particular point by regulating the quantity and quality of new wood that it produces. Thus, the cambium optimizes the mechanical design of the tree.

With this brief account we have covered enough tree biology to realise how cruelly we often treat our trees.

The root system, so essential for the tree's supply of water and nutrients, needs its own supply of both water and oxygen, but there is many a street tree, with its roots almost completely concreted over, that can be compared with a man who is being simultaneously suffocated and dehydrated.

The tree which loses a third of its bark during your attempts to park your new sports cabriolet and loses a bit more when you drive away, is rather like a man who has had some of the veins in his legs ligatured but who is regarded as a bit of a hypochondriac when he complains that his feet are going to sleep.

A tree that has been savagely pruned back has a much reduced ability to manufacture sugar and starch and so has less building material for further growth. It is like a child who, only 20% nourished, can no longer keep up its growth.

True, all these comparisons are rather unsatisfactory and yet they provide us with a feeling of the many hurts that we can inflict upon a poor tree, trapped in a hostile environment (the air polluted as well!). But it's all even worse than this: this poor, unfortunate creature, half dying of thirst, half throttled and undernourished, is somehow expected to hold up a huge crown with massive limbs, completely resistant to breakage even in the strongest hurricane or in wet snow and tinkling ice. It's like sending a weight lifter suffering from typhus to the Olympics and insisting that he must win.

Admittedly, these scenarios paint a very black picture of the way that we treat our street trees, but they serve to highlight the wretched state that many of them reach due to the physical abuses that people heap upon them. Just occasionally, we are repaid for our unkindness by the mechanical failure of a tree and the dangers which it can entail. The processes leading to such failure can include both the formation of structural defects and the development of decay, as we shall see in later chapters. Sometimes, though, failure can occur from simple ageing of the wood in over-weighty branches (and here ageing should be taken to mean in a very general sense the increasing tendency of the wood to break).

Be that as it may, the possibility that people in our society could be endangered, seriously injured or even killed by trees has made it necessary to legislate in this area. Later in this book, we will consider the question of trees and the law briefly and in general terms.

2.0 MAN'S RESPONSIBILITY TOWARDS TREES

Our respect for Nature is being re-awakened by the threats that our planet now faces from exploitation and pollution. In these times of forest decline and the destruction of tropical rain forests, we cry out for trees to be protected and preserved. And yet, our relationship with trees is opening up an almost unbridgeable chasm between moral and legal attitudes. On the one hand, we love trees, marvel at them or honour them in art and poetry, while on the other we reduce them to objects of potential danger or to shuttlecocks in disputes between neighbours.

As we saw in the last chapter, when trees become a danger to people, it is nearly always people who are themselves to blame because of the past damage they have inflicted on those trees. This fact is often conveniently ignored as far as man's responsibilities towards trees are concerned. We creep away from these responsibilities, first when our planning and our schemes cut into the tree's living space and later when the resulting damage and danger are held up as reasons for sacrificing the tree on the alter of safety.

This negative attitude towards trees, which rears its head in legal disputes, is rooted in the perception of the tree as an object which can be treated according to man's inclination. Thus, it is only human beings who have rights that can be upheld by the courts. A body of opinion has recently emerged, both in Anglo-American and in European circles, which challenges this view, insisting that Nature should be accorded legally enforceable rights [65,69,74]. However, there is little sign that this idea has found much favour with the judiciary or the legislature. Thus, although the laws in most western countries go some way towards protecting nature and trees, they are always geared mainly towards the demands of people. When, on some occasions, trees actually appear to threaten people, any idea that they are worth protecting takes a back seat. Sadly, such threats are often greatly exaggerated because of a clouded perception of safety.

When trees are viewed primarily as an insurance risk, managers and owners often adopt a very negative attitude towards them. The tree is no longer seen as a living thing that deserves love and consideration; 'responsibility' becomes just a matter of restricting the tree so that it can pose no danger to people. In cases where a local authority is accused of failing in its statutory duties towards public safety, the typical view of the judiciary is summed up by the statement that 'People are more important than street trees'. The judgement sometimes made in such cases is that it is not acceptable to allow any risk to life or property for the sake of preserving greenery in our cities *(OLG Köln, WF 1992, 100)*. And yet, for motor vehicles which also figure in many court cases, a different view seems to prevail. It would be quite novel if there were to be a legal presumption that the safety of lives and property should take precedence over the freedom to drive cars. To this extent it seems clear that the car enjoys a higher position than the tree, at least from the legal point of view. One should consider how many deaths and injuries are due to motor traffic, year after year, and how rare is the harm done to people and property by trees crashing to the ground or branches falling off. But this does not stop the courts from erecting the strictest of safety requirements in respect of trees or from regarding trees as the greatest of potential dangers.

Although owners and managers may have some reason to fear individual judgements over accidents involving trees, like one given by the regional higher court in Cologne *(loc. cit.)* the laws in most countries do not strictly require a choice to be made between man and tree. On the contrary, it is purely and simply a matter of assessing whether the dangers posed by the tree could have been anticipated and, further, whether these dangers could have been countered by means of moderate and reasonable remedies. This handbook on tree failure analysis provides an entirely new basis for understanding tree safety, by which dangers can be both foreseen and minimised.

In earlier times, legalistic attitudes to trees were completely different, although things were sometimes taken a little too far, as in the instance of a law of Otto the Great of Germany: 'Whosoever beheads a tree shall himself likewise be beheaded'. To what extent such laws reflected a respect for trees, rather than a desire for straight timber [20] is open to question. But even without an excursion into history, it should never be a matter of man *or* tree; a solution must always be found for man *and* tree. Finally we must be quite clear about one thing; man cannot live without trees, whereas trees are perfectly able to exist without man.

Whatever measures we adopt to minimise the risks from trees, we must guard against taking one-sided or extreme views which can never contribute to the solution of problems facing us. The unnecessary felling of trees is one type of extreme action, but it is equally extreme to try to preserve every tree at all costs, which is the standpoint of many 'greens' of very varied groupings. The compromise between these opposing forces does not always produce a pretty sight. Thus, many old trees and in particular historically significant trees and trees 'protected' as natural memorials are often 'rejuvenated' out of all recognition; that is they are mutilated by being cut back and for safety squeezed into a corset of steel bars and screws. It is painful to look on these trees and one asks oneself why men deny them the right to die. Even in human medicine with its technical advances and increasingly soulless medical gadgetry, some thought is given to issues such as euthanasia and above all the right to die with dignity. A tree too has a right to die and it can be argued that we should find ways – whenever this is possible without danger or unreasonable expenditure – to allow it to die under the public gaze and without prolonging its life artificially.

In present day society, death takes place largely behind closed doors and alone; no longer in the company of those with whom we have shared our life in days of good health. Why should we not bring life full circle again and, for example, leave an old tree standing in a lovely public park and designate an area where it can die, surrounded by the bustle of the life of the park, though at a safe distance from passers-by? What deep respect this dying giant of a tree will arouse, what reverence in the face of the long life that lies behind it and the suffering – as can be seen from the marks it bears – it has often endured. The contemplation of such a tree will remind us that life and death belong together and that man has no need to intervene and regulate everything, and should not appoint himself lord of life and death.

These thoughts may seem rather philosophical, but dead and dying trees are not just something for us to behold; they are also a habitat for many forms of wildlife which depend indirectly or directly on dead wood [20]. Since trees in their dying and death are a source of life for other things, there is all the more reason to let some of them die naturally. However, the wildlife value of deadwood also suggests one exception to the argument that we have expressed against 'mutilation': there are ancient pollarded trees, especially in Britain and in parts of southern Europe, which provide the last refuge of rare species of insects, fungi and bryophytes which once flourished in the primeval forests. If they are not re-pollarded from time to time, they often break up and die, and so there is a case for artificially prolonging the lives of these special trees.

The fact remains, of course, that unhealthy, old and dying trees do endanger people, especially if these trees stand alongside busy roads and in heavily used parks. In these cases there must be a readiness to accept responsibility for trees in the positive sense of the word. Not that this 'Handbook for Failure Analysis of Trees' gives an easy recipe for solving all difficult cases. The Visual Tree Assessment method (VTA) that is described here is no routine method that guarantees safety without the practitioner putting his mind to it very seriously. VTA should train the eye of the practitioner and of the local authority officer to recognize trees that could be dangerous to persons or property. But reading a medical handbook will not, on its own, make you into a good doctor. Every diagnosis first requires a trained eye for the important symptoms, a feeling for the living being – in this case a tree – that is to be assessed.

Nor is VTA a fig-leaf for those who are unable to make a decision to hide behind. For often enough, despite all our knowledge, the tree will defy a final, definitive diagnosis. This means that there will always be a need to exercise one's own responsibility in making decisions such as whether a tree can remain standing, what if anything should be done to it, or whether there is no longer any hope for it. VTA is an aid towards making these decisions but by no means the only one. We must keep an open mind towards a multiplicity of methods and responsibly search out those which we consider to be technically most appropriate for the case in hand. It is therefore essential for us first to scrutinize the various available methods, understand their principles, and decide whether they can provide the sort of results we need. This is no easy task, because the learning process can require us to give up some firmly held beliefs when circumstances demand. The arguments for and against various methods must be discussed on a scientific basis – without getting mixed up in personalities – and each indication of a flaw should be seized upon gratefully so that with its help the right way can be found.

Above all else, the scientist and the practitioner alike need to avoid a blinkered approach to their subjects. The biologist should not say that the mechanics of the tree do not interest him, while the arboriculturist should not pursue his work regardless of new discoveries. But science is of limited value if it fails to address practical problems. All relevant investigations and endeavours need to be put into the service of the common cause; i.e. the protection and conservation of trees, where 'conservation' means the whole cycle of life – death and renewal. And that requires comprehensive thought.

This is where the relationship between statutory duties for safety and responsibility towards trees begins. Sometimes managers need the courage to make unpopular decisions, as in the case of an avenue that can no longer be maintained and must instead be completely replanted to re-create a lovely townscape for our children and their children. We must learn to see not only the particular case but to design concepts for the whole. Thus, there may be individual trees in a valuable, historic park which cannot be made safe without prohibitive cost and which will otherwise be lost one by one. The task is one of redesigning the park, and should be placed in the hands of a suitable expert such as a specialist in historic gardens, while responsibility for forward planning is entrusted to the head of the Open Spaces Department.

Above all, officials who are responsible for safety in parks and highways must lose any excessive fear that they will immediately be liable if someone is hurt. To be sure, recent legal judgements give some cause for such fears, but publications such as this handbook are at last beginning to make the courts more aware that there is a scientific basis for judging whether or not reasonable precautions have been observed, and for accepting that absolute safety is an unrealistic aim. Thus, in the German Federal Court, the following principle has now been established: *'A street tree cannot, of course, be expected to be completely free from defects or potential hazards. Such a state is simply unattainable'*. This principle needs to be established in every country so that all local authority officials with responsibility for traffic safety can rely on its acceptance in the event of litigation involving injury or damage that could not reasonably have been foreseen.

Our improved understanding of the biomechanics of trees can also help to allay unnecessary fears over safety. Thus, for example it has turned out that most types of tree are fundamentally far safer than we supposed until now, having wrongly believed them to be only $1\frac{1}{2}$ times stronger than they need to be under average conditions of rain, wind or snow. The basis for this new understanding is explained in this handbook, together with other biomechanical principles which can help practitioners and managers to make decisions and once more to take on a proper degree of responsibility towards trees.

As we shall see in later chapters, new approaches in judging the mechanical safety of trees are based on knowledge of the biomechanical self-optimization of a tree's form. Those readers who are unfamiliar with mechanics should not worry about feeling out of their depth. Experience at lectures and in discussions with tree and forestry people has made us realise that the potential readers of this book are likely to vary widely in their mechanical knowledge. We recommend those who are familiar with the laws of mechanics and elastostatics merely to read on. But if you are uninitiated in mechanics and are feeling worried, we earnestly advise you to interrupt your steady reading here briefly and to cast at least a bashful look at Chapter 13.1 'Mechanical concepts: the bare essentials'. We have kept technical details to the absolute minimum, you see, and we have tried to present them so as not to cause any great brain pain. A rather more detailed introduction will be found in references [38,39].

Now, with or without incidental lectures in mechanics, we can now look through the next section to learn about all the ways that trees employ to avoid breaking. Using this knowledge we then need to recognise danger signals (symptoms) from the trees' body language which can warn us of potential future problems.

3.0 THE TREE FORM AS AN IDEAL STRUCTURE

3.1 THE TREE'S EXTERNAL LOADS AND INTERNAL STRESSES

The external loads on a tree can be understood in terms of forces and bending and twisting moments, as shown in Chapter 13.1. The inner 'distribution of forces' associated with these external loads is also explained in that chapter. The effects of the individual external loads on the stresses inside the tree are discussed in detail elsewhere [37,38,39], and for present purposes we can refer to the summary in Fig. 2. The load that poses the least threat is the crushing load (B) which is the weight that the tree exerts on its own stem. This is quite distinct from the bending stresses which can occur in a leaning tree. These stresses can reach quite high values, as becomes dramatically clear to us if branches break out when the weight is increased only moderately by snow or ice. However the most important and most dangerous load on the tree is undoubtedly that created by the *wind*, which can introduce both bending (A) and *shearing stresses*. The bending stresses are highest near the periphery of

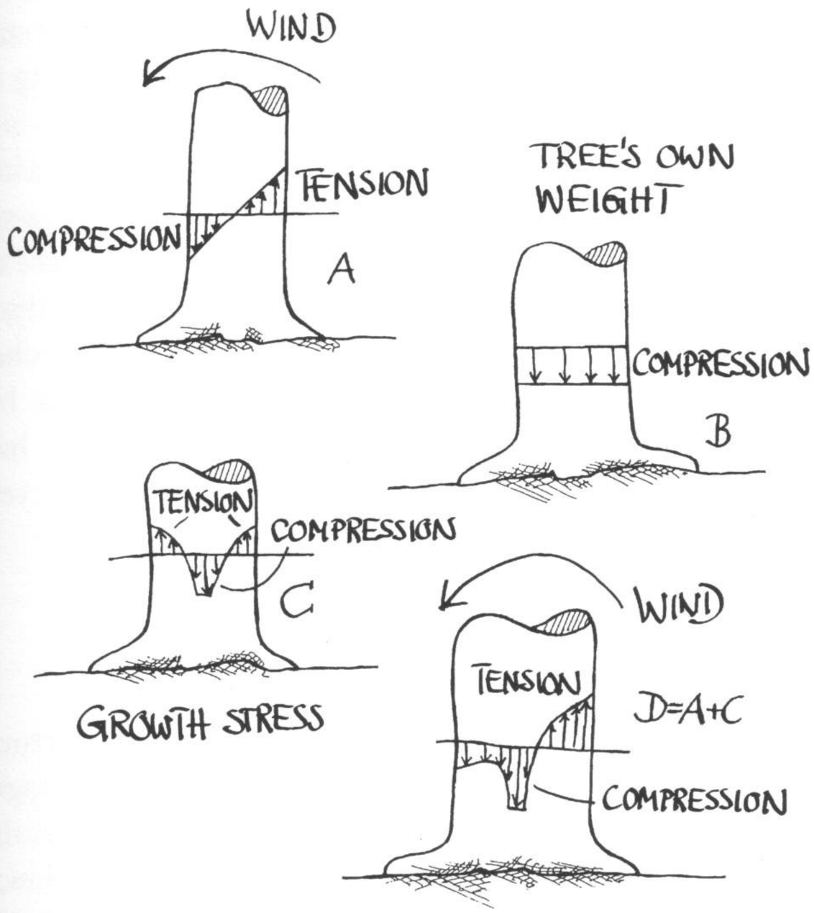


Fig 2. Inner stresses in a tree resulting from external loads [37].

the stem, whilst shear stresses are highest near the middle of the tree, where the bending stresses are zero. This central zone is technically known as 'the neutral fibre'.

A fairly major role is also played by growth stresses (C), which are very clearly and comprehensively expounded in reference [30]. These internal stresses can, incidentally, be a serious problem for timber production because they often result in long cracks (known as end-grain cracks) that appear when the stem is felled and can greatly reduce its value. The growth stresses are a feature of the green tree and quickly disappear after felling. They consist of longitudinal tensile stresses in the outer layers of the wood and compressive stresses deeper within the tree. When the tree is bent under a wind load, the resulting compressive stresses on the lee side of the stem are partly alleviated by the pre-existing tensile stresses in the outer wood (D). Compressive stresses on the lee side pose a greater risk to the stem than tensile stresses on the windward side, because wood fibres buckle much more easily than they tear. Thus, by reducing wind-induced compression stresses, the growth stresses are of great value to the tree.

Growth stresses also exist in the form of pressure which acts in the circumferential direction. This pressure which, like the axial stresses, occurs only in the green tree, can easily be demonstrated by sawing radially into a freshly cut disc. After the saw has been pulled out, the cut in the surface immediately closes. If the disc is dried or if the surface is strongly cooled, the saw-cut gapes wide open. By understanding this, we can see how features such as frost ribs are formed.

We can picture a highly active biomechanical 'inner life' within the stem and branches of a tree, representing mechanical stresses working with and against each other. But why do these stresses not cause the tree to break up, and what actually happens inside the tree if, sadly, it does break? The answers lie in a fundamental principle of biomechanics, a cast iron axiom concerning the construction of biological building components (trees, bones, claws, thorns, teeth etc.) which has been formulated at the Karlsruhe Research Centre over the last few years and which has been validated by numerous examples.

3.2 THE AXIOM OF UNIFORM STRESS

An axiom is a precept which seems obviously true by virtue of its inherent plausibility, but cannot be generally proved. Dogma, by contrast, have more to do with belief than with fundamental truth. What is so inherently plausible about trees? As we shall explain below, and as forest scientists have to some extent known for many years [25,54] a tree is a self-optimising mechanical structure. Its design therefore follows the rule for all such structures which, by definition, make as economic a use of their material as possible and are as strong as necessary. If such a structure is evenly loaded and if all points on its surface have to withstand the same stress, it will have no overloaded areas (breaking points) and no under-loaded areas (wasted material) [39]. *An optimal structure has a uniform stress over the whole of its surface.*

Mechanical optimisation determines biological design from the tusks of a wart-hog to a tree's root; from a tiger's claw to a chicken's leg; from the junction of a branch to our own bones, and yes, even to the finest microscopic 'half-timbering' with which they are filled. The one difference between bones and trees, as far as the *Axiom of uniform stress* is concerned, is that bones can atrophy as well as grow, whereas the tree does not actively dismantle underloaded areas, whatever their origin may have been. All the tree can do is to add extra wood preferentially to its more heavily loaded areas and to deprive less heavily loaded areas, that is the shirkers in its structure, by cutting back further wood production at these points until a state of uniform stress is achieved once more.

Incidentally, it is also shown in reference [39] that machine components can best be optimized by means of computer simulated growth; using this technique, many industrial undertakings already allow their components to 'grow' like trees, by which means they attain lightness and durability in the way that trees or bones do.

But what direct consequences does this wonderful biomechanical principle have for our understanding of trees in particular? Let us first consider for a moment the undisturbed growth of a tree, the unfettered development of its natural form, without having our convertible-driving show-off sharpen his bumper on it. We will not concern ourselves with the repair of such minor injuries until later.

3.3 SELF-OPTIMIZATION OF THE UNDAMAGED TREE

This book, which deals mainly with questions about mechanical failure in trees, cannot explain in full how they optimise themselves mechanically. Details of this are explained elsewhere [37,38,39], and we need concern ourselves here only with the most important aspects of self-optimisation, which are illustrated in Fig. 3. The upward taper of the stem develops essentially in response to wind loading, so that it develops its greatest girth at the base where the greatest bending moment (longest lever arm from the wind contact point) operates. From the requirement for uniform tension come clearly defined h(D)- curves, according to the crown form. This means that the stresses that act on any point on the surface of the tree stem are no higher than the stresses at any other point, when the stresses are averaged over time. The load is evenly distributed (A).

If the two stems of a forked tree are bent apart, the junction undergoes tensile loading. It is shown elsewhere [39,51] that, if the curve between the two stems (as seen in a longitudinal section) were roughly semi-circular, as an engineer would no doubt first design it, high notch stresses would arise. The tree, with its adaptive growth, is clever enough to avoid such points of potential failure. Thus instead of forming a simple semi-circular curve, the tree keeps laying down material at the

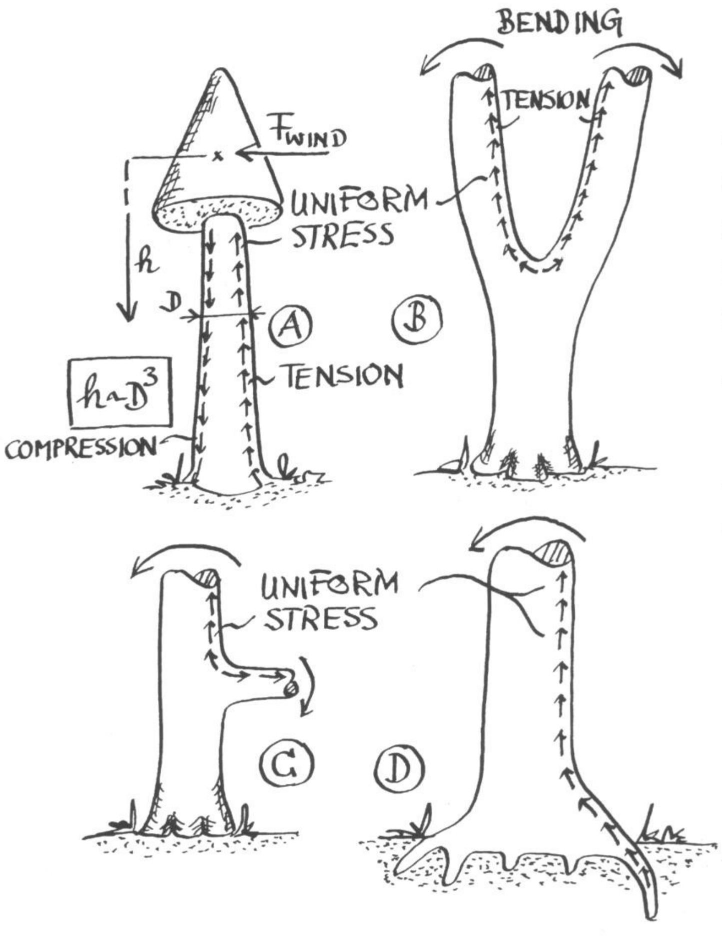


Fig 3. Examples of the development of the tree's shape in accordance with the axiom of uniform stress.

A: Height/diameter h(D) formula for the stem.

B: Fork without notch stresses (double stemmed tree).

C: Branch junction free of notch stresses.

D: Root junction free of notch stresses.

more heavily loaded points until the stresses all over the inside of the fork are absolutely uniform. It is therefore a masterly design of a notch devoid of notch stresses (B). Other junctions, such as those between the main stem and its branches or roots, are similarly 'tailored' to form shapes that are free from notch-stresses (C,D).

But what happens if brute force penetrates into this ideal world of life-long bodily attunement, so that the carefully constructed pattern of uniform stress is disrupted? The living tree does not give up so easily!

3.4 SELF-HEALING IN THE TREE FOLLOWING MECHANICAL WOUNDING

The living tree repairs its wounds in a way that accords with the *Axiom of uniform stress* (Fig. 4A). The infliction of a wound, such as a tree carving or the nibblings of a deer, spoils the state of uniform stress, rather as muddy boots spoil the highly polished marble floor of a luxury hotel. For the tree, the occurrence is very much more painful than this because it could suddenly be cruelly and abruptly brought down to Mother Earth if the little notch acts as a failure point in the next autumnal storm, or presents an inviting little door for all sorts of decay-causing organisms. No wonder then, that the tree hastens to make the wound good at the earliest opportunity. The cambium is clearly able to measure such excessively increased stresses at notches. It then

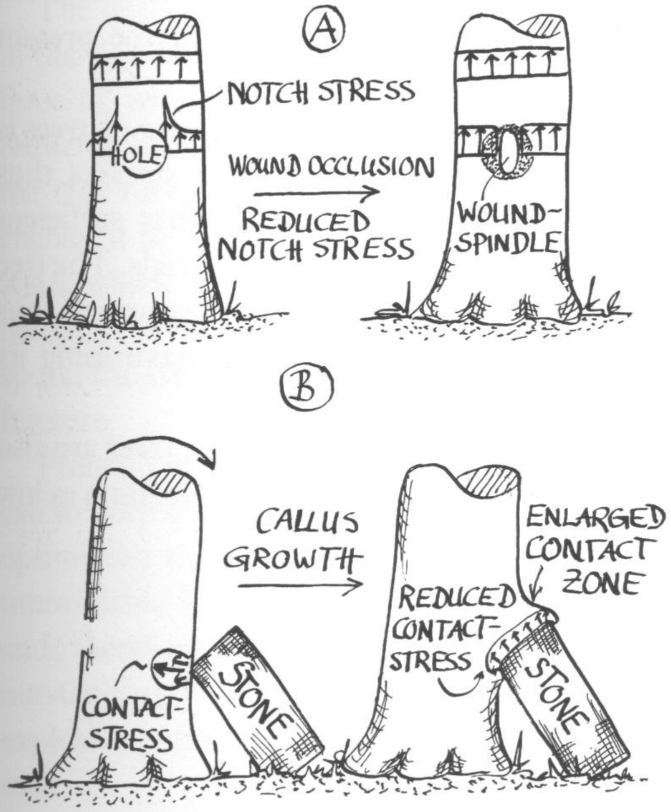


Fig 4. Examples of the tree's self-repair in accordance with the axiom of uniform stress.

A: Greatest wood formation at the point of greatest stress.

B: Levelling out contact stresses by enlargement of the contiguous surfaces.

immediately lays down a particularly large amount of material; that is, an unusually wide annual ring, at the point of greatest notch stresses until the wound is closed and the notch stresses relieved, by which means the tree can best regain its favoured condition of uniform stress. Unfortunately, this leaves behind a zone of wood fibres which deviate locally from a straight line and so can buckle more easily in the future.

And as a last example, the reduction of contact stresses: the pointed corner of a table sticking into one's rear-end quickly allows one to grasp the fact that mere mechanical contact even in the absence of actual injury can seriously disturb the churchyard tranquillity of uniform stress. We humans get a cushion to put under us and in that way distribute the load more evenly. The tree behaves not so very differently (Fig. 4B). If, for example, a rock presses on the tree from the side, it lovingly wraps itself around this object, perhaps even enveloping it [38,39]. In this way the contact area is enlarged and the contact stress is thus reduced, so that the ideal state of uniform load distribution is very quickly approached. (Incidentally, the hand axe with the sharp point with which our charming forefathers used to beat each others' heads was the exact reversal of the cushion effect: minimal contact area brings about maximal local destruction. The spear, the arrow and the blades of stabbing weapons also work in accordance with the principle of maximized contact stress transmitted through very sharp points or blades!). Many more examples in which form is modified so as to match changes in loading are given elsewhere [37,38,39], and the interested reader should study these references in conjunction with the present book.

The main point that we need to make in the particular case of trees is that a tree does all it can to achieve an even distribution of stresses, thus satisfying the *Axiom of uniform stress*, provided that it has sufficient health and vitality and has not yet succumbed to Nature's trials. The tree will maintain this state and will try to restore it if it is disturbed, thus avoiding the formation of potential failure points and maximising its chances of survival.

Apart from their ability to even out mechanical stresses, trees are also 'clever' enough to assume a form which keeps the external loading as low as is possible.

3.5 THE LAW OF THE MINIMAL LEVER ARM AND THE STRATEGY OF FLEXIBILITY

Let us begin with geotropism. Fig. 5 shows the principle. A tree caused to lean, for example by an avalanche, rights itself by laying down reaction wood [37,38,39]. Avoidable bending loads are reduced in this way in that the lever arm on which the tree's own weight is acting is reduced (A). If a leading shoot dies (B), then a strong lateral branch takes the lead, similarly reducing its bending load very much in the process (B).

In the two examples (Fig. 5 A,B), the external bending load due to wind action may remain high enough to require further adaptation of the tree's shape. In this case, the tree's strategy of flexibility, as shown in (C,D), allows it to yield in a rather 'diplomatically cunning' way which saves producing too much extra material. Imagine standing with an arm stretched out sideways, a flag or a small sail in your hand and the wind in your face. Your arm would be twisted backwards. To resist this twisting, you would continuously have to exert your muscle power against the wind. It is easier simply to turn the arm like a weather vane in the direction of the wind. Trees very exposed to wind do this too, although they need rather more time than we do, because their method is to construct a helical arrangement of wood fibres. But they succeed and in this way minimize the lever arm and thus the exterior torsion moment.

The outermost twigs of the tree also fulfil a strategy of flexibility [56] in the way that the herb illustrated in (D) does. When subjected to the force of wind, this simply lies down belly to the ground, in this way reducing the lever arm seized on by the wind to zero. In the same way the tree turns its outermost twigs in the direction of the wind. This enables it to reduce the whole area of its crown that is presented to the wind, which in turn reduces the wind load and therefore ultimately also the wind bending moment in the stem. By 'putting its ears back', so to speak, the tree reduces the bending stress and therefore the risk of stem fracture.

From all of this we can sum up by saying that trees do everything they can to keep external loads small. Even so, they do have to bear loads. By optimizing their form through adaptive growth, they distribute these unavoidable loads so evenly that there are almost no overloaded areas and, therefore, no potential failure points. (However, even in such an outstandingly optimized tree, the branch junction can be a very explosive point because fibres can snap there: this will be discussed later on!)

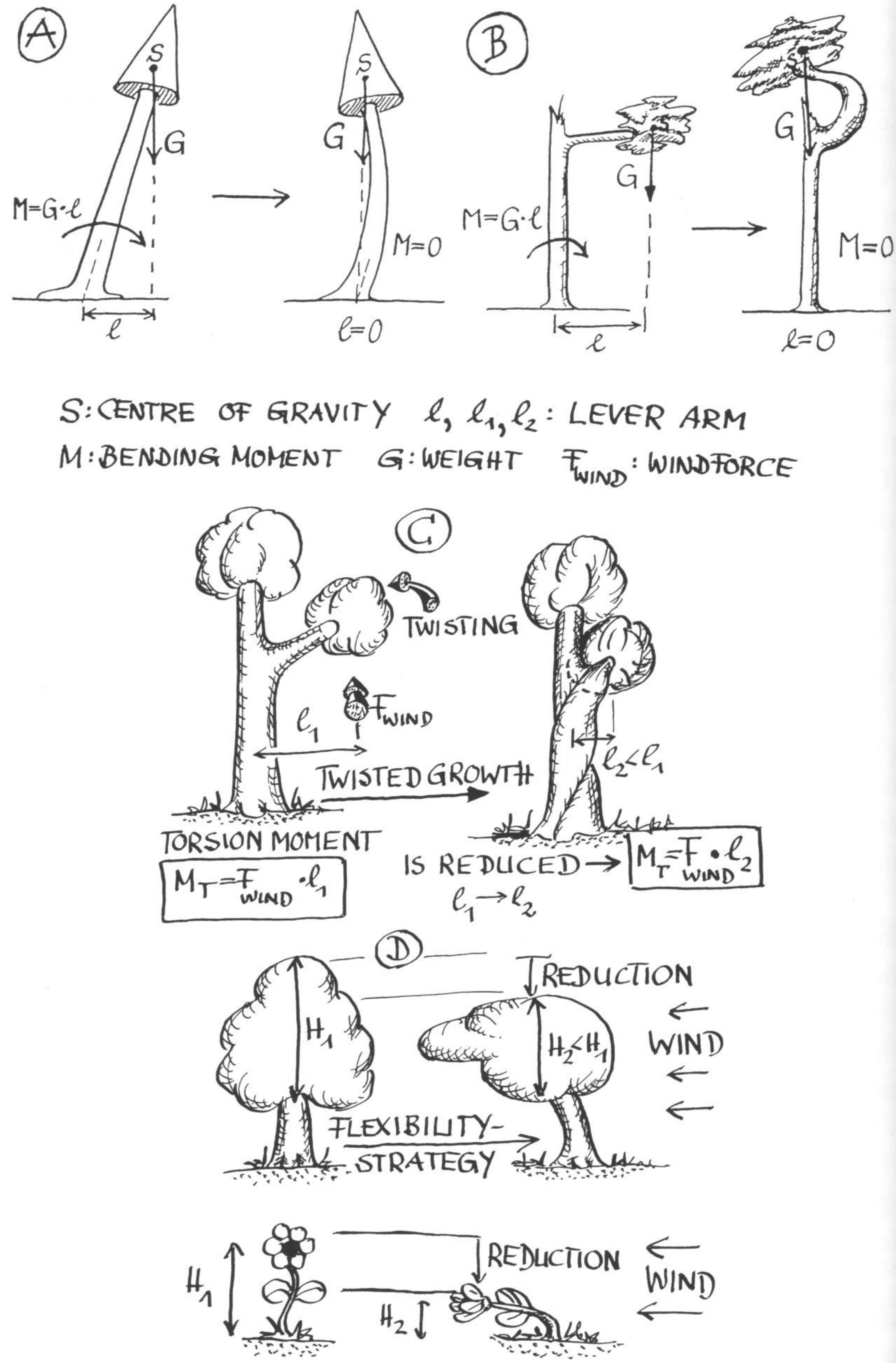


Fig 5. The law of the minimized lever arm.

A: Bowed tree (geotropism).

B: Side branch taking over as leader (geotropism).

C: A long branch twisting with the wind direction (helical growth as a manifestation of the strategy of flexibility).

D: Flowers and foliage flatten themselves.

If, then, everything is so mechanically perfect, how is it that trees ever break? They certainly do everything to avoid their own collapse! To answer this question we must leave the consideration of the single tree and look at its kind as a whole.

4.0 WHY DO TREES SNAP DESPITE THEIR OPTIMAL FORM?

A tree that could bravely withstand the fiercest hurricane might look something like the one shown in Fig. 6. This sturdy fellow, which we have 'designed', looks very different to the more typical tree which stands next to him in the illustration. If two such trees were really growing side-by-side, the powerful dwarf, with his short, thick stem, would quickly be deprived of sunlight by his slimmer neighbour. The advantage may occasionally swing against tall slim trees when they succumb to storms but, on balance, it appears that they gain by economising on materials and reaching for the light. Clearly, it doesn't pay to adopt the over-cautious approach of insuring against any possible collapse; if it did, there would be only short, thick trees, even in dense stands.

Even though trees usually tend to be slender and lightly built, there are big differences between various species. For example, the durable oak, judging by its dense and durable wood, sets more store in getting through a long life unscathed than the poplars and willows, whose rapid growth and less durable wood suggests something of a 'throw-away mentality'. These examples show different ways of achieving success for a species; either to invest in long-lived individuals which are good at hanging on to their little bit of the world, or to reproduce and grow rapidly so that it doesn't matter too much if some individuals die or fail mechanically early in life. Every species has just enough structural strength to meet the requirements of its particular strategy, and this minimum requirement dictates the safety factor for biological structures [1]. In Nature, the death of a single tree is just as unimportant as the death of a single person – its suffering means nothing; all that counts is the preservation of the species.

To summarize, then: trees occasionally break because it is cheaper for the preservation of the species. They limit the breakage rate in a telling way, however, by fashioning the best lightweight design possible.

As far as the *law* is concerned, it's important to realise that trees can fail *even when they are sound*. The courts need to accept that there is a small but definite probability that *even the soundest tree can break*, and that it is therefore not always possible to blame accidents, whether serious, fatal or otherwise, on mechanical defects. There is a parallel here with sports injuries: if someone on a skiing holiday is unlucky enough to allow an unfortunate combination of loads to bear on his shinbone, he will return home with a regrettable spiral fracture. The fracture would be the result of the accident; not of some weakness in his bone; indeed, most sportsmen are healthier and more able to bear loads than the stay-at-homes, though the thin bones of the latter can remain intact for longer if they worry enough about avoiding placing loads on them. This clearly shows how silly it is to assume that there is pre-existing damage behind every accident!

The lesson: it is perfectly normal for trees occasionally to break without there having to be anyone to blame. The breakage of a tree is the natural price that the species must pay for achieving an energy-saving, lightweight structure.

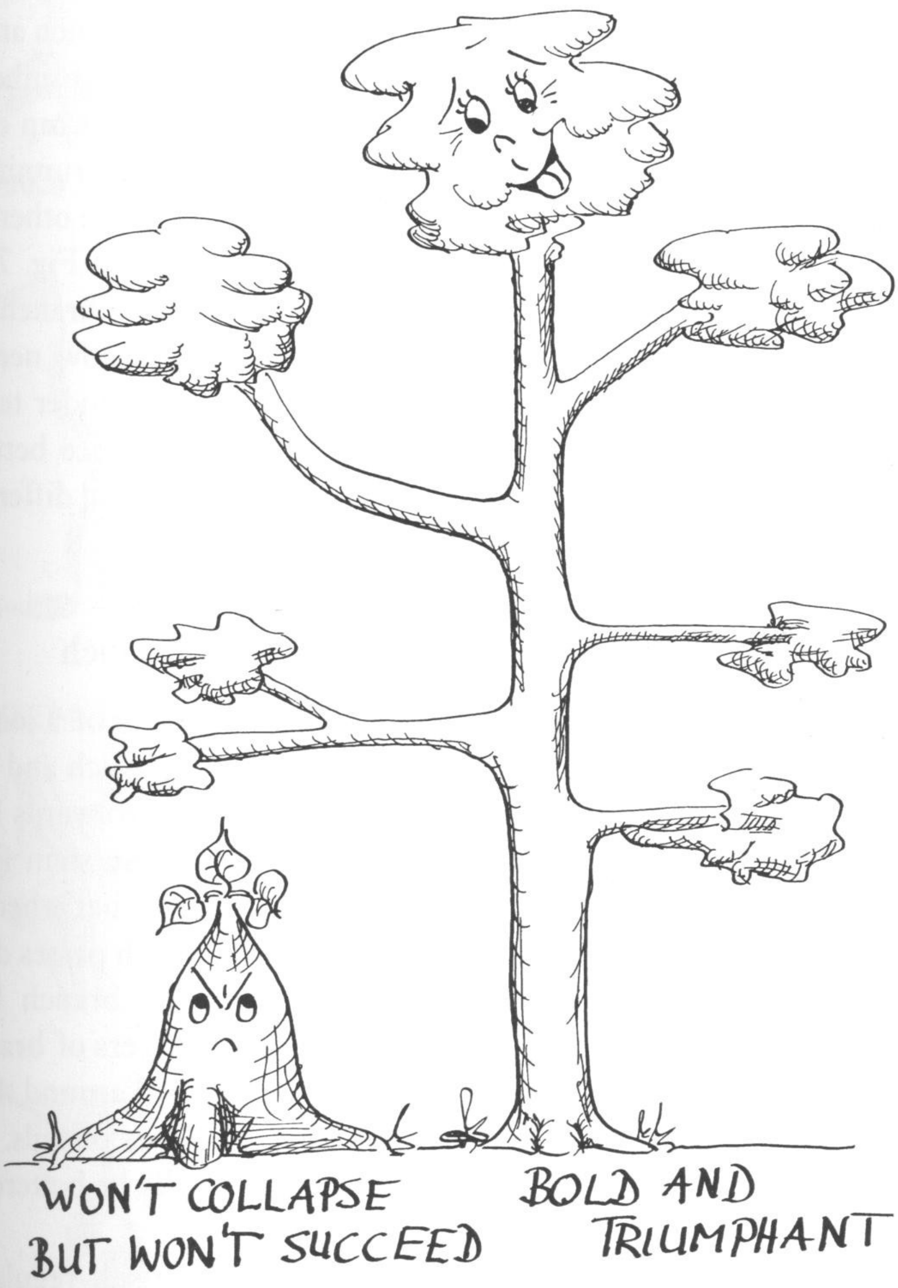


Fig 6. A tree with an absolutely stable form would be rapidly shaded out by more slender trees, which grow in height more quickly at the expense of risking a certain rate of breakage.

5.0 MANIFESTATIONS OF TREE FRACTURES

5.1 FRACTURES CAUSED BY BENDING STRESSES

5.1.1 The branch junction as a point of weakness

It is obvious that a tree must have branches so as to form a crown that spreads out to absorb sunlight but, from a mechanical point of view, it would be a big advantage to have no branches at all. The problem becomes clear when we realise that the junction between a branch and its parent stem, though remarkably well 'engineered', has some inherent weakness because the direction of the stem and branch fibres can differ by as much as ninety degrees; thus bundles of wood fibres running in various directions must be fixed, squashed, woven or in some other way joined together. The three types of weak point, as shown in Fig. 7, are self-explanatory. They develop at the bases of living or dead branches or are left as a result of the decay of dead branches. We now need to examine the ways in which each of these three types fails under tensile and compressive loading. We have to recognise the difference between tensile and compressive loading because there is a fundamental difference between the failure processes associated with each of them.

5.1.1.1 Stem fracture at the junction with a living branch

SHIGO [66] describes the junction (Fig. 8A) as consisting of a joint of woven fibres, in which the branch fibres run along the branch and turn downwards at the junction, while the stem fibres run downwards from above the junction and deviate sideways around it. These stem fibres encircle the branch like a ring or a collar and this means that when the crown sways in the wind, the resulting flow of forces which passes down the stem towards the ground is diverted around the branch base. Mechanically, this is a laminated joint in which annual layers of branch-wood run through the rings of stem-wood that are formed around them, and continue in between the stem-wood layers like a series of tails. The design of this joint is absolutely optimal, and could hardly be bettered in its perfection.

A particular point to be noted here is that there is a self-regulating mechanism which determines how much building material is to be used at the branch junction. If, for example, an older branch bears little foliage and is only moderately loaded by the wind, it produces only a slight mechanical stimulus for further growth. If, on the other hand, the

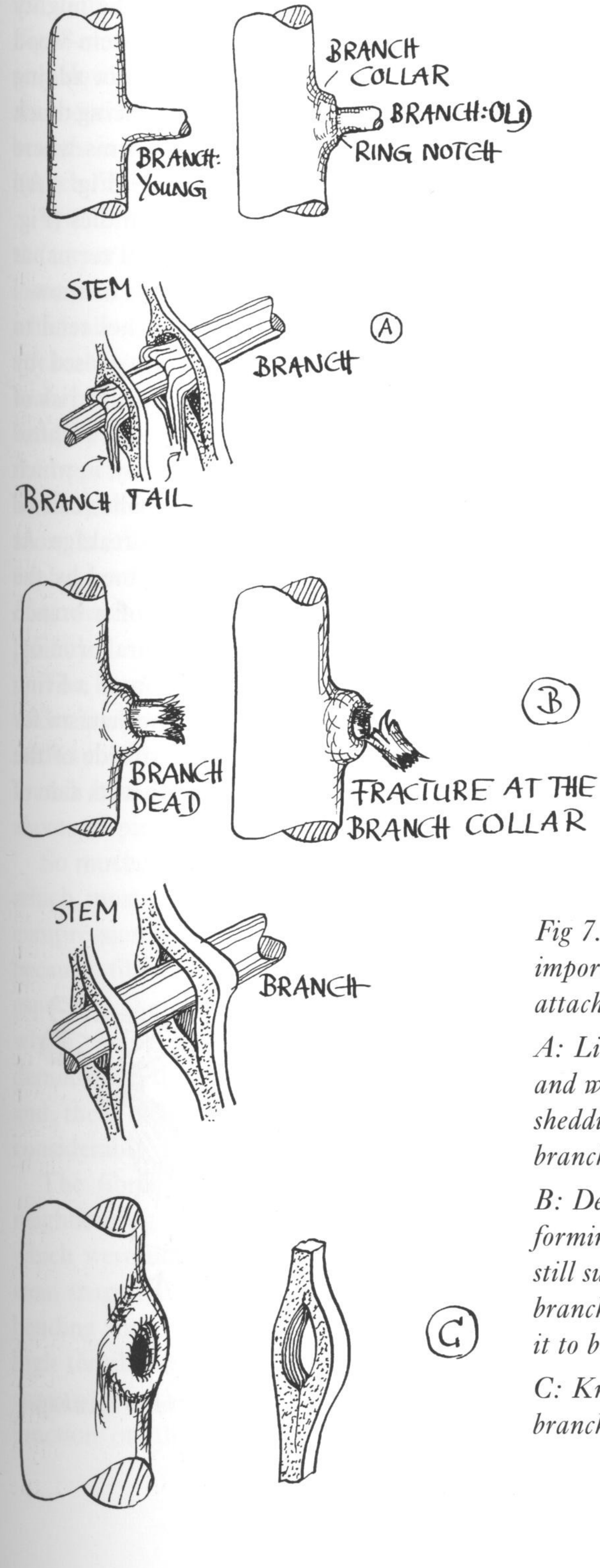


Fig 7. The three most important kinds of branch attachment.

A: Living branches with and without branch-shedding collar, each with branch tail.

B: Dead branch no longer forming branch tails but still surrounded by the branch collar, encouraging it to break off.

C: Knot hole after the dead branch base has decayed.

parent stem is regularly loaded by strong winds far up in the mighty crown, then a large amount of wood will be laid down on the stem-wood that surrounds the old branch. For its part, the branch is not adding much to its girth, because its leaf area is too small to be producing much photosynthetic material, and so a distinct 'branch collar' forms where the faster-growing stem-wood encircles the branch base (Fig. 7A). Collar formation becomes particularly marked if the branch dies (Fig. 7B). The collar is a weak point (or ring notch in mechanical terms) at which the old branch eventually breaks when loaded by wind or snow.

It is an advantage to the tree that waning or dead branches tend to break at the collar, because the resulting wounds can be closed by uninterrupted callus growth and therefore pose the least possible risk of decay extending into the main stem. In most cases, breakage occurs after the branch has been dead for some time and has begun to decay, in which case it breaks particularly close to the parent stem. The collar can be regarded as a sign of a branch that has been prepared for breakage. At least, it indicates that considerably more wood is being formed by the stem than by the branch. Despite the considerable value of a branch collar – even a fairly slight one – in aiding the process of natural pruning, there is some risk of injury to the stem itself at the junction of a living branch. Fig. 8A shows the flow of forces and the failure mechanism for tensile loading. If the branch is growing from the windward side of the tree, then it will be loaded by the wind at the same time that its side of

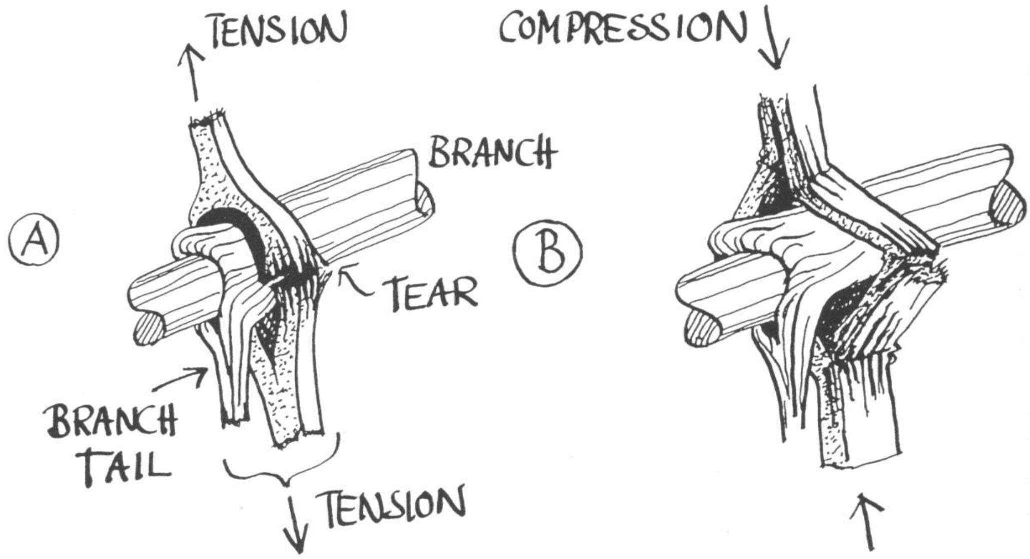


Fig 8. Stem failure at living branch junctions.

A: In the case of tensile loading (fibres tear apart), such as snow breakage of leading shoots of pine.

B: In the case of compressive loading (fibre kinking).

the stem experiences a tensile stress. As we can clearly see by examining Fig. 8 closely, the 'tail' of branch fibres which runs into the stem turns only downwards; never upwards. Thus, the only fibres above the branch are those that belong to the stem. This means that the force flow on the branch is directed downwards below the branch, acting on both the branch fibres and the stem fibres with which they are interwoven.

While the branch is being bent downwards, a point of weakness on the upper side of its junction can come into play. This is created by the loose attachment of the stem fibres on the upper side of the junction which allows them to be separated easily from the branch-wood without any real fracture occurring. This produces a semicircular crack above the branch. Failure starts mainly in the wood on the compressed side of the bending zone where fibre-buckling occurs, but the semicircular crack on the upper side of the branch can then trigger failure on the side of the bending zone under tension; this is particularly common in the case of snow breakage of Scots pine (Fig. 8A). The semicircular crack also explains why it is much easier to tear a branch out of the stem downwards than by bending it upwards – that is up towards the stem [45,66].

The branch junction is also a point where the stem itself can fail under tension. The failure tends to be initiated in the stem fibres about midway within the region where they deviate sideways around the branch base (Fig. 8A). This kind of failure often occurs in the leading shoots of pines under the weight of snow.

So much, then, for tensile loading, but it is compressive loading (B) which most often causes failure in trees. The resistance of wood to compression is often only half as great as its resistance to tension, simply because fibres buckle much more readily than they tear. This is especially the case with the fibres in the vicinity of branch junctions which, being already bent, will buckle even more easily. You can demonstrate this easily by pushing on a bicycle spoke that is already bent and then doing the same to a straight one. The latter will offer considerably more resistance to kinking.

The fibres shown in Fig. 8B that are kinking outwards displace neighbouring fibres and these in turn displace others. Finally fibres which were not previously bent at all will buckle and, in the end, the stem snaps half-way across its thickness on the compressed side of the bending zone. This failure may be sufficient to overcome the relatively high tensile strength of the wood on the tension side of the bending zone, so that the fibres on that side are torn. In this way, a small branch junction on the compressed side of the bending zone works like a spring-loaded device in that elastic energy is initially stored in the wood fibres and is then abruptly set free like firing an arrow from a bow, as longitudinal splitting begins.

5.1.1.2 Stem breakage at the junction with a dead branch

As soon as a branch dies, its vascular trace into the main stem stops developing so that subsequently formed fibres in the main stem are not intertwined with branch-wood 'tails'. In mechanical terms, the dead branch behaves like an iron rod or a broom handle, that is to say, biologically passive. Under compressive loading, the stem can fail at the branch junction in the same way that can happen with a living branch (Fig. 9), i.e., the bundles of stem fibres which curve around the dead branch kink sideways and in this way initiate the failure mechanism. Under tensile loading, there can be some tearing of the stem fibres at the mid-point of their deviation around the branch, as we have already described for a living branch. However, the base of a dead branch is encircled by bundles of stem fibres that have formed after branch death,

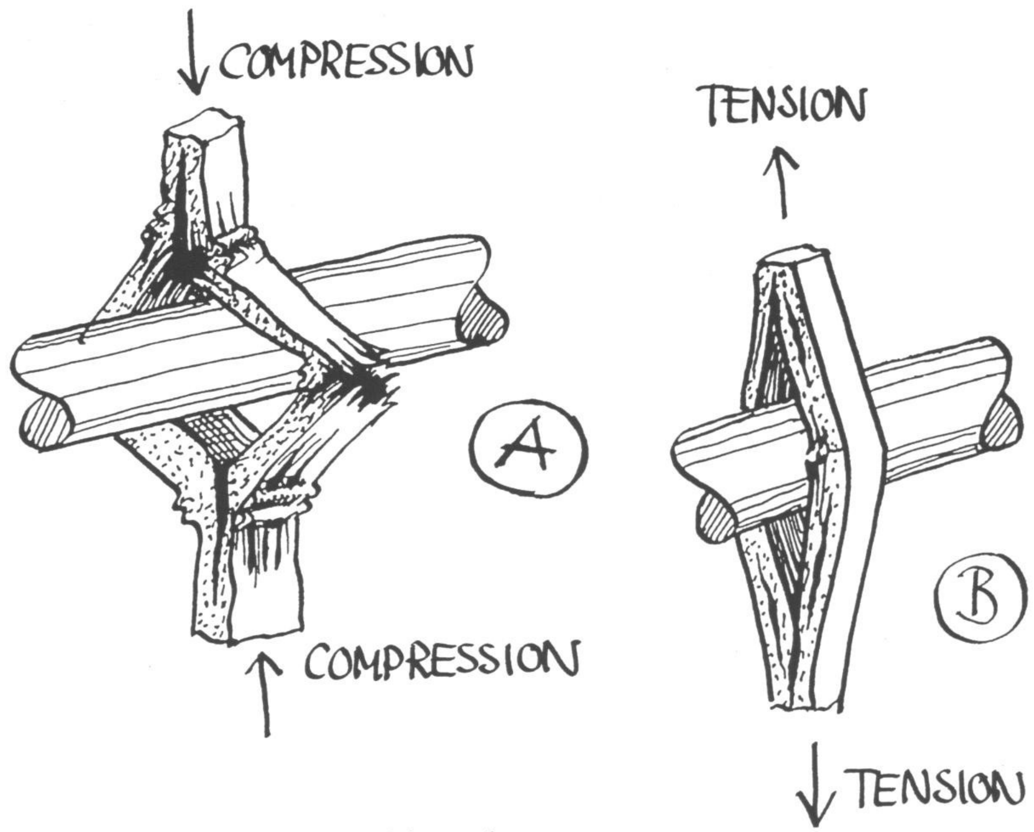


Fig 9. Stem failure at dead branches.

A: Fibre kinking on the compressed side of the bend.

B: Development of axial cracks in the hazard beam formed from the displaced wood fibres. After this the delaminated fibre bundles fracture transversely as a result of tension and superimposed bending.

and these tend to become straightened out by pulling in the same way that fibres straighten in a 'hazard beam'; this type of structure will be described in more detail later. In this situation, these stem fibres are in effect a hazard beam loaded with a lateral tensile stress. If this lateral component in its tensioning becomes strong enough to overcome the lateral cohesion of the wood, the result is a lengthwise splitting (Fig. 9B) and, if the tensioning continues, the delaminated fibre bundle is stretched straight like a rope. As it is not as pliable as a rope, however, it breaks at the points of greatest curvature as the result of bending stresses. A somewhat comparable kind of breakage occurs if you try to bend the point of a ski straight.

5.1.1.3 Stem breakage at a branch hole

Quite often, a dead branch rots away deep into the stem, leaving a hole. The bundles of stem wood fibres that grew around the branch both before and after it died are still directed, now quite unnecessarily, around this hole (Fig. 10). This is a particularly clear illustration of one shortcoming in trees; that wood cannot be remoulded in the way that, for example, can be done very well with the bones of a mammal (provided that the mammal is not too old). The processes of collapse at a branch hole are very largely identical to those at a dead branch.

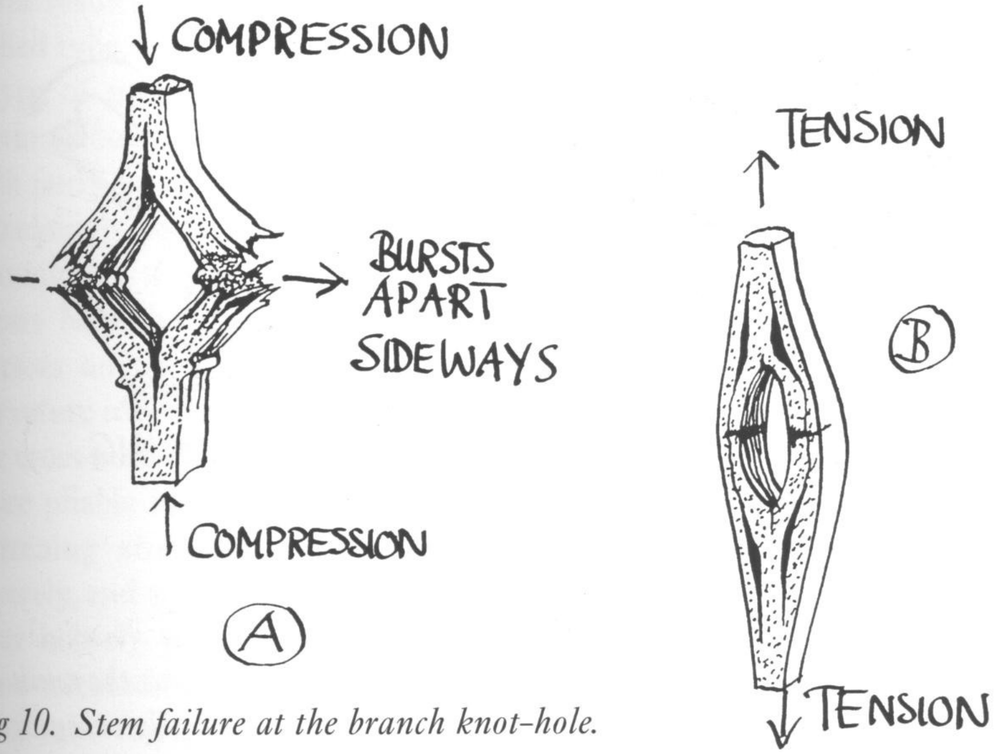


Fig 10. Stem failure at the branch knot-hole.

A: Pressure causing lateral outward snapping.

B: Fibre bundles behaving like hazard beams, splitting axially and subsequently transversely.

The key feature of all types of tree fracture at these weak points where branches join the main stem is that they involve fibres that have previously been bent or laterally deflected in their growth. If storm-broken trees without decay or other defects are examined in nature, the site of breakage is always a branch junction. It is often a great surprise to see cases where a very small branch has acted as the initiator of fracture. Despite its mechanically perfect interweaving of fibres, the branch junction therefore remains a weak point which represents a compromise between the biological need to absorb sunlight and the mechanical need to resist breakage. Even so, aircraft design engineers would consider themselves fortunate if their fibre jointing assemblies came anywhere near this perfection of structure.

5.1.2 Bending fracture of a solid cylinder

The failure of a defect-free stem under bending stress is often interpreted as though it were occurring in a homogeneous cylinder (Fig. 11A), which is relatively easy to understand in mathematical terms. However, this idealized fracture behaviour can only be expected on a branch-free stem, or on a stem which has shed its branches at their collars, and has since covered the resulting wounds with occlusion wood, overlain by several continuous annual rings free from mechanical

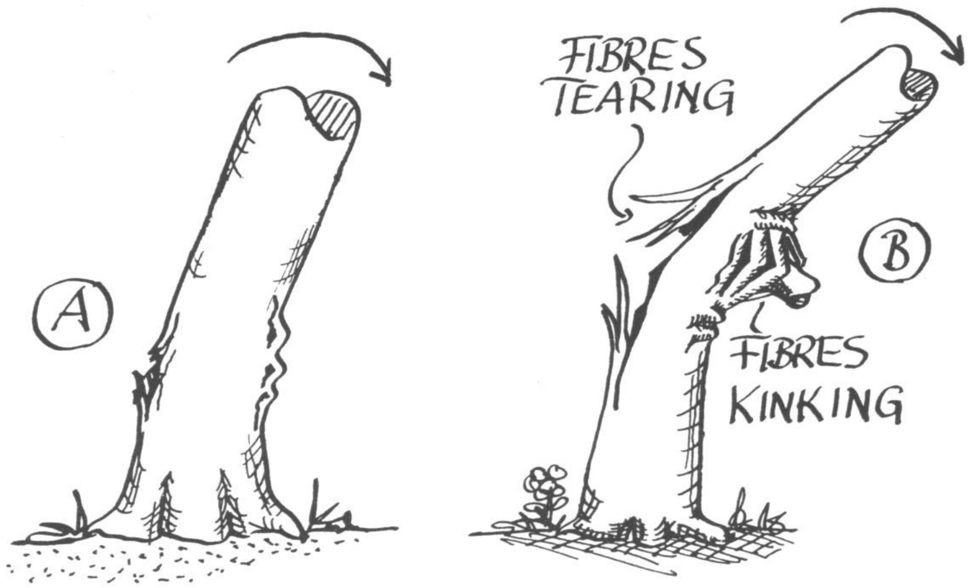


Fig 11. The entire cylinder subjected to a bending load fails as the result of fibre kinking on the compressed side of the bend. This is usually encouraged by the presence of a branch junction.

A: Without a branch.

B: With a branch.

imperfections. It is far more common for the failure process to be complicated by the presence of an old branch, which forms a fracture point as described above (Fig. 11B).

Although the idealised cylinder (A) and the more typical tree (B), differ in the way that fracture starts, the process in both then proceeds with fibre buckling on the compressed side of the bending zone, which tends to be followed by fibre tearing on the tension side. As we have already mentioned, this happens because the fibres buckle far more readily than they tear, so that initially a kink develops in a group of fibres on the compressed side and then quickly runs inwards until perhaps the bending increases enough to cause tensile failure on the other side of the stem, leading to complete fracture. In practice, though, we might have to look at timber structures to see evidence of this type of failure, since trees very rarely show it, and most of those that do are young specimens in which branch junctions trigger the damage. But what if the solid cylinder is a hollow cylinder, a wooden tube or a hollow tree stem?

5.1.3 Flattening of the cross-section of a thick-walled, hollow stem

Before reading any further, you ought just to go out into the garden. Get hold of your unsuspecting garden hose with your hands placed about 5 cm apart and bend it. It gets flatter and flatter. That was bending failure as the result of cross-sectional flattening. If you bent a more rigid, thin-walled tube, it would eventually become kinked due to 'shell-buckling', a type of unstable bending failure which we will discuss in the next section. However, this would not happen with, say, a tough steel tube with fairly thick walls. If such a tube is bent, the cross-section becomes increasingly flat and pliable without actually buckling. How then can this flattening of the cross-section be explained in mechanical terms? Fig. 12 shows how the cross-sectional flattening stresses arise. The bending stresses on the upper side are tensile, on the lower compressive. As curvature increases, more of the stresses are directed inwards, flattening the cross-section. The cross-section that is crushed in this way becomes more pliable just because of this flattening; it bends more sharply, the flattening stresses increase, crushing the cross-section even more severely, and so on and so on. And that is very much what happens with your homely garden hose. However, a hollow tree stem is much less good-natured because wood is not very strong across the grain. While a steel tube forms plastic 'hinges' separated by an angle of 90° at the circumference (and in so doing allows its cross-section to be bent into an impressive figure eight), wood splinters longitudinally at these points into at least four curved boards which break up still further as the bending load increases (Fig. 12B).

A thin bamboo cane or a thickish stalk of straw can provide a beautiful demonstration of the mechanism of axial splintering of a hollow stem as it flattens under a bending load. The point does not need to be laboured that this tree stem, now reduced to a heap of roofing laths, does not have a lot more in the way of bending strength to offer. So, what started off as a completely harmless, elastic change from a circular to an oval cross-section in the hollow stem quickly escalated into suicidal self-destruction with a total collapse of strength. Sometimes, cross-sectional

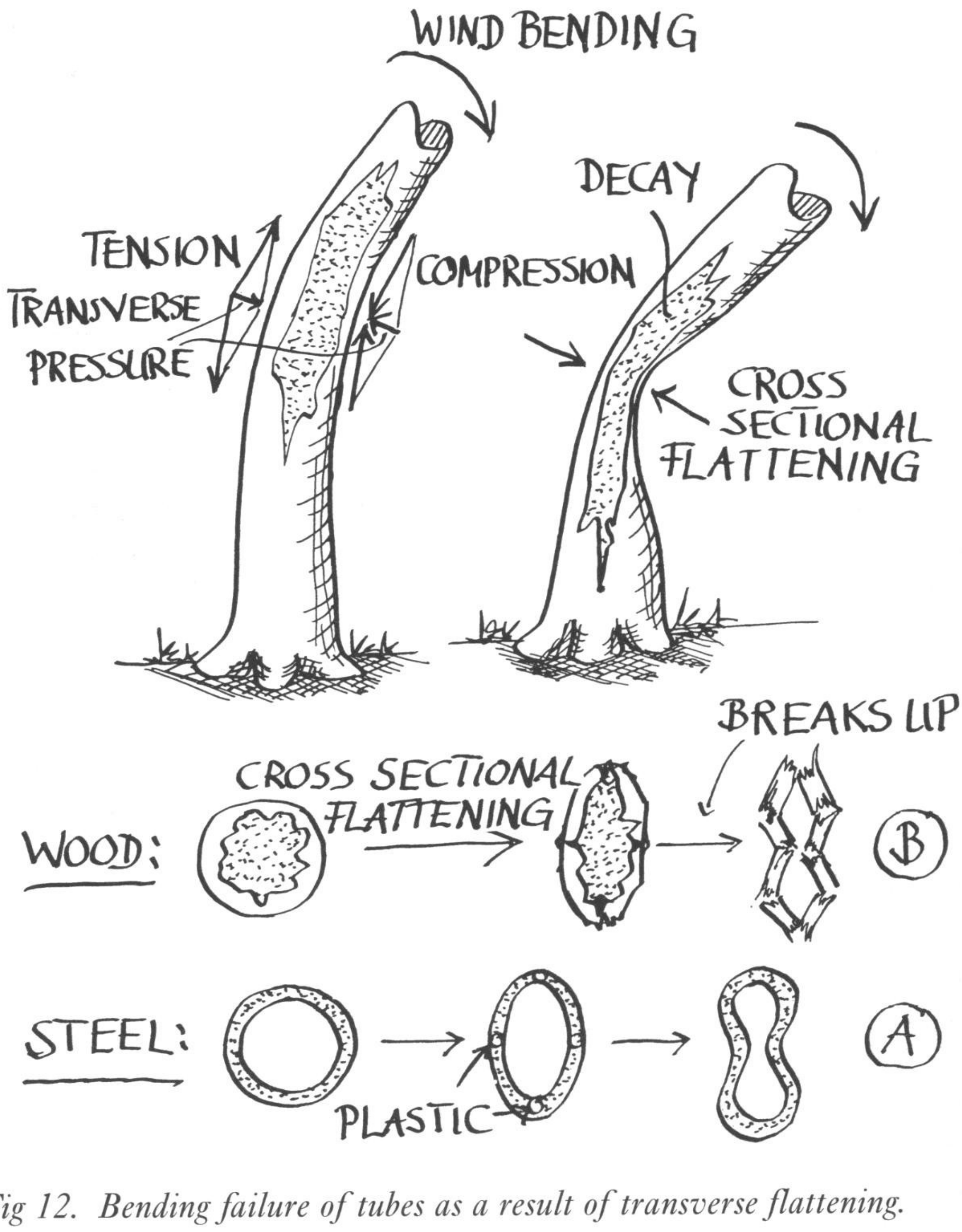


Fig 12. Bending failure of tubes as a result of transverse flattening.
A: Figure 8-shape of steel tubes without longitudinal splitting.
B: Longitudinal splitting and snapping of hollow tree stems.

flattening takes a special form; the so-called hosepipe kinking that occurs where a decayed zone meets sound wood (e.g. in butt rot). This will be discussed later along with 'devil's-ear' failure.

Since cross-sectional flattening can also affect thick-walled tubes, it deserves particular attention. It is particularly significant in cases where the hollow tree is already kinked prior to being bent. Even so, it is very comforting that even soft fillings such as rotten wood in the flattened part of the stem cross-section often upset the calculation to an amazing degree. The authors have seen birch trees which consisted of little more than delicate paper tubes with a ridiculously soft filling material, and yet these happily defied not only gravity but the wind as well. The young branches of the elder trees, under which we played Indians in our tender youth, can similarly thank their airy filling of light pith for their stability. Such fillings, soft though they are, play tricks with cross-sectional flattening and certainly with shell buckling, which will be described shortly. The thought comes to mind that hollow, old trees with worryingly thin walls might be similarly protected from collapse by filling them with a rot-resistant foam.

But what differentiates cross-sectional flattening from a normal bending fracture? Quite simply, cross-sectional flattening will always be characterized by longitudinal splits on the neutral fibres of the bending zone along the hollow stem, whereas in bending fracture there is localized buckling of fibres on the compressed side of the bending zone. There is, however, something else which is nastier than flattening, because it is more abrupt; we refer to the really unstable phenomenon known as shell buckling.

5.1.4 Shell buckling of closed cross-sections

For metal tubes, this mechanism can best be demonstrated by using a drinks can, naturally only after it has been enjoyably emptied. If you bend it, you first have the feeling that it is very stiff and has an extremely high load-bearing capacity. If, while testing your muscle power in this way, you exerted a force just a little bit less than the buckling load, you would need to apply only a very slight increase in load to make the can buckle in a quite deplorable fashion, belying its pretence of strength (Fig. 13). When something similar happens to a thin-walled hollow tree, 'splintering' additionally comes into play. It is difficult to comprehend the exact course of the failure process here. The tree's appearance after the event indicates, however, that axial splitting forms a number of slightly curved 'boards' which then snap. As in a tin can, when a thin-walled hollow tree buckles under bending stress (or, perhaps more correctly shows 'buckling-kinking'), the bearing strength fails spontaneously and collapses without that leisurely course of events that is so typical of cross-sectional flattening. When such unstable failure occurs in building components, it is a designer's nightmare. To bring a little order into the chaos of the terms we are using: The unstable failure of building components is referred to as:-

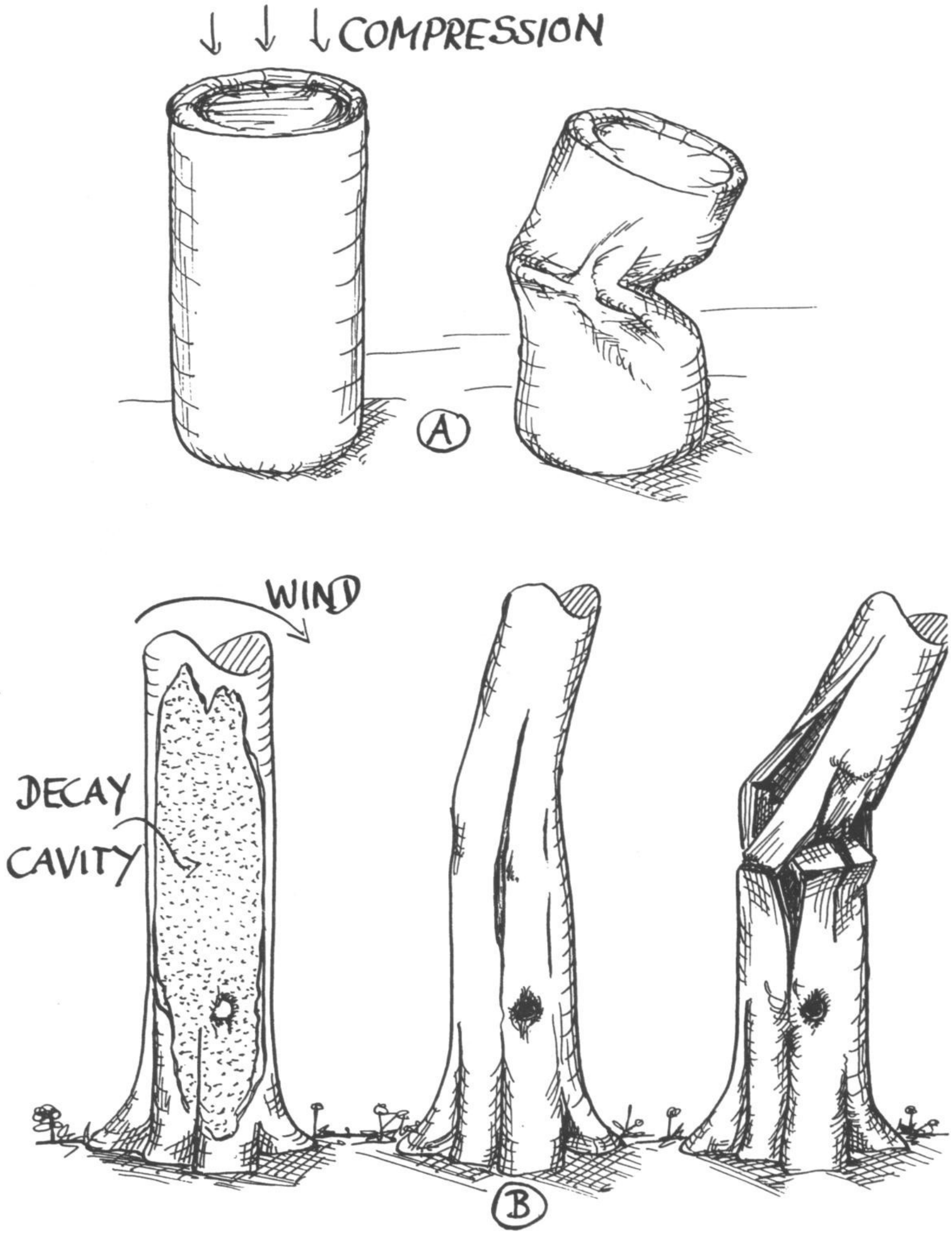


Fig 13. Shell buckling.

A: A drinks can collapses without splitting.

B: A hollow tree with thin walls buckles and breaks up because of limited transverse strength.

- 'KINKING' in the case of rods
- 'BUCKLING' in the case of plates
- in the case of 'shells' (i.e. curved surface-bearing structures) it is also known as 'BUCKLING'.

Our hollow tree is basically a closed shell, but during unstable failure it splinters, and so is actually broken up into several fracture-planks that then invariably fail as the result of rod-kinking. Thus, the unstable failure of hollow trees should actually be called BUCKLING-KINKING. – Enough! We do not want to drive the reader to suicide by quibbling. It is up to the philologists to struggle among themselves with this...

Much more important is the answer to the question: how thin must a wall be for us to expect shell buckling, and how thick should it be for us to expect cross-sectional flattening? It is actually quite hard to find a general answer as long as we are talking not of steel but of wood. However – as we shall see later in the case of hosepipe kinking – we can be certain that shell buckling, as opposed to cross-sectional flattening, only happens with unusually thin shells. Hollow tree stems are sometimes as thin as this, but they usually bear very small crowns which have allowed them to remain standing, as in the case of the old pollarded willows or village oaks and limes that we know so well. The critical wall-failure thicknesses for cross-sectional flattening, as opposed to bending fracture, are explained in the section on hosepipe kinking and devil's ear failure.

It is true that hollow trees with thin walls are treacherous when overloaded, because of the danger of buckling, but at least they provide us with the considerable reassurance of failing in a consistent way regardless of wind direction, as long as the wall forms a closed circle. In unpleasant contrast, the cavity with an opening (the 'open shell') is a load-dependent chameleon with jolly ideas of self-destruction, and the results are very much dependent on the wind-direction.

