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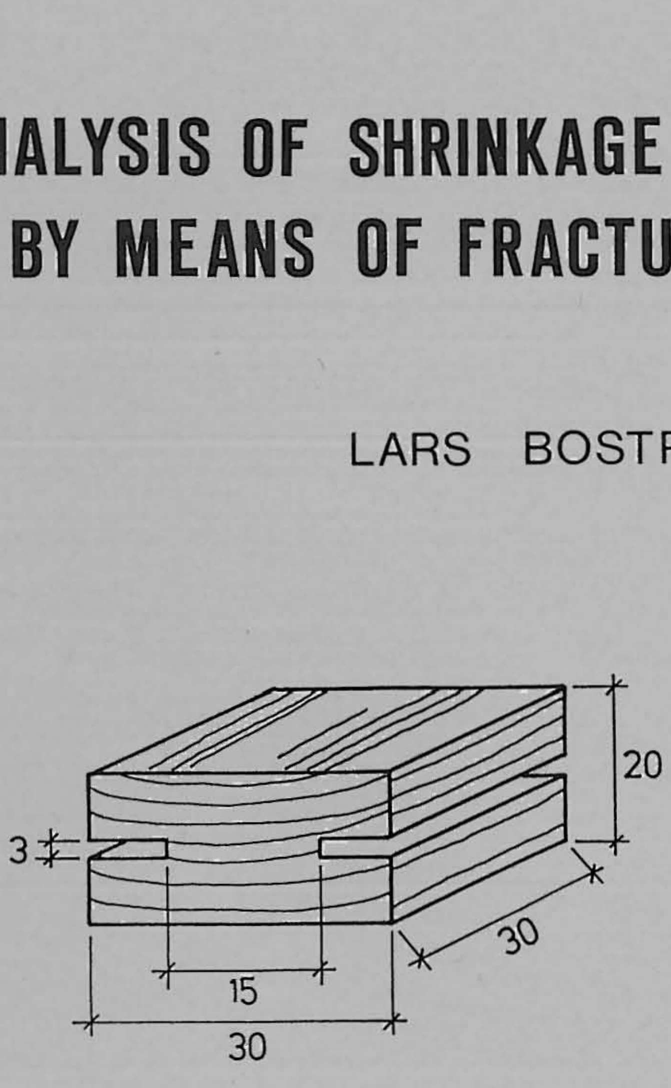
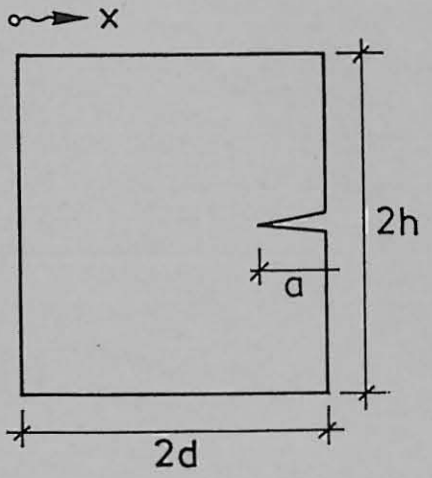
LARS BOSTRÖM





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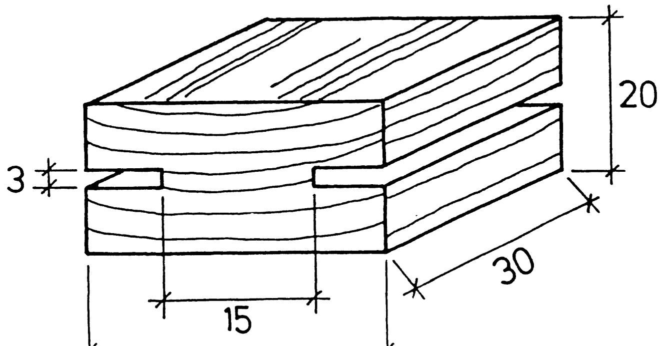

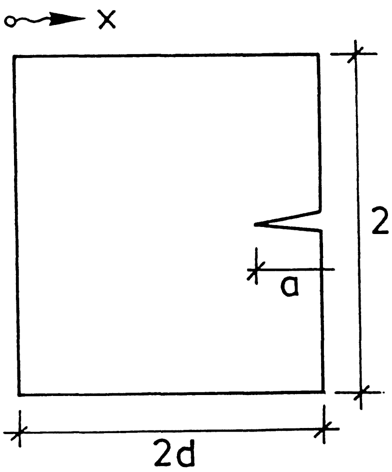

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PREFACE

This report have been made at the Division of Building Materials, Lund Institute of Technology. The researche project in which the work have been carried out is called "Fracture Mechanics - Applied to Wood" and it is the Swedish Board for Technical Development who are financially responsible.

