Value Activation with vertical annual rings — material, production, products

Dick Sandberg
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by

Dick U. W. Sandberg

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Abstract

This thesis is a contribution to the R&D-program Value Activation at KTH-Trä. Two main aspects can be distinguished in the thesis.

(i) A documentation and description of star-sawing technology from the initial idea to the first industrial plant.

(ii) A description of research results within the fields of wood science and production technology, obtained during the development of the star-sawing technique.

The two aspects are strongly linked to each other. The relation between ideas, scientific basis of the ideas and development results, the development of production technology and systems, and the dissemination of knowledge and technology transfer from all levels to the industrial implementation are described. The way in which all these development stages are connected in this work is also discussed.

The thesis presents a new sawing technique developed at KTH, Div. of Wood Technology and Processing (KTH-Trä). The star-sawing concept, i.e. the sawing of the log according to the star-sawing pattern and the further refinement of the sawn product into PrimWood are described in detail.

Experimental results are presented concerning different material properties of timber in general and of timber with vertical annual rings in particular. The investigations refer primarily to distortions and crack formation of sawn timber of different stages: before drying, after drying, and as a result of moisture variations. In addition, the results of a few initial tests are presented where the deformation and crack formation of the wood at the microscopic level are described on the basis of a micromechanical approach. Using a new approach, the effect of weathering on crack formation has been investigated. Test samples with tangential and radial surfaces have been exposed for a period of three years.

After many years of development work, star-sawing can now be carried out on an industrial scale, but the most important feature of the research work has been that the sawing pattern has for a number of years constituted a concrete and reality-oriented basis within the R&D-program Value Activation.

The timber obtained in star-sawing meets several of the most important property requirements of future wood products, including accuracy in size and geometry, no cracks, controlled moisture movement, strength and hardness, and aesthetic and tactile factors.
The realization of an idea

I have seen it at a close distance, during these last years of the 20th century – a different type of doctoral study in a Division with special work forms. Five or six years ago, KTH-Trä chose to let an important idea penetrate its whole activity. The choice was VALUE ACTIVATION, the utilisation of those intrinsic properties of the wood material which were then poorly utilised in the industrial system in our Swedish sawmills. The idea also incorporated a focus on problem-based learning and a comprehensive approach to the subject of wood technology; both the appearance and function of the material, its manufacture and marketing, theory and practice, internal studies and external cooperation with companies. Here, Dick Sandberg now presents his doctoral thesis on this topic.

The activity at the department has been focused on those properties which can be attained with timber in which the annual rings are “vertical”. That which makes the work and the thesis different is that the task has been attacked from the viewpoint that the aim is industrial implementation and knowledge transfer – a possible interpretation of the university’s third task. To attain the goal, traditional scientific methods have been used to determine how “it is”, and the ingenious engineer’s way of working has been followed to create “that which did not exist before”. Since I have been able to follow the work in detail, I know that there has been a continuous feedback between product, market, material and production process – and where necessary, where there have been knowledge gaps, the creation of a deeper scientific foundation; in the best sense, a modern approach to product development.

Our understanding of how wood materials behave, e.g. when they are exposed outdoors, is often stamped by traditions and beliefs rather than by knowledge. A field which is particularly subject to vague beliefs is that which is usually called constructive wood protection and which is concerned with the design of different components, the choice of wood and its orientation in the structure. Scientific confirmation is often lacking here. Whether this depends on the fact that the experiments are difficult to design and evaluate or to the fact that it is not glamorous research field is difficult to say. It is therefore gratifying that this thesis adds an important piece to the large knowledge puzzle, information about the difference in crack susceptibility between a tangentially and radially sawn surface.

It is a well known fact that there is an under-representation of personnel with a higher technical education in sawmills and the timber industry compared with most other industrial branches. Today, however, more and more companies are becoming familiar with the idea of employing graduate engineers, who know wood and who have an analytical ability for problem solving. But what do you do with a doctor in this field? This thesis actually straightens out the question mark into an exclamation mark. The knowledge and ability which are demonstrated here hits the mark with regard to the development of the traditional wood material into competitive and better paid products. And this is exactly what the branch needs!

Stockholm, October 1998

Ingemar Ekdahl

Ingemar Ekdahl is information manager at Trätek – the Institute for Wood Technology Research. He participated in developing the business idea for KTH-Trä in the early nineties and has thereafter e.g. assisted in the supervision of undergraduate students in their MSc thesis projects.
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Chapter 1 Introduction
1 Introduction
In this chapter the arrangement of the thesis, and the R & D-program "Value Activation" at KTH-Trä, of which the thesis is a part is described.

1.1 Background, aim and target group
This thesis is a summary with complementary documentation and analyses. The thesis is based on the one hand on a number of technical reports from Wood Technology and Processing at KTH (KTH-Trä) which are largely written in Swedish, but with an English summary, and on the other hand on the following articles published in scientific journals:


Since the technical reports and articles to a certain extent describe the same thing and since the thesis is written in English, I have chosen to include only the articles listed above in the thesis itself. Appendix 1 presents a list of technical reports which are related to the thesis.

The aims of the thesis are as follows:

(i) To describe and document the origin and development of the so-called star-sawing method as a practical aspect of the R&D-program "Value Activation" at KTH-Trä.

(ii) To investigate some of the material properties, which are very important for sawn timber in general and for star-sawn timber in particular. The important material properties here are primarily those properties, which are related to the deformation and crack behaviour of wood.

(iii) To elucidate the process relating to the implementation of the radically new star-sawing manufacturing system from the university research to the woodworking industry.

The thesis is directed primarily to:

(i) Industrial representatives within the wood-working industries, sawmills, carpenters, furniture companies, wooden house manufacturers, joinery industries and other wood refining companies, who are affected by or participate in product development
and quality work directed towards long-term profitability.

(ii) Representatives of the sawmill industry who have realized that "bulk-sawing" is not in the long term a durable strategy for the Swedish sawmill industry, and possibly those who wish to renew their sawing process to increase the value of timber.

(iii) Researchers within the wood sector who wish to use the techniques developed within Value Activation, i.e. to create wood products and manufacturing systems which are based on the nature of the wood, and where material properties are refined, taking into consideration annual ring orientation.

(iv) Researchers and other persons who seek to transfer R&D-results to an industrial application.

(v) Decision-makers who handle questions concerning the transfer of research results to industrial application.

1.2 Value Activation

Research at KTH-Trä has since the end of 1990 been focused on an integrated R&D-program called Value Activation (Wiklund 1991, 1993). The program is based on a fundamental view of wood material, namely that there are wood properties which are seldom used today but could be useful with new procedures.

Value Activation strives towards a strong integration of the three main tasks of a university, viz. basic education, research and graduate studies, and the dissemination of technology. The research work has been carried out as a problem- or idea-based process, and the basic education has become progressively more integrated with the research and oriented towards problem- and idea-based learning.

The Value Activation program includes many areas within which undergraduates and graduate students actively participate to solve different tasks. The projects within Value Activation involve at least one, but usually several different fields of competence from wood products and their market via production systems to wood structure and properties. The general strategy of the program is to develop the uses, products and production techniques in order to fully utilize wood's property profile. In other words, one tries to use the wood trunk in such a way that the optimum material utilisation in the growing tree is also utilised in final products and constructions.

This strategy was anchored at an early stage within KTH-Trä and outwards towards external financiers.

Wiklund (1992) states that the competitive strength of wood material is greatest when it is used visibly in constructions like carpentry and furniture. When wood is used visibly, advantage is taken of the fact that wood is a natural material with a characteristic appearance, which also gives a certain tactile sense. Potential profits should also be greatest here. As an example, Wiklund (1992) mentions that the cost is about three times greater for wood which has been prepared for furniture and visible features in carpentry than for the V-grade, i.e. ordinary building timber.

Other fields in which wood will have great competitive strength in the future compared with other materials are those of cost-effective constructions and systems, and composites. Value Activation includes the first two of these product areas, viz. visible wood and cost-effective constructions and systems. Within the Value Activation program, Wiklund (1991) has chosen the properties, which he judged to be the most important for future wood products. Wiklund (1991) arrived at the following properties:

(i) Accuracy in size and geometry

(ii) Freedom from cracks

(iii) Controlled movement with changing humidity

(iv) Strength and hardness

(v) Aesthetic and tactile factors

A basic idea within Value Activation is the ability to produce, on an industrial scale, timber and boards with vertical annual rings for products in which e.g. small and controlled moisture movements are important. An idea that was developed at an early stage within Value Activation was
to saw timber with rectangular and triangular cross-sections in a pattern which gives a high volume yield. The method which gives timber with vertical annual rings is called star-sawing. (Figure 1).

Figure 1. Star-sawing - a new sawing pattern to produce timber with vertical annual rings free from pith and most of the juvenile wood.

After many years of developmental work, star-sawing can now be carried out on an industrial scale, but the most important feature of the research work has been the sawing pattern which has for a number of years constituted a concrete and reality-oriented basis within the R&D-program Value Activation.

The timber obtained in star-sawing meets several of the most important property requirements of future wood products which have been mentioned here. The method has many advantages, but it has also given rise to many problems. The problems relate to materials technology, materials science and production technology. This will be illustrated in more detail in this thesis.

1.3 The disposition and limitations of the thesis

The thesis is a contribution to the R&D-program Value Activation at KTH-Trä. Two main aspects can be distinguished in the thesis:

(i) A documentation and description of star-sawing technology from the initial idea to the first industrial plant.

(ii) A description of research results within the fields of wood science and production technology which have been obtained during the development of the star-sawing technology.

These two aspects are strongly linked to each other. The relation between ideas, scientific basis for ideas, development of results, and the development of production technology and systems has been important for the industrial implementation of the R&D-results, and to a high degree also for the progress of my own work. I have also related the dissemination of knowledge and technology transfer from all levels to the industrial implementation. Figure 2 illustrates my view of how the work has been carried out, i.e. the relation between the different development stages. An example is given here of what I wish to describe with Figure 2.

The ideas have been the basis and driving force for the work. In the actual development of ideas, I wish to emphasize the importance of creativity and innovations for the research and development of results. The innovations need not always be as revolutionary as the star-sawing pattern to be important. The less ingenious ideas and innovations are important for solving the many small problems which arise, and to push the work forwards towards a goal.

The ideas have been of different character. Some have involved materials science or manufacturing systems. These ideas have been tested with the help of scientific methodology; i.e. I have sought a scientific foundation. This was for example the case when the influence of the annual ring orientation on crack formation during the outdoor exposure of wood was investigated (Sandberg 1998a, 1998b).

Other ideas have been more related to production technology. These ideas have been tested with a smaller degree of scientific methodology than has been used in the material-related investigations. A normal working procedure, on the one hand to verify the idea and on the other hand to drive forward the technological development.

The relation between idea and development has then been very intensive and the actual development work was subsequently not as systematic and analytical as research directed towards the material properties of wood. The development of a glue-press to join star-sawn triangular profiles into blocks is a good example of this type of development work.
Figure 2. The development of new products - different phases in the work and their interrelationships.

**Aim of the research**
Within Value Activation, the aim is to introduce desired products and production systems for wood, where the value derived from a log is considerably higher than that which is obtained in today’s industrial system. In addition, the dissemination of knowledge that can be used by both the industry and research is very important.
There is also a natural connection between the scientific and development stages. Some of the ideas produced in the more creative development work have been verified and analysed afterwards, i.e. after the idea has been tested in practice. An example is the influence of the different planing parameters on volume yield, which is described in chapter IV. In a similar way, an idea is first established, either through existing knowledge or through testing, to later be adapted and applied in different production systems. The influence of juvenile wood on crack formation and distortion of timber is an illustrative example. It has been known for a long time (see e.g. Koehler 1938, Boutelje 1968) that moisture movements along the fiber direction are greater in juvenile than in mature wood. Intuitively, it can be realized that this can influence the deformation of sawn timber. Removing the juvenile wood in the star-sawing pattern has eliminated this problem.

The generation of ideas in itself has no intrinsic value. There must be a real goal, a target. Within Value Activation, the aim is to introduce products and production systems for wood, where the value from a log is considerably higher than that which is obtained in today's industrial system. In addition, the dissemination of knowledge that can be used by both the industry and research is very important. There is thus a strong interaction between ideas, scientific basis and development, on the one hand, and the spreading of knowledge and industrial implementation, on the other.

The feedback of views and ideas from the industry is very important for the development work, both to provide constructive criticism of ongoing work and to share the competence and experience, which can be found in industry and which can never be created at a university. It should, however, be recognized that the fact that these ideas presented need not mean that the ideas are wrong or inapplicable.

It is obvious that the stages described above cannot be treated thoroughly within a single doctoral thesis. Analysis of the relation between the different stages in Figure 2 is itself a large task. It is therefore natural that certain parts of the thesis have been treated less thoroughly than others. To describe in detail the industrial implementation of the star-sawing technique would mean that all the work within Value Activation program would be described in the thesis, but not even this would be enough to give a complete picture.

1.4 The arrangement of the thesis

I have chosen the following arrangement for the thesis:

Chapter 2 describes the development of the star-sawing method from first ideas to industrial implementation and the design of the first industrial plant. The description is based upon my own view of how the development has progressed and on the experience gathered at KTH-Trä.

Chapter 3 describes the star-sawing method, i.e. the sawing of logs according to the star-sawing pattern and the further refinement of the sawn product into PrimWood. The chapter deals on the one hand with technical solutions and proposals for production layouts, and on the other hand with important parameters, e.g. volume yields, dimensions of timber etc. The basis for this description is primarily experience gathered in test sawing and test manufacture at the pilot plants for star-sawing and PrimWood manufacture. Parts of what is described in this chapter are reported in scientific publications.

Experimental results concerning different material properties of timber in general and of timber with vertical annual rings in particular are presented in chapter 4. The investigations refer primarily to distortion and crack formation of sawn timber in different stages of usage: before drying,
after drying, as a result of moisture variations, and during outdoor exposure. In addition, the results of a few initial tests are given where deformation and crack formation of the wood at the microscopic level are described on the basis of a micromechanical approach. The chapter is a summary of the most important results that I together with co-authors have published or which are in press in scientific journals.

Chapter 5 presents some of the conclusions which can be drawn from the thesis.

References


Chapter 2

Star-sawing - from idea to industrial reality
2. Star-sawing - from idea to industrial reality

Within the R&D-program known as Value Activation, an idea arose at an early stage of producing timber with vertical annual rings with the help of a new sawing pattern, star-sawing. This chapter describes how the work on star-sawing has been carried out from the idea stage until the first industrial company decided to build the first plant.

2.1 Martin Wiklund, professor at KTH

Martin Wiklund, who previously was Managing Director of the Swedish Institute for Wood Technology Research, Trätek, became Professor and head of the Department of Wood Technology and Processing at KTH (KTH-Trä) in the middle of 1990. One of his first tasks was to create and launch program of the department.

In the program formulation, the ambition was to give the department a profile with a coherent R&D-program. The field of work should be so central for the whole subject of wood technology that it would be possible in a natural and constructive way to integrate basic education, graduate studies and research constructively into the program. Another criterion was that the R&D-program should include interesting long-term research, at the same time, as it would also be possible to implement results in industrial applications in the relatively short term.

The activity received support from the sawmill industry and from Nutek during a five-year period. The support was channelled via Trätek. The activity at KTH-Trä increased dramatically when the Value Activation program was inaugurated. Several projects were started e.g. to determine those wood properties that it is most essential to study regarding wood utilization. Several analyses on the dependence of physical properties of wood on e.g. the orientation of fibres and annual rings were also started. At the same time, studies were initiated to solve technical problems of sawing timber with vertical annual rings, a process which appeared at an early stage to be highly desirable.

The work soon showed that properties of wood products that are most highly appreciated are: shape stability, absence of cracks, strength, hardness and appearance. It was shown that these requirements are best accomplished by radially sawn timber.

KTH-Trä’s idea was to achieve this by sawing timber with rectangular and triangular cross-sections in a pattern which gives a good volume yield. The juvenile wood would be removed because of its inferior properties. The star-sawing pattern took shape.

KTH-Trä has subsequently presented ideas for products, primarily based on triangular timber, which have been judged to have a high value for the customers.

2.2 Sawing of the log according to the star-sawing method

To develop and test the star-sawing technique and the different products manufactured from star-sawn timber, the project Production and testing of radially sawn timber (Sandberg 1996a) was started. The aim was to develop a small-scale saw for star-sawing of large logs and to saw material for the manufacture of wood products according to the Value Activation concept. The products produced have been used in different tests and as references in marketing the ideas.

Organization and finance

In 1992, it was realized at KTH-Trä that a plant was required to test certain production technology ideas and to obtain material for the research work. After extensive contacts with different potential financiers, contact was established with the Arjeplog Group, which
undertook the responsibility of coordinating the total financing of the project. Production and testing of radially sawn timber. This was done under the premise that the actual sawing was to be carried out in Arjeplog. The different financiers, all with a connection to the County of Norrbotten, who participated in the financing were the Arjeplog Group, the Three-County Delegation, the Norrbotten County Council, the Norrbotten County Development Fund and the Norrbotten Research Council.

The pilot plant was opened on 24th August 1993 in connection with a KTH-Trä seminar.

Organizationally and administratively, the project was managed as follows. A company, Star-sawing in Arjeplog AB, was formed with Timber-Line & Co AB and A-Trä AB as main owners, but the company was run solely to support KTH-Trä's R&D-program. Star-sawing in Arjeplog AB purchased the star-sawing from Timber-Line & Co AB while A-Trä AB carried out the drying and certain truck transport.

A total of more than 1000 m³ timber was sawn in different batches. The last test-sawing in Arjeplog was performed during spring 1996 and the project was closed down shortly thereafter.

The project Production and testing of radially sawn timber contributed strongly to a rapid testing of the sawing technology and products of star-sawn timber and speeded up the exploitation of ideas produced within the Value Activation program. Both the sawing technique and the properties of timber and raw materials from different parts of Sweden were studied. A number of product prototypes manufactured from star-sawn timber with vertical annual rings were produced. Property tests and market-oriented investigations were carried out for these products. Results showed that the star-sawing method in most cases gives an increased value for timber and products manufactured from this timber.

Results and experiences
The work within the project was divided into three main areas; sawing technique, quality and properties of raw material and sawn timber, and products from star-sawn timber. In the report Development and construction for star-sawing (Brask 1994) a detailed description is given of the building of the pilot plant in Arjeplog and the performance of test-sawing until the first half of 1994. The development which was thereafter carried out in Arjeplog consisted primarily of improvements and extension of peripheral equipment for more rational handling of the timber after sawing.

The pilot plant was constructed as a project within the undergraduate program at KTH-Trä. Thereafter, the equipment was contract manufactured by a mechanical workshop.

When the project started, the chosen sawing method was shown to be very suitable with respect to the early development phase of the star-sawing technique (Sandberg 1996b). However, it was shown that the method was not suitable for the rational and economically profitable production of star-sawn timber (Alvheim and Andrée 1993, Sjöberg 1994, Sandberg 1996b).

The drying of star-sawn timber was carried out together with A-Trä's normal production. A new board stacking method was developed for the triangular profiles (Holmberg and Sandberg 1995a, Sandberg 1996b). The drying of the timber went very well without modification of the drying schedule and further improvements of the drying technique was not considered to be of primary interest at this stage.

Star-sawing is best suited for large and excessively large logs (Sandberg 1996b). Test-sawing was carried out with pine and spruce logs obtained from different regions of Sweden. Results from this work showed that it was not possible to use the same grading rules for star sawn timber as those in current use. To produce high-quality products with vertical annual rings for the carpentry industry, certain grading criteria must be increased, e.g. allowable compression wood, while other grading criteria can be reduced,
e.g. allowable black knots. Sawing logs from different regions in Sweden showed that star-sawing can be applied with advantage to large logs from the whole country. However, it was shown that logs from the mountainous regions were less suitable for star-sawing because of a high frequency of internal defects such as cracks, compression wood and water-stain and to a certain extent microbial decay.

The clearest difference between timber from different parts of the country was found in the volume yield of knot-free boards and in the texture of the timber. The difference in texture consists primarily of different knot appearance and growth rate (annual ring width), while in the knot-free wood differences can be seen in colour nuance, waviness of the annual ring and resin content, and differences can be felt in weight, hardness and brittleness. The differences in texture which can be found in wood from different regions have, in my opinion, received too subordinate a place in favour of strength properties and the visual sorting where knots and other so-called structural and manufacturing errors have been given decisive importance. It should be pointed out, however, that test-sawing with logs from different parts of Sweden was carried out to obtain information on how different wood properties vary between different regions and how this influences the yield from star-sawing. We were well aware that variation in log quality within the same region can be very large and that too far-reaching conclusions should not therefore be drawn from the test-sawings which have been carried out. The knot appearance in the surface of star-sawn timber is different from that of traditionally sawn timber which means that the grading rules used today for timber cannot be applied (Holmberg and Sandberg 1995b). A method was adapted for grading of radially sawn timber and has been introduced and applied in collaboration with customers. The different knot shapes made the further treatment of the timber in certain cases impossible without removal of the knots.

Investigations carried out on star-sawn timber showed that removal of the pith and the juvenile wood was more important for the final timber quality than had previously been assumed. Clear relationships have been found between the occurrence of juvenile wood in sawn timber and the susceptibility to deformation and crack occurrence after drying (Sandberg 1992, 1995a, 1996d, 1997a).

In order to investigate how well suited star-sawn timber was for use in different products, tests were carried out on a selection of products where timber with vertical annual rings is assumed to be especially favourable. Some of the products were completely new while others have been on the market for a long time, but have been given a higher value by being manufactured with vertical annual rings. Results from the different product tests are described here briefly.

The greater hardness of the radial wood surface and the increased shape stability obtained with vertical annual rings are used in solid wood floors. Several different types of floors have been manufactured and tested. The advantages of having vertical annual rings in these floors are unambiguous and the results are directly applicable to industry (Heickerö and Wålinder 1992, Wålinder 1996).

Comparative tests with conventionally and star-sawn panel boards for outdoor use painted with the most common paint types show that radially sawn panel boards have clear advantages. The paint adheres better and cupping and crack formation are practically eliminated (Sandberg 1994, Borgh 1995).

Within the building sector, light beams of various designs have been used for many years. A material-saving I-beam has been manufactured and tested with a web of wood-fibre board and flanges of star-sawn triangular profiles (Stehr 1995, Sandberg and Stehr 1997).

Windows with vertical annual rings should have lower main-
tenance costs and a longer lifespan than ordinary wooden windows. Tests with star-sawn timber show that moisture movements in the corner connections become minimal. The durable heartwood of pine in radially sawn timber is one-dimensionally oriented and can easily be turned outwards where the moisture load becomes extra large (Hjorth and Nylander 1992, Sandberg 1996c).

The possibility of using a triangular profile for mouldings has been evaluated. Technical, economic and aesthetic aspects have been investigated. By using a triangular profile, vertical annual rings are obtained which give more shape-stable mouldings. Test planing showed that a triangular profile can be used as basic material for high quality mouldings to receive a high yield (Envall and Starkhammar 1994).

A fence system for outdoor use has been produced. The geometry and shape-stability of triangular profiles is used to give a fence with a long lifespan without using chemical preservative agents (Alexis et al 1994).

A proposal for a production line for the manufacture of a glulam beam from triangular profiles has been produced. Beams have been manufactured and tested. The beam has controlled moisture movements and internal stresses which arise when moisture variations are minimized since the beam has got vertical annual rings. The side surfaces are radial, which e.g. means slow moisture absorption and small susceptibility to cracks (Bryne et al 1995, Sandberg 1998a).

The cross-section is both hard and durable, which is of interest in products such as e.g. floors, thresholds and staircases. Several endwood surfaces have been manufactured from a triangular profile and have been surface treated in different ways. The boards have thereafter undergone hardness tests and furniture tests. A new method has been presented to reduce the moisture movements in the plane of the endwood surface without chemical treatment (Alfheim and Forsberg 1992, Evansson and Brask 1992, Marelius et al 1993, Holmberg 1998).

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2.3 Dissemination of results from Value Activation

Already in connection with the first presentation of the R&D-program Value Activation for the representatives of the sawmilling and the wood-working industries we were completely convinced at KTH-Trä that the realization of the new concept would take a long time. One of the conditions for any company to be interested in applying the ideas was that they should receive legal protection of incorporeal right. A patent on the basic ideas was thus applied for. This has then been followed up with patent applications on new ideas within the basic concept.

Beginning in March 1991, KTH-Trä has continuously informed the wood-working industries and its representatives about activities and results from the research program. Besides distribution of reports published, KTH-Trä has participated with its own exhibition cases at different national wood exhibitions, has arranged seminars and thematic days and has distributed information through lectures and newspaper articles. During the years 1991 to 1997, KTH-Trä’s research was mentioned in more than 100 articles in Swedish daily newspapers and trade journals. In 1992, KTH-Trä won the region Innovation Cup final contest and in 1996, we were awarded the Elmia Trä prize. The
information has received a great success within the wood-working industries. The interest in Value Activation with vertical annual rings has increased. At KTH-Trä, it was considered important to be able to show areas of utilization and the final products from the star-sawn timber. A large number of product ideas were presented in which the star-sawn timber was used optimally. Many of the products were also considered to have great economic potential.

In the ongoing work within the R&D-program, several products have been produced as prototypes, as seen above. Care has been taken however, not to disperse the activities too much. This means that the greatest effort has been placed on a few projects. Other ideas must wait until the capacity to further develop them becomes available. The continued work was directed towards the actual sawing technology and gluing of the triangles into boards, so-called PrimWood.

In 1993, a seemingly well-founded concept was presented for star-sawing and PrimWood manufacturing of products with vertical annual rings. Many industrial representatives studied the presented concept with great interest and several industrial representatives also thought that star-sawing had a future potential. In spite of this, everybody waited for someone else to take the first step and invest in a plant.

2.4 The development company PrimWood AB

In the course of trying to find companies which were willing to invest in star-sawing, it became increasingly clear that the change in both production technology and product which the star-sawing concept offers was too revolutionary for any company to dare to invest in. It was also difficult to find companies that could cover the whole business context from log to final product that could invest in a new system without influencing their own on going activity negatively. The companies which have the whole chain from raw material to final product however often lack the contractor spirit required to succeed with projects of this type.

At KTH-Trä, it was realized that it was necessary to do more to convince the industry that star-sawing could become more profitable. In 1993, the idea was discussed of forming a development company to run the continued development and to promote the industrial application of the star-sawing concept. At KTH-Trä, however, industrial and marketing experience was lacking which was considered very important to succeed with industrialization. In February 1994, PrimWood AB was formally founded and the part-owners were all employees at KTH-Trä as well as a group of industrialists, the so-called promotion group.

PrimWood AB was formed as a company for the development of production systems for ideas produced within Value Activation. In the first place, star-sawing and PrimWood technology were to be developed. The development of production systems should mainly be carried out by production companies to which PrimWood should give non-exclusive licences. PrimWood can also have a certain part-ownership in the production companies.

It was judged to be essential that persons in the promotion group had knowledge and experience which could be used in the continued development of PrimWood AB. They would also have the time and interest in participating actively in PrimWood’s continued development. Because of PrimWood’s limited economic resources, it would also be necessary for the part-owners to work on voluntary basis to a large extent, which has also been the case. The persons who are today included in the promotion group are:

- Olle Lundqvist, who was a retired technical director from STORA and as a member of the combine management, is responsible among other things for the exploitation of new technology within STORA.

- Per Nydahl, part-owner of Neuman & Nydahl which is a consultant company for company
management questions and manager recruitment questions.