5.1.5 Shell buckling of the walls of open cavities

The stem illustrated in Fig. 14A is relatively good-natured because its failure progresses in a steady way – at least at first – starting with flattening before planking and rod-kinking ensue. In the case of 14B, shell-buckling occurs at the front and the little 'legs' of the hollow stem near the ground break out sideways, while in the case of 14C (reverse shell buckling), the stiff back wall of the tree kinks. Merely from observing nature, it is clear that case C probably affords the greatest load-bearing capacity, especially as many leaf stalks (e.g. sunflowers) seem to 'favour' this cross-section with the open side uppermost (Fig. 15). The authors have seen cases of reverse shell-buckling in willows where the open side of the cross-section was lying almost horizontal (Fig. 16A) and yet were reliably anchored by the 'guy ropes' (upper edges). In the case of forward shell-buckling, it takes a lot of luck or a pile of sand (Fig. 16B) if the tree is to remain standing.

In all the types of failure described so far, the stem was either solid or hollow over its entire length. However, observations of broken trees show that some of the most dangerous situations occur when there is an abrupt transition between a decay cavity and the solid part of the stem. We shall look at this problem in the next section.

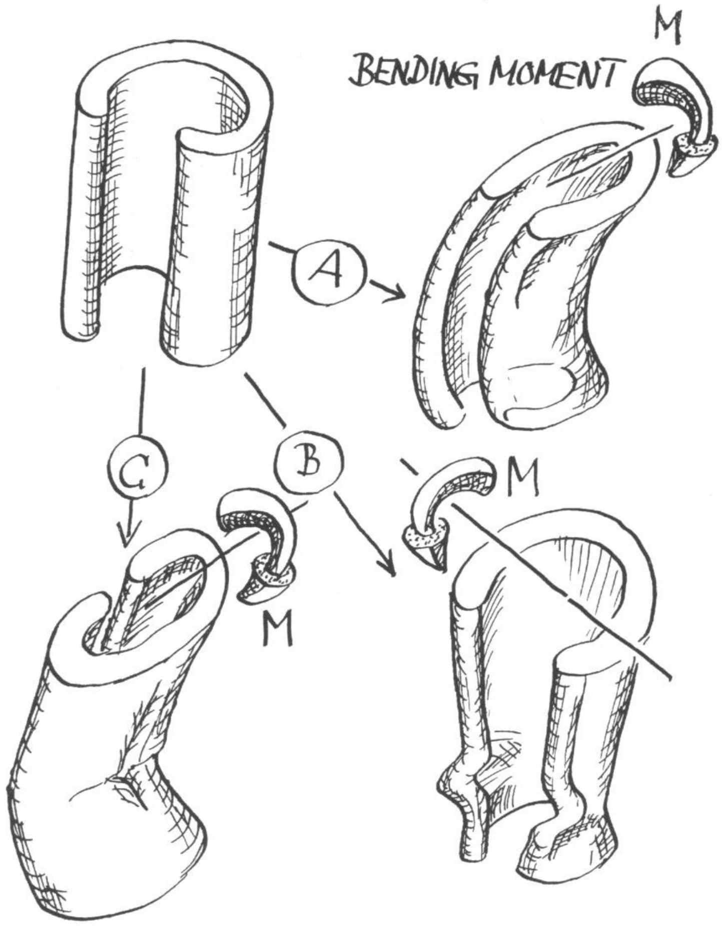


Fig 14. Differing behaviour of shells of open cross-section to winds from various directions.

A: Flattening.

B: Buckling forwards.

C: Buckling backwards.

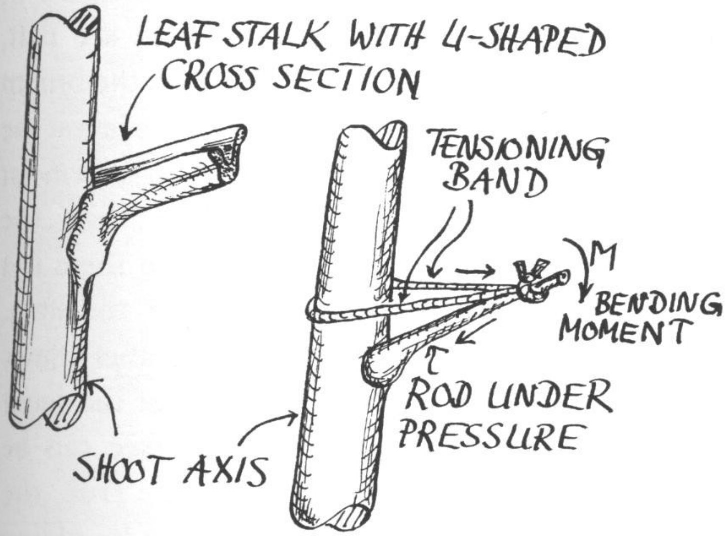


Fig 15. A leaf stalk as an open, upward facing shell: the open upper edges act like tensioning bands, preventing the danger of buckling even under this tensile load.

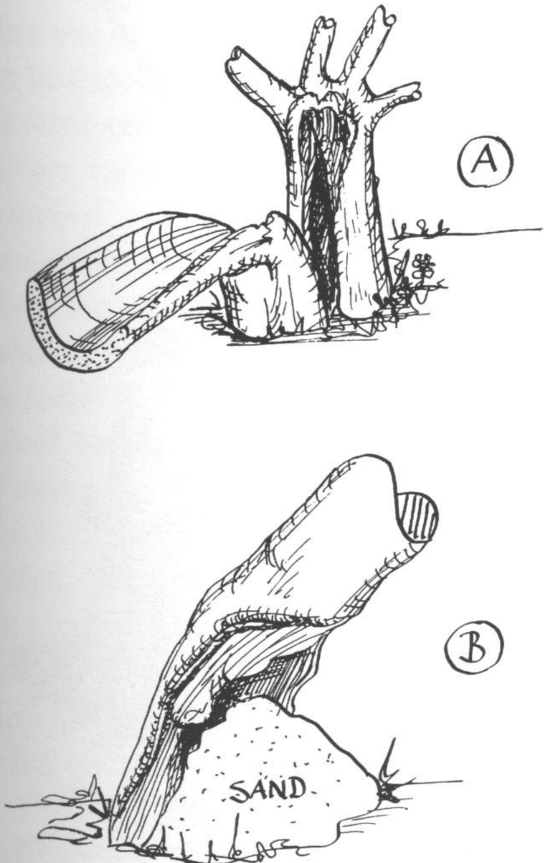


Fig 16. A: An open cross-section of a willow that has failed by buckling backwards, the upper edges of the cross-section still maintaining a sufficient guying effect to hold it horizontal.

B: A tree that has buckled forwards which, without its pile of sand, would have fallen over long ago.

5.1.6 Devil's ears and kinked tubes

In order to understand the principle, let's push a broom handle into our garden hose, which we have so mistreated in our demonstration of cross-sectional flattening. If we then bend it (Fig. 17) we see that, instead of flattening evenly along its length as it did without the broom handle, the hose kinks near the end of the broom handle. We suggest the term *'hosepipe kinking'* to describe this mechanism of *local cross-sectional flattening*. What makes it so much more dangerous than the cross-sectional flattening of completely hollow tubes? When there is a very abrupt transition from the hollow to the solid part of the stem, there is a deviation of the local force flow. As the fungi or other things attacking the tree give little thought to optimising the shape of the decay cavity but rather feast away merrily on the wood, the tree can be threatened by deadly points of stress within its interior. True, the cambium will always try to correct high stresses at the surface by adding new material, as described in Chapter 3, but it can only react to internal notch stresses in this way if they extend out to the surface. This highlights the great disadvantage a tree has compared to a bone: trees

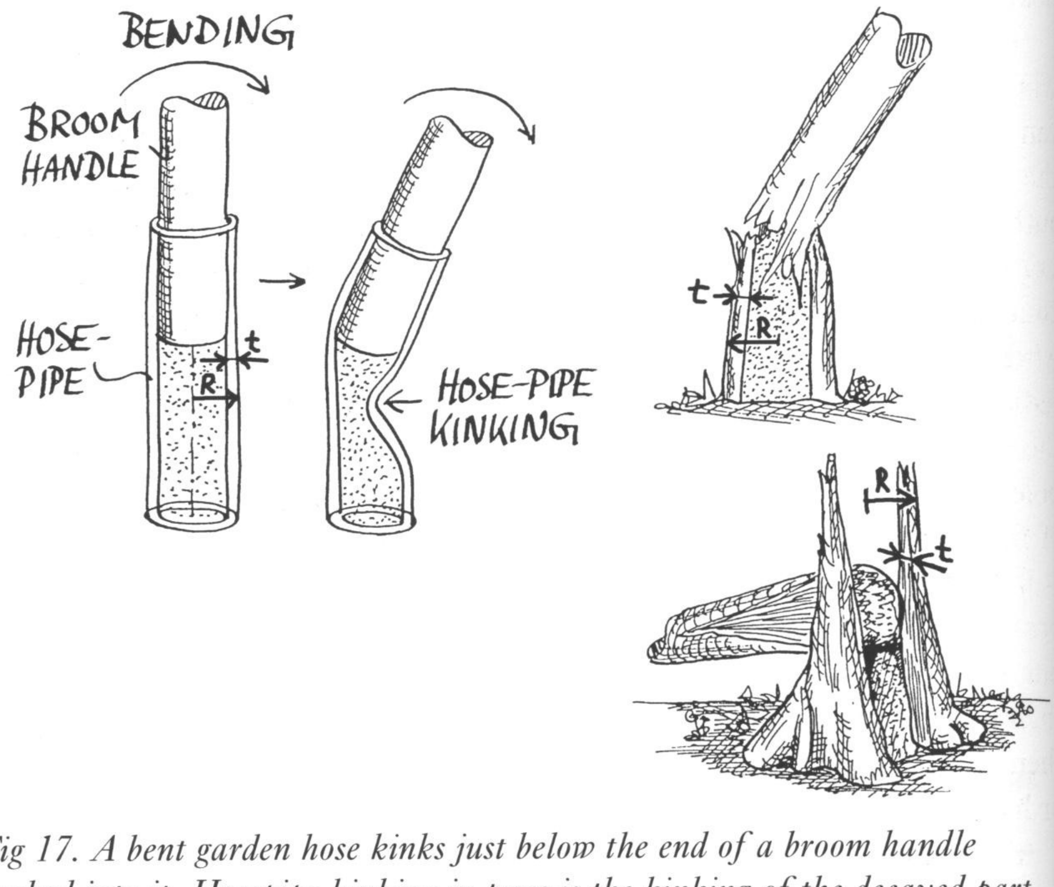


Fig 17. A bent garden hose kinks just below the end of a broom handle pushed into it. Hosepipe kinking in trees is the kinking of the decayed part of the stem immediately below the still solid part. In the case of Devil's ears, two wooden 'ears' split off from the sides of the stem. One-eared devils arise from a combination of bending and torsional loads.

can control their shape only by adding material on the outside of pre-existing wood, although this does enable them sometimes to fill cavities by forming inrolled occlusion wood. Bones can mend their pre-existing material, which wood can never do.

The concentration of stresses in the transition zone between a cavity and the solid part of stem leads to a cross-sectional collapse, or even to hosepipe kinking, much earlier than would be the case with a uniformly hollow tube. The resulting broken stump may take the form known as a 'devil's ear' – with either one or two ears – which is the result only of a particular type of hosepipe kinking. After the tree falls, one or two ear-like points remain sticking up from the base, marking the position where the tree broke at the hollow/solid transition. The likelihood of this 'devil's-ear formation' is often considerably increased by a ring-rot that has spread upwards into the sound stem, and has thus already predisposed the stem to shear along planes which will later give rise to the 'ears'. The double devil's ear mostly arises from straightforward bending loads while single 'ears' examined by the authors in field studies, have been formed mostly due to a mixture of bending and torsion. In the latter case, the side without the ear shows the signs of perfectly normal hosepipe kinking (Fig. 17).

The reader will now anxiously wrinkle his brow and ask himself just when one or other of the many types of failure of hollow cross-sections can be expected to happen, how they are to be distinguished one from the other and *just how hollow a tree can be before it becomes dangerous!* The authors, together with many friends and external co-workers, have so far examined more than 1200 broken and standing broadleaved and coniferous trees. The result, surprising at first, is shown in Fig. 18, where the ratio of the thickness of the remaining wall to the external radius (t/R) of the hollow stem is plotted against the absolute value of the radius R. It did not matter whether it was an unhappy little chestnut pole of barely 15 cm radius or a sizeable butt-rotted spruce with a radius of more than 40 cm – the ratio for broken trees lay mostly between t/R = 0.2 - 0.3 [40]. No tree with a t/R ratio much above 0.3 was found broken. Many trees were still standing with t/R ratios smaller than 0.2, but a high proportion of these had a small wind resistance in relation to their stem diameter because their crowns were much reduced. Several of them had only one branch left, and just a few sported only one branch, or had given up the ghost and had no branches at all!

The idea suggested itself to examine bamboos, elders and other plants with 'hollow' shoots. In the case of elder, a mature stem with many annual rings does not resort to any tricks in defying storms and bravely bearing the burden of snow. In contrast, the one-year-old shoot lives relatively dangerously. It wants to economize as much as possible on wood in order to maximise its investment for rapid growth. In this struggle to reach the light it doesn't pay to use too much expensive material as an insurance against the risk of breaking, since those who adopt this cautious attitude stay in the shade. On the other hand, those who extend themselves too far may break, but the elder indulges itself in this foolishness in the hope that, if mechanically compromised, it will be saved by the soft filling in its 'belly': the pith.

One-year-old annual rings in elder, bamboos etc. often have a t/R ratio of t/R = 1/4 = 0.25. Supplementing our field studies, the elder teaches us exactly how thin the walls of a decayed tree can be without it collapsing through hosepipe kinking, provided that it contains a core of soft, decayed wood instead of being entirely hollow. Bamboos also often have a value of t/R = 0.25 but, instead of using pith to avoid hosepipe kinking, they use rings of stiffening material. The reason that trees up to t/R = 0.3 can still fail as a result of hosepipe kinking (Fig. 18) is probably because they have no residual 'filling' material or, as later examples will show, because of a combination of loads which together can bring the tree down. Incidentally, we discovered after our survey that Wagener [73] and subsequently Smiley & Fraedrich [68] in the USA had

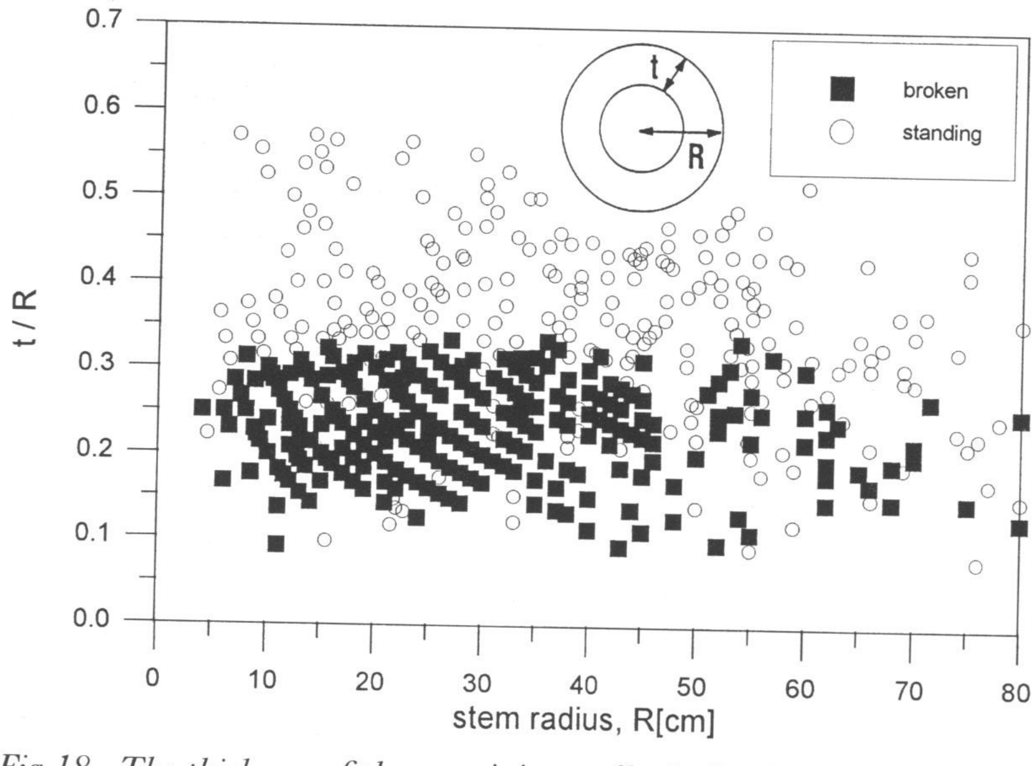


*Fig 18. The thickness of the remaining wall **t** is divided by the external radius **R** as the ratio **(t/R)** and plotted against the tree radius **R**.*

Black squares: broken, hollow trees.

Open circles: hollow but still unbroken trees.

happily come to a similar limiting value for hollow trees by empirical methods, and we have also learned from Brugger [9] of Nurenberg that he has come to the same conclusion.

Although the wall thickness of a hollow cylinder might be assumed to play some part in determining its strength, the reader may still ask why t/R in particular was chosen as the kinking parameter. In the theory of shell buckling, there is always a t/R relationship for the critical buckling stress at which this type of failure occurs. The buckling formulae therefore usually have the form

$$\sigma = f\,(\frac{t}{R}),$$

where the function f(t/R) for the specific loading and tube geometry has still to be specified. At first it is puzzling that such apparently varied types of wood all fail at a uniform t/R ratio. There are several possible explanations for this. Simple bending theory gives a steep rise for a typical curve (= second derivation of the stress at a relative wall thickness between t/R = 0.2 and 0.3). The nature of the material has no influence on this curve at all, so that it is equally valid for all elastic materials; for a steel tube just as much as for wood, rubber, stone or ice. There can be little objection to this simple concept. There is another explanation which, being the subject of current research, is not yet quite so cut and dried. This is based on the optimization of the inner architecture of the tree. Woods that are apparently very different also clearly have some things in common. For example, the moduli of elasticity (E) for the longitudinal and circumferential directions bear a very similar ratio to one another in many species, which is, according to the Wood Handbook [4],

$$\frac{E_{longitudinal}}{E_{circumferential}} = \frac{20}{1}$$

This ratio affects the resistance of the material to buckling. The buckling formula is valid for homogeneous material, while transverse moduli additionally apply in the case of orthotropic industrial materials such as wood. It is significant that the ratio in the above formula is remarkably constant amongst both conifers and broadleaves, which have different evolutionary origins. The uniformity of this ratio of approximately 1:20 among these different evolutionary groups reflects the similarity of the materials from which different tree species are made, and also leaves little doubt that this 'choice' of materials must confer special advantages on the tree. It may also be the reason why the failure limit t/R ≅ 0.3 is so constant. Incidentally, in contrast, the ratio of the E-moduli $E_{longitudinal}/E_{radial}$ varies quite unpredictably amongst different species. It seems, therefore, that this other ratio is less important for the survival of the species.

It is conceivable, indeed, that the value $E_{longitudinal}/E_{circumferential} = 20$ was 'selected' by trees to minimise the risk of their collapse from hosepipe kinking and hence to preserve hollow stems for as long as possible. These ideas, which are still hypothetical, are currently under intensive study at the Research Centre in Karlsruhe, and attempts are also being made to improve bonded fibre materials by copying the inner architecture of wood.

But why are we discussing a formula for hosepipe kinking that is used in industry only for shell buckling? The demarcations between these types of failure are fluid and a clear division between cross-sectional flattening and shell buckling cannot be clearly drawn, given our present state of knowledge. It is, however, certain that the residual load-bearing cross-section represented by the ratio t/R is a good measure of the risks of both hosepipe kinking and shell buckling. Anyone who still doubts this, should study Fig. 18. This diagram on its own is a lesson to us in nature. The fact is that all broken hollow stems lie below $t/R \cong 0.3$. No theoretical 'ifs' and 'buts' can escape this fact. The value $t/R = 0.3$ as an approximate upper limit therefore plays an important role in the failure criteria used in the Visual Tree Assessment (VTA).

5.1.7 'Harp-tree' fractures

'Harp-trees' arise when, for example, a tree is pushed over and cannot regain the vertical by geotropic growth, so that its branches then become stems (Fig. 19A). These are parallel and vertical like the strings of a harp. Because of its position, lying on the ground, the fallen stem is hardly in danger of breaking at all, provided that the wind blows along its length. However, in the case of an above-ground horizontal branch whose side-branches form a harp shape (Fig. 19B), it is not uncommon to find fractures at the branch base. In this case, if the wind blows in the direction of the branch, all the bending moments are added together. The same can happen to a harp formation which arises from a ground-level branch, but slopes upwards instead of lying horizontally. The unfortunate branch base cannot withstand the heavy burden, especially as the combined weight of the branch and its perfectly aligned vertical side-branches is similarly pulling it downwards. In the worst event, snow can add a heavy load. Both 'harp-trees' in contact with the ground and aerial 'harp-branches' can crack at the base if the wind load is from the side, so that the horizontal stem or branch is subjected to a strong torsional stress. Exposure to such stress often encourages abnormal thickening at the stem-bases of 'harp-trees', even where there is no apparent weakening from decay. In this way, the tree prepares itself to withstand an above-average bending and torsional load, in accordance with the *Axiom of uniform stress* (see Chapter 3).

Whenever there is an extra load, there is no doubt that large, old limbs with vertical 'harp-string' side-branches pose a real risk. On such an occasion, the limb can break at its junction with the stem, although if the parent stem is itself leaning, the risk is considerably less. Although failures do occur, the wedge-like thickening of the branch or stem-base exemplifies the wonderful optimization of form in these trees, so full of character, which have been irreparably bowed down by heavy blows of fate and yet persist in their 'will to live'. So long as the heavily loaded stem base is sound, these masters of the art of survival should be spared to be marvelled at.

Another word about Fig. 19A: in a very few instances, it can be a current member of the harp which fails (on the left of Fig. 19A) as a result of the hazard beam mechanism, which will be explained later in

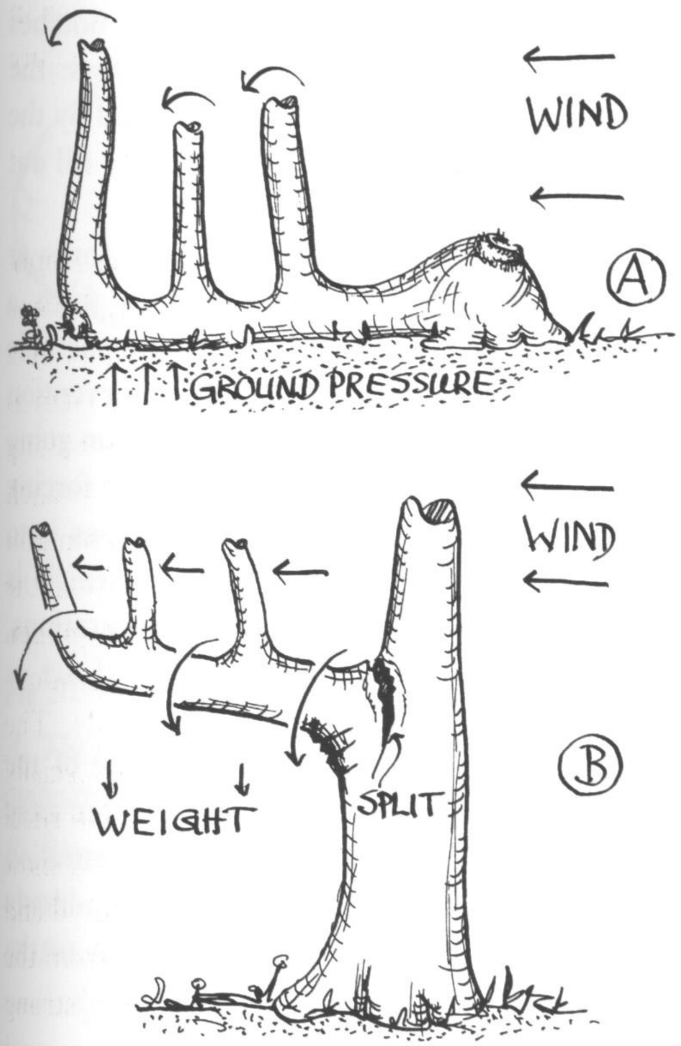


Fig 19. Harp trees.

A: Little danger of breaking because the reclining tree conducts the wind load into the ground as pressure.

B: In this case, the 'strings' of the harp conduct a similarly directed bending moment into the stem which is not lying on the ground, or into the large limb that has to bear the entire bending moment of all the vertical branches. Fracture can result.

Fig. 28. Even the famous Kaiser Wilhelm beech at the Johannes Cross in the Pfälzer Wald (Forest of the Rhineland Palatinate in Germany) broke in this way.

5.1.8 Fracture as a result of removing foreign bodies in previous contact with the tree

If a stone or some other dead or living solid body presses against a tree (Fig. 20), mechanical contact stresses are set up which disturb the *state of uniform stress* which the tree has previously 'striven' to maintain. Hurriedly, the tree enlarges the contact surface in order to equalize the stresses once more. It envelops the foreign body and forms a kind of natural sofa cushion. (We solve our own similar problems in a rather similar way when at a picnic we happen to sit on a stone or the ground is uneven.) The result for the tree is that it increasingly supports itself on its new friend, the stone, the iron railing or the old wall. It trusts it and comes to rely on this mechanical support for the future. If the stone is then taken away, it is tantamount to amputating part of the tree's 'foot'. The load that up until then was carried by the stone, must now be borne entirely by the tree and, worse still, this load must now be diverted around the now completely useless indentations and notches that developed in contact with the stone. Even more bad news: the cambium in the contact zone has often been completely crushed by the powerful mechanical forces there. The tree cannot very quickly fill out these hollows by means of adaptive growth.

In view of these problems, it is very inadvisable to remove stones or other objects that have been supporting a tree. To sever such a tree/stone friendship is rather like treachery and creates a considerable safety risk (Fig. 20B). We can therefore justify such drastic intervention only if we can see that the tree itself, by increasing in girth, is soon going to destroy its mechanical partner, e.g. by pushing over a wall or forcing up or cracking a pavement. One way of coping with such cases is to substitute another object of equivalent mechanical value, which is especially needed if the tree has developed deep indentations, conforming to the shape of the original object; these could act as mechanical notches, i.e., potential breakage points.

It is also undesirable to cut back the crown only on the side of the stone (Fig. 20C). 'Relieving' the load like this can bend the tree away from the stone: the 'cushion' lifts up and in this case the configuration optimized by the tree to withstand a compressive stress is suddenly subjected to a tensile stress in a way that is completely alien to the 'design'. The tree can then break.

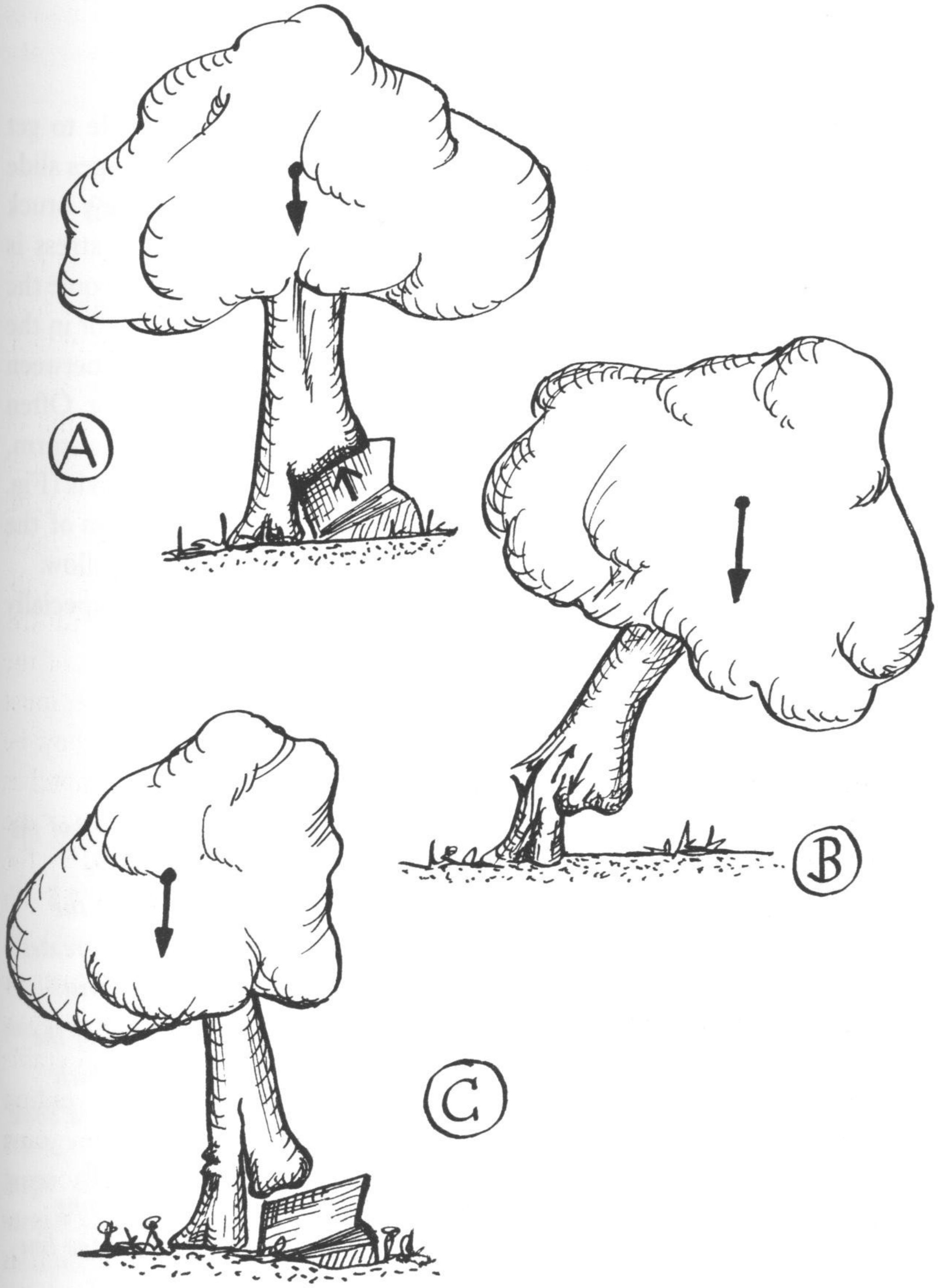


Fig 20. A fracture on removal of a contiguous rock.

A: The tree moulds itself around and encloses the rock while optimizing its configuration.

B: Removal of the rock ruins the optimized configuration of the tree. The consequence is a fracture at the notch that this has created.

C: Pruning off one side of the crown can lift the tree off the rock and similarly initiate a fracture.

5.2 FRACTURES CAUSED BY SHEARING STRESSES

5.2.1 Trunk fractures

Shear stresses are explained in Chapter 13.1. It is also possible to get some idea of what shearing involves by bending a book. The pages slide relative to one another as in Fig. 21A. If the pages are now stuck together, the sliding is suppressed; in other words, the shear stress is transmitted by the adhesive. The shear stresses required to overcome the resistance of the adhesive are greatest in the middle of the book or in the corresponding plane within a tree, where there is a transition between axial tensile stresses and compressive stresses caused by bending. Often in mechanical tensile tests of beams or in trees simply broken in a storm, the base of the structure is seen to have split centrally along its axis (Fig. 21B). As a result of this longitudinal split, the whole optimization of the tree's configuration collapses and transverse fracture tends to follow.

A different kind of shear failure can occur in hollow butts, especially those of old ash trees, and is described next.

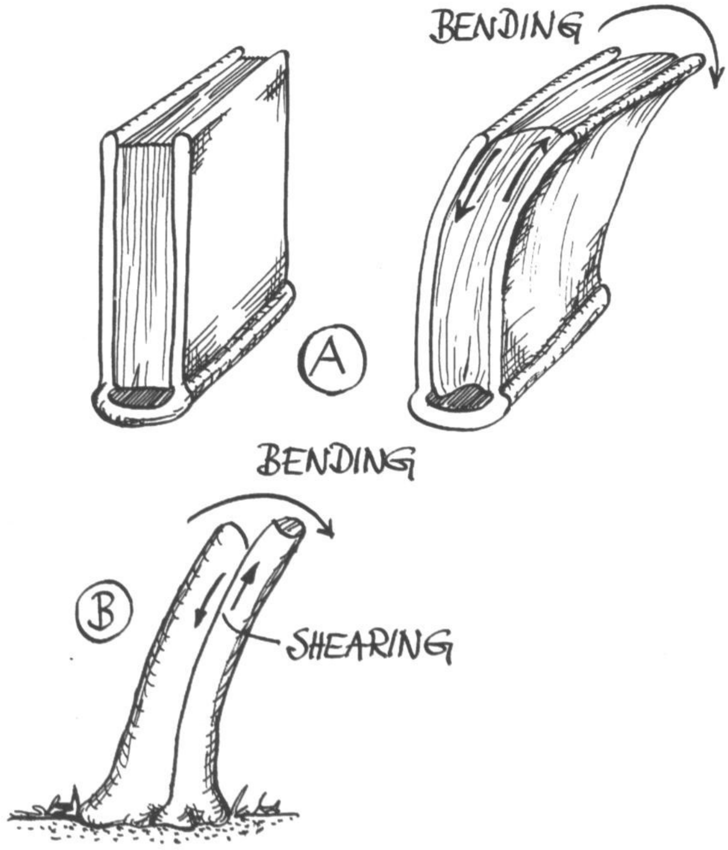


Fig 21. Fracture of the lower stem at the neutral fibres in the bend where the greatest shear stresses occur.

A: Illustration of the shear stresses which arise on bending a book.

B: A lower stem fracture developing upwards along the line of greatest shear stresses.

5.2.2 The basal bell fracture

This failure mechanism, illustrated in Fig. 22, is triggered by a mixture of shear failure and delamination resulting from transverse stresses. If the belling of the stem base is very thin, shell buckling or hosepipe

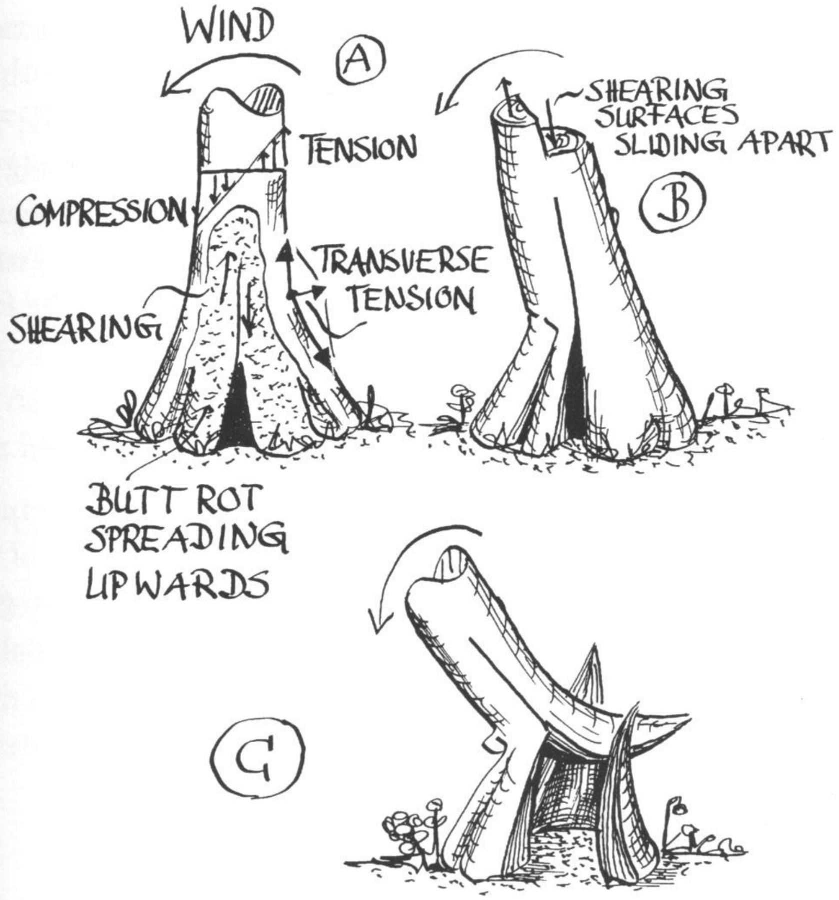


Fig 22. A basal bell fracture in its various stages of development.

A: A basal bell as seen in a hollow ash: shear stresses give rise to cracks.

B: Hosepipe kink fracture on the compressed side.

C: A fully developed fracture with the middle part sheared away and with pieces of the basal bell which, as here, often remain standing.

kinking can play a part as well. This pronounced broadening of the stem base, which is particularly common in ash trees, tends to form around a large decay cavity in response to an associated increase in bending stresses. The central roots below this decayed void are completely decayed. Indeed, the buttresses of the horizontal roots are often thin tubes with mostly well compartmentalized decay, as in the stem.

If such a tree is now bent by the force of the wind, the whole push must be transferred through the thin walls of the bell. This favours longitudinal splitting, since it stretches the belled contour of the tensioned side of the bending zone (transverse tension in Fig. 22A). This splitting pulls one half of the bell sideways away from the other. (In Section 5.4 we shall get to know this transverse tension as a damage-triggering factor in its own right, in the wind fracturing of spruce.) The stretching of the tensioned half of the bell and the axial splitting allow the tree to lean more and more, forcing the compressed half of the bell to kink. With this kinking failure initiated by the central shearing, the tree falls. Despite the pronounced thinning of the stem base, it is often astonishing how long many ash trees continue to survive with such pronounced cavities. The t/R ratio for basal bell fractures is t/R = 0.2 – 0.3, as for hosepipe kinking, which suggests that hosepipe kinking is the end-result of the failure process. Quite often, root buttresses separated from the stem by the axial splitting remain standing like a group of devil's ears as if they had been assembled around the base of the former cavity waiting for the stem to return.

5.2.3 Shear failure along internal cracks under bending stresses

This damage process is largely identical with that of trunk fracture. Its special feature is that the failure is encouraged by the presence of radial cracks (Fig. 23). A standing tree which contains such cracks can give us a clue as to their presence by rib formation, which we shall look at in

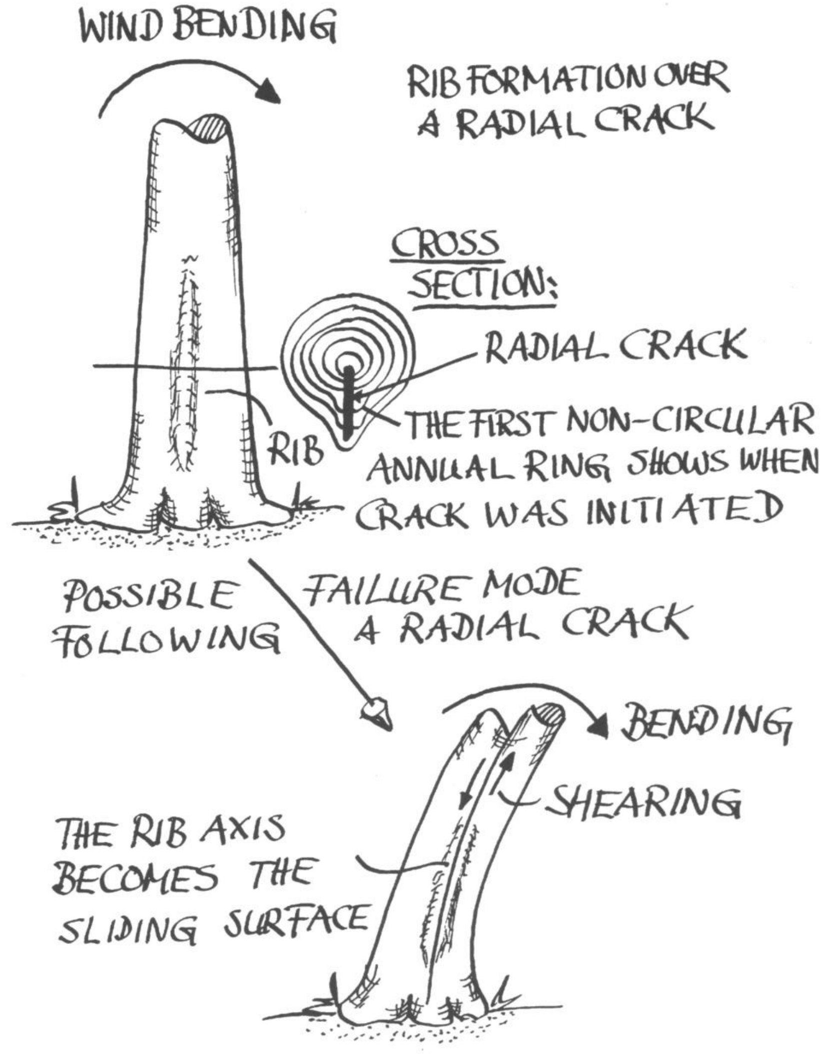


Fig 23. The radial crack associated with a partially or completely occluded stem rib acts as a sliding face in shearing failures.

more detail when we deal with the symptoms of defects. Clearly, failure at a potential shearing surface is much more likely to occur if a crack is present there. This can be seen in the example of our bent book (Fig. 21A): pages only partly stuck together will slide over each other more easily than will pages that are thoroughly glued over their whole surface. The radial cracks in the stem correspond to the parts of the pages where no glue has been applied. However, the main risk from such cracks is not from shearing failure, at least in a moderate wind and with radial, longitudinal cracks in straight trees. It is more likely that the cracks will allow decay fungi to spread across the annual rings to involve the whole of the heartwood and turn a cracked tree into a hollow one.

5.2.4 Fractures at wound spindles and knot holes

Shearing failure can result from the sliding apart of poorly anchored and relatively well anchored parts of the stem. This tends to happen at branch cavities or partly occluded wounds, as shown in the two examples illustrated in Fig. 24. In both cases the tree has a defect on the side of

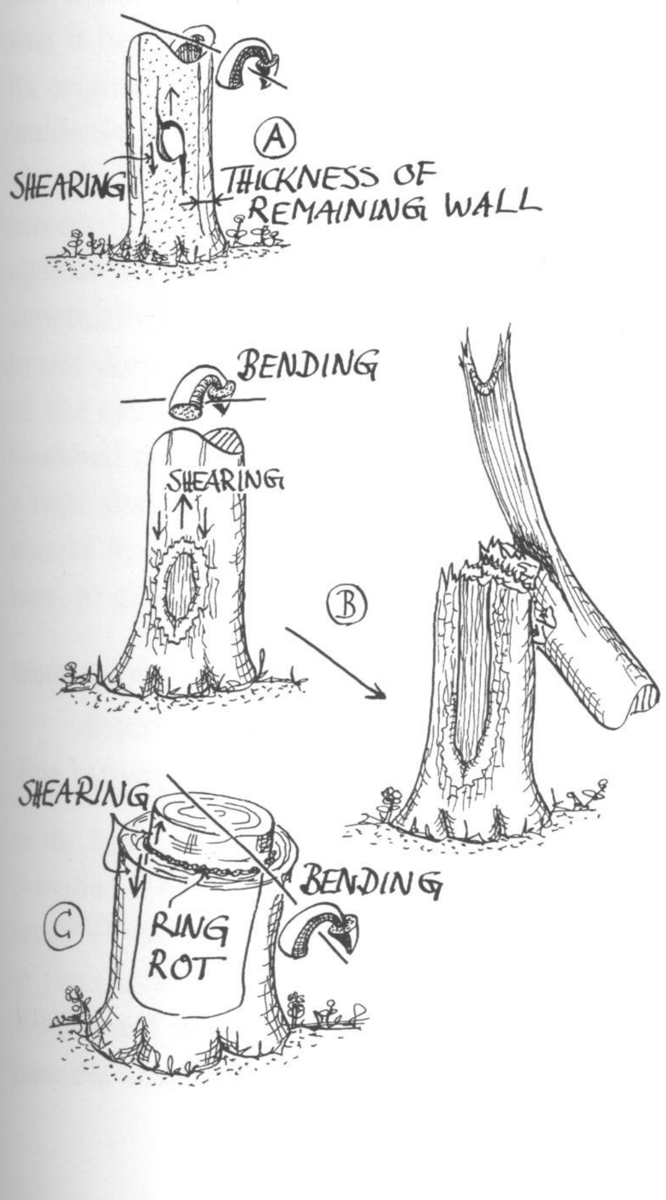


Fig 24. Shearing failure at old wounds.

A: Shearing stresses cause cracks at a knot hole in the hollow tree.

B: Shearing stresses tear out a strip of wood above a partly healed wound in a completely rot-free, solid stem.

C: A weakness between annual rings, caused by a barrier zone or a ring-rot, encourages shearing failure above the wound.

the bending zone under tension. A strip of wood made up of several annual rings is pulled upwards. In the first case, its lower end at the upper edge of the wound or branch cavity experiences no opposing tension. Therefore the vertical tensile stress must be taken up as a shearing stress by the annual rings below or by an adjacent strip of wood.

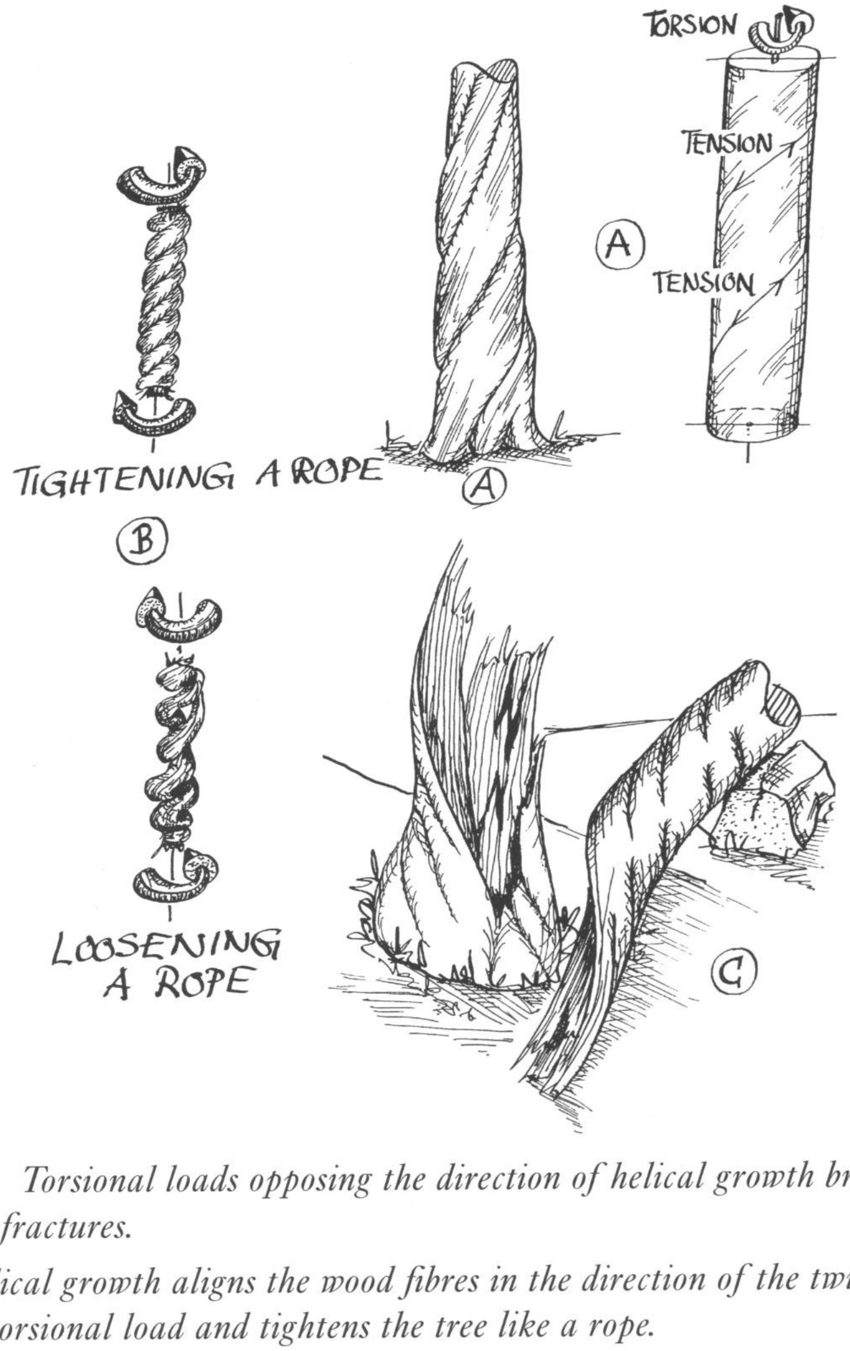


Fig 25. Torsional loads opposing the direction of helical growth bring about helical fractures.

A: Helical growth aligns the wood fibres in the direction of the twisted pull of the torsional load and tightens the tree like a rope.

B: Reversing the direction of twist now compresses the wood fibres longitudinally and creates tensile stresses across the fibres which split the tree. The tree is undone like a rope that is untwisted.

C: An example of a typical helical fracture in an old oak. The fracture occurred after neighbouring trees in the vicinity of the tree fell and the wind load changed.

Even in the second case where wood above and below the wound forms a partly formed occlusion spindle, the spindle may tear under tension. Thus in both situations, we can be left with an unanchored wood strip above the wound which slides upwards if the stress is great enough. The result is a shearing failure between the annual rings. This damage process can be further facilitated by ring rot or by a barrier zone (which is in effect a weak annual ring that has been formed by the cambium following injury). Such pre-existing weak zones further reduce the resistance of the sliding surfaces to shearing. In cases where ring-rot has acted as the trigger for shearing, the resulting separation of these surfaces can allow it to extend further in the plane of the annual rings.

5.3 FRACTURES CAUSED BY TORSION

5.3.1 Torsional fractures opposing the direction of helical growth

The force flow in the components of a structure twisted by external torsional forces can involve some mind-numbing theoretical exercises but, if you want to be spared all this, take hold of a thick rope and twist it in the direction of its lay (Fig. 25). You should note with some pleasure that it becomes increasingly rigid. Then twist the rope back to beyond its original lay and see, with dismay, how this wonderfully stiff object suddenly turns into a sadly limp thing made up of its unravelling strands. The rigidity is precisely that of the helically grown tree which can easily fall victim to a characteristic helical fracture when it is twisted against the direction of the helix. Helical growth can either be genetically determined, or it can develop so as to match torsional stress in one direction. It amounts to sabotaging a tree if, by reducing one side of the crown, by releasing the crown or by other external means, this torsional direction is reversed. The tree is then destabilized exactly like a rope that is twisted against the direction of its lay – something that should be borne in mind when, for example, pruning avenue or street trees to give clearance.

5.3.2 Torsional fractures opposing the direction of helical growth at internal helical cracks

Fractures at pre-existing internal cracks (Fig. 26) are precisely the same as the helical fracture shown in Fig. 25. In this case, however, the tree's previous history has introduced an additional mechanical defect: a radial crack. If the cracked tree is twisted in the direction of the helix, the sides of the crack are pressed together. The crack becomes hardly noticeable. But, woe! if the tree twists the wrong way, the 'rope' slackens off. In this case the enclosed crack is subjected to a transverse load and torn apart.

This dangerous point of potential fracture can very easily cause the tree to fail, even with an only moderate torque loading. Because of this extreme slackening effect, the curving radial crack has to be ranked as far more dangerous than the straight radial crack that we have already described in connection with shearing loads (Fig. 21).

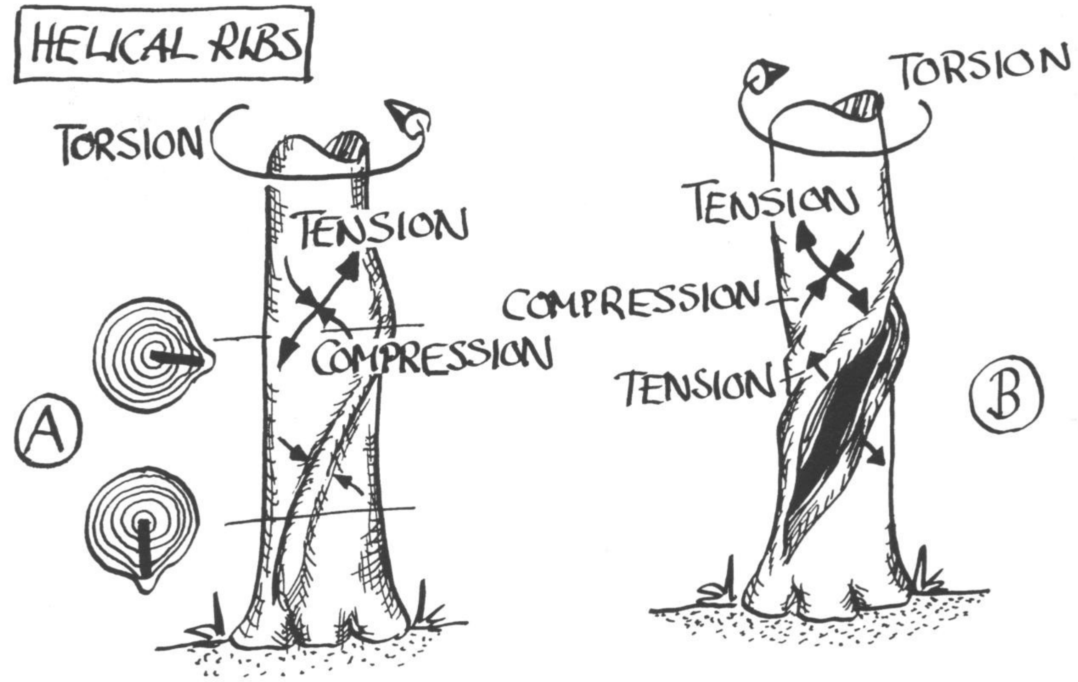


Fig 26. A radial crack follows helical growth and, if the tree is subjected to a torsional load in the opposite direction, exhibits a helical fracture face.

A: The torsion follows the helical growth. The crack, squeezed together, is harmless.

B: If the torsion is in the opposite direction to the helical growth the crack is pulled apart. Helical fracture can follow.

5.3.3 Rotary fractures caused by flailing branches

Anyone who has ever watched from close quarters a tree being swayed strongly in a storm knows what this means. The reader who is a little puzzled should just pick up a domestic iron and sweep his arm weighted in this way in a circle past the side of his body. When the iron is above him, the sceptical athlete's body (his 'stem') is pulled upwards along its length. When the dangerous point of the iron comes round whirling past our expert's knee, an axial stress compresses this sportsman's spinal column. Quite right too! The forces of inertia are to blame. Apart from this stretching and compression, the body swings forwards when the iron swings behind it, and backwards when the iron comes round to the front. Thus the tree stem bends and twists as well as being compressed and stretched – a feast of fidgeting!

The compression and tension waves running up and down the stem are superimposed on bending, torsion and weight loadings (Fig. 27). This mechanically very complex sequence of potentially damaging events was brought to the authors' attention by the very strange fracture of some poplars, which admittedly had strongly one-sided crowns. The unfortunate trees all snapped at about 4-8 metres – not a rot cavity, not a crack, not a defect to be seen! Astonishment stimulated research, and at the Research Centre in Karlsruhe, Jürgen Schäfer produced a simple tree stem with just one large branch as a finite element model for calculation purposes. The branch was pulled to one side and released. An adventure in shaking, waving and jiggling began. The stem bent

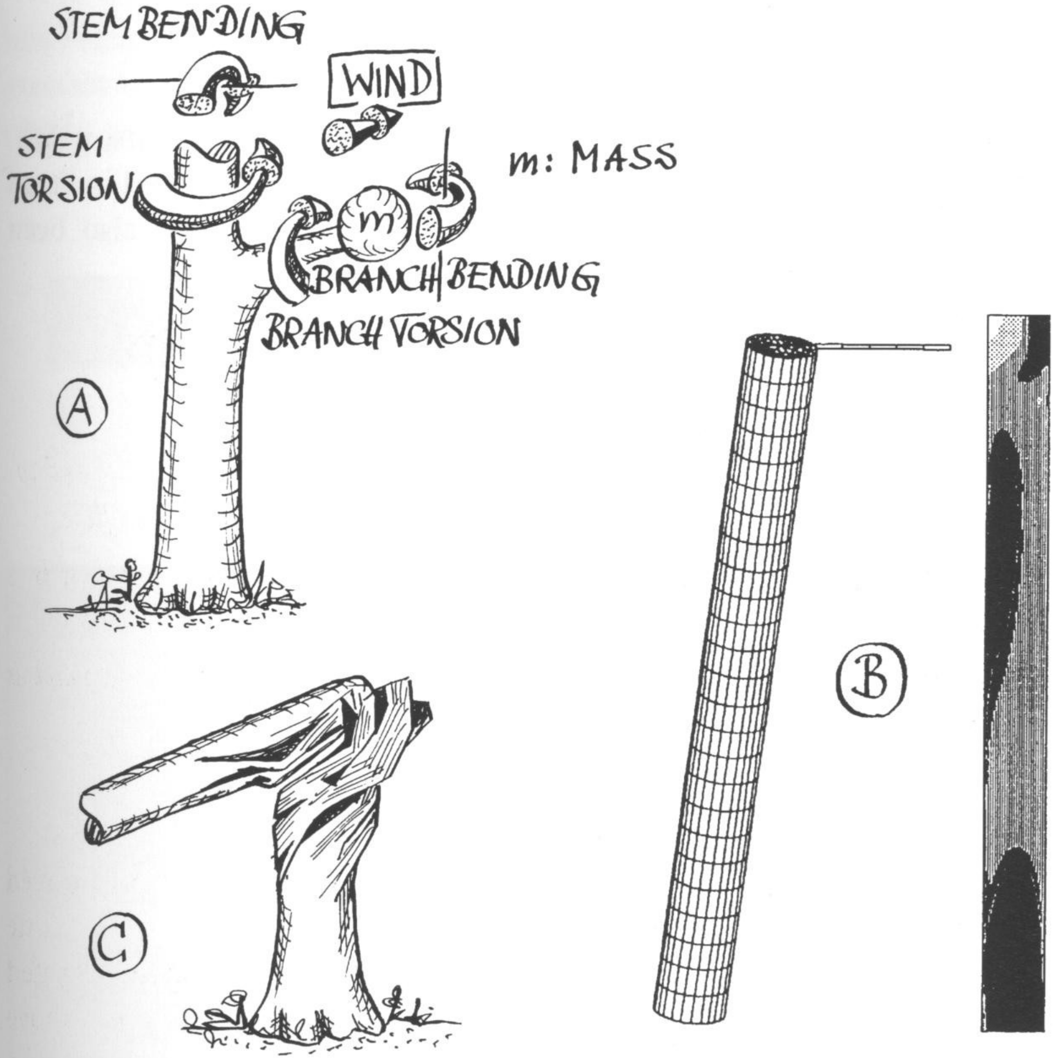


Fig 27. A bending fracture resulting from the branch thrashing about.

A: The swinging of a weight (the weight of the branch) causes vertical tension and compression, with bending and torsion in the stem.

B: Localized maximum stresses can arise from this branch thrashing and complex natural oscillation.

C: The final fracture.

backwards and forwards, the branch thrashed up and down and backwards and forwards and, during the course of this swinging, defined waves of maximal stress travelled quite some way up the stem (Fig. 27B). That was the explanation for the damage, although it was admittedly not entirely simple. This type of damage is absolutely unforeseeable and, because of the virtually unknown individual sway characteristics that vary greatly from tree to tree, it should be classed as an act of God. It is also one of the ways in which completely sound trees fracture, so contributing to their 'natural failure rate'.

5.4 SPLITTING DUE TO TRANSVERSE STRESSES

5.4.1 The hazard beam

The failure of the 'hazard beam' is a course of damaging events, which, like the above case, is quite unforeseeable. It has been described in detail elsewhere [37,38,39,41,49] and computer simulations have also been

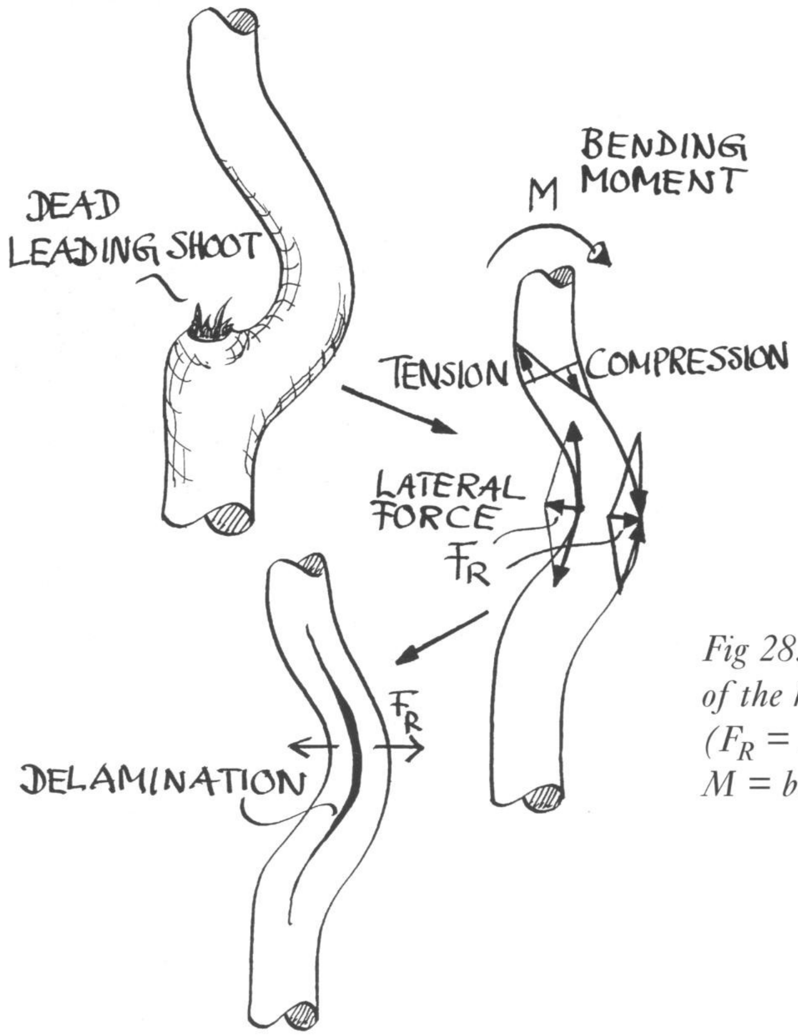


Fig 28. The mechanics of the hazard beam. (F_R = Lateral force; M = bending moment)

provided [49]. Fig. 28 shows the principle. When any crooked part of the tree, is bent back, that is to say straightened, it experiences internal transverse stresses. These transverse stresses cannot be detected by the tree's 'measuring system' in the cambium; i.e. near the surface of the tree, because their value there is precisely nil. And this is exactly what constitutes the hazard in these hazard beams. However, Wolfgang Albrecht has shown in his PhD work that the position where splitting is most likely to occur is also the position of greatest lateral strength. The danger of splitting is counteracted by local adaptation of wood quality within pre-existing wood. The mechanism of this is unknown at present.

Fig. 29 shows the result of a stress calculation, in which we used the finite element method. The central patch in Fig. 29 is the location of the greatest transverse stresses, and shows that the transverse stresses are closely confined to the middle of the hazard beam; this is just where

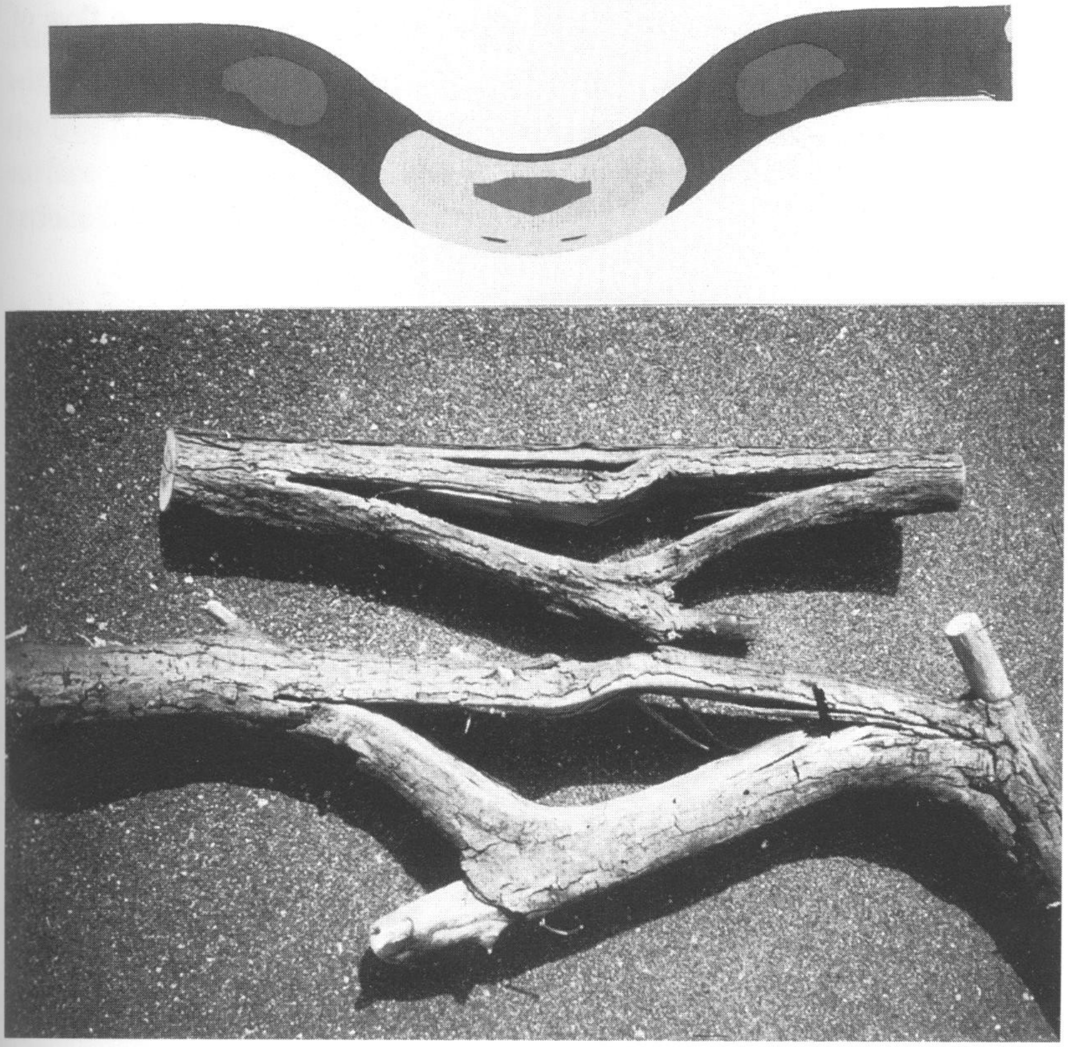


Fig 29. The maximum transverse stresses inside the tree are precisely nil on the tree's surface so cannot be detected by the cambium.

axial splitting is initiated in nature. Often, after the completion of the first longitudinal split, the concave upper part of the hazard beam is still not fully straightened and behaves like a second hazard beam (Fig. 30) which then splits in the same way.

Unlike the concave upper side of the split zone in the beam, the convex lower side never shows secondary splitting. The reason is that it is not straightened any further by continued application of the bending load but, on the contrary, is bent more. This leads to compression stresses across the wood fibres, which are thus pressed together laterally so that any splitting is prevented. The concave upper part can fail again and again, however, until the uppermost bundle of fibres on the side of the bending zone under tension acts like a brace. Such stressed braces are also to be found among muscles in the human skeletal system. So it looks exactly as if the tree, in its distress, performs a kind of hasty act of mechanical desperation by splitting longitudinally and thus modifying its design so that it acquires stressed braces like the mammalian skeleton. It pays for this by opening a door to wood-rotting fungi but it has escaped a transverse fracture which would have interrupted the flow of

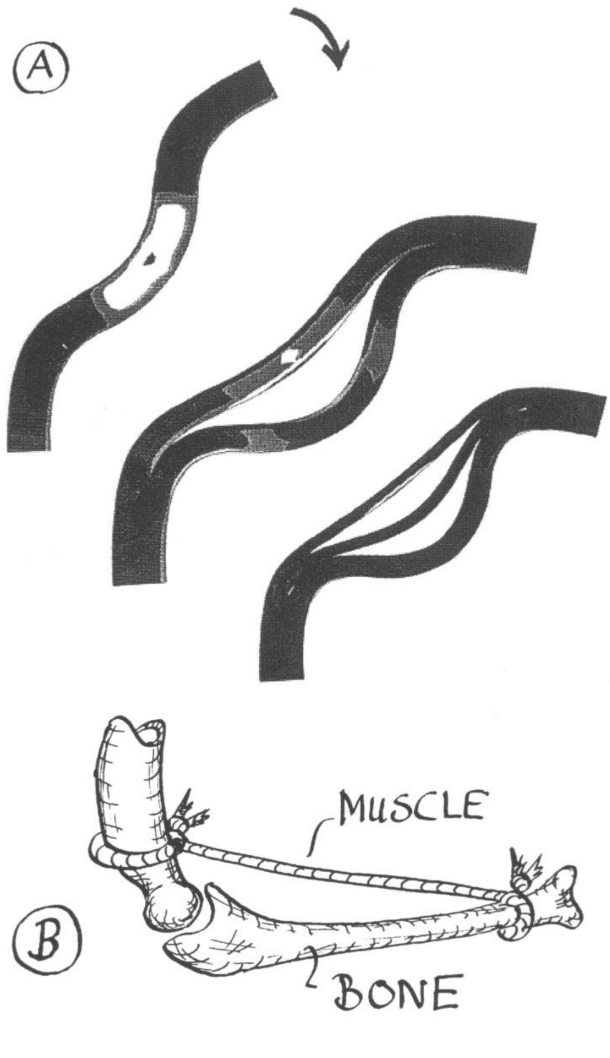


Fig 30. If there is still a slight curve in the concave part of the split bowed tree this in turn forms a new hazard beam that then splits again until it is perfectly straight (A). The outer part is now straight and acts like a tensioning rope, reminiscent of the tensioning bands of the muscles in the skeletal system of mammals (B).

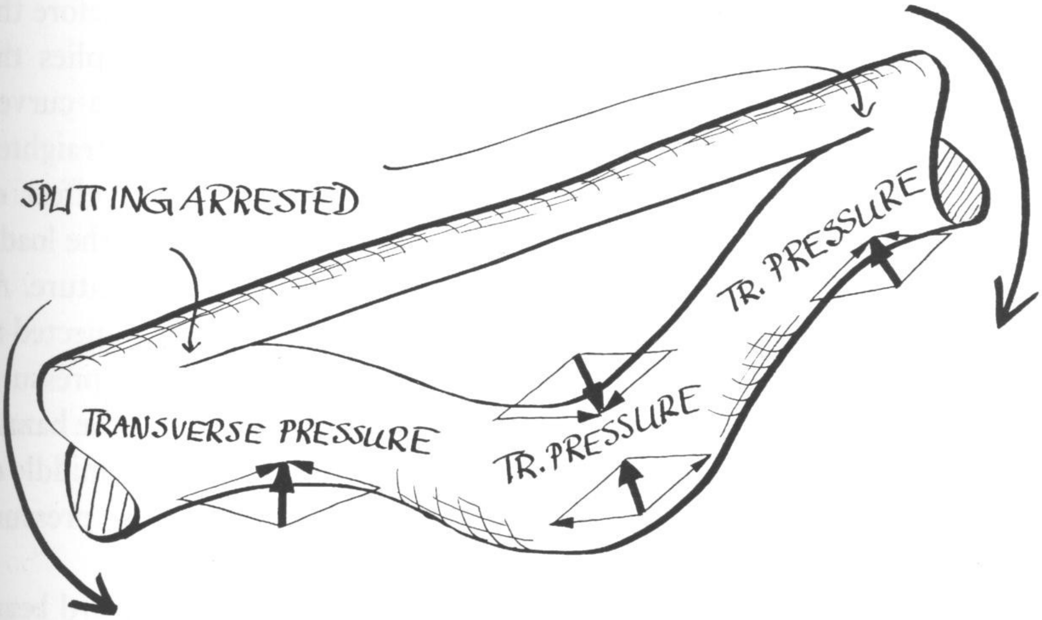


Fig 31. The axial splitting is confined to the curved region because the cracks at the ends of the hazard beam run into a zone of transverse pressure.

assimilates. Sap flows merrily on either side of the longitudinal splits without any significant disturbance. True, the optimal configuration of the tree has been destroyed but the new maximum stresses now lie on the surface of the tree where the cambium immediately gets to work to reduce locally excessive ones.

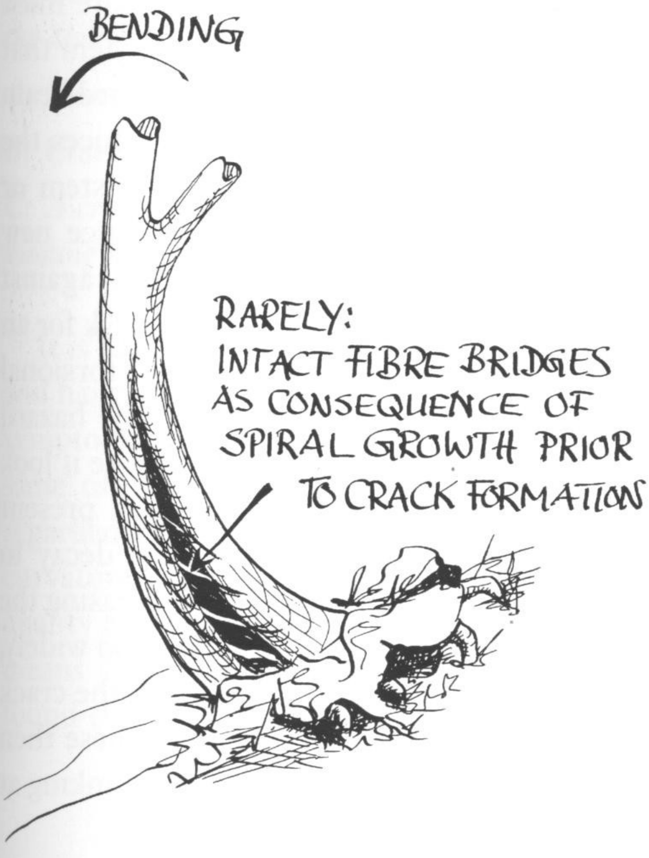


Fig 32. A bowed tree forms a single large hazard beam. A small proportion of such hazard beams fail; they then tend to split all the way to the base, whereas the extent of upward splitting is limited due to the shorter lever arm which produces a smaller bending moment.