I wish to thank professor Arne Hillerborg, head of the Division of Building Materials, who made it possible and inspired me to work with fracture mechanics.

I also wich to thank Tech.Dr. Per-Johan Gustafsson and M.S. Manouchehr Hassanzadeh for their help and interest in my work, Mrs. Britt Andersson who prepared all figures.

Lund 20/8-1987
Lars Boström

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INTRODUCTION

Development of shrinkage cracks is a well-known phenomenon which sometimes gives a pleasant esthetic touch to a construction, but mostly, it is a problem causing reduction of strength and it is also probable that cracks influence the absorbency of water. It is of great importance to find information about the development of shrinkage cracks before being able to avoid them. One way to do this is to do empirical experiments, but the results which can be found by this method are far from sufficient. It is very difficult to find relevant answers about what happens inside the material, and this kind of data is important. Therefore, it is necessary to find a method which in a theoretical way makes it possible to calculate the development of shrinkage cracks, and a model which can be applied when the material is orthotropic.

The objective of this report is to present a theoretical model, a fracture mechanics model called the Fictitious Crack Model, FCM, which can be applied to calculations on the development of cracks in wood. The results from this report are not intended to agree with reality, but they show a possible way to get closer to reality by theoretical methods. The model used was introduced in 1976 by Hillerborg et al. and it was developed for concrete and similar materials. Today it is a universally known model in the area of concrete and similar materials. For those who are not familiar with fracture mechanics Knott (1977) and Modeer (1980) can be recommended.

The first chapter, "Moisture Distribution", shows how moisture distribution has been chosen, and how it has been transformed to an initial strain which is the input data to the FEM-computations.

Chapter two, "Shrinkage Cracks - a Fracture Mechanics Phenomenon", contains a short introduction to the Fictitious Crack Model, and briefly describes the method of calculation. The results indicate the possibilities of predicting a drying process for wood, without getting open cracks. There is also a discussion about the problem with Linear Elastic Fracture Mechanics, which is the most widely spread model in use today.

In chapter three the conclusions are summoned up and some aspects on further research are suggested. It also presents some of the research in the area fracture mechanics which is going on in Lund, and this is the first report in this research project called "Fracture Mechanics Applied on Wood".

CHAPTER 1 MOISTURE DISTRIBUTION

To describe moisture changes in wood, when it is applied to drying, is not the main idea of this report, but it is necessary to know what the moisture distribution looks like in the material at different times in the drying process. This is important because it is the moisture content distribution through the specimen that is the cause of stresses induced in the material, and these stresses can create cracks if they exceed the ultimate stress. Several approximations have been made in this report, not only in order to simplify calculations, but also because some material properties are very difficult to find and use. For example can it be problems to find data about diffusivity and its variations with moisture content. One of the approximations is when calculating moisture distribution it is made in only one dimension, but this approximation is very simple to avoid. Further, the diffusivity is assumed to be constant and the material is assumed to be isotropic. It is possible to make calculations without these approximations, but in this case it is not so important to get exact results. It is more important to show a useful method, which can be used on wood.

The law of mass conservation has been applied in order to determine moisture distribution in wood. The calculations have only been made in one dimension as mentioned above, and the law of mass conservation in one dimension is shown in Equation 1.

$$\frac{\partial w}{\partial t} = -\frac{\partial F}{\partial x} \qquad \text{Eq. 1}$$

Where w = evaporable moisture content kg/m^3

F = moisture flow kg/m^2

In Equation 1 the moisture flow is involved and this moisture flow can be written like Equation 2.

$$F = -\delta \frac{\partial w}{\partial x} \qquad \text{Eq. 2}$$

where δ = diffusivity m^2/s

It is then possible for us to put Equation 2 in Equation 1 and get a differential equation which we can solve. The differential equation is shown in Equation 3.

$$\frac{\partial w}{\partial t} = \delta \frac{\partial^2 w}{\partial x^2} \qquad \text{Eq. 3}$$

Equation 3 has been solved with the initial conditions

$w(x,0) = w_0$

and boundary conditions, see Figure 1.