Urban Sundberg, previously e.g. senior vice president in the forestry concern MoDo, board chairman in Södra and in Trätek.

Kjell Wiklund, previously self-employed with sawmill, planing-mill and timber dealer’s experience. He has also earlier participated as advisor at the pilot plant for star-sawing in Arjeplog, and is thereby very familiar with the problems of star-sawing.

Rudolf Wiklund, previously MD for Geotronics AB and later principal owner of C. E. Johansson AB and Dataliner AB in Eskilstuna. He has great experience of exploiting new ideas for profitable products.

Åke Lundqvist, previously MD in Ericson Radio AB where he developed the mobile telephones within the concern. In 1994, he received KTH’s great prize for this work.

Maths O. Sundqvist, who e.g. is owner of Jämtlamell Industrier AB. Maths became part-owner of PrimWood when Jämtlamell showed a great interest in becoming the first company to invest in star-sawing.

PrimWood has a collaboration contract with KTH during the formation of the company. We were and are very anxious that KTH in the future would become part-owner in the company, which was not possible at the time of PrimWood’s initiation.

**PrimWood’s work procedure**

Within PrimWood AB, two important fields of work were identified. The manufacturing technology needed to be developed further and the market needed to be established for the products manufactured from star-sawn timber. To find areas of usage for the triangular profiles was considered to be a key question. Besides this, it was essential to maintain good legal protection incorporeal right for the whole star-sawing concept.

Within PrimWood, it was understood early how the sawing according to the star-sawing pattern should be carried out. The technology was not considered to be complicated, especially not for the first plant where the capacity probably should be relatively low. Layouts and technical detail solutions were worked out through PrimWood’s agency. This basis was considered to be very important for continued contacts with people interested in star-sawing, and with machine suppliers. In an initial stage, many machine suppliers were very sceptical of the whole star-sawing concept, both from a technical and market perspective. It was finally shown that the ideas for production layouts presented by PrimWood at an early stage could also be applied in the first production plants for star-sawing and PrimWood manufacture.

High-quality knot-free furniture and furnishing solid wood panels of pine, PrimWood, were the products which were considered to be the most suitable usage area for the triangular profiles at an initial stage. KTH-Trä had shown that it was possible to manufacture such a panel and that the properties of the panel were superior to a traditional solid wood panel. However, experience was lacking for the industrial production of PrimWood. Several production ideas in the manufacture were untested and were considered to be technically difficult to realise.

During winter 1994/95, the idea of building a pilot plant for PrimWood manufacture to develop the technology and to produce PrimWood for market tests was discussed. The plant was erected on Åke Lundqvist’s farm Hedabro outside Södertälje. On 30 August 1995, the first PrimWood board was manufactured. However, a further year of intensive development and improvement work was needed before the equipment was in a state that PrimWood could be manufactured with the high quality requirements which had been adopted. The plant was simple in its design but showed how each single production stage could be carried out.

The pilot plant in Hedabro has been of decisive importance for the commercialization of the star-sawing technology. In Hedabro, one
has been able to show in practice a final product in the form of PrimWood and has proven its technical and aesthetic properties. Although the manufacture in Heda has been more or less manual, it has been possible to show that an industrial production in full scale is possible. The reservations which many persons had towards the usage of triangles were thereby removed. This, in combination with the production of materials for market tests, has probably been more important for the industrialization process than the technical advances made in Heda. The development work carried out within PrimWood AB has given rise to several problems which have been solved in minor R & D-projects. To study these problems, PrimWood AB has financed a number of M. Sc projects at KTH-Trä. These projects have been much appreciated by the students since they have concerned future areas within the wood-working industry.

2.5 The first industrial plant

As mentioned earlier, KTH-Trä and in a later stage also PrimWood AB took contact with different wood-refining companies to interest them in beginning to apply the star-sawing method. A company with which early contact was made was Jämtlamell Industrier AB. The first contact was taken in the autumn of 1994 in connection with a visit to KTH-Trä by Jämtland’s county governor Sven Heurngren and a number of industry representatives. The interest in star-sawing and the manufacture of PrimWood was great but on, Jämtlamell’s part, it was perceived that many questions around raw material, production technology, economy and market remained. It was essential to look closer to the purely industrial and economic part before it was decided to go further.

Discussions with PrimWood AB were carried further to answer the questions which had arisen. A visit was carried out to the pilot plant for star-sawing in A rjeplog. The interest increased and the next step was decided. The intention was to investigate conditions for running a star-sawing and PrimWood line within Backe Trä AB. Backe Trä with sawmills in Backe and Tägsjöberg was at this time owned by Jämtlamell, SCA Timber, Ramsele Skogsägareförening and the Westerlund family. To push the star-sawing idea further, the interested parties created a development project within Träinnova. Träinnova is an extensive and long-term regional development project which in cooperation with about 20 wood-treating companies is aimed at increasing further refinement in Jämtland and Västernorrland.

The aim of the project was to produce industrially adapted equipment for star-sawing and PrimWood manufacture in collaboration with machine suppliers and other companies. The work consisted for example in thoroughly evaluating, in co-operation with machine suppliers, the proposals for production layouts produced by PrimWood AB, and to introduce production technology for the treatment stages where standard machines could not be used. Besides this, three test savings were carried out to evaluate the sawing technique and the yield and quality of the sawn products. The sawn material was used for PrimWood manufacture in Heda and for market tests of both timber and PrimWood. KTH-Trä and PrimWood AB were strongly involved in the project, as specialists and to carry out test-savings and manufacture of PrimWood in Heda.

In May 1998, most of the questions had been resolved, the financing was arranged and it was decided to begin the industrial phase of the star-sawing technology. In Tägsjöberg, 100 km north of Sollefteå, a sawmill is built for star-sawing and in the adjacent town Junsele, a plant is built for the manufacture of PrimWood. The plants will be operated within the company NovaWood AB which is owned equally by Jämtlamell, SCA and Ramsele Skogsägareförening.

After all this long-term work, the situation is currently that one company, NovaWood AB will build a full-scale industrial plant based on KTH-Trä’s concept.
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Chapter 3

The star-sawing concept - sawmilling and value added products of triangles
3. The star-sawing concept - sawmilling and value added products of triangles

This chapter presents a simplified geometrical study of the star-sawing pattern to illustrate the parameters which influence the final dimensions of sawn timber. The sawing methods which have been evaluated in the trials and the volume and quality yields obtained are also described. A few comments are then given regarding the log quality requirements associated with the star-sawing.

Finally, a description is given of the principle of gluing the triangles obtained by star-sawing into solid wood panels or beams.

3.1 Sawing according to the star-sawing method

The geometry of the sawing pattern

The star-sawing pattern is intended for the industrial production of timber with vertical annual rings free from pith and from most of the juvenile wood. The sawkerfs are more or less radially oriented from the surface of the log inwards towards the pith area and they are placed so that six timber pieces with equilateral triangular cross-sections are obtained. Between the triangular timber, one or several boards with a rectangular cross-section are sawn, (Figure 3).

If the sawing pattern in Figure 4 is regarded as an ideal geometric case, i.e. an inscribed circle with diameter D, the following can be established regarding the sawn timber dimensions:

a) The maximum timber width, b, which can be sawn is:

\[ b = \sqrt[4]{\frac{4 \cdot 3^{2/3}}{\pi}} \cdot \frac{D}{2} - m \]  \hspace{1cm} (1)

for the centre pieces:

\[ a = \frac{b - m}{2} \]

for the side pieces:

\[ a = \frac{b - m}{2} - 2 \cdot t_s \]  \hspace{1cm} (2)

where \( m \) is the width of the pith-cutter, \( t_c \) is the thickness of the centre pieces, \( t_s \) is the thickness of the side pieces (raw measure) and \( s \) is the width of the sawkerf. In this

Figure 3. Different patterns of star-sawing. Sawing patterns with (a) the same number of pieces with a rectangular cross-section as with a triangular cross-section, (b) twice the number of rectangular pieces, (c) twice the number of rectangular pieces which include the pith, centre pieces.

Figure 4. Ideal case of the star-sawing pattern for estimation of the dimension yield according to formulae 1-3.
case, $t_c$ and $t_s$ are equal and are thereafter called $t$. The notations are illustrated in Figure 4.

b) The relationship between the triangular timber dimension, $a$, and the thickness of the rectangular timber, $t$, for a given log diameter, $D$, and sawkerf thickness, $s$, is given by:

\[ a = \frac{2 \sqrt{3} D - 6.9 b_s - 2 b_c - \frac{1}{3} s}{\sqrt{3}} \]  

(3)

From these expressions, the following conclusions can be drawn:

(i) Besides the log diameter, the width of the rectangular centre pieces is determined by the amount of juvenile wood which is removed, and by the thickness of the pieces.

(ii) The width of the side pieces for a given log diameter is determined by the thickness of the middle pieces, the thickness of the side pieces and the width of the sawkerf.

(iii) At a given log diameter, the width of the rectangular timber is much smaller than in conventional sawing methods, e.g. the main yield in block-sawing.

(iv) There is a clear and simple relationship, at a given log diameter, $D$, between the dimensions of the triangles and the thickness of the rectangular timber.

To further demonstrate the dimensions achieved in star-sawing, Table 1, gives some examples of dimensions for the sawn timber, calculated with the help of formulae 1-3, for some different log diameters. The uppermost part

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of the table shows what happens if the thickness of the rectangular timber is held constant at 50 mm while the diameter increases. In a corresponding way, the middle part of the table shows what happens when the dimension of the triangular timber is fixed at 90 mm. The lower part of the table shows a few patterns which give realistic dimensions for all timber.

In the calculations, the width of the pith-cutter was assumed to be 50 mm, which has been found in the test-sawings to be a suitable dimension for removing the pith and most of the juvenile wood in logs from northern and central Sweden. This also means that the thickness of the middle piece should not be less than 50 mm to avoid the risk of getting pith in the side pieces. With this dimension of the pith-cutter, i.e. greater than 50 x 50 mm, most of the small knots in the juvenile wood are also removed, which is an advantage in producing knot-free components.

On the basis of Table 1, it can be established that log diameters around 20 cm give small dimensions for all the timber. In test sawings it has been difficult to handle small dimensions because the timber easily breaks at large knots. A large proportion of the knots are in fact cleaved longitudinal and so-called splay knots are obtained in the timber surface, (Figure 5). In timber of small dimensions, these occupy a large part of the cross-section and thus weaken the timber.

Figure 5. Splay knots in star-sawn pine.

If the centre and side pieces are sawn to the same thickness and the dimension of the pith-cutter is 50 x 50 mm, the centre pieces are always wider than the side pieces. This “extra” edging of the side pieces is always carried out on the pith side of the timber, which gives an extra margin to the pith.

If the thickness of the rectangular timber is kept constant, the dimensions of the triangles increase with increasing log diameter. In a similar way, the thickness of the rectangular timber varies with log diameter if the dimension of the triangles is fixed.

When the triangles are glued into blocks, it has been found that suitable dimensions of the triangles are between 60 and 130 mm. Too small triangles give handling problems and too thin blocks, and this reduces the flexibility in dividing the blocks into solid wood panels. Too large triangles become difficult to handle and to process.

When the thickness of the rectangular timber increases, the angle between the flat side of the timber and the annual ring near the surface decreases, i.e. the degree of vertical annual rings decreases. This is described in more detail in chapter 4.1.

If consideration is given to the question of which dimensions are suitable from a quality handling and manufacturing viewpoint, the sawing patterns may be as shown in the lower part of Table 1. However, it is doubtful whether logs with a top diameter less than 25 cm should be star-sawn according to the basic pattern, (Figure 3a).

In the test sawings, dimensions which deviate from those calculated were observed. The deviations depend primarily on the cross-section of the logs which had a more or less oval shape and were crooked in the longitudinal direction. Besides this, damage and growth stresses influence edging. Large amounts of reaction wood in the log often made sawing more difficult and gave a poorer yield.

Sawing methods

In order to produce star-sawn timber with rectangular and triangular cross-sections, different sawing methods can be utilized. It is essential that the sawn timber have vertical annual rings (Sandberg 1995b) along the whole length
and that the pith with the surrounding juvenile wood is removed. Two sawing methods have been applied. At an early stage in the development of the star-sawing method, a pilot plant was built in Arjeplog to develop and test star-sawing technology (Sandberg 1996a, Sandberg 1996b). At the pilot plant in Arjeplog, the log was clamped at the ends between two dowels so that it could be rotated. Mantle wood was sawn away and a hexagonal block was obtained. This block was then loosened from the dowels and sawn into rectangular and triangular timber, (Figure 6). The method was shown to be good for its purpose, but was not suitable for commercial production.

With the help of experience obtained at the pilot plant, a new method of sawing was developed (Sandberg 1997c). This method is intended for operation on an industrial level and all sawing steps can after certain modification be carried out using conventional machines available on the market.

The sawing procedure is shown schematically in Figure 7.

The different steps are:

I. The log is positioned with consideration taken to its crook and ovality so that the pith can with certainty be enclosed within the centre plank.

II. Two parallel sawkerfs are made along the periphery of the log so that they just touch the mantle wood at the top end of the log.
log. Two further sawkerfs divide the log into a centre board and two so-called “coffin lids”.

III. The centre board is cleaved into two, as close to the pith as possible.

IV. The two pieces obtained from the centre board are thereafter taper edged, i.e. the sawkerfs are placed parallel to the wane sides of the timber. Through this procedure, higher straight-grained timber is obtained and more of the high-quality sapwood than in conventional edging is achieved. Furthermore, the pith and the juvenile wood are removed. The taper edging thereby increases the certainty that the pith is removed at the butt end of the timber, since the pieces which are edged away on the pith side become wedge shaped.

V. The “coffin lids” are edged to obtain two control surfaces for the subsequent sawing. The edging is done very sparingly and the sawcuts touch the sides of the coffin lid at the top end.

VI. The “coffin lids” are tilted 60° and a board and a triangular profile are sawn. One alternative is to tilt the band saw 30° from the vertical plane.

VII. The remaining, rhomboid piece is sawn in the same way as in VI.

VIII. The boards from the “coffin lids” are taper-edged in the same way as in IV, except that an extra degree of edging to remove the pith is normally not necessary.

IX. The triangular profiles which will be used for knot-free products will to a great extent be cut free from defects and will be finger-jointed. For these triangular profiles, a slightly different edging procedure has been used. The triangular profiles are divided at approximately half their length close to a knot or other defect which has to be removed at a later stage. The two parts are thereafter edged separately. With this method, the tapering of the log can be utilized to a greater extent than if the triangular profiles are edged in one piece.

Test sawings suggest that the method offers a high volume yield at the same time as quality-raising advantages are obtained with the sawn product. The quality improvement is a consequence of the fact that the rectangular timber becomes more straight-grained and that the pith and surrounding juvenile wood can be removed with greater certainty than was possible with the earlier sawing method.

Drying

It has been very easy to dry the sawn timber from the different test sawings without any drying damage. It has been dried in the same drying kiln as conventionally sawn timber and both triangular and rectangular profiles have been dried in the same drying batch. The drying schedules were the same as those used for the drying of rectangular timber. Since it has been possible to carry out drying without any problems, improvements in the drying technique have not been considered to be of primary interest. However, the shape of the triangular profiles has meant that it has been necessary to modify stacking. Four different ways of stacking the triangles has been tested; simple stacking, in blocks, in groups of three, and unedged triangles in groups of three, (Figure 8).

Simple stacking means that the triangular profiles are arranged one by one with a space of about 2 cm between, no consideration being given to annual ring orientation. The method was shown to have a number of disadvantages, e.g. compression damage arises on the profile corner which lies against the row above (Brask 1994; Holmberg and Sandberg 1995a).

Figure 8. A ranangement of triangular profiles; (a) simple stacking, (b) in blocks, (c) in groups of three, (d) unedged triangles in groups of three.
Figure 7. A schematic presentation of the new method of star-sawing.
This yield is shown as an unbroken line in Figure 9. This figure also shows average values for volume yields from test sawings and simulations which have been carried out so far. There is good agreement between the estimated curve for the total yield and later test sawings. The total yield for logs with a top diameter above 25 cm is as an average slightly less than 70 % with respect to the top cylinder volume.

The yield of timber with rectangular cross-section in the test sawings was slightly lower than that shown by the unbroken curve in Figure 9. This was due mainly to the fact that, in the test sawings, we have tried to keep the volume of triangles at a high level to produce as much material as possible for the manufacture of prototype products from the triangles before drying was considered to be impracticable and the control surfaces which were sawn on the “coffin lids” (see Figure 7) also meant that drying batches can be placed with unedged triangles. To dry the triangles with the edge surface intact and without any cracks was not considered to be any problem with modern kilns. However, there is a risk that very small cracks arise on the edge surface. By edging the triangles after drying, these cracks could be removed. The method has been tested and the results showed a low degree of crack formation and 1.5 % higher volume yield than if edging had been carried out in a single stage (Sandberg 1997c). The primary disadvantages are that circa 15% larger volume is dried and that the volume which is edged away cannot be used as pulp chips.

Volume yield

The volume yield for star-sawing has been determined through simulations and test sawings (Nordfors and Sandberg 1993, Beckman and Stehr 1993, Sandberg 1996b, Holmberg and Sandberg 1996, Sandberg 1997c, Sandberg 1998c). Results show that the total volume yield, i.e. both rectangular and triangular profiles, is high in comparison with conventional sawing methods.

Sandberg (1996b) on the basis of simulations and test sawings carried out until 1995 proposed a general yield curve for star-sawing.

V o l u m e yield

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angles. The total volume yield is influenced to a negligible extent by the proportion of triangles sawn in each setting. In the lower unbroken curve of Figure 9, it was assumed that the proportion by volume of triangles in each pattern in the future would be about 40%. In the test sawings, on the other hand, the proportion has been nearly 60%. It is thus the choice of pattern which controls the proportion by volume of triangles obtained, (see equation 3). Figure 9 also shows that the yield decreases with decreasing log diameter. This is a consequence of the fact that the pith-cutter removes a larger part of the log volume, the smaller the log diameter. This is also true of the other residual volumes which are obtained.

Quality yield
When the log is split radially, knots will be cleaved lengthwise and appear as splay knots or spike knots in the timber surface. In star-sawing, as in all other radial sawing methods, splay knots occur considerably more frequently than in e.g. square-sawn boards, where they in principle occur only in the central section. The radial sawing methods also frequently use large logs and in such logs, parts of the knots are often dry or decayed towards the periphery of the log (Holmberg and Sandberg 1995b). This part of the knot will always be found in star-sawn timber, but this need not be the case in the main yield from block-sawing. In the grading rules for quality assortment of pine and spruce, e.g. Gröna Boken (1976) and Nordiskt Trä (1994), the classification of splay knots is severe, i.e. timber with splay knots is often down-graded to a lower quality. In the early sorting of star-sawn timber according to Gröna Boken, a very skew quality distribution was obtained compared with what square-sawn timber from the same logs would have given. A large proportion of the star-sawn timber was classified as grade better U/S or VI. A small proportion of the timber was in the intermediate classes. This distribution depended mainly on the knot appearance of the timber.

Star-sawn timber is intended in the first place for carpentry, furniture and furnishing components where the quality of the whole length of the timber is often less important than how a large part of the piece can be used for different components. As an example, a few “ugly” knots on an otherwise knot-free board of wood are less important for users of knot-free timber than if the knots are small, fresh, and evenly distributed in the timber.

In an attempt to produce a grading instruction for star-sawn timber, especially for timber with rectangular cross-section, the sawn timber was divided into three grades, SI-SIII. Table 2 shows the criteria for these grades. Regarding knots and deformations, the regulations are based on Gröna Boken (1976) but with certain additions. Grade SI corresponds to class I-III in Gröna Boken, grade SII corresponds to grade IV and most of grade V in Gröna Boken. The remaining timber falls into grade SIII. In grade SI, as opposed to Gröna Boken, one to two large edge or face knots are accepted if the timber otherwise lies within this grade. Other defects may occur as indicated in Table 2. The timber is intended to be sawn sharp-edged, but this is of course a question of usage area for the timber. A certain allowable wane can often give a better timber usage.

The grading instructions for star-sawn timber with a rectangular cross-section have been tested with two sawings of pine from Jämtland (Holmberg and Sandberg 1996, Sandberg 1998c) and one sawing of pine from Västmanland (Sandberg 1997c). In all the investigations, the log was of woods scale with a top diameter greater than 26 cm. Table 3 shows the quality distribution from the three investigations. For the triangles, no general grading instruction has been produced because there is as yet no market for this timber. For the use of triangles in defect-free solid wood panels, initial tests have begun by dividing the triangles into classes to see how long defect-free boards can be obtained from each triangle.
Table 2. Quality classification of star-sawn timber with rectangular cross-section.

<table>
<thead>
<tr>
<th>Defect</th>
<th>Quality class</th>
<th>S I</th>
<th>S II</th>
<th>S III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knots and distortion</td>
<td>GB I-III*</td>
<td>GB IV-V</td>
<td>GB V-VI</td>
<td></td>
</tr>
<tr>
<td>Cracks</td>
<td>must not occur</td>
<td>must not occur</td>
<td>may occur</td>
<td></td>
</tr>
<tr>
<td>Pitch pockets</td>
<td>single cases may occur **</td>
<td>single cases may occur **</td>
<td>may occur</td>
<td></td>
</tr>
<tr>
<td>Bark pockets</td>
<td>may occur to a lesser extent **</td>
<td>may occur to a lesser extent **</td>
<td>may occur</td>
<td></td>
</tr>
<tr>
<td>Compression wood</td>
<td>must not occur</td>
<td>must not occur</td>
<td>may occur</td>
<td></td>
</tr>
<tr>
<td>Interlocked grain</td>
<td>must not occur</td>
<td>may occur to a lesser extent **</td>
<td>may occur</td>
<td></td>
</tr>
<tr>
<td>Cross grain</td>
<td>must not occur</td>
<td>may occur to a lesser extent **</td>
<td>may occur</td>
<td></td>
</tr>
<tr>
<td>Water-wood</td>
<td>must not occur</td>
<td>must not occur</td>
<td>may occur</td>
<td></td>
</tr>
<tr>
<td>Cankers</td>
<td>may occur to a lesser extent **</td>
<td>may occur to a lesser extent **</td>
<td>may occur</td>
<td></td>
</tr>
<tr>
<td>Rot</td>
<td>must not occur</td>
<td>must not occur</td>
<td>may occur to a lesser extent</td>
<td></td>
</tr>
<tr>
<td>Insect damages</td>
<td>must not occur</td>
<td>must not occur</td>
<td>may occur to a lesser extent</td>
<td></td>
</tr>
<tr>
<td>Blue stain</td>
<td>must not occur</td>
<td>must not occur</td>
<td>may occur to a lesser extent</td>
<td></td>
</tr>
</tbody>
</table>

GB I-III Gröna Boken quality class I - III

* 1-2 very large edge or face knots may occur if the piece of wood otherwise falls within this quality class.
** If the piece of wood otherwise falls within this quality class and is without other defects.

Table 3. Quality distribution (volume proportion in %) of star-sawn timber with rectangular cross-section from pine timber of woods scale.
The quality estimation has been carried out in accordance with the criteria shown in Table 2.

<table>
<thead>
<tr>
<th>Timber felling area</th>
<th>Top diameter on log (cm)</th>
<th>Quality class</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S I</td>
<td>S II</td>
</tr>
<tr>
<td>Jämtland (1)</td>
<td>32</td>
<td>42</td>
</tr>
<tr>
<td>Jämtland (1)</td>
<td>28</td>
<td>26</td>
</tr>
<tr>
<td>Jämtland (2)</td>
<td>28</td>
<td>26</td>
</tr>
<tr>
<td>Västmanland (3)</td>
<td>29</td>
<td>38</td>
</tr>
</tbody>
</table>

1) Holmberg and Sandberg 1996; 2) Sandberg 1998c; 3) Sandberg 1997c

Logs for star-sawing

As shown above, star-sawing in its basic design (Figure 3) is best suited for relatively large logs, with an approximate top diameter below bark greater than 25 cm. To make a very rough estimate of how much such logs exists in Sweden, the statistics over annual fellings can be regarded. In Sweden, about 65 million cubic metres forest is felled...
annually and about 45% of this becomes saw logs, (Statistical Yearbook of Forestry 1994). A rough estimate, based on private communication with different sawmill managers show that at least 15% of the saw logs has a top diameter which exceeds 25 cm. This means that about 4 million cubic metres of logs are felled annually which from a dimensional aspect are suitable for star-sawing. However, in order to support the above estimation a more detailed investigation need to be done to see the diameter distribution of logs in different regions in Sweden.

3.2 PrimWood - boards glued from star-sawn triangular profiles

Triangles are a product which cannot normally be found on the market and consequently, the areas of use for this product are limited. In an early stage of development of the star-sawing method, a number of proposals were produced for products from triangles, (see e.g. chapter 2.2). One of the products which was considered to be especially interesting from a market perspective and which one wished to develop further was solid wood panels, so-called PrimWood. PrimWood is triangles glued together into a block so that the annual rings in the cross-section of the block form an S-curve. This block can then be divided according to thickness into boards with almost vertical annual rings, (Figure 10). It can be noted that PrimWood is also the name of the development company described in chapter 2.4.

When PrimWood began to be developed into a product, a number of technical, aesthetic and marketing problems arose. One of these was how to treat the knots. It was shown that the knots in the timber used for star-sawing were not acceptable in the high-quality material which was desirable. This depended, on the one hand, on the knot appearance in the timber after the block had been divided and, on the other hand, on the fact that the knots were often dry, partly with bark and/or rot damage (Sandberg and Holmberg 1996). It was therefore decided to manufacture PrimWood completely without knots and defects such as pitch pockets. The work was concentrated primarily towards producing PrimWood from pine, but tests have also been carried out with spruce.

When it was decided to remove all knots and defects from the triangles, finger-jointing was the natural solution to the question of how it would be possible to manufacture long lengths. Finger-jointing can be carried out in different ways resulting in different appearances in the final product. The intention with PrimWood was that it would be aesthetically attractive, of high quality with regard to shape stability and tightness of glue line, and that the production would be rational and industrially applicable.

It was therefore decided to cut the fingers parallel with the tangential surface of the triangles, (Figure 11a). This means that in the surface of the PrimWood, the finger-joint will be visible as a zigzag pattern, (Figure 11b). The primary reason for this direction of the finger-joint was that the block glued from triangles can be divided into an arbitrary number of boards without the joint in the surfaces of the boards becoming crooked.

If the cutting is instead carried out parallel to one of the radial surfaces, there is a risk that an inclined joint is obtained in the surface, (Figure 11c). The inclined joint can be avoided by making an end joint in the cutting at the base and top of the triangle and at the height where the blocks shall be divided, (Figure 11d).

A further question remained and that was which pieces should be joined together. In pine, there is a great difference between sapwood and heartwood, and it is important that the proportion of heartwood is practically the same in the joined pieces in order to obtain a good fit with regard to colour, (Figure 12a). This can probably be solved with vision system and an advanced handling system for the clear pieces, but in our case the problem was solved as follows: When a knot or defect was removed, the pieces on each side of the defect were monitored so that these pieces
Figure 10. PrimWood, defect-free triangles glued together into a block.