Then why, you ask yourself, do the cracks stop extending before the hazard beam has split along its whole length? Fig. 31 supplies the explanation. This longitudinal splitting happens only when a curved beam is subjected to a tensile or bending stress which tends to straighten it; not when its curvature is increased by bending. This effect of straightening the two ends of the beam eventually reverses all the loads, and the beam becomes loaded in a way that increases its curvature. At this stage, although the middle of the split section has been subjected to a transverse tensile stress, its ends are now under transverse pressure. This means not only that no cracks are initiated at the ends of the hazard beam, but also that the longitudinal crack originating from the middle of the beam is immediately arrested at the point of transverse pressure (Fig. 31).

In accordance with theoretical principles, cracking in a hazard beam is always arrested, provided that the beam consists of a localized bend between two straight shafts. Bowed trees (Fig. 32), on the other hand, are often curved along their whole length and the crack-arresting mechanism described cannot then be expected to operate. These continuously curved hazard beams usually split right down to the roots, although the upper part of the crack extends only part way up the stem. This arrest of upward cracking can be explained by the smaller bending moment from the force of wind further up the stem and also because the upper part of the stem is usually somewhat straighter.

Hazard beams are extremely common in trees and their failure must be regarded as unpredictable, even though the proportion of them that fail is small. And yet, it is not unreasonable to think that the hazard beam has some advantage for the maintenance of the species. It reduces the risk of a transverse fracture that would immediately put the stem or branch out of action and thus allows the tree time to produce new branches while the longitudinally split hazard beam battles against decay. The recently cracked hazard beam seldom represents a risk for an individual urban tree, as long as a side-wind does not produce a torsional load. It only becomes hazardous if rot sets in. Occasionally the hazard beam calluses over, producing a nicely closed rib which can make it look harmless. However, in every case the longitudinal crack is still present within the beam and quite often extends outwards to allow decay to develop outwards over the whole cross-section, drastically increasing the risk of breakage (Fig. 33). Even so, if this crack does not gape too widely, the hazard beam will repair itself again by forming ribs (B). If the crack opens very wide the new annual rings roll inwards, although these then become 'stiffening ribs' which reduce the danger of the fibres kinking at the edges of the wound (C).

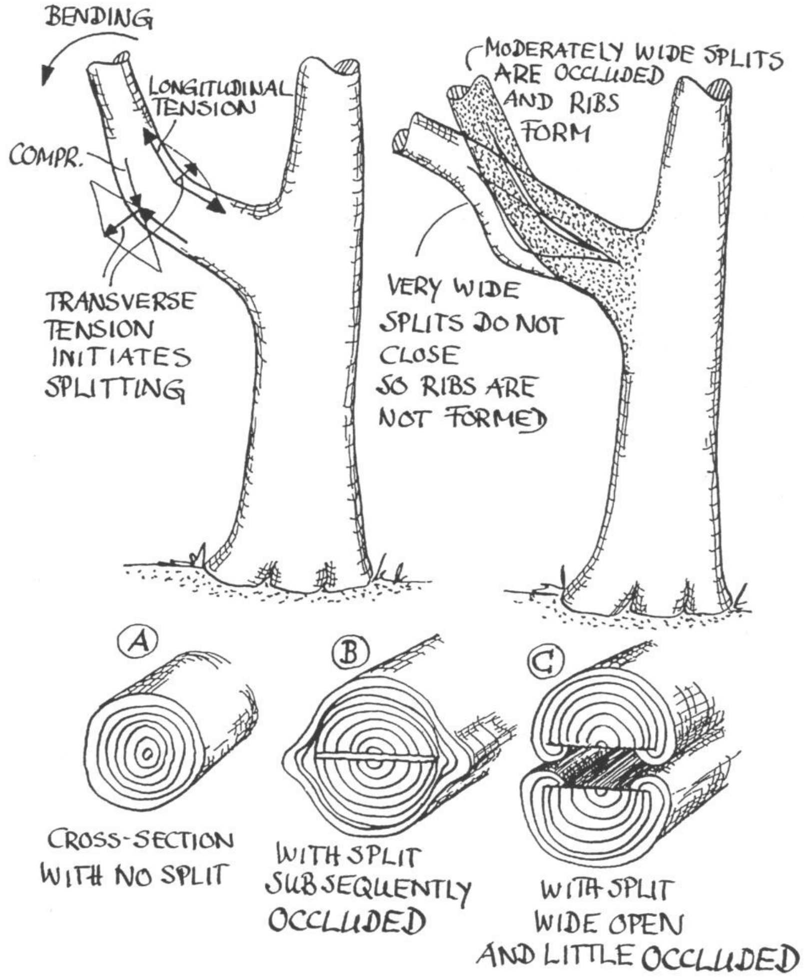


Fig 33. An occluded hazard beam in a Horse chestnut with ribs formed over the diametrical crack.

A: Cross-section with no crack.

B: Cracked cross-section, occluded beneath ribs.

C: A crack which is gaping, but whose edges are becoming very resistant to kinking because of inrolled annual rings.

It is hardly necessary to mention that, once the hazard beam has failed and has then been repaired by rib formation, we can put it on our list of symptomatic and therefore recognizable potential failure points. The same cannot be said for the uncracked, curved branch which can be regarded as a potential hazard beam merely because of its characteristic curvature. It is not feasible to remove all sound parts of a tree that qualify as hazard beams. And it seems clear that such features are by no means confined to any particular tree species, since the authors have found them in almost all species of tree that they have examined.

5.4.2 Root delamination

With its wood fibres running horizontally from the roots and then turning upwards into the stem, the root buttress is another very definite hazard beam, especially in shallow-rooted trees (Fig. 34A). The transverse stresses on the windward side of the stem prime the path of the failure by splitting off a bundle of wood fibres from the stem on the side facing the wind. At first, this bundle acts like a slack rope (B), but it can tighten and thus straighten in a strong steady wind, or with a jerk

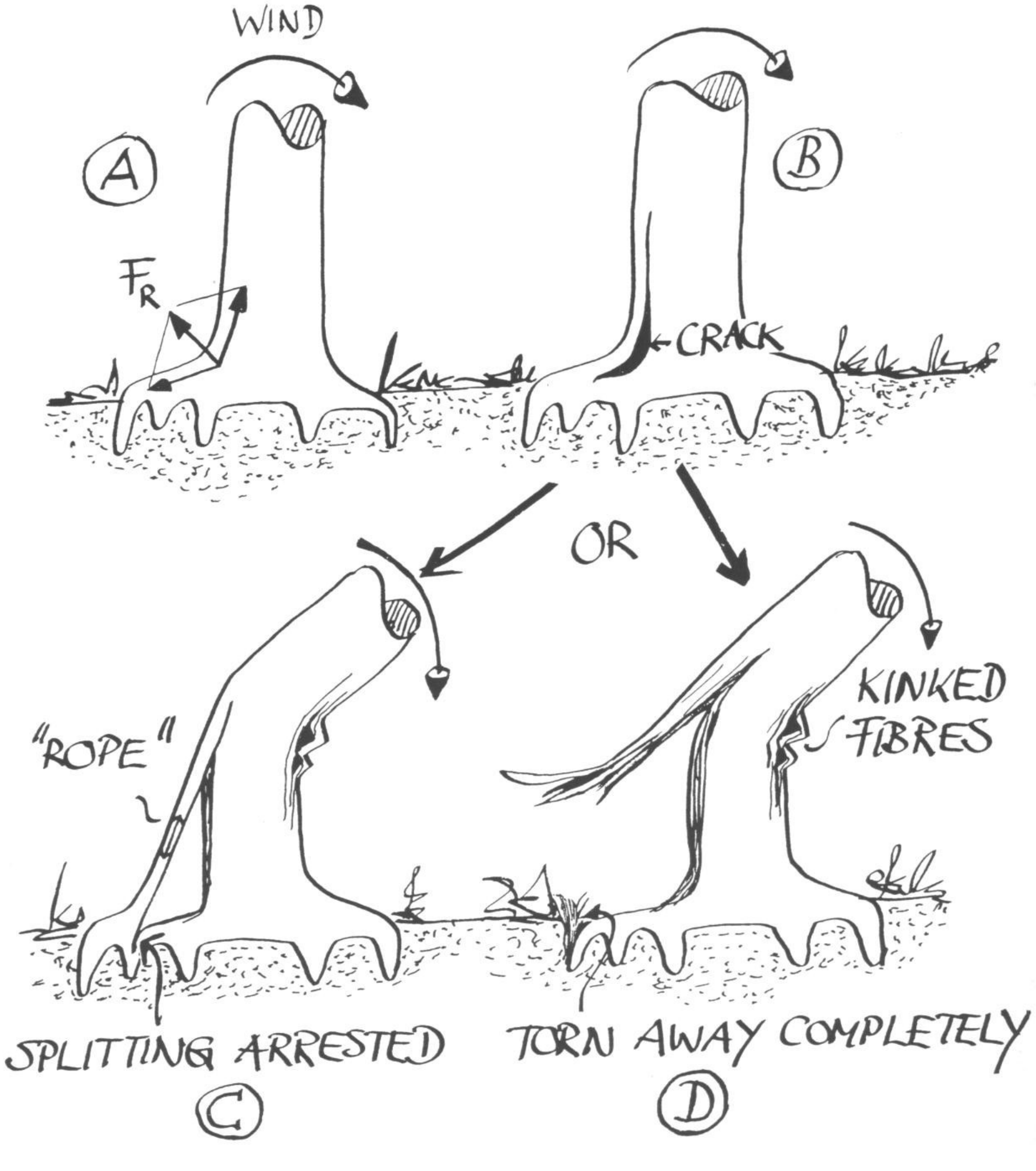


Fig 34. Root delamination as a special case of the hazard beam.

A: How the forces acting perpendicular to the direction of the fibres arise. (F_R = lateral force)

B: A split bundle of wood fibres behaves like a slack rope.

C: As the rope tightens, the tree breaks at a point opposite to the upper attachment of the rope.

D: Alternatively the rope tears away completely at the root flare.

in two successive gusts that coincide with the resonant frequency of the tree. Under severe loading the stem breaks by fibre buckling on the side opposite to its junction with the upper end of the 'rope' (Fig. 34C).

Usually the lower end of the 'rope' terminates at a sinker root that turns the crack downwards. Thus the end of the crack runs into a zone of compression which squeezes it together so that crack stops at this point (Fig. 34C). If it is not the fate of the crack to be captured, so to speak, by one of these sinker roots, the stem above is free to bend so much that it fails by kinking in a gust of wind. As the stem falls, the lower end of the rope of fibre bundles can tear away completely from the upper roots (Fig. 34D). It is also conceivable that the pre-stressed upper part of the root tears away before the stem fails, so that the rope of fibres is catapulted upwards before the stem breaks at about shoulder height with the same end-result. The hazard beam, well camouflaged and concealed in the root buttress, is solely responsible for the longitudinal splitting. On the other hand, once this splitting (delamination) has separated this rope of fibres from the stem, it is the sudden straightening of the rope that finally allows the main stem to break completely by transverse fracture at shoulder height.

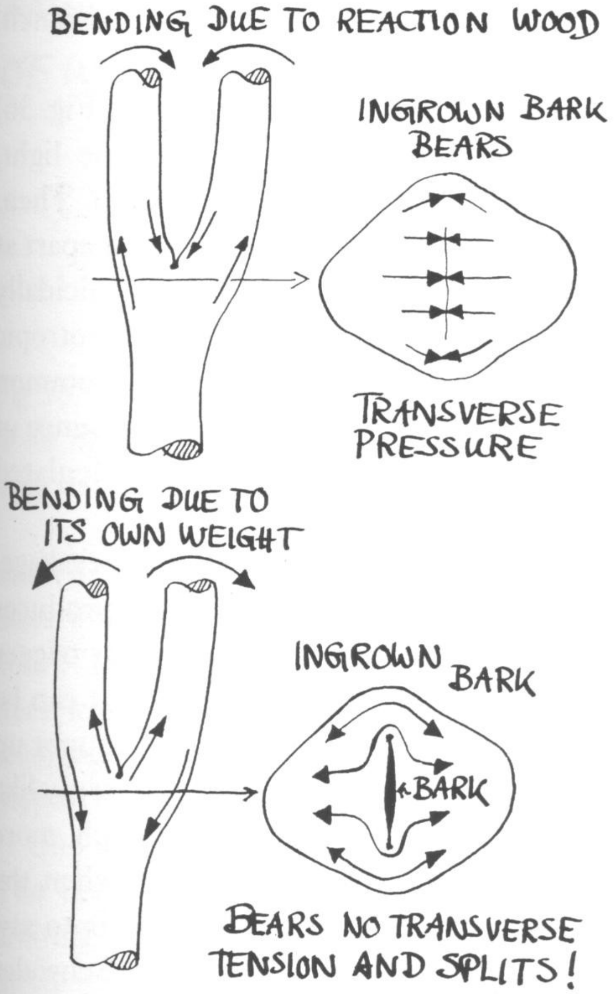


Fig 35. The compression fork, optimized for withstanding the pressure of the two stems pressing against each other, is a structure that is absolutely bound to fail if a tensile load is applied at right angles to the axis of the stems, pulling them apart.

5.4.3 Compression fork fractures

The compression fork has been described in detail elsewhere [37,38,39]. It is optimized for the pressure that the two stems of the fork exert on each other, mostly from the formation of reaction wood. Thus the increasing mechanical pressure of the two stems, which leads to compression fork formation, is due largely to perfectly normal secondary growth thickening. In the best case, the cambium of the two stems unites above the junction so that they become totally surrounded by annual rings that envelope them like a rope (Fig. 35). The resistance that such forks have against being pulled apart under tensile loading comes largely from this external 'welding' since compression forks are not inherently constructed to resist such a force. It is essentially unforeseeable whether a particular 'welded' fork is likely to fail, since the strength of the enveloping wood can vary markedly between species and even between individuals of the same species. Also, the 'crack' which is represented by the included bark is not directly visible from the outside, although pronounced rib formation over the included bark may indicate a weak union. It is also important to look at the 'Chinese moustache' (see below), also known as a 'branch bark ridge', which forms between two members of a fork, as well as between a main stem and a branch. The union may be weak because of a bark inclusion.

The compression fork fracture is further encouraged if (as in Fig. 36) multi-stemmed trees grow away from each other towards the light, rather than staying upright by means of tension wood formation. Then, their growth in thickness acts like a set of wedges to drive them apart at the base of the stem cluster. This means that the cluster is suicidally programmed to fall apart. Sometimes, however, if this phototropic growth is not too strong, a stem cluster can unite to form common annual rings. There is still some risk of splitting due to the presence of the hidden bark-inclusion, but this risk cannot be calculated (Fig. 37).

The simple swaying apart of forks is not the only cause of breakage. Sometimes the swaying is out of the plane of the fork, and this produces tensile stresses on one side of the compression fork that can trigger 'cupboard door' failures (Fig. 38). This is hard to visualise, but can be recognised in practice after the event, if the split stem is still caught up in the crown of a neighbouring tree and remains hanging there truly like an open cupboard door. This cupboard door failure is much more common than one might think, and is most to be expected when the wind is blowing at right angles to the plane of the fork, that is to say, through the fork opening. The retaining belts introduced by Schröder [63] promise to be of use for 'cupboard doors' only when the fork has

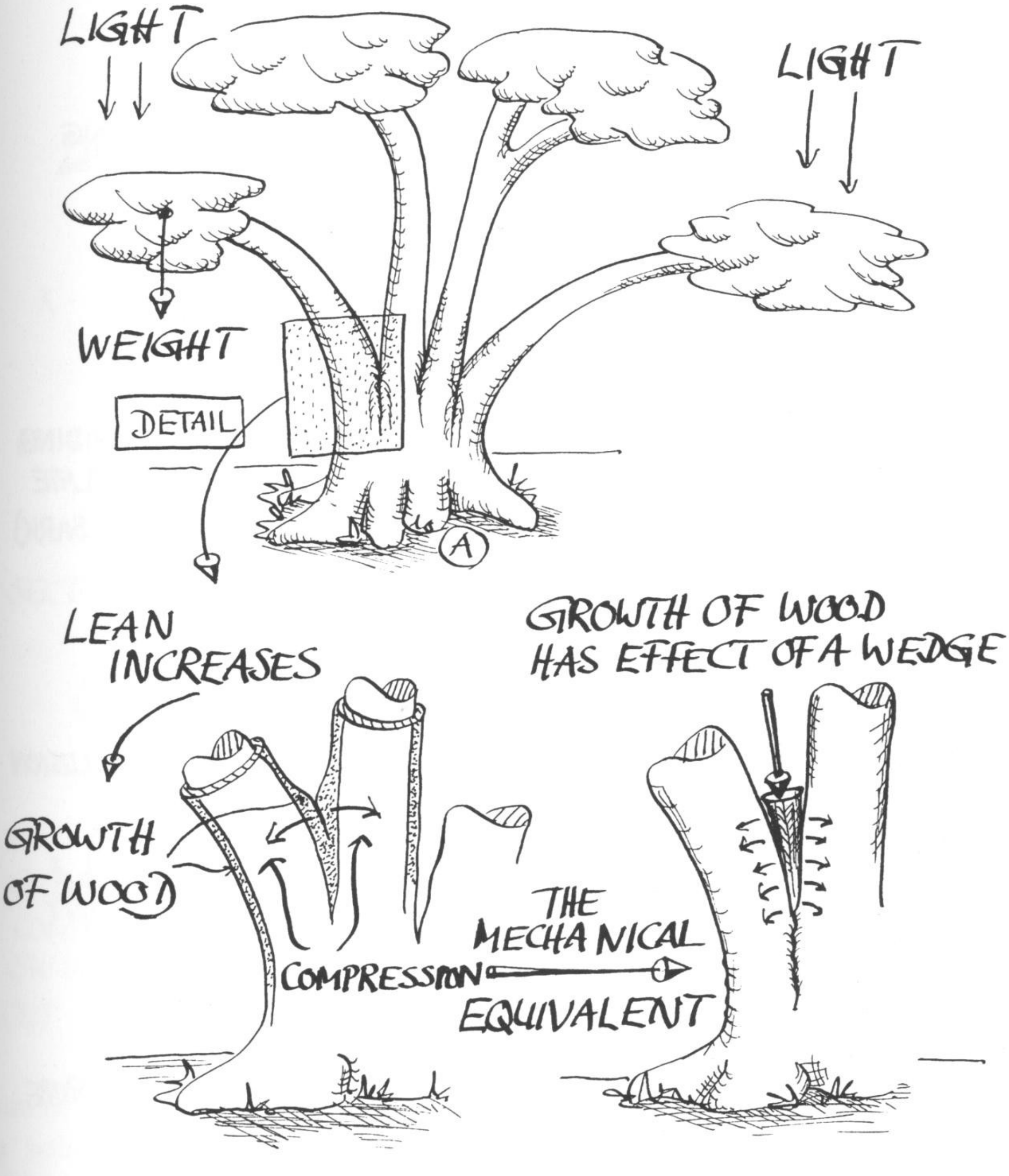


Fig 36. A cluster of beech stems struggling to escape each other so as to get to the light do not form common annual rings but press against each other at their stem bases, which are thus forced apart.

three or more members, but they promise to be very successful in all cases where the risk involves a normal fork fracture without a 'cupboard door'. These belts may also have further potential uses for stabilizing trees with butt rot and gnawed or severed buttress roots as well as for securing dangerously leaning trees that are too valuable to be sacrificed, despite their precarious condition.

One word about the use of bolted rods to stabilise compression forks. The belts tested by Schröder [63] are in many cases a good way of limiting large swaying movements in the two stems. But they must be fitted without any pre-tensioning. If the fork has already split, success

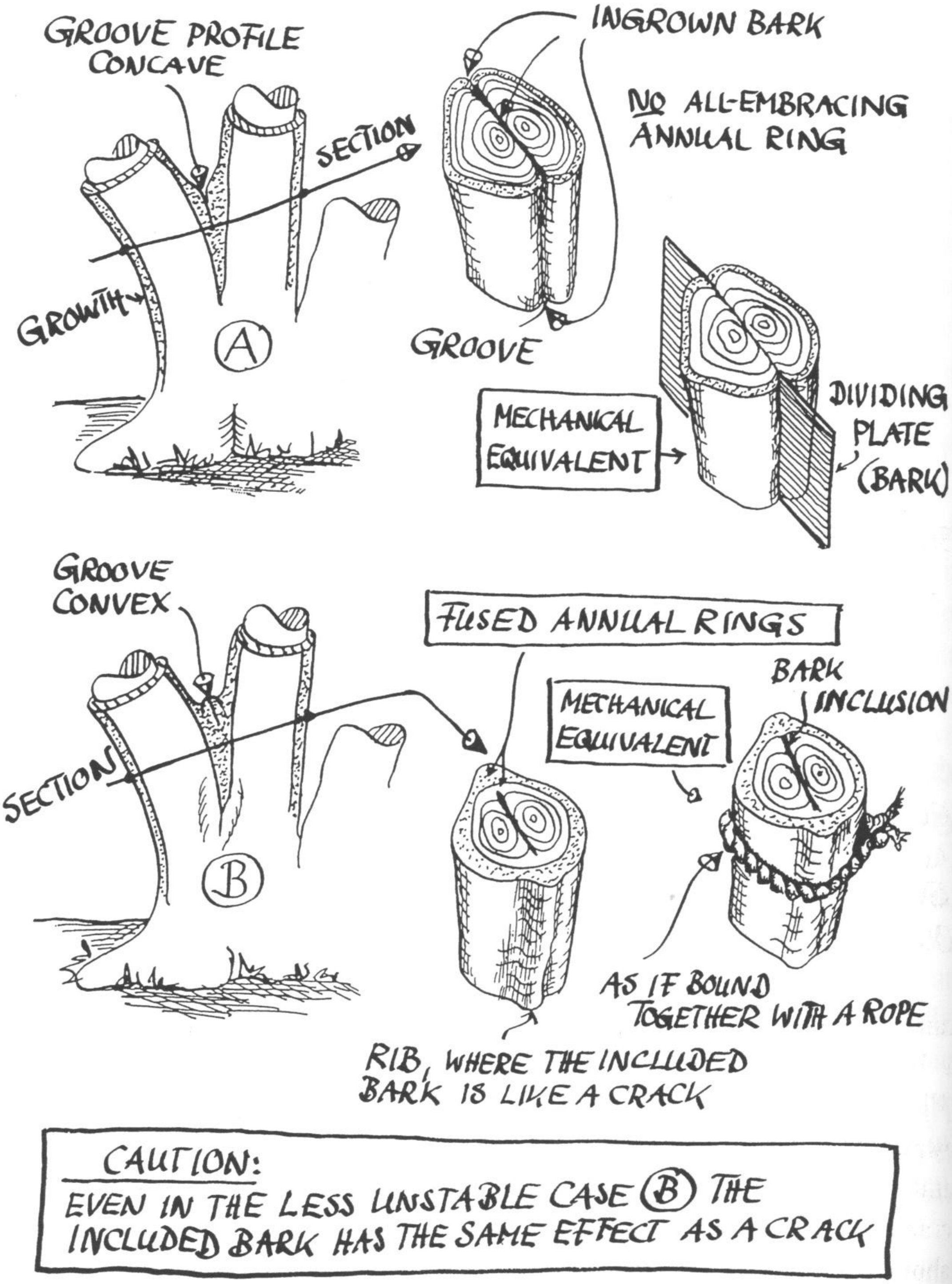


Fig 37. The annual rings of multi-stemmed trees may fuse together, but there are still regions of included bark liable to cause dangerous cracks.

A: Multiple stems not fused together are separated as if by a barrier.

B: Even where some annual rings holding the stems together are present the join is only like a rope encircling the internal crack.

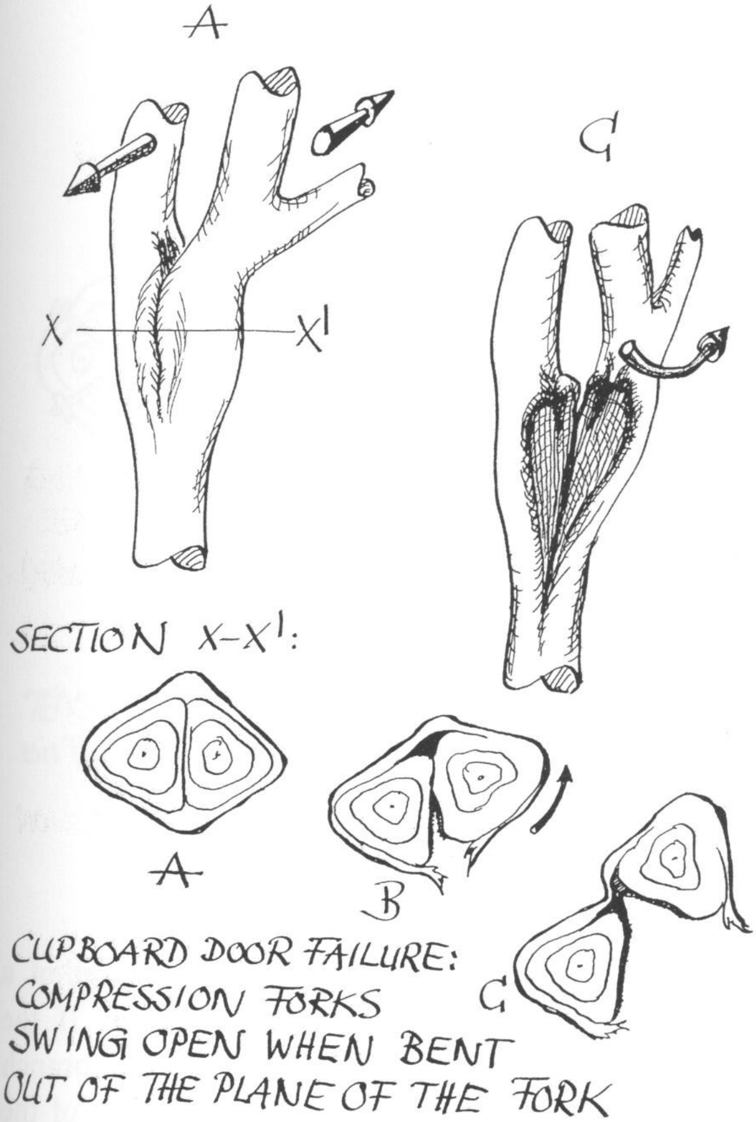


Fig 38. The transverse tension that arises when twin stems are swung out of the plane of the fork can lead to cupboard door failure.

can be achieved only by means of a very low additional cable brace or with a bolted rod inserted about 10 cm above the tip of the crack (Fig. 39). That is to say, if the two stems of the compression fork bend away from each other, the bolted rods work like the fulcrum of a see-saw and the tip of the crack is squeezed together sideways, whereupon the crack loses the inclination to go any further. Since green wood has only about half the compression strength of dry wood, the washers should accordingly have a surface area twice as great as in wooden engineering structures, which is roughly equivalent to a 1.4 times bigger washer diameter. True, this then requires more time for callusing over but it largely prevents the washers from sinking into the wood, which the authors have often seen happen on oak trees. The use of two rods, rather than one, helps to avoid the problem of washers sinking into the wood. As shown in Fig. 39, the rods should be inserted at different angles so as to prevent vertical cracking of the wood between the washers. This arrangement also discourages dangerous cupboard door failure to some extent.

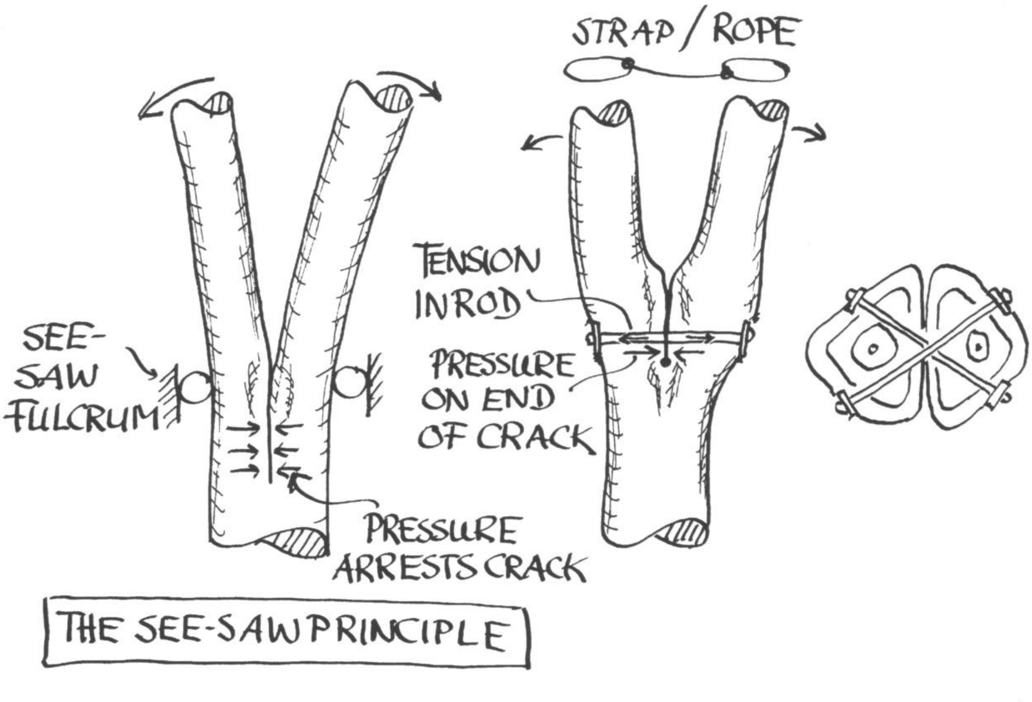


Fig 39. Bolted rods placed above the top of the crack or relatively stiff ties placed low down stop a crack from extending.

5.4.4 Branch failure at a 'Chinese moustache'

The 'Chinese moustache' or branch bark ridge is the bark trace of a fused seam running upwards between the stem and a branch. If the branch angle is steep, there is often included bark between the branch and the stem (Fig. 40), which creates a weak union, as in the case of the compression fork described above. In such cases, wood is merrily laid down by radial growth in the narrow angle between branch and stem. The area of contact between the branch and the parent stem becomes enlarged by mutual callus growth, so that the branch usually looks rather like an eye in cross-section (Fig. 40A). As in the case of a compression fork, any included bark acts like a crack under tensile stress (e.g. from the weight of snow) and can thus trigger a fracture if the junction is not sufficiently strengthened by the annual rings which surround the union and which are common to both stem and branch (Fig. 40B). If this very important external reinforcement is not quite closed on one side, in which case inrolled bark channels can easily be seen on the surface, then the branch can be twisted out sideways in cupboard door fashion (Fig. 40C). Even when the annual rings in the contact zone are fused together as well as they can be, the wood in the fused seam is of relatively low quality. This becomes apparent from the orientation of drying cracks on sawn sections, which tend to form along any fused seams that may be present, and run on the surface straight into the 'Chinese moustache'.

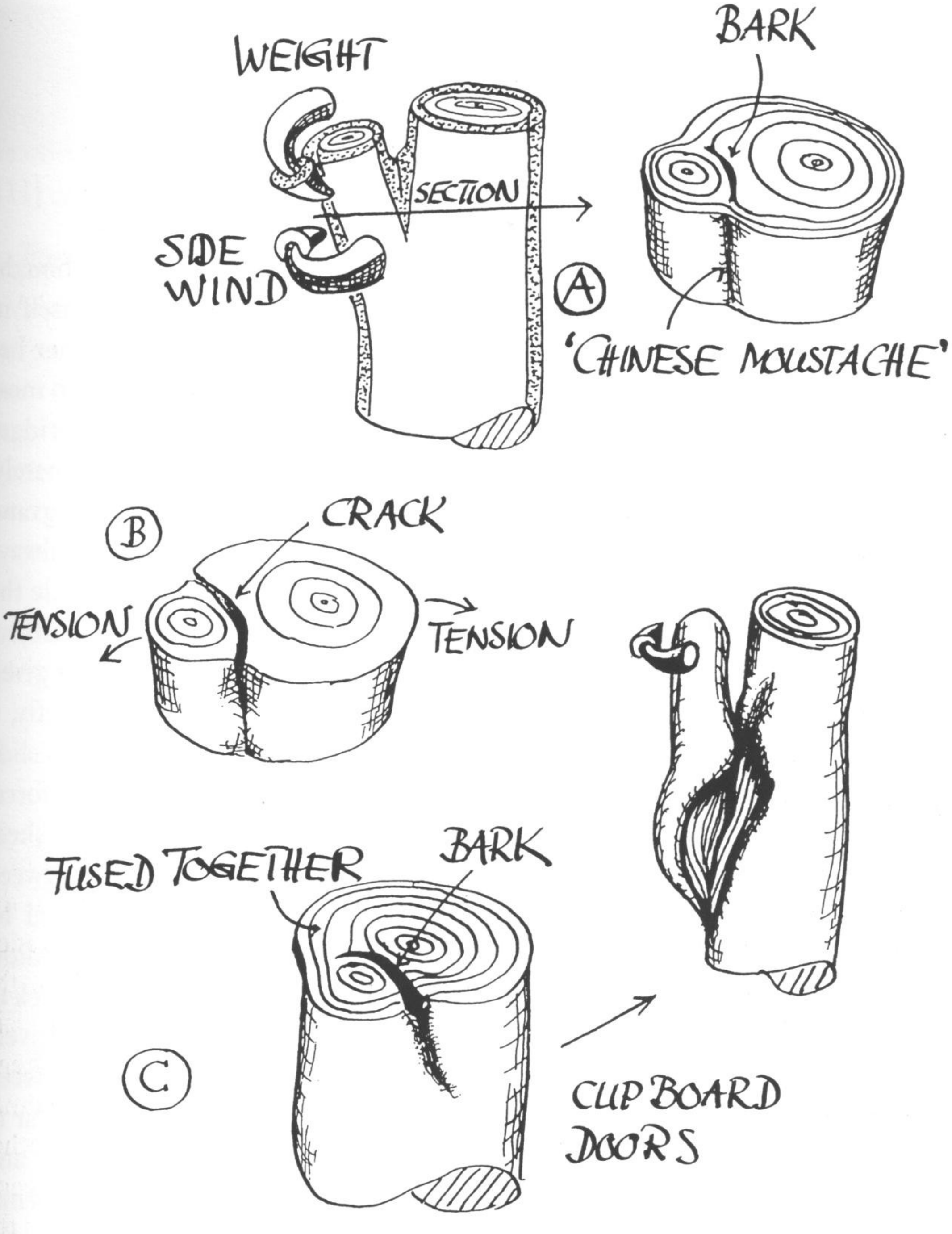


Fig 40. The 'Chinese moustache', like the compression fork, can indicate a weak point if included bark is present.

A: The formation of a fused joint resulting from the pressure that branch and stem exert on each other in the sharp angled crotch as they increase in thickness: three dimensional and cross-sectional views .

B: As the branch pulls downwards, the included bark behaves like a crack under tension and emerges on the outside as a 'Chinese moustache'.

C: 'Chinese moustaches' with included bark are particularly dangerous where the annual rings are fused together only on one side. Such branch junctions are subject to cupboard door failure.

6.0 WINDTHROW: FALLING WITHOUT FRACTURING?

6.1 Mohr-Coulomb's law and the mechanics of roots

Many a fine gardener might hang his head despondently at the thought of a lecture in soil mechanics when he would rather immerse himself in Nature. Don't worry! The authors are fairly sure that the gardener has much more of a 'feel' for the mechanical properties of soil than do most engineers. Incidentally, as Gordon [24] relates, the first English bridges were built purely according to a feeling for mechanics. Unfortunately, there is a widespread and mistaken belief that we always need grand theories to understand or describe things. A good theory is always basically simple and, so with trust in this gospel, we will now tackle the mechanics of soils and of root anchorage. One key term in this subject is shear stress; an explanation of what this is and where it occurs is given in Chapter 13.1, Mechanical concepts: the bare essentials. Briefly, a shear stress is a measure of the tendency for one part of a solid to slide past the neighbouring part. This tendency to slide is the result of a force, and the greater this force, the greater will be the shear stress. The shear stress increases also if there is an increase in the contact force between the two parts of the solid. Resistance against slippage is caused by friction between the surfaces which are sliding or tending to slide. Imagine that two boards are sliding against each other and that a sack of potatoes is then placed on the uppermost board. We know intuitively that the weight of the potatoes will greatly increase the friction between the boards. This extra weight represents a force acting perpendicular to the sliding surfaces (Fig. 41A). We term this force a normal force, and the stress that it imposes on the sliding surfaces is known as a normal stress, represented by the symbol σ_n. The friction that results from the normal stress makes sliding more difficult. It is just the same with soil. In this case we can define a critical shear stress τ, at which two soil surfaces slide over each other when they are pressed together by a normal stress σ_n. When our arrangement of boards weighted down with potatoes reaches this critical shear stress, one board then slides over the other despite being weighed down by the sack of potatoes! The greater the normal stress σ_n, represented in this example by downward pressure, the more effect friction has and the greater difficulty the boards have in sliding over each other. Mohr-Coulomb's law now merely gives a linear relationship, confirmed empirically, which is as follows:

$$\tau = \sigma_n \tan\phi$$

The value ϕ is the angle of shearing resistance, and the slope of the line in Fig. 41B represents $\tan\phi$. (Details about this can be found in textbooks on soil mechanics; for example, by Capper & Fisher Cassie [11] or by Lang and Huder [32].) With increasing normal stress σ_n, the

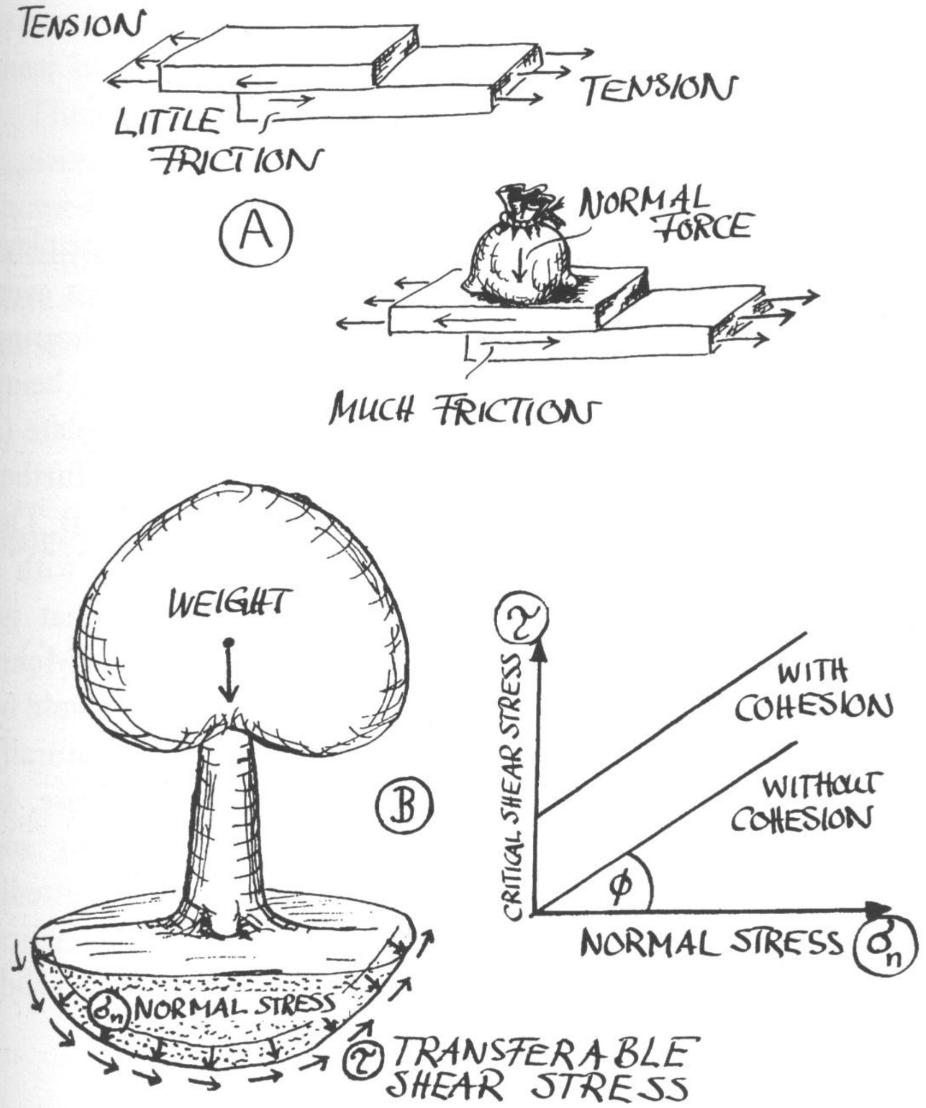


Fig 41. Mohr-Coulomb's Law: this law states that the shearing strength of the soil increases with the pressure on the shearing faces. Thus, the shearing strength of the soil is the resistance of two surfaces to sliding apart.

A: Shearing forces (friction) and normal forces, using two boards as an example.

B: The diagram shows the relationship of the soil's shearing stress failure τ to the pressure σ_n perpendicular to the shearing face. The values τ and σ_n are defined for the root-plate of a tree subjected only to its own weight in the absence of wind. For simplicity, a constant σ_n distribution has been assumed which, of course, is only a very rough approximation.

surfaces slide less and less easily over each other. This truism is illustrated in Fig. 41. But what if the boards are not pressed together at all so that $\sigma_n = 0$, but they somehow get stuck together, that is to say, there is cohesion between them? In that case there is nevertheless a resistance to shearing, even if the normal stress σ_n is equal to zero. We designate this resistance τ_0; in the case of soil, it results from the cohesion of the soil particles. Then Mohr-Coulomb's law becomes

$$\tau = \tau_0 + \sigma_n \tan\phi$$

6.1.1 Shearing of soil and its role in the windthrow of trees

As we shall see later in this chapter, the shape of a tree's root-plate plays a large part in determining the way in which it would be blown over, given sufficiently extreme conditions. The part played by shearing between soil layers differs between these types of windthrow, being simplest to understand when the tree has a ball-shaped root-plate (a heartroot system), which is one of the types discussed in a further section. A simple example showing such a tree is shown in Fig. 41B. The tree loads the ground around the boundary of its root-plate with a normal stress σ_n, the result of its own weight. Provided that no additional pressure forces are contributing to σ_n, we can use the Mohr-Coulomb diagram to calculate the critical shear stress τ, which would be needed to topple the tree. The relationship between τ and σ_n naturally depends on the properties of the material; the soil in this case. In particular, the critical shear stress decreases with increasing soil moisture. Wet soil fails sooner. An explanation for this, admittedly borrowed from popular science, can be seen in Fig. 42. When the critical shear stress τ in the ground is reached, the soil particles begin to slide

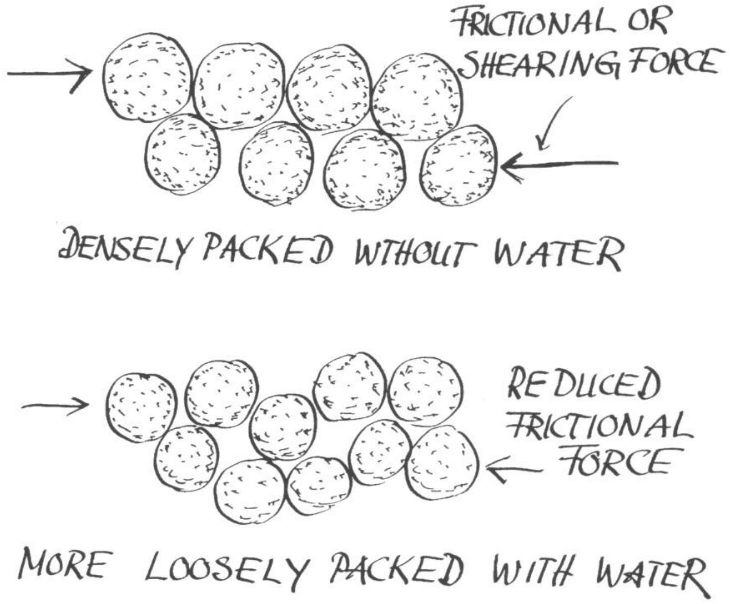


Fig 42. The soil particles stick together more or less like a jigsaw puzzle, collectively giving rise to the soil friction. This is lessened by the lubricating effect of the water between the particles.

over each other. They then bump over each other, so to speak, like two cobbled pavements being rubbed together. Moisture lubricates this movement between the soil particles, making them relinquish their fond fraternal ties. It is all too easy to visualise lubrication by water; anyone who has slipped on a pavement moistened by a shower of rain or perhaps a little slush may have found this out for himself through painful experience! What has happened, in engineering terms, is that the critical shear stress τ has decreased.

The decrease in critical shear stress that occurs after prolonged rain explains why windthrow becomes more likely at such times. Fig. 43 shows how the wind force can overcome the critical shear stress τ. Initially, the wind blowing on the crown lightens the load of the root-plate on the windward side and increases it on the lee side. The frictional resistance on the lee side increases correspondingly but, for the sake of

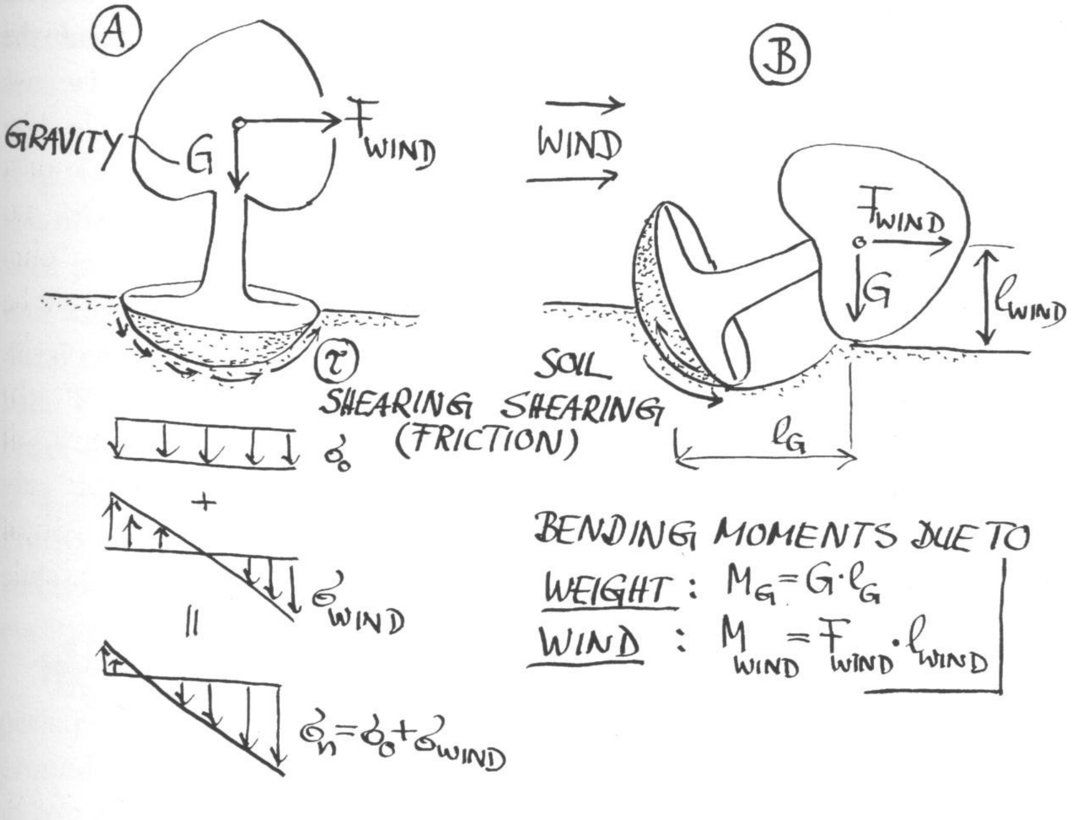


Fig 43. Wind-throw of an idealised tree with a root-plate shaped like an inverted, flattened dome (calotte); the heart-rooting type.

A: The bending load of the wind increases the normal stresses σ_n on the lee side and reduces them on the windward side. Thus the shearing resistance is also shifted to one side.

B: During wind-throw (F_{WIND} = wind force), the shearing resistance of the soil has to be overcome. As the tree falls over the bending moment is reduced and that of the weight increases in its place.

simplicity, we can assume that there is a uniform shear stress τ over the whole of the root-plate. Then, we can readily calculate the maximum bending moment that the wind can exert before the ground's resistance to shearing is overcome. These mathematical models will be demonstrated again briefly later.

It is, of course, only a half-truth to claim that trees depend for their anchorage on the frictional resistance between the root/soil ball and the surrounding ground. There are yet other ways open to the tree for getting a grip on the ground, and these are very thoroughly and graphically described in a review by Coutts [12]. His principal findings are shown diagrammatically in Fig. 44 which illustrates the sequence of events in windthrow. When a tree's anchorage in the ground fails due to a strong wind, it is the soil that begins to fail first. It develops cracks (Fig. 44A) and loses its cohesiveness, at least where the cracks are. Next, the horizontal roots are pulled out of the ground more and more. Here too, shear stresses take effect between the root surface and the

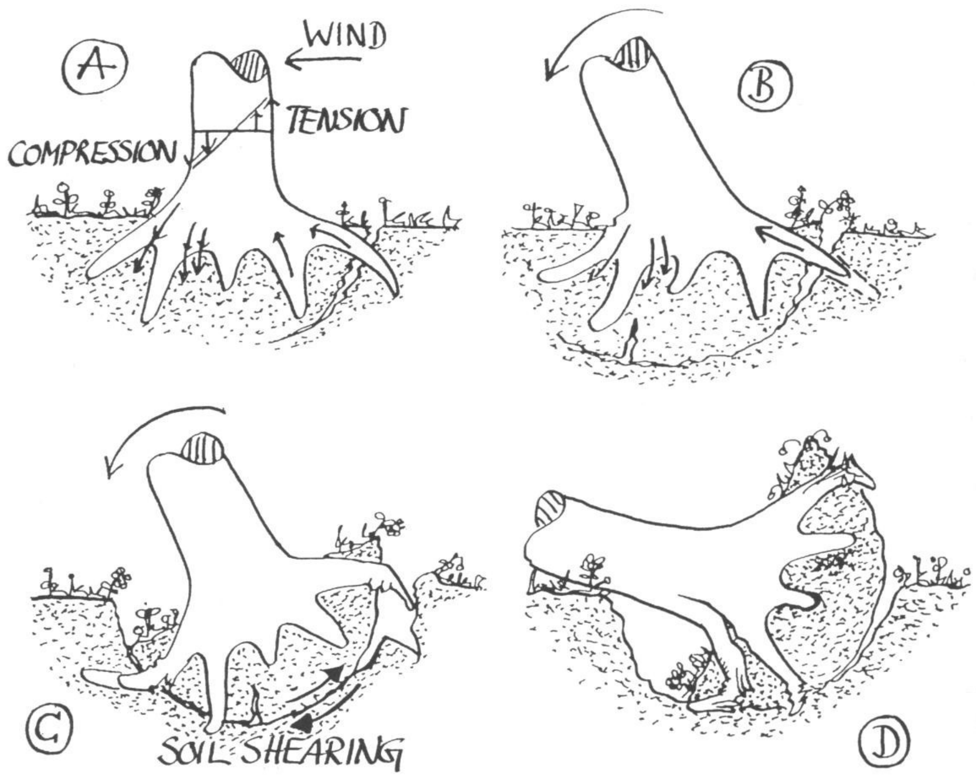


Fig 44. The development of windthrow over time (after Coutts, with modifications).

A: Soil cracks develop.

B: Roots pull out.

C: The root/soil ball slides.

D: Roots break at surface of root ball and/or the butt.

surrounding soil (Fig. 44B), like those between the blade of a sword and its sheath as the sword is drawn. Likewise, the skin of an unfortunate earthworm being dragged out into the light of day by the beak of a ravenous blackbird transfers the same kinds of shear stress into the ground via frictional contact. Windthrow is still incomplete at this stage, and it may indeed remain so if the wind lets up, leaving the tree standing but surrounded by cracks in the ground (A) or leaning slightly with its roots partly pulled out of the ground (B). The tree can regain its anchorage by forming completely new fine roots and, given not-too-thick a stem and enough time, it can right itself again by forming reaction wood which bends the stem back towards the vertical, even though the slightly tilted root-plate still bears witness to the narrowly averted mishap.

Unfortunately, the tragedy sometimes continues after the first two stages of windthrow. The root-plate starts to slide against the surrounding soil when ground friction is overcome, as we have already seen with Mohr-Coulomb's law. So, in a heart-rooted tree, the side of the root-plate away from the wind sinks and the side facing the wind lifts (Fig. 44C). The root-ball rotates in the soil cavity surrounding it. And this often results in root damage: the horizontal roots which have already been pulled out of the ground to some extent do not rotate as an intact unit with the root-ball. Instead they bend between their relatively flexible distal ends and their bases, which are held more rigidly within the root-ball. This can lead to breakage as the bending loads increase, and the break quite often extends as a rootstock fracture running up the stem (Fig. 44D). As the tree leans more and more to one side, its centre of gravity moves away from the centre of the rootstock and introduces an additional tipping moment. This increasingly adds to the wind load and eventually brings the tree over.

The giant is prostrated; in falling was he mighty still! Only now, perhaps, can we fully appreciate that the anchorage of a tree in the ground is a stroke of genius on the part of Nature. Here we have the weight of a tree, with all the bending forces from the wind acting on it, and supported by the yielding ground which has no more inherent resistance against tensile stress than its feeble cohesion can offer! Even in this age of modern engineering science, this must surely draw admiration from us. The stem base ramifies into a multitude of the finest rootlets, each of which in turn transfers its load to a particle of soil, conveying to it a tiny fraction of the wind load introduced from above. To understand all this in exact detail will surely be beyond human comprehension for the foreseeable future.

There are different levels at which we can try to elucidate the mechanics of the soil-root complex. Attempts to create detailed theoretical models of it are beyond our capacity, but we can understand it in more general terms. Thus, we can view it as an elaborate composite material, analogous to reinforced concrete, with tension-resistant roots (steel) and pressure-resistant ground (concrete). It distributes stresses evenly, according to the *Axiom of uniform stress*, and it has an incredible capacity for self-repair and healing. This simple description is all we need for practical purposes, and for applying the VTA principle. And yet we could if necessary carry out the most up-to-date computer simulations and analysis of field data. Our reason for keeping things simple is that a system as complex as this becomes just an academic brain-teaser if we try to explain it entirely by concocting theories bereft of everyday experience. On the other hand, if we were to fall back entirely on real life experiences and observations of nature, we would be unable to recognise all the relationships that the problem represents. If, therefore, we want to describe this mechanical phenomenon effectively, we need to draw upon both the knowledge of the seasoned field observer and the modern computer-based principles of biomechanics which are gaining increasing acceptance in technical practice [39].

6.2 WINDTHROW OF DIFFERENT TYPES OF ROOT SYSTEM

6.2.1 Shallow rooters – they topple like coat stands

So far we have dealt with an ideal tree, as shown in Fig. 43, whose root-plate is shaped like an inverted calotte (i.e., a flattened hemisphere) and which can fail by a rotational movement, as shown in Fig. 44. Let us turn now to the poorest of the poor, the shallow rooter. Of course every forester knows that spruce trees are the most frequent victims of the wind. But why? In Fig. 44 we have seen the multiple ways in which the root-plate can anchor itself in the ground and how the storm overcomes these one after the other. If a tree's root morphology does not allow it to take advantage of every one of these anchoring systems, it will fall more readily than others that are better equipped. Anyone who keeps his trousers up with belt, braces and safety pin loses them less quickly than someone who goes around with the whole outfit relying on a loose button. Unfortunately, spruce trees don't seem to adopt a belt and braces approach, and this becomes clear when we study the way in which they fail (Fig. 45).

As in rotational failure, the ground is the first thing that fails in the windthrow of a spruce tree. Thus, the soil cracks (A), and then, as

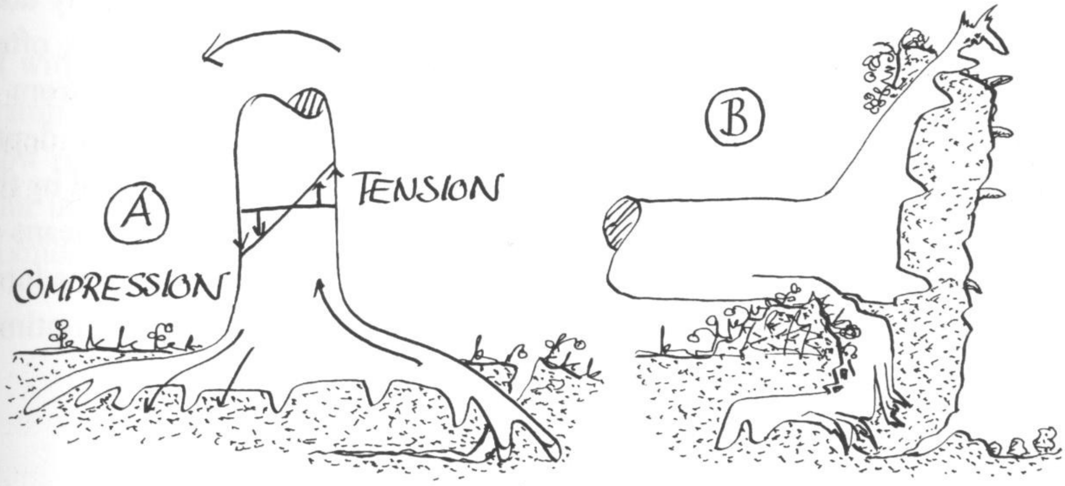


Fig 45. Wind-throw of a shallow-rooted tree.
A: Soil cracks develop and roots slide.
B: The soil plate tears out and tips over with almost no shearing.

before, it can be expected that the roots will be drawn out of their anchorage. The difference in this case is that the flat and thin root-plate tends to hinge over quite easily (B), with hardly any rotational movement. This means that the phase shown in Fig. 44C, where a large shear stress is conducted into the ground, is almost entirely lacking. Why? Because of Mohr-Coulomb's Law! The ground transfers shear stresses only if the sliding surfaces are pressed against each other, like the two boards sliding over each other so enthusiastically in Fig. 41A. If the root-plate lifts, its underside becomes detached from the ground beneath, the surfaces don't rub against each other – so no friction! This tendency to fail through hinging over, like a coat stand on its base-plate, makes the shallow rooters particularly susceptible to wind loading. Very often the central area of the root-plate of such a tree lies loosely in the ground, and any live sinker roots are confined to the very outer edge of the root-plate, thus conducting a load into the soil in a ring. This is rather as though our coat-stand were secured weakly to the floor by some screws around the rim of its base-plate. For a shallow rooter, the one and only way out of the problem is to form a long lever arm with a stiff buttress, i.e. a large root-plate. But a problem still exists because, wherever a horizontal root joins the stem on the windward side, a hazard beam lurks within, nursing a desire to split (Fig. 34). The greater the bending stress in the root junction, the greater too is the danger of splitting, especially in trees with weak rays like spruces and poplars. All that can help the tree to cope with a large root-plate of this kind are its buttress roots [37,39]. Lombardy poplar, which regularly develops such roots on the windward side when growing on high water-table sites, is very resistant to root delamination. Thus, if it does fail, it usually does so because extensive butt-rot leads to hosepipe kinking (Fig. 17), often when the buttress roots are quite thin-walled. Therefore, from a biomechanical point of view, a poplar with restricted rooting depth seems to be better anchored than a spruce. This view is confirmed by the marvellous way in which tropical trees balance on wet land by means of their giant buttress roots. If your biology or your living conditions force you to adopt a shallow-rooted design, then buttress roots are the optimal structure.

6.2.2 Heart rooters – every possibility utilized

We have already examined the case of the heart-rooted tree in connection with shear stresses in the soil. When this sort of root system is well developed, it is particularly stable, as if a kindly gardener had caringly planted it, complete with a well formed root-ball. Such trees often remain stable, even when large and old, because they can be uprooted only by rotational movement (Figs. 43 & 44) which must overcome the considerable amount of friction between the root-ball and the surrounding soil. The maximum frictional effect is achieved by the kind of root-plate that we have described above for the ideal tree; i.e. one that forms a slightly flattened hemisphere, rather like a calotte.

Of course no system is so perfect that it is entirely without snags. Thus, since this type of tree depends so much on ground friction for its stability, it becomes vulnerable if this friction is severely reduced by prolonged rain etc.; i.e. when the critical shear stress between the root-ball and the surrounding soil is reduced. If this happens, then windthrow can yet again walk away victorious. In constantly wet soils, where in any case the lack of oxygen restricts the ability to form a ball-like root system, a shallow widely spreading root-plate is a better safeguard against windthrow. It can also save on materials so that, in the case of the Swamp cypresses, there is enough left over to develop pneumatophores. One is tempted to speculate that, in such species, there is an evolutionary advantage in the tendency to form a wide flat root-plate. The poplars of the Rhine flood meadows also produce shallow, wide root-plates that act by being securely attached to their stems via the 'tension straps' of the buttress roots.

Apart from its tendency to slide over in wet ground, the heart-rooted tree can be regarded as the king among trees as far as the mechanical properties of its root morphology is concerned. This has been demonstrated by Andreas Baumgartner's computer simulation using the SKO method, as explained elsewhere [39].

6.2.3 Tap-rooters – the fence post method

As with heart-rooted trees, you will not find trees with tap-roots in a swamp. Apart from the fact that waterlogged soil holds too little oxygen to allow roots to grow deeply, a tap-root would have very little mechanical value in such wet conditions. This is why swamp trees like mangroves rely on spider-like spreading roots for their support. Similarly, on soils that are

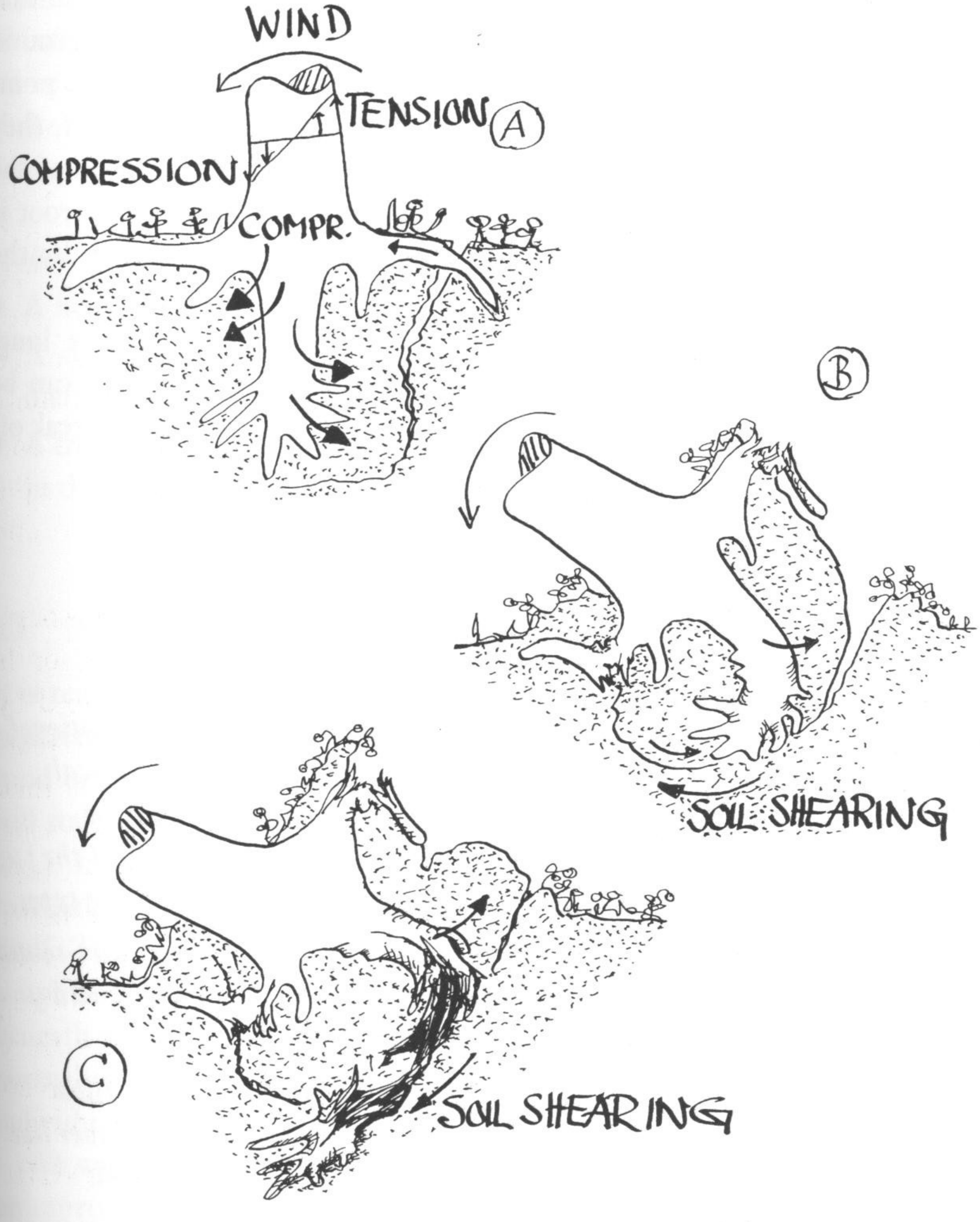


Fig 46. Wind-throw of a tap-rooted tree.

A: Soil cracks develop.

B: Depending on the number of lateral roots, a root ball, which can vary in size, rotates and comes out of the ground.

C: A long tap root may break at the surface of the root ball.

often frozen, trees such as spruce tend to lift and stretch out their 'legs' as far as possible in order to live. It is in freely drained soils that tree species with the ability to retain tap-roots in maturity are able to display this morphological trait in all its glory. It is then that they have the great advantage of being able to exploit the merest trace of water even at great depth, and the tap-root then anchors the tree like a fence post.

The anchorage of a tap-rooted tree has its limits like any other system, and Fig. 46 shows the stages by which this anchorage can fail. The mechanism is easy to envisage: force a steel tube into the ground and work it like a crowbar. Soil cracks very soon form close to the point where the stem emerges from the ground and, if the root is stiff, they can also form near the deeper half of the tap-root on the lee side of the tree (Fig. 46A). If there are a lot of lateral roots and if the tap-root is quite flexible, the failure is more like the rotational type shown by the heart-rooter (B).

An interestingly different kind of failure can occur when a long, respectably stiff tap-root bravely holds out against the wind. It can be wrenched out like a crowbar, which is an unlikely event, or it can break off

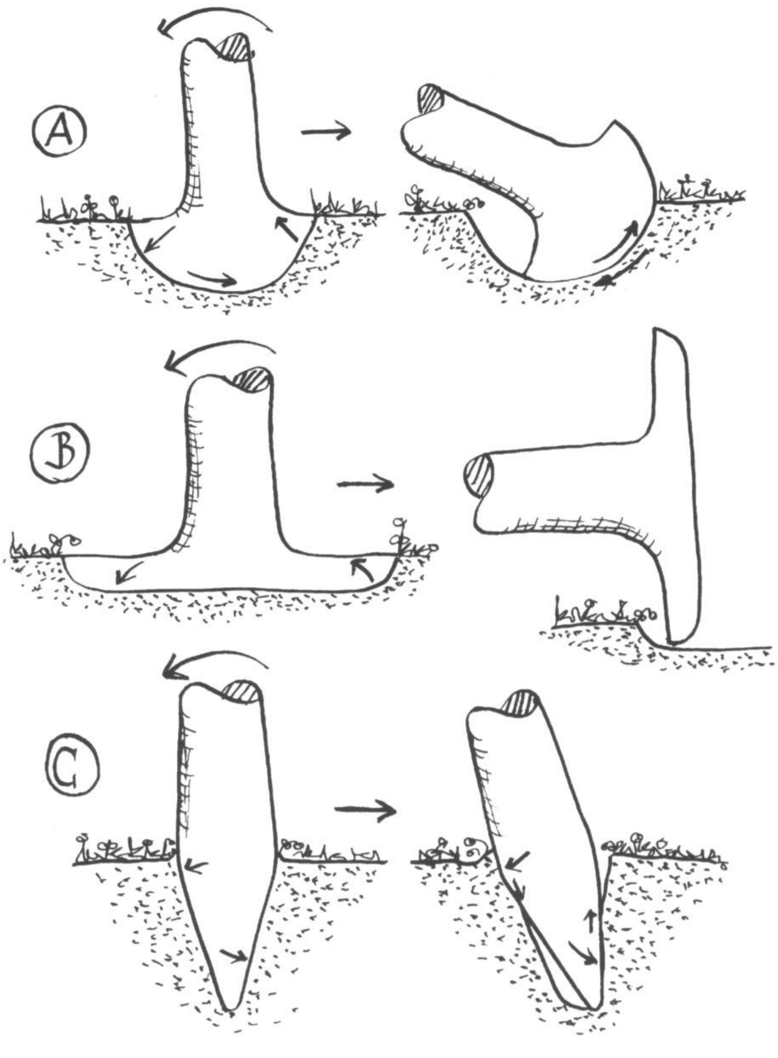


Fig 47. A simplified, notional, soil-mechanical model for the behaviour of the three rooting types.

A: The heart-rooted tree rotates in a socket.

B: The shallow rooter tips over like a coat stand.

C: The tap-rooter is levered out like a crowbar.

somewhere near the boundary of the root-ball. This releases a considerable amount of bending energy and so the tree may fall to the ground with correspondingly great force as soon as the tap-root breaks. This tends to happen especially when the root-ball is too small to provide much ground friction, which would retard the windthrow enough to allow the tree to tilt over relatively slowly. We have demonstrated the retarding effects of ground friction in tests where we pulled urban trees over experimentally. Some of these trees even remained standing at an angle of 45° after the load had been removed. Ground friction sufficient to hold up a tree in such a leaning position tends to occur with rotational failure; a shallow rooted spruce would be more likely to fall once its anchorage was damaged.

A short, much simplified summary (Fig. 47):

- A heart-rooter falls over as the root-ball rotates, as in a hip joint.
- A shallow rooter falls over like a coat stand, after the root-plate is dislodged.
- A tree with a well developed tap-root falls over like a fence post stuck in the ground.

6.3 A SIMPLE WINDTHROW MODEL

It is really quite difficult to construct a simple model, as soon becomes apparent if we take into account the influence of a one-sided load due to wind or the weight of an asymmetric crown. For present purposes we will start with a straight tree whose crown is initially symmetrical (Fig. 48A). In the absence of wind-loading the only thing that presses the root-ball into its bed is the weight of the tree, including the root-ball itself. The pressure is not equal everywhere, of course, as is shown in simplified form in our diagram. Rather, it will be greatest directly beneath the stem. We will not worry about the exact distribution of the normal stresses which, in any case, may depend on the morphology of individual roots.

We will just confine ourselves to a simple theory which is admittedly an approximation, but whose simplicity makes it transparent enough for us to keep sight of the point at which truth finishes and fantasy begins. Thus, we will assume that the normal stress is uniformly distributed, and we will also suppose the distribution of bending stresses to be linear, which can equally be regarded as an approximation. According to Mohr-

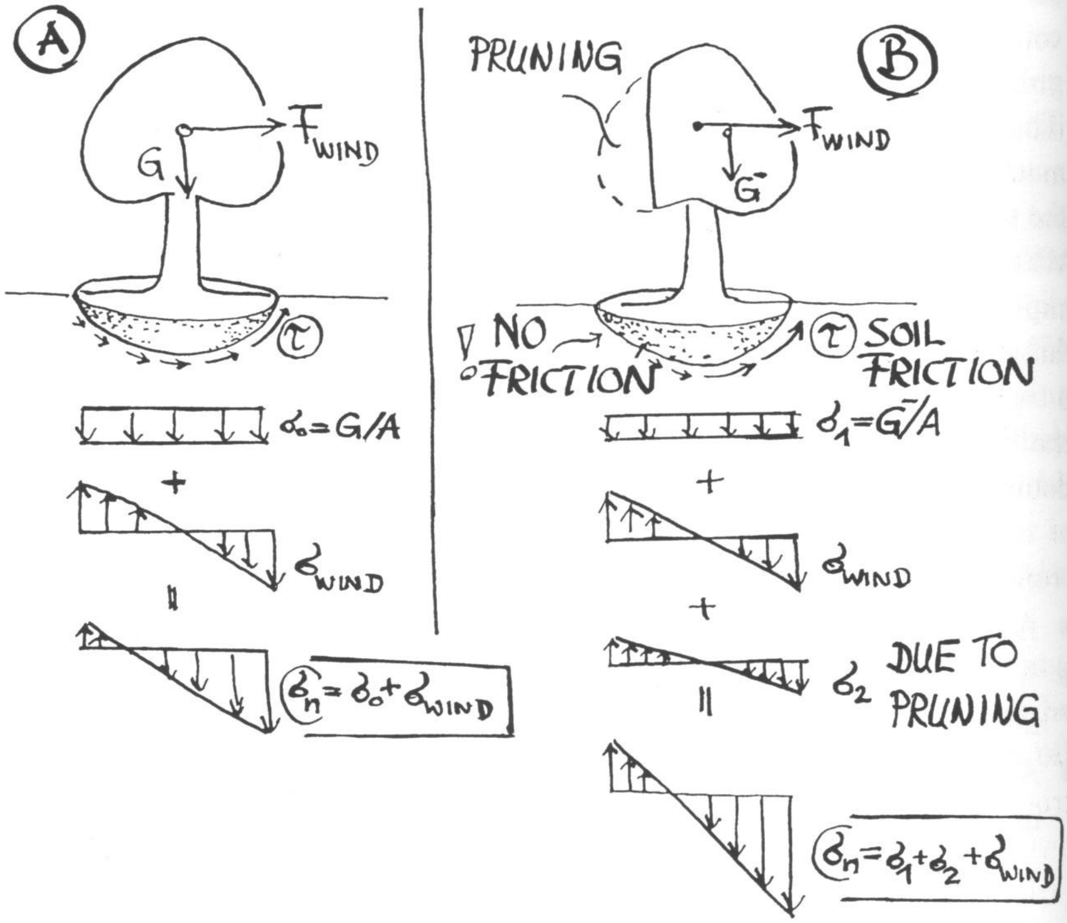


Fig 48. The effect of a one-sided crown on anchorage.

A: A symmetrical crown with wind load, the soil friction reduced on the windward side. (A = cross-sectional area of the circular root plate)

B: A one-sided crown; the soil friction is very greatly reduced by the wind load and asymmetric crown.

Coulomb's law, the friction will be uniform throughout the boundary region of the root-ball, provided that there is a simple weight loading and that σ_n is equal to a constant.

Unfortunately, we run into problems of soil mechanics as soon as there is the slightest bending load from whatever source. If, for example, we are dealing with a lopsided crown or a leaning tree, bending stresses are immediately superimposed. The root-ball is raised a little on one side and depressed a little on the other. This means that, according to Mohr-Coulomb's law, the ground friction is reduced on the lifted side and increased on the other side, which together would make the tree more likely to blow over because the area of the shearing surfaces has been reduced. Normally, the tree counteracts this by forming more and longer roots where the soil is weak. Of course, the wind can also introduce severe bending stresses which shift the ground friction, and therefore the distribution of the critical shear stress τ, drastically to one side. But you are only really reduced to tears if you have to contend with a crown that has been cut back on one side and with a wind rotating the tree in the same direction. The crown shape and the wind then combine forces to lift the pruned side of the crown, so reducing the normal stress σ_n and indeed even perhaps transforming it into tensile stresses (i.e., lift!). When this happens, the effective sliding surface between the root-ball and its bed in the ground is so severely reduced that the tree blows over far more easily (Fig. 48B). The authors heard of a case where a willow on a lake-side was flat on the ground and pointing away from the water the very day after having been pruned on the side facing the lake. No doubt the tree had enough trouble standing upright anyway, on account of the high soil moisture content on the lake side, so that cutting the crown back finished it off.

Put simply, the message of this apocalyptic preliminary deliberation is as follows:- *soil gives way by shearing when it is subjected to a critical shearing stress, and this stress depends on the compression stress affecting the sliding surfaces and on the characteristics of the soil itself (cohesion, friction angle)*. So, the ground friction becomes less if the compression stress on the sliding surfaces decreases. Anyone who removes the branches from one side of a tree not only introduces additional bending loads via the stem into its zone of anchorage but also compromises the anchoring area on its pruned side. If you carry a bucket of water in each hand, your legs are loaded equally. If you put one bucket down, one leg has to bear more than the one that has been relieved of its burden and is transferring less normal force into the ground. It is important to realise that a particular problem arises in soil mechanics when tree root systems are involved. This comes from the effect of wind loading, any change in which will alter the friction between the root-plate and the surrounding soil. The effect of this is that the shear stresses that are transmitted to this region – and therefore also the shearing strength – become non-uniform.

In view of this complication, it may seem that we have made an over-simplification in assuming for our model that ground friction is uniform over the boundary of the root-ball (Fig. 49). Despite this, such assumptions have a thoroughly respectable textbook usage [64], since the results are generally very good at describing what happens in practice. Thus, we are able to calculate the maximum possible forces, better described as torsion moments, which act against the tendency of the tree to tip over. These models will be thoroughly researched for trees in the future.

The following observations are based on a plausible *Axiom: The tree is a chain of links of equal strength*. We can think of the stem collecting the

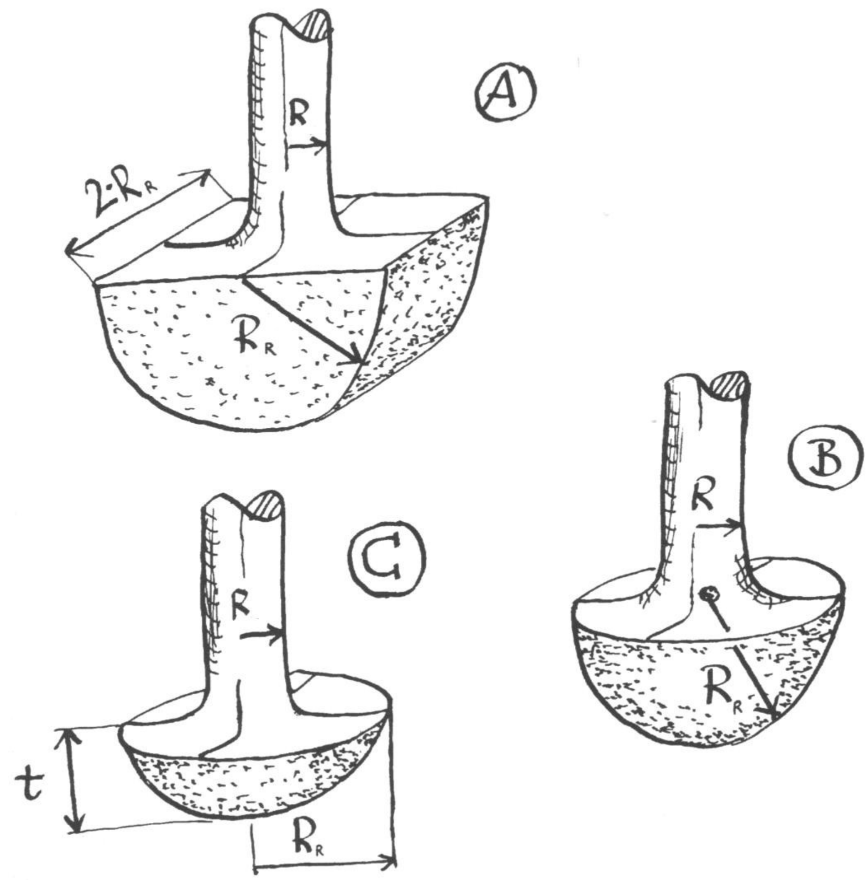


Fig 49. A simple model for estimating soil friction moment loadings when the tree is being pushed over using the method of Scott.

A: The roller model.

B: The hemispherical model.

C: The calotte (flattened dome) model.

bending loads that arise in the branches, conducting them downwards into the roots and redistributing them through a brush-like root structure that finally passes the load into the ground. (Some of the wind energy is dissipated within the tree, especially in the crown, but we can neglect this for present purposes.) The whole process is thus reminiscent of a yacht in a very, very viscous lake with the root-plate as the boat's hull. In an unpruned, healthy tree the relative areas of the crown (sail), stem cross-section and the root-plate will be perfectly matched to the wind load as 'measured' by the tree. It would be life-threateningly extravagant for the tree to treat itself to an impressively thick trunk beyond the needs dictated by the windiness of the site or the size of its crown. The root-plate must also be appropriately designed; too much economy here would be like trying to set weightlifting records while wearing stiletto heels. This truism of structural balance is beyond question, because it represents the very principle that a tree's growth is adapted to mechanical requirements. It also explains much about the success of evolution in trees! A single oversized link in the chain would be a wasteful structure which would not increase the tree's overall load-bearing capacity. Conversely, an even distribution of the excess material present in the outsize link would benefit all links in the chain. But enough of that – trees are unaware of man's vanity, and thus sensibly dispense with pretentious structures.

The philosophy of a chain with uniformly strong links is illustrated in Fig. 50. The wind load is often described by the equation:

$$F = \frac{\rho}{2} v^2 A \cdot C_w \qquad \textit{where} \begin{cases} F = \textit{wind load} \\ v = \textit{windspeed} \\ \rho = \textit{air density} \end{cases} \quad \textit{and} \begin{cases} A = \textit{Crown area} \\ C_w = \textit{a constant} \end{cases}$$

but this does not provide any usable results as far as trees are concerned [52], particularly because the windspeed, the wind-dependent crown area and the value C_w are in practice unknown. Attempts to insert a range of hypothetical values simply do not provide a basis for making precise or reliable statements. If, despite this, anyone wants just to make an estimate in order to get a feeling for how these things happen, it is fairly easy to estimate the target area of the crown. There is no need to spend time trying to calculate the exact cross-sectional area of the complex crown,

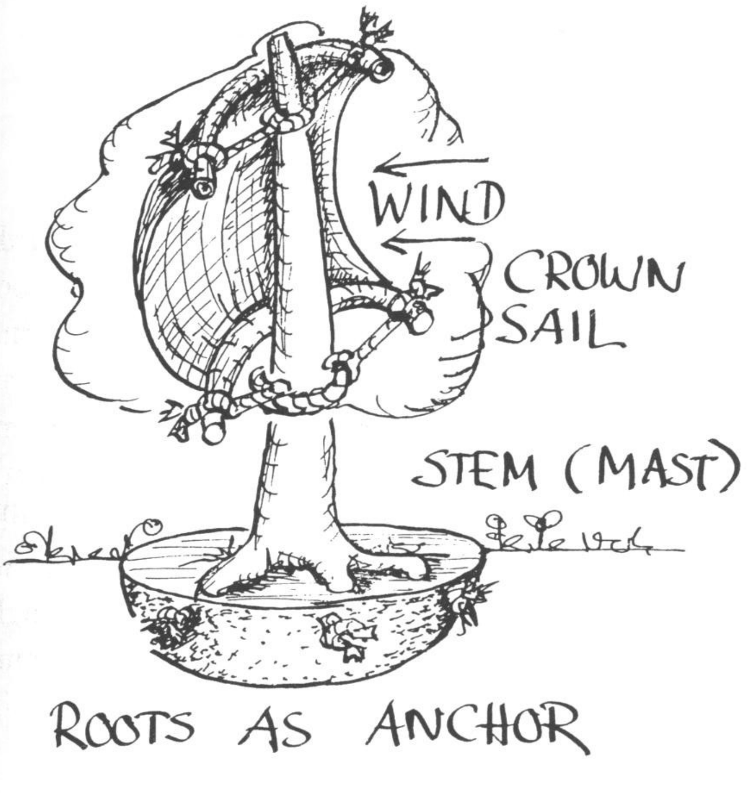


Fig 50. The tree as a chain of equal links. The incoming wind load is transferred via the stem into the root ball and from there into the ground.

which will in any case change shape with the next breath of wind. A simple geometrical approximation will suffice. If a rectangle is chosen, the intersection of the diagonals will mark the height of the effective lever arm, so that the bending moment from a given wind force could be calculated. Unfortunately, however, the wind load cannot be estimated accurately enough for practical purposes by this means, as will be demonstrated later.

As it happens though, there is someone on this imperfect world who is able not only to estimate the wind load accurately but who can measure it exactly – *the tree* itself! Its ever watchful cambium lays down wood wherever it is needed, by reacting both to the overall windiness of its surroundings, and the periodic oscillations in windspeed; i.e. gusts. This adaptation of stem-form is a record of past wind loads.

No tree in the world would be foolish enough to lay down more material than it absolutely needed! Bearing this mind, we recommend the following procedure: *forget about estimating the wind load and just measure the girth of the stem!* You don't need a computer for this, by the way; just a tape measure. Once you know the girth of the stem, you then deduce the diameter of the root-plate. *The breaking moment of a healthy, undamaged stem is the maximum wind load that it can withstand. According to the principle that the tree is a chain of equal links, the root-plate must fail at the same bending moment.* On this basis, an assessment procedure for assessing tree stability is being developed at the Karlsruhe Research Centre. This could run as follows:

Procedure for evaluating a tree's stability:

1. Measure the stem's girth and calculate the stem radius R above the root buttresses.
2. Calculate the radius that the root-plate radius needs to have, using the VTA diagram (Fig. 51), the basis of which will be explained in the next section.
3. Dig at points around the base of the tree, at a distance equal to the calculated radius. If sound roots of any substantial diameter (say, 4 cm) are found all the way round, there then there are no discernible grounds for doubting the stability of the tree.
4. If nothing is found there, or only rotten roots, dig a little nearer to the stem until eventually sound roots are found. If part of the root-plate has been effectively lost due to decay, it is necessary to find whether the remaining area still provides an adequate safety factor; i.e. are there sufficient mechanical reserves to compensate for the defect?

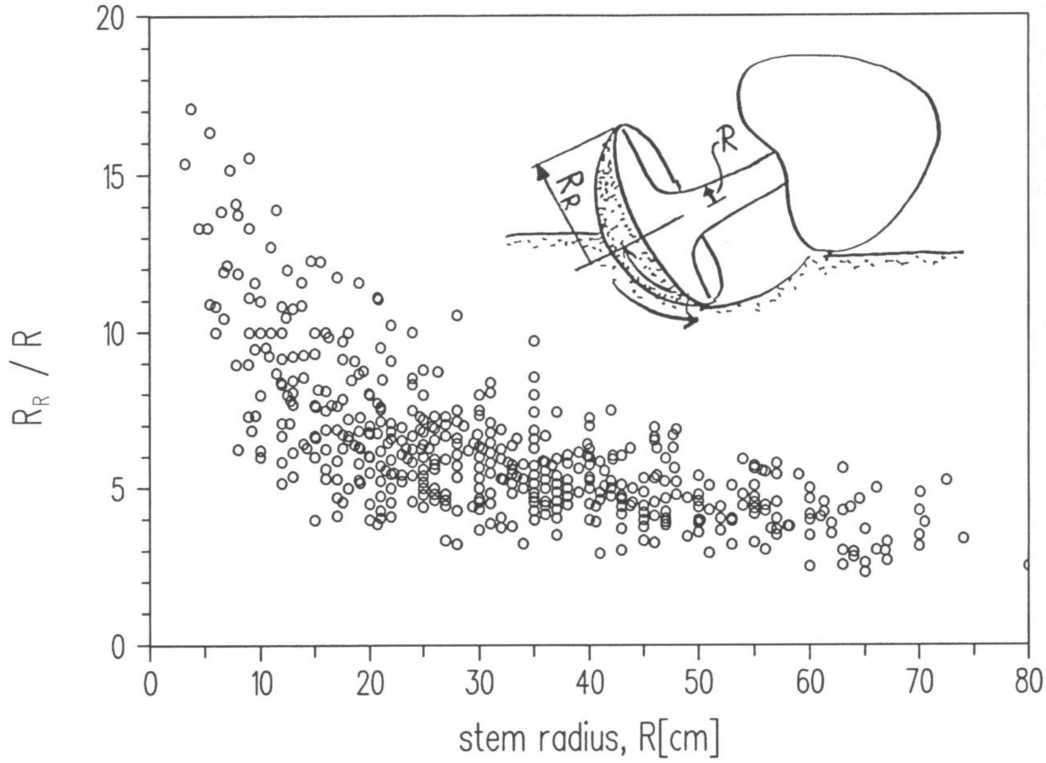
This procedure is applicable only to trees which have circular root plates, like many of those in parks and gardens, where there tend to be few barriers to lateral root growth. Anyone who would like to try applying the procedure should refer to the VTA diagram in Section 14.1. Field studies on windthrown trees in various soils, which were initially done without measuring the shearing strength of the ground, do indeed confirm the existence of a stem/root-plate correlation, as is described in the next section.

6.4 FIRST FIELD STUDIES ON WINDTHROW

In order to get some idea of the relationship between stem radius R and root-plate radius R_R, 2300 windthrown broadleaved and coniferous trees of every morphological root-plate type were measured. The result is given in Fig. 51. Although all the trees and soils are lumped together in one diagram, the following trend can be distinguished: thin stems have relatively large root-plates, that is high R_R/R values. In absolute terms a fat oak tree naturally has a bigger root-ball than a two-year-old pine. But *relative* to stem radius, fat (i.e. heavy) trunks require less room for anchorage. Nothing is easier to explain! The fat, heavy trees press down more heavily than thin ones on the frictional surfaces between the root-ball and the surrounding ground (high normal forces in Fig. 41!). The resulting friction and hence the shear strength are high, and so a relatively small root-plate is sufficient for anchorage. Thus, root-plates supporting thin stems sometimes need to be over 15 times the stem radius while those of thick stems may need to be no more than three times the stem radius. It should also be noted that young trees may need to have relatively extensive root systems for biological, as well as mechanical, reasons.

The upper values of the data in Fig. 51 form a curve which represents the R_R/R values above which no failures have been discovered in nature, even amongst flat-rooters. Thus we can use these data as a VTA diagram for assessing the stability of a tree, as indicated in the second step of the procedure outlined above. After the radius R of the stem has been measured, a root-plate radius of R_R is obtained from the upper limiting curve of Fig. 51.

A further set of data, which are not shown in Fig. 51, were obtained from about 1000 forest trees (conifers) winched over experimentally by the Forestry Commission at Roslin, Scotland. These data fitted very well into the diagram in Fig. 51, although most of the trees were in the lower range for stem radius, i.e. R = 10–20 cm. The soil type was recorded in these Scottish studies, and was found to have less influence on the root-plate radius than is generally supposed. Another thing that might be expected to affect the R_R/R ratio is the varied root morphology of different species [15], but all the studies – including ours! – [42] showed



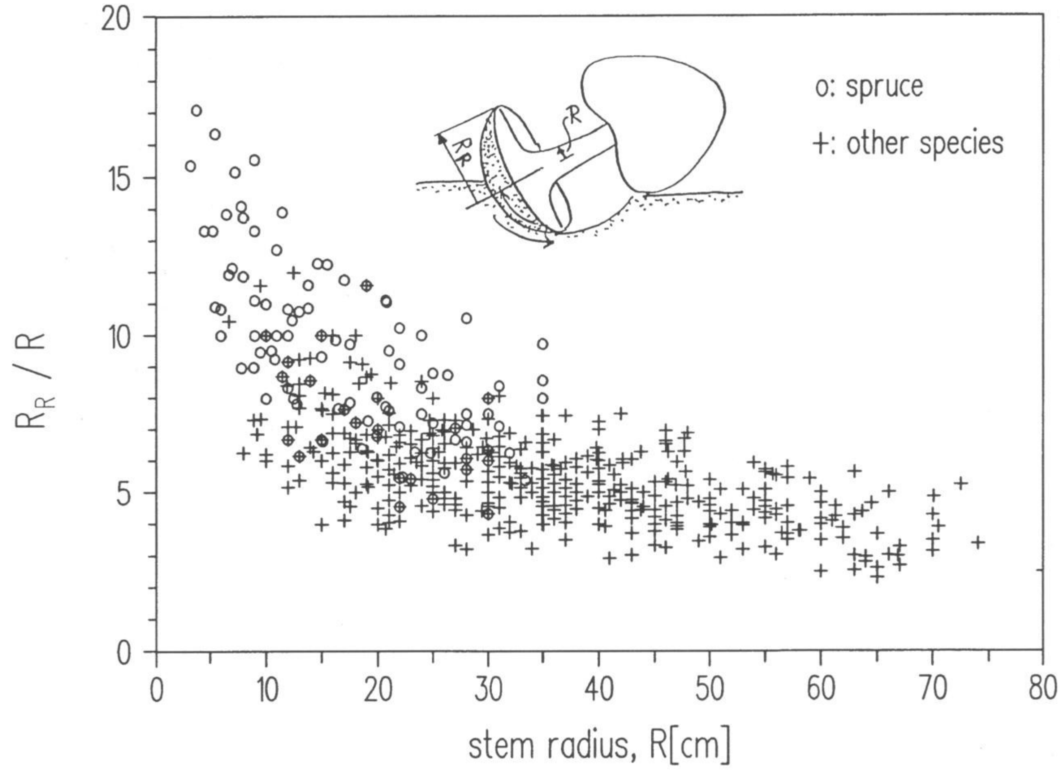


Fig 51. R_R/R ratio (root-plate radius/stem radius) plotted against the stem radius from field studies of windthrown trees. (The upper plot is all trees studied; the lower plot shows the difference between spruce and other tree species)

that this also caused no drastic deviation from the curve. All we found was that the data for Norway spruce, an extremely shallow rooted species, lay mainly towards the top of the curve (Fig. 51b). Incidentally, if one wishes to know the maximum bending moment that a tree is conducting into its rooting zone (e.g. when planting on the roofs of buildings), it is worth knowing that it has precisely the same value as the breaking moment at the foot of the tree. Here once more, the philosophy of the 'chain of equal links' makes it absolutely unnecessary to estimate the wind load.

Before we come to the warning signals given by trees of defects in trees, we should briefly draw attention to the opportunity for examining trees that have suffered total windthrow.

6.5 EXAMINING ROOT CROSS-SECTIONS

If a living tree falls over these days, its often high value is reason enough for asking what caused the giant's demise. Diagnosis does not seem an easy matter when the cause might either be a straightforward case of root-rot, or the aftermath of some previous excavation. But it is possible to find evidence of external causes which, paradoxical as it might seem,

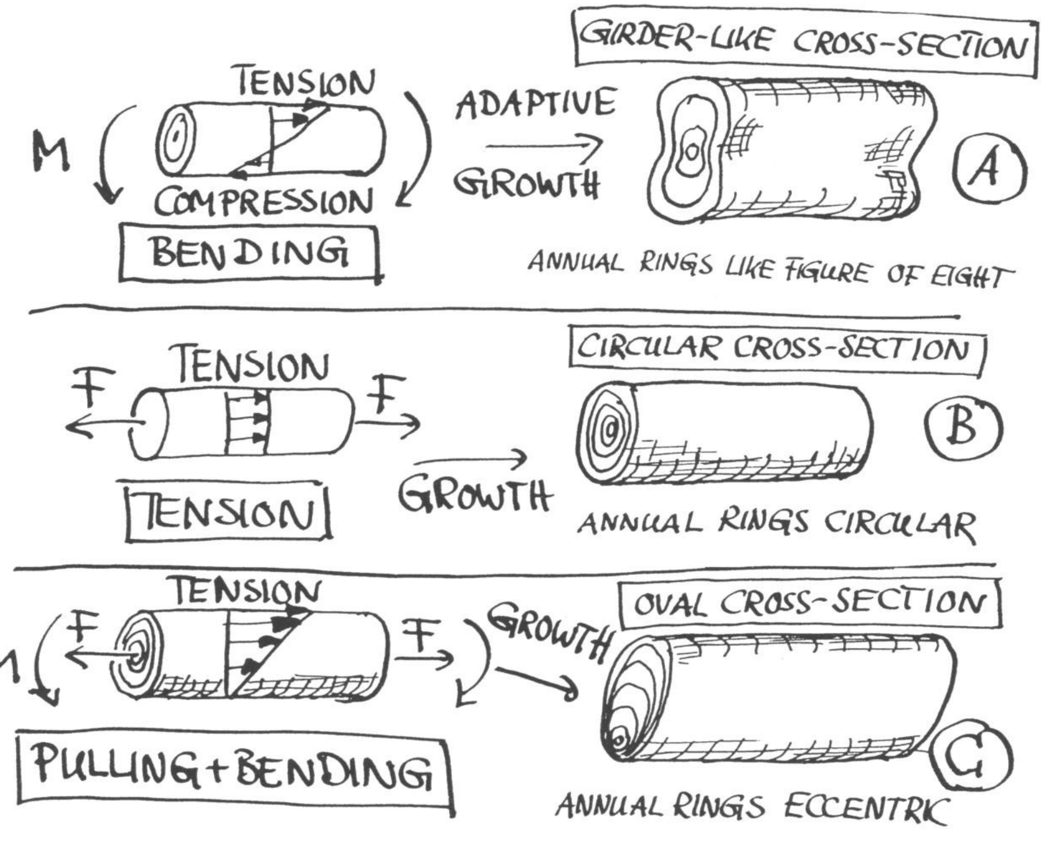


Fig 52. External loads, internal stresses and the effect on the configuration of annual rings in a root section.

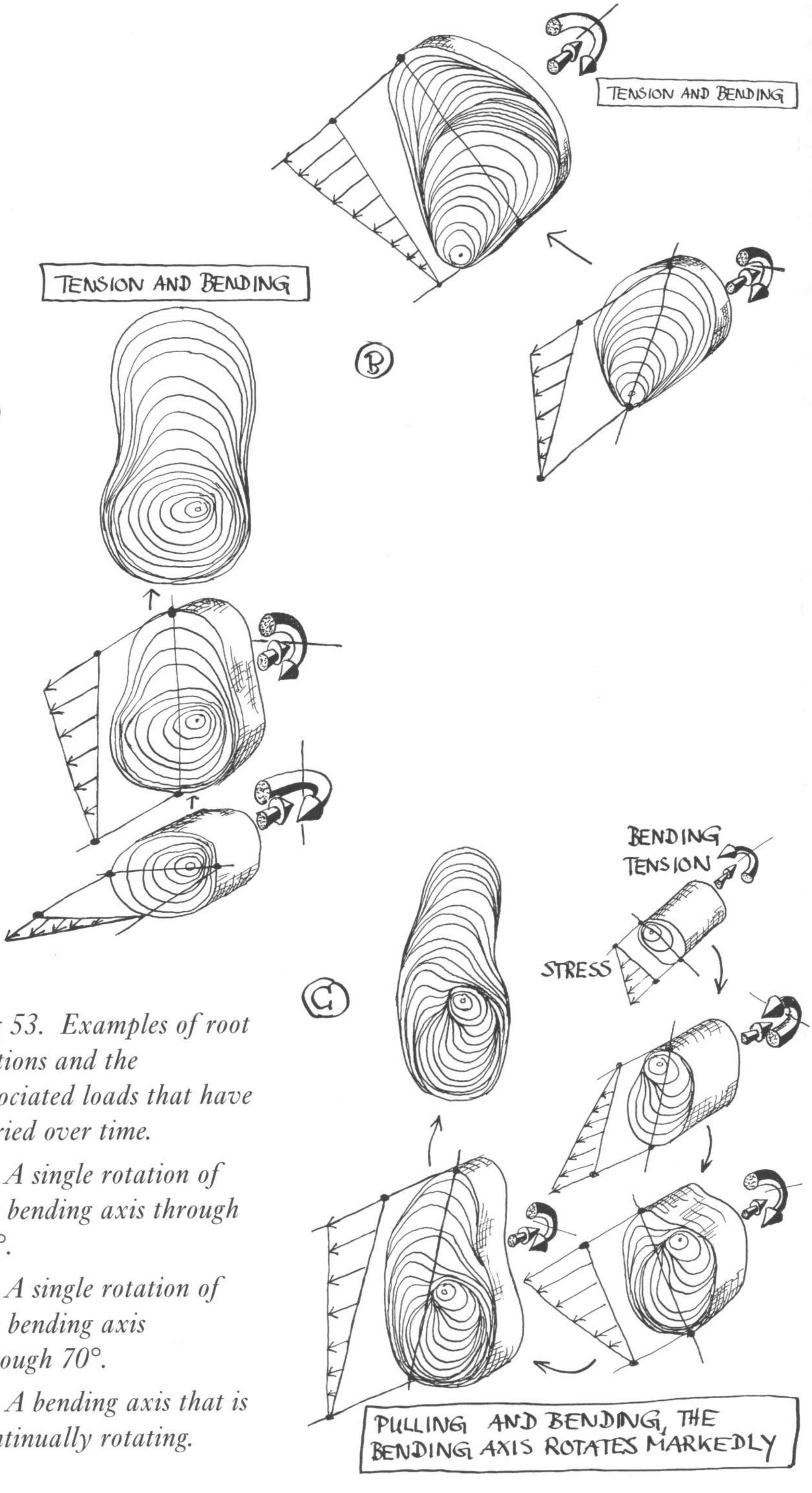


Fig 53. Examples of root sections and the associated loads that have varied over time.

A: A single rotation of the bending axis through 90°.

B: A single rotation of the bending axis through 70°.

C: A bending axis that is continually rotating.

have led to damage because of the way in which the tree had previously optimised its form. The tree's shape becomes optimised for a particular set of loads, and this means for certain that it could succumb under altered loads. For example, there can be serious consequences from changes in wind direction caused by activities such as the demolition of a building, the erection of a new one, or the felling of neighbouring trees.

The method of root inspection that we are suggesting here is based on the *Axiom of uniform stress*, which has been described elsewhere [39,48]. The average thickness of an annual ring is regulated by biological factors and by the growing conditions, whereas its relative thickness at different points on its circumference is directed mainly by the stresses imposed by the mechanical loading at each point. This pattern of growth in response to loading will undoubtedly change if the loading changes. It therefore provides us with an accurate record of the patterns of loading that were applied to the root throughout its life. Fig. 52 shows some loads and typical root shapes. Each root began with a circular cross-section which later grew into a different shape, corresponding to the load placed upon it and the resulting distribution of stresses on its cambium. Fig. 53 shows a number of self-explanatory examples of sawn cross-sections whose annual ring patterns provide information about changes in the external loadings. Importantly, any such changes can be dated by ring counts. The best information can be obtained near or within the buttress zone, where there is usually no problem of 'missing' annual rings. *This record of loadings, produced by growth, cannot be falsified and is therefore of value as irrefutable evidence in a court of law [48].*

So far, we have examined the ways in which trees can be damaged, under the two headings of breakage and windthrow. Another subject which is related to windthrow is the damage that tree roots can cause to underground pipelines, as we shall see in the next chapter.

7.0 WIND, ROOTS AND PIPELINES

7.1 INTRODUCTION

Some of the ways in which tree roots typically interact with soil need to be understood, with special reference to the *Axiom of uniform stress* and *Mohr-Coulomb's law* of soil mechanics. As pointed out throughout this book, the *Axiom of uniform stress* is a natural law of design that quite simply means that a tree, in common with all biological load bearers, always tries to distribute stresses evenly, thus avoiding local over-loading or under-loading of its structure. This principle also applies to engineering components; if they are optimised in this way, they can bear loads up to 100 times more load cycles than otherwise.

All of us, in our tender youth, have systematically employed *Mohr-Coulomb's law* – that is when we built sandcastles on the beach! If you want to build a particularly durable earthen wall, you tamp down the earth tightly, i.e., you compress it. Fig. 41 now shows the generalization of this childhood experience, still in a rather popular scientific presentation. If a sack of potatoes is stood on two planks placed one on top of the other, these slide less readily over each other. The friction is proportional to the 'normal pressure' that acts on the sliding planes perpendicular to the surface.

Similarly, a tree experiences downward pressure at the edge of the root-plate, i.e. from its own weight. The greater this so-called normal pressure σ_n is, the greater is the shearing strength of the soil and the smaller the risk of windthrow.

The shearing strength τ of the soil is proportional to the pressure σ_n on the shear faces:

$$\tau = \sigma_n \tan \phi + \tau_o$$

This equation expresses *Mohr-Coulomb's Law,* which we discussed in the last chapter. In it, ϕ is the so-called 'friction angle' and τ_o a measure of the adhesion between the soil particles. This natural adhesion gives some shearing strength to the soil, which can to some extent resist a slight tensile load caused by wind forces, even without the additional effect of the weight of the root-plate. However, Fig. 54 shows that in such cases the soil is less strong on the windward side and that soil cracks can eventually form here, as the process of windthrow is initiated. The tree counteracts this tendency, since it can respond to the mechanical stimulus of one-sided loading by forming thicker and longer roots on the windward side, on the uphill side of trees on slopes or on the upper side in the case of a strongly leaning tree. It is just that the roots are more heavily loaded and in accordance with the *Axiom of uniform stress*, more material is laid down at more heavily loaded sites, in order to equalize the load once more. It's perfectly easy to understand this effect by an analogy with reinforced concrete. If the concrete (soil) is poor, more steel (roots) is introduced in order to increase its tensile strength. In practice, this response has been recently demonstrated by biologists at the University of York and co-workers from the Forestry Commission's Research Station at Roslin (Scotland) who subjected young trees to one-sided wind loading. Thus, theory, experiment and field observation agree very well.

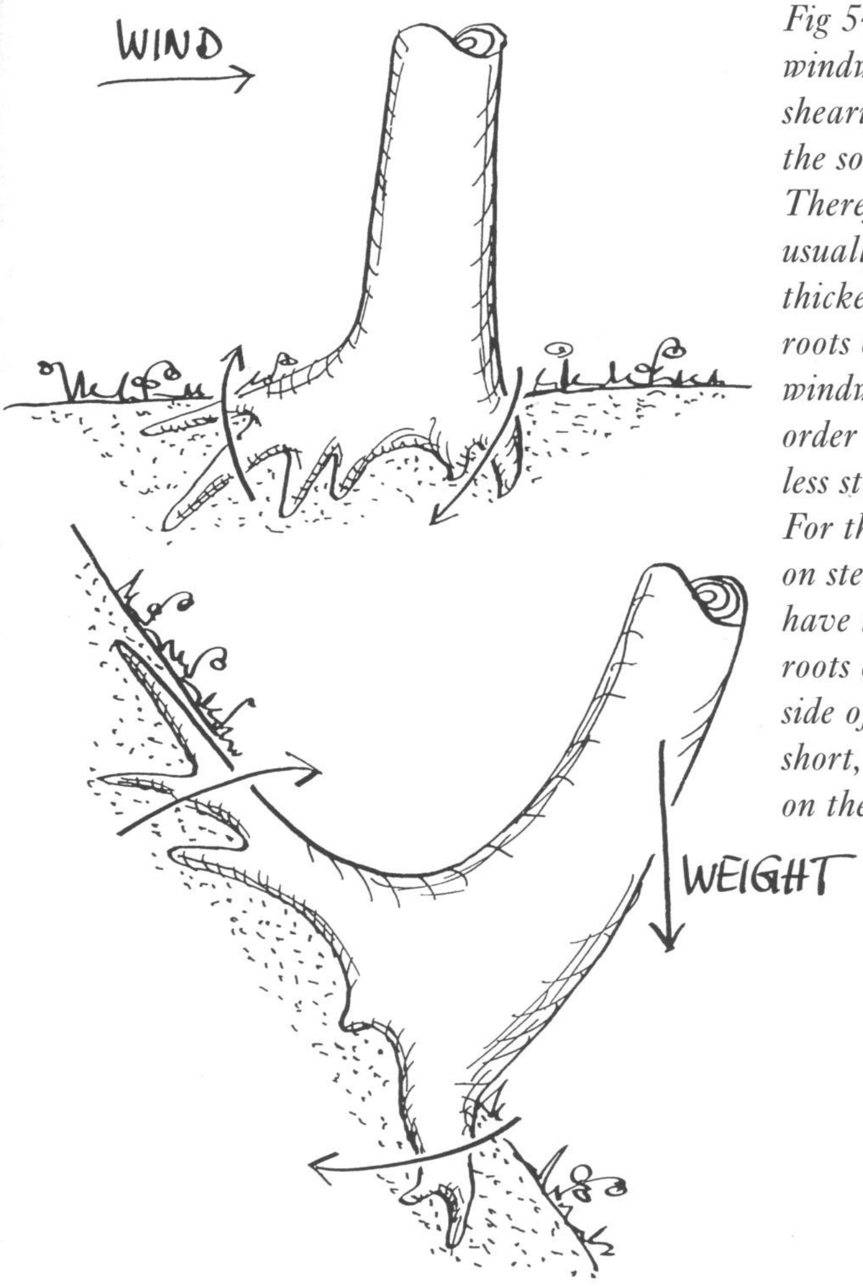


Fig 54. On the windward side the shearing strength of the soil is less. Therefore, the tree usually produces thicker and longer roots on the windward side in order to reinforce the less stable soil there. For this reason trees on steep slopes also have long, rope-like roots on the uphill side of the slope and short, strut-like roots on the downhill side.

As far as pipelines are concerned, it should be borne in mind that they are most likely to be affected by tree roots on the windward side of any trees that they pass, although this may not always apply if other factors affecting root growth (e.g. hydrotropic effects) are involved. With this prior knowledge, several mechanically determined root formations around pipelines can be readily explained.

7.2 THE MECHANICS OF ROOT-PIPELINE INTERACTIONS

7.2.1 The tensioning sling beneath a pipe on the windward side

Fig. 55 shows the principle. The length of root, mainly under tension, only yields a little when loaded and transfers the wide movement of the tree jerkily into the pipe. A plane tree root 10 cm in diameter has a mean breaking load of 42,000 kp. The working load is obtained by dividing this by the safety factor for trees S~4.5, giving about 9,000 kp. So under moderate wind loading there is roughly the weight of 2–3 elephants pulling sideways on the pipe. Not surprisingly, this can produce cracks on the pipe's upper side.

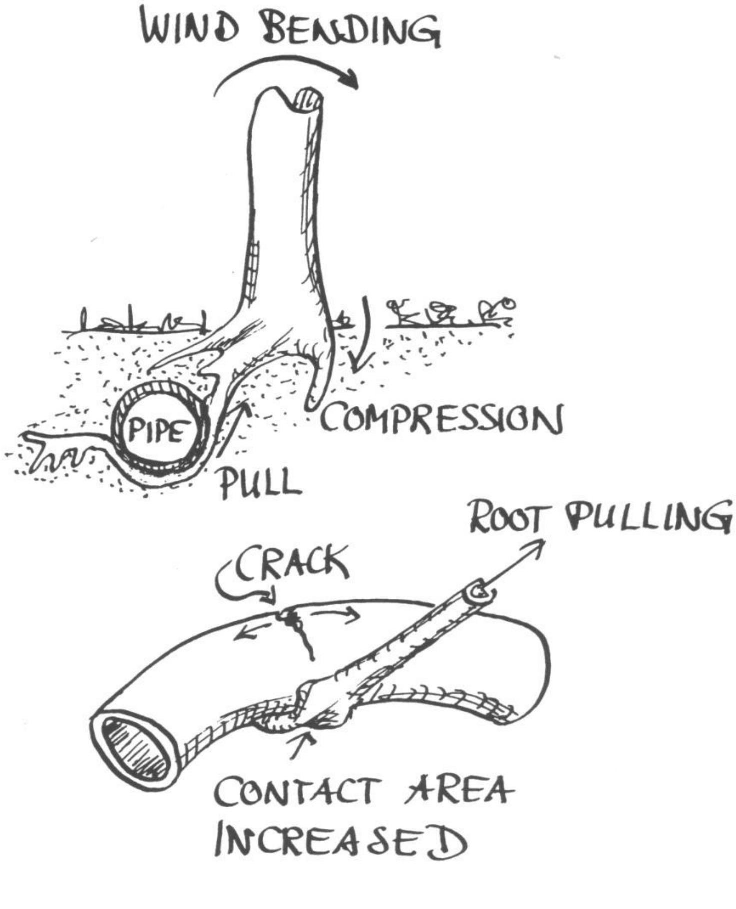


Fig 55. The tugging-cradling root passing under a pipe on the windward side represents, in the authors' opinion, the worst type of interaction between a tree and an underground service. Cracks appear in the upper side of the pipe.

7.2.2 The piston on the lee side pipe

It can be shown theoretically that a root lying on a pipe on the side away from the prevailing wind (lee side) at a distance of 1 m from the tree must be 5 times thicker than the tension sling in Fig. 55 if it is to be much of a danger to the pipe. As Fig. 56 shows, a plate-like root prop forms on the upper side of the pipe, helping to even out the contact stress. The load is not introduced into the pipe here in a jerky fashion but rather as a continuously increasing load with the tree's wind movement, because the partial slackening and jerky tightening of the tensioning sling do not operate here. The tree's movement is damped down more gently and more continuously.

7.2.3 Knot formation at contact points with pipes

The formation of 'knots' (Fig. 57) is probable, particularly where pipes lie side by side or one above another. These are the consequence of contact stresses in the same way as the piston in Fig. 56. The frictional forces which develop around the pipe resulting from the diversion of the

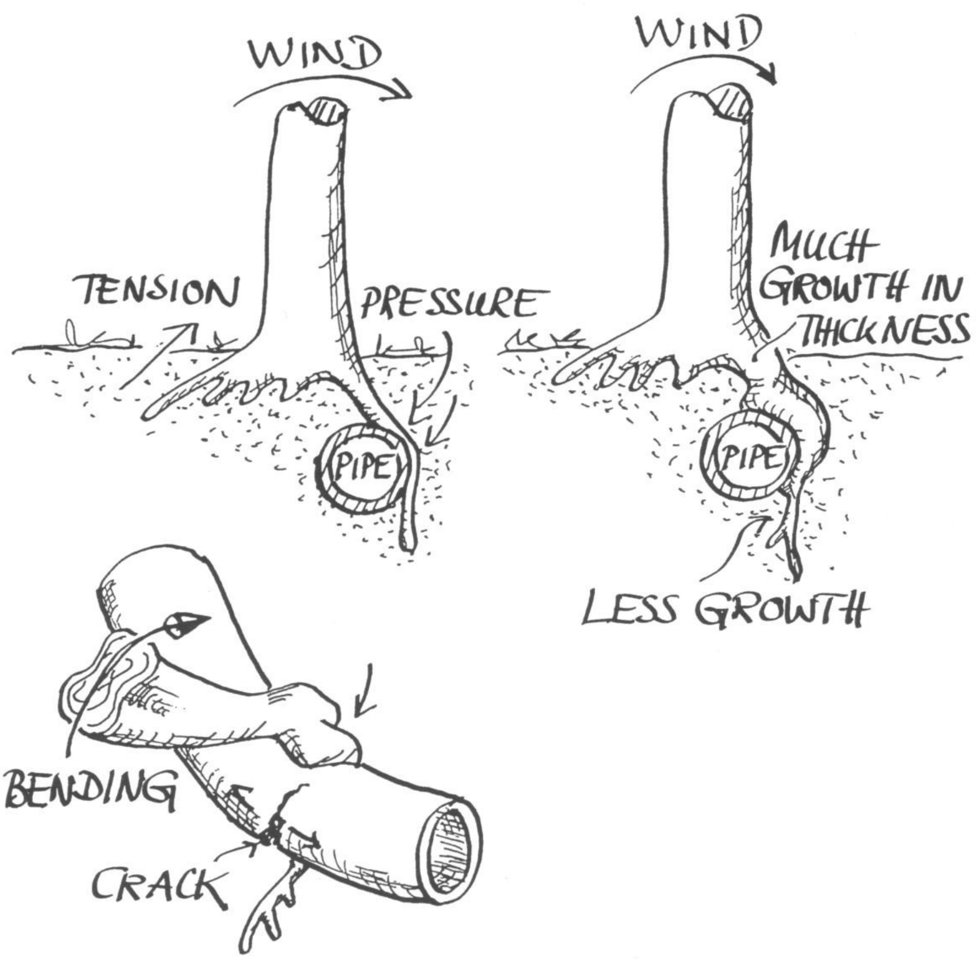


Fig 56. When the pipe is on the lee-side, the risk of its cracking is less than that of a windward-side pipe, unless the roots are considerably thicker than the tugging-cradling root depicted in Fig. 55

roots around it are a possible additional load. After a knot has formed successfully, wedge-type transverse forces develop and these add to the tensile load transmitted by the root.

7.2.4 Trees directly above a pipe

This arrangement is recommended in British Standard 5837, 'Trees in relation to construction' as an alternative to laying the pipes at a 'safe' distance from the tree. In fact, in a side wind the pipe then lies in the neutral pivot of the swaying motion where the soil is neither lifted up on the windward side nor pressed down on the lee side. If the pipe is laid very deep, there might be a moderate lateral pressure. This arrangement deserves sympathetic examination. Things are different where pipes pass under trees that are wind-loaded in the direction of the pipe (Fig. 58). In this case too, there is a risk, albeit a much smaller one, that tension slings may develop on the windward side and pistons on the leeward side. The danger of fracturing is not nil. However, as the trees standing above the pipe one behind the other shelter each other from the wind blowing in the direction of the pipeline, the risk is similarly small. This is another situation where 'knots' can form.

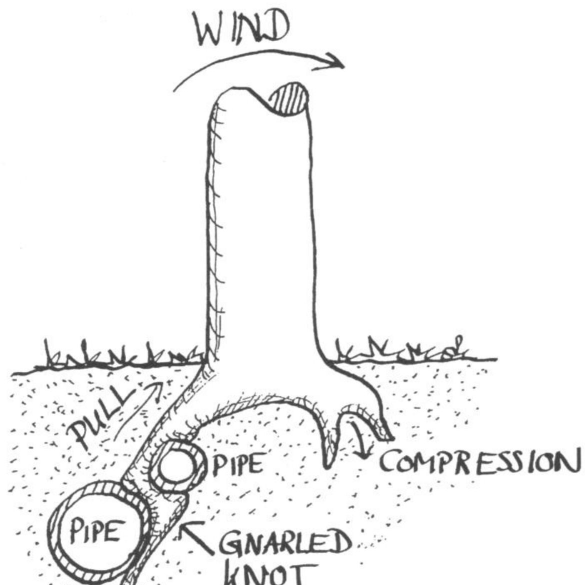


Fig 57. Knots of roots between pipelines can act like wedges, regardless of the way in which the pipes are placed in relation to the tree, though again the snatching load exerted by roots is the most dangerous effect.

7.2.5 Positioning of pipelines; options under current guidelines

In Britain, recommendations for minimum distances between trees and pipelines are mainly intended to avoid excessive damage to existing roots during construction work. We need to ask whether these recommendations, which are laid down in BS 5837, can also help to avoid damage to pipelines which might be caused by roots moving in strong winds. If such damage is to be avoided, the pipeline should preferably not pass within the area of the root-plate. As explained in the previous chapter, the root-plate is the central part of the root system which tilts over or rotates if the tree becomes windthrown.

We can get some idea of the size of root-plates for different sizes of tree by looking at the results of a field study carried out by the Karlsruhe Research Centre in co-operation with the Helge Breloer Bureau (Haren, Germany). In the study, which involved windthrown specimens of all the main native tree species, the radius R_R of the upturned root-plate and the stem radius R just above the root buttresses were measured for each tree. The resulting relationship, based on data from about 2,300 trees, is shown in Fig. 59. We have shown these data together with the minimum distances recommended in Britain and Germany for the separation of trees and pipelines. The German recommendation of a horizontal distance of 2.5 m for all trees – supposedly based on experience – falls well within the range of R_R values, and is therefore obviously too arbitrary to be applied irrespective of the size of the tree. On the other hand, the British recommendation, which varies according to the age and size of the tree, seems to allow an adequate clearance between the pipeline and the root-plate. However, it is worth remembering that R_R values measured after windthrown tend to be an under-estimate of root-plate radius, since some of the anchoring roots generally break off and remain in the surrounding soil.

Recommendations are all very well, but we know that in practice pipelines often pass very close to trees, either because site conditions do not allow sufficient clearance near existing trees, or because tree roots have grown close to existing pipelines. Countless trees would have to be removed if there were strict adherence to the recommendations; even in Germany, where the apparently inadequate distance of 2.5 m applies. In Britain, it is recognised that pipes or cables sometimes have to be laid within the root-plate area. In the case of new plantings, the current guideline of the National Joint Utilities Group is that pipes and cables should be laid within ducts, preferably at least 600 mm deep., which can resist root penetration and which will allow future replacement of the services with minimum soil disturbance. For exisiting trees, BS 5837 recommends the use of thrust-boring for the insertion of pipes and

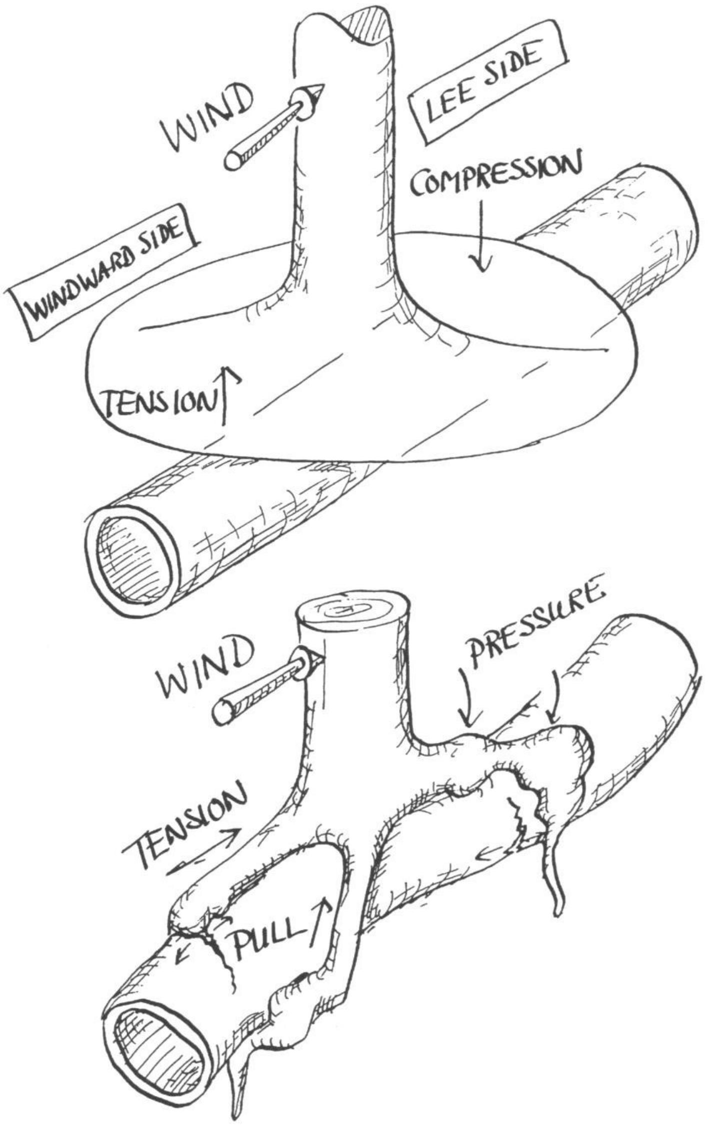
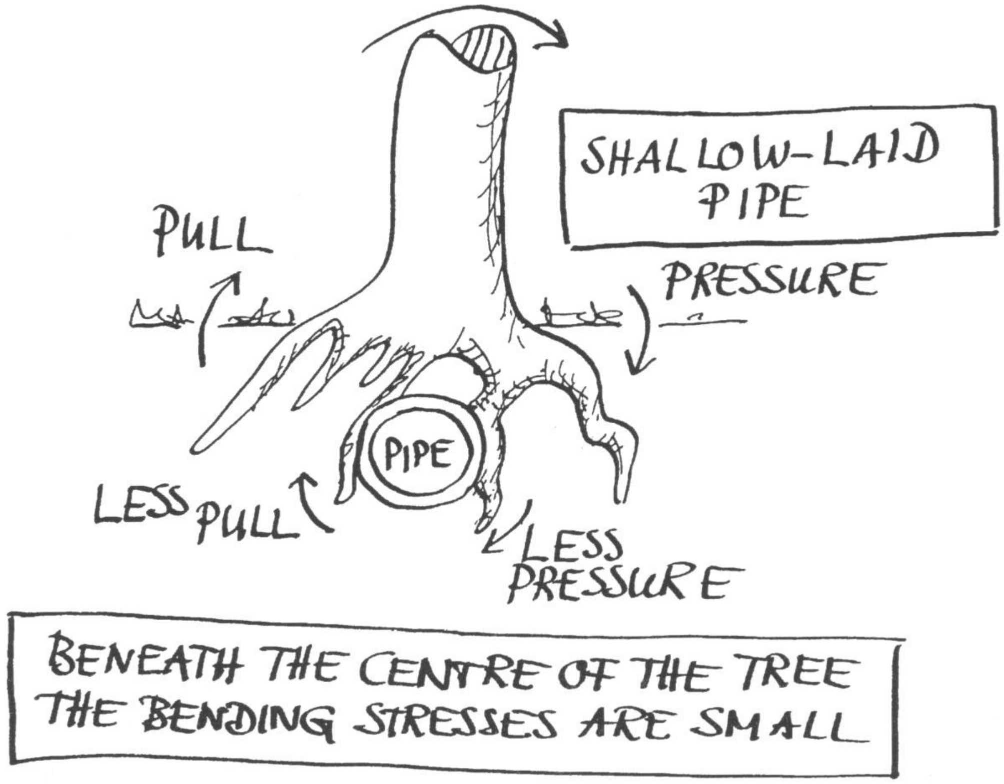


Fig 58. Pipes laid rather shallowly are moderately endangered by trees directly above them if these are subjected to a wind load in the direction of the pipeline.



cables which need to be laid within the protective distance. If this is impracticable, the next best option is to cut a narrow trench radially towards the stem base and to pass beneath the centre of the tree by undercutting a short distance.

As mentioned in section 7.2.4, the alternative recommendations under the British Standards, which allow a pipe to pass directly under a tree, might give such a pipe somewhat better protection from mechanical forces than one which passes a short distance away on the lee or windward side.

7.2.6 An example of damage

In the German town of Viersen, about 13 years ago, the roots of a plane tree began to grow under a gas pipeline which ran past the windward (west) side of the tree at right angles to the prevailing wind direction (Fig. 55). For a decade the tensioning sling formed by the roots subjected the pipe to increasingly strong transverse forces, at a point where there happened to be a welded joint, conceivably of poor quality. This led in stages to the development of fatigue cracks, which resulted in rupture. After this, a combination of many unfortunate coincidences led to an explosion. The accident might never have happened, and would

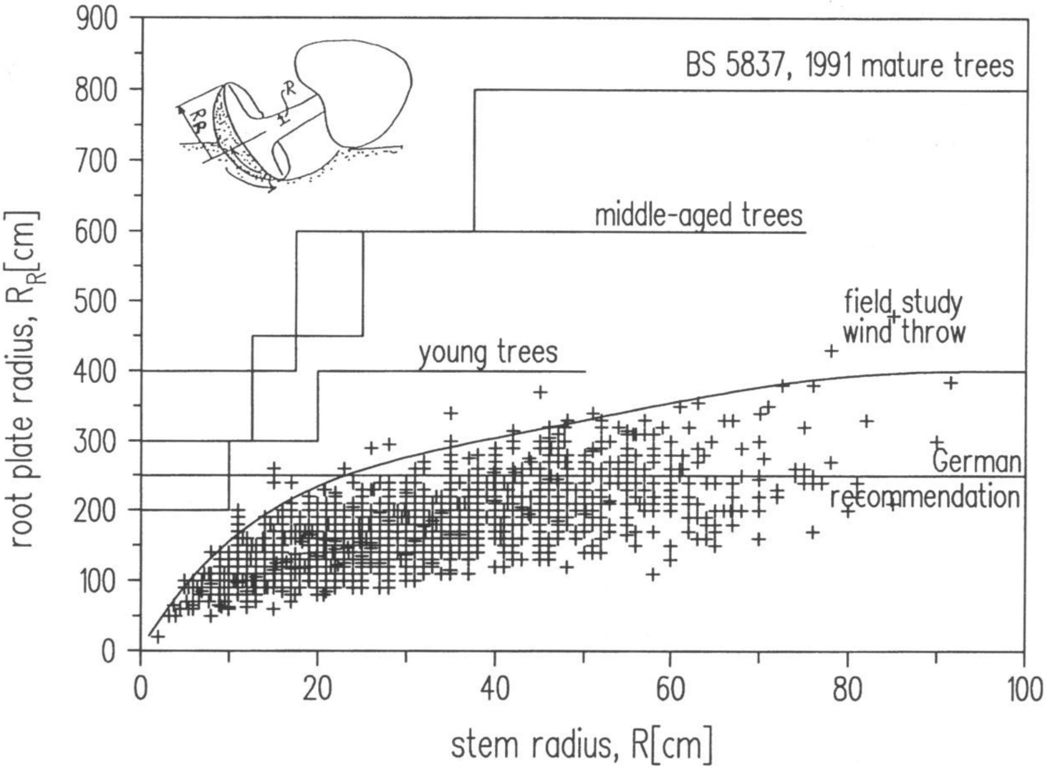


Fig 59. Root-plate radius R_R plotted against stem radius R, as measured above the buttress roots is shown here in relation to root spread values given in BS 5837. The values in BS 5837 include hydrotropic roots that have little or no mechanical role.

certainly not have occurred for many years if the weld had been properly made or/and not positioned above the root sling. Fig. 60 shows the sling of roots in which the pipe lay, a cross-section sawn through the root – from whose annual rings the load history can be read – , and a section through part of the weld in the pipe. The weld has two clear cracks running in the margin of the weld material, i.e. in the so-called heat-altered zone.

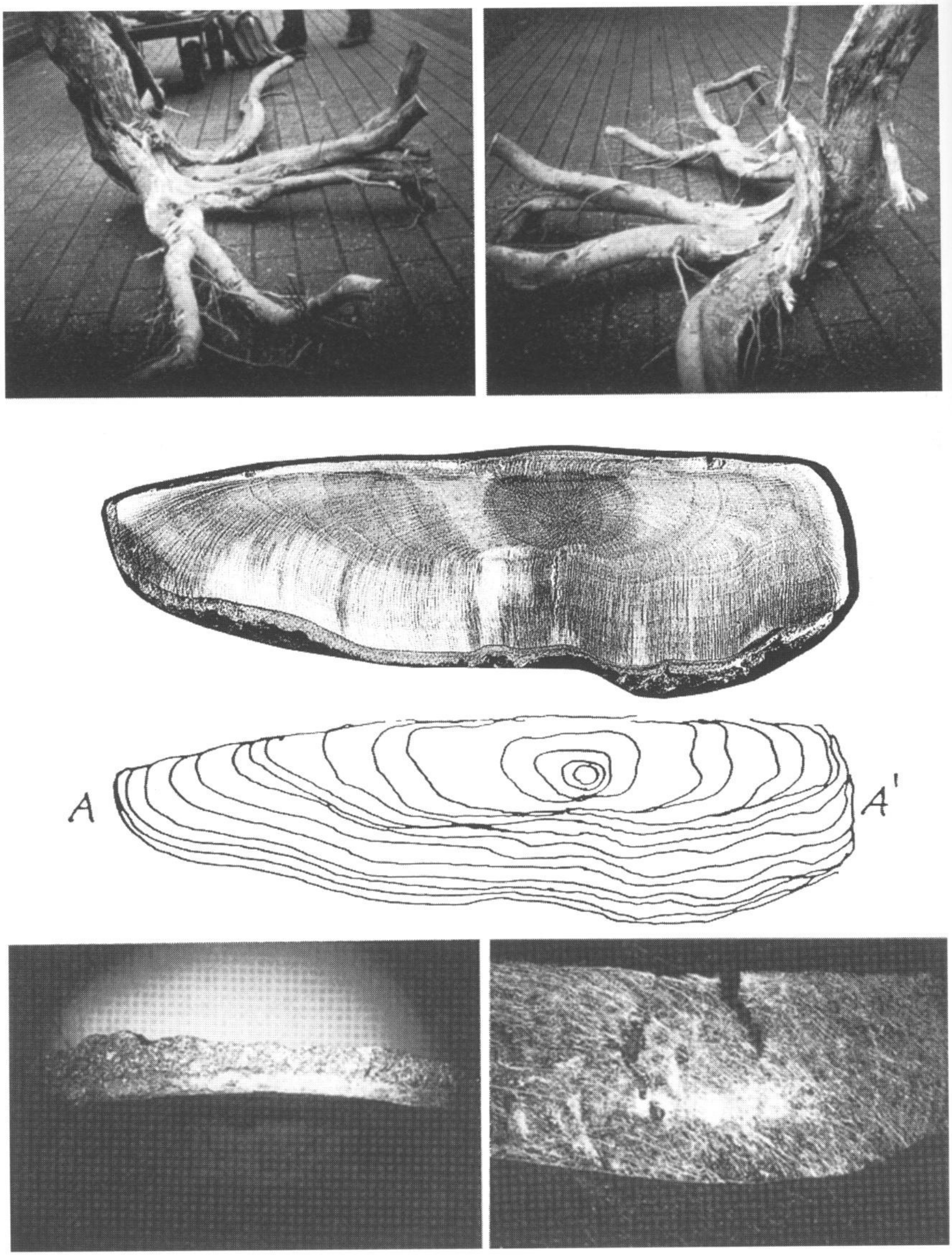


Fig 60. After more than 10 years, the cradling roots were enough to fracture a poorly made welded joint lying above them. The loading history can be read at the saw cut. The poor weld is clearly recognizable.

It was an unequal fight. The root continually improved the natural optimization of its configuration in accordance with the *Axiom of uniform stress* while the welded joint deteriorated as a result of material fatigue and the eventual formation of cracks. Similar growth responses were found in the roots of neighbouring trees.

The formation of tension slings or 'pistons', wherever roots meet obstructions like pipelines, is entirely predictable from the natural law that is represented by the *Axiom of uniform stress*. However, the above example, tragic as the consequences were, involved a series of coincidences (not all detailed here) which must be judged very exceptional. Even so, anyone who understands anything about probabilities knows that even the most improbable of events can occur at any time, however rare it might be.

Before this underground excursion amongst roots and pipelines, we examined the various types of mechanical damage that can affect trees above and below ground. This naturally raises questions about the possibilities of avoiding damage and of diagnosing and anticipating risks. In the next chapter we shall see that trees' body language often gives us clues that indicate the presence of internal mechanical defects.

8.0 RECOGNISING PREDICTABLE TREE FAILURES; THE PRINCIPLES

We are not going to reiterate each of the ways by which a tree can fail. Instead, we shall see how danger signals develop; i.e. how the fracture threatens to occur and how the tree warns us of it.

8.1 SYMPTOMS OF DEFECTS: WARNING SIGNALS IN THE BODY LANGUAGE OF TREES

From *the Axiom of uniform stress*, which is mentioned in this book and explained more thoroughly elsewhere [37,38,39], we can immediately deduce what symptoms the tree will produce in reaction to a weak spot. *In reality, there is actually only a single symptom: the presence of apparently superfluous material!* A tree whose cross-section is mechanically weakened by cracks, decay cavities, injuries from animals etc. will lay down more material in the weakened zone than elsewhere so as to restore the disturbed uniformity of stress. The resulting anomalies in shape are the tree's warning signals which should alert us to the possible presence of mechanical defects in these zones.

Since the general idea of the *Axiom of uniform stress* always implies that trees automatically repair their mechanical defects, it might be supposed that signs of such repair (i.e. 'symptoms') are nothing to worry about. However, there are instances where the repair is not adequate, and this possibility needs to be investigated during a safety inspection. By the way, we are fairly well convinced that the body language of trees is already being adequately interpreted at this level, and perhaps more subtly, by tree specialists who have built up their experience without having known about our axiom in any explicit sense.

The art now is to deduce the particular kind of defect which has given rise to the anomalous shape or to decide by normal inspection that the symptom is not significant. Each type of defect is associated with a characteristic shape, and so we should be able to make a diagnosis in just the same way that a doctor can diagnose gastritis from a coated tongue and other symptoms that go with it (!). Diagnosis of defects in trees or timber has been demonstrated qualitatively in earlier work by Ehsen [18], Lockard *et al.* [34] and Matheny & Clark [36].

We must begin by saying that we are far from knowing all variations in symptoms. Feedback from practice in the field will be needed here in the next few years. Even so we are already in a position to present you with a catalogue of symptoms in this book. It is the basis of a biomechanically based system of visual assessment that we have named VTA: Visual Tree Assessment, and this English name is being used both in Germany and elsewhere in the world. You can apply this system by examining the tree thoroughly and using the information given in the catalogue of symptoms that now follows.

8.2 SYMPTOM EVALUATION – VTA (VISUAL TREE ASSESSMENT)

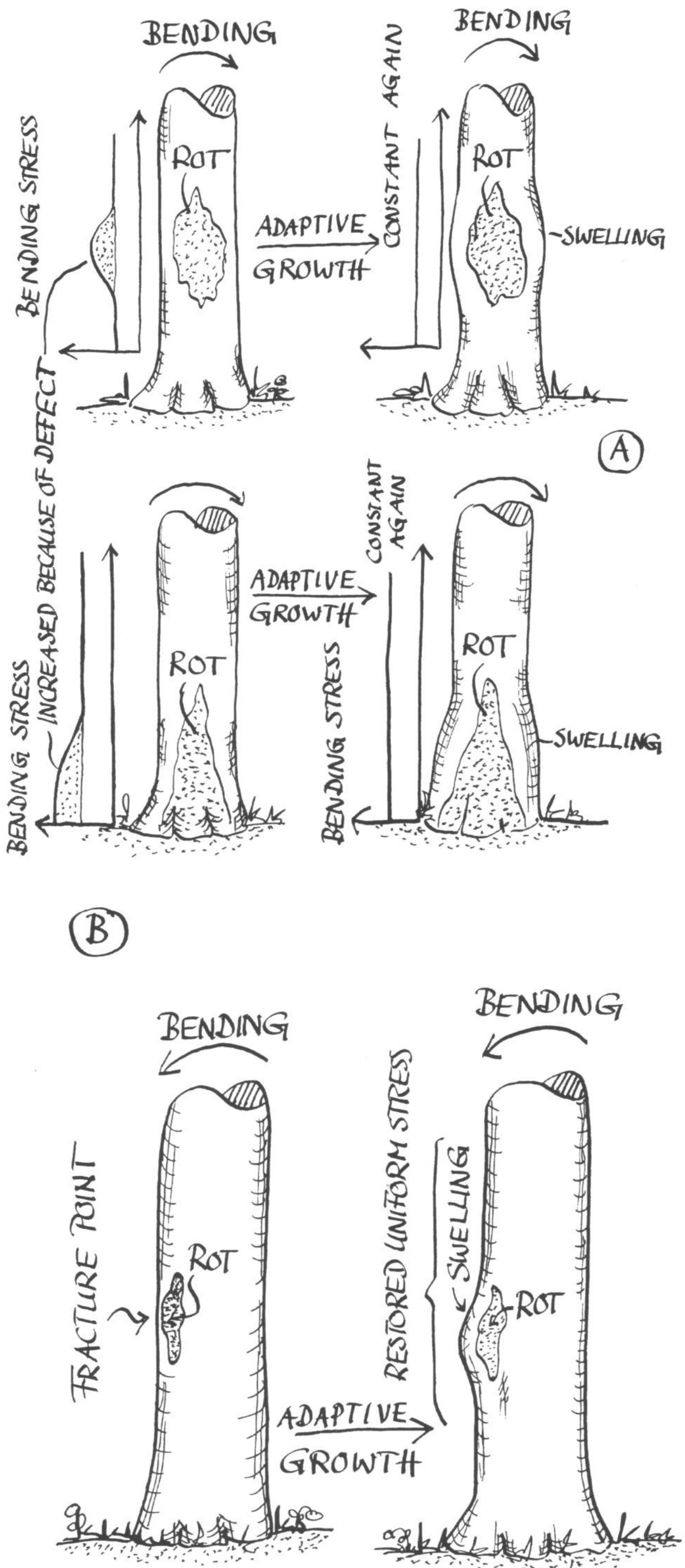
First we want to introduce two symptoms geometrically very different from each other. We will present a brief computer simulation for these two symptoms, showing the way that they arise. Then we will bring in the remaining symptoms to complete the catalogue, as described in part elsewhere [39,45].

8.2.1 The swelling (convexity)

Fig. 61 shows the basic forms that swellings can take. If a central decay cavity with a symmetrical cross-section develops in the stem, a ring swelling develops (A). The tree looks like a snake that has swallowed a frog. Ring swellings produced in this way extend some considerable distance up and down the stem. If, on the other hand, decay develops on one side of the tree, e.g. following injury in that area, then the symptom accompanying it is a bulge on that side, rather than a ring swelling (B).

If a tree shows an abrupt bulge which does not taper off gradually up and down the stem, the defect may be something quite other than decay; it may be localised fibre kinking, as reported by König [29]. Apparently, wood with partly kinked fibres is relatively soft and behaves mechanically rather as though it had been weakened by decay. The abrupt swellings produced by the tree's reaction to this type of weakening are illustrated in Fig. 61C. A bulge of this type consists of a wave-like development of annual rings over the zone of kinking, which can be envisaged as forming a transverse band-like region in the first instance. If such a bulge is tapped with a mallet, it sounds no different from sound wood.

A bulge associated with fibre kinking presents only a small risk of failure, but the zone of kinking does become dangerous if it enlarges enough for the lean of the tree to increase. Cases like this can often be recognised from transverse cracks in the outer bark plates on the opposite side of the tree, which on their own would represent a relatively benign defect. Incidentally, Trendelenburg [71] described these swellings as softer (lower E-modulus) and more deformable. They must


BENDING
BENDING STRESS
INCREASED BECAUSE OF DEFECT
ROT
ADAPTIVE GROWTH
CONSTANT AGAIN
BENDING
ROT
SWELLING
A
ADAPTIVE GROWTH
ROT
BENDING STRESS
CONSTANT AGAIN
ROT
SWELLING
B
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BENDING
RESTORED UNIFORM STRESS
SWELLING
ROT

Fig 61. A and B

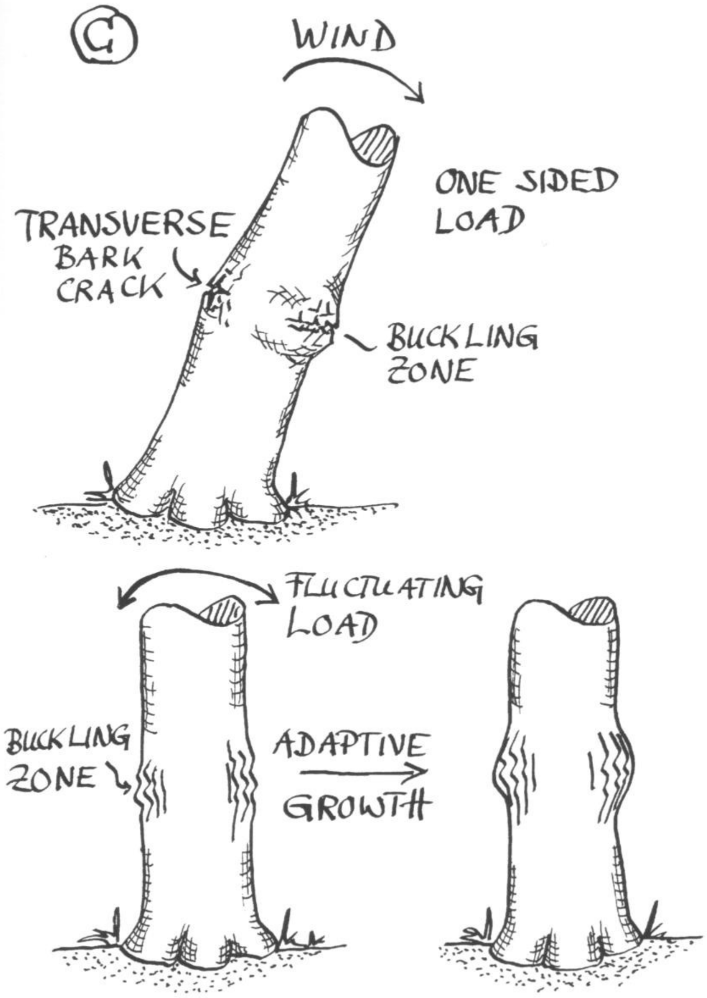


Fig 61. The swelling as a symptom of a defect.

A: Ring swelling associated with a roughly symmetrical decay cavity.

B: A bulge as a symptom of a decay cavity close to one side of the tree.

C: A more sharply defined swelling repairing a zone of fibre kinking. This can be one-sided or symmetrical.

therefore work like the callus surrounding a fracture in the bone of a mammal, that is as a shock absorber. Once a zone of fibre kinking has developed, sudden heavy loads, e.g. in gusts of wind, would tend to enlarge the zone, but the swelling filled with wavy annual rings should clearly prevent this by acting as an elastic cushion. If the wind load is on one side, or if the tree is heavily leaning, these swellings are mainly on the compressed side of the bending zone. On the other hand, if the wind direction is constantly changing, a veritable lifebelt of a swelling can form right around the tree.

For the reader interested in theoretical mechanics, we are now going to run through the mathematical proof that, by forming a ring swelling, the tree can re-establish its ideal state of uniform stress (Fig. 62). The calculations were done for us by Harald Gerhardt. Anyone who would like to read more about the CAO method of computer simulation of adaptive growth is referred to reference [39]. Bending stress calculations (Fig. 63) show that a significant increase in stress, and with it the formation of swellings on the surface of the tree, is only to be expected when a decay cavity occupies more than 70% of the stem diameter. (The calculation was based on the simple bending theory of hollow flexible

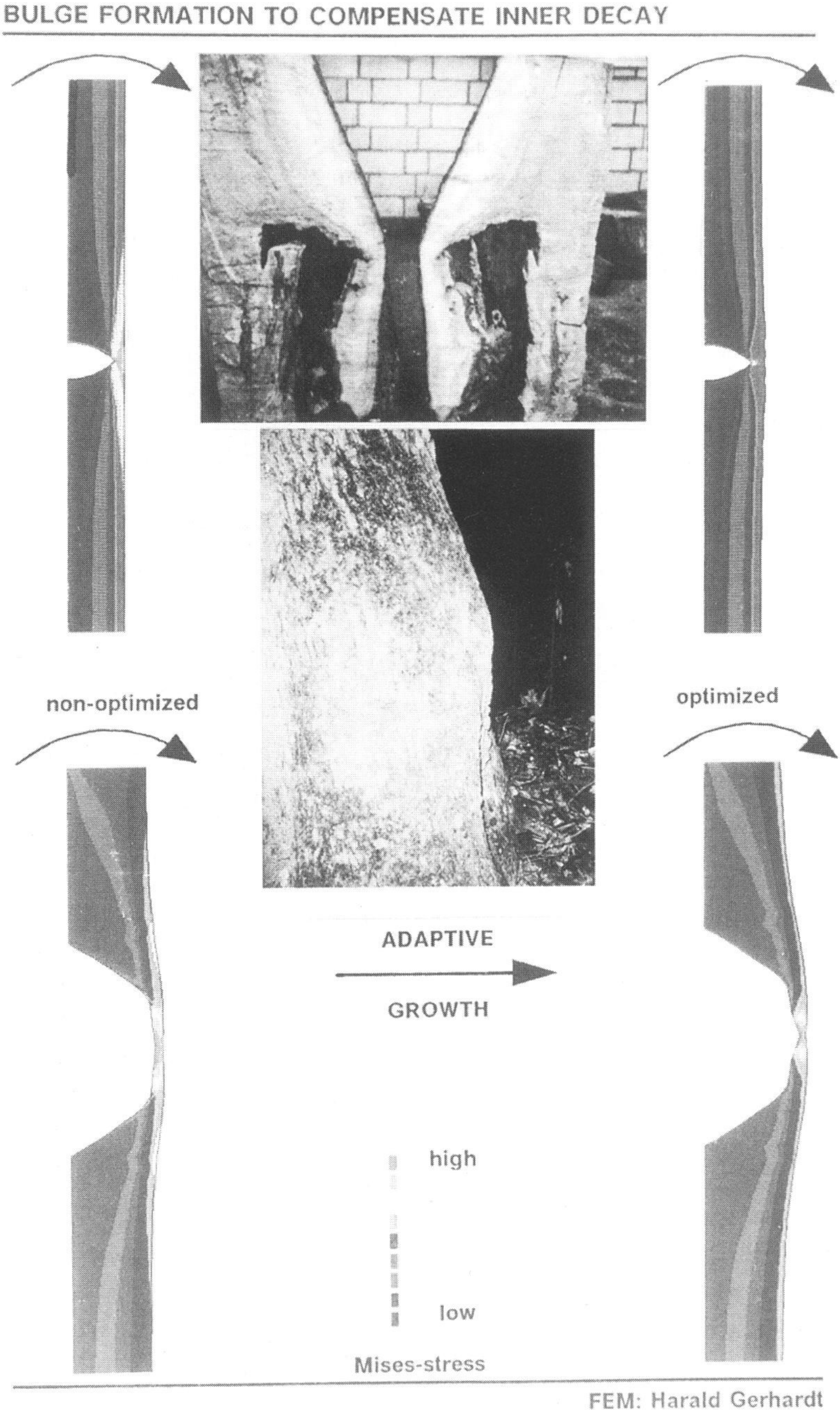
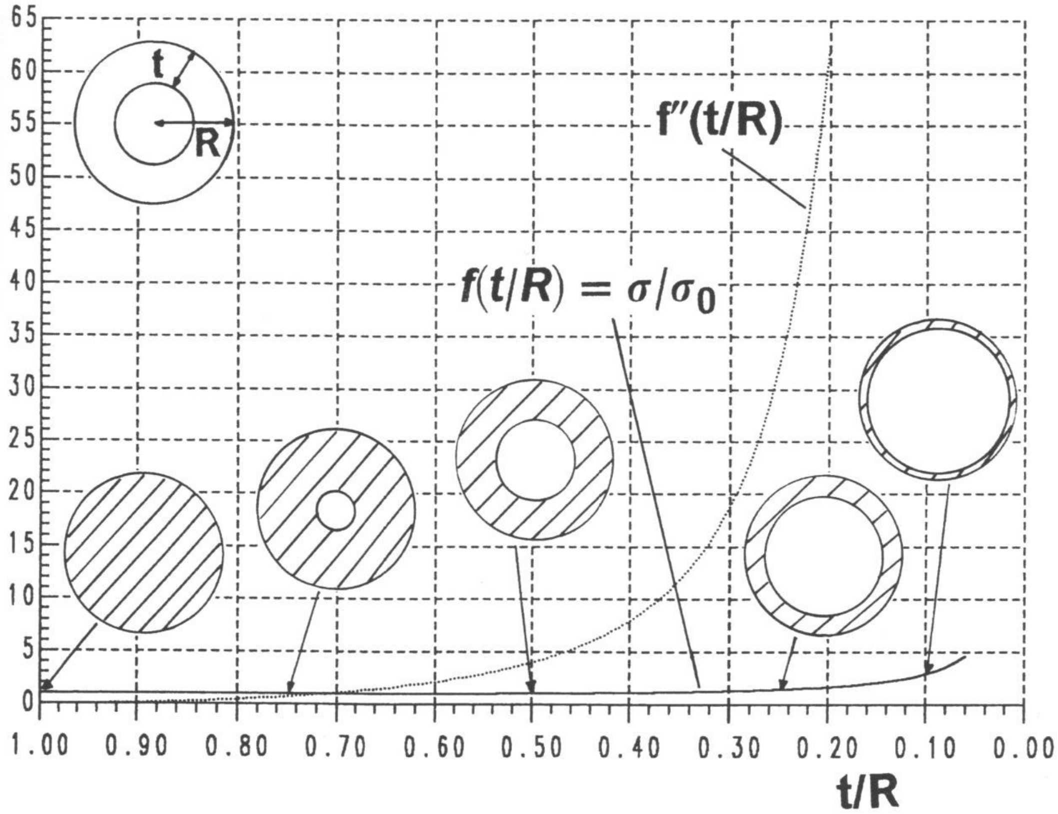


Fig 62. A CAO simulation of adaptive growth demonstrates the restoration of uniform stresses. Here the symptom is a sign of successful self-repair. (Mises-stress is an average of all the stresses at the local point concerned.)