Figure 11. Finger-jointing of the triangles can be carried out in different ways giving a different appearance of the join in the visible surface. Finger cutting parallel to the tangential surface of the triangles (a) gives a zigzag pattern in the surface when the triangles have been glued together (b). If the finger cutting is carried out parallel to the radial surfaces, the risk is great that the join becomes inclined (c). This can be avoided if the cutting tool is designed with an end joint in the surface of the board (d).

could be joined together. This results in an almost perfect pattern fitting, i.e. the proportion of heartwood in the joined pieces is practically the same and the annual ring pattern on the radial surfaces coincides between the joined pieces, (Figure 12b). The annual ring width and the texture of the timber on both sides of the joint are also similar. This is only valid however when pieces from the same triangle are joined. If a triangular board is changed, a slightly poorer pattern fitting is of course obtained because the texture

Figure 12. If triangles of pine with different proportions of heartwood (a) are joined together, a poorer pattern fitting is obtained regarding colour than if the pieces have practically the same heartwood proportion (b).
varies between different boards. This effect is reduced the more homogeneous the material is with regard to texture. In order to obtain an even texture in the whole PrimWood panel, consideration must also be given to the texture of the single triangle when glued together into a block, so-called pattern fitting in the width of the block, (Figure 13). This pattern fitting is carried out visually when the triangles are placed together in a block and the pattern fitting is to a high degree dependent on the person who carries out the work.

In order to obtain good pattern fitting and to carry out the cutting of the fingers without error, it is very important that fibre disturbances around the knots are removed.

In star-sawing, a certain volume of clear pieces will be obtained which are relatively long, i.e. longer than 1 metre (Sandberg 1996, 1998a). It is not desirable to finger-joint these boards, but instead to manufacture PrimWood without a finger-joint. If long pieces which are not to be finger joined are selected more or less at random, it will be difficult to obtain a good pattern fitting of the remaining pieces. This is a problem which results in the manufacture of three varieties of PrimWood with regard to pattern fitting. These three varieties are all knot- and defect-free:

   I. PrimWood without finger-joint and with a certain pattern fitting in the width of the block.
   II. PrimWood with a pattern-fitted finger-joint and a certain pattern fitting in the width of the block.
   III. PrimWood with a finger-joint where no consideration has been given to pattern fitting.

A rough calculation made on the basis of empirical investigations (Sandberg and Holmberg 1996, 1998a) suggests that the distribution between the different varieties will be approximately 30 % of I, 50 % of II and 20 % of III. In order to manufacture these three varieties of PrimWood, the triangles should be divided into two groups with respect to the frequency of defects before the removal of defects; one group for the manufacture of PrimWood I and III, and one group for the manufacture of PrimWood II.

Other factors which influence the appearance of PrimWood are e.g. the choice of glue, the number of finger-joints per unit surface and the length of the fingers. These parameters have been studied to a
Production steps and volume yields

The manufacture of PrimWood takes place in six steps:

1. Sorting of triangles into two groups with respect to the frequency of defects.
2. Removal of defects and sorting of defect-free pieces which will not be joined.
3. Finger joining
4. Planing
5. Assembling and gluing into blocks
6. Division of blocks into boards and possible dimension adjustment and sanding.

The volume yield for the different operations has been investigated (Sandberg and Holmberg 1996, 1998a). The average value for the volume yield from a dried triangle of pine to a sanded PrimWood board was 53.8% (Sandberg and Holmberg 1998a). This is a high volume yield for defect-free pine board. It can be established that three operations are decisive for the yield, the removal of defects, the planing and division of blocks, and the sanding of the panels.

In the investigation by Sandberg and Holmberg (1998a), the losses in removal of defects constituted less than 15% of the volume of the triangles. The knots were responsible for most of the cutting spillage. Because of the appearance of the star-sawing pattern, long lengths of timber are obtained which are knot-free. The proportion of knot-free material that can be obtained from star-sawn pine and spruce timber has been investigated for timber from different parts of Sweden (Sandberg and Holmberg 1996). In the investigated material around 25% knot-free pine with a length greater than 2 metres was obtained from southern and central Sweden. For the wood from northern Sweden, the corresponding figure was 5%. In this case, the fibre disturbance around the knots had also been removed.

For the same raw material, a larger volume and longer knot-free timber are obtained with star-sawing than can be obtained from the main yield in block-sawing (Neubauer 1998). This is a consequence of the fact that the main yield from block-sawing contain knots from practically every branch whorl in the tree, whereas in star-sawing, the knots in one branch whorl will not be found in all the pieces, Figure 14. Neubauer shows through simulations from the pine stem bank (Grundberg et al 1995) that from block-sawn timber, knot-free boards with a length of up to 600 mm can be cut and that the knot removal constitutes 13% of the volume. When the same logs are star-sawn, the corresponding values become 2000 mm and 9%.

Star-sawn timber can be planed with lesser losses than conventionally sawn timber because timber with vertical annual rings lacks cupping. The height of the triangle, and thus the height of the glued block, must agree exactly with the board dimensions into which it is desirable to divide the block, so that there are no excessive volume losses. By deciding already in the planing stage which thicknesses are to be extracted from the finished block, these losses can be avoided.

A great advantage in using triangles in the manufacture of panels is the flexibility which is obtained since the height of the block is determined by the height of the triangles, which in turn can be determined in the planing without great volume losses. Flexibility is thereby also created in the sawmill where rectangular timber can be sawn according to demand and triangles suitable for PrimWood manufacture can be produced at the same time.
Beckman, E.; Stehr, M. 1993: Stjärnutbyte – Volymutbyte vid stjärnsågning (Stärnutbyte - volume yield when sawing according to the star-sawing pattern.), KTH, Wood Technology and Processing, Internal report No. 9/3 (in Swedish)


Chapter 4

Some properties of star-sawn timber and the dependence of these properties on annual ring orientation and distance from the pith
4. Some properties of star-sawn timber and the dependence of these properties on annual ring orientation and distance from the pith

Star-sawing gives timber with vertical annual rings which is free from pith and juvenile wood. Traditionally, this timber has been considered to have properties which are favourable in the advanced use of timber. In the investigations reported in this chapter, the truth of this statement has been examined.

The implication of the vertical annual ring concept is first described. Thereafter, the influence of the position of the timber in the log cross-section on distortion and crack-formation during drying, moisture cycling and outdoor exposure is discussed.

Finally, some results are described from a number of fundamental material investigations where attempts have been made, at macroscopic and microscopic levels to find explanations and mechanisms for the importance of annual ring orientation for the distortion and crack susceptibility of timber at the macroscopic level.

4.1 Definition of vertical annual rings

Vertical annual rings are a quality designation of timber which has been used by craftsmen for hundreds of years. The term also implies how timber should be removed from logs to make the best use of the inherent properties of the wood. Timber has vertical annual rings if it is sawn or cleaved radially from the log and the degree to which the annual rings are vertical is reflected in cross-sections of the timber, (Figure 15).

Two properties of timber are of primary interest when vertical annual rings are referred to, namely texture and shape stability. Texture refers to the appearance of line and colour in the timber surface as a consequence of the annual ring pattern. This varies when the annual ring orientation in the cross-section of the timber is changed. The texture is thus dependent on the angle at which the annual ring meets the surface of the timber, (Figure 16). Timber with vertical annual rings has the radial texture of the wood on the flat side, with a striped pattern which is crossed by rays in certain species. In contrast to the radial surface, the tangential surface of the timber has a considerably more mottled surface in which the opening of the rays can be seen as small longitudinal flecks in
certain species. The radial and tangential textures of pine are shown in Figure 16.

With texture it is difficult to determine when deviation from vertical annual rings are so great that the texture does not meet the requirements with regard to pattern which are referred to as vertical annual rings. Figure 17 shows the texture of pine with some different annual ring orientations. It is evident that the change in texture when annual ring orientation is changed from 90 to 60 degrees is moderate, and that the texture becomes mottled when the annual ring orientation is changed from 60 to 30 degrees and begins then to be more similar to the texture of the tangential surface, i.e. at 0 degrees.

Shape stability refers to the ability of the timber to maintain a given geometric shape during use. This concerns on the one hand the distortion of the timber in the longitudinal direction, i.e. crook, bow and twist and, on the other hand the change in shape of the timber in the cross-section, e.g. cupping. Vertical annual rings, refers primarily to the shape stability in the cross-section of the timber.

Regarding shape stability in the cross-section of the timber, there are two factors which must be taken into consideration, namely annual ring curvature, or the distance from the pith, and the inclination of the annual ring in relation to the timber surface. To illustrate what happens to the shape of cross-sections with change in moisture content, Figure 18 shows a few different timber pieces sawn at different distances from the pith and with different annual ring orientations. The figure shows the change in shape on drying from a moisture content higher than fibre saturation, but changes in shape will also take place during moisture changes which occur during the normal usage of timber and after timber has been further treated.

Figure 18a shows a cross-section taken close to the pith so that half the annual ring circumference can be found in the cross-section. During drying, this timber will change shape drastically, the timber becomes cupped. Even if such a piece is planed after drying,
the moisture movement will affect so that the cupping will be seen.

The timber in Figure 18b has been sawn more or less radially from the log the annual rings are strongly curved and the closer to the periphery of the log, the more vertical the annual rings become. During drying, the thickness shrinkage on the pith side (radially) will be about half that on the sapwood side (tangentially). This means that the cross-sectional shape of this timber will not be maintained if the moisture changes.

In order to prevent changes in shape caused by the annual ring curvature and because of the annual ring orientation in relation to the surface, timber should be sawn free from the area around the pith and with the annual rings parallel to two of the sides of the timber, (Figures 18c and 18d). The piece of timber in Figure 18c must be sawn so far from the pith that the annual rings become practically straight in the cross-section. The closer to the pith this piece is sawn, the greater is the tendency towards cupping. The cross-section in Figure 18d shows what is usually meant by vertical annual rings. The cross-section shape remains practically unchanged when the moisture content varies. The shrinkage and swelling movements are approximately twice as large in the thickness direction of the timber as in its width, i.e. tangential in thickness and radial in the width of the timber. A certain variation in thickness is obtained from the pith side towards the sapwood side because of variations in annual ring curvature and density.

When the annual ring orientation of the timber is changed from completely vertical (90 degrees), the shrinkage and swelling of the timber width increases. Sandberg (1995b) has defined vertical annual rings by maximizing this movement increase to 10% of the purely radial moisture movement. For pine and spruce, the requirement for vertical annual rings is then that the annual ring inclination defined as the angle between a tangent to the annual ring and the flat side of the timber should be between 60 and 90 degrees.

It is evident in Figure 19 that, for vertical annual rings in the whole piece of timber, the distance to the pith must be at least 25 mm at a thickness of 30 mm and 90 mm if the timber is sawn with a thickness of 100 mm. This means that the width of the pith cutter must be twice the distance to the pith, i.e. 50 and 180 mm, respectively.

Considering the crack formation on the pith side of the timber during drying, Sandberg (1995a, 1996d, 1997a) has shown that, if the timber is sawn at least 30 mm...
from the pith, then crack formation is radically reduced. In these measurements, some consideration has been given to the irregular path of the pith in the log.

Characteristic for timber with vertical annual rings is the shape-stability of the timber in the cross-section during moisture changes, that the moisture movement is minimal in critical directions, i.e. in the width of the timber, and that the timber has a radial texture on at least two sides, usually the flat sides. To fulfil these requirements or characteristics, the pith and most of the juvenile wood are removed, which means that the timber becomes less susceptible to cracking and that the shape stability in the longitudinal direction (crook, bow and twist) is improved. Radial surfaces are also harder and more resistant to wear than the corresponding tangential surfaces (Thunell and Perem 1948, Perem 1949, Kühne 1955, Holmberg and Wålinder 1997). During outdoor exposure, radial surfaces are also considerably more resistant than tangential surfaces, as shown in 4.3.

4.2 Distorsion and cracks in timber after sawing, drying and cycles of wetting and drying

When speaking of distorsion in timber, one refers to the change in shape of the timber in an unloaded state. Four different forms of distorsion are recognized: cup, crook, bow and twist, Figure 20.

Distorsion in timber can be the result of stresses in the living tree, so-called growth stresses, or they can arise during manufacture, primarily during drying, as a consequence of the inherent properties of the wood or of the actual refining process. In the same way, cracks can already exist in the trunk or can arise in the refining process. Cracks and distorsions cause losses, and in some areas of use the timber can become practically useless. To reduce the problems of distorsions and cracks, work has been carried out for many years to improve and develop new drying methods, to avoid the build-up of large stress concentrations in the timber. The result has been that it is possible today to deliver timber from many sawmills which is fairly free from cracks and is also conditioned so that it is relatively stress-free.

In the continued handling of the timber after it has left the sawmill, it will in most cases be exposed to a very varying climate, which leads to changes in the moisture content. Already at the end of the 1950s, Armstrong and Kingston (1960) discovered that, if small loaded specimens of wood were exposed to different humidities, the deformation increased drastically compared with when the climate was constant. In the same way, the recovery after unloading was accelerated by a cyclically varying moisture content. This phenomenon is usually called mechanosorption. On an everyday level, this behaviour can be recognized at a building site and where timber which has been out in rain and nasty weather without being covered. The timber is often twisted and crooked, although it was probably straight when it left the sawmill.

Within this field, I have gone further back in the chain, really to the actual wood material, to investigate the causes for the cracking and

Figure 20. Definition and measuring of warp: (a) crook; (b) twist; (c) bow; and (d) cup.
distortion in timber. I have also gone forward slightly in the chain to see what may happen to the timber when it reaches the final user.

Two parameters have been given a more central role in the investigation, viz. the annual ring orientation in the cross-section of the timber and the distance of the timber from the pith. Both parameters are strongly related to the star-sawing pattern. Thus to investigate the influence of annual ring orientation seems to be natural. The distance from the pith has been chosen because it is an easily measurable parameter and has a certain relation to the juvenile wood. The concept of juvenile wood is really undefined in this context. In these investigations, consideration has also been given to other relevant parameters which may influence distortion and crack formation. The influence of drying methods has intentionally received less attention, because considerable research resources are spent in this field in other places and this knowledge will also be applied to the timber investigated here.

Most of the studies are empirical and of a comparative nature. Here, I try briefly to illustrate the influence of a few factors on distortion and crack formation. This means that in this presentation of the results, the influence of the other factors is given a minor role. I have also intentionally avoided introducing a statistical analysis around the results, in order to make the description more accessible for the reader. The complete analyses of the test results are available in published reports and articles, (Sandberg 1995a, 1996b, 1997a, Sandberg and Holmberg 1998b).

**Cup**

Cupping is the change in shape which is clearest in its nature and has to a certain extent already been discussed in relation to vertical annual rings in chapter 4.1. The cupping of timber has two causes: a) The difference in shrinkage and swelling in the tangential and radial directions, i.e. the shrinkage and swelling anisotropy, and b) the curvature of the annual rings in the cross-section of the timber, when the radius of curvature is small.

If both these conditions are met at the same time, timber which is not loaded so that the cupping is counteracted will become cupped with any change in moisture content. The smaller the difference between the radial and tangential moisture movements and the greater the radius of curvature of the annual rings in the cross-section of the timber, the smaller is the cupping. The cupping will of course also depend on the magnitude of the moisture movements, i.e. there is a moisture content and density dependence, and on the width of the timber.

From these arguments, it follows that undried timber will not exhibit cupping, as has also been shown by Sandberg and Holmberg (1998b). Figure 21 shows the average degree of the cupping for about 300 planks of pine and 400 of spruce with different annual ring orientations (Sandberg and Holmberg 1998b). The cupping is normalized and determined on the concave flat side of the timber after the timber has been dried to about 18% moisture content.

Figure 21 shows that the cupping is greatest for timber which is sawn close to the pith and with horizontal annual rings (F in Figure 21). If the timber is sawn further from the pith with increasingly more vertical annual rings, the cupping decreases. Timber containing pith often cracks...
during drying, and this reduces the cupping.

The cupping of timber can be reduced if the timber is dried under load. This cupping reduction is in general not permanent. Sandberg (1997a) has shown that the cupping increases in the case of timber which has been dried under load if the timber is moistened. Figure 22 shows the increase in cupping of dried timber of pine and spruce which has been exposed to three cycles of wetting and drying cycles down to practically the same moisture content as the timber had before the moisture cycling (Sandberg 1995a, 1997a). If the timber initially exhibited cupping, the moisture cycling meant that the cupping increased in all cases. A deviation from vertical annual rings at the butt end of certain timber pieces of pine in group B (Figure 22a) meant that this timber showed cupping.

**Bow and crook**

One of the reasons for removing the juvenile wood in star-sawing already when sawing the log is that the longitudinal shrinkage in the juvenile wood is greater than in the mature wood and that the presence of the juvenile wood thus deforms the timber during drying.

Figure 23a, which shows bowing before and after drying of pine, illustrates clearly how the bowing increases drastically during drying of the pieces in which juvenile wood is present along one of the flat sides of the timber (F in Figure 23a). In the same way, there is a clear increase in crooking during drying when juvenile wood is present along one of the edge sides, (A in Figure 24). For most of the pieces (ca 70%), the crook and bow during drying are directed towards the pith side of the timber, i.e. where the juvenile wood is placed, (see definition of warp in Figure 20).

Timber sawn further from the pith consequently shows less distortion during drying, (Figures 23, 24). The timber which has the pith enclosed shows relatively little bow and crook. This can depend on a certain symmetry around the pith which balances the drying stresses which arise, to the hindrance of bow or crook due to load, or to the fact that the shape change appears as twist (see Figure 29).

The radially sawn timber with rectangular cross-section exhibits a large percentage increase in bowing during drying (A and B in Figure 23). One reason for this is probably that this timber has a large proportion of splay knots on the flat side (Sandberg and Holmberg 1996) and that the shrinkage due to the knots leads to an increased bow during drying. Figure 25.

For all groups (A-H) in Figures 23 and 24, the timber exhibits bow and crook already before the drying. This distortion comes from stresses in the living tree, so-called growth stresses. In general, the growth stresses in the tree trunk are such that there are compressive stresses in the centre of the trunk in the longitudinal direction which are gradually transformed into tensile stresses in the radial direction towards the periphery (Archer 1986). Corresponding stress fields are found in the radial and tangential directions. Growth stresses are dependent on the tree species, growing conditions et c. Compression wood is an example of wood with often high internal stresses.
stresses and also a large longitudinal shrinkage, Figure 26.

The star-sawn triangles (H in Figure 23, 24) have a relatively large bow before drying which in 70% of the cases is directed towards the sapwood. The star-sawing pattern means that the triangles are sawn far from the pith and a large part of the volume of the triangles lies in the periphery of the trunk where the longitudinal tensile stresses dominate. During drying, these stresses are released or balanced and the triangles become practically straight.

Timber which has been loaded during drying has in the unloaded state been exposed to three wetting and drying cycles to study the change in crook and bow (Sandberg 1995a, 1997a). Regardless of how the timber had been sawn in the log, the distortion increased when the timber was exposed to moistening cycles (Figure 27, 28). In the case of pine, it is evident that the absolute deformation increase was greater in the pieces sawn close to the pith (C and F in Figure 27, 28), but in the case of spruce, the difference is not so clear.

**Twist**

Twist is almost non-existent before drying (Figure 29). Only the timber with enclosed pith and the triangles show a certain degree of twisting before the drying. This suggests that the twisting is not influenced to any great extent by stresses in the timber. Several earlier investigations have shown that the twisting after drying is largely dependent on the fibre angle and the annual ring curvature in the timber (see e.g. Stevens and Johnston 1960, Balodis 1972, Forsberg 1997). This is also reflected in the results shown in Figure 29. Timber sawn close to the pith (A, C, D, F in Figure 29), where the fibre inclination is great, consequently exhibits a large twist. The timber which is sawn further from the pith
shows slightly less twisting, whereas the star-sawn timber is the least twisted. The triangles show the earlier pattern with less distorsion during drying.

Several investigations have shown that the twist decreases if the timber is loaded during drying, (Johnston 1957). In moisture cycling of unloaded timber which has been dried under load, the twisting also increases to a certain extent (Figure 30). A n increase in twisting occurs regardless of the annual ring orientation in the cross-section of the timber.

**Crack-formation**

Figure 31 shows the relative crack length in the timber before and after drying, where the relative crack length is calculated as the total crack length in each plank divided by the plank length. It is evident that the mean relative crack length is highest in the timber sawn close to the pith (A, C, D and F in Figure 31). Cracks are present before the timber is dried, and a closer analysis reveals that they occur to a great extent adjacent to the pith (Sandberg 1995a, 1996d, 1997a, Sandberg and Holmberg 1998b).

These cracks are so-called "pith shakes" which radiate out from the pith and become narrower towards the periphery of the trunk (Manuaal in Forest Technology 1922, König 1957, Grönlund and Hägglund 1987). When the timber is dried, these pith shakes create sites for further cracking, which is consequently greatest in timber sawn close to the pith (Figure 31). The fact that timber in groups B, E, G, H (Figure 31) do have cracks before drying depends to a certain extent on the fact that the path of the pith through the trunk is not straight and may come too close to the timber during sawing. When the dried timber is remoistened, the crack length increases slightly (Figure 32). This increase...
is greatest in timber sawn close to the pith.

**Comments on the above results**

The above results show unambiguously that the orientation of the annual rings and the position of the timber in relation to the pith are important factors affecting the distortion and cracking of the timber. It should however be noted that the timber which was used for the investigation was primarily intended for star-sawing, i.e. consisted of large butt logs and middle logs, and this means that it is inadvisable to draw general conclusions from the results. Nevertheless it can be said that, if large-sized logs are to be sawn, then star-sawing or some similar method of sawing is a suitable technique if straight and crack-free timber is desired. It may also be interesting to note that the star-sawn triangles show extremely little distortion and crack formation compared with other sawn timber.

The increase in distortion during humidity cycling can appear to lack an upper limit, but this is not true. The upper limit for how much the distortion can increase during moisture cycling is presumably that which is observed if the timber is dried without any load and so that the stresses in the timber are reduced to a minimum. The increase in crack formation during humidity cycling should then be reduced.

**4.3 The change in wood surface during outdoor usage above ground**

In Sweden, the “permanence” of timber is related primarily to the ability of the timber to resist attack from different fungi. Insect attack of timber in constructions and the change in appearance of the timber in outdoor use are of less importance. It is the interaction between the ability of the timber to maintain the moisture content at a low level and the wood’s intrinsic strength, the amount of nourishing substrate for micro-organisms, the chemical nature of the cell wall and the temperature which are the real criteria for the resistance of timber to decomposition (Öqvist 1988). For timber in ground contact, there are classification rules regarding the degree of permanence. A similar
One problem is that the permanence of timber above ground in outdoor situations cannot be measured in a useful practical way. On several occasions, substitute criteria have been resorted to such as e.g. annual ring width. As an example, attempts have been made in the case of wooden windows to find relationships between the following factors and permanence without finding any clear relationship: differences between summer and winter felled timber (Boutelje and Nilsson 1985), annual ring width (Rydell 1981; Grönlund and Rydell 1983; Boutelje and Nilsson 1985), density (Grönlund and Rydell 1983; Steffen et al 1990), artificial drying versus air drying (Träteknikcentrum 1987). The raw material for most investigations of this type has been timber produced by conventional methods, i.e. square-sawn timber. This has meant that the importance of the annual ring orientation for the permanence of the timber in outdoor exposure has been neglected.

In order to investigate whether annual ring orientation of the exposed surface has any influence on how timber surfaces without surface treatment change on outdoor exposure, a field trial was carried out with pine and spruce timber (Sandberg 1997d, 1998a, 1998b). Star-sawn triangles were used as test material, which meant two important advantages. On the one hand, test specimens with radial or tangential surfaces could be produced from largely identical material and, on the other hand, the star-sawing pattern meant that the pith and the adjacent area were excluded. It is known that in the area around the pith, particularly in pine, so-called pith shakes may occur which can distort the test result (Manual in Forest Technology 1922; Durst 1955; König 1957; Grönlund and Hägglund 1987). To investigate the influence of impregnation, some samples were pressure impregnated with a CCA-agent, some were coated with linseed oil and others were left untreated.

The results after about three years' weathering showed clear differences in crack formation, (Figure 33). The radial surfaces had shorter and a considerably smaller number of cracks than the tangential surfaces, (Figure 34). On radial surfaces, there was no clear difference between pine and spruce. On the tangential surfaces, on the other hand, pine had more cracks than spruce. The investigation showed that neither treatment of the surface with linseed oil nor impregnation influenced the occurrence of cracks. No relation
between the density of the timber and the crack formation was proven. In order to find explanations for the clear differences in crack occurrence between radial and tangential surfaces, a microscope study of the test material exposed outdoors was carried out (Sandberg 1997d, 1998b). Differences were also evident at the microscopic level, (Figure 35). One reason for the variations in crack formation may be differences in the shrinkage and swelling of the early- and latewood in combination with the influence of sunlight. This hypothesis must, however, be investigated more thoroughly.

4.4 Preliminary studies of the mechanisms for distorsion and crack formation in wood

The mechanisms and thus also the reasons why timber is deformed, and in certain cases becomes cracked, must be searched for at a lower structural level of the wood. In order fully to understand the deformation behaviour of the timber, e.g. when it undergoes a moisture change and is at the same time subjected to a mechanical load, it is certainly necessary to start from its molecular structure. The absolute forefront of wood material research is today approaching the molecular level. In this final section of the summary part of this thesis, I wish briefly to present some investigations in which the behaviour of the wood at a microscopic level has been studied. The aim of the investigations has primarily been to build up my own knowledge within this field, but I hope also to contribute with a small piece of the puzzle to help research forward.

Wood is a hygroscopic material, and this influences to a great extent its deformation under load. The deformation of wood during loading can be divided into different components: a part which is elastic, a part which depends on the shrinkage and swelling of the wood, and a part which is called creep. In speaking of creep in wood, one distinguishes between creep when the moisture content...
in the material is constant (viscoelastic) and creep when the moisture content is varying (mechanosorptive). All these components are dependent on the moisture and temperature state of the wood material, but this will not be treated here in detail.

Figure 36 shows in general what the deformation can look like in a wood sample in loading and unloading at a constant and at a varying moisture content. In loading, a purely elastic deformation (a) is first observed and this is followed by a viscoelastic deformation. When the humidity is changed, the deformation follows the characteristic sawtooth pattern shown in Figure 36. In unloading, the elastic deformation (d) recovers instantaneously and this is followed by a delayed recovery (e). If the atmospheric humidity is varied in the same way as when the load was applied, further recovery occurs (f). Figure 36 shows the recovery during wetting and drying cycles, with the characteristic, sawtooth-shaped recovery curve. When the sample has been exposed to a high load, the deformation may not recover completely, and the sample then exhibits a so-called permanent deformation (g). The permanent deformation is usually classified as a plastic deformation if no visible failure has occurred in the material. From a strictly materials science viewpoint, plastic deformation means that secondary bonds in the material have been broken and recreated while the material has been deformed, i.e. sliding has taken place between the molecules. This means that the material must be free from micro-cracks if the deformation is to be regarded as purely plastic.

Figure 36. General description of the deformation of a wood sample in bending as a function of time in different loading modes, (Kingston 1962).

Creep tests under a bending load have been carried out on clear small samples of pine (10 x 10 x 360 mm) in order to investigate the reasons of for the “plastic” deformation (g in Figure 36) and to investigate whether the annual ring orientation in the cross-section of the wood influences the creep behaviour (Kuukkanen and Nordqvist 1992, Sandberg and Johansson 1995, Sandberg 1998d), (Figure 37).

The annual ring orientation seems to have no decisive importance for the deformation of the samples (Sandberg 1998d). The deformation or bowing showed a pattern similar to that observed in similar earlier tests. It was, however, observed that those samples where the external load was applied in radial direction developed a torsion which increased as a result of the moisture cycling, as shown in Figures 39.

Torsion is here defined as the angular difference between the ends of the samples, for the angle formed by the vertical side surfaces of the sample with the horizontal plane which coincides with the plane in which the support points can be found, (Figure 38).