Computing: Dagmar Erb

Fig 63. The increased stresses on the surface of the tree resulting from its hollow condition become significant only when the defect reaches 60–70% of the stem diameter. The curve f" of the σ/σ_0 *curve rises rapidly between t/R = 0.2 and 0.3!!*

beams). Bending stress can also increase when a similar proportion of the cross-section is occupied by decayed wood, though not if the decay is of a brittle type. It is not surprising that hollow or substantially decayed trees can retain much of their strength, since the long bones of our own skeletal system are hollow and yet are not at any great risk of damage even if we use them for making over-ambitious jumps. On the other hand, if the hollowing out is sufficient to cause an increase in stresses, this can be rectified by an increase in radius (i.e. the formation of a swelling).

Figure 64 demonstrates as simply as possible the important relationship between stress and hollow cross-sections. It shows three cross-sections which all exhibit the same stress if subjected to the same external bending load, and so entirely satisfy the *Axiom of uniform stress.* The radius of the hollow is determined by the extent of decay, but it is the exterior radius of the tree over which the stress is distributed; i.e., the larger the external radius, the thinner the walls can be. *But:* as the walls become increasingly thin, the danger of shell buckling and of hosepipe

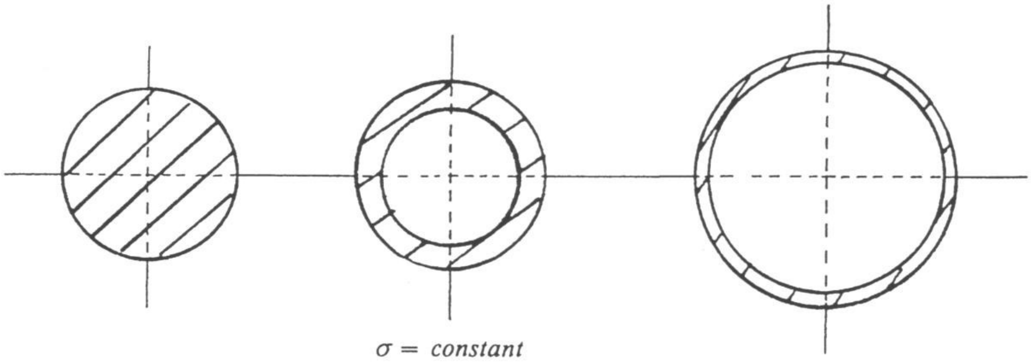


Fig 64. Three cross-sections with equal external stresses on the surface.

kinking increases. And the tree cannot predict these types of failure because they represent a spontaneous change of shape. This cannot be countered by adaptive growth. It is therefore necessary to show that this type of failure can be discounted as well, and we therefore need to apply the criterion $\frac{t}{R} \geq \mathbf{0.3}$ which has already been introduced (Fig. 18). Even so, this test has its own limitations. If, for example, large parts of the crown are missing then it is quite all right for the remaining cross-section to be thinner than indicated by this ratio. Pollarded willows or roadside lime trees sporting a military haircut are examples familiar to all of us. These sturdy, thin-skinned individuals mostly have no great potential for causing damage and in situations away from roads or buildings they can be fenced off from public access if really necessary; this should be acceptable to anyone who is particularly fond of them.

8.2.2 The longitudinal rib

Longitudinal ribs develop almost exclusively due to the presence of longitudinal radial cracks (Fig. 65A). The origin of the crack is immaterial; it could have extended outwards from internal decay following the xylem rays, from the included bark of an old occluded wound, or from a partly healed frost crack. A CAO computer simulation carried out by Matthias Teschner showed that torsional loads play a particular part in the formation of ribs. The simulation is shown in Fig. 65B. One begins with a circular cross-section with a radial crack. When the computer is instructed to simulate growth into a state of uniform stress, the rib forms. No other manipulations of any kind were carried out. These mathematical examples (there are more of them!) show that the *Axiom of uniform stress* is the only adequate basis for characterising and evaluating defects.

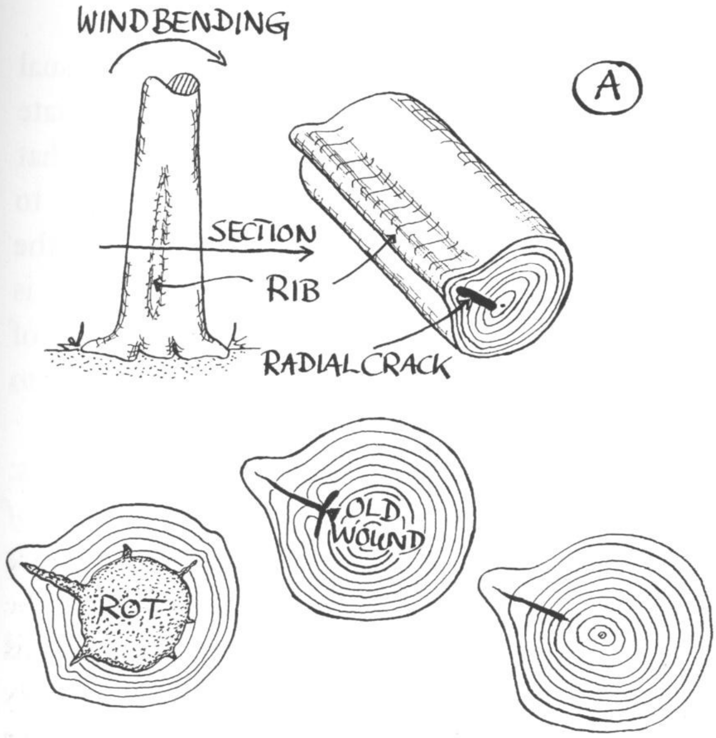
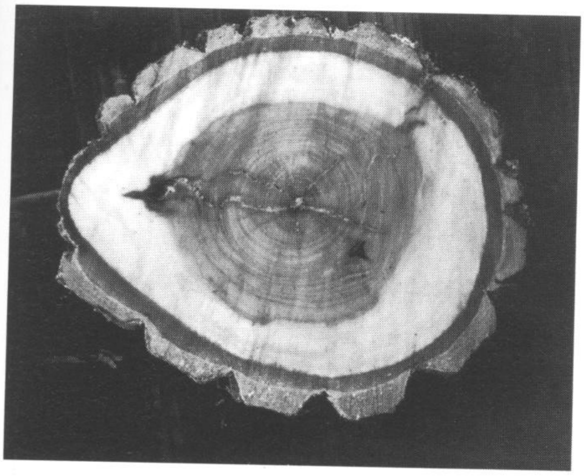
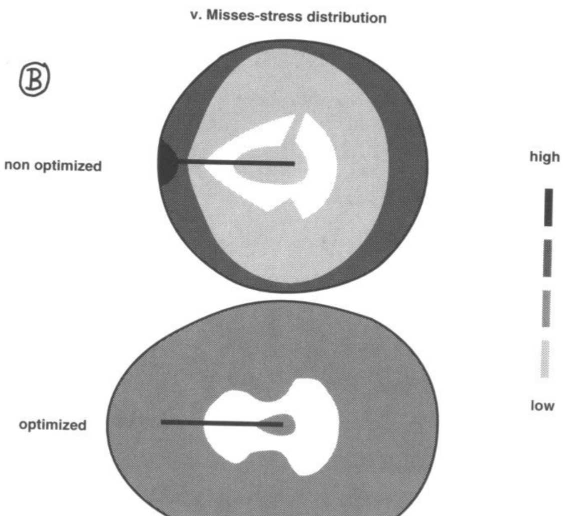


Fig 65. Longitudinal ribs as a symptom of a radial longitudinal crack in the tree.

A: Radial cracks with differing causes lead to the same defect symptom.

B: CAO simulation of rib development.





8.2.3 Symptom evaluation

After a symptom of a defect has been identified during the visual assessment of a tree, it must be properly evaluated, so that appropriate action (if any) can be taken. It would be utterly senseless to suggest that the remedy for every tree afflicted with some symptom should be to change its position to the horizontal using a howling chain saw. On the contrary – in the first place, if a tree develops a defect symptom it is signalling its will to survive. It works hard to repair a likely point of fracture. This is also a sign of vitality. It would never occur to a tree to repair itself it were already half dead.

This straightaway suggests the rule for the evaluation of symptoms: *if the tree succeeds in repairing itself, that is in re-establishing the state of uniform stress, then it should be left alone.* (In the case of hollow trees, it should also be established that the cross-section will not collapse.)

We can discuss symptom evaluation in detail by using the decayed cavity as an example. The basic sequence of equations is given in Fig. 66. We need to answer the following question:- Are the additional repair structures (symptoms) formed by the tree enough to maintain uniform stress on the surface of the tree despite the defect? For this, the residual cross-sectional thickness of the tree bearing the defect has to be measured, which can be done using methods described below. Once this thickness is known, then the question *fell or leave alone?* can be answered by deciding whether uniform stress has been, or is being re-established. If the maximum bending stress σ_0 in the defect-free cross-section is:

$$\sigma_0 = \frac{M}{W_0} \tag{6}$$

and the corresponding value, σ, in the defective cross-section is:

$$\sigma = \frac{M}{W} \tag{7}$$

it follows from the *Axiom of uniform stress* that:

$$\sigma = \sigma_0 \tag{8}$$

the moment becomes:

$$\frac{M}{W} = \frac{M}{W_0} \tag{9}$$

and it is clear that:

$$W = W_0 \tag{10}$$

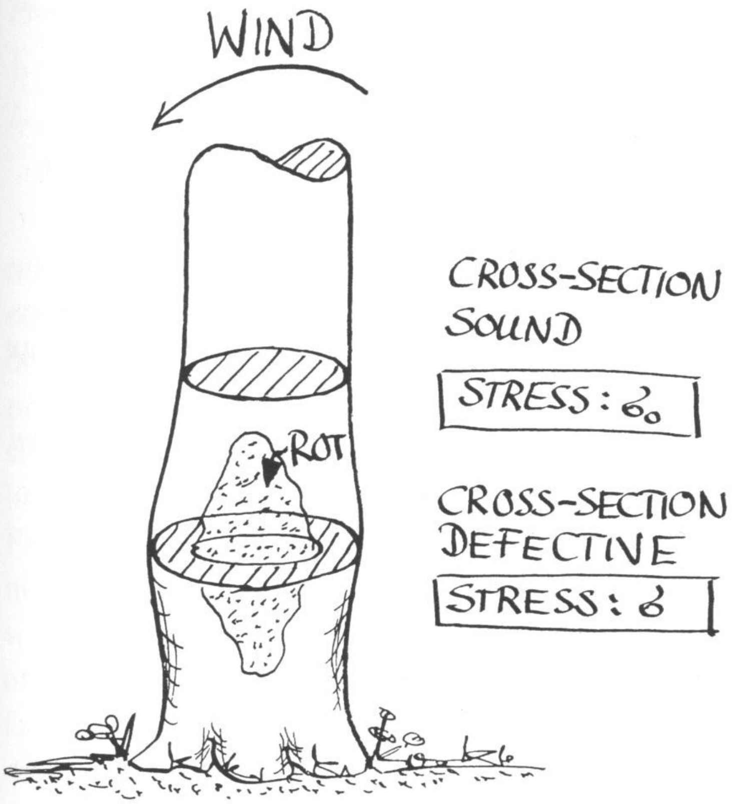


Fig 66. Symptom evaluation according to the axiom of uniform stress.

The tree may be retained if the sound and the defective cross-sections have the same moment of bending resistance. Only then would the repair, represented by the production of symptoms, be successful. Even if **W** is smaller than $\mathbf{W_0}$ it may still be possible to grant the tree a reprieve by lightening the crown, or by trusting the tree's safety reserves to tolerate the increased stress. These reserves are determined by the safety factor **S**, which we shall discuss later. It should be noted, by the way, that only the radii (i.e. the geometry) of the cross-sections enter into equation (10). Neither the wind load nor the characteristics of the material need be known for this evaluation.

Unfortunately, it is not enough just to find whether equation (10) is fulfilled. True, the cambium of the tree is in the best position to 'measure' the uniformity of the stresses on the surface and to re-establish where necessary by adding new material. But, as we have seen in our examination of the hazard beam, there are some types of cross-sectional change that a completely defect-free and intact tree is not in a position to 'anticipate'. What does this mean for our assessment? Fig. 67 shows several types of abrupt change that can affect a stem. The key feature of all such events is that they suddenly change the status of a cross-sectional form which has developed over many years, during which the tree has lavished care and attention on itself by 'obeying' the *Axiom of uniform stress*. This does not necessarily mean that the cross-section takes on a different appearance from the outside. A fresh

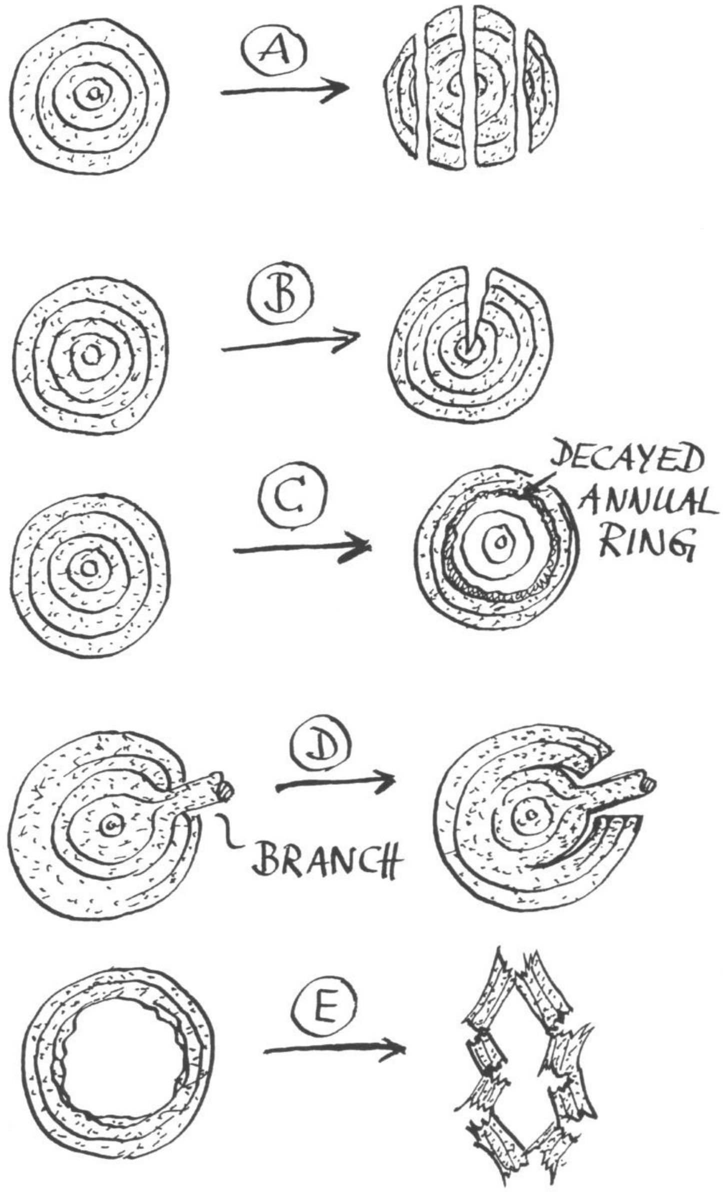


Fig 67. Changes in the cross-sectional integrity of the tree, with or without a mechanical defect, can destroy the tree's matched configuration in an instant.

A: Longitudinal splits.

B: Radial split.

C: Internal annular cracks.

D: Partial collapse from snapping at branches.

E: Cross-sectional flattening and hosepipe kinking.

longitudinal crack, with no accompanying ribs, may be hardly noticeable to an observer and yet its formation has abruptly nullified the tree's lifelong work of adaptive growth; the collapse of its optimization of form.

A particularly dangerous type of cross-sectional change involves *flattening* (E). It can occur not only with thin-walled cross-sections, which show *shell buckling*, but also with relatively thick-walled cross-section, when an abrupt transition from a cavity to a solid part of the stem leads to *hosepipe kinking* with the formation of devil's ears. For design engineers, shell buckling is a nightmare because of the way that the damage starts and develops with virtually no prior warning.

When the state of uniform stress is shown to have been maintained or restored as in Equation (10), there is a further need to determine whether there is a danger of splitting, buckling or cross-sectional flattening.

Prerequisites for leaving the tree alone are, therefore:

1. The maintenance of uniform stress despite the presence of a defect.
2. The proof that the defective cross-section will fail neither as the result of a normal bending fracture nor from a cross-sectional collapse.

The second of these criteria raises some difficult problems of mechanical instability, but it has been approximately solved using computer methods at the Karlsruhe Research Centre. However, in view of the complexity of the theory behind this, and the need to test its practical application, it was also desirable to carry out an empirical field study for determining the permissible thickness of the residual wall of a hollow tree. The results of such a study are shown in Fig. 18. Incidentally, we shall see from the VTA failure criteria that a normal bending fracture hardly ever happens in the case of a hollow tree with a closed cross-section. An exception to this is the bending fracture of thin stems at branch junctions. Hollow or heart-rotted trees usually fail from hosepipe kinking, sometimes showing devil's ear failure, if the residual wall thickness gets to less than 0.3 R. Simple bending fracture without cross-sectional collapse is, indeed, to be expected mainly with very thick-walled open cross-sections or else at other defects (branches etc.).

This commentary on the way things happen should help to explain the principles that underlie the philosophy of assessing tree safety according to the *Axiom of uniform stress*. However, we have not yet looked in detail at the practical steps by which we can evaluate a defect after first recognising the symptoms. In particular, the reduction in strength of the defective cross-section must be quantified, since VTA has so far indicated only that:

1. there is a defect inside,
2. we can make a rough deduction about the form of the defect.

The methods described in the following sections should show how the defect can be investigated more precisely and in particular how the thickness of the residual wall of a hollow stem can be measured. We also suggest that an almost identical, albeit simplified, set of geometrical criteria can be applied in the case of non-circular and eccentric defects. On this basis, the final risk assessment can then be made using the VTA tables in Chapter 14.

The thickness of the remaining wall surrounding a defect is seldom the same everywhere around the circumference. It would require a computer to cope in detail with the complexities of eccentric defects, but the field practitioner can make an adequate assessment by adopting the simple rules explained in the next section, while remembering that the object is to retain the tree for as long as possible with the minimum risk. Here it is essential to distinguish between the notional failure geometry for bending fractures and for hosepipe kinking and, as we will now see, this is quite easy.

8.3 DETAILED DIAGNOSES

8.3.1 Sounding with a hammer

With a little practice it is sometimes possible to refine one's diagnosis with a mallet or a rubber or plastic hammer and to discover the spot where the wall is thinnest. In order to stay on the side of safety, as far as bending fracture is concerned, we assume that the residual wall is equally thin all the way round the tree (Fig. 68A). This procedure accords entirely with Shigo's model of compartmentalization which assumes that the decay can, at worst, occupy all the wood that was present at the time of the event that initiated it. (How we measure the thickness of this thinnest wall will be explained later.)

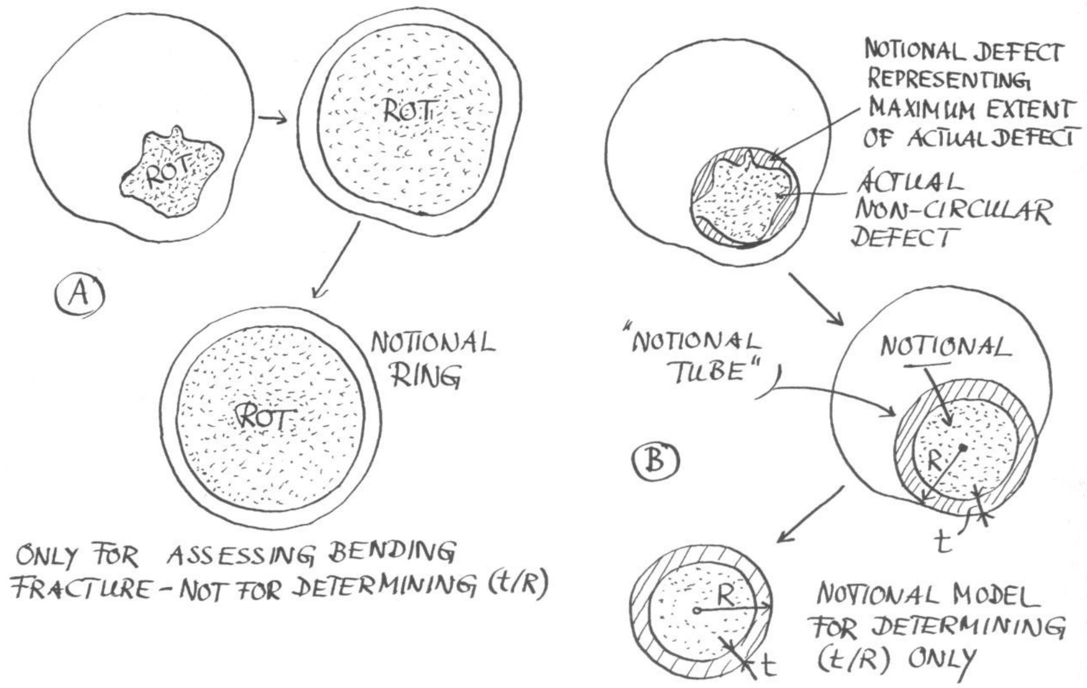


Fig 68. Asymmetric defects; actual size and shape, compared with notional boundaries, giving a better safety margin.

A: For bending fracture.

B: For hosepipe kinking.

It should be noted that the notional defect defined in Fig. 68A should be applied only for evaluations relating to bending failure. It would be to do the tree an injustice if we were to apply the same notional defect when assessing the risk of shell buckling, in which case a larger R value actually has a negative effect in that it gives small (t/R) values. It is then appropriate instead to apply the notional defect shown in Fig. 68B. As we have already mentioned, the VTA tables show that bending fracture usually plays a part only in the case of open cross-sections, and that evidence of safety is usually assured if the requirement (t/R) > 0.3 is fulfilled. These procedures (see Fig. 68B) have been verified for us by Achim Zipse [unpublished data].

The simple acoustic signal from tapping is, however, not unambiguous in every case. It can be misleading, and it is difficult to use when trying to measure the axial extent of defects. One way of obtaining more accurate results is to use an electronic impulse hammer. Dr. Klaus Bethge at the Karlsruhe Research Centre has tested such a device and has adapted it for use in practical tree diagnosis.

8.3.2 Sounding with the stress-wave timer

A not particularly cheap variant of this device is a hammer with a sound transducer, a wave oscilloscope and, for documentation, a thermal printer. A second transducer is placed on the other side of the stem.

A less costly version (Fig. 69) uses two screws inserted on opposite sides of the stem. A hammer blow on one screw sends a sound signal

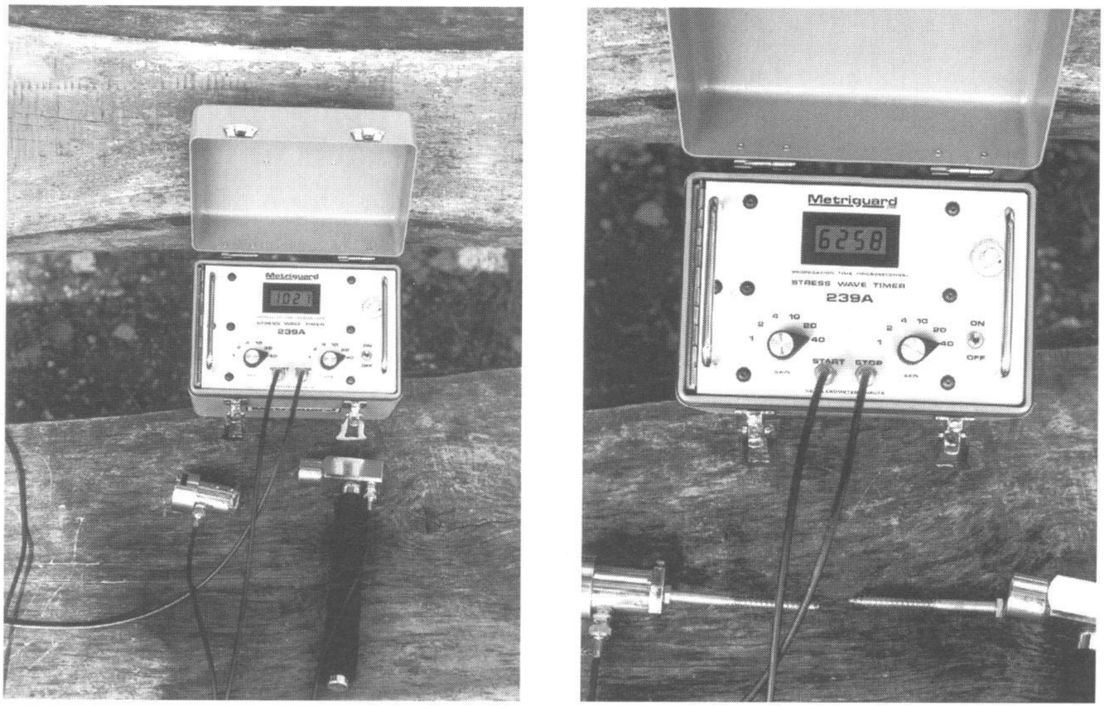


Fig 69. The Metriguard stress-wave timer and accessories.

across the stem to the other screw, which receives the signal and has a transducer attached to it. Long sound transmission times in comparison to the healthy part of the tree indicate defects. Short transmission times indicate freedom from defects. This method, which is used in the USA to detect decay in timber products such as poles, is very good for detecting cases where a very large part of the cross-section is weakened, and equally for ascertaining the axial extent of decay. Unfortunately, however, there are certain types of decay (e.g. that caused by *Ustulina deusta*) which cannot be readily detected by this method, and the operator therefore needs to know the cause of any decay under test. The screw wounds are fairly shallow and, being confined to active sapwood, can be regarded as giving little or no problem. Fig. 70 shows this robust diagnostic method in operation.

The limitation of sounding methods is that they do not tell us much about either the severity of strength loss in partly decayed wood, or the state of the decay process; i.e. is it well compartmentalised or is it still extending? To the best of the authors' knowledge, this question cannot be answered at a reasonable cost without some form of boring deeply into the tree.

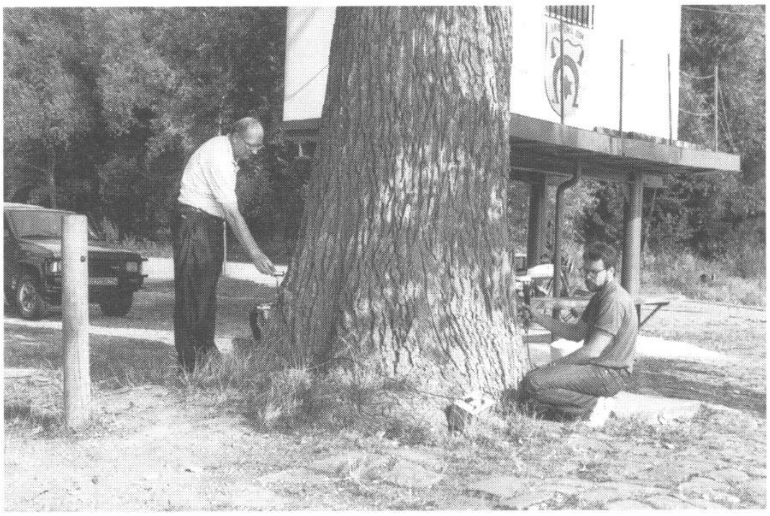


Fig 70. The method demonstrated by Dr. Klaus Bethge and Gerhard Thun in use on a tree.

8.3.3 'Resistograph'

Put simply, the *'Resistograph'* is a 'smart drill' that records how much energy it needs to drill a certain distance into the stem. This energy measurement is naturally a measure of the mechanical properties of the wood [16,60,61] along the length of the drill hole. A rapid fall-off in drilling energy at a certain depth may for example indicate a sharp-edged decay column, which is perhaps compartmentalised, while a steady fall can lead to the conclusion that the wood quality deteriorates gradually with depth. As well as providing this useful information, the *'Resistograph'* has the considerable advantage of making only a small hole that is not likely to cause any serious development or extension of decay. The authors see it as a good practical tool, especially as a somewhat cheaper version has become available recently for field use.

Thorough field evaluation of the *'Resistograph'* is being carried out at the Karlsruhe Research Centre in co-operation with others, and this should reveal the full potential of the device. Work is also under way to evaluate the effect of various decay types on the mechanical characteristics of the material. The results of these studies should make it possible to say which mechanical properties (modulus of elasticity, breaking strength, breaking energy etc.) correlate best with drilling energy.

8.3.4 'Fractometer'

In the course of a safety inspection, measurements sometimes indicate that the thickness of wood surrounding a defect is close to the minimum needed to provide an acceptable safety margin. It is then important to test the strength of this wood. A test core is taken with an increment (Pressler) borer from the defective zone that has been detected from an external sign of decay or a symptom recognised by applying the VTA system. This core is now broken at approximately one-centimetre intervals by manually winding a spring-loaded rotor in the 'Fractometer'. This little measuring device was conceived at the Karlsruhe Research Centre and produced by Erich Hunger and co-workers in Wiesloch, with much loving attention to detail. Each time the core breaks, the bending moment, M, is recorded from a scale on the instrument. The angle, ϕ, through which the core bends immediately before breakage is also recorded. When, in the following formula, $\phi = \alpha$, fracture occurs.

$$U = \int_0^{\alpha} M d\phi \qquad (6)$$

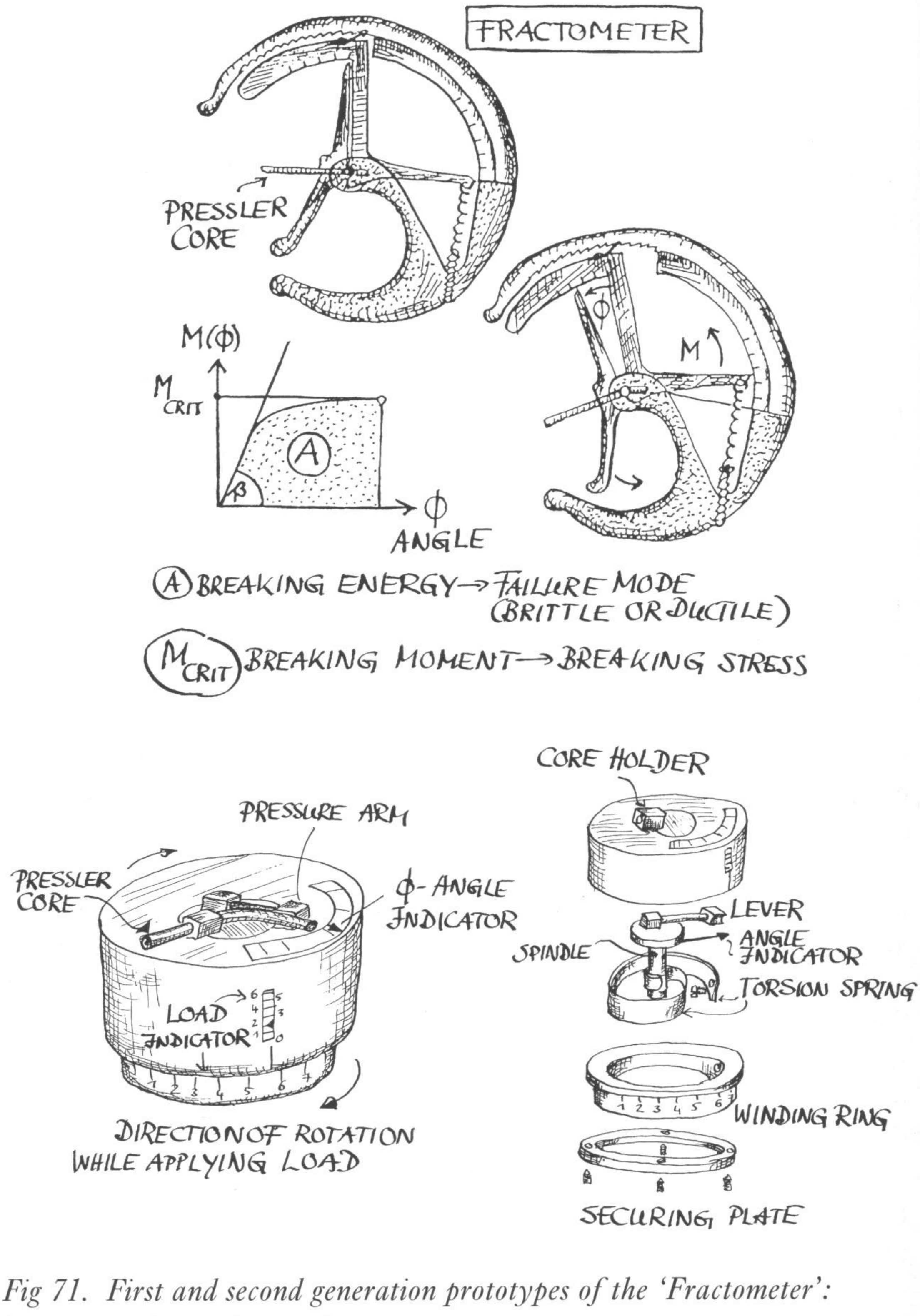


Fig 71. First and second generation prototypes of the 'Fractometer': its construction and operation.

The area under the M (ϕ) curve (Fig. 71) measures the energy that must be expended to break the wood sample. From the point of view of fracture mechanics, this, together with the directly recorded breaking moment characteristic of the material, is the one which best represents

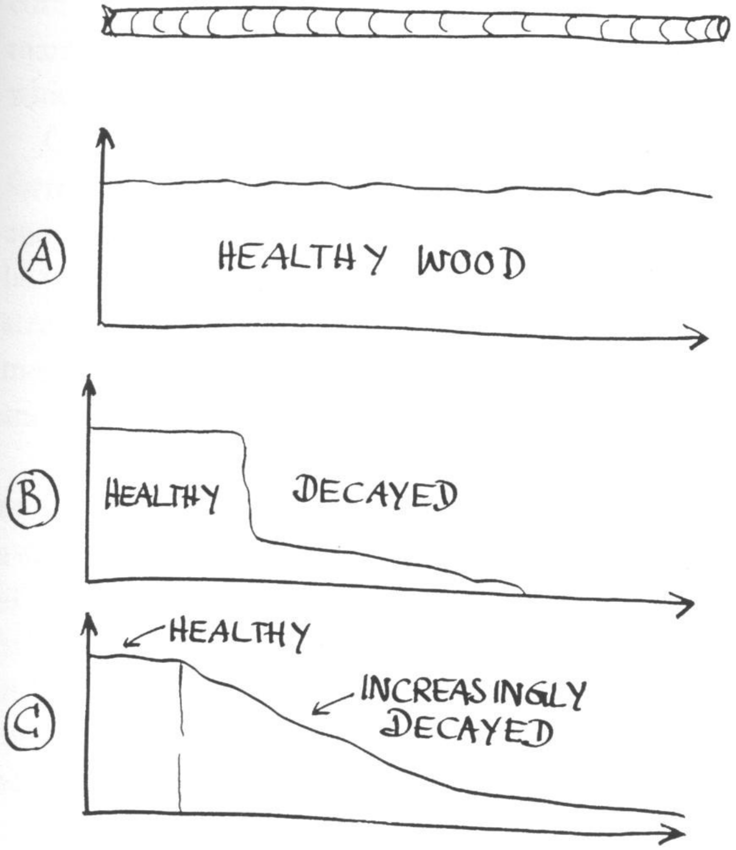


Fig 72. Typical breaking load or energy distribution along the Pressler core, measured by the 'Fractometer'.

A: Healthy tree without defects

B: Tree with well compartmentalized defect.

C: Tree with poorly compartmentalized defect.

the breaking resistance of the wood. Fig. 72 shows some typical breaking energy profiles, plotted along the length of cores taken through wood surrounding cavities.

The question suggests itself, why is the breaking angle measured in addition to the breaking moment? Naturally the breaking moment alone gives valuable information, but it can give incomplete information for wood that breaks in a ductile fashion. A comparison with something from everyday life should illustrate this. Take a biscuit and a fresh bread roll and try to break them. The roll breaks much more gradually and at higher bending loads, since it obviously goes through a much greater ϕ deformation in the process and is tougher. This means that it has greater breaking energy (Fig. 73), which distinguishes it from the biscuit which fails abruptly. Even so, someone who was short of time and needed to make a quick decision would find it easier if, instead of initially trying to calculate the area under the M (ϕ) curve, he simply read off the breaking moment and angle. The little bit broken off is discarded and the next measurement can be made. If the wood is brittle, the values given for breaking energy and breaking moment are very clearly lower.

The authors are naturally aware that this *'Fractometer'*, described in reference [50], is not the discovery of the century but merely a practical little device for the tree specialist at what is certainly a reasonable price. In all modesty though, the *'Fractometer'* provides a result that can be documented and that can also be presented to a court of law in written

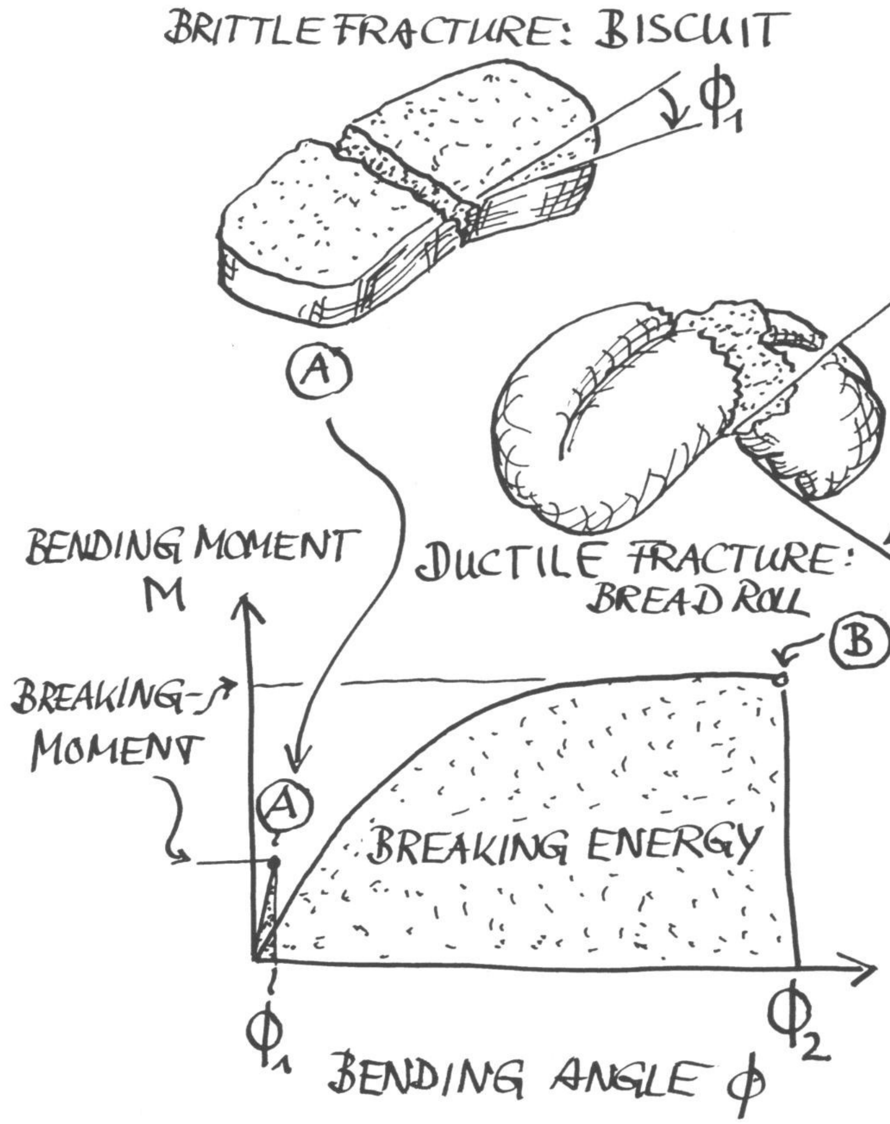


Fig 73. Abrupt wood fracture (A) with little breaking energy, like a brittle biscuit, and a benign wood fracture with high breaking energy, like a tough bread roll (B).

form. It represents an advance over the experience that many of us have had after merely handling an increment core. One looks rather helplessly at this slightly brown-stained object, poking at it with a finger, and wondering whether it could possibly confirm what the practised ear or the impulse hammer had perhaps told us when the tree was sounded. We see enormous potential for this little pocket testing machine, in the wood processing industry, especially for the '*Fractometer* III' which can measure nearly all strength properties which are relevant to the failure of wood or wood products. Many problems of wood testing such as the crushing effect of clamping samples for tensile strength testing and the need to avoid knotty zones can readily be solved by using increment core samples. Results are impressively reproducible. Erich Hunger, the manufacturer, has improved the *'Fractometer'* with many good ideas for which we sincerely thank him.

Once an increment core has been extracted, the widths of the recently formed annual rings can tell us something about the tree's growth rate and hence its ability to lay down new wood over the defect. This is, however, no more than very indirect evidence as far as judging the strength of the remaining wood is concerned. The *'Fractometer'* measures the key mechanical properties of the wood rigorously, directly and without compromise.

The angle of the M (ϕ) curve, by the way, is also a measure for the modulus of elasticity across the direction of the fibres. Thus, each time a sample core is broken, we can learn the breaking energy, the modulus of elasticity and the breaking stress at a given point along its length. So, by taking a series of such measurements, we can get a very good indication of the mechanical properties of the wood across the sample cross-section, as well as getting some ideas of whether the decay has been contained.

Just a word about *'the ethics of boring'*. The use of augers and increment borers is not without risk to the tree, as arboriculturists in various countries have pointed out. There is some risk that decay will develop from the resulting hole, and probably a greater risk of the outward extension of any decay that had previously been compartmentalised. In Germany, these risks were voiced by the late Werner Koch, an outstanding specialist in the field of tree evaluation, who convincingly warned against the casual use of increment borers both orally and in writing. This warning was completely justified, and it is indeed unacceptable to inflict a bore-hole on a tree that is merely suspected of being defective. However, there are ways of making sure that the *'Fractometer'*, and hence the increment borer, is used only where strictly necessary for hazard assessment. This means we must first apply a planned series of other methods, starting with visual assessment (VTA) and then other techniques such as sounding (with or without electronics) or the use of relatively harmless devices producing narrow drill-holes such as the *'Resistograph'*. This can be done by following a 'recipe', as explained later in this book. If a core eventually has to be taken, it is not just tossed aside after a cursory glance but is guaranteed immediately to provide the required information on the fracture mechanics. Especially in the case of poorly compartmentalised decay, the thickness of the effective remaining bearing wall can be ascertained only from a core. We therefore consider it justifiable to bore a tree before it is condemned to be felled.

8.4 PROCEDURE FOR MECHANICAL TREE ASSESSMENT USING THE VTA METHOD

The evaluation procedure is presented as a flow chart in Fig. 74 and also a field guide in Chapter 14.1 where it forms a recipe that includes all the VTA diagrams needed for defect evaluation. The fundamental first step is the visual assessment, which involves not only mechanical criteria, but also a judgement of the tree's biological state of health, taking into account features such as foliation, bark condition and the presence of any fungal fruit bodies. While the tree is being evaluated for soundness, it is particularly important to look out for possible symptoms of mechanical defects, that is those structural repairs that have been described in earlier examples.

If a reparative symptom is found, the only assumption that can be made in the first instance is that the tree has a defect which it is attempting to counter by means of adaptive growth. *On no account must every tree bearing symptoms be immediately felled!* In the human sphere this would mean dispensing with all medical treatment and the immediate liquidation not only of all who are ill, but also of all those who are recovering. Both are inconceivable.

After identifying a symptom visually, – which the practised defect hunter can in fact occasionally do even from a moving car – the defect can now be evaluated in detail with more refined methods such as sounding with or without electronic aids. In a simple hammer test, decayed areas sound dull, while undamaged areas sound brighter. Cracks or zones of kinked fibres can barely be detected acoustically.

If, for example, a decay cavity has been located by recognising symptoms and/or sounding methods, it is now necessary to determine the thickness of the residual load-bearing wall's cross-section. An initial indication of this can be obtained with minimal injury to the tree by examining the shavings from a narrow drill bit, or with the *'Resistograph'*, which provides information about the mechanical properties of the wood over the stem cross-section. If the results indicate that the thickness of the effective wall is close to the minimum value, it becomes necessary to take increment cores so that the wood strength over the cross-section can be directly measured with the *'Fractometer'*. Although the cutting of increment cores might increase the risk of the extension of decay, it is morally justified in such cases, and is indeed essential to provide information which may help to avoid the unnecessary felling of the tree. To the best of the authors'

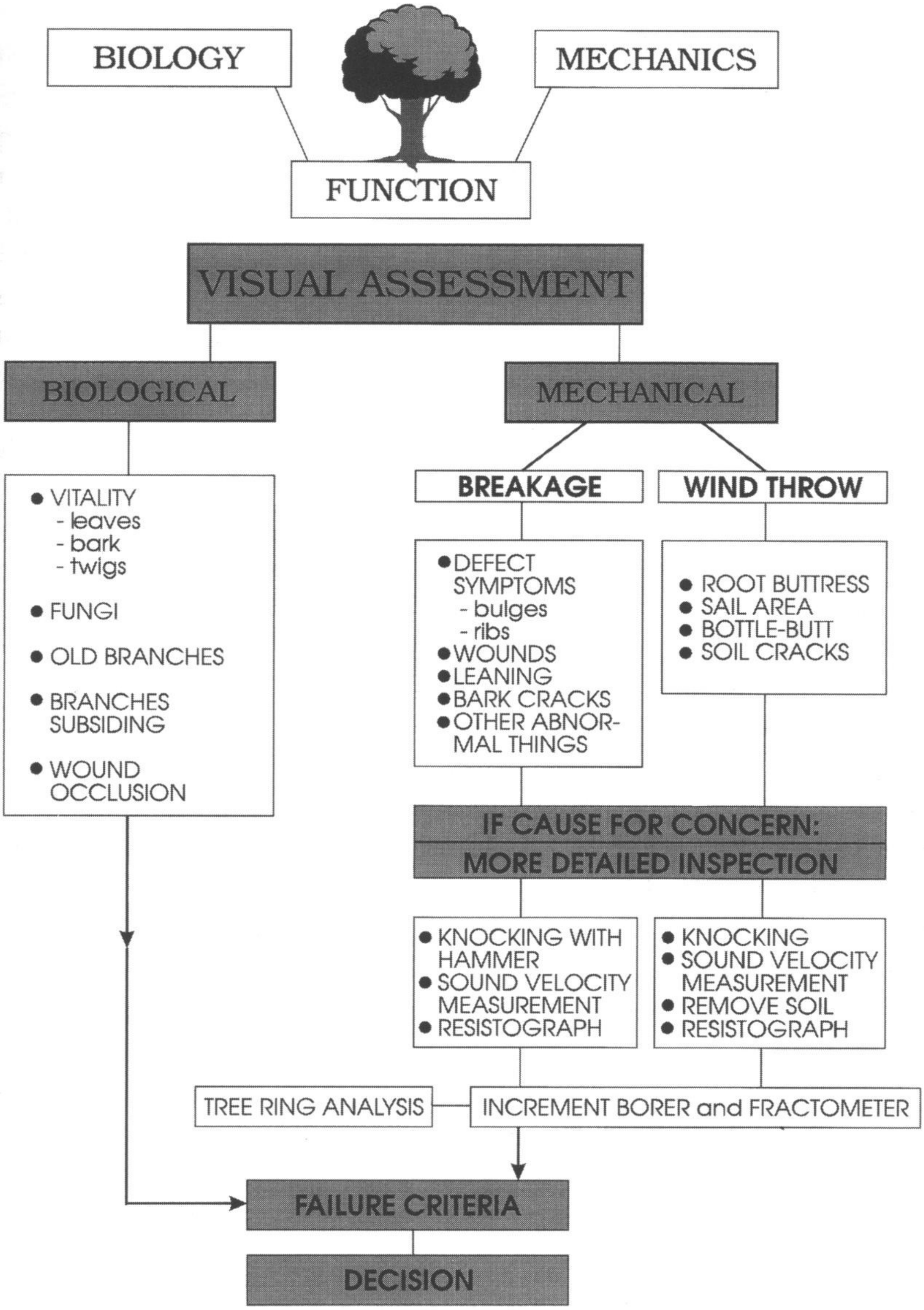


Fig 74. Schematic representation of the procedure for evaluating a tree with the VTA system.

knowledge, which is supported by comprehensive research in Germany and abroad, it is not possible in the present state of the technology to obtain this information without Pressler cores.

Once the *'Fractometer'* breaking strength has been assessed, simple calculations provide the resistance moment for the residual cross-section and from this the bending stresses in the defective area. If the tree has restored the condition of uniform stress by laying down additional material, then the tree can be retained without further action. In addition to this, it must be shown that the hollow cross-section is not splitting, bulging, flattening or in any other way changing its cross-sectional shape, because such deformations would alter the moment of bending resistance and hence the stresses, so that the *Axiom of uniform stress* could not be invoked. To aid all these stages in the procedure, the practitioner should refer to the VTA failure criteria in Chapter 14.

If a recent violent event has been responsible for the defect, there will obviously not have been enough time for adaptive growth to have produced a symptom, or to have corrected the increase in stress. In such cases one must combine a biological assessment with the use of the VTA diagrams. Thus, by assessing the vitality of the tree it is possible to decide whether the tree is likely to be able to repair the damage, thus producing symptoms in the process. At the same time, the VTA diagrams should be used to decide whether the tree has a sufficient mechanical reserve (i.e. safety factor; see Chapter 10), to compensate for the present weakening of the structure. If both tests turn out in favour of the tree, then it is given a period of probation in which to repair the defect. If not, one has to consider whether felling or pruning is necessary.

Once again, here are the essential steps in the tree assessment procedure.

1. Visual assessment: Is the tree in good health (vital)? Are there any symptoms of defects?
2. Sounding and/or using fine drilling methods to evaluate the defect further, i.e. locating its axial extent and identifying the weakest places – usually also at the point of most pronounced symptom development (the stress-wave timer gives better results and they can be documented).
3. If there is an increasing suspicion that an unstable defect is present, this is investigated by drilling with an increment borer and testing with the *'Fractometer'*; the thickness of the residual wall is determined and its strength established.
4. Evaluation of defects, applying the VTA failure criteria in Chapter 14.

5. Remedial action: if the defect evaluation gives proof that the risk of breakage is high, and if the tree lacks vigour, the dangerous part should be reduced, supported or removed, depending on circumstances and the type of tree. If it must be retained because it is a particularly historic or unusual tree, then it can be made safer by, for example, roping it off, sensible crown reduction (only if decay has been compartmentalized), additional support with a restraining belt of the Schröder type [63], or cabling.

The tree evaluation scheme presented here has the advantage of not requiring an estimate of wind load – something whose feasibility, especially in urban areas, is doubted by the authors among others. One problem is that the windspeed in an urban area can vary greatly between, for example, a secluded corner of the churchyard to a gusty street corner. Added to this, there is variation in the resistance coefficient C_w between trees even of the same species, let alone those of different species. To cap all this, trees actually change their wind resistance with the wind speed, much more so with some species than with others. Against this background of different and largely unknown factors working with and against each other, it is a delusion to imagine that the wind load can be reliably calculated.

The VTA method suggested here is based on the *Axiom of uniform stress* and therefore on the Darwinian view that the tree at each location knows for itself just how thick and resistant to bending it has to be. Otherwise the species would not have survived. If, therefore, we want to know whether the tree can be left alone, we only have to check whether the symptomatic part shows the same stresses as it did before the defect appeared, and also whether or not it is likely to fail by hosepipe kinking etc. Since the only requirement is to compare the healthy and defective cross-sections of the tree, we can happily dispense with the use of strength tables, which provide averaged ideal values that may not apply with accuracy to the particular tree concerned. In contrast, it can be safely assumed that the accuracy of the VTA comparison of the cross-sections is the greatest that can be achieved, especially if wood strength assessment in the affected region is carried out with the *'Fractometer'*. Furthermore, local increases in bending stresses only play a role in the fracture of trees where the cross-section is gaping very wide open, as the VTA diagrams in Section 14.1 will show. In the usual case of closed or only moderately open cross-sections the condition $t/R > 0.3$ is usually completely sufficient if the residual wall is of sound wood.

Thus, we have reduced everything to the technical problem of ascertaining the thickness of the residual wall as accurately as possible, and today that is already feasible, with minimal damage to the tree using the *'Resistograph'*. And there is no doubt that the next few years will bring further technical improvements.

The world would be wonderfully uncomplicated if people could be spared the considerable alarm caused by trees that break without giving any prior warning of symptom formation or, indeed, even without noticeable wind loading. The next Section is devoted to damage of this kind – which is to do with the embrittlement of the tree. The summer fracture of green limbs ('summer branch drop'), which seems to be related to water shortage is described in Chapter 13.

9.0 UNPREDICTABLE TREE FRACTURE

9.1 ASYMPTOMATIC DEGRADATION OF MATERIAL

Mechanical components generally fail if, at some point within the structure, the stress reaches a critical value for the material concerned. We will refer to this value as the breaking stress. A distinction must be made between failure under a compression load and a tensile load; in the case of wood, the tensile strength is often about double its compressive strength. Thus it is easier to cause fibres to kink by compressing wood, than to break them by pulling. This means that when trees fail under a bending load, the failure usually begins on the compressed side of the bending zone due to fibre kinking before the fibres tear on the side under tension.

Written down as a formula, the failure criterion is therefore fulfilled if

$$\sigma = \sigma_{crit.} \qquad (12)$$

stress applied = breaking stress

where σ is the greatest stress somewhere in the structure and $\sigma_{crit.}$ is the failure value that has to be determined experimentally as the characteristic value for the material. In some situations, as we saw in the case of hazard beams, the processes leading to potential failure are determined not by compressive strength, but by the tensile strength perpendicular to the grain. We are less concerned with this distinction when dealing with critical stress, $\sigma_{crit.}$, which is the stress at which the wood begins to fail regardless of the type of failure.

In dealing with defects and their symptoms, we learnt that the introduction of defects into the tree can disrupt the even distribution of stress *(as conceived in the Axiom of uniform stress)*, so that local concentrations of stress occur. These stresses are represented in Equation (12) by the value σ. They can be corrected by the response of the tree's cambium in laying down extra material, which incidentally serves us as a warning symptom of the situation. This is the tree's answer to its misfortune, but there are some types of defect to which it cannot respond adequately. If, then, the concentrations of stress are not corrected, the left hand side of the equation can become bigger and bigger until the critical value for the material, $\sigma_{crit.}$, is reached and the tree fails.

A particularly treacherous type of failure process occurs when wood is weakened without there being any local increase in stress, so that the tree is not stimulated to compensate for the weakness by laying down extra material. This means that the left hand side of Equation (12) remains constant, while the right hand side decreases. This happens particularly with brittle decay, which reduces the breaking stress (or breaking energy) of the affected wood, but does not reduce its stiffness, as measured by Young's modulus of elasticity.

When decay weakens wood without making it less stiff, the flow of forces streams happily through the decay zone, so that the stresses in the vicinity of the cambium are not increased. In these cases the tree is, so to speak, satisfied with its figure – all stresses are evenly distributed. The tree has no reason to restore the damage (and thus to provide some warning symptoms) because there are simply no concentrations of stress to make it aware of its plight! Meanwhile, failure has become more likely because the $\sigma_{crit.}$ value on the right hand side of Equation (12) is reduced due to the brittle decay. The same can also happen due to other changes in wood which make it brittle, although still very little is known about this. We should just be content simply to know that the quality of the material has deteriorated and accordingly $\sigma_{crit.}$ is reduced. Because of this, even the normal working stresses that result from wind loading are enough to fulfil Equation (12) and to initiate failure in an embrittled tree. The tree can even fail under its own weight, particularly if it is a leaning tree. The moisture content of the wood also plays a part in brittle failure, as tree people well know.

Once again: there is an essential difference between predictable and unpredictable stem failure. In predictable failure, the stresses increase even though the strength of the material might not have deteriorated. In unpredictable failure, the stresses remain the same despite a deterioration in wood quality. *But because growth symptoms appear in response to increases in stress, there can be no such symptoms at all in cases where the material deteriorates but the stresses remain constant.* Neither can it be of any use in such cases to carry out tree-pulling tests to see if the stem shows increased flexure. Apart from the fact that brittle decay does not increase flexure, there is no way of knowing at which height the strain measurement should be made – unless the zone of potential failure is known, which it cannot be without using other techniques. It is even possible to imagine that the test load applied in one direction of pull or the other could initiate micro-injuries which might increase the danger.

When, in such cases, we describe *failure* as unpredictable, we do not mean to say that the *presence of defects* is undetectable. Areas of brittle decay, for example, can often be recognised by the skilled practitioner who is familiar with external signs of decay, even in the absence of large fungal fruit bodies [76]. Even the less obvious kinds of weakening, that occur from changes in the wood structure, can to some extent be predicted, although this requires a rather uncertain kind of medicine: experience! Thus, the seasoned inspector with long years of practical experience has seen so many cases of brittle failure, in old chestnuts or poplars for example, that he can often sense where the weak points are. Ultimately though, this practitioner is as helpless as any of us if he is required to say something about the 'safe' length of life remaining to a tree.

If brittle decay has been detected, or if weak points are suspected on the basis of experience, the *'Fractometer'* may be able to tell us whether the weakened zones are large enough to pose a hazard. Experiments have so far indicated that the *'Fractometer'* can measure strength reductions in brittle decay which would not be immediately obvious from merely examining a sample increment core. Especially in the case of the early stages of brown-rots, the *'Fractometer'* will register a reduction in breaking energy and breaking stress before there is much loss of density. Such rots, except when well advanced, exhibit an almost ceramic-like fracture face whose hardness even withstands a hunting knife extremely well. In such cases, only the *'Fractometer'* can provide the evidence here of reduced breaking energy (brittleness) under field conditions.

The *'Fractometer'* can also be used to detect embrittlement caused by changes in the wood structure. If such changes occur, they can cause breakage in structural formations which in their own right are points of potential failure. Unfortunately, suspicion of such failure often applies to some of the loveliest old trees. Roping such trees off is sometimes the only way to preserve these doughty veterans without endangering passers-by. If a tree like this has shown any unforeseen fractures, the *'Fractometer'* should provide a means of detecting any changes in the material properties of the wood, using comparative sample cores from various places in the tree. The results might at least help to show whether there was any negligence on the part of whoever was responsible for the tree. Thought might then also be given to undertaking *'Fractometer'* tests on similar neighbouring trees.

Apart from this, there are a few indicators of a general nature that can provide a helpful checklist both for the experienced practitioner and the relative novice. These are set out in the next section.

9.2 WEAK SPOTS AND POINTERS TO THEM THAT ARE NOT THE RESULT OF EXTRA GROWTH

Even if sometimes we cannot foresee fractures that result from changes in the wood, there are signs that could make us suspect that they could occur. We need to ask the following questions:

- Does the tree look generally old and decrepit?
- Are there limbs that appear to be dead or excessively long or heavy?
- Have such limbs perhaps already got branch-shedding collars, i.e. ring-shaped potential fracture points at their bases?
- Are there cracks in the crotches of pressure forks?
- Are there branches that have subsided at localised 'hinges' with loosened bark and/or axial bark folds on the underside?
- Are there longitudinal cracks in the bark on the compressed sides of bends and transverse cracks on the sides under tension? Do these cracks cut across the bark plates? (Fig. 75)
- Are there cracks in cavity fillings or wound sealants?
- If any steel cables or bands are present, are they taut or perhaps slack; also, if there are washers on tie-rods have they sunk in as if stamped in?

With the exception of the branch-shedding collar, these symptoms are formed not by adaptive growth but through passive changes in the tree's form. You can add to them as you wish. The collection of examples at the end of the book will do. Once you have assembled your perhaps incriminating evidence of impending failure, you need to ask one general question: *Are there any indications of slow, creeping changes in the tree's form, i.e. signs of passive deformation in response to gravity and wind?* We can recognize these passive symptoms most easily in brittle parts of the tree, i.e. in the bark, in cavity fillings or wound sealants. The sinking of washers into the wood as a result of overloaded tie-rods is also a passive symptom, and so on...

By the way, when we recognise transverse cracks in bark or areas of loose bark as a symptom of stretching in the wood below, we are applying a principle used in tests on ductile steel. A brittle varnish is applied to the area of the steel sample which is expected to show a plastic flow in the test. If such flow occurs, so that the steel stretches considerably, the varnish cracks and some of it flakes off. The rhytidome (outer bark) on a tree loosens in exactly the same way when the wood stretches strongly and also when growth is vigorous under the affected area of bark. Such growth can occur locally during active formation of

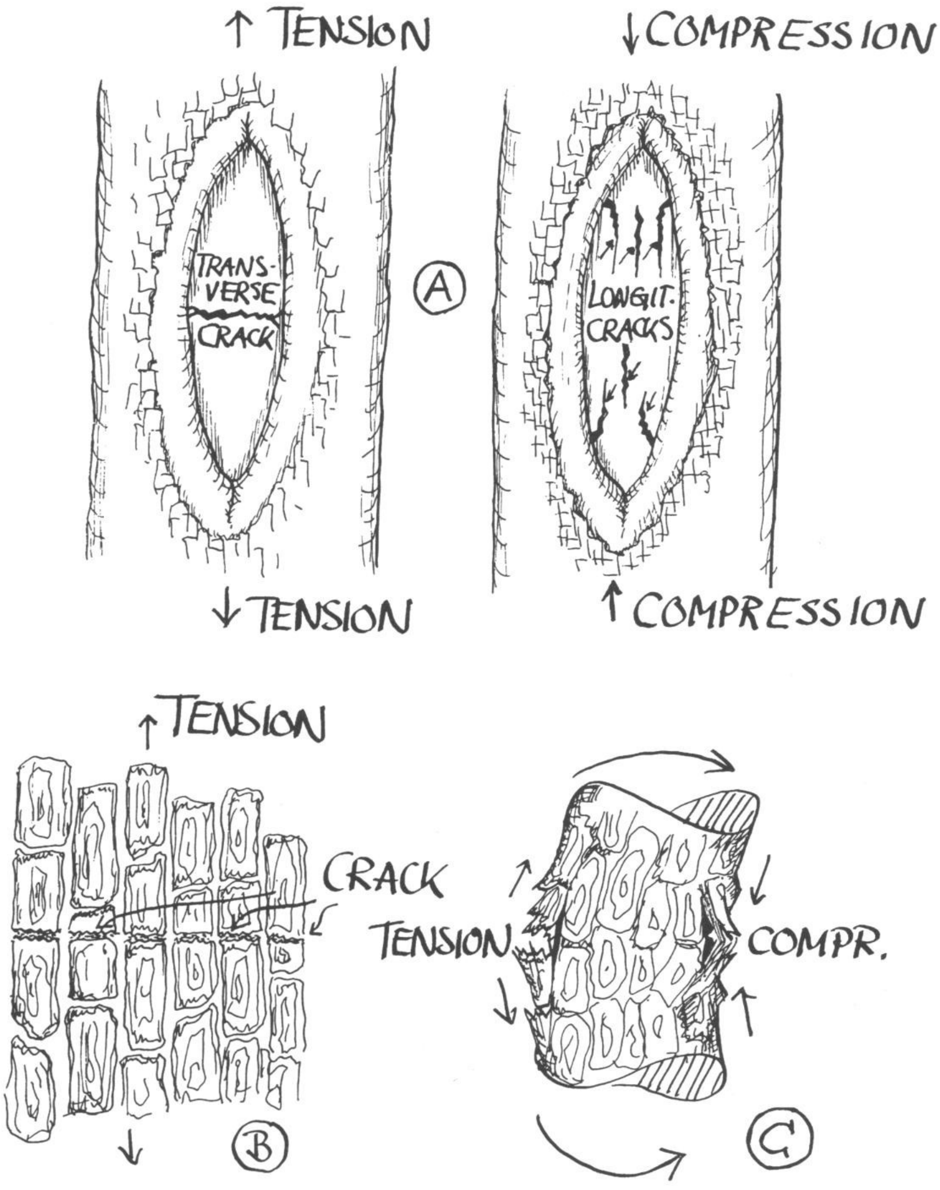


Fig 75. Indicators of defects, formed passively with little change in configuration.

A: Cracks in cavity fillings or wound sealants (transverse [tension] or longitudal [compression]).

B: Cracks across bark plates (tension) at a uniform level.

C: Locally increased loosening of pieces of bark cortex (tension or compression or bark buckling [compression]).

swellings (symptoms) in response to mechanical stress. The bark plates in such areas can often be pulled off more easily than from less mechanically compromised areas on the tree's surface. *The bark is in this sense the tree's varnish.*

We can at this stage look again at the branch-shedding collar, which was described in Chapter 5. The collar at the branch base is formed actively by the stem [37,38,39]. If the branch is vigorous, the collar will form part of a smoothly flared branch base, since the branch is adding enough wood to fill out the ring notch at the edge of the collar. A less healthy branch takes on a more passive role, and so allows this abrupt notch to form, perhaps showing how tired it is of life and how much it looks forward to falling (Fig. 76).

This brief excursion into the world of unpredictable damage, or rather of damage not betrayed by actively formed symptoms, shows us that a great mistake was made by certain authorities, at least in Germany, who gave the impression in the past that tree safety could be diagnosed with absolute certainty, given enough costly experimental proof. We only have to look at failures due to hazard beams, torsional fractures, shearing failures and torsional bending fractures consequent on branch flailing as well as all fractures of double stems to realise this. *There will never be an absolutely stable tree! – A natural failure rate even among completely healthy trees is the price to be paid for the energy saving lightweight structures of Nature. The demand for an absolutely safe tree is therefore contrary to the logic of the laws of nature.*

Those who wish to live with trees must similarly be able to live with a certain degree of risk of those trees breaking. We should at least accept this in the same way as we are ready and willing to do in the case of the not infrequent failure of mechanical components. Not long ago, one of the authors witnessed the sad fate of a nifty little sports car going along at about 30 m.p.h., which broke its axle and did the splits in a most deplorable way, despite having been designed to hurtle along the motorway at 120 m.p.h.

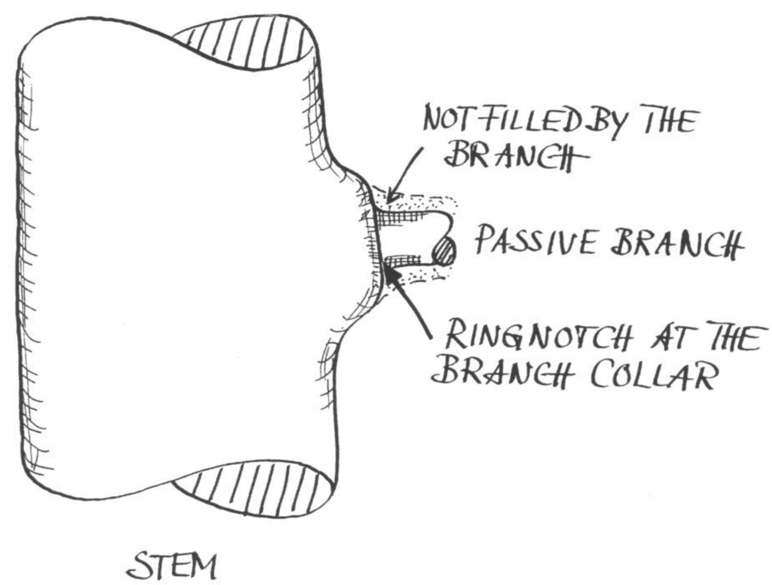


Fig 76. The branch-shedding collar as a product of active stem growth but passive branch behaviour: the ring notch is not filled in with branch wood. The branch no longer does anything to optimize its own configuration.

There is honestly even less reason for getting hysterical over tree safety than over the safety of machines. Trees attempt – whenever possible – to repair themselves by adaptive growth, while the component of the machine, as a lifeless object, stoically allows its crack to develop and waits to be written off without any hint of a response.

One particular role of this chapter is to emphasise that the concept of unpredictable failure can have important legal implications, as will be explained in detail in Chapter 12. Anyone who ignores a defect symptom is disregarding a warning signal and in certain circumstances is behaving negligently. However, in cases where someone fails to react to a process that is fundamentally unpredictable or asymptomatic, he cannot have the responsibility for any resultant losses laid upon him. *It was a thoughtless error of the past to give categorical assurances of safety without trying to distinguish between types of failure and without taking account of the natural failure rate even among healthy trees.* And it was equally mistaken to give the safety factor for trees as 1.5, a value which -whoever thought it up and for whatever reason – haunts tree specialists.

10.0 SAFETY FACTORS IN ANIMALS AND TREES

Before we start dealing with numerical matters, here are just a couple of quick thoughts about our everyday baggage, our bony skeleton. Excess baggage, even something as treasured as a beautiful antique iron inherited from one's granny, is probably not the sort of thing that you would eagerly put in your backpack when going for a 15 mile walk to enjoy some lovely weather, even if you wanted to prove your own sprightliness. The more you move around, the greater the penalty for every excess pound that you carry with you, and this has played a part in the evolution of things such as a mammal's skeleton. The antelope that carries around more weight of bone than it needs for shifting itself ends up as the first canapé in the leopard's jaws [39].

On the other hand, we would all be prepared to tolerate a little extra weight if we stood still on the spot without moving. This is precisely the case with trees, whose roots don't feel like going for long walks nor are designed to. It seems plausible enough that one's ability to tolerate excess weight is very much related to one's need to move around. Thus we can conclude that the tree, anchored firmly to the spot and subjected only to swaying, geotropic, phototropic and hydrotropic movements, can afford to invest more heavily in material than, for example a gerbil. The thing that now decides just how large this investment should be is the need for a mechanical safety factor. This factor represents whatever proportion of the material that is needed to support special loads; a sort of nest-egg of building material. It is usually defined as follows:

$$S = \frac{\underline{\textit{Breaking stress of the material}}}{\textit{Working Stress}} \tag{13}$$

The breaking stress can take various values for different types of failure; e.g. bending strength of wood when simply bent, the shearing strength under a sliding load and the transverse strength in the case of a hazard beam. The working stress represents the range of stresses that arise in the structural component (bone, tree, claw, muscle etc.) in the course of everyday life. If the ratio between these two values (i.e. the safety factor) is five, then the normal load can be increased fivefold before the component breaks. The fat cat can therefore still afford to jump off the desk without having to go to the vet directly afterwards. Of course there is a limit here too, as Alexander [1] described so well. The preservation of a species is costly when an individual dies and has to be replaced. But it would undoubtedly be more expensive to design each individual to withstand even the most unlikely load. Therefore there is a certain breakage rate in nature and this includes our own bones too. (Incidentally, it would be worth considering how we should cope with this cost of dying in the case of amenity trees. Failure to accept that occasional failures are inevitable can incur high costs for trying to ensure absolute safety: tree surgery, specialists' reports and so on.)

But just how large are safety factors in nature? An interesting list is presented by Currey [14] who refers to work by Rubin and Lanyon [62] among others. The results are pleasingly enlightening. However disparate the animals examined might be (they ranged from dogs via kangaroos and pigs to horses, buffalos and elephants), the safety factor for their bones lies mostly between 3 and 4. This is remarkable, considering, for example, how differently a kangaroo and an elephant move! This can be regarded as a *generalization of the Axiom of uniform stress*. Under normal circumstances, all mammals load their bones to only about a quarter of their breaking strength. The safety factor covers the risk of uninvited higher loadings such as falls, fights and so on.

Alexander [2], by the way, also gives safety factors for the shells of *Nautilus and Sepia* which are mostly not exposed to any unexpected loads. They live at a certain depth in the sea and their only concern is that the pressure of the water column above them does not become too great [2]. You could jokingly compare them with a man who does nothing but lie in bed all day and to whom, therefore, nothing much can happen. The shells of these animals have a safety factor of about S = 1.4. In view of this, it is extremely odd that certain German arboriculturists once seemed to believe that trees, exposed to all the elements, should have a similar safety factor, i.e. about 1.5. The reason that trees have a safety factor of about 4.5 is not only that they need it, but also that they can afford to carry the necessary weight of material, having no need to walk around. Mammals, on the other hand, while also requiring a high safety factor for the strength of their bones, cannot afford to carry excess weight. Thus, their safety factor is usually between 3 and 4.

We do not know of any investigations into the safety factor of trees from the literature. We therefore set up some experiments to investigate this at the Karlsruhe Research Centre, though these have not yet been concluded. Fig. 77 shows the principle. Rectangular windows were cut into several trees which were then left. The increase in stress resulting from this treatment was calculated for us by Jürgen Schäfer using the finite element method. For the size of window and of stem shown in Fig. 77A this amounted to 4.5 times the stress applied to the exterior. If this tree, which has been standing now for almost three years, does not fracture under the load of some future storm, then its safety factor is at least 4.5, i.e. S ≥ 4.5. Trees with much larger windows fractured straight away.

Even the Mississippi beavers have made their contribution to science, as we can see from Fig. 77B. They gnawed this stem on one side only, and so the rest of the cross-section remained intact and the tree thrived. Indeed, the beaver gnawings also gave estimated safety factors of S ≥ 4.0.

The case of the beaver gnawings proves in particular the diagram presented at the bottom of Fig. 77B with the stress s in the notched cross-section divided by the stress value σ_0 in the undamaged circular cross-section plotted against the relative notch depth. Compared with a stem that had an ungnawed cross-section, the tree that broke (on the right of the sketch above) had stress values about five times higher, while the one that is still standing (left) had value about four times higher.

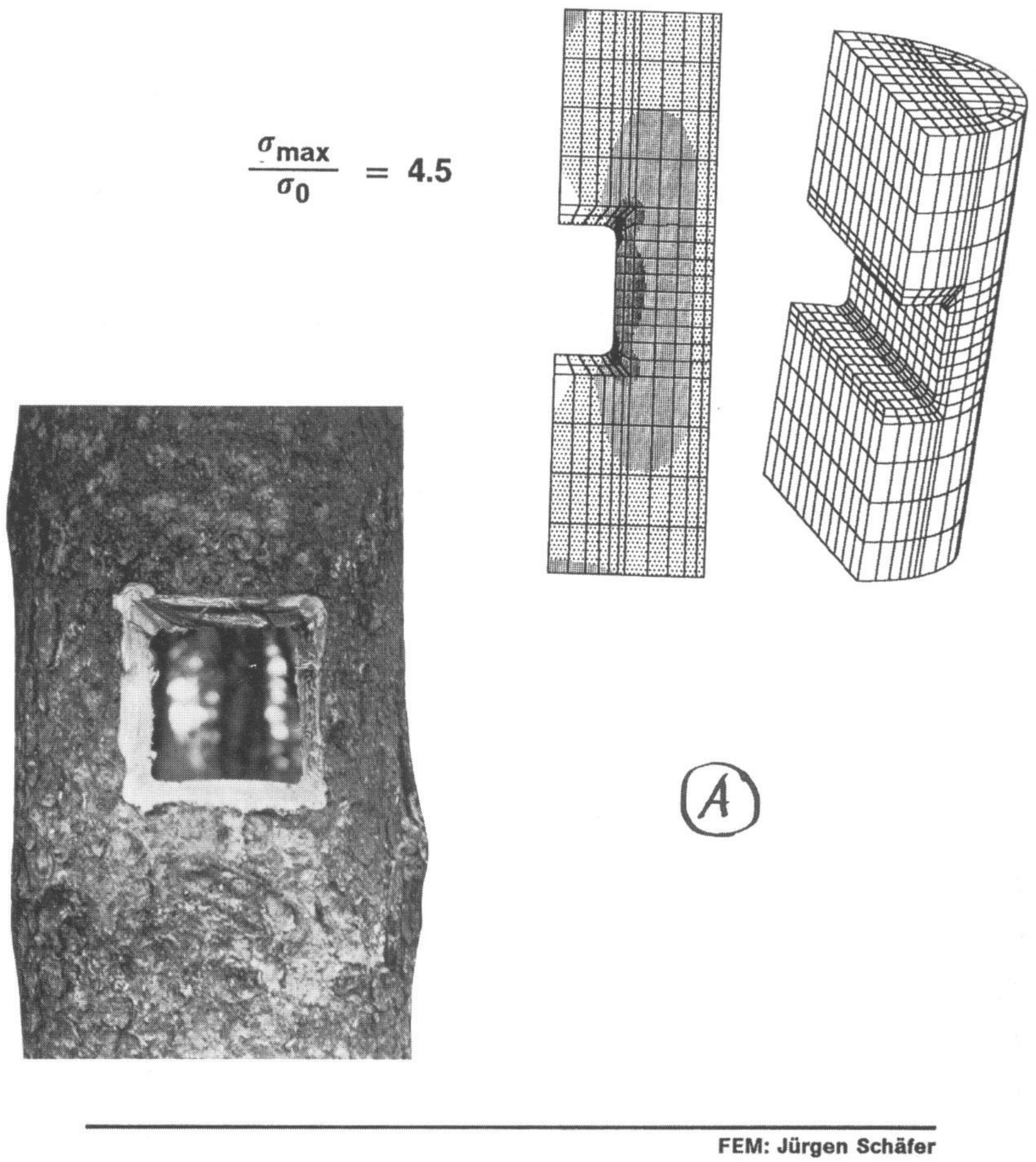
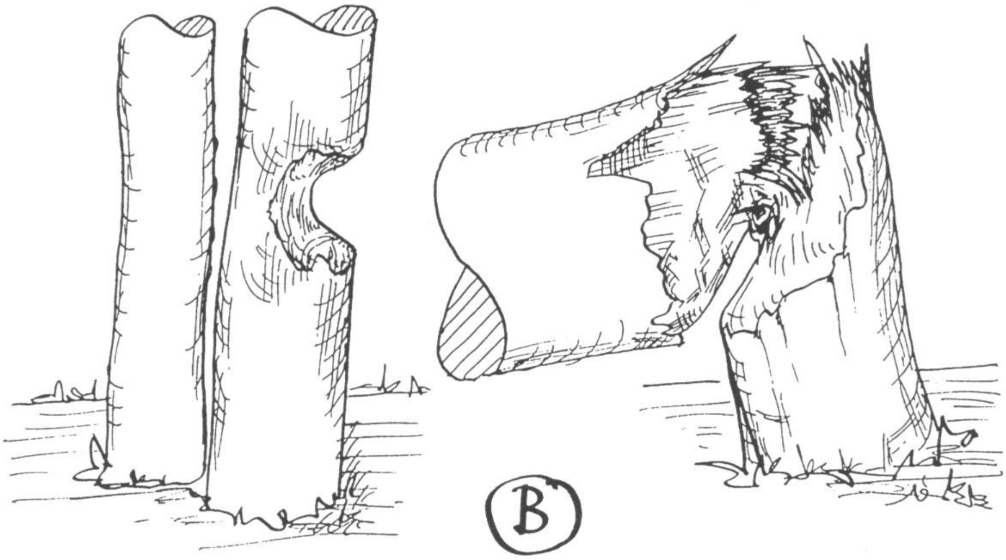
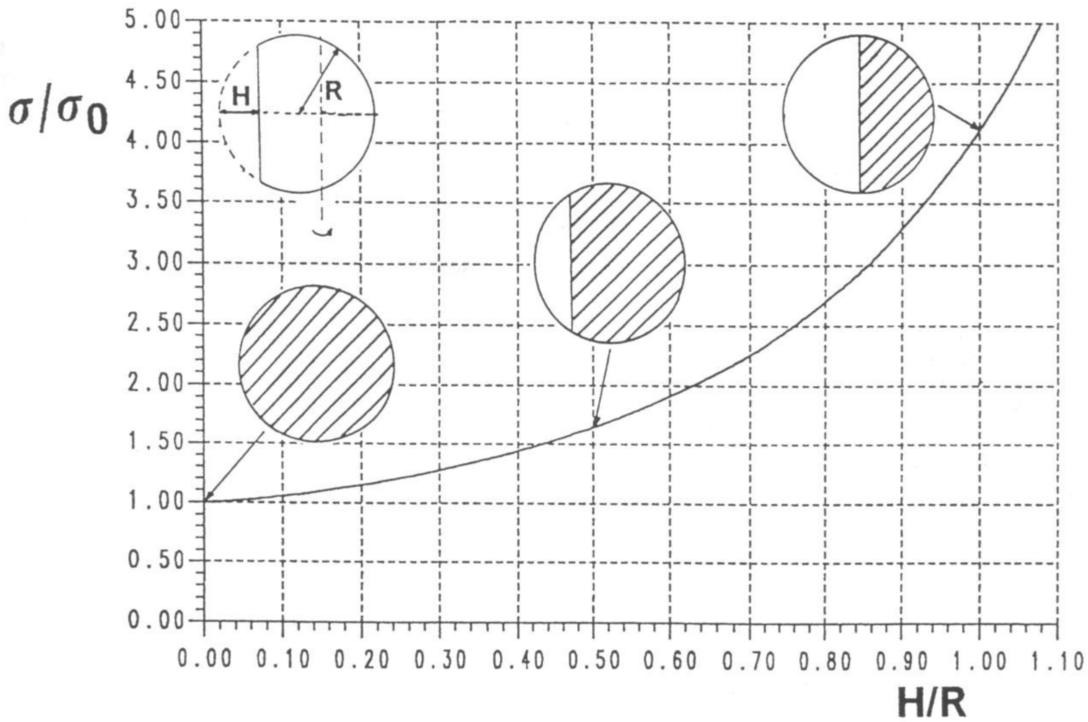


Fig 77A



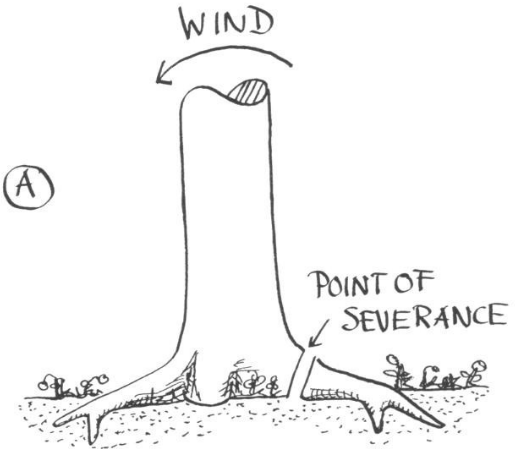


Computing: Dagmar Erb

Fig 77. Field experiments for determining the safety factor in resistance to stem-breaking in trees (sawn sections: Jörg Sigmund).

A: Window cut in tree.

B: 'Beaver gnawings and related increase in stress' (Prof. Dr. Kübler kindly showed us these trees).



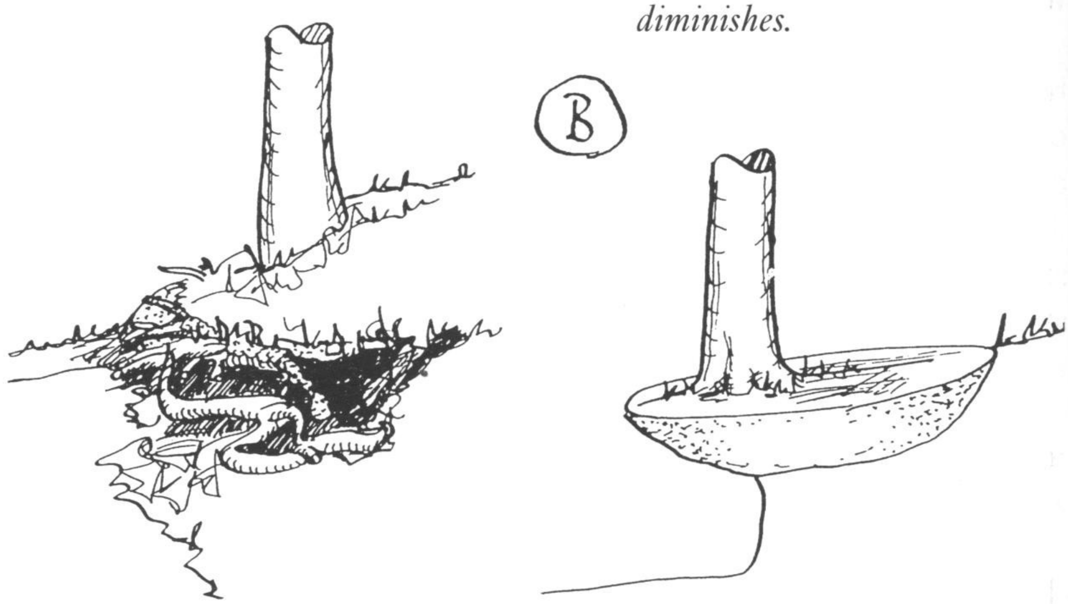
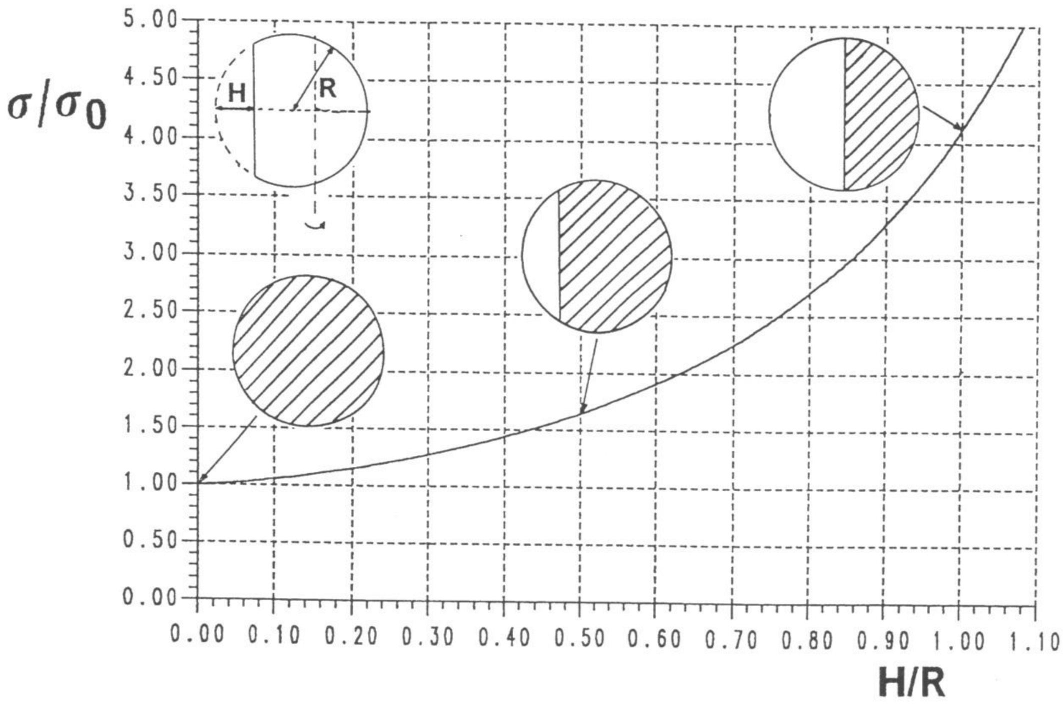


Fig 78. Field experiments for determining the safety factor for tree root-plates following damage.

A: Severed root junction.

B: Tree with roots on one side only and diagram showing the increase in stresses as the size of the residual root-plate diminishes.



Computing: Dagmar Erb

Both trees were fully foliated and fully exposed to the wind. One can be sure that equally good safety factors are built into the root system, since the roots are a continuation of what we understand to be a chain of equally strong links. However, to test this, some field experiments on this subject have been set up, (Fig. 78A) in which buttress roots bearing significant loads were severed. The sacrifice of these trees is the price that must be paid for developing a sound understanding of mechanical safety factors, rather than relying on speculation. These experiments are comparable with earlier preparations of corpses by the anatomists without which we still would not know today where our appendixes were.

We who were involved in the experiments felt deeply within ourselves how close we humans are emotionally to trees. One can keep telling oneself that these experiments must be done in order to assess many other trees better, just as the corpses of those earlier times had to be dissected by the first anatomists – but if you cut through a tree's root and then leave it standing, you have a guilty conscience about it. There are bonds between man and trees that cannot be dismissed, however logical the arguments may be...

Clues to the safety factor of trees can be found even when the wood itself is not damaged (Fig. 78B). This happens when soil erosion exposes a root-plate. Thus, when half of a root-plate has been exposed by erosion, the tree remains standing. The erosion results in a reduction of the bending resistance to a quarter of its former value and seems to confirm that the root system does indeed have a safety factor of at least four, i.e. $S \geq 4.0$.

But what sort of conditions make a tree's safety factor necessary? It seems more necessary in the case of hollow trees with open cross-sections and thick walls than for those with closed cavities, as we shall see later from some examples. In the case of a sound tree, the suggestion is that it needs a safety reserve when periodic gusts of wind set it swaying at its natural frequency. You can imagine this in the same way that a suspended punch-bag can be made to swing widely with very little effort by maintaining its oscillation frequency. This process is called resonance because the natural frequency and the external stimulus match each other. (At branch junctions, where wood strength values are relatively low, as shown experimentally by Dr. Klaus Bethge of the Karlsruhe Research Centre in collaboration with the Forest Products Laboratory, Madison, USA, it is conceivable that the tree is relying rather heavily on its safety factor. In particular, the frequent breakage by snow of young pines at branch whorls indicates that the safety factor there is occasionally used to its limit; in other words the tree does not always cover the risk.)

The fact that trees do occasionally fail even without defects shows that they do not 'try' to attain an excessive safety factor which would involve the squandering of material. Nevertheless, the tentative value of $S \geq 4.5$ for the safety factor of trees may seem high to those unfamiliar with Alexander's work. Incidentally, Gordon [24] reports safety factors of $S = 4$ to 8 in old English bridges of c. 1850. If in spite of this a bridge collapsed now and then, this was probably because the maximum working stresses had been underestimated. This type of error seems quite plausible in view of the fact that the effect of notch stresses was not understood by engineers until much later.

Knowledge of the safety factor is of enormous importance for, in particular, evaluating violent injuries to trees. It also plays a big part where open cross-sections with large openings but thick walls are involved, where hosepipe kinking is not relevant. Investigations into determining the safety factor with precision and complete confidence will no doubt continue for some years yet at the Research Centre at Karlsruhe, just because a few storms must rage before the results can be trusted. This lengthy research period is, nevertheless, also the reason for our presenting these interim results here. The safety factor $S \geq 4.5$ for trees under a bending load requires further confirmation and must be treated by the reader with the greatest of care. We advise most strongly against its uncritical use in the giving of expert opinion until the results have been finally vouched for. Nonetheless, the authors' decision to present it here was based on some pieces of evidence that the safety factor is indeed somewhat larger than $S = 4.5$.

Now that we have presented and defined the limits of the VTA method of tree assessment and explained the tree safety factor, we can turn our attention to other methods which fit less well into the concept that has been presented, but which can be briefly mentioned and evaluated.

11.0 OTHER DIAGNOSTIC METHODS

11.1 PULLING TESTS

In these tests the tree is subjected to a modest bending load, and the resulting strain at the tree's surface on the tension side of the stem is measured by means of a strain gauge. Then, a calculation is carried out, by extrapolation, to determine the wind load on the tree at which the breaking stress of defect-free wood would be reached. As a piece of scientific research, the use of a pulling test is undoubtedly a valuable approach which has added to the long-term development of knowledge in the field of tree mechanics. However, in the light of a thorough study of the current literature, including that in the English language, we must fundamentally challenge the value of such tests for diagnostic purposes. We have set out our reasons for this view [47], which can be summarised as follows:

- *Stiffness measurement says nothing about breaking load*

  Stiffness and strength are two different mechanical properties, independent of each other. In the end it is stiffness that the pulling tests measure, from which the strength (breaking load) is then deduced. A statement made in this way about strength on the basis of a measurement of stiffness is fundamentally inadmissible.

  (Incidentally, J.E. Gordon describes this difference very humorously in his book [24]: 'A biscuit is stiff but weak, steel is stiff and strong, nylon is flexible and strong, raspberry jelly is flexible (low E-modulus) and weak'. It is not possible to make the difference between stiffness and strength any clearer than this to a layman in mechanics.)

- *Only the tree itself can measure the wind load*

  The estimation of wind load on trees is intrinsically very imperfect.

  a. The C_W value (drag coefficient) varies from species to species, from tree to tree within a species and even within a single tree according to the direction and season, not to mention the additional and often unknown effect of the wind speed.

(Reference: Mayhead [53], who, incidentally, determined values for conifers and explicitly warned against using his results because more exact C_W values are required in order to pass judgements.) Mayer [52] considers it almost impossible to use the equation

$$F = \frac{1}{2}\rho C_w v^2 A \qquad (14)$$

for practical purposes because neither C_W nor the effective crown area, A, is known.

b. The sail area, A, remains unknown even if it is painstakingly scanned into the computer using the most refined methods. That is because each individual tree reduces this area in a way that is absolutely beyond calculation by 'laying back its ears' more and more as the windspeed increases.

c. In urban areas the windspeed for each tree in its particular site is practically unknowable. False assumptions mount up in significance here, because the wind force increases with the square of the windspeed.

- *Small tensile loads cannot provide evidence*

The extrapolation of supposedly non-damaging experimental loads does not take into account the fact that trees nearly always break at points of imperfection, defects, branches etc., whose influence is not included in 'strength tables'. Nor are shearing failure or cross-sectional collapse included.

The ideal defect-free tree – if there were such a thing – would in any case be no candidate for a mechanical test. Of the processes leading to a tree's fracture shown in Fig. 79, only the encircled case is to some extent described by the test, though even then only with the proviso that the tree has no branches or other fracture trigger points. For all other damage mechanisms, the pulling test only gives information up to the height at which the load is applied. As the load must be fairly low, at least if the test is to be largely non-injurious, the region covered by the loading is too small. The estimate of stability is therefore completely valueless in these cases while, for the ideal tree, it is superfluous.

- *The configuration of the defect cannot be ascertained in this way*

It is erroneous to believe that one can draw conclusions about the shape of an internal defect, based on a few selected external measurements. We really need as many equations (and therefore measurements!) as there are unknowns. The decayed part may not be circular, or may be eccentric, or have ragged edges, and may vary in shape with height. Selective strain gauge measurements will give no information about such things.

- *The method should not be described as 'non-injurious'*
  It is inadmissible to describe a method as non-injurious if roots are torn when it is employed. Acoustic measurements with buried microphones [12] showed that even a moderate amount of pulling on

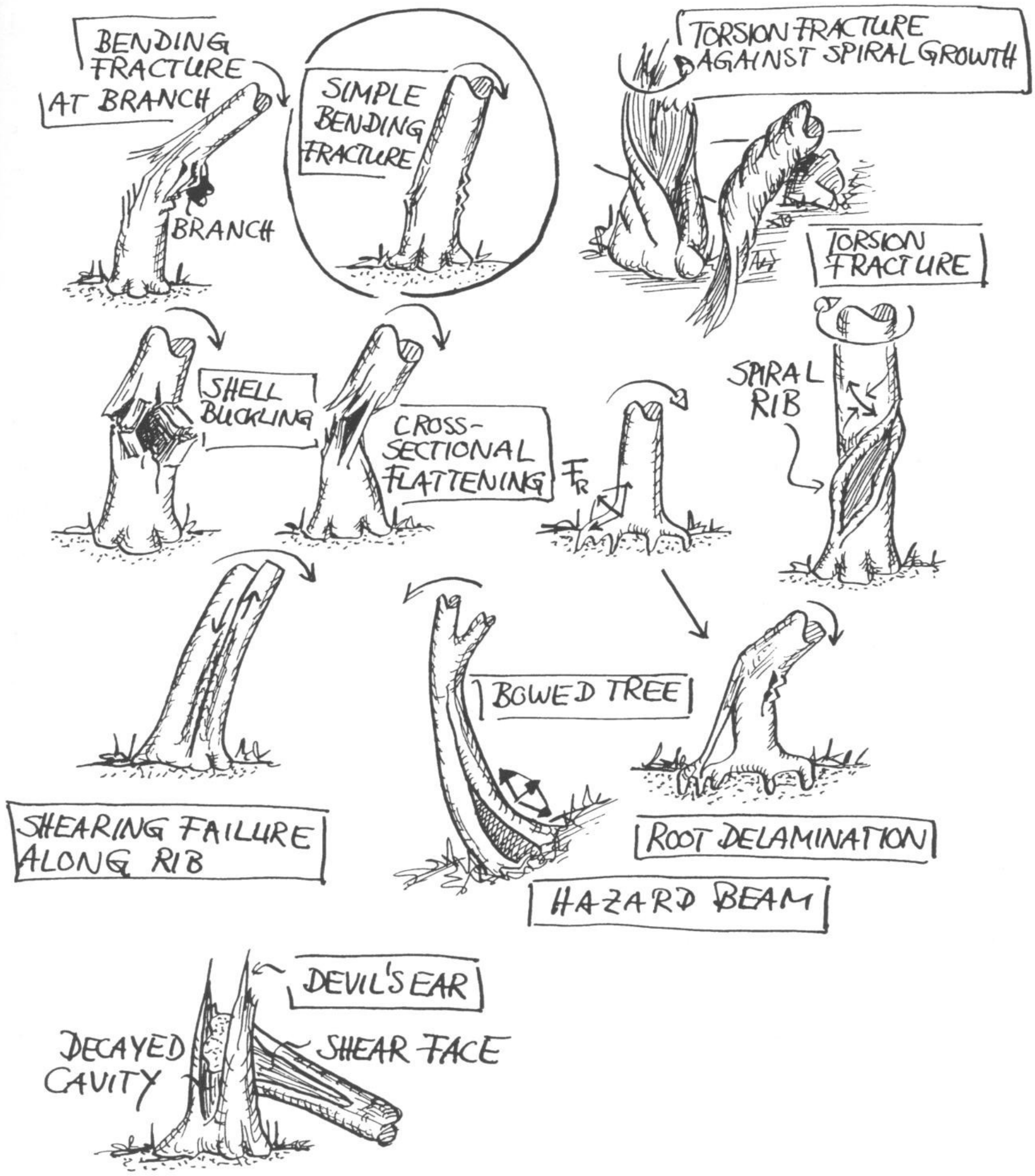


Fig 79. Only the type of fracture encircled here can be anticipated by means of pulling tests and even then only if the tree has the ideal characteristic value given in the strength table.

a tree very quickly caused audible tearing of roots. The argument that the wind also causes root damage has absolutely nothing to do with it. Neither one of them, wind nor pulling test, is non-injurious.

- *A lengthy period under load is worse than wind*

  According to Fraser [21], the static pulling test gives results that are dependent on time because under a steady load the soil yields more and more, so that the holding force on the rope decreases. This, by the way, may cause greater root injury than a more snatching kind of load from wind which allows load on the soil-root connection to be repeatedly relieved in between gusts. When one is relying on a tree pulling test to indicate whether the tree is safe to all intents and purposes, it is inevitable that over-estimates will be made regarding wind speed, the C_W value and the sail area, while the safety factor may be under-rated. In this way one would err on the side of caution at every turn and in some circumstances would give the go-ahead for trees to be felled even when they could be left alone.

- *Similar difficulties regarding resistance against windthrow*

  The shortcomings in the determination of wind load arise in just the same way in testing for stability, which is supposed to rule out the possibility of the tree's falling over.

  In addition, the following also applies here:

  Anyone who wishes to ascertain the breaking load of a tree must break it. It is not enough just to bend it a bit by pulling at it. The same applies to the windthrow load, which can be measured only by pulling the tree over; i.e. causing failure of the root-soil compound material. *Ascertaining breaking load and windthrow load non-destructively by means of pulling tests is in principle not feasible.* Nothing therefore justifies making judgements for loads higher than those applied in the test.

- *Solutions*

  Konrad Lorenz [35] writes: 'The ability of the doctor, the skill of the vet and the most basic ability of the ecological surveyor lie in their being able to look at a living system purely through their feelings and initially without pondering over it and to see that something is not quite right. This capacity is known as the 'clinical eye' of the experienced doctor... It is a false hope that this power of our perception could be replaced by the vast amount of data that has been acquired and its manipulation by computer.'

If we want to retain a tree for as long as possible, we need both this traditional experience and, additionally, a sound knowledge of trees and their body language as defined by the *Axiom of uniform stress* [37,38,39]. In this sense, the authors are proposing a development of the classic visual assessment which experienced arboriculturists have used for a long time, and have used to remarkable effect in their assessment of safety and which are validated by the results of applying modern biomechanics.

11.2 ELECTRICAL METHODS

The use of a pulsed, direct current electrical resistance meter, such as the '*Shigometer*' or the '*Vitamat*', can allow the mapping of zones of decayed wood along the length of a drill-hole or of a metal probe driven into the tree. Provided that the moisture content of the wood is at or above fibre-saturation, the main factor determining the electrical resistance is the concentration of mobile ions, which is usually very different between sound and degraded wood. As a mapping device, an electrical resistance meter provides rather similar information to that available from visual drilling or boring tests. It provides no information about the strength properties of the wood.

12.0 TREE ASSESSMENT AND LEGAL JUDGEMENTS – Some guidelines for the practitioner

The practitioner on site must be familiar with the law as it relates to tree assessment so that he understands to what extent he might be held responsible in the case of accident.

In recent times some countries such as Germany have seen published judgements concerning the duty of tree owners and managers to ensure public safety. Due to the inconsistency, and to some extent contradictory nature, of these judgements, they do more to confuse the issue than to clarify it. However, if experience in Germany is any indication of the latest developments, we are now beginning to see the emergence of a more realistic approach. We will explain and comment on some recent cases which illustrate this *(cf. Versicherungsrecht – VersR 1994(9), 357-361 – OLG Rechtsprechung 1993 mit Anm. d. Verf.)*

12.1 THE REASON FOR INCONSISTENCIES IN LEGAL JUDGEMENTS CONCERNING TREE ASSESSMENTS

The principles governing the requirement to protect passers-by from hazard trees have been laid down by the Supreme Federal Court of Germany (SFC) in the guiding judgement of 21.1.1965 *(Neue Juristische Wochenschrift (NJW) 1965, 815 and VersR 1965, 475)* which emphasises that:

> *'A street tree can certainly not be required to be absolutely free of imperfections and dangers. It is simply not possible to achieve such a state of affairs.'*

This conclusion cannot be reiterated often enough, particularly when looking at judgements passed in the Federal Republic of Germany during the years 1987-1992. This was a period when the German courts went out of their way to set ever more stringent requirements on those whose duty it was to ensure traffic safety, especially regarding the extent to which trees should be inspected. For the practitioner on the spot, it was impossible to understand the technical basis on which the judgements were made, and this resulted in a number of unnecessary fellings and in blanket tree surgery.

These judgements were largely spurred on by self-appointed experts, who appeared as expert witnesses. Such individuals tended to succumb to the temptation to demonstrate everything that they knew about the danger of particular tree diseases and defects. Thus, when judgements were made on the extent to which accidents had been foreseeable, attention was often wrongly paid to evidence (e.g. of decay) that only came to light after the event. If the same specialist had stood in front of the tree three weeks before the accident and had been asked for his diagnosis and, more importantly, his prognosis, the result would have looked different in many instances.

Furthermore, the methods of examination described to the court as necessary by the specialists – and in practice not carried out – are often drawn up according to information that has only been acquired after the accident and so are largely inapplicable. However, the judgement of the Supreme Federal Court in Germany to which we refer here, specifically required only those inspection procedures *'which are judged objectively to be necessary to the avoidance of danger and which, according to objective standards are reasonable'*.

In an earlier judgement of 21.12.1961 (VersR 1962, 262) the Supreme Federal Court had already laid down that:

> *'The extent of the monitoring and safeguards called for cannot be measured by what would be needed in order to eliminate every danger, for it is not possible for traffic to be made absolutely safe. Therefore it cannot be concluded from the occurrence of the accident alone that there was a neglect of duty.'*

This leaves open the question of the actual extent of the safeguards that are needed. Monitoring, i.e. the tree inspection, is of primary interest here. What sort of information is the tree assessor – the practitioner on site – expected to gather so as to avoid possible charges of negligence against himself or his employer? How does he do this, and what action must he take?

12.2 TYPES OF TREE ASSESSMENT

There is general agreement among practitioners and in legal judgements that in principle a visual inspection is sufficient and that a detailed technical examination is only required in particularly suspicious circumstances.

12.2.1 The visual assessment

Various authorities have prescribed differing methods for conducting the visual inspection (e.g. ground inspection as opposed to the use of platforms or climbing), as well as different criteria to be applied.

12.2.1.1 Visual assessment from the ground

As given in the judgement made by the German Supreme Federal Court (SFC) on 21.1.65 *(loc. cit.)*, the visual inspection is a thorough, purely optical check on the condition and health of the tree made from the ground. However, the increasing use of hydraulic platforms for tree inspections in Germany later led to stipulations that these devices should be used routinely. This was stated in the severe judgements of the Regional High Courts (RHC) of Hamm *(Oberlandesgericht Hamm, Urt. vom 14.7.1987-9 U 295/86-)* and Cologne *(OLG Köln, Urt. vom 8.2.1988, VersR 1990, 287)*. However, the Regional High Court in Düsseldorf had previously addressed this question in a judgement on 22.4.1982 *(VersR 1983, 61)*. In this judgement, a clear distinction had been drawn between the purpose of visual inspections made from the ground or from an hydraulic platform. The ground inspection was identified as the norm, while the platform inspection was to be regarded as a more detailed technical examination.

12.2.1.2 Visual inspection from the hydraulic platform

There are some situations where inspection from an hydraulic platform could help to rule out any chance of error in a routine survey. For example, dead branches in a tall tree might not be visible from the ground. However, the unreasonable expense of using platforms routinely has been recognised in German court judgements. Thus, in RHC judgements made in both Düsseldorf *(Urt. v. 8.2.1988 -7 U 196/87)* and in Cologne *(Urt.v. 28.1.1993, VersR 1993, 989)*, there was unequivocal support for the view that platforms need to be used only when circumstances indicate the need for a detailed technical inspection.

So, in principle, visual inspections from the ground are sufficient even for very large and tall trees, as far as the German courts are concerned. But if these inspections reveal any signs of crown deterioration such as extensive areas of dead leaves or wilted shoots, an hydraulic platform must be used, though only for a further visual inspection in the first instance. From the legal point of view, this additional inspection may be defined as a detailed technical examination or 'further action' (as described in the RHC in Cologne, *OLG Köln, Urt. v. 28.1.1993*). However, there is no requirement for a more detailed investigation, unless the aerial inspection indicates the need for it; for example, when fungal infection is suspected in the main stem so that removal of the dead branches would not be a sufficient safety measure. Examination of the tree is done in stages, and the more intensive methods are applied only when necessary.

12.2.1.3 VTA (Visual Tree Assessment)

Until very recently, the visual inspection of trees has provided few indications of their structural safety because there were few criteria by which the observations could be assessed. But, as in other areas of research, understanding of the living tree has taken on new dimensions. The trend is a return to Nature for a proper understanding of growth inter-relationships. The tree shows through its configuration what is wrong with it. This understanding is the basis for the visual assessment system known as VTA, which has found worldwide recognition and is described in this book.

VTA is based on the *Axiom of uniform* stress, which states that trees grow with such a configuration that all stresses on their surfaces are distributed evenly. If this state is disturbed the trees repair themselves by forming locally thicker annual rings. These reparative structures are symptoms of defects. So, for example, the rib is a defect symptom for a crack in a tree, while the swelling or bulge indicates a cavity or soft wood.

Tree workers who have learned about trees' body language through practical experience, have long been aware of these reparative structures. VTA places the traditional visual assessment on a biomechanical footing and provides failure criteria. At the same time guidelines are given as to when detailed technical examinations become necessary.

12.2.2 The detailed technical examination

The procedures to be adopted in a detailed technical examination (defined as 'further action' by some courts in Germany) depend on the prevailing state of experience and technology, as was recognised by the German SFC in the test-case of 21.1.65. This means that the local arboricultural officer must keep himself abreast of technical developments. He must check which investigatory methods are scientifically contestable and so can be regarded as of little or no value. For a new investigatory method to become an accepted standard, it needs both to gain scientific acceptance and to be satisfactorily evaluated under practical conditions in the field. Only then can reliance be placed on them when legal judgements are made. Currently available methods of investigation are described in this book.

12.2.3 VTA in legal judgements

VTA has won immediate acceptance into the legal process. In Germany, the Regional High Court at Karlsruhe *(Urt. v. vom 23.12.1993, VersR 1994,358)* has already made use of the current literature by dismissing a charge of liability against the local authority responsible for traffic safety because there were no warning signals in the *'body language of the tree'* even though the interior of the tree concerned was undoubtedly rotten. The judgement also mentioned the detailed technical investigations that are possible with the stress-wave timer *('Metriguard Hammer')* and the *'Fractometer'*. However, the Karlsruhe RHC concluded in agreement with the prevailing legal opinion that detailed examinations of this kind should be required only *'if symptoms of a defect could be detected by a purely external, optical inspection'* which was simply not the case here. This is the VTA methodology. In connection with the judgement of the Karlsruhe High Court, the Administrative Court in Düsseldorf *(Urt. v. 4.5.1994 – 7 K 4554/90-)* has meanwhile given a similarly 'tree-friendly' judgement with the help of VTA criteria and, in passing a legal opinion on VTA, observed that:-

> *'This qualified visual inspection is scientifically accepted'*

Shortly afterwards the Düsseldorf RHC based its judgement of 24.10.1994 (NJW-RR 1995, 726) on VTA only.

12.3 THE FREQUENCY OF TREE INSPECTIONS

The local arboricultural officer must not only know how to carry out inspections but also how often he must undertake them. In the judgement of the German Federal Court which we have cited here, an open question remained concerning the frequency of inspection that might be required. However, this question plays an important part in many legal decisions involving legal liability. Even so, the timing between inspections cannot be considered in isolation. It always depends on the site and the state of the trees. It is obvious that young, healthy trees demand less checking and that older, already defective trees must be checked more often and more thoroughly.

In cases where legal judgements have specified how frequent inspections should be, there have been wide discrepancies. In the most extreme case, a quarterly inspection was stipulated *(LG Münster, Urt. v. 10.7.1986 – 15 O 615/85-)*. In most cases the frequency expected by the German courts for routine inspections is bi-annual for older street trees; once in leaf and once out of leaf *(OLG Koblenz, Urt. v. 2.2.1987, Natur und Landschaft 1988, 76; OLG Düsseldorf, Urt. v. 15.3.1990, VersR 1992,* *467)*. But in this connection it must not be forgotten that the circumstances of each case are different. Thus, in the case of a tree on private land, the Krefeld Regional Court on 16.8.1989 *(NJW-RR 1990, 668)* rejected the need for a general bi-annual inspection if there were no particular circumstances to warrant it; this judgement was later confirmed by the RHC in Düsseldorf. On the other hand, the Regional High Court at Zweibrücken called for elms affected by Dutch elm disease to be inspected twice a year *(Urt. v. 3.4.1992, Neue Zeitschrift für Verwaltungsrecht – NVwZ 1992, 456)*, although pointing out the exceptional circumstances here: 'In the course of development of an acute disease, elms can have lost their stability in as little as six months from the first visible onset of the disease, so that their state of health must be assessed twice a year from the first visible signs of disease'. Conversely, this means that healthy trees need not necessarily be inspected twice a year.

The conclusion to be drawn from all this it is not feasible to make general rules governing the frequency of tree inspections. Neither a regular annual nor a regular bi-annual inspection is required, nor even a quarterly inspection of trees in roads and squares. The frequency of inspections depends entirely on the condition of the trees, their location and the traffic there.

In Germany, the 'Arbeitskreis Stadtbäume' ('Street tree team') recommends an annual tree inspection as the norm. This should be written into the technical standards.

12.4 THE COST OF TREE INSPECTIONS

The cost of tree inspections rises in relation to their frequency and intensity. In the RHC judgements which we have cited from Hamm and Cologne, the Court in each case ignored the aspect of costs, pointing to the pre-eminence of human life. When the Cologne judgement of 8.2.88 was given, it hit the headlines in the daily papers, which proclaimed: *'Man more important than street tree'*. This view has been revised in the meantime and the headlines referring to a more recent judgement read differently: *'80-year-old tree takes priority'*. This case involved damage to a caravan (caused by a branch protruding into the legitimate path of the vehicle) for which, precisely because of this priority, no damages were payable by the local authority *(OLG Düsseldorf Az.: 18 U 228/93)*.

In the earlier and relatively severe judgements mentioned here, there was a failure to accept the principle that the cost of tree inspections is an important and legitimate consideration in deciding what can reasonably be required. This is the principle enshrined in the judgements of the SFC on 21.1.65 that we have cited. The SFC has applied the same principle in other situations; for example, in connection with the obligation of householders to keep the pavements in front of their premises gritted in icy weather. In this instance the SFC cited its established ruling according to which the duty to maintain safe passage for vehicles does not apply unconditionally. 'It exists rather in so far as it is reasonable, and this depends partly on the ability of those responsible to pay' *(BGH, Urt. v. 5.9.1990, VersR 1990, 1148)*. More recently, the German courts have returned to this principle, as evidenced by five judgements from Regional High Courts during 1993 alone *(VersR 1994, 357ff)*. In a case involving the external inspection of a tree to ensure traffic safety, the RHC in Hamm had already established that the person responsible was not obliged routinely to remove vegetation to allow a close examination of the roots. This applied at least in this particular case, where the number of roadside trees in the operational area of the person concerned was such that such costly measures were judged unreasonable because they were not affordable with the resources at his disposal. The same court expressed a similar opinion in its judgement of 26.1.1993 *(VersR 1994, 357)*, when, on grounds of cost, it rejected both detailed root examinations and infrared photographs as the norm for tree inspections.

In its judgement of 28.1.1993 *(loc. cit.)*, The RHC in Cologne has now similarly come into line with the judgement of the SFC on the duty to keep traffic safe in the presence of trees, for it observes that: *'The extent and intensity of obligatory inspections must not be pressed too far but must be kept within the bounds of reasonableness, at the same time taking into account the ability of the person responsible to pay.'*

12.5 THE PREDICTABILITY OF DAMAGE

The following observation made by the Administrative High Court (AHC) at Münster *(Urt. v. 8.10.1993, Agrarrecht – AgrarR 1994, 245)* is important for the local arboricultural officer who should invoke it if appropriate:

> *'It is usually not possible to predict with any precision, or even in terms of overall probability, whether an old and already damaged tree might fall over or break up during bad weather or in a storm, or at least lose substantial branches and thus endanger persons or property.'*

In this case, the Münster AHC was recognising the need to strike a balance between the need to protect trees and the duty to ensure the safety of passers-by. Its decision was thus to reject extreme demands for safety that would have involved disfigurement of the tree through crown reduction.

12.5.1 Theoretical and actual danger

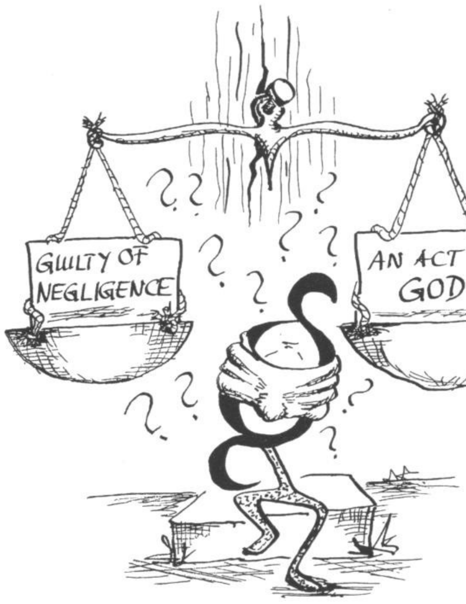
In its revised judgement of 1992, the Cologne RHC had already made comments about the predictability of damage which were very relevant to the work of local arboricultural officers *(Urt. v. 11.6.92, VersR 1992, 1370)*. In this case, which involved an oak about 100 years old, the Cologne RHC did not consider that the tree's age of itself gave any grounds for taking special control measures. The Court dismissed an action for damages on the grounds that there had been no reason to warrant a detailed examination, and that the subsequent fall of a fully foliated branch was not foreseeable from a visual inspection. This was the first judgement in which the Cologne RHC took account of the environmental importance of trees, while also making a ruling which differentiated between theoretical and actual danger. This ruling was important from the point of view of local arboricultural officers. In the reasons given for the judgement the following was said in this connection:

> *'The fact that the branch extended over the road and was relatively large did not of itself entail an obligation to remove it. The contrary view would lead to the necessity of sawing all branches off trees as a precautionary measure, even if they are sound and not recognizably in danger of falling, since there is at least the theoretical danger that they could harm the road user. Such a far reaching obligation to prune trees does not, however, exist. It would go far beyond what can be expected of the person responsible for traffic safety and would also not reflect the environmental importance that should be accorded to trees.'*

It is, however, necessary to recognise real danger when it exists, and the way in which this must be judged has been set out by the Düsseldorf Administrative Court in the judgement of the 4th of May 1994, which we have mentioned in connection with protected trees and the duty to maintain safety for traffic. According to this, an actual danger is to be assumed if the probability of an accident is thought to be significant. The VTA system can help Court judges decide when this situation might apply; i.e. whether damage from a tree was foreseeable.

12.5.2 Acts of God

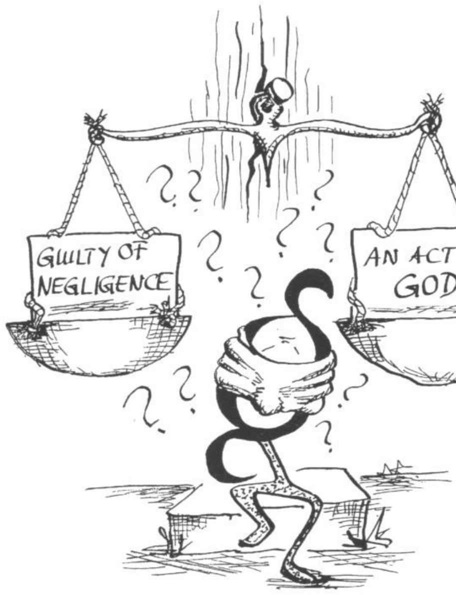
For those who are responsible for ensuring the safe passage of traffic, liability for accidents caused by trees always ends where the resulting damage is attributable to an Act of God. Much uncertainty prevails among arboricultural officers over Acts of God in such situations. The assumption that accidents which occur at wind speeds of Force 8 and above are all Acts of God which automatically waive liability is a false one. The consequence of this assumption would be that liability did not apply in the case of a branch that was recognizably in danger of breaking, as long as any failure occurred in a storm with a windspeed above Force 8. Persons with statutory duties for public safety could then secretly hope for such a storm to occur, thus relieving them of all responsibility for any unsafe individuals among their trees.



In general, an Act of God is defined as an inevitable event that could not have been avoided, even if the person concerned had taken the greatest care that could possibly have been expected in the circumstances. An Act of God is an objective concept that, in connection with trees and the duty to keep traffic safe, can only be interpreted in the sense of the cited judgement of the SFC of 21.1.1965 which established the principle for the German courts. Consequently, if damage caused by a tree occurs when the wind is above Force 8, the event is only attributed to an Act of God if the collapse of the tree represented an unforeseeable event which could not have been avoided with appropriate and reasonable means. As a result it is the technical criteria alone and not the wind strength that determine the predictability of damage and which thus determine whether anyone is liable. According to this judgement of the SFC, the appropriate technology and knowledge that are available at the time of a tree inspection should be applied, and this means that the practitioner is expected to keep abreast of all new developments. In this context, the biomechanical VTA visual assessment which is based on the body language of trees offers reliable and far reaching assistance.

To differentiate between an Act of God, that relieves anyone of liability, and negligence, i.e. conduct that gives grounds for liability, the following is relevant for the tree inspector:

> *Anyone who does not take heed of defect symptoms that today can be evaluated by means of VTA is behaving negligently.*
>
> *If, on the other hand, a tree of optimal form fails as a result of a deterioration of its substance without recognizable symptoms, this constitutes an Act of God.*



12.5.3 Negligence in civil and criminal actions

The definition of negligence in civil law is different from that in criminal law. If, for example, a branch breaks out of a street tree and falls on a car, injuring the driver and damaging the car, the injured party can make a claim for compensation by bringing a civil action on the grounds that there has been damage to person and property. He or she may also start legal proceedings for a criminal action if there is not already a public interest in a criminal prosecution, based on injury to the person through negligence.

In both cases, the legal system tests whether the person responsible for traffic safety has been negligent. However, the legal process sets different standards for civil and criminal negligence. Civil negligence – when a claim for compensation is tested – is measured according to an objective standard. The thing that counts here is not the knowledge of the person responsible, not his ability to have predicted damage; it is instead the knowledge that he should have had and exercised as holder of that position.

In Germany at least, if the responsibility for traffic safety lies with a civil authority, then the standards laid down for the type and extent of tree inspections are considerably more rigorous than is the case with a private citizen or layman. The standard of care depends on the legal, administrative and technical knowledge that the employee must acquire for the execution of his duties. A nature conservation authority and an open spaces department must be familiar with the current state of knowledge – including VTA. This applies not only to the responsible official in charge but also to the employees working on the trees, to whom the necessary training must be made available.

In the case of claims for compensation, the official or employee of an authority can himself be sued only in the case of intent or gross negligence. As a rule the State or the responsible authority is liable. Gross negligence exists only if the necessary care vis à vis traffic has been neglected to a very serious degree. This would be the case if even the most basic observations had not been carried out and no attention paid to signs that would have been evident to everyone. Such a scenario could be imagined if, despite the obvious presence of fruit bodies of a wood-rotting fungus, no detailed examination of the tree had been undertaken. The same would apply if advanced subsidence cracking in a leaning tree had been ignored.

These principles, with their far reaching potential to absolve officials or employees of civil authorities from responsibility, apply only in civil actions. In criminal hearings where negligence on the part of an official has involved harm such as personal injury, the court must determine to what extent the conduct of the official concerned should be held against him. If conduct by an official or anyone else has led to criminal injury, that person can be judged to have been criminally negligent and deserving of chastisement even if he contravened the law unintentionally or unknowingly. In cases where a tree has caused damage or injury due to the alleged dereliction of duty on the part of an official, the overriding question will be whether he had properly exercised his personal knowledge, ability and freedom of action to ensure that the tree was inspected to the standard required. The question is not whether he acted according to the knowledge expected in general in this situation. However the only test cases in this area have involved the most extreme instances of negligence in civil compensation claims.

12.6 Tree inspections according to today's legal situation

The experience in Germany has been that there has been a shift in the administration of justice as far as the statutory duty to ensure protection from hazardous trees is concerned. Demands for erring on the side of safety, often excessively so, gave way to the more moderate Regional High Court judgements in 1992 and especially in 1993, which are cited here. This trend, which has continued into 1994, reflects a new and increasing sympathy for trees. It also reflects especially an understanding that the prediction of damage is often impossible.

In the judgement of the Karlsruhe RHC (21.12.93) which is cited here, it states:

> *'Not every falling branch or collapsing tree leads to those responsible for civic safety being held liable. Indeed, damage caused by trees can in certain cases be regarded as part of the general risk inherent in life'*

This epitomises the view that any judgements about fulfilment of the duty to protect passers-by must be based on a awareness that trees are living things and that they are important for everyone, especially in these times of forest decline.

The kind and extent of the measures required for civic safety are dependent on:

a) the condition of the tree – the tree species, its vitality (irrespective of age), pre-existing damage and all growth peculiarities; simply the dangerousness of the tree,

b) the location of the tree – the kind of road or path or square or the proximity to areas open to traffic and all peculiarities of the site,

c) the kind of traffic – its importance and frequency and all peculiarities of the traffic at the site in question.

The duty to ensure safety for passers-by continues to be a major consideration in individual cases, but the subject can be viewed from a different perspective. Thus the Schleswig RHC declared in its judgement of 7.4.1993 *(VersR 1994, 359)*:

> *'As has increasingly penetrated the general consciousness in recent years, there is a widespread interest in maintaining tree cover, including that in public roads, so that a balance must be struck between the interests of public safety and ecological interests in maintaining tree cover.'*

In addition to this, the practitioner should understand that, even where tree inspections have been lacking or deficient, he cannot be held liable for damage in every case. Any damage must be shown to have occurred due to the lack of an adequate inspection, i.e. negligence was causal and therefore a basis for liability. The Karlsruhe RHC *(loc. cit.)* has specifically emphasized this requirement because the authority accused in this case was not found liable since the tree inspections, though deficient, were not proved to have had a causal role. This was because even a proper inspection would not have revealed the damage to the poplar tree in question which led to the accident.

The essential need to prove causality between an accident and the lack of an adequate inspection was highlighted in an earlier judgement of the Bonn Regional Court on 8.8.91 *(AgrarR 1993, 123 mit Anm. d. Verf.)*. In this case too, the omission of a tree inspection was not the reason for the damage caused by the breaking of a branch. In its judgement of 23.6.94 *(VersR 1994, 359)*, the Stuttgart RHC did not regard the failure of the accused to remove an old, defective tree as grounds for liability because the eventual breakage of the branch which led to the accident 'was in no way related to the general condition of the tree'.

It is important for the practitioner on the ground to be just as familiar with whatever aspects of the law impinge upon his work, as with the technical details. This applies especially to local authority arboricultural officers who have duties towards the safety of persons and property, especially with regard to any requirements for tree inspections.

PART 2:

A PRACTITIONER'S GUIDE

13.0 MECHANICS: PRACTICAL APPLICATIONS IN ARBORICULTURE (CF. [38])

13.1 MECHANICAL CONCEPTS: THE BARE ESSENTIALS

13.1.1 External loads

A beam which is clamped at one end will bend if a force F is applied to its free end. The force is opposed by the resistance of the clamp, so that a bending moment $\mathbf{M_B}$ is produced; this is why the beam bends, rather than rotating freely (Fig. 80). If the clamping arrangement takes the form of a crank lever, as shown in Fig. 80, the arm of the lever level with the line of force is subjected simply to bending, as in the earlier case. However, the long arm of the lever will undergo a torsional moment so that it is twisted around its axis. This arm is subjected to bending as well as to torsion, but this is of no further interest to us here.

The two examples above should help to introduce the concepts of *bending moment and torsional moment*. For simplicity, the arrows in the diagrams show only these main moments, although additional arrows could have been added to show other moments and reactions to the forces. The reactions to the forces are shown separately below. Axial forces pulling or pushing at one side of a vertical bar lead to reactive

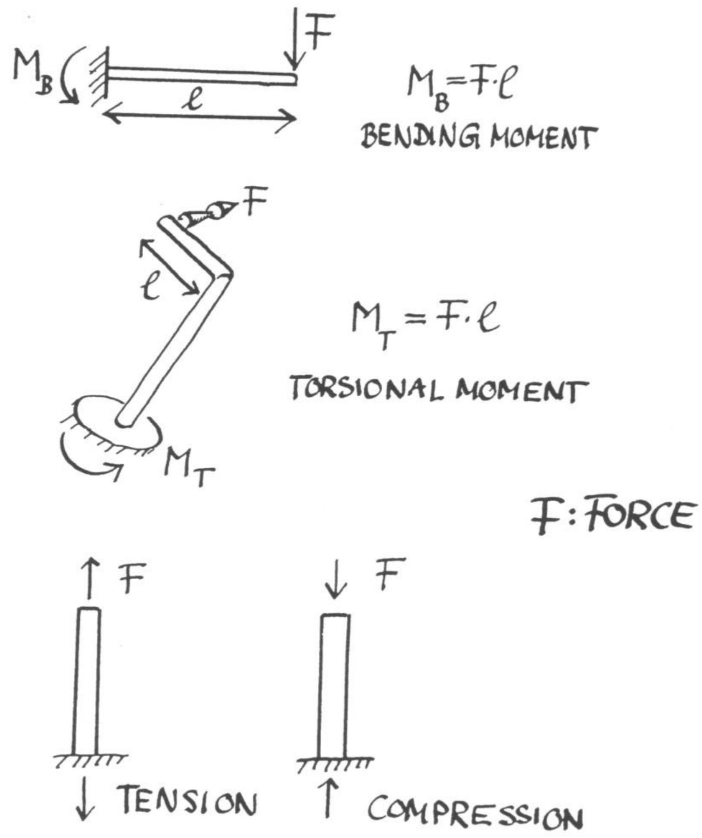


Fig 80. Classification of external loads into bending moment, torsional moment and axial forces.

tensile or compressive forces at the other end. We can regard the beam as a sort of 'messenger', since it conveys the external load to the clamp. In order to do this, it has to become distorted, as shown in our example where it twists, stretches or becomes shorter. These distortions in the beam are just enough to create an equilibrium between its inner, mechanical stresses and the exterior load. Each of the stresses has a particular inner distribution which depends on this load. At the clamping point, this distribution of stress is, in a sense, the mechanical 'message' that the beam transmits. In turn, the structure supporting the clamp provides the resistance to the force, so that the beam does not fall down, twist off or fly away.

13.1.2 The component's internal answer to external loading: stresses

The typical distribution for some stresses is shown in a simplified form in Fig. 81. Thus, as we have already mentioned, when a rod or beam is bent, the stresses that it undergoes range from tensile on the convex side of the bending zone to compressive on the concave side. This is the kind of load that is experienced by a tree bent by the wind. When this happens, the resulting compression on the concave side of the bending zone is added to the axial pressure which results from the tree's own weight. As we shall see later, the wind load is far more significant than this pre-existing compression.

In effect the bending stresses that develop in a structure under external loading represent its internal response to that load (Fig. 81). It resists stretching, so that tensile stresses develop, and it resists shortening so that compressive stresses develop. Also, surfaces within the structure resist sliding over each other, as represented by shear stresses. If any of these stresses exceeds a certain value, the structure fails. Such values are termed 'characteristic values' of the particular material involved, since they characterize its strength.

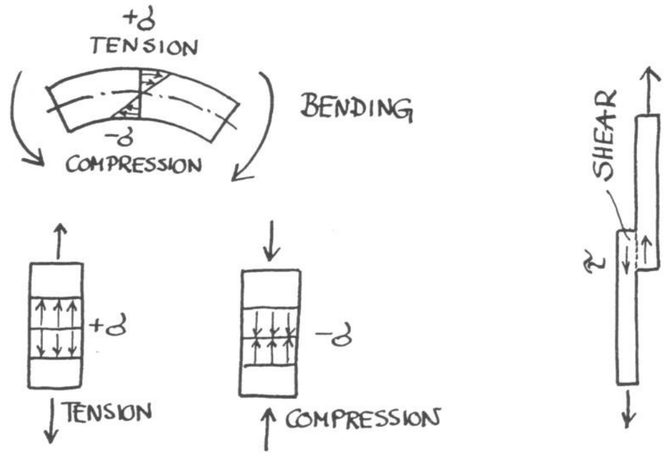


Fig 81. Simplified classification of internal stresses that can be induced in the component by external loads into tensile, compression and shearing stresses

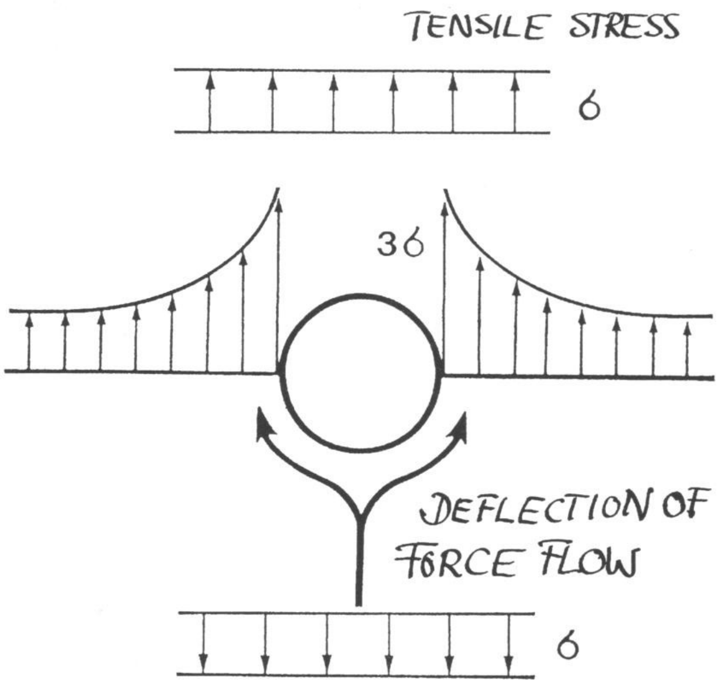


Fig 82. An externally applied stress is increased at least threefold by a circular notch (hole) because the force flow is deflected around it.

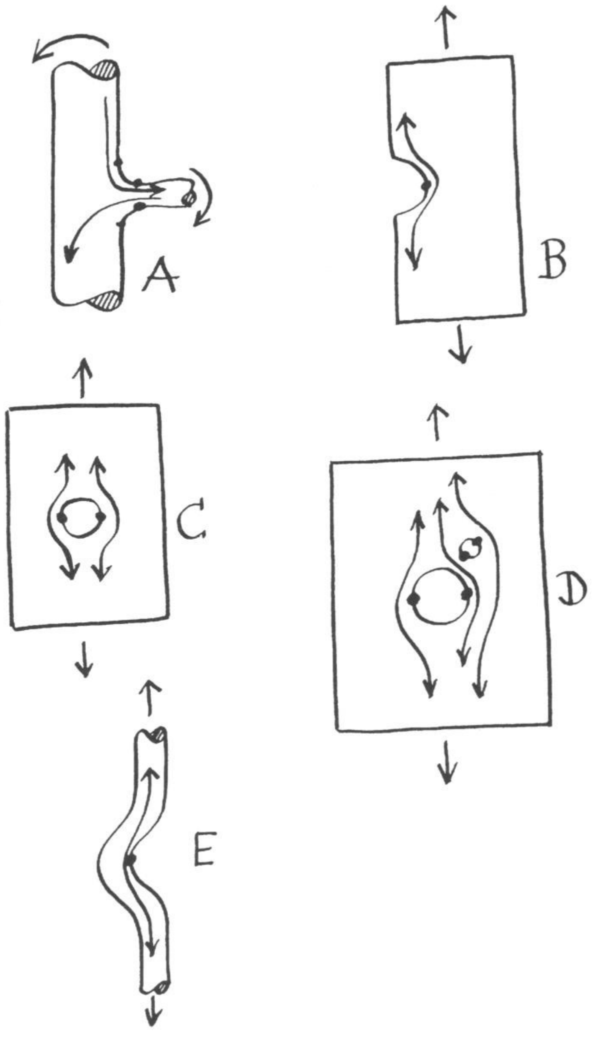


Fig 83. Every force flow deflection (arrows) can cause locally high stresses. These notch stresses can be expected at the places marked with black spots.

And this brings us to an important point:- a structure fails as soon as the stress reaches the critical value at any point within it or on its surface. Thus, a well designed structure does not have any points where concentrations of stress could occur, so leading to failure under comparatively small loads. The characteristic of such a structure is that, when loaded, it distributes the stress homogeneously so that no point bears any more or less load than any other. Conversely, a 'flawed structure' is characterized by one or more potential fracture points where locally high stresses develop. Failure is predictable in certain kinds of structure that show such faults. This is mostly the case at so-called 'notches', which is an engineer's description of any concave configuration within a component which diverts the force flow around it. In manufactured components, notches such as the circular hole in a tension plate cause excessively high local stresses which typically amounts to at least three times the stress applied from outside (Fig. 82). In Fig. 83 some notches of this type are shown. The dark spots are the sites of local stress peaks, that is notch stresses. They occur where the force flow, diverted by the notch (arrow), is greatly intensified; i.e. a higher force flow per surface element is conveyed. Biological structures, that are capable of adaptive growth, now achieve the incredible: notches that have grown naturally cause no notch stresses [39].

This little excursion into technical mechanics was intended just to provide a rough classification of the mechanical loads to which our tree is exposed; namely, axial forces (compression, tension), bending moments and torsional moments. The tree's reaction to external loads consists of internal stresses that we subdivide into tensile, compressive and shear stresses. Bending stresses are a combination of tensile and compressive stresses distributed in a certain way over the cross-section.

As the tree will evidently fail when a critical stress is reached, and as this stress is the result of external loads, it always tries to develop a crown shape which keeps all external loadings as small as is compatible with photosynthetic requirements, and which equalizes unavoidable stresses *(the Axiom of uniform stress!)*.

13.2 MECHANICS OF WOOD – HOW THE TREE HOLDS ITSELF TOGETHER

(first published in 'Deutscher Gartenbau, 16/94')

The self-explanatory diagrams in this section provide a concise picture of wood biomechanics.

Summary:

1. The wood fibres are orientated along the force-flow, so that the risk of their shearing apart is minimised.
2. The xylem rays provide considerable strength in the radial direction, so minimising the risk of splitting.
3. The pattern in which the wood fibres are glued together via their 'lignin chimneys' gives maximum strength where the danger of longitudinal splitting would otherwise be greatest.
4. The tangential growth stresses act laterally on the rays, helping to prevent their separation from the fibres, which could propagate subsidence cracks.

In short: Wood quality is at its highest where the tree is most threatened, that is, at the points of greatest internal stress. Growth stresses hold the xylem rays and fibres together, especially in places where there is a high risk of failure. The growth stresses thus counteract the most dangerous external loads.

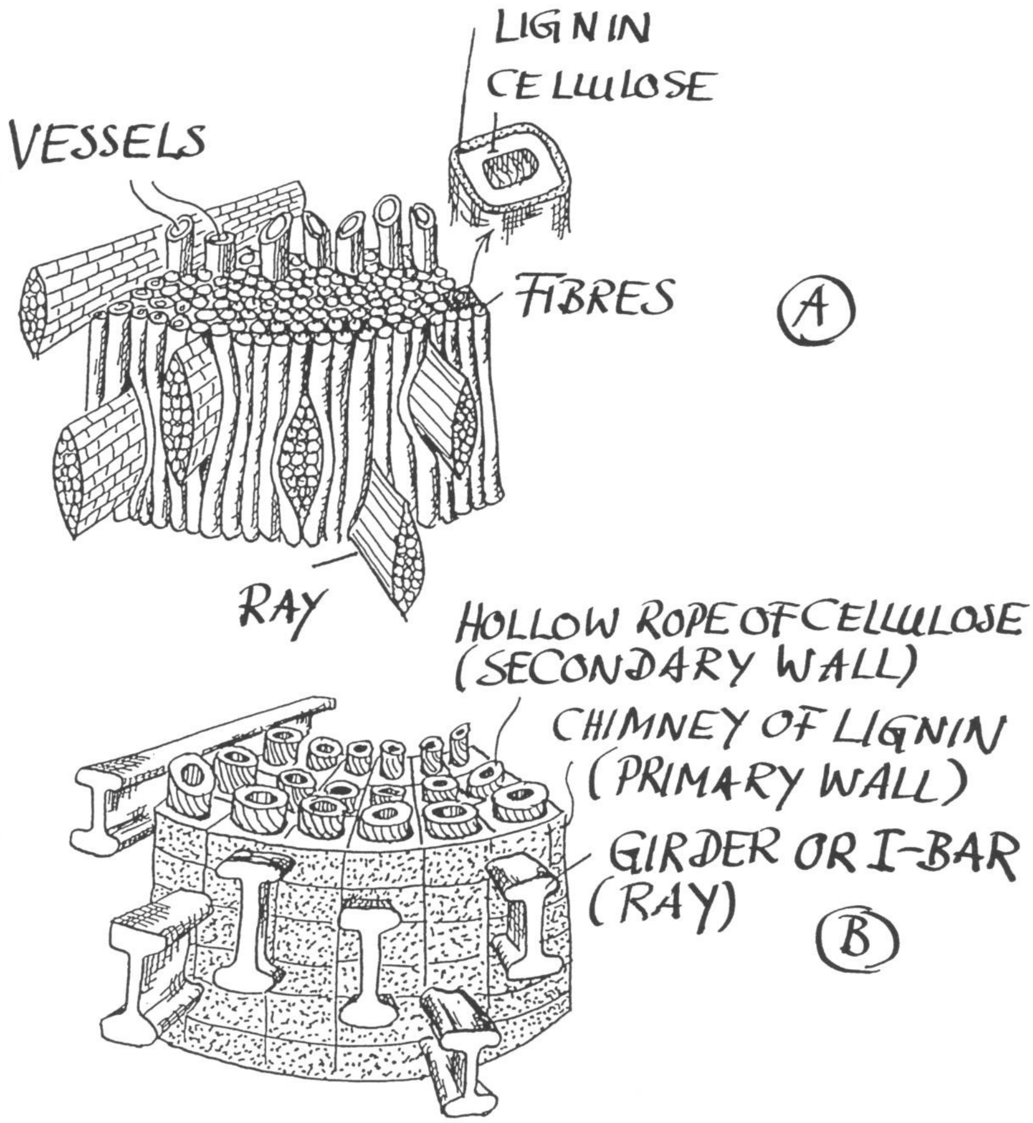


Fig 84. Portion of an annual ring of ring-porous wood.

A: Sketch of actual appearance, with magnified view of one cell consisting of a lignin-rich primary wall and cellulose-rich secondary wall. The rays are spindle-shaped in cross-section with the wood fibres gently deflected around them.

B: Mechanical model in which the primary wood cell walls are joined together like a system of lignin chimneys. The chimneys of brittle lignin each contain a hollow cellulose cable that is flexible but has high tensile strength. The rays function as a radial reinforcement, depicted here as I-bars.

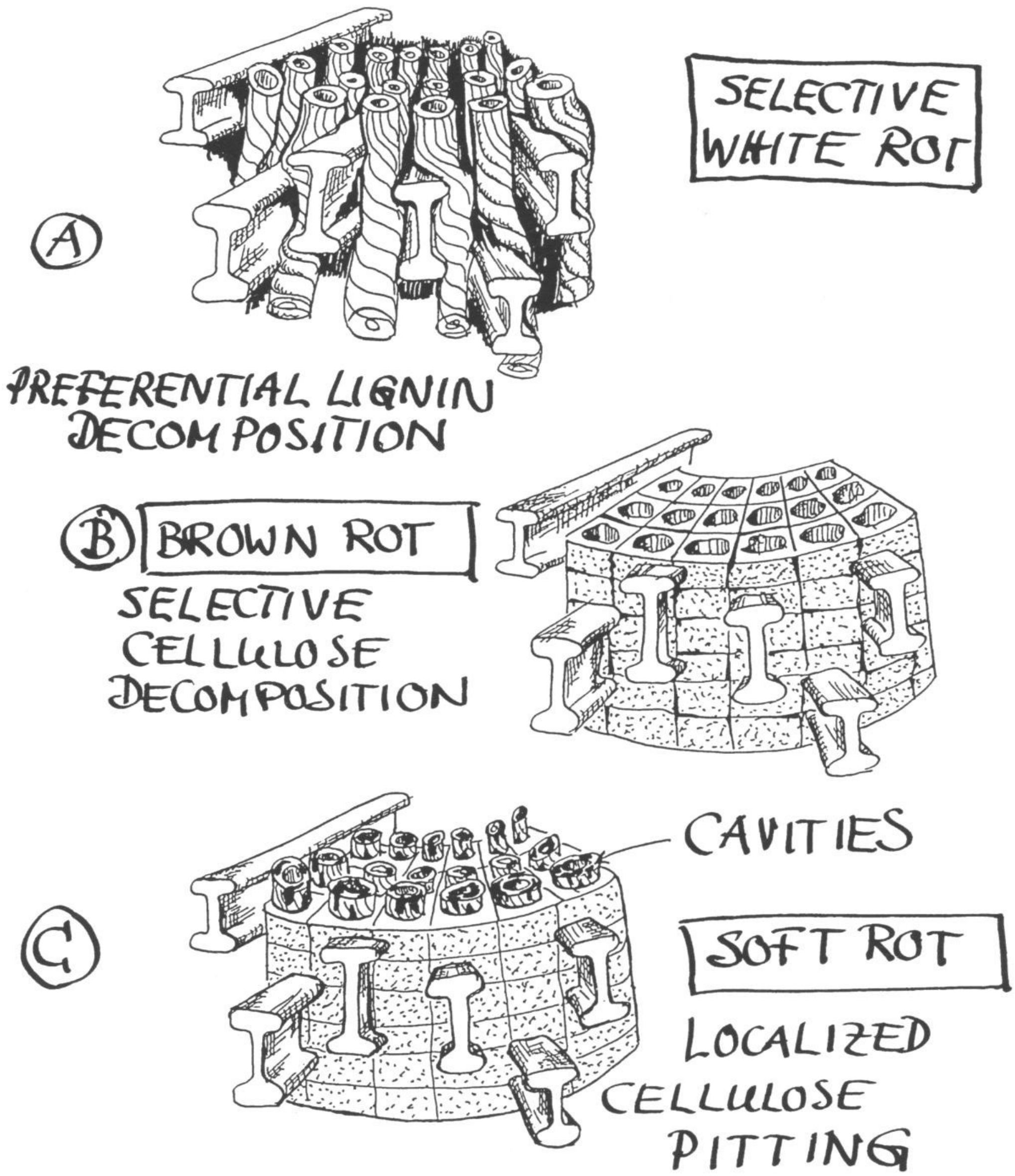


Fig 85. Mechanical model of pattern of wood decomposition caused by decay.

A. Selective white rots dismantle the lignin chimneys. The material that remains is flexible but is still quite resistant to tensile stress.

B: Brown rot selectively destroys the hollow cellulose cables and leaves a stiff but brittle framework of lignin chimneys behind. A tree damaged in this way can fail like a brittle biscuit and without prior warning.

C: Soft rot eats holes in the hollow cellulose cables but embrittles the wood far less actively than brown rot. Soft rot acts, therefore, as a more benign form of brown rot.