Figure 37. The direction of the load (L) and the location of the support points on the test samples under (a) radial and (b) tangential load. The radially loaded samples were under tension on either (c) the sapwood side or (d) the heartwood side.
Figure 38. Determination of the torsion of test bodies exposed to a bending load. The angles \( \alpha \text{butt} \) and \( \alpha \text{top} \) are determined at the butt and top ends respectively and the torsion is calculated as the difference between these two angles.

Figure 39 shows a clear difference between tangentially and radially loaded samples. The tangentially loaded samples show a small degree of twisting, whereas the radially loaded samples are twisted considerably more. The relative humidity was varied between 23 % and 85 % at a constant temperature of 20°C. The time for one cycle with a dry and humid climate was ca. 30 days.

When the samples were loaded, they showed no tendency to twist, and after 14 days in a constant dry climate the twisting tendency was still low. When the humidity was increased, a drastic increase in the twisting took place in the case of the radially loaded samples. Figure 39 shows that the torsion increases with increasing load, which is natural. It is also evident that the torsion takes place in different directions in the case of the radially loaded samples.

Figure 39. Torsion of samples of pine (10 x 10 x 360 mm) under a bending load subjected to a cyclically varying relative humidity (T = 20°C), (Sandberg 1998d). The samples have been loaded at levels of (a) 5 %, (b) 20 % and (c) 40 % of the bending failure load at a moisture content of 12 %. See Figure 37 regarding loading directions.

RSD – Radial load, sapwood side under tension.
RKD – Radial load, heartwood side under tension.
T – Tangential load.
loaded samples, depending on whether the heartwood side of the sample is loaded under tension or under compression. In absolute figures, however, the torsion is practically the same.

One hypothesis is that the fibre inclination on the tangential surfaces of the samples influences the torsion.

The samples with the highest load failed in an early stage of the tests, which means that the torsion curves (Figure 39c) are very irregular.

The samples were unloaded and moisture-cycled further. The deformation and the torsion recovered to a certain degree but not 100 %, which is a well-known phenomenon.

Samples used for creep tests have, after the test was completed, been studied in a microscope (Sandberg and Johansson 1995, Sandberg 1998d). The aim has been to investigate whether structural changes had occurred in the wood material during the creep tests. In these studies, damage was observed in the cell-walls, Figure 40. This damage can to a certain extent explain the non-reversible deformation (g in Figure 36).

In the investigations of creep deformation, it was suggested that a creep test might be carried out directly under a microscope. The idea was to obtain a picture of how material at the cell-wall level deforms and how and where damage is initiated at the micro-

level. Creep tests under a tensile load were therefore carried out using the ESEM technique (Kifetew and Sandberg 1998). The tests were found to be very difficult to perform and a lot of effort was spent on the technical performance of the tests.

Figure 40. Damage in the cell-wall after the creep test was completed. Magnification 750 x.

The initial investigations were devoted to investigating how the electron beam influences the test material. Within this field, a lot of knowledge can be obtained from other materials fields, but in this case it was also important to build up our own knowledge and skill with the instrument. The results showed that the influence of the electron beam was considerable, due to the high electrode voltage with which we worked initially. This is discussed in an article by Kifetew and Sandberg (1998).

In the work on the permanent deformation after a creep test (g in Figure 36), speculations arose regarding the extent to which wood can be deformed if the wood after subsequent moistening is to resume its original shape (Sandberg and Johansson 1995). This phenomenon is also discussed in chapter 4.2 in relation to the distortion of timber which has been dried under a load.

In order to test the extent to which wood can be deformed and still resume its original shape after moistening, tests were performed with isostatically compressed wood. Isostatic compression, which means that the wood is compressed under the same pressure from all directions, was chosen because this gives large deformations at the same time as little external damage is visible on the wood. Tests were carried out at the macroscopic level and the analysis was done using a microscope.

Figure 41 shows the cross-section of compressed pine where the density has been increased to ca 1200 kg/m³, (Sandberg 1998e). The isostatic compression was carried out at room temperature and the samples had a moisture content of ca 10 %.

It can be seen in Figure 41 that the cells are very deformed. When these samples were again moistened, the cells resumed their original shape (Figure 42).
When the cell structure was studied more closely, very little damage was found, Figure 43.
In certain areas, however, folds or the beginnings of cracks can be seen in the actual cell wall, Figure 44.
This study shows examples of the incredible ability of the wood material to resume its natural and original shape after a very large deformation. In order to prevent this from taking place, the glass transition temperature of the wood polymers must be exceeded when the wood is deformed. The results can also be related to the question of whether it is possible in today’s drying plants in sawmills to load the timber during drying so that the distortion is reduced. The timber from the sawmills will in fact be exposed to countless moistenings and dryings before it reaches the final user.

Figure 41. Cross-section of isostatically compressed earlywood of pine. Magnification 245 x.
Figure 42. Cross-section of isostatically compressed earlywood of pine after moistening. Magnification 900 x.
Figure 43. Isostatically compressed pine after moistening. Magnification 2100 x.
Figure 44. Folds or indications of cracks in isostatically compressed pine. Magnification 2000 x.
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och gran (Picea abies Karst).


Chapter 5

Conclusions
5. Conclusions

Research at KTH-Trä has since the end of 1990 been focused on an integrated R&D-program called Value Activation. Value Activation strives towards a strong integration of the three main tasks of a university, viz. basic education, research and graduate studies, and the dissemination of technology. The research work has been carried out as a problem- or idea-based process, and the basic education has become progressively more integrated with the research and oriented towards problem- and idea-based learning. A new sawing pattern, star-sawing, passes through both education and research as a continuous thread.

One of the aims of this thesis is to elucidate the process relating to the implementation of the radically new star-sawing production system from university research to the wood-working industry i.e. a practical aspect of the R&D-program Value Activation at KTH-Trä.

The relation between ideas, scientific basis for ideas and development results, and the development of production technology and systems has been important for the industrial implementation of the R&D-results, and to a high degree also for the progress of the work presented in this thesis. I have also related the dissemination of knowledge and technology transfer from all levels to the industrial implementation.

In the thesis some of the material properties which are very important for timber in general and for star-sawn timber in particular have been investigated. The important material properties here referred to are primarily those properties which are related to the deformation and crack behaviour of wood. The results show that star-sawing gives timber that have an accuracy in size and geometry, is free from cracks and has a controlled movement with changing humidity.

The Value Activation program has so far shown that there are great possibilities of utilizing the properties of wood in a better way than our conventional wood production concept can achieve. New wood products with desirable properties can be developed. Most of these products are expected to give a greater added value to the wood. The R&D-program will continue with the further development of improved products and also with the development of cost-efficient production systems for implementing the ideas from our R&D in profitable production units.
Radially sawn timber
Star-sawing - a new method for producing timber with vertical annual rings

D. Sandberg
Summary
This work presents a new method of sawing to produce pith-free timber with vertical annual rings and without juvenile wood. The method, which is called star-sawing, gives sawn timber with two different shapes, viz, conventional timber with a rectangular cross-section and timber with a triangular cross-section. The volume yield for star-sawing has been determined with the help of computerized simulations and test sawings. The results show that star-sawing is best suited for logs with a top diameter greater than 200 millimetres. Both a high volume yield and suitable dimensions of the sawn timber were then obtained. The volume yield of timber with vertical annual rings in star-sawing is about 0.70 calculated with regard to the top cylinder volume under bark.

1. Introduction
The shrinkage anisotropy of the wood means that timber exposed to moisture changes will in most cases change both in its dimension and in its shape, i.e. deviations will occur from the original, usually right-angled parallelepipedal shape. The changes in shape appear as distortions and angular changes in the cross-section and are due mainly to the fact that the sides of the timber are not parallel to the anatomical primary directions in the wood, the radial and tangential directions. The distortions and angular changes in the cross-section become more evident the greater the difference between the radial and tangential moisture movements (Schwab 1978).

It has been known for a long time that if timber is sawn radially from the log, no or very small changes in shape occur. The timber then has vertical annual rings. The dimensional changes associated with moisture changes are still present, of course, but the radial moisture movement occurs only along the width of the timber and the tangential changes only in its thickness direction. The sides of the timber are thus parallel to the main directions of the wood and the movement as a result of any moisture change can be predicted. If the annual rings are not completely vertical, the moisture expansion across the width of the timber will increase, as will the changes in shape. To prevent a greater degree of annual ring inclination from causing any perceptible deterioration from the timber properties associated with vertical annual rings, the angle between the flat side of the timber and the annual rings shall lie between 60 and 90 degrees. This applies to pine (Pinus silvestris L) and spruce (Picea abies Karst) (Sandberg 1995a).

There are several methods of producing timber with vertical annual rings. The methods which give timber with a rectangular cross-section adopt in most cases the traditional quarter-sawing pattern, as in Figure 1a. With other methods which give timber with vertical annual rings, sectors are sawn with a more or less triangular shape, Figure 1b. A compilation of some of these methods has been made by Polaczek (1990).

It is well known that the juvenile wood, the annual rings closest to

Figure 1. Example of two sawing patterns which give timber with vertical annual rings. a) quarter sawing, b) sector sawing.
the pith, differs considerably from the wood located in the periphery of the trunk. In the case of spruce (Picea abies Karst) it has been found for instance that the fibres of the juvenile wood are shorter and have a lower stiffness and density than other wood (Boutelje 1968). It has also been found that the fibril angle is greater in the juvenile wood than in the mature wood, which means that timber which contains juvenile wood will be deformed during drying (Danborg 1990). It has also been shown that if timber contains pith or if any part of the timber has been sawn close to the pith, the timber has a greater tendency to crack (Sandberg 1995b). These properties of the juvenile wood mean that it should be removed already at the time of sawing in order to obtain straight timber free from cracks.

At the Royal Institute of Technology, KTH, Division of Wood Technology and Processing, a new sawing method to produce timber with vertical annual rings has been developed during recent years. The method is called “star-sawing” and is part of an extensive R&D-program, “Value Activation”, which is aimed at producing timber and materials with vertical annual rings on an industrial scale and with good profitability for products in which e.g. small and controlled moisture movements are valued highly. The object is thus to activate values in timber which with today’s industrial technology are dormant (Wiklund 1993).

2. Star-sawing

It seems obvious that if the timber is sawn radially from the log, without pith and juvenile wood, properties are obtained which are much better than those of conventionally sawn timber. Star-sawing is a new method for producing such timber. The yield from star-sawing consists of timber sections with both rectangular and triangular cross-sections, all with vertical annual rings. Figure 2 shows the star-sawing pattern.
2.1 The adaptation of the sawing pattern to the log geometry

The star-sawing pattern is well adapted to the circular cross-section of the log. The sawing pattern in its basic design gives six pieces with a triangular cross-section and six pieces with a rectangular cross-section but, depending on the desired timber thickness and the dimensions of the triangular profiles, several more rectangular pieces can be sawn to maintain a high volume yield, Figure 3a. For non-circular logs, it is also possible to adapt the sawing pattern to the shape of the log, Figure 3b. Non-circular logs usually contain reaction wood in parts of the cross-section. In starsawing, the log can be positioned during insertion so that the reject as a consequence of the reaction wood is minimized. It is also possible to saw timber pieces with a large proportion of reaction wood, for use in products where the properties of the reaction wood are particularly valuable.

Removing the pith and the juvenile wood is one of the most critical steps in star-sawing. The path of the pith in the length direction of the log is often very irregular. Top fractures and other types of damage which frequently arise during the growth of the tree often cause a fairly large displacement of the location of the pith. If the log is crooked, the pith will follow this crookedness, at the same time as the pith becomes displaced from the geometrical centre of the log cross-section. This means that high demands must be made on the position of the log so that the pith and the surrounding juvenile wood can be “captured” and separated from the other wood.

A method which has proven useful to remove the pith and the surrounding juvenile wood effectively is to place two parallel sawkerfs on each side of the pith at a distance which corresponds to the thickness of the rectangular timber. If the log is crooked, the log is rotated until the plane in which the crookedness lies is parallel to the sawkerfs. The timber section containing the pith is then sawn with a pith-catcher which can be adapted to the extension of the pith and the juvenile wood.

2.2 Dimensions of the sawn timber

The appearance of the star-sawing pattern means that the width of the timber becomes considerably smaller than in e.g. square sawing, for the same log diameter. This means that star-sawing is best suited for coarse logs where the top diameter is greater than 200 millimetres. The dimensions of the timber with a rectangular cross-section have been chosen so that they agree with the standardized dimensions used in e.g. Sweden (SIS 1970). In the case of triangular profiles, there are no standardized dimensions and in the test sawings carried out, triangular profiles with sides of 80, 100 or 120 millimetres have been obtained. Besides the timber from the actual star-sawing, sideboards are also obtained from the slabs. These boards have horizontal annual rings, however, but with a uniform annual ring orientation and they are often knot-free and of very good quality.

Figure 3. Variations of star-sawing to achieve optimum utilisation of the log volume. a) Sawing pattern with twice the number of timber pieces with rectangular cross-sections. b) Sawing pattern adapted to the non-circular log cross-section.
2.3 Pilot plant for star-sawing

In order to develop a system for the star-sawing technology and to test the properties of the sawn timber and of the products in which the timber is used, a pilot plant for star-sawing has been built. The sawing is carried out mainly in a horizontal bandsaw of the "Forestor" type which has been rebuilt to cope with star-sawing. Figure 4 shows the sawing procedure used in the plant. This method of star-sawing is neither the most optimum nor the only method, but it was shown in this first phase of development to be very suitable. The log is lifted into the band saw and is centered with the help of underlying lifting arms and is then fastened at the ends between two pegs, Figure 4a. The outer part of the log is sawn away after which the log is rotated in steps of 60 degrees and sawn, so that a six-sided block is obtained, Figure 4b. The log is loosened from the pegs and lowered onto the sawing bed. A pith plank and two blocks, the so-called coffin lids, are sawn. The coffin lids are turned and fastened, after which two timber sections are sawn from each block, Figure 4c. The remaining blocks with rhombic cross-section are placed in a fixture and sawn, Figure 4d. After this sawing step, two blocks with rhombic cross-sections are obtained. These are turned and placed in a fixture before the sawing continues, Figure 4e. The rhombs stand freely in the fixture, i.e. without being fastened.

2.4 Drying of star-sawn timber

The timber sawn in the pilot plant has been dried in a chamber drier at a sawmill. The kiln schedules used are the same as those used to dry conventional timber at the sawmill. In the drying, the triangular profiles have been stacked according to two different methods, completely block stacked and in groups of three, Figure 5. In the stacking of the triangular profiles, the tangential surface, from which evaporation is considerably more rapid than from the radial surface, is always placed against

Figure 4. Sawing procedure in the pilot plant for star-sawing. The pictures show log and timber cross-sections.

a) The log is positioned and fastened between two pegs so that it can be rotated.
b) The suspended log is turned and sawn into a six-sided block.
c) The six-sided block is loosened from the pegs and lowered onto the sawing bed. A pith plank and two blocks, the so-called coffin lids, are sawn.
d) The "coffin lids" are turned and fastened, after which two timber sections are sawn from each block.
e) The remaining blocks with rhombic cross-section are placed in a fixture and sawn.

Figure 5. Board stacking methods tested during the drying of triangular profiles. a) Tightly packed profiles. b) Triangular profiles placed in groups of three.
some other surface to ensure some degree of deceleration of the moisture evaporation. Preliminary tests show that timber with vertical annual rings and without pith and juvenile wood can be dried with a conventional drying program with a good result and without cracks. This is also true of the triangular profiles. The greatest difference in drying between the two stacking methods for the triangular profiles has been found to be that the free profile corners of the grouped profiles become too severely dried (Sandberg and Holmberg 1995).

3 Volume yield in star-sawing

The basic idea of star-sawing is to obtain products with the highest possible value from a given raw material. This means that the volume yield in the sawing need not necessarily be maximized. From an economic viewpoint and for environmental reasons, however, it is very important that as large a part of the log as possible is used. The yield values reported here refer only to volume yields for timber with vertical annual rings.

3.1 Simulation of the volume yield

Star-sawing has been simulated in a computer with the help of the so-called OPTSAW-system. This system is a computer-based simulation aid, developed at the Swedish Institute for Wood Technology Research, with which it is possible to analyse quantitative and economic relationships between the quality of logs and the quality of sawn timber. The OPTSAW-system consists of three main components: A log bank consisting of more than fifty "real" trees of pine, the internal and external geometries of which have been measured and digitalized. With these data as a base, the trunks have then been reconstructed in a computer and a trunk database has been established. In addition, the system consists of software for simulated sawing and calculation of the quality and value of the stems. For a deeper study of the OPTSAW-system, Drake and Johansson (1987) and Liljeblad et al (1988) are referred to. The OPTSAW-system can simulate the sawing methods square sawing and through-and-through sawing. In order to simulate star-sawing, new software has been developed (Nordfors and Sandberg 1993).

3.1.1 Input data for the simulation

The simulated sawing differs from the real sawing at the pilot plant in that no six-sided block is sawn. Instead, all sawn timber are edged after they have been sawn free from the log. This gives a greater flexibility in the choice of dimensions for an individual piece of timber. The width and thickness of the rectangular timber have in the choice of sawing patterns followed standardized dimensions. All timber sections have been sawn without wane and no volume optimization has been carried out with regard to the length/width ratio during the edging. As in the pilot plant, a timber section

<table>
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<th>Top diameter (mm)</th>
<th>Sawing pattern (no)</th>
<th>Thickness of the timber with rectangular cross-section (mm)</th>
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</thead>
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<td>12 16 19 22 25</td>
</tr>
<tr>
<td>141-160</td>
<td>6-9</td>
<td>16 19 22 25</td>
</tr>
<tr>
<td>161-180</td>
<td>10-13</td>
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<tr>
<td>301-320</td>
<td>47-51</td>
<td>25 32 38 50 63</td>
</tr>
</tbody>
</table>
containing the pith has been sawn, after which a so-called pith-catcher has been used to remove the pith and the juvenile wood. In the simulation, the width of the pith-catcher has in all cases been 15 millimetres and the width of the sawkerf 4 millimetres. The shrinkage during drying of the rectangular section has been set to 4 per cent in the tangential direction and 2 per cent in the radial direction, and the volume shrinkage of the triangular profiles has been set to 4 per cent. The longitudinal shrinkage has been neglected. This shrinkage corresponds to a final moisture content of about 15 per cent after drying. In the simulation, no consideration has been given to the yield of chips, shavings and sideboards, which is very important for the value yield in the sawing, but does not affect the calculation of volume yield for the timber with vertical annual rings.

The logs from the stem bank used in the simulation have a top diameter of between 140 and 305 millimetres and an average length of 4.7 metres (standard deviation 0.8 m). The logs have been divided into diameter classes with an interval of 20 millimetres and for each class a few different sawing pattern alternatives have been determined, with the constraint of a condition for the relationship between the cross-sectional areas of the triangular profiles and of the rectangular timber, for each diameter class. The area ratio, i.e. the ratio of the cross-sectional area of the rectangular timber to that of the triangular profiles, was found to lie between 0.40 and 2.0 for all log diameters. The condition means that only realistic timber dimensions will be sawn in the simulation. Table 1 shows alternative simulated sawing patterns. Only the log diameter and timber thickness determine the sawing pattern. The dimensions of the triangular profiles will be determined in the subsequent edgeing operation. It is possible either to saw the same dimension on all triangular profiles or to determine individually the dimensions of each individual profile. In the simulation, we have chosen to saw sharp-edged triangular profiles with the side length in a 5 millimetres module. Only sawing patterns in which six rectangular and six triangular timber sections are sawn have been used in the simulation.

3.1.2 Results

Figures 6 and 7 show the volume yield, calculated with regard to the top cylinder volume under bark, as a function of the top diameter. Figure 6 shows the total yield and the corresponding yield for the timber with rectangular cross-section for the sawing patterns which gave the highest total yield. The logs have been divided into diameter classes according to the top diameter in intervals of 10 millimetres and the average value has been calculated within the classes for the sawing patterns which gave the highest total yield. Figure 7 shows the sawing patterns which within each diameter class...
gave the highest yield of timber with a rectangular cross-section.

Table 2 shows examples of dimensions of the timber from sawing patterns which gave the highest total yield. Table 3 shows timber dimensions in the corresponding diameter classes for the sawing patterns which gave the highest yield of timber with a rectangular cross-section.

3.2 Test sawings
Since the start, ca 600 cubic metres of timber have been sawn in the star-sawing pilot plant. Continuously during the test sawings, logs have been chosen for which the quality and volume yield have been determined. On the basis of the results obtained, the position and sawing methods have been refined. The volume yield calculations reported here apply at a stage when the methods for insertion and sawing of the log were optimized to the full extent that was considered possible in the pilot plant.

3.2.1 Test material and choice of sawing pattern
50 logs of pine have been randomly chosen from a log catch of 250 logs. The top diameter under bark varied between 325 and 440

<table>
<thead>
<tr>
<th>Top diameter (mm)</th>
<th>Rectangular*</th>
<th>Triangular profile</th>
<th>Volume yield</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dimension (mm)</td>
<td>Number of pieces</td>
<td>Side length (mm)</td>
</tr>
<tr>
<td>150</td>
<td>25 x 63</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>25 x 50</td>
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<td></td>
<td>25 x 38</td>
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<td></td>
<td>60</td>
</tr>
<tr>
<td>200</td>
<td>32 x 75</td>
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<td>50</td>
</tr>
<tr>
<td></td>
<td>32 x 63</td>
<td>3</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>32 x 50</td>
<td>1</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td>80</td>
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<tr>
<td>250</td>
<td>50 x 100</td>
<td>2</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>50 x 75</td>
<td>1</td>
<td>70</td>
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<td></td>
<td>50 x 63</td>
<td>3</td>
<td>90</td>
</tr>
<tr>
<td>300</td>
<td>38 x 125</td>
<td>2</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>38 x 115</td>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>38 x 100</td>
<td>2</td>
<td>110</td>
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<tr>
<td></td>
<td>38 x 75</td>
<td>1</td>
<td>130</td>
</tr>
</tbody>
</table>

* Refers to the timber with rectangular cross-section.
millimetres. The average length was 4.5 metres (standard deviation 0.4 metres). All logs were made up of butt logs of good quality, and crookedness and eccentricity only occurred in the logs to a very limited extent. The width of the pith catcher has for all sawing patterns been at least 50 millimetres. The width of the sawkerf was 3 millimetres and, after the subdivision, the timber was dried to a moisture content of 15 per cent.

### 3.2.2 Results

Figure 8 shows the volume yield as a function of the top diameter for all test logs. The yield is calculated with regard to the top cylinder volume under bark i.e. in the same way as in the simulated yield calculations. Table 4 shows examples of sawn dimensions and corresponding yields for four different sawing patterns.

### 3.3 Discussion

The simulations of star-sawings and the tests sawings show that the yield in star-sawing is considerably higher than for traditional sawing methods, e.g. through-and-through sawing, square sawing and quarter-sawing. The simulation results show that the yield with respect to

<table>
<thead>
<tr>
<th>Top diameter (mm)</th>
<th>Rectangular profile</th>
<th>Triangular profile</th>
<th>Volume yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top diameter</td>
<td>Rectangular *</td>
<td>Number of pieces</td>
<td>Number of pieces</td>
</tr>
<tr>
<td>(mm)</td>
<td></td>
<td>(mm)</td>
<td>(mm)</td>
</tr>
<tr>
<td>150</td>
<td>25 x 63</td>
<td>2</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>25 x 50</td>
<td>2</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>25 x 38</td>
<td>1</td>
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<td></td>
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<td></td>
<td>60</td>
</tr>
<tr>
<td>200</td>
<td>38 x 75</td>
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</tr>
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<td></td>
<td>38 x 63</td>
<td>4</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>70</td>
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<td></td>
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<td></td>
<td>80</td>
</tr>
<tr>
<td>250</td>
<td>50 x 100</td>
<td>2</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>50 x 75</td>
<td>1</td>
<td>70</td>
</tr>
<tr>
<td></td>
<td>50 x 63</td>
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<td>300</td>
<td>38 x 125</td>
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<td>50</td>
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<tr>
<td></td>
<td>38 x 75</td>
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<td>38 x 50</td>
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<td>90</td>
</tr>
<tr>
<td></td>
<td>38 x 75</td>
<td>1</td>
<td>95</td>
</tr>
</tbody>
</table>

* Refers to the timber with rectangular cross-section.
the top cylinder volume varies between 0.50 and 0.75.
Approximately half the timber volume is made up of timber with a rectangular cross-section and the remaining part of timber with a triangular profile. Boards are also obtained from the slabs, but this yield has not been included in this investigation. The total yield is not affected noticeably by whether the yield of timber with rectangular cross-section is maximized or not, as is evident if Figures 6 and 7 are compared. On the other hand, the scatter in the yield of rectangular timber becomes much smaller when the yield is maximized.

The yield decreases strongly for small log diameters, especially when the log diameter is less than 200 millimetres. There are several reasons for this, but the most important is that the standardized module measurements for rectangular timber agree poorly with the sawn dimensions. This causes large waste in the edging stage. Tables 2 and 3 show that the dimensions for both the rectangular and triangular timber are very small. From a handling and allocation viewpoint, small timber dimensions are usually not preferable to coarse dimensions. The knots in radially sawn timber can also have such an extension in the timber, especially in small dimensions, that they constitute a great risk of failure already in an unloaded state. This means that from a production technical viewpoint and with consideration to the volume yield, star-sawing in the form stated in this article should be carried out on large logs, e.g. with a top diameter greater than 200 millimetres. The lower limit for the log diameter must of course be determined with consideration given to the products for which the timber shall be used.

On the basis of the simulation results, it was considered suitable in the pilot plant for star-sawing to saw only logs with a top diameter

<table>
<thead>
<tr>
<th>Top diameter (mm)</th>
<th>Rectangular* Dimension (mm)</th>
<th>Number of pieces</th>
<th>Triangular profile Side length (mm)</th>
<th>Number of pieces</th>
<th>Volume yield Total</th>
<th>Rectangular*</th>
</tr>
</thead>
<tbody>
<tr>
<td>325</td>
<td>50 x 125</td>
<td>1</td>
<td>100</td>
<td>6</td>
<td>0.64</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 x 75</td>
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<tr>
<td>340</td>
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<tr>
<td></td>
<td>63 x 115</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>63 x 100</td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>440</td>
<td>50 x 175</td>
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<td>100</td>
<td>6</td>
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<td>0.47</td>
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<tr>
<td></td>
<td>50 x 150</td>
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<td></td>
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<td></td>
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<tr>
<td></td>
<td>50 x 125</td>
<td>2</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>50 x 100</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Refers to the timber with rectangular cross-section.
greater than 300 millimetres. Figure 8 shows that the volume yield in the test sawings lies at the same level as in the simulation, i.e. about 0.70 for the total yield and 0.35 for the rectangular timber. Figures 6 and 7 show that a slightly higher total yield can be expected than that obtained in the test sawings. This is due to two essential differences in sawing manner between the simulation and the test sawing. Firstly, the width of the pith-catcher has been increased from 15 millimetres in the simulation to at least 50 millimetres in the test sawings. It was found in practice that it is very difficult to remove the pith and the juvenile wood with the help of a pith-catcher which is smaller than 50 millimetres. Secondly, only three dimensions of triangular profile were sawn in the test sawing, 80, 100 and 120 millimeter sides, and only one dimension per sawing pattern. In the simulation, the dimension was determined individually for each triangular profile in the sawing pattern, which meant that the yield could be increased slightly. In general, this means that the yield in the test sawing was slightly less than that in the simulation. The tendency for the total yield to decrease in Figure 8 is also a consequence of the fact that only three sizes of triangular profile were sawn. An increase in the number of sawing pattern alternatives probably causes the total yield to stabilize at about 0.70.