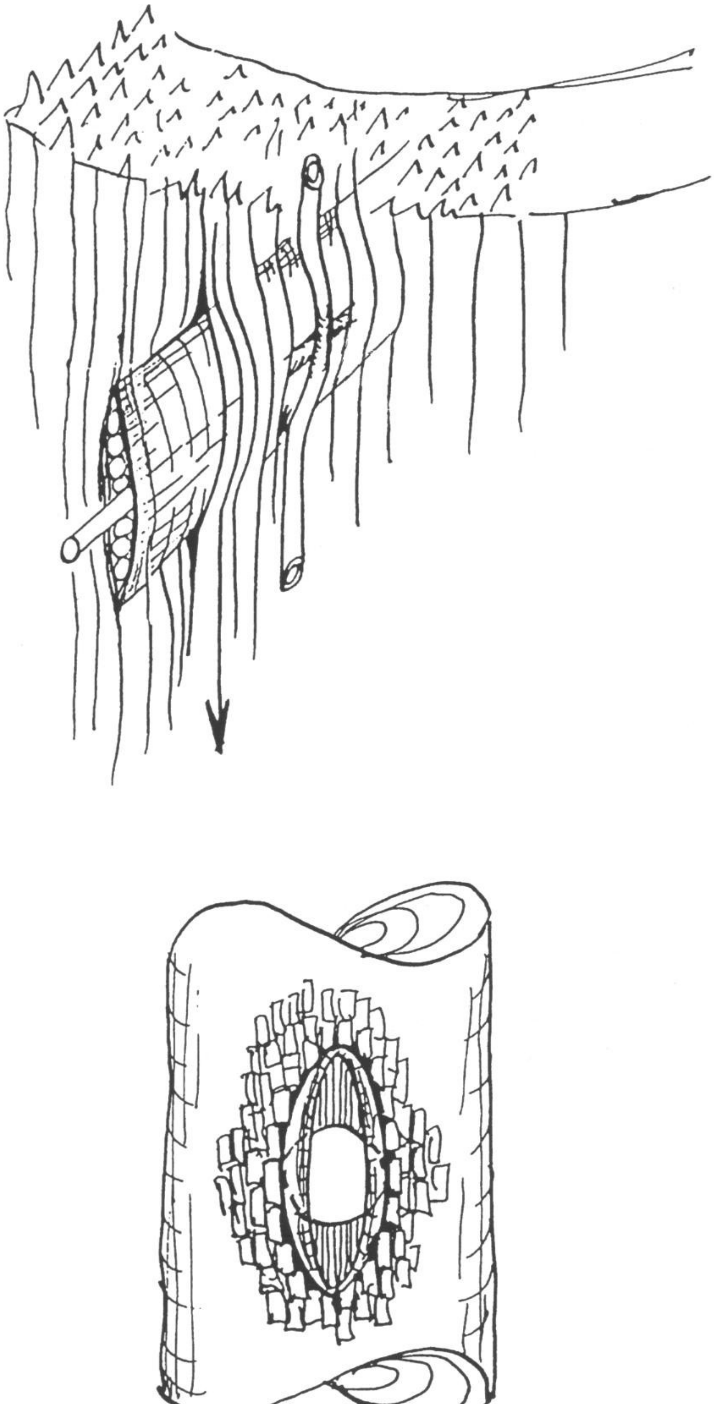


Fig 86. The spindle-shaped cross-section of the ray is optimal for deflecting wood fibres, and at the same time the force flow, gently around an obstacle. Similar spindle shapes appear when a hole is drilled through a branch. The cambium dries out in the non-loaded zone above and below and the wound wood forms a spindle shape around the drilled hole.

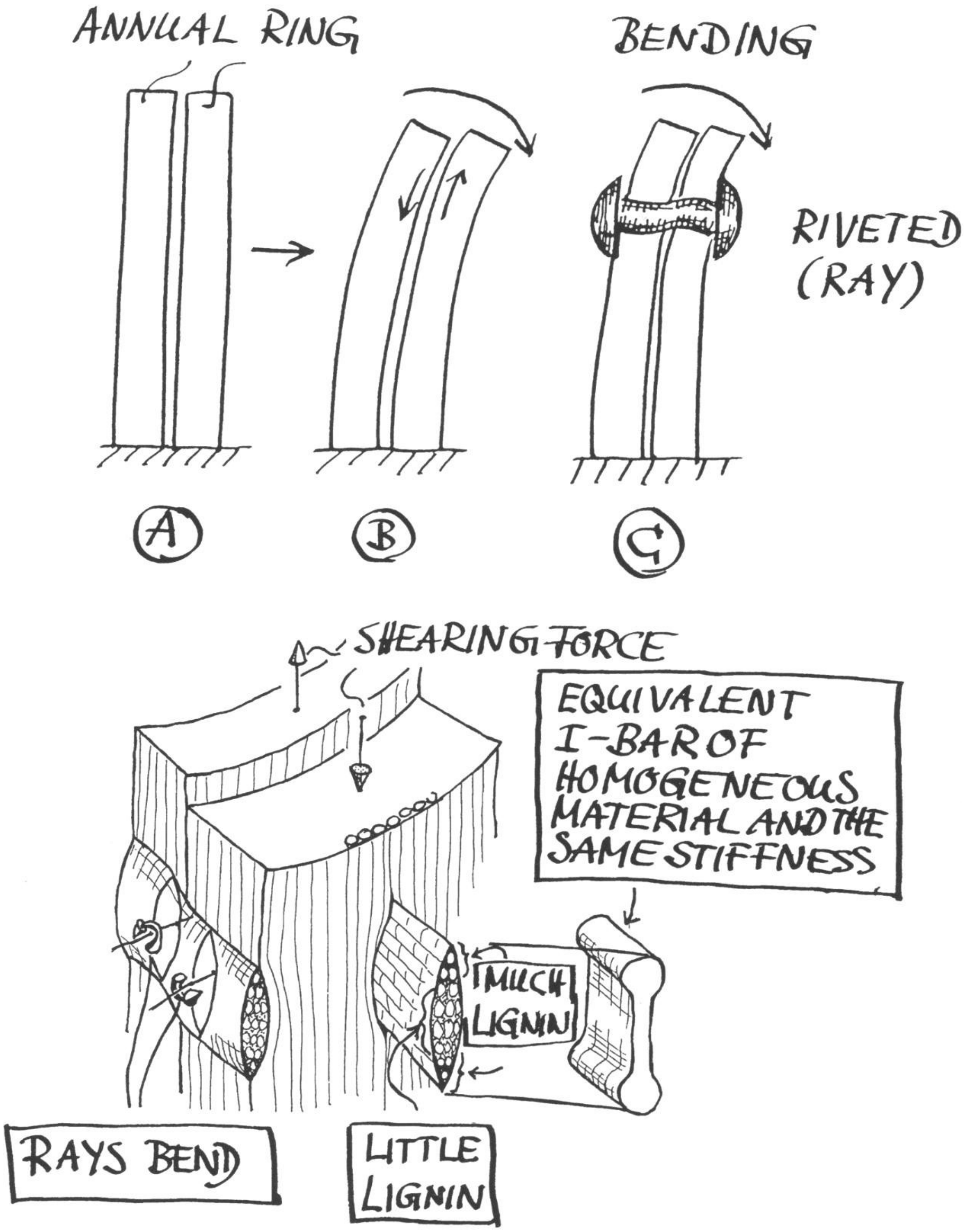


Fig 87. The rays also have the function of suppressing sliding movements of annual rings against each other by bolting them together. This can subject the rays to bending loads, which they can resist because of their lignin content. As Francis Schwarze (Freiburg) has shown in the case of ash wood, there is more lignin at the upper and lower ends of the spindle, so that the ray has the mechanical properties of an I-bar, despite its spindle-shaped cross-section. Rays with very elongated cross-sections may instead experience a shearing load.

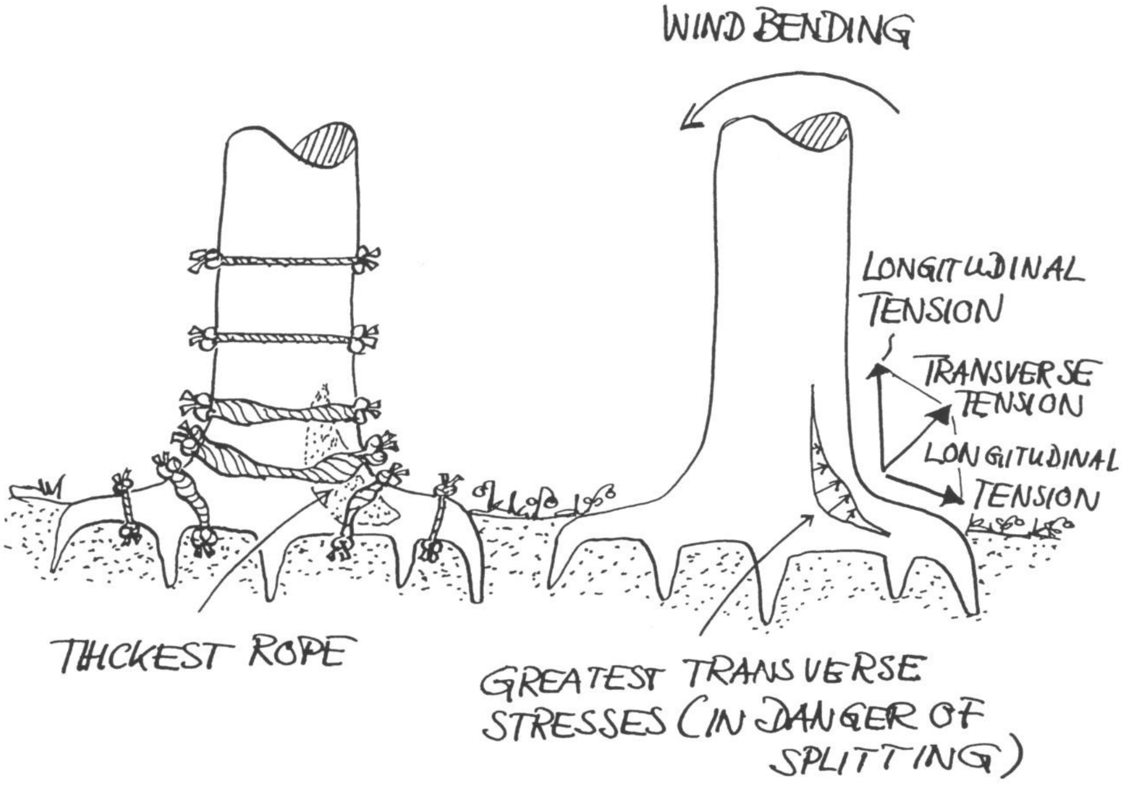


Fig 88. As well as acting as cross-bolts, the rays are responsible to a considerable degree for regulating the radial strength. Measurements in root buttresses undertaken by Wolfgang Albrecht with the 'Fractometer' at the Karlsruhe Research Centre showed the greatest transverse strength to be where the greatest radial stresses were also operating, that is where the wood is in danger of splitting.

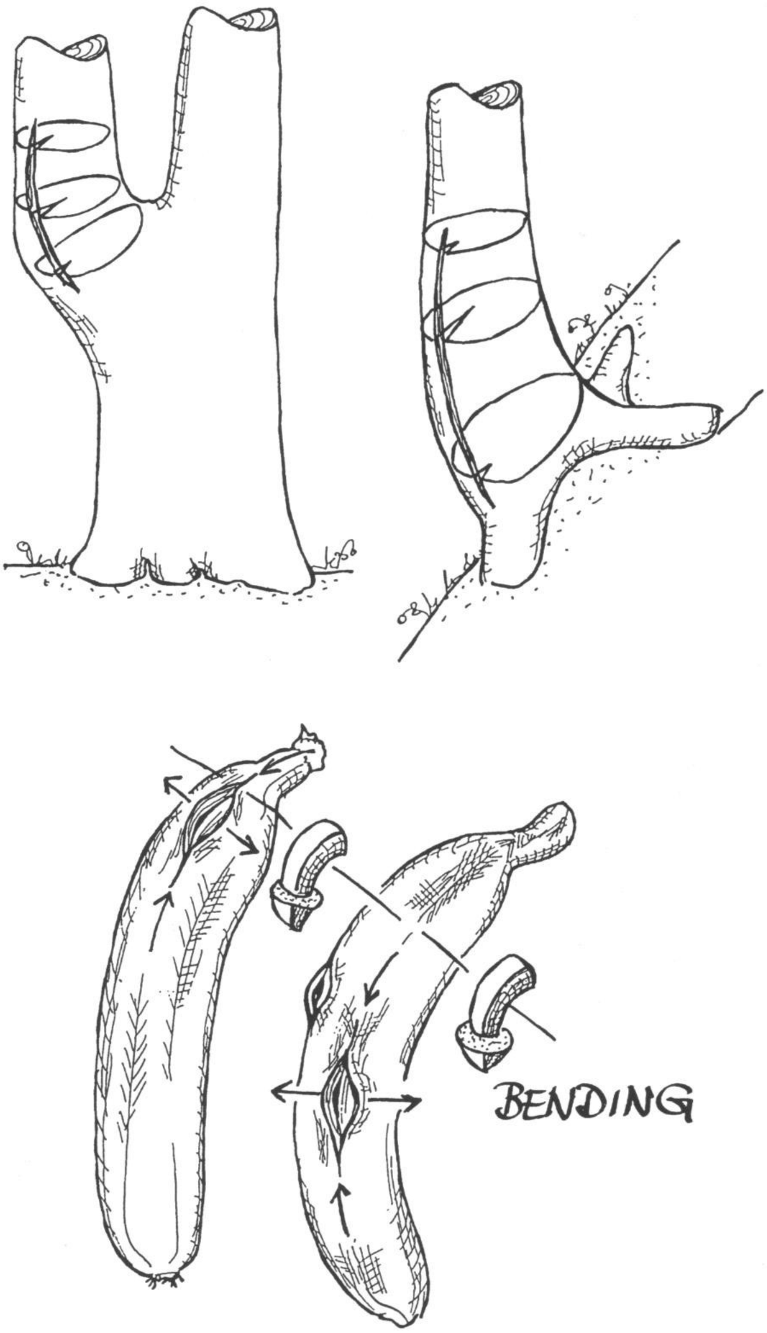


Fig 89. Subsidence cracking occurs when curved parts of a tree are straightened. It brings to mind the way a fresh banana splits open if it is bent straight.

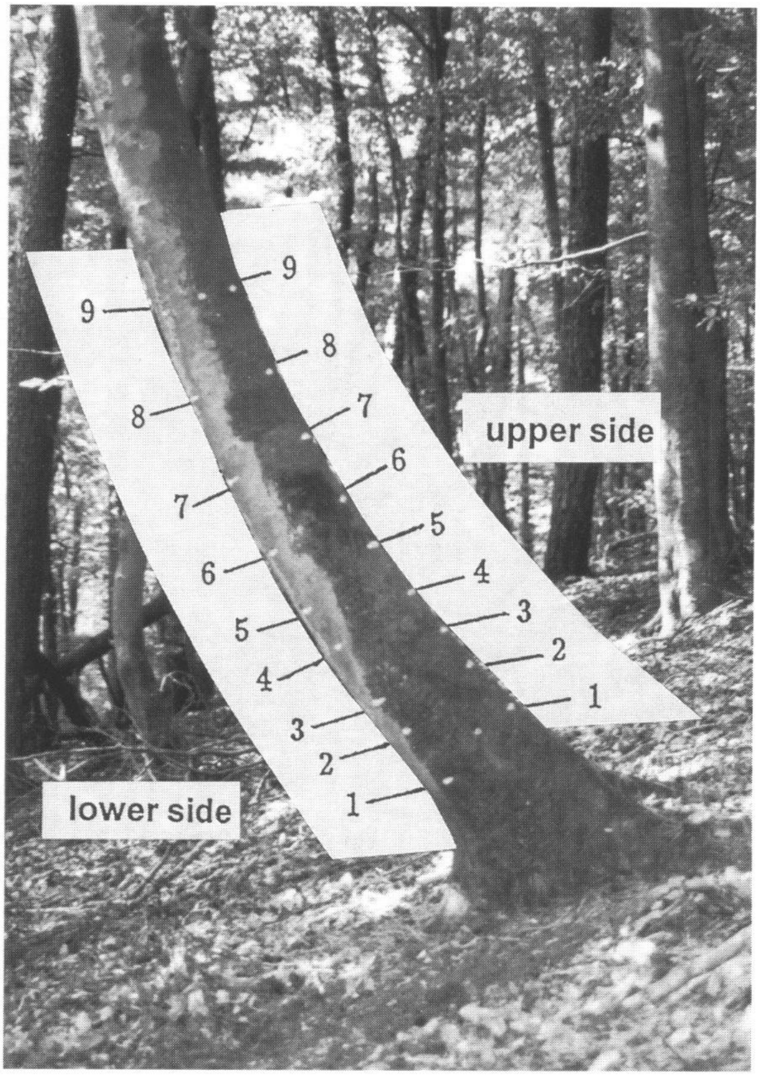
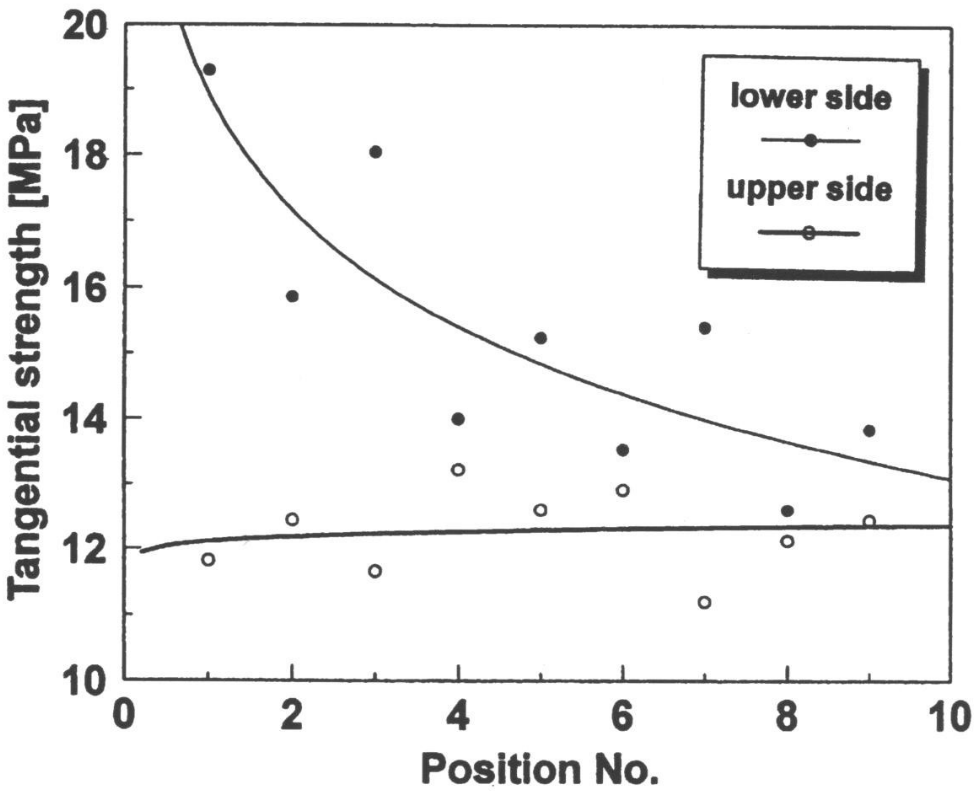


Fig 90. Curved, leaning trees counter the risk of splitting by producing the highest tangential strengths in the region of the greatest curvature on the endangered underside of the tree. This was demonstrated with the Fractometer by Roland Kappel and Frank Dietrich at Karlsruhe.



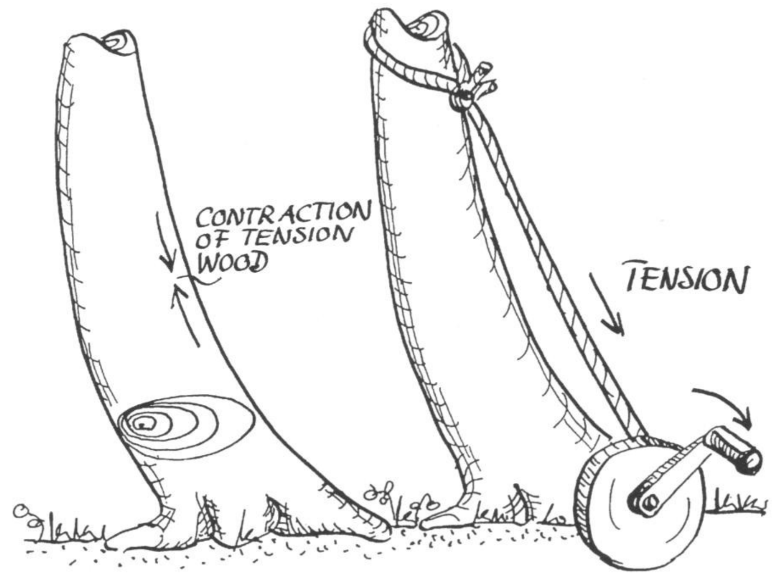


Fig 91. Leaning broadleaved trees are prevented from subsiding by forming tension wood on their upper sides.

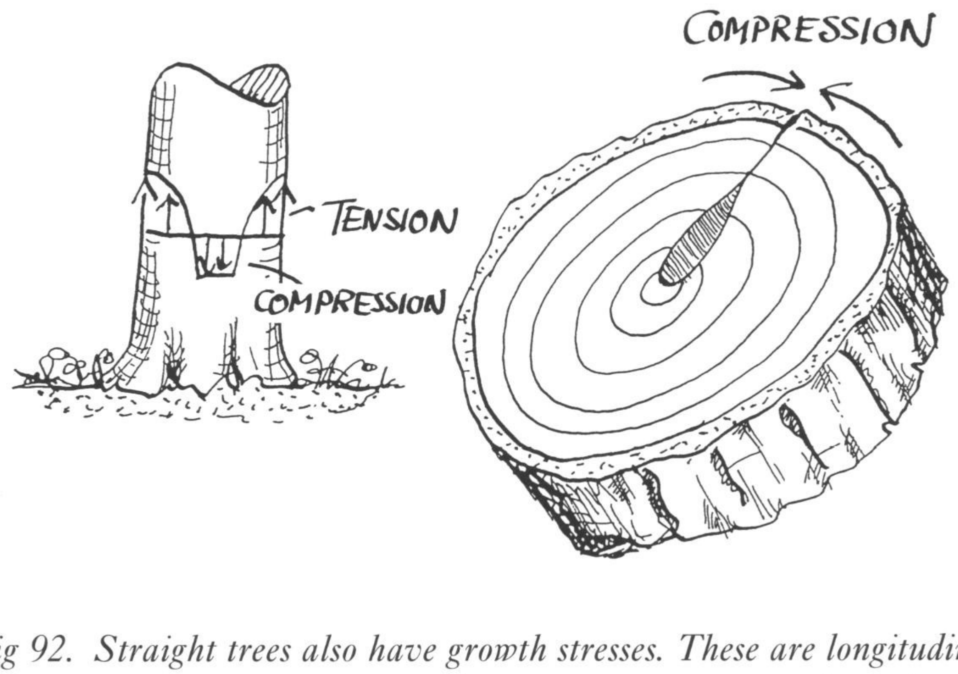


Fig 92. Straight trees also have growth stresses. These are longitudinal tensile stresses and circumferential compressive stresses on the surface of the stem. The latter can be readily demonstrated by making a radial saw cut: it is squeezed shut. This tangential pressure also bears on the spindle shape of the rays in a highly beneficial way.

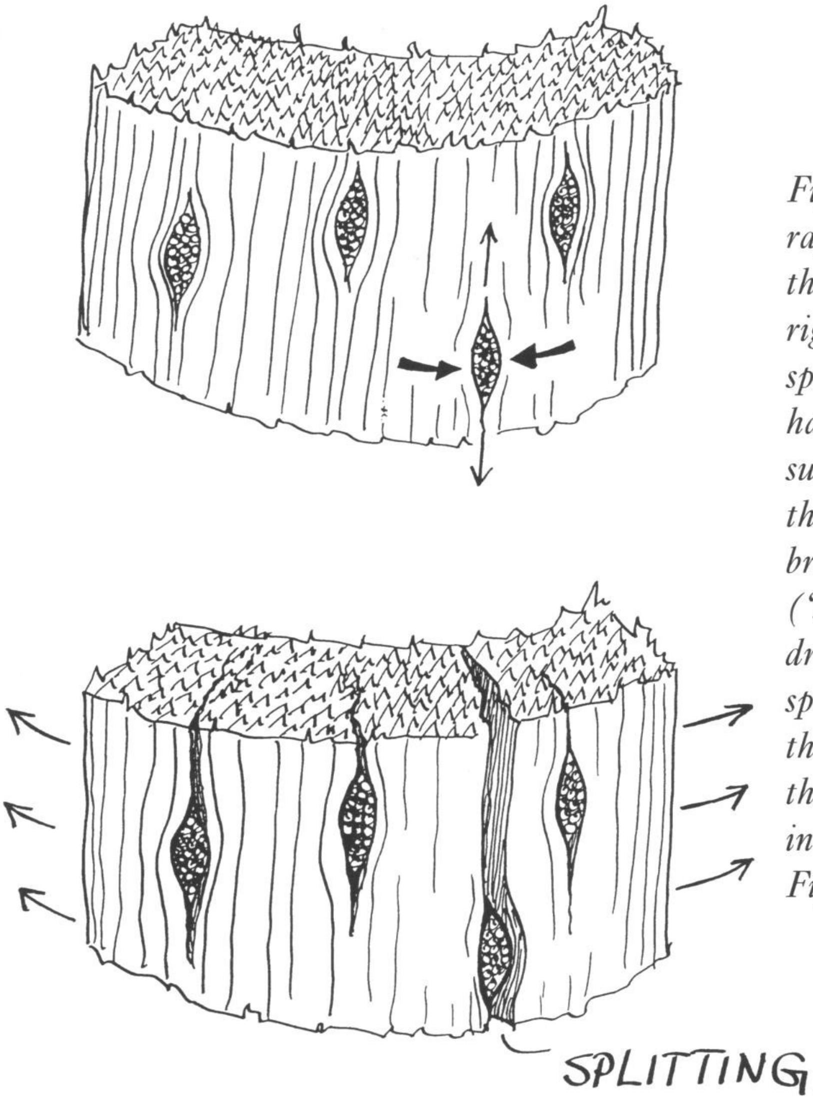
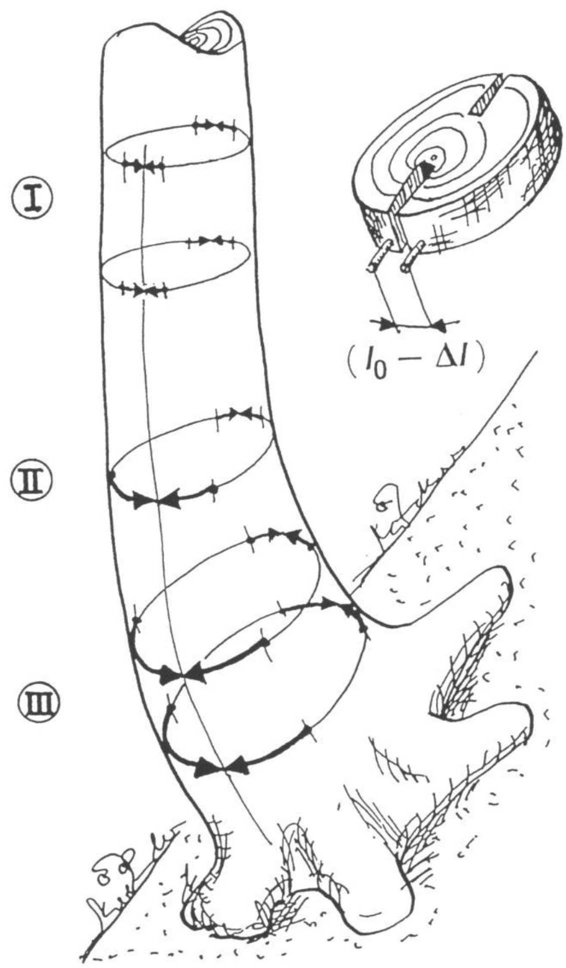


Fig 93. The wood rays become cracks if they are pulled at right angles to the spindle direction. This happens in the case of subsidence cracks and the fracture of green branches in summer ('summer branch drop'). Trees specifically protect themselves against these failures as shown in the following Figures.



l_0: ORIGINAL DISTANCE
Δl: CLOSURE OF SAW CUT

Fig 94. The tangential growth stresses are highest where the danger of subsidence cracks is especially high. This was demonstrated by Frank Dietrich at the Karlsruhe Research Centre by systematically sawing up curved trees into discs. Two nails were driven into each disc on the upper and lower side of the tree, between which radial saw cuts were made. The saw cuts on the underside of the bowed region of the tree always closed up much more than those on the upper side. On the other hand, in the upper, erect part of the tree, where the danger of subsidence cracks does not exist, all the radial cuts closed up to roughly the same extent.

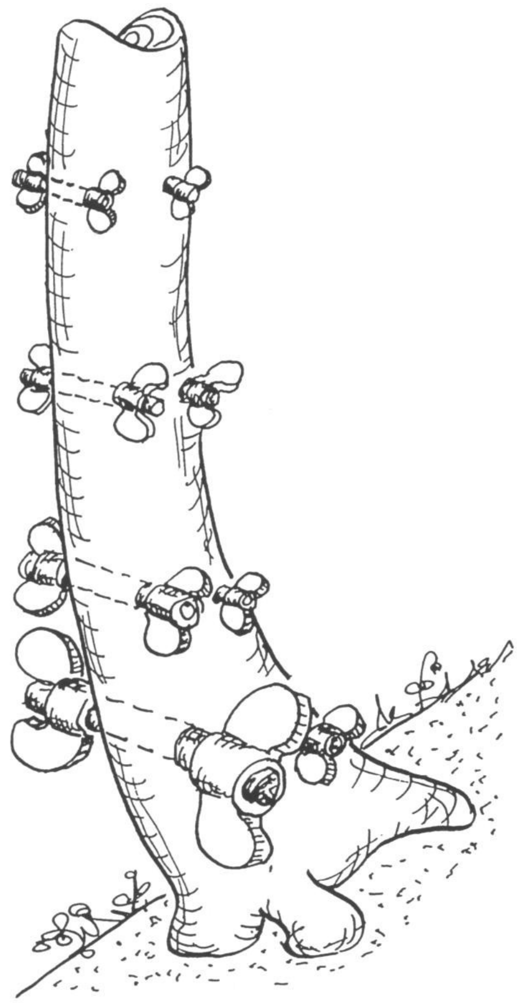


Fig 95. Greatly simplified, the combination of Figs. 90 and 94 looks like this: The tangential strength and growth stresses are greatest where the danger of cracks forming is greatest

13.3 BARK PHYSIOGNOMY AS A SENSITIVE BIOMECHANICAL WARNING SIGNAL

(First published in: 'Deutsche Baumschule', 1/94)

13.3.1 The place of bark in the VTA (Visual Tree Assessment) system

The VTA method helps defects in trees to be recognised, using external structural features. The basis of this is the idea that a tree wants a uniform distribution of its mechanical stresses and restores this if it is disturbed. If, for example, cavities or cracks cause locally higher stresses, then the tree lays down thicker annual rings forming a 'reparative structure' in the area affected, so that locally high stresses are evened out once more. Together with these repairs that are actively formed from the living cambium, there are also signs of defects that arise from dead parts of the tree, e.g. from the outer bark.

13.3.2 Bark – trees' crackled varnish symptoms

If one wishes to locate points on, say, a sample of steel where a given load produces locally high stresses, this can be done in the laboratory by first coating the sample with a brittle lacquer. Then, under loading, the lacquer cracks precisely at any points where a certain stretching is exceeded. Areas where the lacquer peels off have been loaded beyond this limit. If you dip your hand in thin plaster, let it dry and then move your hand you will get a good idea of how this lacquer works. The bark has the important function of, among other things, protecting the tree against the sun. It also serves as a mechanical protective shield. For the tree assessor it has a further advantage:

The bark is the stress-locating lacquer of trees!

We find crackled-varnish phenomena mainly among the thicker-barked kinds of trees, on mature oak stems or branches for example. Among thin-barked species like beech these stretch symptoms are less pronounced, and it is more usual to find puckering of the bark on the compressed side of the bend. You can also imagine these as creases in a rough leather jacket that has not seen any oil for a long time.

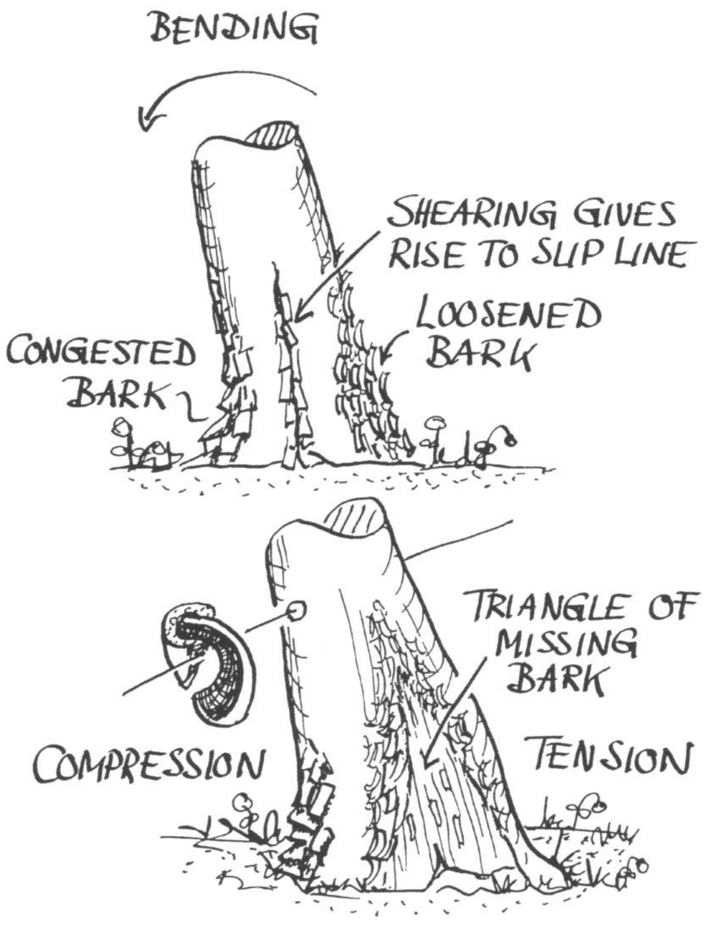


Fig 96. Various symptoms indicating the subsidence of leaning trees.

Now we have learnt that the loosening of bark is an indication of intense local stretching and therefore of large loadings, let us consider a few examples and practise this special aspect of Visual Tree Assessment.

13.3.3 Examples of applications

13.3.3.1 Subsidence of leaning trees

Relaxation can occur in the tensioning band of reaction wood that is found on the upper side of leaning broadleaved trees. The cause can be water shortage in very hot weather but also a reduction in vigour. This phenomenon, which can be likened to the slackening of a tensioning 'rope', allows the tree to subside by a creeping process of the wood. If a leaning tree is becoming dangerous in this way, the bark can reveal this. Figure 96 shows some phases of bark-loosening on the side of the bend under tension and the bark congestion on the compressed side. At an extremely advanced stage, a bare triangle will be visible on the side under tension. Occasionally shearing cracks also form. These arise when the two halves of the tree slide against each a little like the pages of a book that is bent. The slip line is usually visible in the bark long before cracks arise in the wood.

More will be said later about so-called 'subsidence cracks' that also occur in the stem of leaning trees.

13.3.3.2 Horizontal cracks, loose bark or bare wood overlying decayed areas

When decay spreads rapidly, the tree's response to the resulting increase in local stress (i.e., increased wood formation) is not always rapid enough to re-distribute the stress evenly. The tree lags behind and the bark foots the bill in that it is no longer a match for the suddenly far greater loads (Fig. 97).

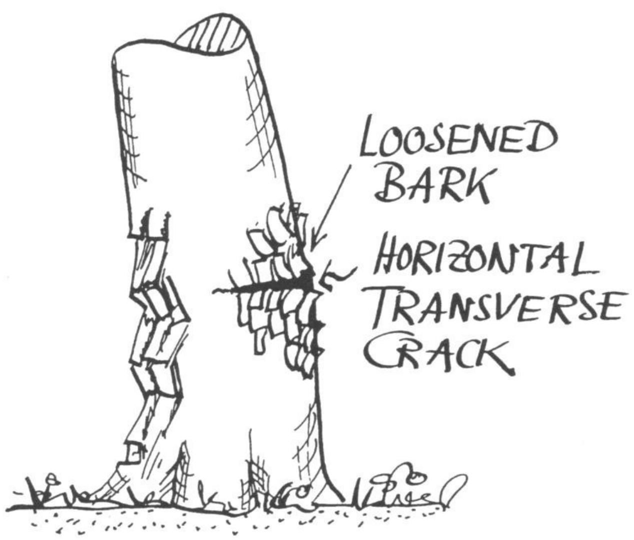


Fig 97. Localized disruption and mechanical symptoms in the bark near the top of a decay cavity. Bark can also look like this in regions of localized fibre kinking.

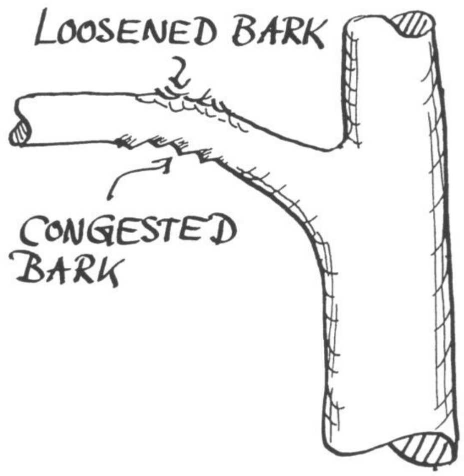


Fig 98. Signs in the bark of localized branch subsidence taking place at some distance from the branch base.

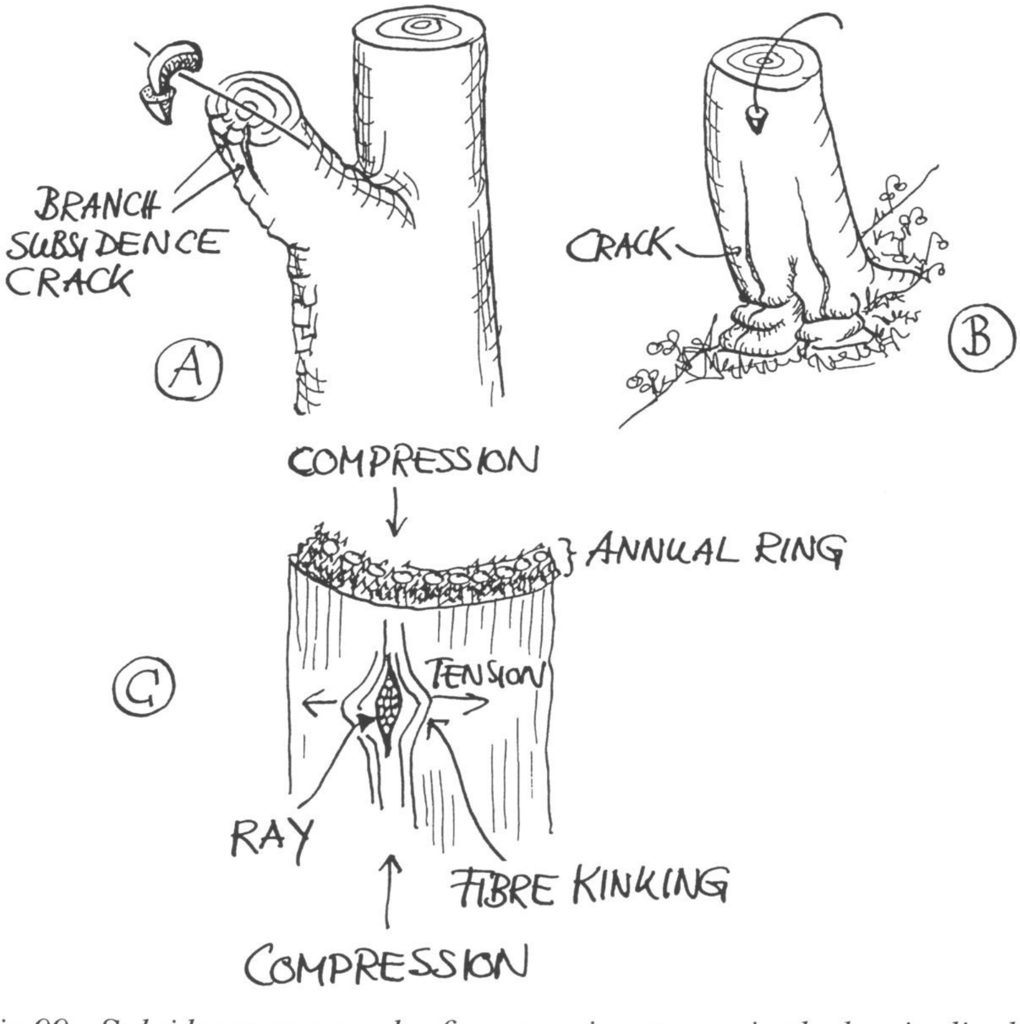


Fig 99. Subsidence as a result of compressive stresses in the longitudinal direction giving rise to transverse tensile stresses:

A: Subsidence crack in the underside of a branch.

B: Longitudinal cracks at the base of a beech due to stem subsidence.

C: The rays are often the starting point for the cracks.

13.3.3.3 Subsidence of heavy branches at a distance from the stem

Particularly with Black poplars, you quite often find fairly localized branch bending (Fig. 98) accompanied on the underside by congested areas of bark and on the upper side by bark loosening. In some cases, this local branch subsidence is associated with axial splitting on the underside of the branch. We should therefore like to call these splits 'subsidence cracks' (Fig. 99). They can also be found running through the bark of thin-barked species, and quite often split the natural bark plates longitudinally.

13.3.3.4 Cracks at the 'Chinese moustache'

Branches often subside near the point of stem attachment because this region includes a weak collar of stem fibres, which are laid down in successive layers each year around the branch base, as is the case, for example, with a weak leading shoot. In this same region, the fibres of the branch all turn downwards into the parent stem like tails, which are enveloped by the collar. If the branch subsides, these branch 'tails' are pulled slowly upwards out of the collar (Fig. 100A). The 'Chinese moustache' is a welded joint formed in the meeting zone of the cambium of the branch and of the stem. If a branch subsides, this point is subjected to tensile stresses which result in loosening of bark and finally the formation of cracks. In contrast the bark beneath the branch becomes congested (Fig. 100B). If it is not quite clear whether a branch

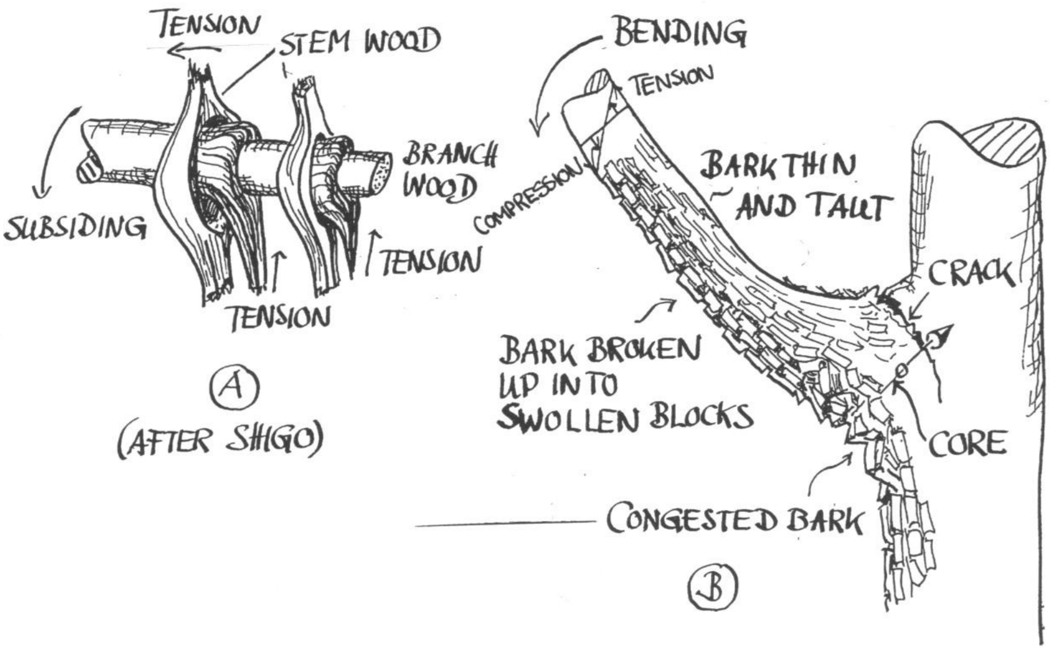


Fig 100. Subsidence close to the stem of heavy branches.

A: Internal mechanism.

B: Bark features.

is hazardous enough to require action, a radial boring can be made below the 'Chinese moustache' (Fig. 100B) to check whether the bark crack has yet penetrated into the wood.

13.3.3.5 Compression-fork cracks

Figure 101 shows a case where the bark shows clear indications of an internal crack. In cases where a main stem divides into a weak fork, splitting in the region can be controlled by bracing the fork with threaded bolts as recommended by standards such as ZTV-Baumpflege in Germany and BS 3998 in Great Britain. One of these bolts is placed about 10 cm above the tip of the crack in order to arrest it. The use of these threaded bolts is in some ways like a human hip replacement operation. As in the case of a human patient, some prior investigation is needed, so that, before bolts are inserted, a boring should be made to confirm that there are indeed cracks in the wood as well and not only in the bark (Fig. 101). If the Pressler core falls to pieces the top of the bole is really split. Shigo too gives similar advice for the expert application of threaded bolts [67].

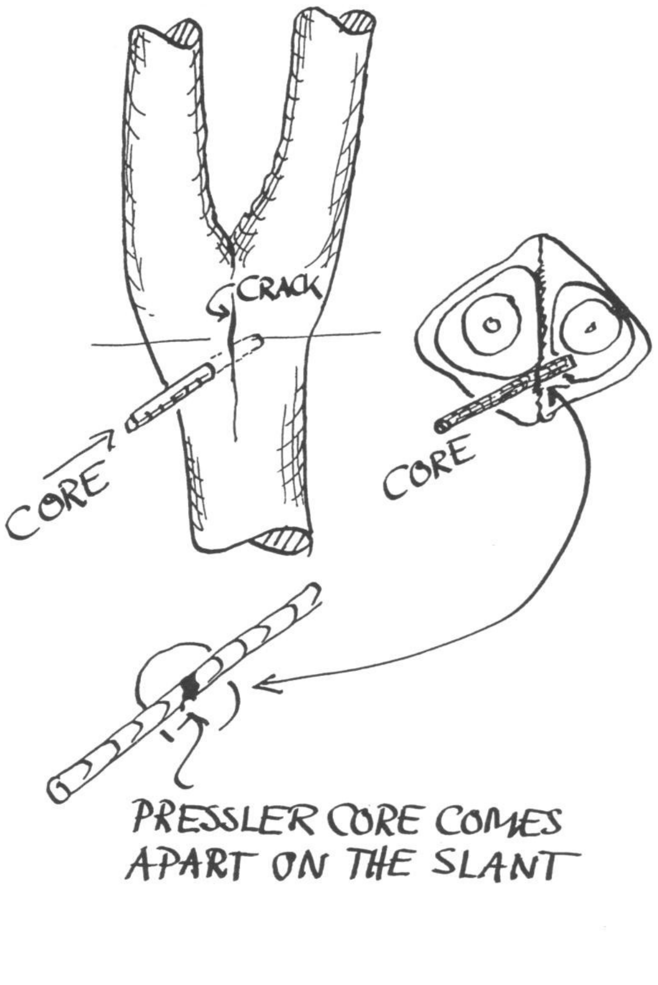


Fig 101. Cracks at pressure forks: bark crack and drilling direction for confirmation of crack in wood.

13.3.3.6 Compression bark and tension bark

Finally, there is one more widespread phenomenon that the authors have observed on a range of tree species and in various parts of trees; bark on the compressed side of the bend forms thicker, chunkier structures than the thinner plates of bark under tensile load (Fig. 102). A possible explanation for this is that, on the side under tension, the bark breaks up more readily than on the compressed side. It therefore falls off long before it can grow into such pronounced chunks as those formed on the compressed side.

13.3.4 Summary: the significance of bark 'symptoms' in tree inspection

The 'crackled varnish' symptom shown by bark is undoubtedly the most sensitive mechanical indicator of high local stresses. It warns of such defects even before the cambium, however, active it may be, can provide a symptom in the form of reparative growth. Understanding the language of the bark is therefore without question the most sensitive way of understanding the body language of trees and is an important aspect of VTA.

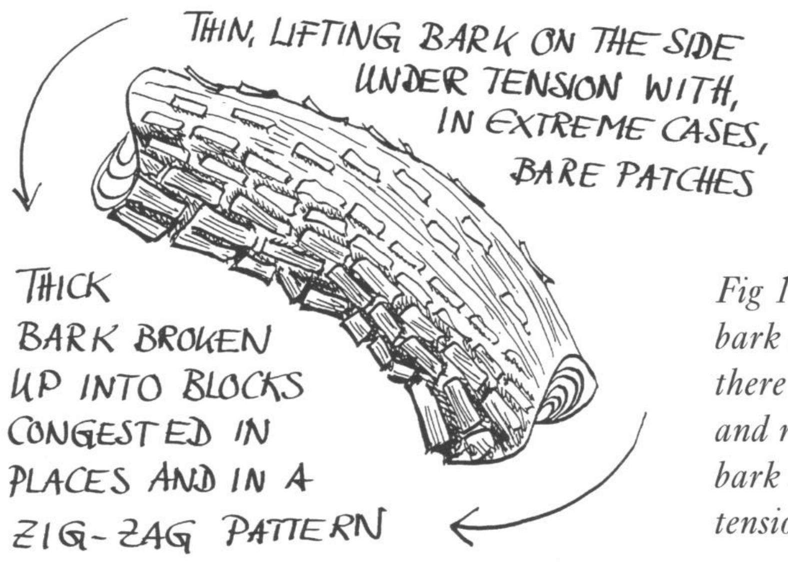


Fig 102. Thick, chunky bark congested where there is axial pressure, and rather thin and taut bark where there is axial tension.

14.0 A PRACTICAL GUIDE FOR TREE INSPECTION

14.1 FIELD INSTRUCTIONS FOR INSPECTING TREES USING THE VTA METHOD: VISUAL TREE ASSESSMENT

(First published as: Mattheck, Breloer: LÖLF-Mitteilungen 4 [1993])

If we want to identify trees which have a relatively high risk of failure, we need to understand their laws of growth and their construction. If something upsets the normal pattern by which stresses are evenly distributed over a tree's surface, the tree will try to restore the state of uniform stress. It does so by forming locally thicker annual rings. We can recognise these repairs as symptoms of defects. So for example, a rib is a symptom of a crack in the tree, while a swelling or bulge can indicate a cavity or softened wood. Experienced arboriculturists have been aware of such signs of repair for a long time. VTA puts this traditional visual assessment on to a biomechanically sound footing and defines failure criteria. If symptoms of defects are noticed, these must be confirmed by means of rigorous investigatory methods and then evaluated. At the Karlsruhe Research Centre, comprehensive field studies have been carried out with the *'Metriguard'*, a stress-wave timer. This detects with certainty decay where lignin has been decomposed, and its use involves very little injury to the tree. If abnormally low sound velocities or other indications give cause for concern, an increment core is taken and its strength determined with the *'Fractometer'*. In this way invasive techniques are used only when there is good reason to suspect that the tree may be dangerous.

The rooting stability of trees can also be assessed with VTA. Any defects, once recognised and quantified are evaluated using VTA criteria, and finally a management decision for the tree in question is reached with the help of biomechanical criteria.

VTA helps to explain unpredictable damage, such as embrittlement of the wood or alterations due to temperature (which might be the cause of summer branch drop), and to distinguish it from damage that can be foreseen. Nature's principle of light structures allows a natural failure rate even among healthy trees so as to reduce the costs of the success of the species. There are no promises where tree safety is concerned. VTA compares the safety of the defective tree with that of the defect-free one that could also break in the normal course of events.

VTA proceeds in three stages:

1. Visual inspection for defect symptoms and vitality. If there is no sign of a problem, the investigation is concluded.
2. If a defect is suspected on the basis of symptoms, its presence or absence must be confirmed by a thorough examination.
3. If the defect is confirmed and appears to be a cause for concern, it must be measured and the strength of the remaining part of the tree evaluated.

The tree as a chain of links matched to the load

We should always remember that, with regard to the force flow, the parts of the tree must be matched to each other (Fig. 103). The tree is a chain of equally strong members. The stem gathers, so to speak, the bending loads borne by the branches and conducts them downwards into the rootstock from which they are redistributed through a ramifying root system that finally transfers them to the ground. The whole is therefore somewhat reminiscent of a sailing boat in a very, very glutinous sea with the root plate as the boat's hull. Thus, in an unpruned, healthy tree, the sail area of the crown, the girth of the stem and the spread of the root plate are perfectly matched to the wind load as measured by the tree.

- *The crown as a sail in the wind*

  Leaves, twigs and branches take up a load from the wind and introduce it via the limbs into the stem.

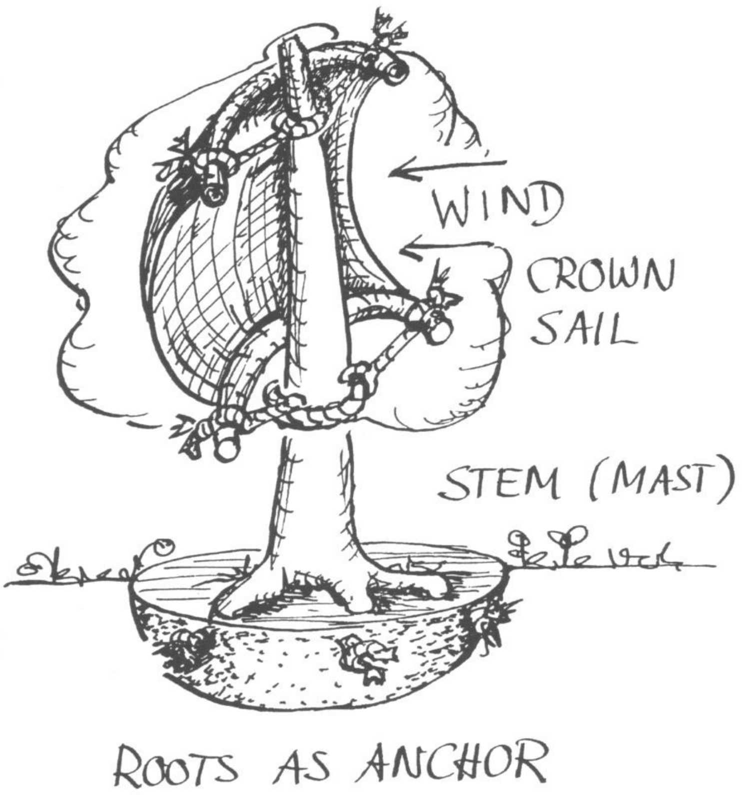


Fig 103. The tree as a chain of links each matched equally well to the load.

- *The mast as courier with the load*

  The stem collects the wind load as the mast of a ship collects the power of the sails and conducts it into the root plate.

- *The ship's hull in the ground*

  In the root plate, the load is distributed via the root buttresses to major and fine roots. Finally, the whole wind load must be taken up by the ground around the root ball.

  The dimensions of the hull (root-plate) are largely determined by the wind load introduced from the mast and the shearing strength of the soil. This applies to the static roots, that is to say to those which are found within the upturned root-plate if the tree becomes windthrown. Roots growing hydrotropically can range for many metres beyond this and are of little biomechanical significance. Therefore anyone who uses a simple tape to measure the girth of the stem of the *uninjured* tree above the root buttresses has all the information that he needs about the wind load that is introduced from above and what has to be transferred into the ground. The sail determines the thickness of the mast and this in turn the radius of the hull. To understand one link in the chain is to know everything about the loading!

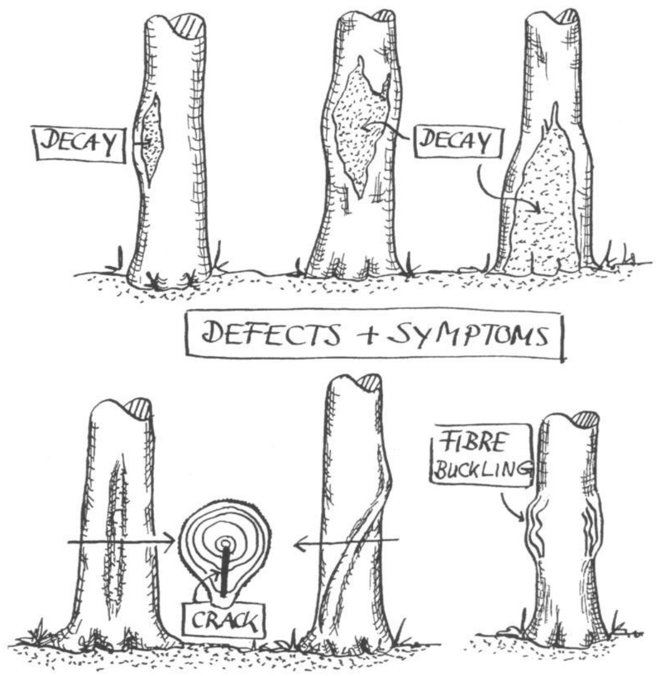


Fig 104. The principal symptoms of mechanical defects.

Safety from breaking

1. *Vitality*
   Foliation, dead branches, branch-shedding collars, loose bark, poor growth, delayed wound healing, missing cambium.

2. *Fungal attack*
   Fruit bodies, liquid flowing from open wounds without other fungal signs.

3. *Symptoms of mechanical defects*
   In general, the presence of any apparently superfluous woody growth is a symptom of a defect. The number of potential fine distinctions in the form and size of defects is virtually unlimited, but a few basic, actively produced types of symptom can be distinguished (Fig. 104):

a. *Ring swellings and bulges*
   The large variety of symptoms in this family is shown in Fig. 105. Often the bark is split open by local reparative growth or has lifted slightly.

Fig 105. Examples of swelling and bulge formation in response to various internal defects.

– Bulges as symptoms of one-sided zones of decay close to the bark. Confirm by sounding with mallet (not always reliable!).

– Ring swellings as symptoms of more or less symmetrical zones of decay.

– Bulges and ring swellings with clearly defined margins as symptoms of fibre kinking (soft wood without decay). On sounding seems like healthy wood.

b. Ribs and helical ribs

A collection of examples of ribs is shown in Fig. 106.

– Ribs as symptoms of radial cracks. A round-edged rib indicates successful healing or at least several annual rings bridging the crack. A sharp-edged rib indicates a continually extending crack and unsuccessful healing.

– Helical ribs as symptoms of radial cracks where growth has spiralled. They occur only as the result of torsional loading counter to the direction of helical growth and often result from a one-sided crown or wind load.

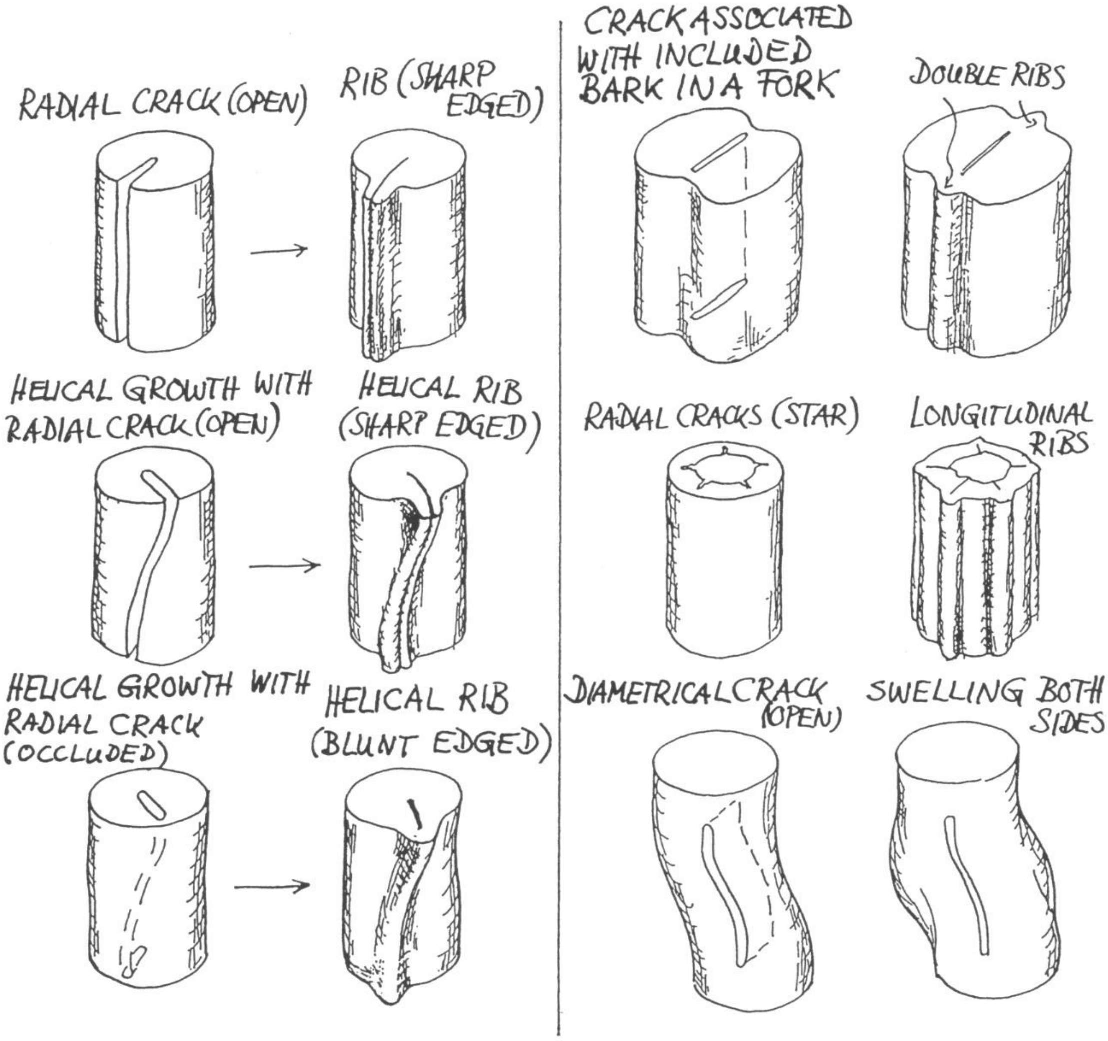


Fig 106. Examples of rib symptoms.

4. *'Crackled varnish' signs of brittle fractures (see also Chapter 13.3)*
Unlike symptoms produced by reparative growth, these symptoms consist of localised brittle fractures at the surface which can be due to underlying partial failure (Fig. 107).

–Transverse cracks that often pass through the normal bark plates indicate that the wood has been severely stretched as the result of localized wood failure or else as the result of increased growth (a symptom of repair).

–Localized patches of loose bark that lift away similarly indicate fast growth; possibly the first sign of symptom formation or a sign of increasing tensile stress.

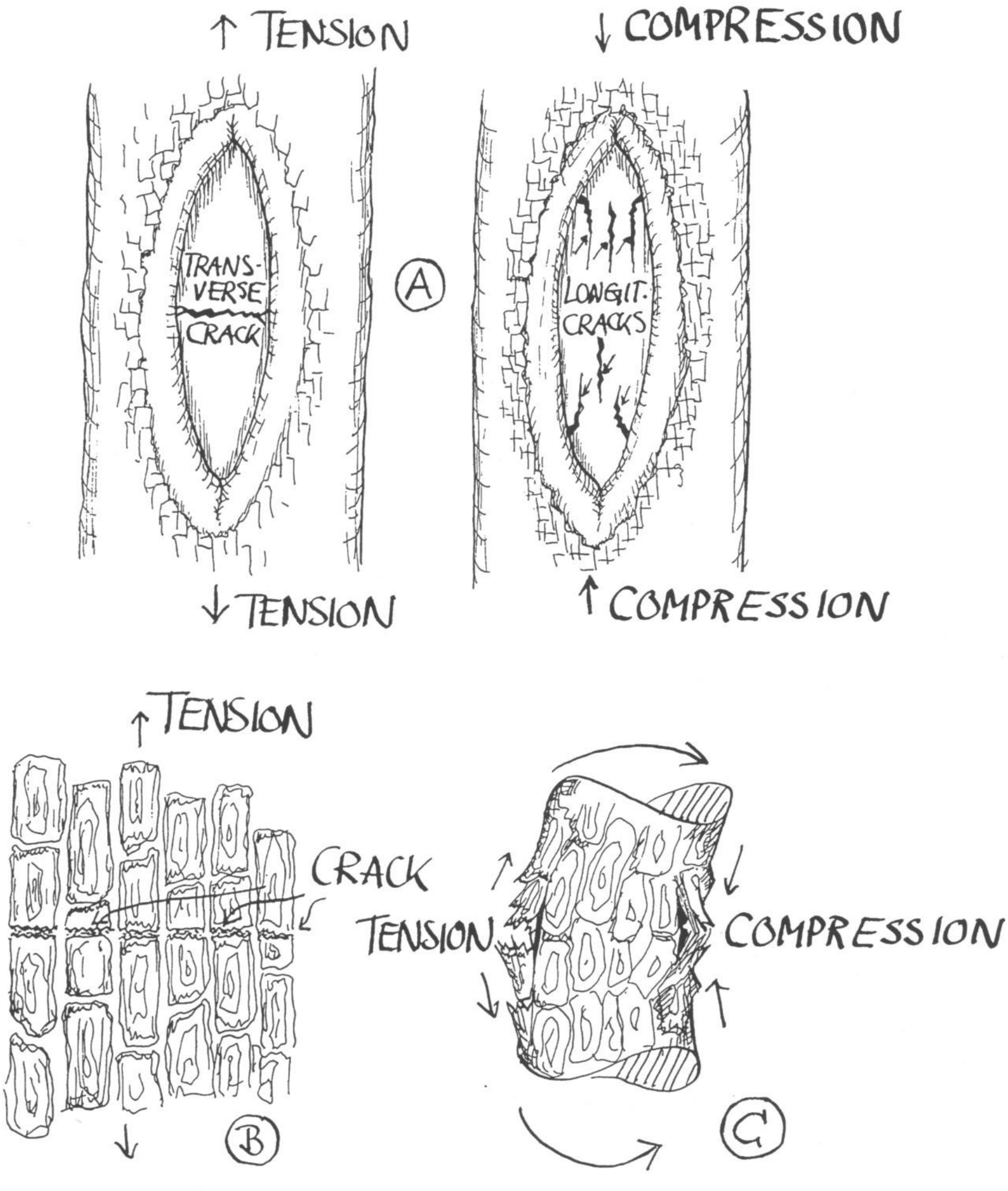


Fig 107. Bark cracks indicate locally severe stretching. Transverse cracking means axial tension, longitudinal cracks or bark congestion means axial compression.

- Transverse cracks in cavity fillings or wound sealants indicate increasing tensile loads (Fig. 107).

5. *Embrittlement of the tree*
   In field conditions, the *'Fractometer'* is at present the only means of detecting embrittlement with certainty and of measuring it. Embrittlement usually involves the preferential decomposition of cellulose but retention of lignin. This means that stiffness is preserved but breaking strength falls rapidly. Biomechanical symptoms are usually entirely absent.

6. *Signs from tree strengthening devices*
   - Cables or straps that are too tight indicate either that they have been installed incorrectly or that the parts of the tree concerned are subsiding, as also shown in most cases by cracks and ripple-like creases in the bark at the base of the affected branch (lower side).
   - Washers sinking into the bark as if stamped in indicate overloaded threaded bolts.

7. *Confirming defects and determining the thickness of the residual wall where decay is present to rule out failure by buckling or hosepipe kinking.*
   - *Simple apparatus:*
     Mallet, tape measure, steel spike, increment borer, bicycle spoke, binoculars.
   - *Sophisticated apparatus:*
     Stress-wave timer, *'Resistograph'*, *'Fractometer'*.

In most cases the point of most marked symptom formation is also the thinnest place (Fig. 108). This can often but not always be confirmed by tapping with the mallet. Decay in which lignin has been decomposed can be confirmed with absolute reliability with the stress-wave timer. In many cases the thickness of the remaining wall can be measured from the exterior with a steel skewer or something similar. If not, the wall thickness must be measured harmlessly with the *'Resistograph'* or, less harmlessly, with the increment borer. A bicycle spoke, as Herr Braukmann of Rastede in Germany has suggested, can often be very usefully hooked inside with the head end at the inner edge of the bore hole, although this will not tell you anything about the strength of the residual wall. The apparatus that in our opinion is at present the most suitable for use in connection with VTA is described in more detail in Chapter 14.2.

Recommendations for measurements that are to be used with the VTA diagram:
In the case of asymmetric zones of decay it is sensible to define the wall thickness as shown in Fig. 108; that is, always to measure the thinnest part of the wall. The radius is then the distance from the centre of the decayed area to the nearest point on the surface of the tree.

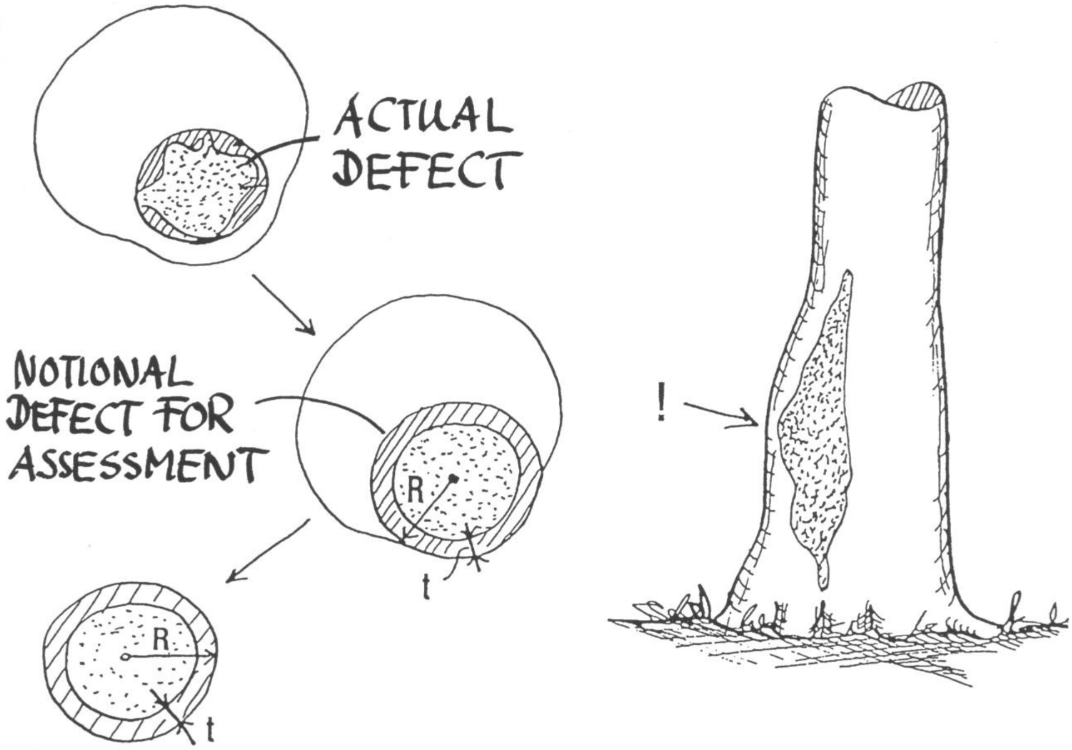


Fig 108. The thinnest part of the residual wall is usually at the point of most pronounced symptom formation.

8. *Open cross-sections*

   As the safety factor for stems is greater than S = 4.5, bending fractures only play a part in widely gaping cross-sections. To exclude the possibility of failure from cross-sectional flattening (Fig. 109) it is therefore sufficient to fulfil the requirement *t/R > 0.3 to 0.35* for trees with full crowns. Here *t* is the thickness of the healthy remaining wall and *R* the radius. (A field study on broken and standing hollow trees in Germany, England and the USA showed that almost all the trees that broke had a t/R ratio below 0.3 (Fig. 110). Whenever there is any suspicion that the t/R ratio in a hollow tree could be close to 0.3 – 0.35, the *'Fractometer'* should be used to determine whether the strength of the residual walls is satisfactory. The failure criteria can also be applied to eccentric cavities (Fig. 108) if the decay occupies more than half of the stem diameter.

Stability

In assessing stability, the following points should be noted:

1. *Symptoms of damage in the rooting area*
   - Dead branches on one side sometimes indicate damage to roots on one side.
   - Lack of growth, especially with signs of root death such as dry, crumbly bark on root buttresses, indicates that the roots are becoming less firmly anchored.

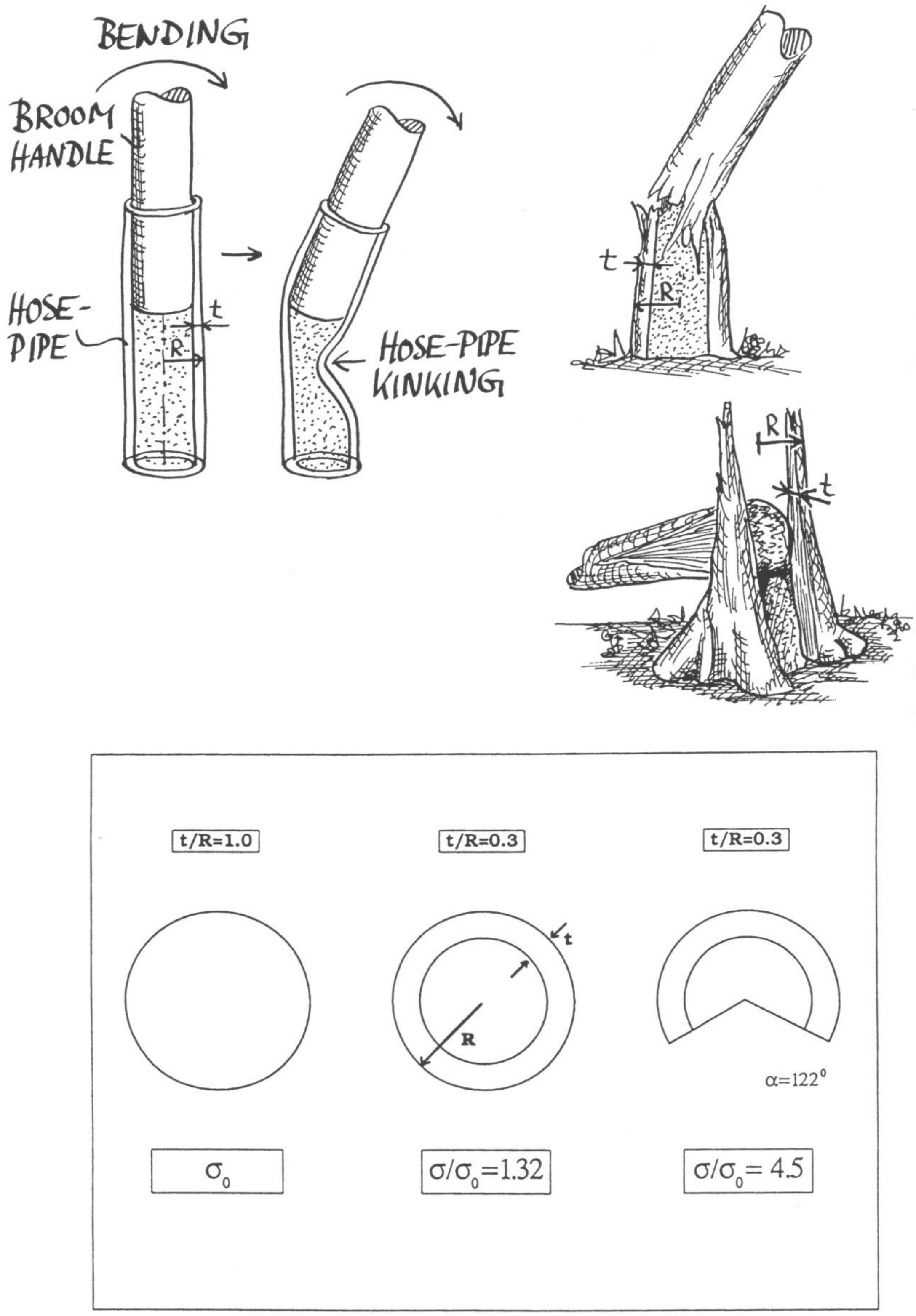


Fig 109. In practice, trees with closed or almost closed cavities are extremely unlikely to fail as the result of bending fractures. Where the thickness of the sound residual wall is less than 30-35% of the stem radius, failure results from cross-sectional flattening. Where there is an opening occupying 120° or more of the circumference, failure from bending fracture or cross-sectional flattening is probable.

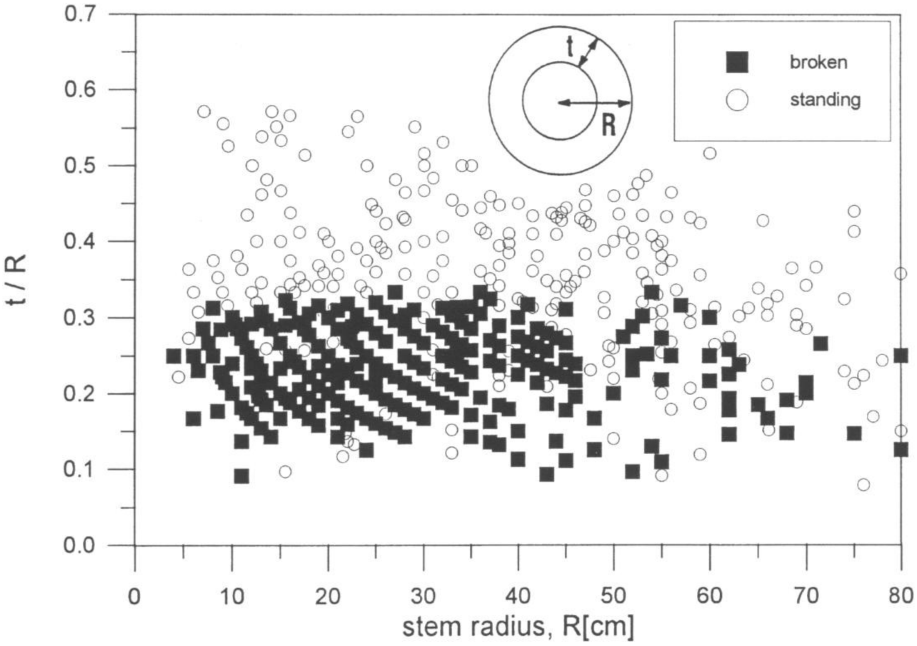


Fig 110. The tree fracture VTA diagram, which is based on a field study, shows cross-sectional flattening fractures occurring only when t/R is less than 0.3 - 0.32. The failure of hollow trees with reduced crown sail area tends to happen only if the t/R ratio is even smaller, often when t/R = 0.25.

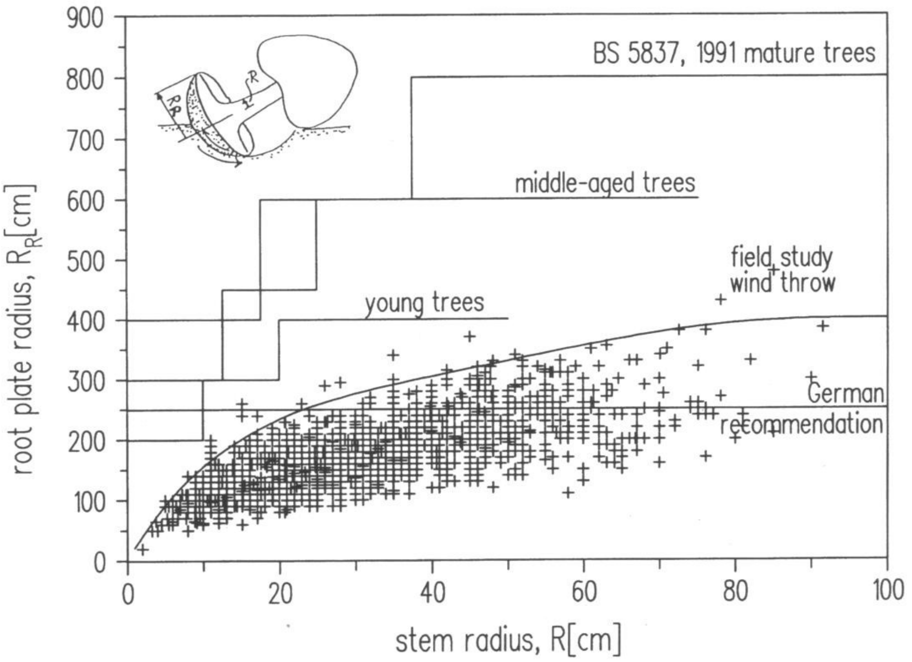


Fig 111. VTA windthrow diagram for park and garden trees. Above the area with the plotted points, no windthrow was observed. The contour of the area's upper boundary is therefore a failure boundary curve. The stepped line is taken from the British Standard BS 5837 which also includes mechanically non-functioning roots. This British recommendation and the German 2.5 m recommendation are the distances given for the protection of roots from building operations in the vicinity of trees.

- Greatly increased growth of individual root buttresses, usually accompanied by longitudinal cracks in the bark or a 'full' appearance of the tree surface, indicates an increasing load on these roots. Causes of this include: death of other roots, changes in the wind load, an upset to the symmetry of the crown, or a reparative response to internal decay.
- Cracks in the ground on the windward side indicate the start of windthrow.

2. *Excavations in the rooting area and the VTA diagram*

Field studies on windblown trees produced the diagram in Fig. 111.

Evaluating the root-plate

- Measure the stem radius R.
- Determine the static root-plate radius R_R in the VTA diagram (Fig. 111).
- Excavate at a distance R_R from the centre of the stem. If there are no healthy roots there, dig again closer to the stem. The closer to the stem that major root loss is found, the more heavily the crown has to be reduced. The method, unmodified, can only be employed for park and garden trees because trees in built-up areas or by roadsides usually have asymmetric root-plates. For such trees, there is no substitute for a very detailed assessment of any damage that may have resulted from trenching or other activities.
- Decay in the larger roots

  Damage at the stem base can be detected with the stress-wave timer. The same applies to the root buttresses (see also Fig. 113). If butt-rot is present but has not developed sufficiently in the stem to increase the risk of breakage ($t/R > 0.3$), it is nevertheless necessary to ascertain whether 50-70% of all root buttresses are sound [36]. This can be done with a 3 mm twist bit or with the '*Resistograph*'. If there are badly decayed buttresses, the extent and type of the decay should be evaluated with the '*Fractometer*'. Root damage requires more individual measurement than in the case of hollow stems, and is more difficult. Roots on the windward sides of trees and the 'upper' roots of trees are most important. Also the size of the absent or damaged buttress or sector of the root-plate must be taken into account.
- Trees without safety reserves

  Fig. 112 shows a number of damage types where, with a full crown, the trees no longer have any safety reserves, i.e. they are at the end of their safety tether.

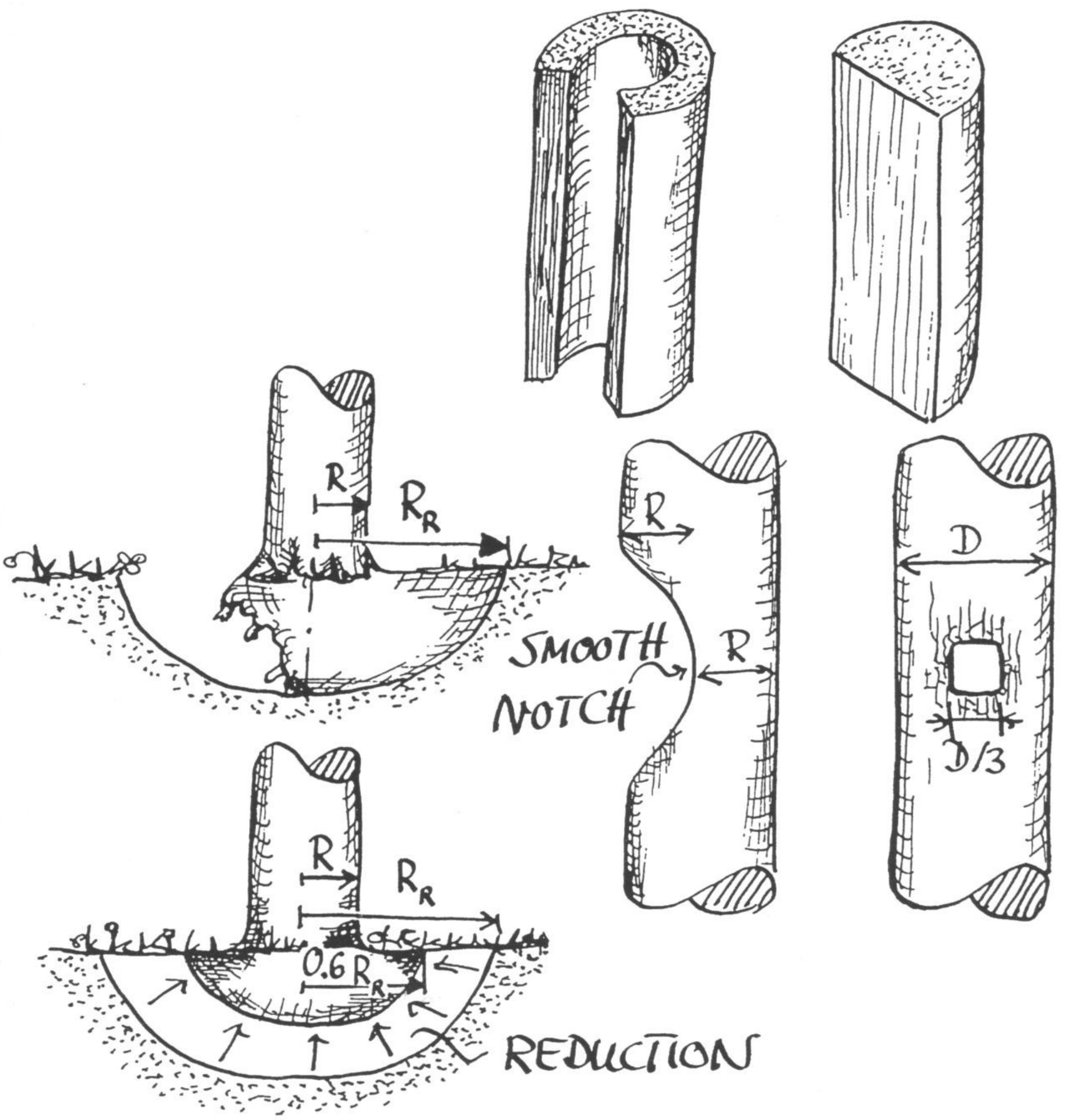


Fig 112. Trees with stresses increased 4.5 times by defects and which therefore have no mechanical reserves left at all.

Apparatus for checking and measuring defects

VTA interprets the body language of the trees and provides failure criteria. Therefore VTA is not wedded to any particular defect-measuring instrument and is open to new methods. For example the following instruments seem to be scientifically proved and reasonably priced:

1. The STRESS-WAVE TIMER (e.g. *'Metriguard'*) detects decay, cracks, included bark etc. from the drastic reduction in the velocity of sound. Fig. 113 shows the principle and the approximate nominal sound velocity values for healthy woods. Where decay or wetwood is extensive, the sound velocity is reduced to half or less, except in the case of certain types of decay. The shallow penetration of the screws minimises damage to the tree.

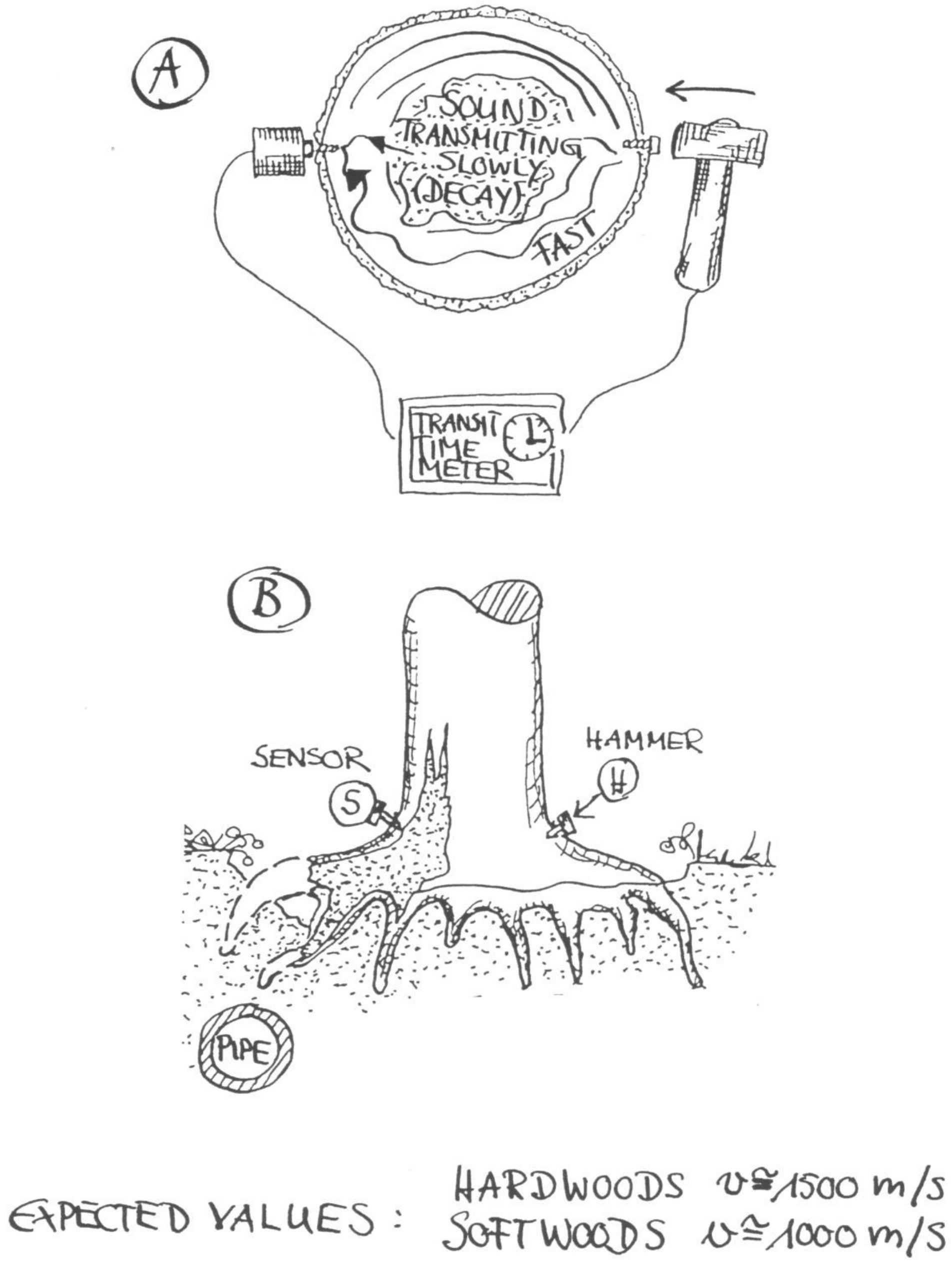


Fig 113A. STRESS-WAVE TIMER showing measurement of sound transmission time and expected sound velocity values for healthy trees. The apparatus consists of three parts: 1. Hammer with built-in acceleration rate pick-up; 2. the sensor that is fixed to the tree opposite the hammer and also contains an acceleration rate pick-up; 3. the actual transit time meter housed in a steel box.

Fig 113B. An initial stability test can be made by taking soundings at the base of the tree just above ground level. If decay is suspected, the root buttresses should be cleared of soil and if necessary the condition of the wood checked. Where a tree is concreted in, the last resort is to probe the buttress zone by drilling a deep hole from the stem base with a long drill-bit of the type supplied with the endoscope.

2. The 'RESISTOGRAPH' drives a thin needle drill into the tree with a constant forward speed. The drilling effort along the route of the bore hole is clearly determined by the mechanical properties of the wood. Decay detection and wall thickness measurement is carried out in one operation. Wetwood has a higher drilling resistance than normal wood.
3. INCREMENT BORER AND 'FRACTOMETER'- The effective load-bearing thickness of the residual wall can seldom be determined solely by examining an increment core. Use of the *'Fractometer'* determines whether the wood making up the wall has the required strength (Fig. 114).

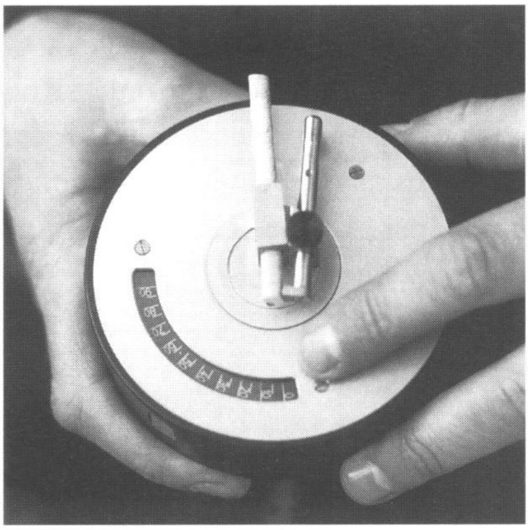


*Fig 114. The 'Fractometer' measures the breaking strength of an increment core. As the term **'breaking'** strength implies, it cannot be measured non-destructively.*

The *fracture characteristics* are ascertained as follows:

a Take a sample core with the increment borer from the part of the tree where you wish to determine the fracture characteristics.

b Check that the load indicator is set at zero (= 10).

c Insert the test core into the holder.

d Hold the *'Fractometer'* in the left hand and turn the rotating ring of the *'Fractometer'* firmly in a clockwise direction (as viewed from above). The coarse load indicator moves upwards in the graduated window and the fine indicator can be read on the side of the barrel.

e As you continuously increase the load by continuing to twist you must watch the bending angle indicator. It is best to read the increasing angle out loud. As the test piece breaks, the angle increases without the need for any further increase in load. This wood failure can proceed slowly and gradually or rapidly with a brittle fracture. Note the maximum value that the angle reaches ($\phi_{Fracture}$) before the failure begins.

f When the core has broken completely, you can read off the load shown in the side window.

g The table in Fig. 115 shows you a few examples of breaking-load values, expressed in *'Fractometer'* units, from trees commonly present in Europe.

h The fracture angle and the *'Fractometer'* load value allow you to ascertain the effect of the decay on wood stiffness and wood strength (Fig. 116), and thus to deduce whether lignin or cellulose has been preferentially decomposed.

If the average strength value has dropped to 1/4.5 of the nominal value, the tree has practically no safety reserve left, even if it is not hollow at all. This also applies in the case of wood that has become embrittled in the absence of external symptoms.

Leaning trees

Every branch, from the purely biomechanical point of view, is a leaning tree. If every leaning tree were a dangerous tree, then every leaning branch – and therefore nearly every branch! – would be a dangerous branch. Nevertheless, the loading on a leaning tree is naturally higher than on an upright one, and so it needs to resist the resulting tendency to subside gradually and eventually to collapse. It does this by forming extra supporting material, especially reaction wood.

Species	Fracture Moment in Fractometer Units		
	Green	Yellow	Red
Hardwoods			
Ash	80-59	58-38	37-18
Birch	40-30	29-20	19-10
Black alder	50-38	37-25	24-12
Black locust	120-89	88-58	57-27
Black poplar	20-15	14-10	9-5
Common beech	120-89	88-58	57-27
Copper beech	120-89	88-58	57-27
Elm	110-82	81-54	53-26
Hornbeam	120-89	88-58	57-27
Horse chestnut	70-52	51-34	33-16
Lime	60-46	45-30	29-14
Lombardy poplar	20-15	14-10	9-5
Maple	120-89	88-58	57-27
Oak	120-89	88-58	57-27
Plane	120-89	88-58	57-27
Sweet chestnut	50-38	37-25	24-12
White poplar	20-15	14-10	9-5
Willow	20-15	14-10	9-5
Softwoods			
Douglas fir	7-6	5-4	3-2
Fir	15-12	11-8	7-4
Larch	15-12	11-8	7-4
Pine	15-12	11-8	7-4
Spruce	20-15	14-10	9-5
Yew	90-67	66-44	43-21

Fig 115. Some characteristic breaking values of trees commonly grown in Europe can be read direct from the 'Fractometer' scale. The table is the result of a preliminary field study and will be continually updated in the coming years.

Green: good wood quality.

Amber: reduced wood quality.

Red: poor wood quality.

fractometer fracture moment	fractometer fracture angle	decay effect	wood property
large	small	low	high stiffness and high strength
large	large	lignin destruction	low stiffness but high strength
small	small	cellulose destruction	high stiffness but low strength
small	large	lignin and cellulose destruction	low stiffness and low strength

Fig 116. A ranking of 'Fractometer' wood quality measurements, evaluated according to whether lignin or cellulose has suffered selective fungal degradation.

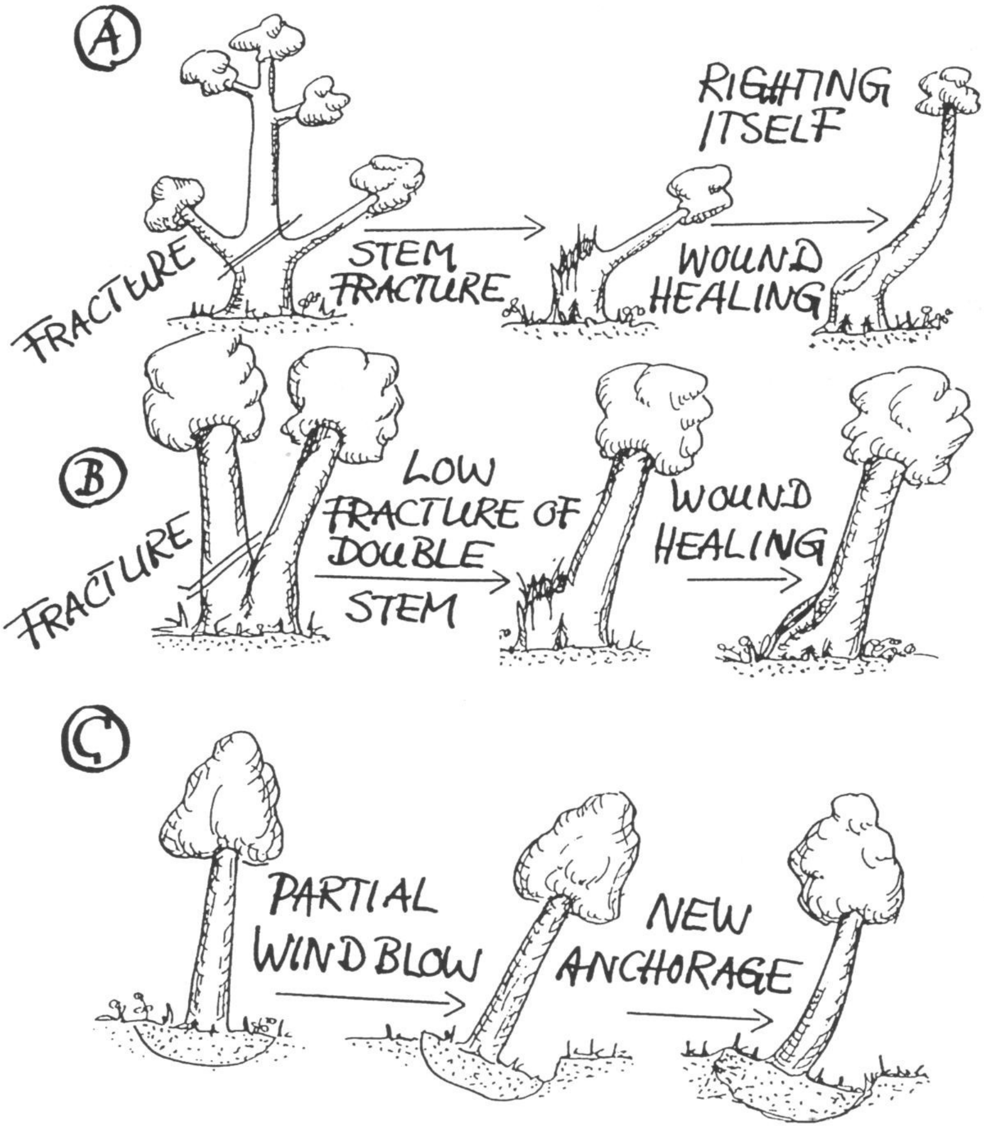


Fig 117. How trees can come to be leaning.

There are various ways in which a tree can acquire a lean (Fig. 117). Leaning trees not only experience the bending loads produced when they sway in the wind, but also a static bending on account of the eccentricity of the crown's centre of gravity. This is dangerous because, under a static load, wood can creep and the tree can only counter this (by forming reaction wood) while it has sufficient vigour. There are therefore some fracture mechanisms that are particularly common in the case of leaning trees (Fig. 118).

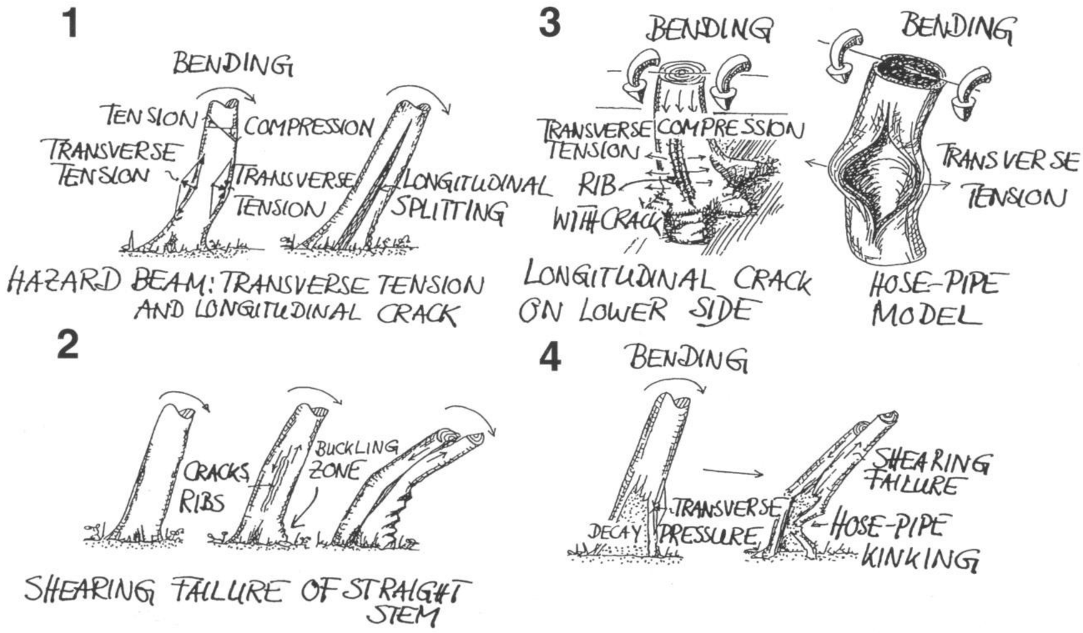


Fig 118. Types of failure in leaning trees: 1. Longitudinal splitting as bowed trees straighten. 2. Shearing failure of a straight but leaning tree. 3. Bursting as the result of transverse tensile stresses. 4. Hosepipe kinking or shell buckling of hollow trees.

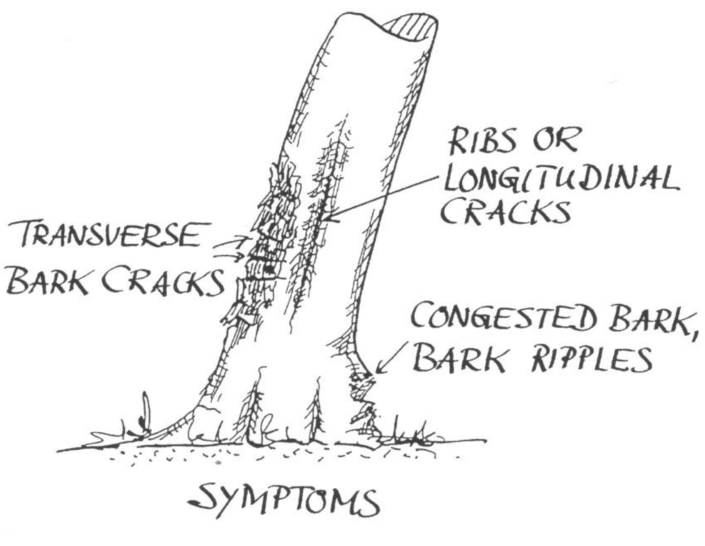


Fig 119. First signs that a leaning tree is beginning to collapse by subsiding.

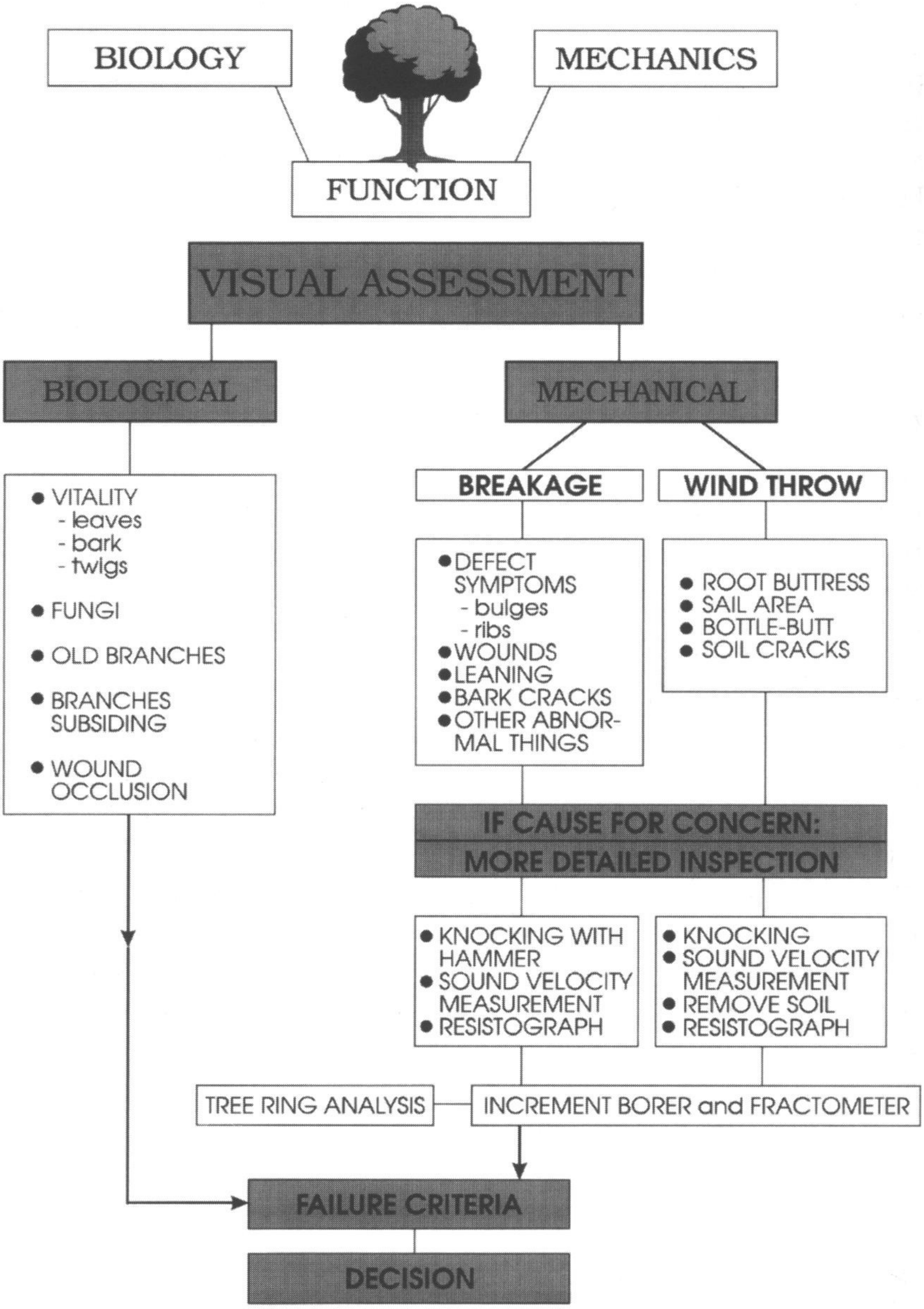


Fig 120. The Visual Tree Assessment (VTA) procedure for assessing trees. As the suspicion increases that defects are present, the examination becomes more thorough and searching.

The worst signs of a potential fracture in a leaning tree are transverse cracks or areas of abnormally loose bark on the upper side of the lean (i.e. facing away from the ground), together with longitudinal cracks or ribs on the neutral sides of the lean, where the greatest shearing stresses are acting. On the underside of the lean, and particularly above the root buttresses, early signs which commonly occur are concertina-like bark folds, congested wood or longitudinal cracks (Fig. 119). Figure 120 shows a schematic sequence of tests that are carried out during a VTA examination, with increasingly detailed ones being used if concern mounts.

Caution

As already pointed out, there are occasions when even healthy and completely defect-free trees break or become windthrown. This represents a 'normal failure rate', which is the price of the energy-saving, lightweight structure that favours the species to compete with others in a cost-effective way.

We can use VTA to state to what extent a defective tree is at greater risk of breaking, compared with a completely sound one. However, since nature's principle of lightweight structures allows a natural failure rate to occur even without defects, there can be no absolute guarantee of safety. This needs to form an integral part of the law, as has been established in the German Federal Court with the judgement of 21.1.1965 (see Chapter 12), even though more recent legal rulings seem to have forgotten this!

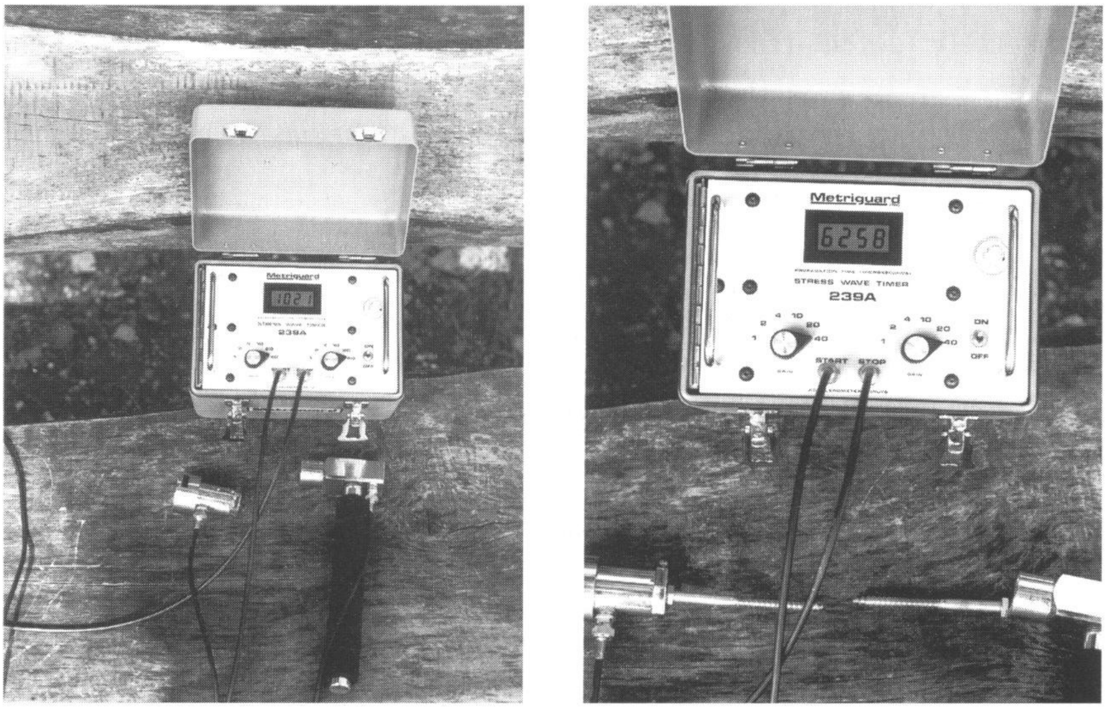
The judgement of 1965 stated: – 'Indeed, every tree in a street represents a potential danger because, as the result of natural events, even healthy trees can be uprooted or snapped or parts of them can be broken off. Furthermore, ill-health or decay in a tree is not always identifiable from the outside'.

'However, this does not justify the removal of all trees from the vicinity of streets, since passers-by must accept that certain dangers that do not arise from human activity but depend on the circumstances or forces of nature are unavoidable.'

14.2 ADDITIONAL INFORMATION ON USING INSTRUMENTS FOR TREE INSPECTION

14.2.1 The velocity of sound in trees, as measured with the stress-wave timer

A table of the velocities of sound in healthy trees is to be found in Fig. 121a. Some idea of the effects of various defects on these values is given in Fig. 121b. In the presence of most kinds of defect the sound velocity is drastically reduced. Embrittlement of a tree is not always detected. Wetwood reduces the velocity considerably, although strength may still be good.



The Metriguard stress-wave timer and accessories.

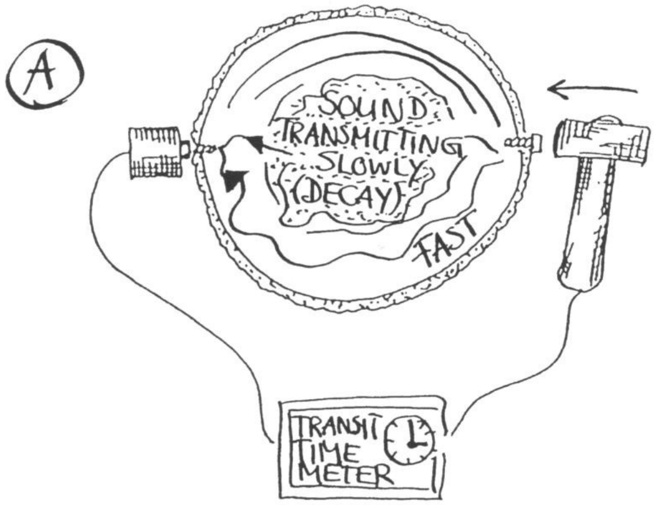


Fig 121a. Sound velocities across the stems of healthy trees.

Expected value for hardwoods: $v = 1500 \text{ m s}^{-1}$.

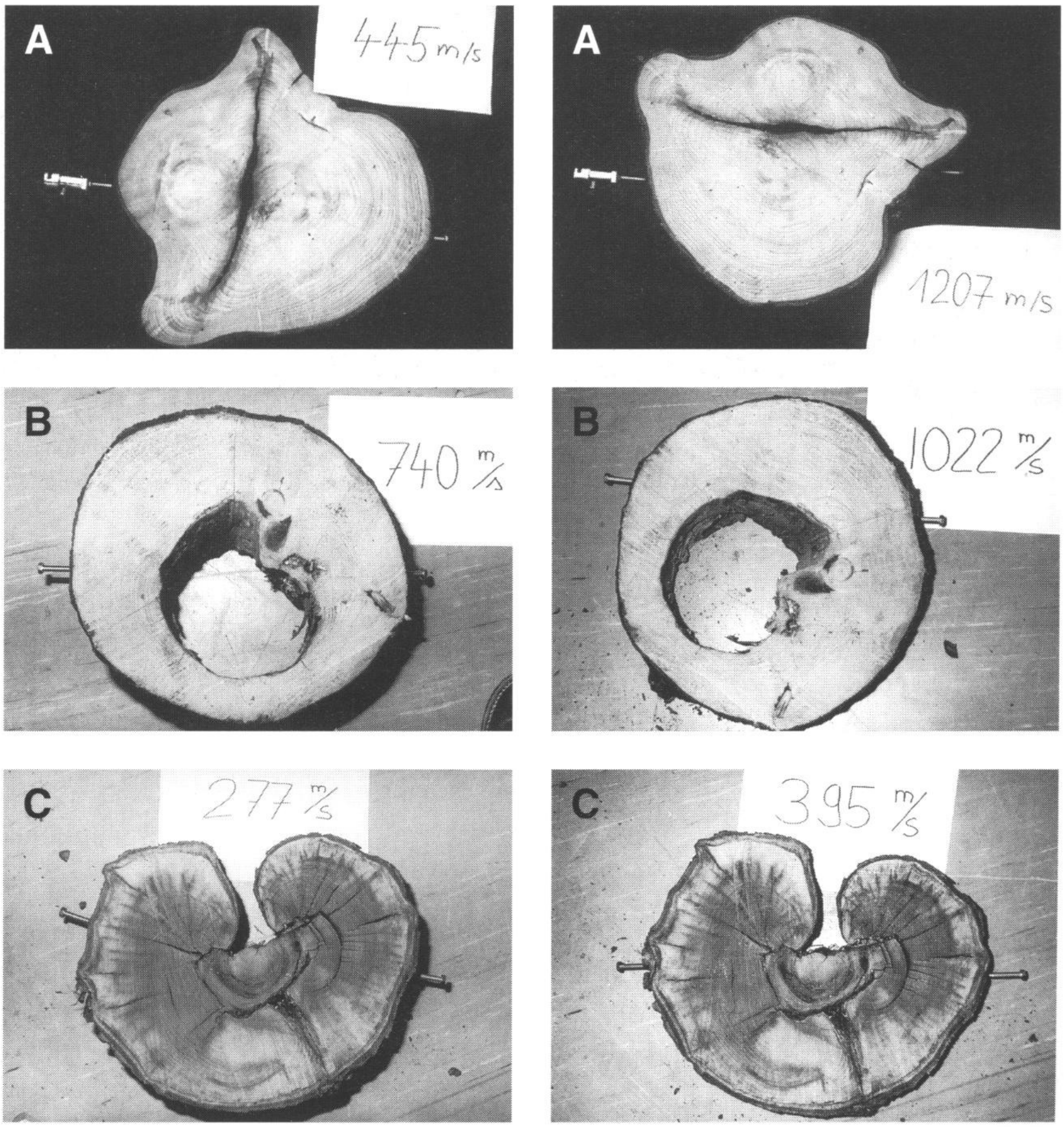
Expected value for softwoods: $v = 1000 \text{ m s}^{-1}$

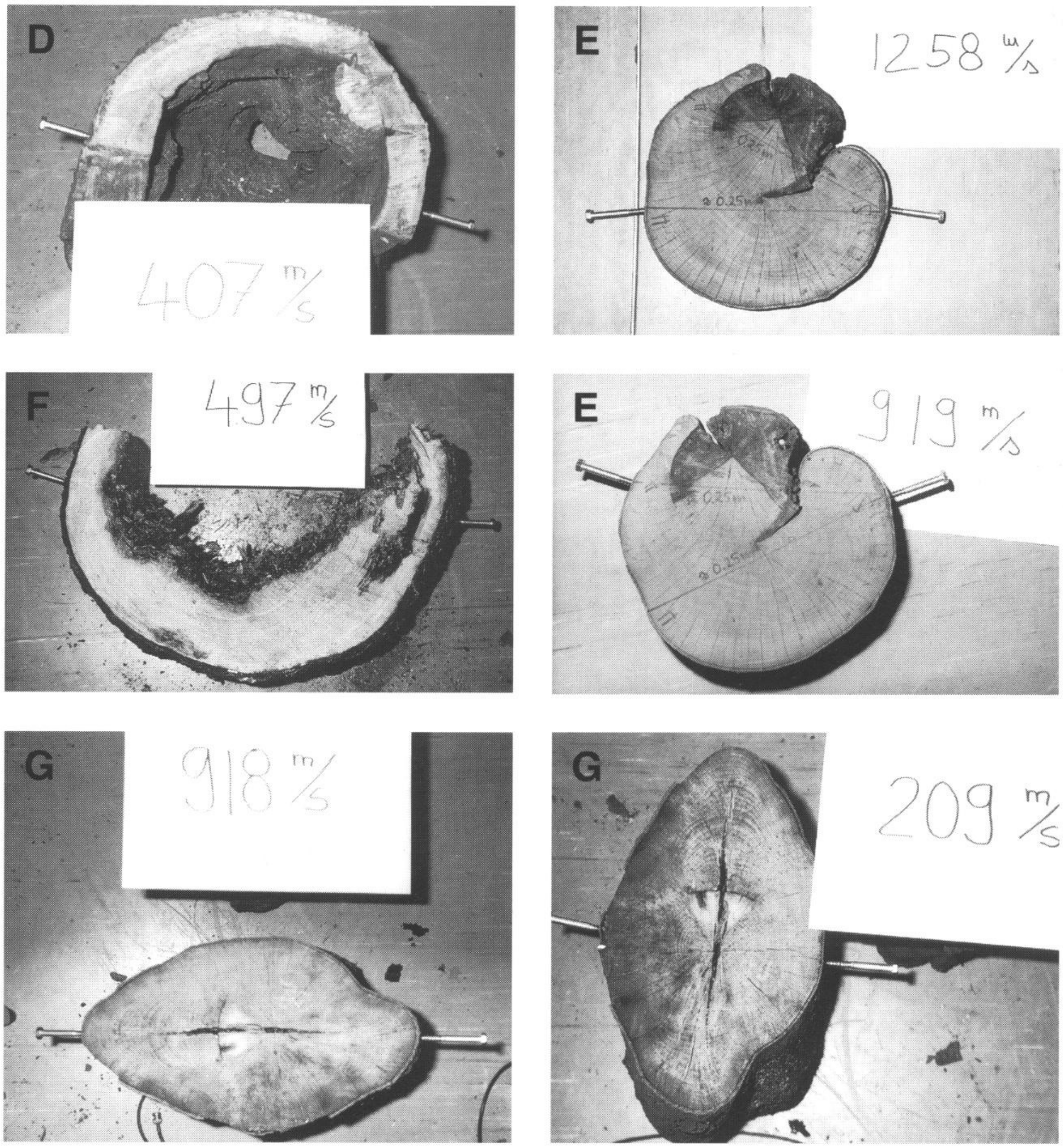
Fig 121b. Sound velocities in the presence of defects.

A,B,F: Spruce.

C: Sweet chestnut.

D,E,G: Beech.





14.2.2 Practical advice on using the *'Fractometer'*

(First published as: Mattheck, Breloer, Bethge, 'Das Gartenamt 2/94'. The text that follows here contains a few amendments to the Tables.)

14.2.2.1 Introduction to the principles

Many handbooks published over the last few decades have given tables showing the stiffness and strength characteristics of dry, as well as green woods. This makes it possible to compare the timber of various species and to choose appropriate ones for particular uses. These wood tables always give the values for wood without branches, ascertained from large numbers of test measurements.

Bethge showed, among other things, that these ideal values for branchless wood in the tables could sometimes be reduced by 80% merely from the presence of branches. In addition, when wood becomes decayed, its mechanical properties depend on the type of decay; either pliable and soft, or hard and brittle, as is known by anyone who has ever extracted a Pressler core from rotten wood. Troll [72] has introduced the apt analogy between wood and reinforced concrete (Fig. 122). The cellulose, with high tensile strength but relatively high flexibility, corresponds to the steel reinforcement, while the lignin - stiff, but weak under tension – can be likened to the cement.

Brown-rot fungi, in the early stages of decay, preferentially decompose the cellulose chains (see Figs. 84 & 85) in a random and rather scattered fashion, corresponding to the rusting of the steel in the concrete and which can reduce the tensile strength to an unbelievable extent. Quite often, the loss in density at this stage is still quite small. An unexpected brittle fracture with surfaces like broken pottery is often the result.

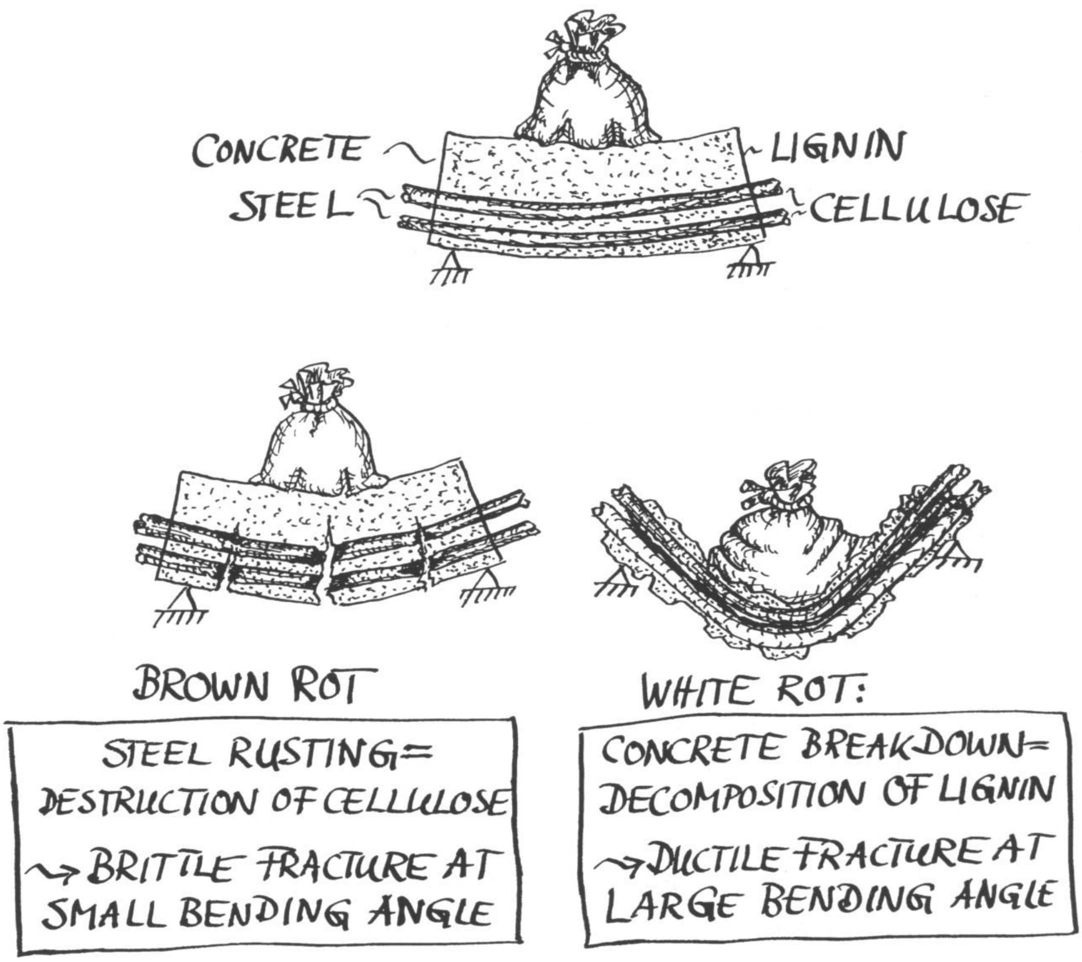


Fig 122. The selective breakdown of cellulose (left), leaving behind the stiff lignin, which undergoes a brittle fracture. Selective breakdown of lignin (right)leads to a soft-ductile type of fracture.

In contrast, white-rot fungi break down lignin in the early stages of decay. This can be in preference to cellulose decomposition, leading to a reduction in stiffness without much loss of tensile strength. Thus, the wood becomes flexible and remains tough. Some species of white-rot fungi break down cellulose simultaneously with lignin, so that the wood loses both tensile strength and stiffness.

Although knowledge of type of decay can be important in the assessment of tree safety, the main thing that counts initially is the form of the tree and of any zones of decay; i.e. the tree's biomechanical structure. An example is the extent to which stems may be hollowed out before becoming more liable to breakage: a field study showed this to be about 70% of the radius.

On the other hand, the material strength of a tree can be low enough to place it at a high risk of breakage, even in the absence of any obvious structural defects. This can be due to decay without external symptoms, or to inherent weaknesses in the wood which are not apparent from merely looking at an increment core.

For these reasons, neither strength values nor structural characteristics can be used in isolation for the assessment of an individual tree. The tree's material strength will not always fit in with the mean values known for the species concerned, quite apart from any alteration in wood quality caused by decay fungi or other wood damaging agents.

Thus, where structural features of a tree or suspicions of poor material strength place the safety of a tree in serious doubt, the only answer is to ascertain on the spot the characteristics of the material, while causing as little damage as possible. It is for this purpose that the *'Fractometer'* was developed. Since then it has already been employed by practitioners and we too have gained our own experience. The aim of this work is to summarize these field experiences.

14.2.2.2 The 'Fractometer' – its possibilities

The *'Fractometer'* is a pocket wood-testing device. As mentioned in the Field Guide section above, it places a bending load on a core that has been taken with an increment borer. In this way, the bending fracture moment, the breaking angle and the breaking energy can be determined. Fig. 123 shows a photograph of it.

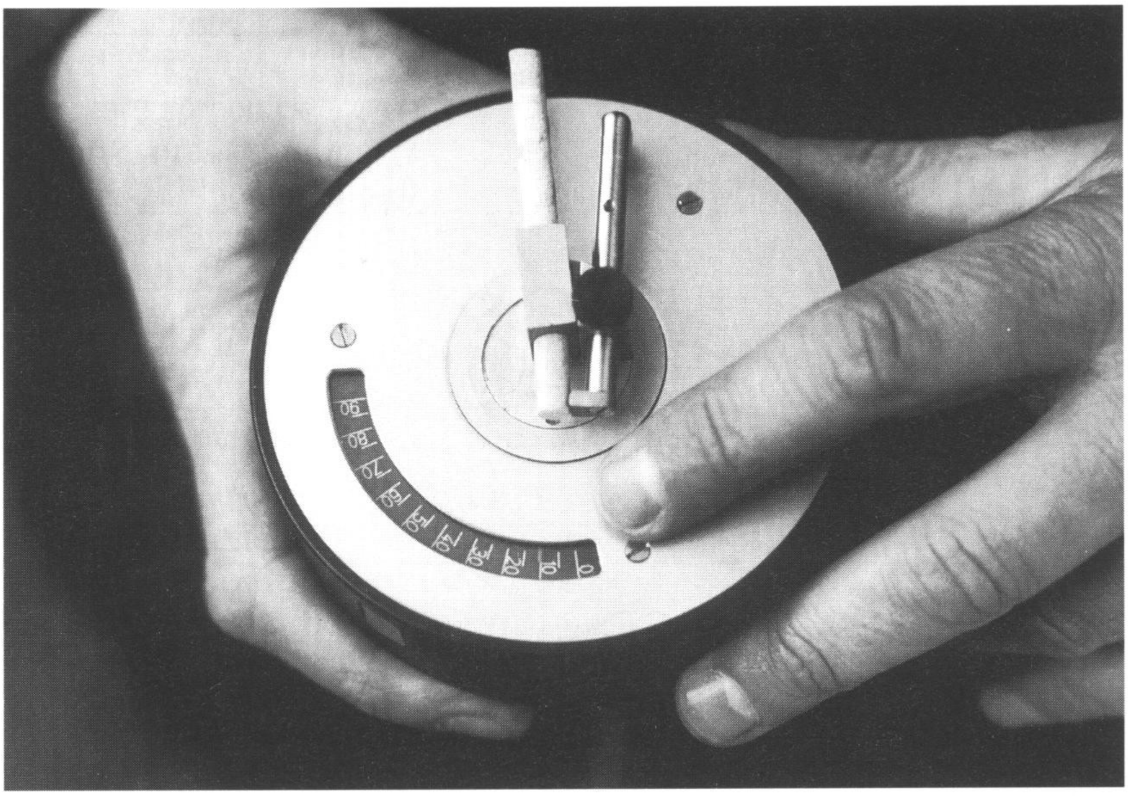


Fig 123. The 'Fractometer' - a pocket wood testing device.

14.2.2.3 The 'Fractometer' table (with updated values)

New field studies have led to the augmentation of the *'Fractometer'* table and have in particular allowed strength values to be subdivided into three categories. The table makes clear the enormous range of variation in the characteristics of the material even within a species, and so confirms the remarks made about the limited applicability of 'catalogue' values to the individual tree.

The values in the table were obtained by breaking cores in the orientation shown in Fig. 124, so that the rays, buried in the tree like radiating sword blades, were bent in the direction of their greatest stiffness (Fig. 124). If, on the other hand, the core is rotated through 90° and then placed in the *'Fractometer'*, this corresponds to a distribution of bending stresses as would usually be found if the tree were being twisted. For this purpose, the cores are orientated as shown in Fig. 125, so that the rays are loaded while lying on their more flexible, flat sides. Smaller breaking loads are usually measured in this case.

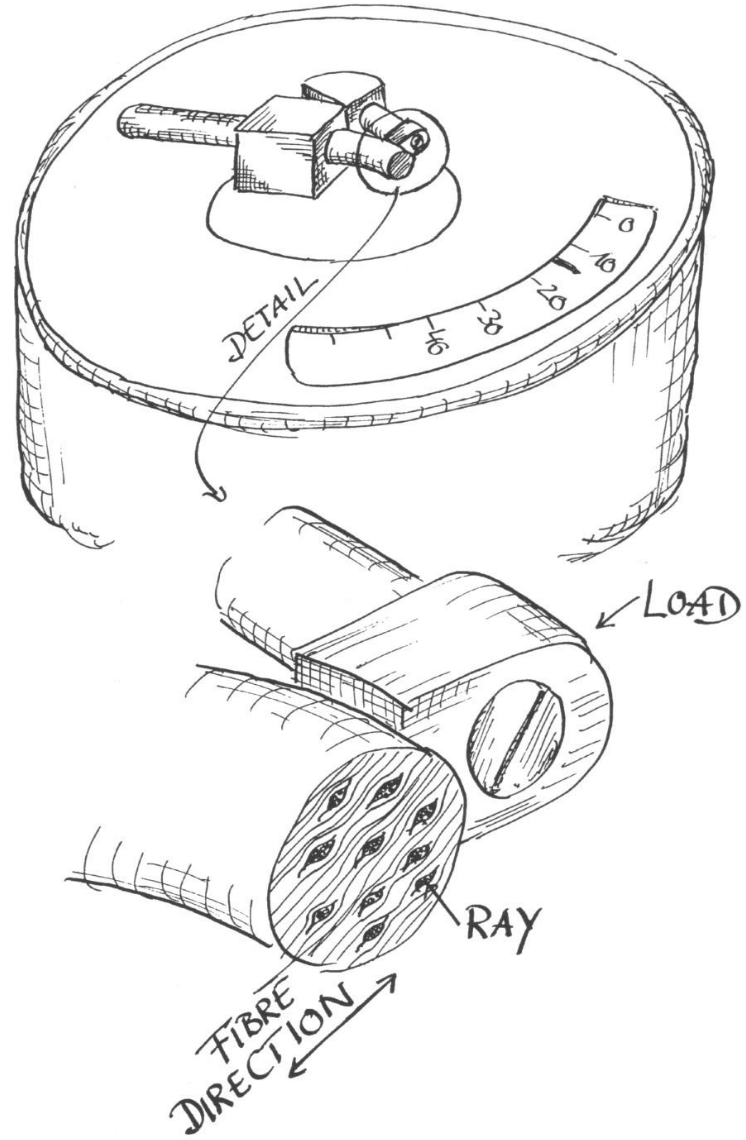


Fig 124. By aligning the fibres in the plane of the 'Fractometer face' the normal wind loads are simulated by the ' Fractometer'.

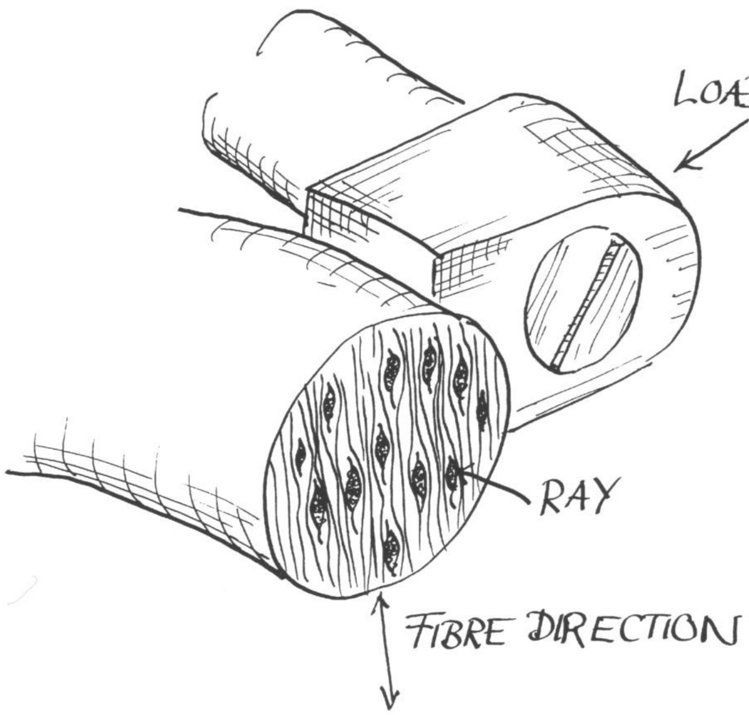


Fig 125. If the fibres lie perpendicular to the 'Fractometer' face, the bending load is applied to the flat side of the rays; the breaking load is smaller and the breaking angle is often greater.

Species	**Fracture Moment in Fractometer Units**		
	Green	**Yellow**	**Red**
Hardwoods			
Ash	80-59	58-38	37-18
Birch	40-30	29-20	19-10
Black alder	50-38	37-25	24-12
Black locust	120-89	88-58	57-27
Black poplar	20-15	14-10	9-5
Common beech	120-89	88-58	57-27
Copper beech	120-89	88-58	57-27
Elm	110-82	81-54	53-26
Hornbeam	120-89	88-58	57-27
Horse chestnut	70-52	51-34	33-16
Lime	60-46	45-30	29-14
Lombardy poplar	20-15	14-10	9-5
Maple	120-89	88-58	57-27
Oak	120-89	88-58	57-27
Plane	120-89	88-58	57-27
Sweet chestnut	50-38	37-25	24-12
White poplar	20-15	14-10	9-5
Willow	20-15	14-10	9-5
Softwoods			
Douglas fir	7-6	5-4	3-2
Fir	15-12	11-8	7-4
Larch	15-12	11-8	7-4
Pine	15-12	11-8	7-4
Spruce	20-15	14-10	9-5
Yew	90-67	66-44	43-21

Fig 126. Table of 'Fractometer' breaking values from a field study on tree species common in Europe. Values in the green area indicate relatively stability if no unusual loads or geometrical defects (notches, cavities, cracks) are present. In the amber zone, some crown reduction may already be advisable, and in the red area this is usually unavoidable; even felling may be necessary. It is dangerous to use the table blindly: the tree must always be considered as a whole (e.g. a poplar giving a reading even as high as 80 'Fractometer' units would be felled if it had clear signs of localized wood failure and was leaning heavily).

14.2.2.4 Evaluating decay with the 'Fractometer'

Obviously the *'Fractometer'* cannot be used for the identification of fungal species, but it can very definitely enable one to determine without difficulty the effect of decay and the degree of damage. In addition it is possible to ascertain whether a brittle or a ductile fracture can be expected. In this connection Fig. 126 should be studied once more. It can quickly be seen that the ranking given in Fig. 127 must be correct. *'Fractometer'* values that qualify as either high or low for the species of tree in question can be read from the Table in Fig. 126. A few examples should clarify this:

fractometer fracture moment	**fractometer fracture angle**	**decay effect**	**wood property**
large	small	low	high stiffness and high strength
large	large	lignin destruction	low stiffness but high strength
small	small	cellulose destruction	high stiffness but low strength
small	large	lignin and cellulose destruction	low stiffness and low strength

Fig 127. Table for evaluating 'Fractometer' measurements with regard to decay and the quality of the remaining wood.

1. Oak: *'Fractometer'* breaking moment = 92
'Fractometer' breaking angle = 37°

Diagnosis: Degradation of lignin, many sound cellulose fibres, ductile fracture possible later, formation of symptoms (growth swellings) near the decayed area to be expected.

2. Oak: *'Fractometer'* breaking moment = 31
'Fractometer' breaking angle = 16°

Diagnosis: Degradation of cellulose, much lignin remains, brittle fracture possible, symptom formation (swellings, bulges) not necessarily to be expected.

Since brittle fracture tends to take place without warning, and since brittle decay tends to usually produce little sign of symptoms in the form of reparative growth, the second oak is considerably more dangerous.

14.2.2.5 'Fractometer' results and site-related considerations

The relative values of *'Fractometer'* breaking strength and breaking angle are affected not only by wood decay. They also vary between tree species, between individual trees and between normal wood and reaction wood. For example, limes, planes and birches have relatively high bending angles and break at an angle of about 25° in a ductile fashion even when healthy. In contrast even sound beech break at angles of 16-20°, and are rather brittle.

The following checklist should help you to decide what sort of *'Fractometer'* readings should be expected from the tree in order to assure relative safety, and to suggest sensible remedial measures where necessary.

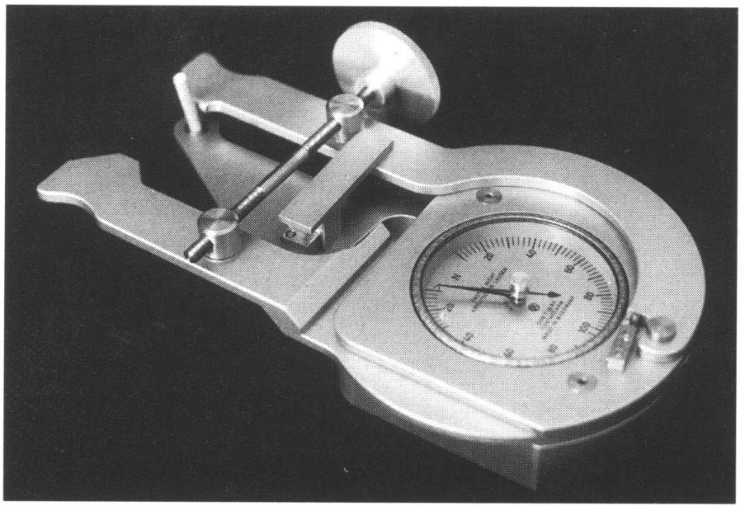


Fig 128. The 'Fractometer' Mark II measures bending strength radially and compression strength axially, i.e. in the direction of the fibres.

High strengths are required if:

1. The tree has a full crown and is leaning.
2. The tree has been newly exposed and not crown-reduced, so that it is experiencing an unaccustomed wind load.
3. The tree exhibits structural defects such as cracks (indicated by ribs), cavities (indicated by swellings) or if its stem cross-section or its root-plate has been damaged. The remaining sound walls of hollow trees should register higher strength values. To this extent the *'Fractometer'* value of the remaining wall is also a measure of the tree's will to survive. It should be higher than in parts of the stem where there is no decay. If the tree produces no especially good wood for its remaining walls, then it has 'given up'.
4. The site is in a high-risk category, for example because of the frequency of traffic movements.

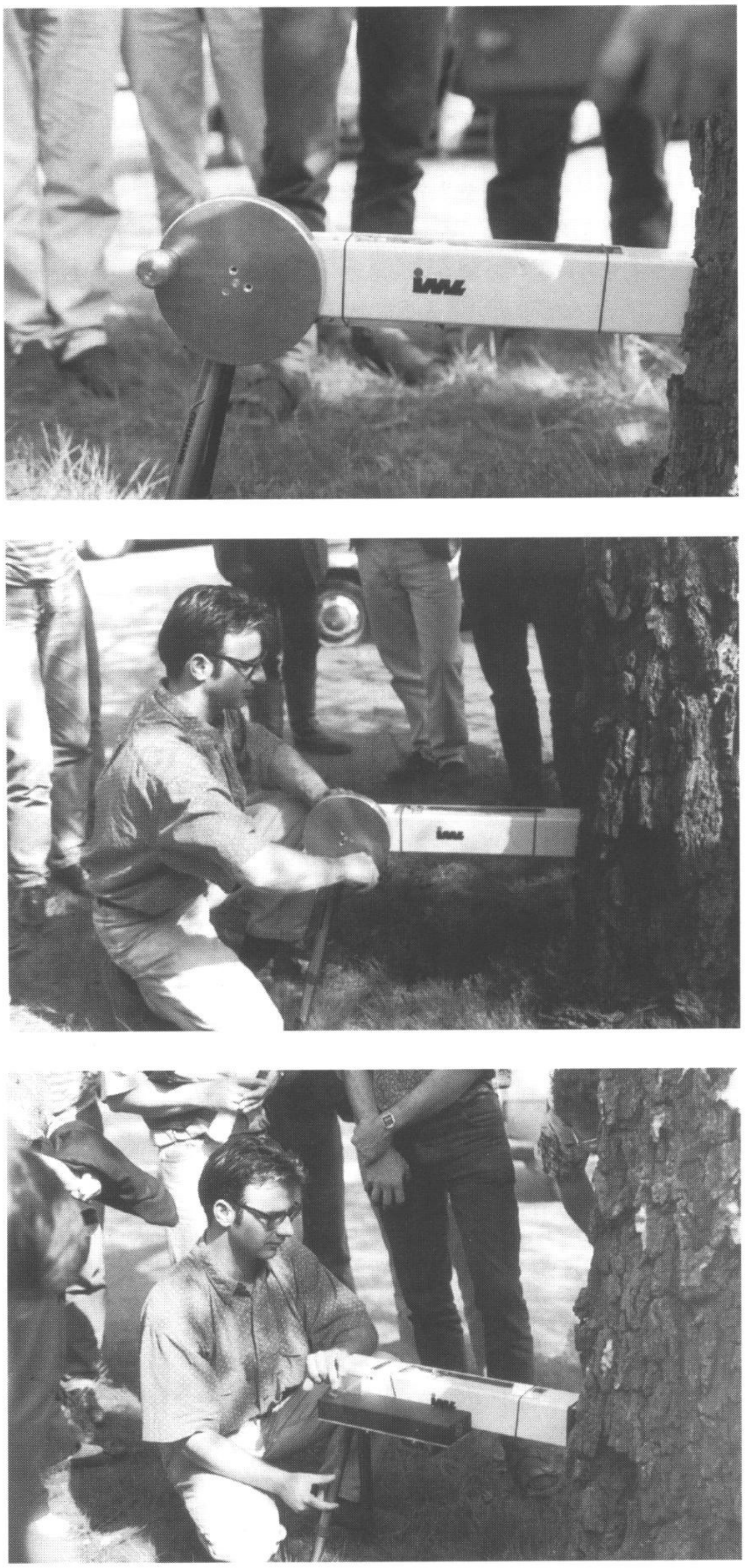


Fig 129. The 'Resistograph' M is the purely mechanical version of the tried and tested 'Resistograph'. It can be driven either by hand by means of a crank or by an electric motor. The needle drill is 30 cm long. The inner workings of the drill are entirely mechanical with no electronics (Demonstrated by Bernd Lüll).

Additionally:

The underside of a leaning broadleaved tree should be particularly rich in lignin (small *'Fractometer'* breaking angle) and the upper side should have tension wood that is particularly flexible and tough.

Lower strength values are permissible if:

1. As a result of crown reduction or some other 'reefing' of the sail area, the tree is subject to smaller loads than would otherwise occur.
2. The tree is on a low-risk site, for example because there is little or no traffic.
3. The tree's wind loading has been decreased as the result of subsequent building or faster growing trees.

14.2.2.6 Concluding remarks on the 'Fractometer'

The authors have themselves found the *'Fractometer'* to be satisfactory in field use. The device allows the evaluation of the local wood quality. It also enables something to be said about the type of damage caused to the tree by decay, and in particular allows a broad distinction to be made between the likelihood of a ductile or a brittle fracture.

After a brittle fracture has occurred, the *'Fractometer'* can help to rehabilitate the person responsible for the tree because this type of failure is often not foreseeable.

In no case is the *'Fractometer'* a substitute for dendrological information, but the measurements obtained with it can complement the experience of the arboriculturist and in that way add quantitative measurements to his or her assessment. On the other hand, an unimaginative technical assessment of trees can easily end in disaster. The authors therefore recommend that the tree is always regarded as a whole and that the healthy tree – not the technical list! – used as the standard for comparison. As we have pointed out, even such a tree can break, since a natural failure rate is the price paid for the energy-saving lightweight structures of nature. This is a price that we also have to pay as a similar drop-out rate when in sporting accidents even completely healthy bones break and we don't immediately go looking for predisposing injuries or calling for the public prosecutor.

14.3 NEW DEVICES

At this point the authors would like to express their warmest thanks to the trees' friend and industrialist, Erich Hunger, IML Instrument Mechanics Laboratory (IML-Instrumenta-Mechanik-Labor) at Wiesloch, Germany and to his capable colleagues for their contribution to the development of the *'Fractometer'* Mark I and the fine quality of the workmanship put into it. New devices have now come from this valuable co-operative work on tree diagnosis and wood research. These are the *'Fractometer'* Mark II (Fig. 128), which can determine the strength of wood both across and along the grain, and the '*Resistograph*-M' (Fig. 129), which, like the original version, detects decay with a thin needle drill, but can be driven into the wood either electrically or entirely by manual cranking. The drilling resistance is plotted on a waxed paper strip. We wish the two new devices the best of luck, as we do the old tried and tested and already widely distributed *'Fractometer'* Mark I, and hope that, with these professional measuring techniques, the evaluation of lovely old trees can be done even more satisfactorily in future.

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Your eyes are ears.
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the body language of the trees.

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Page numbers in bold type indicate illustrations

CLAUS MATTHECK: Born in Dresden in 1947 he obtained his doctorate in theoretical physics in 1973 and first lectured on failure analysis at the University of Karlsruhe in 1985, then on biomechanics as Associate Professor. He was awarded The Industrial Research Foundation's science prize for the computer simulation of biological growth in 1991, the Karl-Theodor-Vogol-Foundation's literature prize for technical journalism in 1992, the European Community's George Winter prize for biomaterials in 1993. Employed in public service at the Karlsruhe Research centre since 1980 he is also a licensed tree consultant and expert witness in the mechanics and fracture behaviour of trees. In addition to many papers in technical journals, his publications include "Design in Nature" Rombach 1993 and "Wood – the internal optimization of trees" Springer 1995.

HELGE BRELOER: Born in Mönchengladbach in 1937 she studied jurisprudence in Cologne, Freiburg and Munich obtaining her First Degree in Cologne and her Second Degree in Hamm in 1965. She is a licensed tree consultant and expert witness in the evaluation of trees and has contributed to numerous publications on the subject of trees and the law.

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