On the basis of the simulated yield results and experience from the sawings carried out in the pilot plant, a yield curve according to Figure 9 can be expected.

4. Conclusions

Star-sawing is a new sawing method to produce timber on an industrial scale with vertical annual rings and free from pith and juvenile wood. This timber has several advantages compared with conventionally sawn timber, among other things very small changes in shape as a result of moisture content changes. The star-sawing method gives two shapes of the sawn timber, viz. timber with a rectangular cross-section and timber with a triangular cross-section. The sawing pattern is well adapted to the more or less circular shape of the log cross-section and permits a large variety of different patterns depending on the shape of the log cross-section. This means that the volume yield in star-sawing becomes high. The yield of timber with vertical annual rings for star-sawing is about 0.70 and approximately half this yield is made up of triangular profiles. Besides this, high-quality timber with horizontal annual rings is also obtained from the slabs.
References


Sandberg, D. 1995a: Vertical annual rings in pine (Pinus silvestris L) and spruce (Picea abies Karst), Royal Institute of Technology, Wood Technology and Processing, Report TRITA-TRÄ R-95-13


Wiklund, M. 1993: Value activation – new sawing pattern give improved properties on wooden products. Paper at the 11th International Wood Machining Seminar, Honne
Radially sawn timber. Knots - number, type and size in star-sawn triangular profiles of pine (Pinus silvestris L) and spruce (Picea abies Karst)

D. Sandberg, H. Holmberg

Chapter II
Summary

This paper describes the appearance and number of knots in star-sawn triangular profiles of pine (Pinus silvestris L) and spruce (Picea abies Karst). The emphasis is placed on obtaining the volume yield of boards with a given knot appearance, together with the sizes of the fibre disturbances around the knots and how they effect the yield. The test material has been taken from three regions in Sweden and is made up of butt logs of pine and of normal and fast-growing spruce.

The results show that a large proportion of the knots found in the triangular profiles from butt logs are unacceptable in further refinement of the timber and must be removed. Very few healthy knots can be found.

To produce knot-free boards, a volume reduction of on average 8 and 21 percent is obtained for pine and spruce respectively, calculated with respect to the original profile volume. If the fibre disturbance around the knots is also removed, a further volume loss of 5 percentage for pine and 6 percentage for spruce is obtained.

The boards produced have a broad spectrum of lengths between 2 and 500 centimetres for pine and between 2 and 400 centimetres for spruce.

1. Introduction

The number of knots in timber and their location, shape and nature are very important for e.g. the appearance, strength properties and susceptibility to deformation of the timber. The knots often play a decisive role for the price-setting of the timber and for its aesthetic value. Depending on the location of the sawkerf in relation to the longitudinal axis of the knot, the section through the knot can be round, oval or more or less triangular. The choice of sawing pattern will thus strongly influence the geometrical appearance of the knot in the sawn timber surface.

A new sawing method for producing radially sawn timber is under development at the Division of Wood Technology and Processing at the Royal Institute of Technology in Stockholm, KTH. The method is called star-sawing and is a part of the R&D-program "Value Activation" which is aimed at producing timber and boards with vertical annual rings on an industrial scale and with good profitability for products in which e.g. small and controlled moisture movements are highly valued. It is thus desirable to activate values in timber which with today's industrial technology are dormant. The R&D-program and the sawing method are described in greater detail in two articles by Wiklund (1993) and Sandberg (1996).

The star-sawing pattern gives timber with both rectangular and triangular cross-sections. All the timber have vertical annual rings and are free from juvenile wood. The term "vertical annual rings" here means that the angle between the annual rings and the flat side of the timber is greater than 60° (Sandberg 1995). In star-sawing, as in all radial sawing methods, the radial sawkerfs cleave the knots longitudinally and a larger proportion of splay knots are obtained than in through-and-through sawing and block-sawing. These knots are often unacceptable from a strength viewpoint and must be removed. Star-sawing is especially suitable for large log dimensions. The top diameter should be greater than 200 millimetres to ensure that the sawn timber do not become too narrow (Sandberg 1996). A large proportion of the timber which assumes these proportions is made up of butt logs.
and the knots in these butt logs are often of such a nature that for aesthetic reasons they should be removed. It has been found among other things that butt logs of pine have a low proportion of healthy knots in comparison with middle and top logs (Nylinder et al 1995).

2 Aim
The purpose of this investigation is to determine the nature and number of knots in star-sawn triangular profiles from butt logs of pine and spruce. On the basis of these basic data, the yield is calculated for the production of knot-free triangular boards.

3 Materials and methods

3.1 Test material
The test material has been taken from three regions: southern, central and northern Sweden. The logs is so-called oversized which in this case means that the top diameter exceeds 35 centimeters and the selection has been made so that only timber of U/S and fifth quality (V) has been included in the study material. The logs from southern Sweden was felled during January 1994 and was made up of pine and normal and fast-growing spruce. “Fast-growing” here means an average annual ring width greater than 10 millimetres. The logs from central Sweden was made up of normally grown oversized pine and spruce which was randomly taken from the logs catch of a local sawmill. The logs is presumed to be representative of oversized logs in this region. The logs from northern Sweden is made up of normally grown pine and spruce from two sawmills and the same selection method has been used for the logs from central Sweden. All logs have been quality graded according to the regulations applied in Sweden by an authorized log-grader before they were sawn (Timber Measurement Council 1990).

3.2 Sawing and drying
All logs were sawn according to the star-sawing method. Sawing patterns were chosen so that the sides of the triangular profiles were 120 millimetres (dried measurement) and the rectangular timber had a thickness of 50 or 63 millimetres (dried measurement). In each sawing pattern, a pith-catcher was sawn away. The width of the pith-catcher was at least 50 millimetres and the thickness was the same as for the rectangular timber. After the sawing, the timber was stacked and dried according to a conventional drying schedule in a drying chamber. Table 1 presents a compilation of the extent of the test material.

3.3 Measurement method
For each triangular profile, the relative positions and extensions of the knots were determined on the three sides of the profiles. In addition, the lengths of the profile which must be removed to obtain, on the one hand, knot-free timber boards where only the knot is removed and, on the other hand, boards where the fibre disturbance around the knot is also removed, were determined. Each knot was classified according to shape and type according to the assessment rules applied in the Nordic grading rules for sawn timber goods (Timber Grading Committee 1976).

Table 1. The extent of the test material and the lengths of the profiles.

<table>
<thead>
<tr>
<th>Test group</th>
<th>Total length (m)</th>
<th>Number of profiles</th>
<th>Average length (m)</th>
<th>Number of butt logs</th>
</tr>
</thead>
<tbody>
<tr>
<td>pine central Sweden</td>
<td>221</td>
<td>46</td>
<td>4.8</td>
<td>8</td>
</tr>
<tr>
<td>pine northern Sweden</td>
<td>189</td>
<td>39</td>
<td>4.9</td>
<td>9</td>
</tr>
<tr>
<td>pine southern Sweden</td>
<td>109</td>
<td>24</td>
<td>4.5</td>
<td>3</td>
</tr>
<tr>
<td>total pine</td>
<td>519</td>
<td>109</td>
<td>4.7</td>
<td>20</td>
</tr>
<tr>
<td>spruce central Sweden</td>
<td>176</td>
<td>35</td>
<td>4.9</td>
<td>7</td>
</tr>
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<td>5.0</td>
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<tr>
<td>spruce southern Sweden fast*</td>
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<td>38</td>
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</tr>
<tr>
<td>spruce southern Sweden</td>
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<td>12</td>
<td>4.4</td>
<td>7</td>
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<tr>
<td>total spruce</td>
<td>519</td>
<td>109</td>
<td>4.7</td>
<td>24</td>
</tr>
</tbody>
</table>

*fast = fast-growing spruce with an average annual ring width greater than 10 mm
4. Results and discussion

4.1 Log quality

The quality of the logs used in the investigation is shown in Table 2. For the logs from central and northern Sweden, the distribution between U/S and fifths is very similar, whilst the normally grown pine and spruce timber from southern Sweden has an over-representation of fifths. Compared with the official statistics over the distribution of logs grades, the logs from northern and central Sweden has a higher proportion of U/S.

Table 3 gives the quality distributions for pine and spruce logs according to the Swedish Forestry Statistics for 1994 (National Board of Forestry 1994). The down-grading of the logs from the best quality to fifths is related mainly to the knot distribution in the logs. The difference between U/S and fifths from a knot viewpoint is primarily that the healthy knots can be 15-20 millimetres larger in fifths than the healthy knots in U/S. The maximum number of knots in both classes is equal. Besides this, knots with rot must not occur in U/S, whilst these knots can occur in fifths. The assessment of the logs has been made with the assumption that they will be block-sawn.

4.2 Distribution of knot types and their nature, dimensions and accompanying fibre disturbance.

Tables 4 and 5 show the distribution between knot types, their nature and the extent of fibre disturbance in the longitudinal direction of the profiles. For the tangential surface of the triangular profile (a) and its radial surfaces (b, c), the proportion of each type of knot is indicated for each test group with regard to the total number of knot surfaces. For each knot type, the proportions of the total number of knot surfaces having a certain nature is also indicated. The sides of the triangular profile are observed separately, which means that the same knot can appear simultaneously on three sides of the profile and thus be observed as three different knots. Also indicated are the average length of the removals required to remove only knots (L_knot), the average value of the extension of the fibre disturbance in the length direction of the timber on the root side (L_root) and top side (L_top) of the knots, and the removal required to obtain

<table>
<thead>
<tr>
<th>Region</th>
<th>Pine U/S</th>
<th>Pine V</th>
<th>Spruce U/S</th>
<th>Spruce V</th>
<th>Others U/S</th>
<th>Others V</th>
<th>Others</th>
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</thead>
<tbody>
<tr>
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<td>0.28</td>
<td>0.68</td>
<td>0.04</td>
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<td>0.61</td>
<td>0.01</td>
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<td>central Sweden</td>
<td>0.34</td>
<td>0.62</td>
<td>0.04</td>
<td>0.69</td>
<td>0.30</td>
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<td>0.08</td>
<td>0.69</td>
<td>0.27</td>
<td>0.04</td>
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</tr>
</tbody>
</table>

Table 2. Quality of the logs in the investigation.

<table>
<thead>
<tr>
<th>Test group</th>
<th>Quality of log</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 2 3 4 5 6 7 8</td>
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</tr>
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<td>U/S</td>
</tr>
<tr>
<td>pine northern Sweden</td>
<td>V</td>
</tr>
<tr>
<td>pine southern Sweden</td>
<td>V</td>
</tr>
<tr>
<td>spruce central Sweden</td>
<td>U/S</td>
</tr>
<tr>
<td>spruce northern Sweden</td>
<td>U/S</td>
</tr>
<tr>
<td>spruce southern Sweden</td>
<td>V</td>
</tr>
<tr>
<td>spruce southern Sweden</td>
<td>V</td>
</tr>
<tr>
<td>spruce southern Sweden</td>
<td>V</td>
</tr>
</tbody>
</table>

*fast = fast-growing spruce with an average annual ring width greater than 10 mm
Table 4. Knot distribution in pine.

<table>
<thead>
<tr>
<th>Test group</th>
<th>Knot type</th>
<th>Proportion</th>
<th>Number of knots with a certain nature</th>
<th>Knot extension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>a</td>
<td>b,c</td>
<td>a</td>
</tr>
<tr>
<td>central</td>
<td>spike knot</td>
<td>0.15</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>knot cluster</td>
<td>0.06</td>
<td>0.06</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>splay knot</td>
<td>0.10</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>edge knot</td>
<td>0.02</td>
<td>0.24</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>oval knot</td>
<td>0.15</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>pearl knot</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>round knot</td>
<td>0.16</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td>northern</td>
<td>spike knot</td>
<td>0.11</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>knot cluster</td>
<td>0.09</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>splay knot</td>
<td>0.06</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>edge knot</td>
<td>0.03</td>
<td>0.20</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>oval knot</td>
<td>0.03</td>
<td>0.21</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>pearl knot</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>round knot</td>
<td>0.14</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>southern</td>
<td>spike knot</td>
<td>0.09</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>knot cluster</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>splay knot</td>
<td>0.15</td>
<td>0.05</td>
<td>0.02</td>
</tr>
</tbody>
</table>
| 4.3 Yield of boards with healthy knots and knot-free boards. When producing the triangular profiles to boards with a certain knot appearance, consideration must be given to the shape and nature of the knot on all profile surfaces. The location of the cross-cut is determined by the total extension of the knot in the profile volume, with or without taking the fibre disturbance into consideration. Table 6 shows volume yields for both knot-free material and material with healthy knots. Tables 4 and 5 show that a large proportion of the knots in this timber are either loose, dry or contain rot. Few healthy knots can be found. Table 6 shows that there is little difference in volume yield between knot-free material and material with healthy knots. A certain increase in the yield could be expected, however, if the proportion of healthy knots were considered, as shown in Tables 4 and 5. The explanation of why this is not the case is obtained if the whole extension of the knot is observed. Closest to the pith, the knot is often healthy and well grown into the surrounding wood material. Further from the pith, the knot often becomes dry, bark-drawing or damaged by rot as a consequence of the natural pruning. In the triangular profiles, this corresponds to healthy edge knots on the radial surfaces and a dry, loose or bark-drawing round or oval knot on the tangential surface of the profile. The change from healthy to dry knot is often clearly visible on splay knots which are usually healthy closest to the pith but deteriorate towards the sap-wood side. Tables 4
and 5 only take into consideration the nature of the knots on one side of the profile, independently of the appearance on the other sides. This means that we overestimate healthy knots in Tables 4 and 5 when we wish to produce boards with healthy knots on all sides. The yields produced in Table 6 take into consideration the nature of the knots on all sides in the determination of the length of the removed section, so that there is only a small difference in volume yield between knot-free boards and boards with healthy knots.

When the knots are removed, a wide spectrum of boards of different lengths is obtained. Figures 2 and 3 show the cumulative volume distribution for the knot-free lengths. Figure 2 shows the distribution for knot-free material where the fibre disturbance around the knot has not been removed. Figure 3 shows the corresponding distribution without fibre disturbance. Figures 2 and 3 show that pine has a larger volume proportion of knot-free boards over a given length of the corresponding boards than spruce. As an example, the proportion by volume (with regard to the original triangular profile volume) of the knot-free pine material without fibre disturbance from central Sweden and shorter than 25 centimetres is 0.10. The corresponding proportion for spruce

Table 5. Knot distribution in spruce.

<table>
<thead>
<tr>
<th>Test group</th>
<th>Proportion</th>
<th>Number of knots with a certain nature</th>
<th>Knot extension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b,c</td>
<td>a</td>
</tr>
<tr>
<td>central</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>spike knot</td>
<td>0.08</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>knot cluster</td>
<td>0.11</td>
<td>0.16</td>
<td>0.05</td>
</tr>
<tr>
<td>splay knot</td>
<td>0.06</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>edge knot</td>
<td>0.04</td>
<td>0.13</td>
<td>0.01</td>
</tr>
<tr>
<td>oval knot</td>
<td>0.01</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>pearl knot</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>round knot</td>
<td>0.19</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>northern</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>spike knot</td>
<td>0.08</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>knot cluster</td>
<td>0.15</td>
<td>0.20</td>
<td>0.03</td>
</tr>
<tr>
<td>splay knot</td>
<td>0.08</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>edge knot</td>
<td>0.05</td>
<td>0.13</td>
<td>0.01</td>
</tr>
<tr>
<td>oval knot</td>
<td>0.03</td>
<td>0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>pearl knot</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>round knot</td>
<td>0.12</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>southern</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sweden</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>spike knot</td>
<td>0.12</td>
<td>0.18</td>
<td>0.03</td>
</tr>
<tr>
<td>knot cluster</td>
<td>0.12</td>
<td>0.18</td>
<td>0.03</td>
</tr>
<tr>
<td>splay knot</td>
<td>0.12</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>edge knot</td>
<td>0.12</td>
<td>0.12</td>
<td>0.02</td>
</tr>
<tr>
<td>oval knot</td>
<td>0.03</td>
<td>0.13</td>
<td>0.01</td>
</tr>
<tr>
<td>pearl knot</td>
<td>0.22</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>round knot</td>
<td>0.18</td>
<td>0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

*fast = fast-growing spruce with an average annual ring width greater than 10 mm
from central Sweden is 0.20. Further, the proportion by volume of knot-free boards of pine with a length greater than 200 centimetres is 0.27, but only 0.02 for spruce. For the same species, however, there is no clear difference in length distribution for the knot-free boards between the different regions. It may seem natural to assume that the proportion by volume of knot-free boards will increase with increasing growth rate of the tree because of an increasing distance between the branch whorl. For spruce, this does not seem to be correct since the yield for fast-growing spruce from southern Sweden is of the same magnitude as that for spruce from northern Sweden, Table 6.

The investigation has been carried out with only one dimension of triangular profile, a 120 millimetre side. The dimension of the profile will probably influence both the nature and frequency of knots in the surfaces of the profiles. The dimension investigated here is the largest which is now sawn and it is improbable that any considerably larger dimension will be sawn. Compared with profiles with a side of 120 millimetres, smaller profiles will show a higher proportion of loose and dry knots. This is a consequence of the fact that these profiles will be sawn further from the pith, i.e. the smallest distance between the pith and the profile will increase if the same log diameter is used for the different sawing patterns. On the other hand, the consequence of a smaller profile dimension may be that the distance between the knots increases because it is less probable that a small dimension goes through a branch whorl than it is for a larger dimension. This must be investigated more closely, however.

5. Conclusions

Triangular profiles produced with the star-sawing method have vertical annual rings and are free from juvenile wood. This means that the timber becomes straighter and flatter, has considerably more uniform dimensions and has a more predictable movement as a result of moisture variation. From a knot point of view, the triangular profile has the advantage compared with conventionally sawn timber that there can be no completely hidden knots in the profile which will appear at a later refinement stage. A knot in a triangular profile will always be visible on one of the three sides of the profile. The two radial surfaces of the profile can, however, contain splay knots which are unacceptable from a strength and aesthetic viewpoint. Judging from these results, it seems evident that triangular profiles of pine and spruce from butt logs constitute a good starting material for the manufacture of knot-free boards with very good properties, which in a later refinement step can either be joined into greater lengths or be used directly in manufacture.

Table 6. Volume yields for boards of triangular profiles.

<table>
<thead>
<tr>
<th>Test group</th>
<th>Share of total profile volume</th>
<th>Knot-free boards with fibre disturbance</th>
<th>Boards with healthy knots and without fibre disturbance</th>
<th>Knot-free boards without fibre disturbance</th>
<th>Boards with healthy knots without fibre disturbance</th>
</tr>
</thead>
<tbody>
<tr>
<td>pine central Sweden</td>
<td>0.90</td>
<td>0.90</td>
<td>0.85</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>pine northern Sweden</td>
<td>0.92</td>
<td>0.93</td>
<td>0.89</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>pine southern Sweden</td>
<td>0.94</td>
<td>0.95</td>
<td>0.89</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>spruce central Sweden</td>
<td>0.84</td>
<td>0.84</td>
<td>0.79</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>spruce northern Sweden</td>
<td>0.74</td>
<td>0.74</td>
<td>0.69</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>spruce southern Sweden fast*</td>
<td>0.74</td>
<td>0.74</td>
<td>0.69</td>
<td>0.69</td>
<td></td>
</tr>
<tr>
<td>spruce southern Sweden</td>
<td>0.83</td>
<td>0.83</td>
<td>0.77</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>average pine</td>
<td>0.92</td>
<td>0.92</td>
<td>0.87</td>
<td>0.88</td>
<td></td>
</tr>
<tr>
<td>average spruce</td>
<td>0.79</td>
<td>0.79</td>
<td>0.73</td>
<td>0.74</td>
<td></td>
</tr>
</tbody>
</table>

*fast = fast-growing spruce with an average annual ring width greater than 10 mm
Figure 2. Cumulative volume distribution of knot-free boards with fibre disturbances from knots.

Figure 3. Cumulative volume distribution of knot-free boards without fibre disturbances from knots.
References.


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Radially sawn timber.
The influence of annual ring orientation on crack formation and deformation in water soaked pine (Pinus silvestris L) and spruce (Picea abies Karst) timber

D. Sandberg
Summary

This work describes deformation and crack formation in sawn timber of pine and spruce after first drying and subsequent cycles of resoaking in water and drying. The influence of annual ring orientation and the occurrence of juvenile wood was determined. In addition, the influence of compression wood, annual ring orientation at the edges of the cross section, the position of the board surface in relation to the pith, and the condition of the board surface i.e. whether wet or dry during resoaking were studied.

When timber is exposed to repeated cycles of wetting and drying, warp, viz spring, bow, twist and cup, increases and is greater after the first cycle. The influence of annual ring orientation on spring, bow and twist depends on the type of deformation and on the kind of wood. Generally, the results indicated that timber with vertical and semi (half) vertical annual rings show less deformation (mean values) than plain sawn timber and timber containing pith. Cup is mainly caused by transverse anisotropy and is strongly influenced by the radius of the annual ring. Therefore, timber with vertical annual rings do not show any cup. Spring, twist and, especially bow are strongly influenced by compression wood. Large amounts of compression wood in sawn timber increases such deformation.

The distance between sawn timber in the log and the pith with surrounding juvenile wood is of vital significance for cracking. During moisture cycling, the amount of boards that develop cracks increased irrespective of their prior location in the cross section of the stem. Timber sawn from near the pith or distinctly containing pith has a higher relative crack length compared to timber sawn away from and lacking pith. In timber exposed to repeated cycles of wetting and drying the crack length increases irrespective of its prior location in the stem.

1. Introduction

Cracks and major distortion can make timber unusable for some applications. Various kinds of deformation in sawn timber, usually referred to as warp, can be a consequence of primary stresses in the log, so-called growth stresses, or they may arise during processing, especially when drying timber. If these stresses, which are a consequence of shrinkage, become greater than the fracture strength of the wood material, cracks will develop in the timber.

The anisotropic, hygroscopic and non-homogeneous nature of wood creates feasible conditions for warp. The most troublesome characteristic of wood in structural applications and furniture manufacture, is its hygroscopicity. During the late 1950’s Armstrong and Kingston (1960) observed that when small wood samples are subjected to flexural load and exposed to cyclic humidity variations, the deformation increased dramatically compared to when constant climatic conditions were used. Similarly recovery after unloading was accelerated by varying humidity. This phenomenon is usually referred to as mechanosorption.

The influence of juvenile wood on warp has been investigated by several researchers, including Hallock (1965), Balodis (1972), Danborg (1990) and Perstorper et al. (1995). Their results show that occurrence of juvenile wood normally increases warp in softwood.

Timber with vertical annual rings, i.e. radially sawn timber, undergoes no, or very small changes in shape because the sides of the timber are parallel to the main directions of the wood.

A new method of sawing, Stara-sawing, to produce industrial pith-free timber with vertical annual rings and without juvenile wood has been proposed (Sandberg 1996a). It has been shown that timber produced with this method is less subjected to cracking, especially when the timber is exposed to moisture variation, than timber produced with traditional sawing methods (Sandberg 1996b).

The objectives of this work was to study the influence of annual ring orientation, pith and juvenile wood on warp and to investigate macroscopic cracks induced in timber exposed to moisture changes.
2. Material and method

2.1 Log selection and sawing

Six butt logs of Scots pine (Pinus silvestris L.) and seven of Norway spruce (Picea abies Karst.) were randomly selected from a local sawmill in northern Sweden. The logs were oversized which in this case means that the top diameter exceeded 35 centimeters. Only timber of U/S (the best quality) and fifth quality (V) was included in the study. The down grading of the timber from U/S to quality (V) is mainly due to knot distribution in the log. The logs were presumed to be representative for oversized logs in this region. Before sawing, the cross section of each log was coloured in an area with a radius of 30 millimeters around the pith. This coloured area was later used to detect the distance from the pith for each board, and was chosen as a borderline between juvenile and mature wood as far as slowly grown wood from northern Sweden is concerned.

To obtain boards with different annual ring orientations and different distances from the pith, the logs were sawn according to both “through-and-through” sawing and “star-sawing”. Triangular profiles were not included in this investigation. To avoid one annual ring orientation being sawn from only one, or only a few logs, half of each log was sawn through-and-through and the other half in the Star-sawing pattern, (Figure 1). The boards were kiln dried using a conventional drying program to a moisture content of 18±3 %. All the boards were sawn with a cross section dimension of 50 by 100 mm.

2.2 Density and moisture content determination

When the test was finished, three two-centimeter-long cross sections were cut from each board, one at each end and one in the middle of the board. These specimens were used to determine the density and the moisture content. The specimens were free from knots and wood near knots, but compression wood may be present in some specimens. The moisture content was defined as the ratio: of the mass of water in the specimen to the dry weight of the specimen.

2.3 Wetting cycles

The boards were exposed to three cycles, lasting 20 days and nights, of wetting and drying. Before the first wetting, the weight of the boards was determined. In the wetting phase the boards floated freely for 30 minutes in a tray with water. Then, before being weighed, the boards were placed in a frame for 15 minutes with the wet side up to let free water on the surface penetrate into the wood or evaporate. Thereafter, the boards were dried

Figure 1. The sawing pattern used in the investigation. Half the log was sawn through-and-through and the other half using a star-sawing pattern.

Figure 2. Definition and measuring of warp: crook (a), twist (b), bow (c), and cup (d).
for 20 days and nights at a temperature of 21±1°C and 39±5 % RH. The same surface was soaked in each wetting phase. Before the test was started the boards were conditioned for two weeks at the same climate as mentioned above.

2.4 Warp measurement

Warp was measured after every drying cycle. Cup was measured at five locations along the length of the board: five cm from each end of the board and at three equidistant locations between these two end measuring points. Crook, bow and twist values were measured over the entire length of the board and the values were later reduced to equal lengths of three metres according to Mörén (1987). Figure 2 illustrates the principles for measuring warp used in this investigation.

For analysis, the boards were divided into four groups according to the annual ring orientation in the cross section. The first group contains boards in which pith was enclosed in the cross section, in the whole or in a part of the total length of the board. The other three groups contained boards with horizontal, semi-vertical and vertical annual rings. Figure 3 illustrates examples of timber with different annual ring orientations. Vertical annual rings exist in the cross section when the angle between a tangent to an annual ring at half of the thickness of the board and the face side is between 60 and 90 degrees (Sandberg 1995), (Figure 4). Similarly, boards with horizontal annual rings exist when the same angle was between 0 and 30 degrees. When the angle was between 30 and 60 degrees the boards are said to have semi-vertical annual rings.

2.5 Determination of compression wood

Compression wood has a much greater longitudinal shrinkage than normal wood (Timell 1986). This will cause more warp in boards containing a greater proportion of compression wood. A common complication is how to determine the proportion of compression wood and how to find a fast and reliable measure. One of the best measures of compression wood is through the combination of volume proportion and location of compression wood in the board. Such methods are however very timeconsuming. It is more convenient to select parts of the board where the occurrence of compression wood may be determined. In doing so, it is important to select samples which are representative of the board. When warp is investigated, it is also important to avoid small local areas of compression wood, for example around knots, that may be of minor importance for the global deformation of the board. It should, however, be noted that shrinkage of knotted wood and by wood surrounding knots may to a large extent influence the total warp of the board. In this investigation, the specimens used to determine the density have also been used to detect the presence of compression wood.

The boards were classified into four classes, C0 - C3, with respect to the occurrence of compression wood in three cross sections cut from each board. Class C0 has no compression wood in the cross sections; class C1 has visible compression wood in one of the three cross sections; class C2 in two and class C3 in all three cross sections.
As mentioned earlier, the specimens were cut free of knots and local compression wood areas beneath knots were avoided as far as possible.

2.6 Crack measurement
The total length of visible cracks on each surface of the boards was determined after the described conditioning period and after the last wetting cycle.

2.7 Statistical methods
A common complication when analysing experimental results in wood is that the values do not have a normal distribution. Söderström (1990) has shown that the assumption of normal distribution when analysing lengths and areas of cracks is poor. The results of the present investigation have also indicated that warp is not normally distributed. For this reason, a non parametric test was used when the results for the test groups were evaluated as mean values (Montgomery 1991). In this statistical method, normally distributed test parameters are not necessary. The tendency of a test group (boards with different annual ring orientations and distances from the pith) to show a special property (warp or cracking) was tested using a homogenity test (Blom 1991). Unless otherwise mentioned, a confidence interval of 0.95 has been used in all the tests.

3. Results and discussion

3.1 Density
Table 1 shows the mean values for dry density of the boards and the density separated into mean values for root, middle and top parts of the boards. The density values are quite normal for butt logs from northern Sweden. It should be noted however that the density of pine is the least at top end and increases towards the butt end of the log. In spruce this density difference is negligible.

Normally, compression wood has a higher density than normal wood (Timell 1986). When specimens of compression wood were excluded from the samples of normal wood, no difference in the density values occurred. This fact suggests that the fraction of compression wood in the specimens was relatively low. Therefore the influence of compression wood with its higher density was slight.

3.2 Moisture cycling
Figure 5 shows the mean values of the moisture content variation in the boards during the test. The moisture content was determined for three cross sections after the last wetting cycle. It is assumed that the mean value of the moisture content for these three cross sections was equal to the mean value of the moisture content of the board. The moisture content was then determined before and after each wetting phase.

As shown in Figure 5, the moisture content during the wetting phases increases only a few percent. It should be noted that the variation in moisture content in those parts of the boards which in contact with water was much higher.

Table 1. Density (Kg/m3) of boards in the investigation. Root, middle and top reflects the location of the specimens in the board. The mean value of these three measurements is also given.

<table>
<thead>
<tr>
<th></th>
<th>Root</th>
<th>Middle</th>
<th>Top</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine</td>
<td>476</td>
<td>422</td>
<td>389</td>
<td>426</td>
</tr>
<tr>
<td>Spruce</td>
<td>353</td>
<td>350</td>
<td>351</td>
<td>351</td>
</tr>
</tbody>
</table>

Figure 5. Variation of moisture content in the boards during the test.
3.3 Influence of annual ring orientation and wetting on warp

Figure 6 shows the measurements of warp such as crook, bow, twist and cup for the boards during three cycles of wetting and drying. According to the annual ring orientation in the cross section, the boards are divided into four groups. Group A has the pith enclosed in the cross section in all of, or in a part of, the length of the board. Groups B, C and D correspond to the horizontal, semi-vertical and vertical annual rings, respectively. Diagrams in Figure 6 have four bars for each group. The first bar represents the warp before the wetting cycle, while the second to fourth bars correspond to warp after one to three cycles of wetting and drying.

3.3.1 Crook

In both pine and spruce except for spruce group A, crook increases for each cycle of wetting and drying, independent of the annual ring orientation. Crook for pine with vertical annual rings (group

Figure 6. The influence of annual ring orientation (A-D) on warp in boards of pine and spruce during three cycles of wetting and drying. The first bar reflects warp before wetting, the second bar warp after the first cycle etc. A - pith enclosed in the cross section, B - horizontal annual rings, C - semi-vertical annual rings, D - vertical annual rings.
D) seems to be lower than for the other groups, but this difference is not significant. Due to great scattering of the crook values, no significant differences were found between groups A to D. The relatively low crook for spruce in group A may reflect the high number of cracks in these boards (see section 3.5).

In both pine and spruce, no correlation was found between the distance from the pith and the crook. This was expected, as no consideration was given on how the edges of the boards were oriented in relation to the pith. In spruce, boards with crook (measured as shown in Figure 2) on the edge oriented towards the pith demonstrated significantly more crook than boards where the crook was oriented in other directions. This indicates that juvenile wood has an influence on warp. The greater crook for pith-associated boards is consistent with several studies, for example Kloot and Page (1959) and Perstorper et al. (1995).

### 3.3.2 Bow

Independent of the annual ring orientation of the boards, bow increased in both pine and spruce during moisture cycling. Before the first cycle of wetting and drying no difference in bow between the groups in pine was found. When the boards were resoaked, bow for the boards with vertical and semi-vertical annual rings (groups C and D) was significantly lower than those with horizontal annual rings and pith. Spruce did not show any significant differences between groups A to D. When both pine and spruce are considered, the only difference was found in group D, where spruce has significantly more bow than pine.

When the boards were resoaked in each cycle, the same face was in contact with water. The influence of resoaking on bow is illustrated in Figure 7. Before resoaking, the bow was at the same size as for the wetted and the non-wetted face, for both pine and spruce. During the wetting cycles the behaviour of the boards was completely different for pine and spruce. Pin demonstrates a slight increase of bow, regardless if it occurs on the wetted surface or not. There was no significant difference in bow between the boards as far as the wetted and the non-wetted face was concerned. In spruce, the boards with bow on the wetted face showed an increase of bow during moisture cycling. On the other hand the boards with a non-wetted face showed a decrease of bow. This means that the deformation measured as bow always increased on the wetted face.

### 3.3.3 Twist

In the same way as for crook and bow, twist increases when the boards are exposed to cycles of wetting and drying. The increase in twist was greatest for boards in group A, which may be considered natural as these boards contain pith. The level of twist was expected to be greater for boards in group A compared to groups B-D. The relative low twist in the boards belonging to group A may be a consequence of a higher number of cracks (see section 3.5) in these boards. Several researchers (e.g. Mishiro and Booker 1988; Perstorper et al. 1995) found that twist was more pronounced in boards taken near the pith than in others.
boards sawn distant from the pith. This study, however, shows no significant differences between twist in groups A-D or between pine and spruce.

### 3.3.4 Cup

Cup was measured at five locations in each board. Here, the greatest of these five measurements was used to measure cup. Since the width of the boards was 100 mm, the cup was small and only a couple of mm. The change of cup during moisture variations was even smaller and was hard to detect with the measurement accuracy used.

As shown in Figure 6, cup was highest for boards in groups A and B as a consequence of the anisotropic nature of the wood material and the curvature radius of the annual rings. Thus boards with horizontal annual rings sawn near the pith usually have more cup than boards with the same annual ring orientation sawn at the periphery of the log.

Pine with vertical annual rings also showed cup. That may be explained by the annual ring orientation at the butt end of some of the boards which was not vertical due to buttress. When the maximal value were used for cup, the cup at the butt end will represent the board.

### 3.4 Influence of compression wood on warp

In Figure 8 crook, bow and twist are shown for the four different levels (C0-C3) determined for compression wood. In pine the number of boards in levels C1-C3 was low (3-4 boards), which means that too far-reaching conclusions should not be drawn for a separate level.

The effect of compression wood on bow was more pronounced...
than on crook and twist (see Figure 8). For both pine and spruce, boards with compression wood (levels C1-C3 as one test group) have significantly more bow than boards without compression wood. A significant difference regarding crook and twist was found in spruce, where the amount of crook and twist in level C3 were higher than in the other groups.

### 3.5 Cracks

The results from crack measuring are presented as the relative crack length, and the ratio between the total length of the cracks and the length of the board for both pine and spruce.

The boards are divided into four groups with regard to annual ring orientation and the distance between the pith and boards. The four groups are:

- **A** Boards with pith enclosed in the cross section in all of, or in the part of the length. This group includes the same boards as in group A, previously described in section 3.3.
- **E** Boards sawn at a distance less than 30 mm between the pith and any part of the board. In this group the annual ring orientation varied from 0 to 90 degrees. Boards in group A are not included in this group.
- **F** Boards sawn at a distance greater than 30 mm between the pith and any part of the board. The annual ring orientation in the boards from this group was between 0 and 60 degrees.
- **G** Boards sawn at a distance greater than 30 mm between the pith and any part of the board. The boards in this group have vertical annual rings, i.e. 60 to 90 degrees.

#### 3.5.1 Presence of cracks and relative crack length in the boards

Figure 9 shows the relative length of cracks before and after the wetting cycles. The influence of pith and juvenile wood on crack length in the boards is obvious. Boards sawn at a distance greater than 30 mm from the pith (groups F and G) have significantly lower crack lengths than boards sawn nearer the pith. This applies to both pine and spruce.

Between groups A and E, and groups F and G, there is no significant difference regarding crack length. Between pine and spruce, differences regarding crack length was significant only for group F.

A shown in Figure 10, the proportion of boards without cracks relative to the total number of
boards in each group is higher for spruce than for pine. This was probably due to the higher density of pine.

Pine has a greater tendency to form new cracks than spruce when the boards are exposed to cycles of wetting and drying. After the wetting cycles, spruce has almost the same proportion of boards without cracks as it had before, (see Figure 10). It should be noted that none of the boards with the pith enclosed in the cross section have been dried without cracks, (see group A in figure 10). Furthermore, the amount of boards with cracks was 3-4 times greater in boards sawn near the pith (group E) than in boards sawn away from the pith (groups F and G).

### 3.5.2 The influence of pith on crack formation

The previous analysis of cracks was based on a board as a unit. Here each surface will be examined separately. Figure 11 shows the crack length for pith surfaces versus non-pith surfaces and the changes regarding crack length during the wetting cycles. The pith surface means that the surface (or surfaces) of the board was oriented towards the pith. The boards in group A are excluded in the analysis as these boards do not have pith surfaces. In both pine and spruce, where boards from groups E, F and G have been analysed as one group, the pith surfaces show crack lengths that are significantly higher compared to other surfaces. This applies both before and after the wetting cycles. Homogeneity tests show that pith surfaces tend to crack to a larger extent than other surfaces. It should be noted that the development of cracks on the bark surface in boards with horizontal annual rings during drying is common, especially when the annual ring curvature are small, i.e. the boards are sawn near the pith.

When the crack lengths of each group (E-G) are analysed separately, the variation makes it difficult to draw any distinct conclusions. However, spruce in group E had significantly higher crack lengths on the pith surfaces, both before and after wetting, (see Figure 11). The increase of crack

![Figure 10](image-url)
length during wetting was also higher on the pith surfaces. Pine did not show these results. This may be a result of the trend for pine to crack more easily than spruce, and that the cracks initiated on the pith surfaces in pine develop into the adjoining surfaces, especially when the pith is located close to the edge between two surfaces.

Spruce boards sawn at a distance greater than 30 mm from the pith (groups F and G) did not show any difference in crack length between the surfaces. Pine in group F, on the other hand, had a pith surface with greater crack length before the wetting cycles, and in group G both before and after the wetting cycles. The development of cracks in pine, group F, also indicates that cracks initiated on the pith surfaces may propagate to other surfaces during the wetting cycles.

The distinct difference in crack length on spruce pith surfaces between boards sawn at a distance of less and greater than 30 mm from the pith indicates that the pith with the surrounding juvenile wood has a great influence on the proportion of cracks in sawn timber.

In pine, the influence of pith and juvenile wood on the proportion of cracks ranges over a greater distance from the pith compared to spruce. Thus, in pine, the difference in crack length between boards sawn at a distance greater, or less than 30 mm from the pith, is not as clear as in spruce.

Figure 11. Crack length for pith surfaces contra non-pith surfaces. The boards are divided into three groups (E, F, G) according to annual ring orientation and the distance between the pith and the board.
3.5.3 Influence of other factors on crack propagation

The influence of the annual ring orientation on crack formation was also investigated on both wet and non-wetted surfaces. Crack formation in the boards was not dependent on annual ring orientation.

For pine and spruce the mean value of moisture content at the end of each wetting cycle was lower than that at the beginning of the test, (see Figure 5). Decrease of the moisture content may result in an increase of cracks in the boards when compared to a constant moisture content at the end of each cycle.

4. Conclusions

The results show that if boards are sawn radially from the log, without pith and juvenile wood, properties are obtained which are better than those of conventionally sawn timber.

Warp in terms of crook, bow, twist and cup as well as number of cracks in sawn timber from both pine and spruce increase when timber is exposed to repeated cycles of wetting and drying. Warp increases in each wetting cycle. The greatest increase occurs after the first cycle.

The influence of annual ring orientation on warp, except for cup, was not clear. Generally, the boards with semi-vertical and vertical annual rings have lower mean values for warp than boards with horizontal annual rings and boards with the pith enclosed. As a consequence of the great variation in warp, it was difficult to detect any significant (confidence 0.95) differences between boards with different annual ring orientations. Where differences in warp were found, the warp was significantly lower in boards with semi-vertical and vertical annual rings.

Cup is greatly influenced by the curvature radius of the annual rings as a consequence of the anisotropic nature of wood. This means that boards with horizontal annual rings, sawn near the pith, have the greatest cup. Consequently, boards with vertical annual rings show no cup.

Compression wood has the greatest influence on the increase of warp. Bow is more sensitive to compression wood than crook and twist.

This study, however, demonstrates that the number of cracks in boards was clearly related to the juvenile wood and the distance from the pith in sawn timber. The number of boards with cracks was 3 to 4 times greater in timber sawn near the pith, that is when the distance between the board and the pith was less than 30 mm, compared to timber sawn further away from the pith. When the boards were exposed to wetting and drying cycles, the number of boards with cracks increased in both pine and spruce. The relative crack length in boards sawn near the pith was greater than in boards sawn away from the pith. During wetting and drying, the crack lengths increase regardless of the location of the board in relation to the pith.

When the four surfaces of the board were examined separately the results show that pith surfaces have greater relative crack lengths and a greater tendency to crack than the other surfaces, especially when the boards are sawn near the pith.
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Chapter IV

Radially sawn timber. Gluing of star-sawn triangular profiles into form-stable products with vertical annual rings

D. Sandberg, H. Holmberg
Summary
A method is presented for the gluing of star-sawn triangular profiles of pine (Pinus silvestris L) into form-stable wood products with vertical annual rings. The triangular profiles are free from pith and from most of the juvenile wood.

The method is based on dried and conditioned triangular profiles. Undesired defects are removed and the wood is finger-jointed into long lengths. In the finger-jointing, consideration is given to the appearance and annual ring orientation of the joined materials. After the joining, the triangular profiles are planed and glued into rectangular blocks with vertical annual rings. These blocks can then e.g. be used as construction beams or be divided into solid wood panels.

A pilot plant has been built for the manufacture of knot-free solid wood panels based on the proposed method. Results show a total volume yield of 53.8%. Three critical production stages can be distinguished: removal of knots and defects, planing, and division of blocks into boards. These three operations are together responsible for more than 93% of the total losses in the manufacture.

The removal of knots and defects meant a volume loss of 12.8%. 13% of the manufactured units were 2.1 m long without finger-jointing and free from knots and defects. The average length of the remaining pieces used for finger-jointed units was 0.41 m.

1 Introduction
The function and properties of wood products are greatly influenced by the natural properties of the wood and how these are used in the product concerned. There are four main conditions which are characteristic of wood. It is an anisotropic and heterogeneous material, a material with great variability and a material with pronounced hygroscopicity. All this is related to the fact that the wood material is built up in an optimum way to meet the specific requirements of the living tree.

When the log is divided into planks and boards to be used in different products, complications can arise if one does not use the available knowledge. By starting from an understanding of the properties of the wood material, it is in many cases possible to manufacture a product which meets the specific demands of different uses.

For timber, such requirements are often related to accuracy in measurements and geometry, crack-freeness and controlled movement during moisture changes. Changes in the moisture content below the fibre saturation point cause changes in shape and dimensions. The wood swells and shrinks, and this takes place mainly across the fibre direction.

However, the longitudinal moisture movement of the wood can be considerable in reaction wood, juvenile wood, and in areas with severe fibre disturbances. For pine and spruce, it is usually assumed that the tangential movement is approximately twice as large as the radial movement. This means that changes in shape appear as distortions and angular changes in the cross-section if the side surfaces of the timber are not parallel with the main directions of the wood.

The importance of the annual ring orientation for moisture movement of furniture boards has been investigated by several researchers, e.g. Peck and Selbo (1950), Selbo (1952), Perry (1953), Marian and Suchland (1955). They state that in order to obtain a dimensionally stable furniture board, it shall be constructed of timber with vertical annual rings, i.e. the annual rings shall be largely perpendicular to the surface of the timber.

Sandberg (1996a, 1997) has shown that for pine and spruce, there is a clear connection between the occurrence of cracks in timber from butt logs and the distance from the pith from which this timber has been sawn. Timber containing pith, and wood without pith where the shortest distance between the pith and the timber is less than 30 mm, have considerably more cracks than timber sawn at a greater distance from the pith.
Star-sawing is a sawing method for the production of timber with vertical annual rings which is free from pith and most of the juvenile wood (Sandberg 1996b), (Figure 1). The yield from star-sawing consists of timber with both rectangular and triangular cross-sections, all with vertical annual rings. In star-sawing, as in all radial sawing methods, the radial sawkerfs cleave the knots in the length direction and a greater proportion of so-called splay knots is obtained than in through-and-through sawing and block-sawing. These knots are often unacceptable aesthetically and from a strength viewpoint, and they must be removed. Sandberg and Holmberg (1996) have mapped the knot appearance and knot frequency in star-sawn triangular profiles of pine and spruce.

In the present investigation, a method is presented for gluing together star-sawn triangular profiles into form-stable products with vertical annual rings and radial surfaces.

Figure 1. Star-sawing, sawing pattern for producing timber with vertical annual rings.
2 Principles for gluing triangular profiles into a block with a rectangular cross-section

The further refining of the triangular profiles takes place in five main steps:
1. Removal of unacceptable knots and defects.
2. Finger-jointing of clear pieces.
3. Planing of triangular profiles.
4. Gluing of triangular profiles into blocks.
5. Further treatment of blocks through planing and sanding, or division of the blocks into boards or other components.

2.1 Removal of defects

Depending on what final product is to be produced, the extent of defects, e.g. knots, pitch pockets, reaction wood, allowed in the product will vary.

A large proportion of the knots found in a star-sawn triangular profile, primarily from butt logs, have proved to be less suitable for further refinement of the wood and must be removed (Sandberg and Holmberg 1996). A great advantage of a triangular profile over conventionally sawn timber when knots are to be removed, is that the knots in the triangular profile are always visible on at least one of the surfaces. This means that, after the knots which are visible on the surface have been removed, no knots remain hidden in the profile to appear in subsequent operations.

Fibre disturbances around knots reduce the strength and can cause pick-up when finger-jointing and planing. In the manufacture of e.g. high-quality furniture, fibre disturbances can be troublesome because they locally give different moisture movements, and can lead to undesirable visual changes in the surface. For certain applications, it can therefore be advantageous to remove the surrounding fibre disturbance together with the knots.

2.2 Finger-jointing to obtain long lengths

Finger-jointing of a triangular profile is in principle carried out with the same methods as are used in the finger-jointing of conventional timber. Certain modifications of the equipment are necessary to adapt e.g. transport and holding devices to the triangular shape of the timber. Different finger lengths are used in the finger-joint depending on whether the joined timber is to be used for construction purposes or in applications where the strength of the join does not have high priority. The timber can either be joined continuously and then cut into desired lengths or joined directly into predetermined length modules. In each join one of the joined pieces shall be displaced half the division of the fingers to avoid displacement in the join which in subsequent treatment operations can cause volume losses.

In the finger-jointing, one should try as far as possible to keep together the timber sections cut from the same triangular profile to obtain a homogeneous annual ring structure (pattern fitting) across the finger-joint. In order also to minimize stresses which arise in the join because of different swelling and shrinking movements in the different directions of the timber, the annual ring orientation shall coincide in the joined pieces (Sandberg 1996c). Figure 2 shows examples of a finger-joint where two pieces from the timber wood section have been joined after an intervening knot has been removed. In general, it is more favourable to have radial surfaces than tangential surfaces when pattern fitting is desired between the joined pieces.

The finger-joint can be oriented in two different directions in relation to the annual ring orientation.
in the cross-section of the triangular profile: parallel to the tangential surface of the triangular profile or parallel to one of its radial surfaces, Figure 3. In principle, the orientation of the join can be chosen arbitrarily if this is proven to be advantageous from a technical or aesthetic point of view. This is not discussed in greater detail here, however.

In joining tests, it has been found advantageous to orient the finger-joint parallel with the surface which in subsequent treatment steps is to be glued into the construction, Figure 3a. This is, on the one hand, because errors develop in the surface in the transition between the joined wood pieces and, on the other hand, because the join can become wave-shaped in the surface because a lack of full parallelism between the direction of the fingers and the surface leads to an uneven pressing pressure, Figure 4.

The orientation of the finger-joint parallel to the surface in the triangular profile which will later be glued into the block means that the characteristic zigzag pattern of finger-joints becomes visible on the surfaces of the block, Figure 5.

2.3 Planing of triangular profiles

The finger-jointed triangular profiles are planed on all sides. In order to facilitate the subsequent pressing of the profiles into blocks and to determine the height of the glued block, one of the edges of the profile is also planed off. The triangular profile is oriented before the planing so that the surface obtained when the edge is removed can be used to achieve the correct annual ring orientation in the glued block.
2.4. Gluing of triangular profiles into blocks with a rectangular cross-section

After the planing, glue is applied to two of the four surfaces of the triangular profile and the profiles are placed together into a block with the same annual ring orientation, Figure 6. The tangential surfaces of the triangular profiles are glued into the block.

2.4.1 The choice of glue and the design of the glue-line

The choice of glue is, in the first place, dependent on the function of the final product and on the environment in which it will be used. In supporting building constructions, high demands are made on the strength and permanence of the glue-line. In these contexts, resorcinol-formaldehyde-based glues are often used. In the gluing of components for indoor use, where the loads on the glue-line are considerably less than in building constructions, PVAc-glue can be used. Depending on the production rate required in the gluing, a suitable method of curing for the glue must be chosen, e.g. pre-heating of the glue surfaces or high-frequency curing.

A further aspect regarding the choice of glue is whether or not the glue shall give a coloured joint. With a colourless glue, an almost invisible glue-line is obtained. With a coloured glue, visible glue-line are obtained. This can be used to create aesthetically attractive patterns in the glued products.

Because of the shape of the triangular profiles, the glue-line forms an angle towards the side surfaces of the glued block, Figure 6, which means that the glue surface becomes larger than if the glue-line were perpendicular to the surface. The larger glue surface means that the stress on the glue-line is reduced.

2.5 Treatment of blocks and repair of pitch pockets

The glued blocks can after gluing be either directly planed and sanded or split into sheets or boards. Pitch pockets can be very troublesome, especially in furniture and furnishings. In contrast to knots, pitch pockets can be concealed inside the triangular profile without being visible on any of its surfaces. This can mean that the pitch pockets in subsequent treatment become visible, with accompanying trouble. Discarding the product in a late refinement stage involves high costs, and repair is often the most economic solution. The extension of the pitch pocket in the tree means that in the radial surface of the sawn timber, the pitch pocket will appear as an oblong, elliptical cavity, extending between two annual rings (Weslien 1993). Since the main extension of the pitch pocket in the radial wood surface, as opposed to the tangential surface, lies in the length direction of the wood, almost invisible repairs can be carried out. These repairs are also relatively simple and can be made rationally.

2.6 Pilot plant for further refinement of a triangular profile

A pilot plant has been built to remove defects from triangular profiles and for joining, planing and gluing of these profiles into blocks. The aim is to create on a small scale new production technology for the gluing of a triangular profile. Properties of different products manufactured by the proposed method will also be tested.

2.6.1 Design of the pilot plant

The triangular profiles, dried to a moisture content of 8 to 10 per cent, arrive from the sawmill or storage. At the crosscut saw, undesired knots and defects are removed. The defect-free pieces are then joined together continuously to lengths of 2.10 metres in order, as far as possible, to achieve good pattern fitting between the joined pieces. Triangular profiles without defects and which need not be joined to attain a length of two metres are placed aside for the manufacture of products without finger-joints. The smallest length which can be used in finger joining is 80 mm.
The fingers are cut parallel to the tangential surface of the triangular profile. After being pressed together, the joined boards are stored until the glue has hardened.

Planing takes place in a five-spindle universal planer (Weinig 17215, 1960). In order to manage the planing of the triangular profile in one step, the press and feed have been redesigned. One of the edges of the triangular profile is planed in the top cutter. After the planing, glue is placed on two of the four surfaces of the profile and a number of profiles are placed together into a block. In the press used, only rectangular blocks can be pressed, which means that one of the profiles must be cleaved into two halves and be used as side pieces on the block. The manufactured blocks have an area of 2.10 x 0.35 m² and the thickness can be varied between 50 and 100 millimetres, depending on the dimensions of the triangular profiles included.

The pressing of the triangular profiles into blocks differs considerably from the conventional gluing of timber with a rectangular cross-section since a large pressure is required on all of the surfaces of the block. In the prototype press used, active pressure is applied to the edge sides of the block, whilst the thickness is fixed, Figure 7. Because of friction, this means that the pressure is not constant over the width direction of the block. This problem is avoided if an active pressure is applied on all surfaces of the block.

3 Volume yield in the manufacture of a pine solid wood panels from a star-sawn triangular profile

In general, board materials manufactured by gluing together pieces of timber side by side are called solid wood panels. A solid wood panel is usually manufactured from planks which are cleaved in the length direction into lamellae and are planed before being glued together into a board. This method of manufacture gives large volume losses and lamellae are glued together with different annual ring orientation.

In the present study, star-sawn triangular profiles have been used for the manufacture of a knotfree solid wood panel with vertical annual rings. The volume yield has been studied in the manufacture of two grades of material, one with a finger-joint and one without a join.

3.1 Materials and methods

Star-sawn triangular profiles of saw-falling qualities have been used. The timber from which the triangular profiles were sawn came from Jämtland in Sweden and had a top diameter of between 260 and 340 mm (Holmberg and Holmberg 1996). A total of 7.8 m³ triangular...
profiles with side measurements between 60 and 110 mm have been made into solid wood panel blocks.

The wood quality for the triangular profiles used has not been determined, but the quality was estimated by determining the quality of adjacent rectangular boards from the same log. According to Table 1, quality classes S1, S2 and S3 are specially adapted for star-sawn timber, but correspond roughly to the quality classes U/S, V and VI in the Nordic grading regulations for sawn-timber (Timber Grading Committee 1976). A detailed description of the quality classes for star-sawn timber is given by Holmberg and Sandberg (1996).

Measurements have been carried out manually at four different stages in the production:

I. The dimensions of all incoming triangular profiles have been determined with regard to the largest and smallest side and length.

II. After cutting, the cut pieces have been placed continuously together into modules with a length of 2.10 m.

III. Random samples have been taken for the measurement of dimensions before and after planing.

IV. For each finished solid wood panel block, the thickness, width and adjusted length have been determined and also the dimensions of the triangular profiles included.

The glued blocks have not been divided into finished boards in this investigation. Losses in the division of the blocks into boards have been determined on the basis of experience of values for sawkerfs and sanding losses.

### 3.2 Results and discussion

#### 3.2.1 Yield

The yield is shown for each part operation, i.e. the analysis of each operation is based on 100% input material to that operation, Table 2. In the investigation, the length of the jointed boards has varied depending on the number of joints. A large number of joints gives a shorter length than when the number of joints is few. The losses in the final adjustment of the block length have therefore been greater than can be expected in an industrially adapted plant.

The yields of the final production stages, division and sanding, are based on the following

<table>
<thead>
<tr>
<th>Operation</th>
<th>Yield (%)</th>
<th>Proportion of total loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting</td>
<td>87.2</td>
<td>27.7</td>
</tr>
<tr>
<td>Finger jointing</td>
<td>98.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Planing</td>
<td>76.6</td>
<td>43.5</td>
</tr>
<tr>
<td>Gluing of blocks</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>End cutting in blocks</td>
<td>97.4</td>
<td>3.7</td>
</tr>
<tr>
<td>Division, sanding</td>
<td>84.2</td>
<td>22.1</td>
</tr>
<tr>
<td>Total of all operations</td>
<td>53.8</td>
<td>100</td>
</tr>
</tbody>
</table>

1) The yield in the planer is based on the total loss for all planed units, cf. Table 3.
2) The variation in the length of the triangular profiles included in the blocks has been much greater than can be expected in an industrial plant.
3) Yield calculation based on: blocks with a height h≥60 mm give two boards, blocks with h<60 mm give three boards. Sawkerf 3 mm and sanding loss 1 mm per surface.

<table>
<thead>
<tr>
<th>Table 1. Quality distribution for the rectangular boards, (Holmberg and Sandberg 1996).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top diameter interval of the logs</td>
</tr>
<tr>
<td>Q. Quality</td>
</tr>
<tr>
<td>260-340 mm</td>
</tr>
</tbody>
</table>

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assumptions: if the block has a height which is greater than 60 mm, three boards are produced from this block, otherwise only two boards are produced. Each sawcut is assumed to remove 3 mm and the sanding loss is assumed to be 1 mm per board surface, i.e. 2 mm/board. The losses in format cutting of the boards and in edge sanding have not been included in the yield calculations.

As shown in the Table 2, the most demanding steps are the removal of defects, planing, division and sanding of the blocks into finished boards. Altogether, these production steps cover more than 93% of the total loss in the solid wood panel manufacture.

### 3.2.2 Defect removal and joining

In the defect removal stage, all knots with surrounding fibre disturbances, and defects which affect the appearance of the finished board have been removed. This gave a loss of 12.8%.

The length yield in the cutting is shown in Table 3 and Figure 8. Of the total incoming volume, 13% is defect-free and unjoined 2.1 m units. If shorter lengths than 2.1 m are extracted, the volume of material to be joined decreases. This will be natural in practice.

The finger-joining causes a loss which depends on the finger length, in this case 10 mm. In total, the finger cutting has given a loss of 1.7%. This loss can be reduced if shorter fingers are used. The shortest length of the pieces which has been joined is 80 mm.

### 3.2.3 Planing

The yield for the material which has been measured before and after planing is shown in Table 4, with regard to the smallest and largest sides and with regard to their average value. The yield varies between 75 and 84%, which suggests that the dimensional accuracy of the triangular profiles was very poor. If the accuracy can be improved, the yield in the planing will probably be improved.

The planing of the triangular profiles is the operation which gives the greatest volume loss in the solid wood panel manufacture. It is therefore very important that the planing is carried out with as high precision as possible.

| Table 3. Number of joints after knots and other defects have been removed and the average length of the cut pieces. |
|--------------------------------------------------|--------------------------------------------------|
| **Number of joints per metre** | **Average length of pieces per unit** |
| Including unjoined boards | 1.73 | 0.45 |
| Excluding unjoined boards | 1.99 | 0.41 |

| Table 4. Yield (%) in planing based on the different dimensions of the joined pieces before planing. |
|--------------------------------------------------|--------------------------------------------------|
| **Number of units** | **Yield in the planer based on:** |
|                   | **smallest dimension** | **largest dimension** | **average dimension** |
| 138               | 83.7 | 75.0 | 79.2 |

Figure 8. Distribution of the number of joints per 2.1 m length.
Figure 9 shows the yield in the planing for different planing depths. The planing depth is very important for the yield, especially if the triangular profiles are small. The average dimension of the triangular profiles in this investigation was 90 mm and the yield in the planing was 76.6%, as shown in Table 2. This suggests, Figure 9, that the average depth of the planing was more than 3 mm.

In the planing, one of the edges of the triangular profile is also removed, primarily to guarantee a satisfactory gluing of the blocks and to fix the thickness of the block. The cutting of this edge causes no great volume loss. Figure 10 shows the theoretical yield when one of the edges of the planed triangular profile is removed. The loss is 1-2%, which is neutralized by the advantages which are obtained.

The thickness of the block is determined by the heights of the triangular profiles. If the height of the triangular profiles is limited already in the planing, large volume losses can be avoided compared with when the thickness of the block is adjusted on the finished glued block. The theoretical yield is also influenced when the thickness of the block is reduced by "h" mm. This can be achieved on the one hand by planing the edge of the triangular profile, or on the other hand by reducing the thickness of the finished glued block by "h" mm. When the edge of the triangular profile is planed, only 1-2% of the volume is lost. When instead the thickness of the block is reduced, the losses are at least twice this and can in some cases amount to 10% of the volume of the block.

In the drying, the cross-sections of the triangular profiles become deformed slightly so that the edge angles deviate from the angle which they had after sawing, i.e. normally 60°. Angular deviations can also occur as a consequence of incorrect sawing and these errors are often considerably greater than the angular errors arising in the planing. Angular errors mean that the side surfaces of the triangular profiles must be treated further in the planing so that surfaces suitable for gluing are obtained. It can be seen in Figure 11 that this loss is independent of the dimensions of the triangular profile and that large angular errors give considerable volume losses. Angular errors which arise in the drying are of the order of 1°, which according to Figure 11 gives a volume loss of 2%.

3.2.4 Gluing of triangles into blocks, and division of the blocks into boards

In the gluing of the blocks, one of the triangular profiles has been divided lengthwise to be used as sides of the block, so that the cross-section becomes rectangular. The volume loss in this division is less than 1% and has not been included in the account of the volume yield, Table 2.

The losses which arise in the division of the block into boards depend on how many boards are to be extracted from the block, whether the division of the block works out evenly, the thickness of the sawkerfs and the sanding losses. In the present investigation, the blocks have not been divided. From experience, it is known that the sawcut requires 2.5-3.0 mm and that a sanding loss of 1 mm is sufficient to give a fine surface.

Figure 12 shows the volume yield in the division of blocks into 2, 3 or 4 boards. "1 board" means that the block is sanded only on the side surfaces. Division of the blocks and the sanding normally reduce the yield by between 10 and 20% but the losses increase drastically if many boards are sawn from thin blocks.

4 Conclusions

The triangular profiles obtained in star-sawing constitute a high-quality raw material for the manufacture of wood products. Triangular profiles have vertical annual rings and are without pith and most of the juvenile wood. This means that the profiles are stable in shape, but the appearance and nature of the knots are often such that they cannot be accepted
The wood pieces obtained after knots and other defects have been removed are finger-joined into long lengths. By taking the annual ring orientation into consideration in the finger-joining, the stresses which arise when the moisture ratio of the wood changes are minimized. The uniform annual ring orientation in the finger join also facilitates pattern fitting between the joined pieces regarding the structure of the wood surface.

The method presented for the gluing of triangular profiles into blocks shows how triangular profiles can be further refined into form-stable products on an industrial scale. The tests which are now being carried out in a pilot plant show that knotless solid wood panels can be manufactured according to this method and with a high volume yield.
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Chapter V

Weathering of radial and tangential wood surfaces of pine and spruce. 1. Crack formation and colour changes in exposed surfaces

Dick Sandberg
Summary
The development of cracks and changes in appearance have been investigated on radial and tangential surfaces of pine (Pinus silvestris L) and spruce (Picea abies Karst) which have been exposed outdoors for 33 months. Untreated samples, samples impregnated with a CCA-agent and samples surface treated with linseed oil have been tested.

The annual ring orientation is the most important factor for crack development on weathering. The type of wood, impregnation treatment and surface treatment with linseed oil have only a marginal effect on the crack development. No relation has been found between the density of the samples and the crack development.

After 33 months of outdoor exposure, tangential surfaces of pine have 13 times more total crack length per unit area than the corresponding radial surfaces. In spruce, the total crack length on the tangential surfaces is 6 times greater than on the radial surfaces. Tangential surfaces of both pine and spruce have a greater number of cracks per unit area and wider cracks than the corresponding radial surfaces.

Tangential and radial surfaces show the same colour change in the surface as a result of weathering.

Introduction
Wood exposed to weather and wind without being protected with some kind of surface layer, e.g. a paint layer, degrades as a result of three different processes: photochemical degradation depending primarily on the ultraviolet radiation in sunlight; mechanical degradation caused largely by shrinkage and swelling with changing moisture content; biological degradation due to fungal and insect attack and bacteria.

The photochemical degradation is a very slow process which during a decade degrades only a few millimetres of the wood surface and leaves the underlying wood practically unaffected (Hon et al 1978). The combined effect of water and sunlight degrades the main components of the wood and transforms the wood surface into a network of weakly connected cellulose fibres which are strongly contaminated by spores from microorganisms (Sell et al 1969).

Mechanical degradation also takes place relatively slowly and results primarily in an aesthetic degradation of the wood surface in the form of cracks and loose wood fragments on the surface. On the other hand, biological attack can in a short time lead to large damage to the wood material if the temperature, moisture level, and supply of oxygen and nutrients are favourable.

On a macroscopic level, the colour change of an untreated wood surface is one of the first and perhaps the clearest sign of the degradation of the wood during outdoor exposure. Visible light and UV-radiation alter the colour of the wood to a darker or lighter shade, depending on the type of wood (Sandermann et al

Figure 1. The star-sawing pattern showing (a) wood with a rectangular cross-section and triangular profiles, (b) production of samples from the triangular profiles. For test piece a1, a3, a5, ..., one of the radial surfaces has been exposed and for test piece a2, a4, ..., the tangential surface has been exposed. The length a1=300 mm, k=knot.
After a long period of outdoor use, all types of wood develop a greyish appearance (FRN 1966, Sell et al 1971). This depends on the fact that water-soluble decomposition products are removed and the more or less delignified fibres are exposed. If, on the other hand, the wood surface is protected against rain, it develops a dark red-brown surface (Browne 1959).

Visible cracks arise in the wood surface during outdoor exposure because of the growth of microcracks formed during the drying of the wood, photochemical reactions or moisture-induced stress fields (Coupe et al 1967). Stamm (1965a) considers that wood for outdoor use should have vertical annual rings. This minimizes the risk of cracks as a consequence of anisotropic moisture movements. Cracks in the radial surface are also smaller than in the corresponding tangential surfaces (Browne 1960, Stamm 1965a, 1965b).

The aim of the present investigation is to demonstrate possible differences in the degradation process between radial and tangential wood surfaces of Scots pine and Norway spruce exposed outdoors above ground.

**Material and method**

Star-sawn timber of pine and spruce with a triangular profile has been used in the investigation (Sandberg 1996). The test material was sawn from one pine and two spruce logs. After sawing and drying, some of the triangular profiles have been pressure impregnated with a CCA-agent. From each triangular profile, between 7 and 14 knot-free and defect-free test pieces with a length of 300 mm have been prepared. Figure 1 shows how the samples have been produced.

After being cut into lengths of 300 mm, the samples were planed on all surfaces to facilitate the determination of crack lengths. The samples were planed with the top end in the planing direction to a depth of 0.5 mm. The final width of the side varied between 75 and 125 mm. The dry density was determined for all samples: pine 475±25 kg/m³ and spruce 416±25 kg/m³. The end-wood surfaces were sealed with an oil alkyd primer and a silicone-based sealing compound. Some of the samples were brushed with linseed oil before the outdoor exposure began.

Table 1 presents a summary of the test material. The samples were exposed in Stockholm for 33 months (September 1993 - May 1996) at an inclination of 45 degrees towards the south.

After the outdoor exposure had been completed, all samples were conditioned for two months at a temperature of 24°C and a relative humidity of 66%. Thereafter, the lengths of all cracks with a crack width greater than 0.25 mm, which was the smallest crack size which could be measured in practice, were determined. Cracks with a width less than 0.25 mm were assessed visually. In the statistical evaluation of the results, a “non-parametric test” has been used with 0.95 confidence limits for the group mean values (Montgomery 1991, Sandberg 1995).

<table>
<thead>
<tr>
<th>Treatment of test body</th>
<th>Pine Radial</th>
<th>Pine Tangential</th>
<th>Spruce Radial</th>
<th>Spruce Tangential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>6</td>
<td>5</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td>Treated with linseed oil</td>
<td>5</td>
<td>6</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Impregnated with CCA-agent</td>
<td>13</td>
<td>13</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Impregnated and treated with linseed oil</td>
<td>12</td>
<td>13</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td>Total number of samples</td>
<td>36</td>
<td>37</td>
<td>44</td>
<td>41</td>
</tr>
</tbody>
</table>

* Refers to the annual ring orientation of the surface exposed at an inclination of 45° in a southerly direction, see also Figure 1.
Results
Cracks wider than 0.25 mm on the exposed surfaces

Table 2 shows mean values for the sum of the crack length per unit area (total crack length on the surface divided by the area of the surface) on the exposed surfaces after 33 months' outdoor exposure and subsequent conditioning.

The results show a clear difference between radial and tangential surfaces, regardless of impregnation or surface treatment. The difference between radial and tangential surfaces is statistically significant. On the other hand, it is not possible to find any influence on crack length from impregnation or linseed oil treatment.

Figure 2 shows the average of the total crack length for the exposed radial and tangential surfaces in pine and spruce. Pine shows a slightly greater mean crack length than spruce on the tangential surfaces, but a shorter crack length on the radial surfaces. The statistical analysis shows, however, that there is no significant difference in mean crack length between pine and spruce, either on the tangential or on the radial surfaces.

Figure 3a shows the mean value of the number of cracks per unit area which are wider than 0.25 mm. Figure 3b shows the average value of the greatest crack width for the samples, i.e. the maximum crack width has been determined for each test piece. Both quantities have been determined on the exposed surface.

The radial surfaces have a significantly smaller number of cracks than the tangential surfaces and the maximum crack width is also significantly smaller.

In the case of the radial surfaces, it is not possible to show any significant difference between pine and spruce, either for the number of cracks or the crack width. On the other hand, tangential pine surfaces have significantly more cracks and a smaller maximum crack width than spruce surfaces.

No influence on the crack formation of either surface treatment with linseed oil or impregnation has been found.

Table 2. Average of the total crack length per unit area (m/m²) after 33 months' outdoor exposure and subsequent conditioning to a moisture content of 12 %.

<table>
<thead>
<tr>
<th>Treatment of test body</th>
<th>Pine Radial</th>
<th>Pine Tangential</th>
<th>Spruce Radial</th>
<th>Spruce Tangential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>2.1</td>
<td>25.5</td>
<td>2.9</td>
<td>27.3</td>
</tr>
<tr>
<td>Treated with linseed oil</td>
<td>4.1</td>
<td>28.6</td>
<td>6.7</td>
<td>27.2</td>
</tr>
<tr>
<td>Impregnated with CCA-agent</td>
<td>1.1</td>
<td>29.8</td>
<td>0.1</td>
<td>31.0</td>
</tr>
<tr>
<td>Impregnated and treated with linseed oil</td>
<td>2.7</td>
<td>27.3</td>
<td>6.0</td>
<td>23.9</td>
</tr>
<tr>
<td>All samples in the group</td>
<td>2.2</td>
<td>28.1</td>
<td>4.4</td>
<td>26.1</td>
</tr>
</tbody>
</table>

* Refers to the annual ring orientation of the surface exposed at an inclination of 45° in a southerly direction, see also Figure 1.
Cracks with a width less than 0.25 mm on the exposed surfaces

Cracks with a width less than 0.25 mm are usually short, only a few mm, and many. In practice it has not therefore been possible to determine the crack length for these.

Table 3 shows the number of samples with small cracks visible to the naked eye on the exposed surface and where on the surfaces these cracks occur most frequently.

Table 3. Number of samples with small cracks (crack width less than 0.25 mm) on the exposed surface after 33 months' outdoor exposure and subsequent conditioning to a moisture content of 12%.

<table>
<thead>
<tr>
<th>Main crack orientation</th>
<th>Pine</th>
<th>Spruce</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Radial'</td>
<td>Tangential'</td>
</tr>
<tr>
<td>The annual ring border</td>
<td>33</td>
<td>2</td>
</tr>
<tr>
<td>Earlywood</td>
<td>29</td>
<td>1</td>
</tr>
<tr>
<td>Latewood</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>The whole exposed area</td>
<td>3</td>
<td>25</td>
</tr>
<tr>
<td>Total number of samples</td>
<td>36</td>
<td>37</td>
</tr>
</tbody>
</table>

* Refers to the annual ring orientation of the surface exposed at an inclination of 45° in a southerly direction, see also Figure 1.

Cracks wider than 0.25 mm on the non-exposed surfaces

Besides the surface exposed in the southerly direction, each test piece has two adjacent sides which have not to the same degree been exposed to sunlight. These two surfaces have degraded more slowly than the exposed surfaces.

Figure 4 shows the crack length for the non-exposed surfaces. In the same way as for the exposed surfaces, the average of the total crack length on the radial surfaces is significantly smaller than that on the tangential surfaces. As can be seen in Figure 2, the average of the total crack length on the non-exposed surfaces is smaller than on the exposed surfaces. For the radial pine surfaces, the average of the total crack length on the non-exposed surfaces is 55 times smaller and on the tangential surfaces 6 times smaller than on the exposed surfaces.

![Graph](https://via.placeholder.com/150)

Figure 3. Average values for (a) the number of cracks per unit area and (b) the maximum crack width on the exposed surfaces after 33 months' outdoor exposure and subsequent conditioning to a moisture content of 12%.
Cracks develop in wood surfaces during outdoor exposure are, as already shown, particularly visible on tangential surfaces. Figure 5 shows the characteristic appearance of a radial and a tangential surface from the present investigation. On the tangential surface (Figure 5d), cracks are clearly visible. On both the radial and the tangential surfaces, a large number of small cracks can be found which are, however, difficult to see in Figure 5.

The degradation follows the annual ring pattern in such a way that the earlywood degrades more rapidly than the latewood and valleys develop in the wood surface. The surfaces develop a corrugated appearance, which is particularly clear on the radial surfaces.

Figure 5 also shows an example of a colour change in samples after outdoor exposure. This colour change is particularly evident on the exposed surface. The surface changes colour to silver-grey, regardless of whether or not the wood is impregnated, Figure 5.

At the upper edge of the samples in Figures 5b and 5d it is evident that the part of the surface which has been protected against sunlight but exposed to rain and snow has a colour which is different from that of the remaining surface. The influence of the sunlight on the colour change is clarified if the backs of the samples are studied. Practically no colour change has occurred on these surfaces.

**Density**

Figure 6 shows the average of the total crack length as a function of density for all the samples. No relationship has been found between crack formation and the density of the samples.

**Discussion**

The samples included in this investigation have mainly been exposed to simultaneous photochemical and mechanical degradation.

The chemical reactions in the wood surface initiated by sunlight lead to a change in colour of the surface. This process is similar for radial and tangential surfaces.
Figure 5. Colour change of wood surfaces after 33 months' outdoor exposure. Radial surface of spruce (a) before and (b) after exposure. Tangential surface of unimpregnated pine (c) before and (d) after exposure.
The photochemical degradation takes place in a thin layer of the wood surface and this means that the strength of this layer is reduced (Derbyshire et al 1981, 1995, Raczkowski 1980). When the wood material is exposed to moisture variations, stresses develop in the cell walls and between cells, and these lead to damage and to the propagation of existing cracks. The photochemical reactions which take place in the wood surface during outdoor exposure accelerate this process, but they are not the main reason for the great difference in numbers of cracks between radial and tangential wood surfaces.

If the crack length ratio between tangential and radial surfaces is studied for the exposed surfaces (Figure 2) and for the non-exposed surfaces (Figure 4), it can be established that this ratio is smaller for the exposed surfaces, which implies that the difference in crack development between radial and tangential surfaces is not a consequence of photochemical degradation. On the other hand, strong exposure to sunlight and rain means that the size and frequency of cracks increase strongly.

The difference in crack susceptibility between radial and tangential surfaces is mainly the result of stresses which arise in the wood as a consequence of anisotropic moisture movements of the wood material and moisture gradients between the surface of the test pieces and its internal region, i.e. mechanical degradation. The shrinkage and swelling in the tangential direction are about twice as large as the radial moisture movement. Tangential surfaces thus move more than radial surfaces. This means that the stresses become higher in the tangential direction than in the radial direction when the moisture movement in the surface layer is limited by underlying wood which does not have the same moisture content as the wood in the surface layer. This relationship applies in the case of rapid moisture changes in the surface, e.g. when the surface is alternately exposed to rain and is dried out in strong sunlight. Moisture gradients then arise between the surface area and the underlying wood material. This results in the formation of more cracks on tangential surfaces than on radial surfaces.

The latewood shrinks and swells more than the earlywood. In the radial direction, the moisture movement in the latewood is about 3 times higher than in the earlywood and, in the tangential direction, about 1.5 times greater in the latewood (Boutelje 1962, Vintila 1939). When the moisture content in the wood changes, the early- and latewood thus move to different extents. In the radial direction, the layers are oriented in series and the early- and latewood layers can move practically independently of each other. In the tangential direction, the early- and latewood are parallel, which means that the moisture movement is limited by the individual layers and that stresses arise in and between these layers, see e.g. Kifete (1996). This is a reason why tangential surfaces crack more than radial surfaces.

On the radial surfaces, cracks occur first at the annual ring border (Table 4) and thereafter in the earlywood (Table 2). On the tangential surfaces, cracks appear first in the latewood (Table 4) and then develop across the whole of the exposed surface (Table 2). This agrees with results reported by Coupe et al (1967). The fact that cracks do arise at the annual ring border on the radial surfaces is a consequence of the large and abrupt change in density which takes place in the transition from latewood to earlywood. It seems that cracks also arise at an early stage in the latewood on the radial surfaces, but these cracks are difficult to observe because the late wood strips are very thin, about 0.25 mm.

The strains to which the wood material is exposed in pressure impregnation can cause damage to the material, which can mean that impregnated wood would be more susceptible to cracking during weathering than wood which is not impregnated. This hypothesis is not supported by the result of the now reported investigation.
Conclusions

The annual ring orientation in the wood surface has a great influence on the susceptibility of the surface to crack. To avoid cracks occurring on wood used outdoor, wood pieces with annual ring orientation perpendicular to the exposed wood surface should be selected. This is especially important if the wood lacks a covering surface layer, e.g. paint, or if the surfaces are strongly exposed to weather and wind.

For wood of pine or spruce exposed outdoors without a covering surface layer, the annual ring orientation in the wood surface is more important for the crack development than the density of the wood or the type of wood. Impregnation treatment with a CCA-agent or surface treatment with linseed oil has no more than a marginal influence on the crack formation.

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Chapter VI

Weathering of radial and tangential wood surfaces of pine and spruce.

2. Microscope studies

Dick Sandberg
Summary

The degradation of radial and tangential surfaces of pine (Pinus silvestris L) and spruce (Picea abies Karst) has been studied at the micro-level. The surfaces were untreated, impregnated with a CCA-agent or treated with linseed oil.

Tangential surfaces have more and deeper cracks than radial surfaces. The cracks on the tangential surfaces occur frequently in both earlywood and latewood. On radial surfaces, cracks occur primarily at the annual ring borders, but to a certain extent also in the earlywood.

The radial cell wall of the earlywood has a large number of pores which are degraded at an early stage. Decomposition of the cell wall takes place on both radial and tangential surfaces. Cracks arise which follow the S2 fibril orientation in the different cellwall layers. Delamination in the middle lamella is especially noticeable in the latewood on tangential surfaces. No differences have been observed regarding linseed oil treatment, impregnation or type of wood.

Introduction

The sensitivity of the wood to degradation is one of its greatest weaknesses in outdoor usage. Like all biological materials, wood decomposes under the influence of the surrounding environment. When wood is exposed outdoors above ground, a complex decomposition process continues in the material as a consequence of chemical, biological, mechanical and light energy related factors. A common name for this process is “weathering” (Feist 1982).

The factors which are generally considered to cause changes in weathering on wood surfaces are: sunlight (UV, visible and infrared radiation), moisture (dew, rain, snow), temperature and oxygen (Hon 1983).

Because of the limited ability of light to penetrate into wood (Browne et al 1957), the effect of the weathering is limited to a thin surface layer and the erosion is slow, 5-12 mm per 100 years (Feist et al 1978).

Investigations of the effect of weathering on wood, carried out by different researchers, have dealt with several aspects, e.g. colour change (Fengel et al 1984, Sandermann et al 1962, Sel et al 1971), erosion (Arnold et al 1992, Feist et al 1978, 1984), free radicals (Hon et al 1980, 1981, 1991), surface wetting characteristics (Kalnins et al 1992, 1993), anatomical changes (Miniutti 1967, Borgin 1970, 1971, Borgin et al 1975, Derbyshire et al 1981), and strength (Derbyshire et al 1995, Raczkowski 1980). Of the whole electromagnetic spectrum, it is only the shortwave and energy-rich region which has a measurable influence on wood and which is thus of technical interest. As a consequence, a large number of studies have been carried out within this field and summaries of earlier results have been published by e.g. Kenaga et al (1959), Desai (1968), Kringstad (1969) and Hon et al (1979, 1991). Sandberg (1998) has shown a clear difference in crack occurrence on a macroscopic level between radial and tangential surfaces in pine and spruce weathered over a period of ca 3 years. Cracks on the tangential surfaces were shown to be more and also larger than cracks on the radial surfaces, for untreated, impregnated and linseed-oil-treated samples. The aim of this investigation was to use the test material from the investigation reported by Sandberg (1998) and on a microlevel characterize differences in crack pattern between radial and tangential surfaces.

Material and method

The test material used in this investigation has been taken from an investigation into crack formation in weathered wood surfaces (Sandberg 1998). Machineplaned radial and tangential surfaces of pine (Pinus silvestris L) and spruce
(Picea abies Karst) were exposed at an angle of 45° in a southern direction in Stockholm during 33 months (September 1993 - May 1996). After the exposure, the samples were conditioned for two months at 24°C and 66% RH. The test material consisted of untreated samples, samples which had been pressure impregnated with a CCA-agent, samples which had been coated with linseed oil and samples which had been both impregnated and linseed oil treated. 40 samples with an approximate size of 10 x 50 x 10 mm3 (WxLxT) were selected randomly from 158 weathered samples. To investigate the cross section, the cross section was prepared with the help of UV-laser ablation to minimize the risk of artefacts in the preparation (Seltman 1995, Stehr et al 1998). Otherwise, no preparation of the samples was carried out.

Microscopic changes in the wood surfaces were investigated by ESEM (Philips ElectroScan 2020).

Observations and comments
In the investigation of the exposed surfaces, the analysis has taken place at three structural levels:
- macroscopic cracks which propagate along practically the whole length (300 mm) of the test body and with a relatively large depth.
- small short cracks, normally with a depth of within one or a few annual rings.
- decomposition of the actual wood fibre and middle lamella.

The first level of degradation occurs primarily in tangential surfaces. This has been shown in an earlier investigation (Sandberg 1998) and has been treated only marginally in this investigation. The two subsequent degradation levels occur in both radial and tangential surfaces, with slightly different processes, however, which will be illustrated here. In the analysis of the different surfaces, no significant differences have been found regarding linseed oil treatment, impregnation or type of wood, and the influence of these parameters will not be further discussed.

Figure 1a shows an example of a planed and unexposed wood surface. The surface in the lower part of the picture has been treated by UV-laser ablation to remove the layer of crushed fibres which was a result of planing. Figure 1b shows a corresponding surface after weathering for 33 months. In large parts of the exposed surface, the cell structure is exposed and it is possible to distinguish different structural elements, which it is impossible to see in the unexposed planed wood surface, Figure 1a. Figure 1b shows how the uppermost layer of crushed fibres has cracked as a consequence of the weathering. Sunlight during simultaneous moistening and drying of the surface means that cracks develop and that the fibres which have been partly compressed in the planing operation rise. The surface is opened successively and fibre fragments are broken apart and eroded by rain and wind. In Figure 1b, fracture across the fibres as a consequence of tensile stresses is
also shown. The fracture region normally stretch 3-10 cell rows down into the surface.

Exposed radial surface

On the radial surfaces, cracks can be found in practically every annual ring border, (Figures 2a and 2b). The cracks are usually a few millimetres deep and extend parallel to the annual ring border.

The crack extension almost always takes place in one of the first early wood cell rows and seldom more than two rows from the annual ring border, (Figure 2b).

In the earlywood, besides the deep cracks in the annual ring border, relatively small and shallow cracks occur, (Figure 3). These cracks do not in general become deeper than about 10 cell rows before the surrounding material has eroded away.

In the latewood, cracks seldom occur and, in those cases where cracks do appear, they are small, only a few cell rows deep.

The earlywood erodes more rapidly than the latewood, which probably depends on the fact that the latewood has a higher density than the earlywood. Figure 4 shows a latewood strip where the surrounding earlywood has been decomposed and removed by wind and weather. The thin and brittle strips of latewood are broken after some time.

The radial cell walls of the earlywood of both pine and spruce contain a large number of bordered pits. These are degraded at an early stage. The same phenomenon has been observed by e.g. Miniutti (1967) and Borgin (1970, 1971).

Figure 5 shows pits at an early stage of degradation. The pit openings have been enlarged and through the pits, diagonally oriented cracks have developed. During the continuing decomposition, these cracks propagate through the cell wall. According to Turkulin et al. (1997), these are a consequence of stresses which arise in contraction of the actual pit chamber. Torus also erodes at an early stage. Figure 5 also shows that the wart layer is largely lacking and that cracks have begun to develop in the cell wall. This type of crack is found in both the early- and latewood. The

Figure 2. Cracks at the annual ring border on a radial surface. (a) Crack opening at the surface of untreated spruce at 175 times magnification. (b) Crack a millimeter below the surface of impregnated pine at 250 x magnification.

Figure 3. Crack in the earlywood on a radial surface of impregnated pine at 220 x magnification.

Figure 4. Latewood strips of untreated pine in 265 x magnification, where the surrounding earlywood has eroded.

Figure 5. Early stage of the degradation of a radial cell wall of impregnated and linseed oiled spruce at 1000 x magnification. Torus is destroyed, the pit openings have been enlarged and cracks have arisen through the pits and in the cell wall.
orientation of these cracks suggests that these follow the fibril orientation in the S2-layer of the cell wall.

In the continuing degradation, the pit openings are further enlarged and the whole pit finally erodes away. The crack formation in the cell wall continues and degradation products are rinsed away until only a close-meshed network of fibril bundles remains, (Figure 6). The microfibrils are thus shown to be the most stable part of the actual tracheid, and the degradation continues with reduced adhesion between microfibrils and between the different cell layers.

**Exposed tangential surface**
In contrast to the radial wall, the tangential cell wall contains no or very few ring pores and consequently, the degradation pattern for the tangential surfaces becomes different. The tangential surfaces develop more, but also considerably larger cracks than the radial surfaces. Figure 7a shows a typical tangential surface, with on the one hand a large deep crack and on the other hand diagonal cracks in the cell walls, which is also common in the radial cell walls. Failure across the fibre occurs on the tangential surfaces, (see Figure 7b).

On the tangential surfaces, cracks occur often in both the early- and latewood. The cracks are initiated in the surface layer, in both the early and latewood, and propagate through the different annual ring layers. Figure 8 shows a crack which has been initiated in the earlywood on an exposed tangential surface. The crack has propagated through the whole earlywood layer and has reached the latewood. The crack propagation in latewood in the outermost exposed surface layer showed a similar development.

Figures 9a and 9b show delamination between fibres in early- and latewood for an exposed tangential surface. The delamination is especially clear in the latewood. The cracks in the latewood extend into the middle lamella with a depth of up to ten cell rows, Figure 9a. In the earlywood, the cracks are shallower and the delination against adjacent cell walls is not as sharp as in the latewood, (Figure 9b).

Figure 10 shows how the different layers in the cell wall are delaminated during the degradation. The different cell wall layers and the fact that the crack propagation has a different orientation in the different layers are evident. Figure 10 also shows a crack running...
along the length of the fibre which has propagated through the whole thickness of the cell wall.

Conclusions

Weathered pine and spruce show a degradation process which is strongly dependent on the annual ring orientation in the exposed surface. At a macroscopic level, tangential surfaces develop long and deep cracks which open the wood structure and facilitate continued decomposition. Radial surfaces, on the other hand, show only very small cracks. Sandberg (1998) has analysed these degradation processes.

On a microscopic level, it is also possible to see clear differences in degradation between radial and tangential surfaces. Tangential surfaces have more and deeper cracks than radial surfaces. The cracks on the tangential surfaces occur frequently in both early and latewood. On radial surfaces, cracks occur primarily at the annual ring border, but to a certain extent also in the earlywood. The radial surface develops a corrugated appearance because the early- and latewood decompose at different speeds. On an ultrastructural level, decomposition of the pores is the clearest difference between radial and tangential surfaces. The radial cell wall has a large number of pits which decompose at an early stage. In both radial and tangential surfaces, degradation of the cell wall takes place. Cracks arise which follow the fibril orientation in the S2 cell wall layer. Delamination in the middle lamella is especially clear in the latewood on tangential surfaces, but it also occurs in the earlywood. The microfibrils are the parts of the tracheid which are most resistant to weathering.
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Material damage due to electron beam during creep test in environmental scanning electron microscopy (ESEM)

G. Kifetew and D. Sandberg
Summary
This study describes the development of cell wall damage (creation of checks) across or in the vicinity of pits during testing microtomed samples in the Environmental Scanning Electron Microscopy (ESEM). Four microtomed sapwood samples of normal grown spruce (Picea abies Karst.) were prepared in green condition. One sample was investigated in an unloaded condition, while three specimens were tested under constant tension load and at different moisture level. Regions of the moisture cycled samples that had been exposed to electron beam during image acquisition showed damages that run through pits and their surroundings. Specimen loaded in green condition and dried in the chamber without beam exposure for two hours except during imaging did not show any noticeable cell wall damage. The result indicated that the electron beam might be the major source of damage initiation. Therefore, it is essential to take care on the circumstance of the test and in explaining the observations made in ESEM studies.

1. Introduction
Wood is a complex anisotropic, heterogeneous and hygroscopic structural material. Due to its wide structural application, the long term behaviour of wood has been a research area during the last decades. However, the relationship between the long term behaviour of wood under varying load and moisture conditions and its anatomical structure at a cell wall level has not yet been clearly understood. Hence, the conventional Scanning Electron Microscopy (SEM) and ESEM are some of the convenient tools that can be applied for such investigation.

SEM technique has been utilized in describing the failure morphology of wood under different loading conditions. The effect of low moisture content in a specimen and the high vacuum of the SEM on the failure behaviour of wood have been studied by Kyanka (1976) and others (see Hoffmeyer and Hanna 1989). In the past, Côte and Hanna (1983), Zink et al (1994) and Kifetew et al (1997) have used SEM technique to characterize wood fracture surfaces. Hoffmeyer and Hanna (1989) have utilized the SEM to study the influence of electron beam on the failure morphology of spruce (Picea abies).

Recent improvements have permitted ESEM to be a suitable technique in investigating biological tissues that contain water in form of vapour or liquid. Thus, compared to the conventional SEM, drying and coating a specimen can be eluded and therefore, allows investigation in the chamber at low vacuum. Taking advantage of the development, Mott et al (1996) and Shaler et al. (1997) have tested individual fiber in tension using ESEM. Their observation suggested that tension failure was related to pit. Accordingly, in this study the authors have tested several microtomed green sapwood samples of normal grown spruce (Picea abies) in the ESEM to relate the surface deformation of wood under constant tension load and varying moisture conditions to its anatomical structure. Kifetew (1996) have utilized a regular grid pattern for measuring deformation field on wood during drying. Similarly, in this study an earlywood zone with several pitted cells was selected to identify the identical points to obtain the surface deformation. Further, during the process of utilizing ESEM in determining the surface deformation of wood, damages have been observed at or in the vicinity of pits. However, most SEM fracture surface studies have demonstrated the resistance of pits to a transwall failure i.e. failure that runs all the way through a pit. A literature review of the subject has been presented by Kifetew (1996). Nevertheless, damaged pits have been detected by Turkulin and Sell (1997) in SEM studies on Scots
pine and Norway spruce samples exposed to natural and artificial weathering. Feist and Hon (1983) have observed a diagonal microchecks passing through the bordered pits after 1000 h UV irradiation. Jenkins and Donald (1997) have investigated the sensitivity of cellulosic fibers to the electron. They think that damage mechanisms are enhanced by the continual presence of water vapour in the ESEM chamber. Therefore, the principal objective of this study has been concentrated in studying the influence of electron beam, moisture variation and loading condition on the cell wall structure of wood.

2. Material and methods

Four sapwood samples of normal grown spruce (Picea abies Karst.) were cut in the green condition using a slide microtom along the fiber direction. The cross-sectional dimensions were 0.2 mm by 10 mm, and the length was about 45 mm. One test sample was air-dried for about two days and the remaining three specimens were preserved in the green state prior to tensile loading parallel to the grain. During the test, all the samples were mounted on a microtensile stage that fits inside the ESEM.

Several regions, referred to as A, B, C etc were selected for image acquisition. On each sample, a distinguishable earlywood zone with several pitted cells was selected as region A and the initial image was recorded prior to loading and changing the moisture state. This was done in order to record any damage that might have been introduced onto the specimen surface during sample preparation and air-drying. Another region of interest, B, was also selected as a standstill position during the drying and wetting periods. At this position, the gun alignment which normally has x,y-"coordinates of (0,0) was changed to another x,y-co-ordinate position in order to avoid a direct beam exposure of this region. Other regions were chosen as comparison sites in case damage was detected in region A during the test procedure.

The accelerating voltage during the tests was 15kV. Drying and wetting of samples was carried out at about 666 Pa, 30°C and 1333 Pa, 10°C respectively. In most cases, images were recorded at a magnification of 300X, but some images were also acquired at high magnifications. Failure loads in tension parallel to grain of two green and two air-dried samples were determined in order to estimate the constant load level that could be exerted on the sample. Thereafter, each sample was loaded at a rate of 0.1 mm/sec to a level of 15N. One specimen was investigated in the unloaded condition.

In the report, although only four samples, i.e. one control sample and three samples at different moisture conditions are included, for each condition several specimens were tested and a number of micrographs were recorded.

The experimental procedures for each sample can be summarized as follows:

a) Unloaded and moisture cycled green sample: Region A was selected and an initial image was acquired in the green condition. To protect region A from long-term beam exposure, a new region of interest B was selected as a standstill position. The specimen was dried for 30 min and the second image of region A was recorded. The sample was then exposed to two moisture cycles of 10 min wetting followed by 30 min of drying.

During the wetting/drying procedure, the electron gun alignment was directed away from region B. Images of region A in the dry state were recorded after each wetting/drying cycle. Additional sites were also selected and images were recorded for comparison purposes.

b) Tensile loading and moisture cycling a green sample: An initial image of region A was first recorded and the sample was loaded. After loading, the second image of the region was acquired. A new region B was selected as a standstill position and the sample was dried for 30 min and the dried image of region A was recorded. The sample was then exposed to two 10 min wetting periods...
followed by 30 min drying cycles. Images of position A in the dry state were recorded after each wetting and drying cycle. Additional regions of interest were selected for recording images in order to identify changes.

c) Tension loaded and moisture cycled air-dried sample: The initial image of region A was recorded, the sample was then loaded and a second image acquired, then it was dried for 30 min in the chamber. The procedure that followed after drying the sample for 30 min i.e. the selection of other regions, the wetting and drying cycles and the acquisition of images were the same as for sample b).

d) Tension loading and drying a green sample: Region A was selected and an initial image was recorded, the sample was loaded and the second image acquired, and the sample was then dried for two hours. During the drying period, the beam was completely shut off. After two hours of drying, images of region A were recorded. Additional regions were also selected for image acquisition for descriptive purpose.

3. Observations

Although, for each sample, images were recorded at several regions, the analysis presented in this study was concentrated only on region A. Micrographs of other regions are considered when a relative explanation becomes essential due to damage in region A.

Unloaded and moisture cycled green sample

During recording of the initial green state image, region A was exposed to the electron beam for 2.1 min, but the region showed no damage. Nor did the second image recorded after the sample had been dried for a period of 30 min and exposed to the electron beam for a total of 5.1 min (Figure 1a) reveals any noticeable damage. Damage started to appear on the image (Figure 1b) which was made.

Figure 1. Micrographs of region A a) after 5.1 min and b) after 8.25 min of beam exposure
Figure 2. Micrographs of region A after a) 4.0 and b) 7.0 min of beam exposure.

Figure 3. Micrographs after of region A a) 5.0 min and b) 8.0 min of beam exposure.
after the first wetting/drying cycle and a 8.25 min beam exposure. After two wetting/drying cycles and a total of 15.55 min of beam exposure, region A exhibited more damaged areas.

**Tensile loaded and moisture cycled green sample**

While the initial and the second (Figure 2a) images were recorded, region A was beam exposed for 4.0 min. However, neither image revealed any noticeable damage. Furthermore, the image recorded after the sample had been dried for 30 min, by exposing the region to an electron beam for a total of 5.5 min, still did not exhibit any damage. An image that revealed some damaged pits and its surroundings was recorded after the first wetting/drying procedure and after beam exposure of the region for a total of 7.0 min (Figure 2b).

**Tension-loaded and moisture cycled air-dried sample**

The first undamaged image of region A was recorded after 3.5 min of beam exposure prior to loading and additional drying. The second image was made after loading and exposure of the region for a total of 5.0 min (Figure 3a). These images showed no noticeable damage, but the image recorded after the first wetting/drying cycle and a total of 6.5 min of beam exposure showed some slightly damaged areas near the pits. Damaged areas can clearly be observed on images recorded after the second wetting/ drying cycle (Figure 3b) and 8.0 min of beam exposure.

**Tensile loaded and dried green sample**

To acquire the reference image, 4.5 min of beam exposure was required and the region showed no damage. The specimen was then dried for two hours in the chamber while the electron beam was completely shut-off i.e. 0 kV. Images were acquired to detect any damage or structural changes on the surface of...
the region of interest, but no noticeable structural change or damaged surface could be detected after the region of interest A had been exposed for a total of 9.5 min (Figure 4).

Comparison sites
Before any conclusions were drawn about the structural change due to the development of damage, images of some new and randomly chosen regions on each sample were recorded. These regions were considered to be comparison sites for the changes noticed on the surface of region A on each sample. The maximum time required to expose a region to electron beam during image recording was 2 min. As shown in Figure 5, none of the images of the newly selected regions revealed any noticeably damaged area.

4. Discussion
The reason for choosing region B was to use the site as a standstill position during the drying and wetting periods in order to protect region A from long-term beam exposure. This was done because we were not sure whether the change in electron gun alignment at region A could achieve the expected goal and prevent the region from beam exposure.

It is recognized that recent improvements and the use of ESEM have made it possible to investigate wood fibers with water in the form of vapour or liquid. Therefore, specimen drying or coating can be avoided and this makes possible the observation of a sample in the chamber at low vacuum. However, to acquire an image, sample exposure to the electron beam can only be reduced and cannot be completely avoided.

The micrographs presented in this study showed a clear difference in the occurrence of damage depending on whether or not specimens have been exposed to electron beam for a longer time i.e. a minimum of 6.5 min and a maximum of 8.25 min and have been wetted and dried. All the three specimens that were tested with or without a constant load have experienced two wetting/drying cycles at different and varying pressure and temperature levels. These samples have shown distinct pit damage and its surroundings. However, other sites used for comparative purpose showed no sign of cell wall damage.

This investigation has disclosed the development of damage during attempts to study the creep deformation of wood and its anatomical structure relationship in the ESEM. Therefore, the study suggests that precautions be taken in identifying the weakest links and in labelling the sources of failure initiation in wood cell wall structure under direct ESEM studies.

5. Conclusion
The aim of this investigation was to study the effect of electron beam, constant load and repeated drying and wetting on cell wall damage. The micrographs of both loaded and unloaded samples exposed to moisture cycles and an electron beam have revealed damage that in most cases runs through a pit and its surroundings. However, a green sample tested under constant load without electron beam exposure during two hours of drying except during the period when images were acquired, showed no noticeable damage. These results indicate that the electron beam may be a major cause of damage initiation. Therefore, care should be taken when explaining the observations made in ESEM studies.
**References**


Chapter VIII

The influence of pith and juvenile wood on proportion of cracks in sawn timber when kiln dried and exposed to wetting cycles

D. Sandberg
Subject
The presence of macroscopic cracks has been determined after cycles of drying and wetting of Scots pine (Pinus silvestris L.) and Norway spruce (Picea abies Karst).

Materials and methods
Six logs of Scots pine and seven logs of Norway spruce from the north of Sweden have been sawn into 45 and 70 boards respectively, all with the cross section dimension 50 by 100 millimeters. The boards were kiln dried with a conventional drying programme to a moisture content of 18 ± 3 %. After two weeks conditioning at a temperature of 21 ± 1 °C and 39 ± 5 % RH, the total length of cracks in every board was determined. Thereafter, the boards were exposed to three cycles lasting 20 days and nights, each cycle including, first, a 30-minute wetting phase in a water bath and second, a succeeding drying phase in the same climate as in the earlier described conditioning period. After the last wetting cycle the total length of cracks for each board was determined. The boards were divided into three groups:
A. Boards with the pith enclosed in the cross section in all of, or in parts of the length.
B. Boards sawn with a distance less than 30 millimeters between the pith and any part of the board. Boards from group A are not included in this group.
C. Boards sawn with a distance greater than 30 millimeters between the pith to any part of the board. The distance 30 millimeters has been chosen as a borderline between group B and C based on the anticipation that, as far as slow grown timber from northern Sweden is concerned, the major parts of the juvenile wood have been removed if timber is sawn further away from the pith than 30 millimeters. The sawing pattern has been chosen in such a way that it is possible to find boards in groups B and C with an annual ring pattern that is horizontal and the whole range of annual ring patterns up to the ones that are vertical (Sandberg 1995).

Figure 1. The variation of the average moisture content in the timber during the test.
Results

Figure 1 shows variation of the average moisture content of the timber during the test. The charts in Figures 2a and 2b show the relative length of the cracks before and after the wetting cycles. The relative length of cracks is here understood by the ratio between the total length of the cracks and the length of the timber.

As can be seen in Figure 2, the relative length of cracks in the timber is being reduced by the distance from the pith for both spruce and pine. The wetting cycles, however, resulted in an increased length of the cracks for all the groups. This increase is slightly bigger for pine than for spruce. The high relative length of cracks in group A is a consequence due to the shrinkage anisotropy of wood which, among other things, implies that the radial shrinkage is roughly 50% of the tangential shrinkage. When the pith is enclosed in the cross section of the timber there is a demand that the timber has to be plasticized during the drying period in order to make the shrinking stress relax without causing cracks.

The fairly great relative length of cracks in group B compared to the ones in group C cannot be explained only by referring to the anisotropic moisture movement found in wood. The similarity between group B and C, considering the dimensions and the annual ring patterns in the cross section, also indicates that the amount of cracks is not only dependent on drying factors.

This study, however, demonstrates that the proportion of cracks in timber is a factor clearly related to the distance from the pith. In addition, the proportion of cracks can be related to the pith cracks, which are present before the log has been sawn or the reduction of the radius of curvature of the annual rings close to the pith. This reduction increases the stress level during drying as a result of the shrinking anisotropy, which in turn results in increased cracking. It is also possible that the properties of the juvenile wood affect the cracking behaviour.

References


Figure 2. The relative length of cracks regarding pine (a) and spruce (b) after drying and after the following cycles of wetting and drying. The categories A, B and C represent different distances between the sawn timber and the pith.
Chapter IX

The influence of annual ring orientation on strength and dimensional changes during moisture variation in finger-joints

D. Sandberg
**Subject**

This investigation elucidates the significance of uniform annual ring orientation on the dimensional changes and strength of finger joined boards.

**Materials and methods**

30 radially sawn Scots pine (Pinus silvestris L.) boards free from knots and visible defects with a cross section of 45 by 45 mm and 900 mm length, were cut into two equal lengths. Each pair was finger-joined in two ways. Half the boards, i.e. 15 pairs, were joined using the same annual ring orientation in both pieces. In the remaining 15 pairs, one of the boards was turned 90 degrees. This means a board with vertical annual rings was joined to a board with horizontal annual rings, (Figure 1).

The joins were glued using a PVA-c-glue (Bostic 742, harder 743) and the end grain was sealed with silicon. The boards were conditioned to a moisture content of 8%. The length:width ratio of the finger-join was 10:3.5. The cross-sectional dimensions were measured on both sides of the finger-joins at intervals of 5 mm over a distance of 50 mm and then at a distance of 75 mm and 100 mm.

The boards were then soaked in water for 7 days, which resulted in a moisture content above fiber saturation at a depth of at least 10 mm from the surfaces of the boards. After wetting, the cross-sectional dimensions were measured again as described above. The boards were then dried using a conventional drying schedule (drying temperature 50° C) for 10 days followed by a conditioning period of 3 weeks to a moisture content of 8%. Thereafter the boards were loaded to failure in a 4-point bending test.

**Results**

Figure 2 shows the mean swelling values of the surface of the boards as a function of the distance from the finger-join. Since the tangential shrinkage and swelling due to moisture movement was about twice as large as the radial shrinkage, non-uniform swelling occurs in the finger-join with crossed annual rings, i.e. in the finger joined boards with both vertical and horizontal annual rings, (Figure 2b). In finger-joins with a uniform annual ring orientation the swelling was uniform as shown in Figure 2a.

As a result of non-uniform swelling and shrinkage in the join when boards with different annual ring orientations are joined, stresses will develop in the join. These stress variations may, ultimately, lead to a weakened join. As for the appearance, a uniform annual ring orientation is preferable. If the joined boards are orientated in a such way that the radial surfaces are exposed and colourless glue is used, the join has a very homogeneous pattern. This implies that the width of the annual rings in the joined boards and the shade of colour of the wood are practically the same.

The result of the strength test did not show any significant differences in failure strength between the two groups, i.e. finger-joined boards with the same annual ring orientation contra finger-joined boards with both vertical and horizontal annual rings.
Figure 1. Finger joined boards from the investigation. The upper board has the same annual ring orientation in the whole length. The lower board was joined by boards with vertical and horizontal annual rings.
Chapter X

Bending strength of I-beams with webs of wood-fibre board and flanges of star-sawn triangular profiles

D. Sandberg, M. Stehr
Subject
To determine some bending strength parameters of I-beams with triangular flanges and wood-fiber board webs.

Material and methods
Twenty three beams with wood-fiber board webs K-board K40 (BFS 1993) and triangular flanges of pine (Pinus silvestris L) prepared by star-sawing (Sandberg 1996) were prepared and loaded in bending to failure, (Figure 1). The flanges were considered to be a structural lumber K24 or lower (BFS 1993). The cross-sectional dimensions of the beams are given in Figure 2. The flanges and webs were glued using a resorcinol-formaldehyde adhesive (Cascosinol 1711, hardener 2520).

The beams were loaded to failure using a four-point loading technique (Nordtest-standard 1987), and the failure load, modulus of elasticity and ultimate moment to failure were determined. During the experiment, the mean moisture content and the density of the flanges were 10.3 % and 417 Kg/m³ respectively.

Results
Table 1 shows the mean values for 23 beams loaded in bending to failure. The results obtained are equivalent to an I-beam with a rectangular cross section flange having the same section modulus as the triangular flange.

Compared to solid cross-section beams, an I-beam has the advantage of providing the greatest moment of inertia for the amount of material employed. Using an I-beam with a triangular flange rather than a rectangular flange, it is possible to achieve additional advantages such as:

• A better material utilization, where a 7% small volume of timber is needed in a triangular flange to give the same section modulus as a rectangular flange.
• Since it is free from the undesirable juvenile wood, a beam with a triangular flange can offer a high density structure with a better shape and dimensional stability.
• The beam can offer a better shape stability if the triangular flange is glued to the web, since the position of the annual ring orientation is maintained as shown in Figure 2.

Table 1. Strength values in bending for the beams in the test (mean values of 23 beams at 10.3 % moisture content)

<table>
<thead>
<tr>
<th>Property</th>
<th>Mean value</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate moment to failure (kNm)</td>
<td>11.2</td>
<td>3.3</td>
</tr>
<tr>
<td>Bending stiffness (kNm/m)</td>
<td>392</td>
<td>66.9</td>
</tr>
<tr>
<td>Edge bending strength (MPa)</td>
<td>35.7</td>
<td>10.5</td>
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<tr>
<td>Modulus of elasticity (GPa)</td>
<td>10.9</td>
<td>1.7</td>
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<tr>
<td>Failure load (kN)</td>
<td>16.9</td>
<td>5.0</td>
</tr>
</tbody>
</table>

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BFS 1993: Boverkets konstruktionsregler 94, Boverket 1993:58, ISSN 1100-0856 (in Swedish)
Nordtest method 1987: Lightweight beams of wood, NT Build 327

Figure 2. Cross-section dimension for the beam in the investigation. The length of the beams was 4.2 m.
Figure 1. Cross-section of a conventional light-weight beam (left) and a light-weight beam with triangular flanges (right).


Appendix 1

The thesis is based on the one hand on a number of technical reports from the Division of Wood Technology and Processing at the KTH (KTH-Trä) which are largely written in Swedish, but with an English summary, and on the other hand on articles published in scientific journals. The articles are presented in chapter I - X, and the technical report are listed below:


Sandberg, D. 1995: Influence of annual ring orientation on crack formation and deformation in water soaked pine (Pinus silvestris L) and spruce (Picea abies Karst) timber. TRITA-TRÄ R-95-16 (in Swedish)


Sandberg, D. 1996: Improved wooden windows. Annual ring orientation, cracks and heart wood - three important factors influencing the durability of timber used in windows. TRITA-TRÄ R-96-23 (in Swedish)


Sandberg, D.; Wålinder, M.; Wiklund, M. 1997: The concept of Value Activation- a better utilization of wood. TRITA-TRÄ R-97-27 (in English)


Appendix 2

Division of the work in the papers between authors

Paper II:
Sandberg initiated the work and mutually the authors performed the experiments, analysis, and wrote the paper.

Paper IV:
Sandberg initiated the work and mutually the authors performed the experiments and analysis. The paper was written by Sandberg.

Paper VII:
Sandberg initiated the work and mutually the authors performed the experiments and analysis. The paper was written by Kifetew.

Paper X:
Martin Wiklund initiated the work. Stehr performed the experiments and mutually the authors performed the analysis and wrote the paper.