$w(0,t) = w_1$
$w(2d,t) = w_1$

These boundary conditions constitute a rough approximation. At the start of the drying process the moisture content at the boundary is not equal to w_1, but at least these boundary conditions give an idea about the drying process. Under such conditions, then, the solution is

$$w(x,t) = \sum_{n=1}^{\infty} -\frac{2w_0}{n\pi}(\cos(n\pi)-1)\sin(\frac{n\pi x}{2d})e^{-\lambda_n^2 t} \qquad \text{Eq. 4}$$

where

$$\lambda_n = \delta (\frac{nx}{2d})^2$$

This is the solution for a one dimensional case and in the calculations the diffusivity has been choisen to δ = 0.2•10-6 m2/s, which is a normal value perpendicular to the grain. Of course, this solution is very approximative, not only because the diffusivity is constant but also due to the boundary conditions. But with the curves determined by means of the equation it is possible to make further calculations about how a crack propagates through a specimen of wood when it is applied to drying. It is possible to refine these calculations by the use of a non constant diffusivity, which can be found for some species of wood. In Bertelsen (1984) the diffusivity can be found for spruce. Furthermore the law of mass conservation can be solved in more than one dimension, but these refinements are of minor significance in this report.

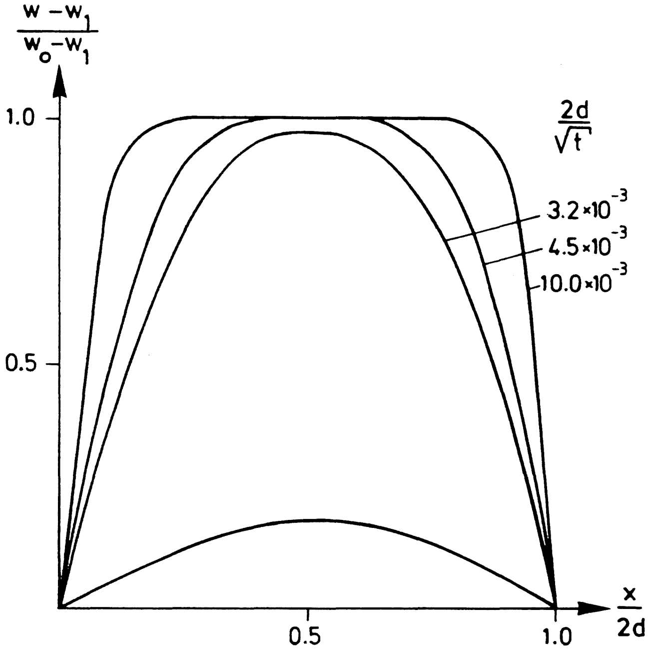


Figure 1. Moisture distribution through a piece of wood at different $2d/\sqrt{t}$. Definition of d, see Figure 3.

Distribution of Shrinkage Strains

The shrinkage that occurs in the material due to drying can be described by the moisture content, see Figure 2. The shrinkage increases approximately linearly up to the fiber saturation point from which point the shrinkage is zero, Hillerborg et al. (1983). By this relation, it is possible to calculate the shrinkage when the material is dried by

$$\varepsilon = \varepsilon_{max} \frac{w_0 - w_1}{w_f} \qquad \text{Eq. 5}$$

where w_0= moisture content when the process begins
w_1= moisture content at the end of the process
w_f= moisture content at fiber saturation point
ε_{max}= shrinkage when dried from 100% RH to 0% RH

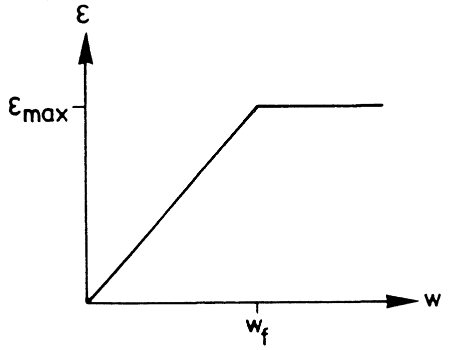


Figure 2. Shrinkage as a function of moisture content.

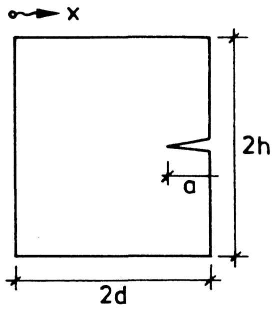


Figure 3. Geometry of specimen on which moisture distribution have been calculated

The shrinkage through the specimen can now be calculated by Equation 5. The shrinkage distribution, or initial strain are shown in Figure 4. This initial strain are used as input data for the Finite Element Method calculations, (FEM), and it is the initial strain differences through the material that cause stresses in the material.

A distribution of the initial strains in the specimen is shown in Figure 4. The figure also shows the initial strain through the specimen at different times in the drying process or at different width of the specimen.

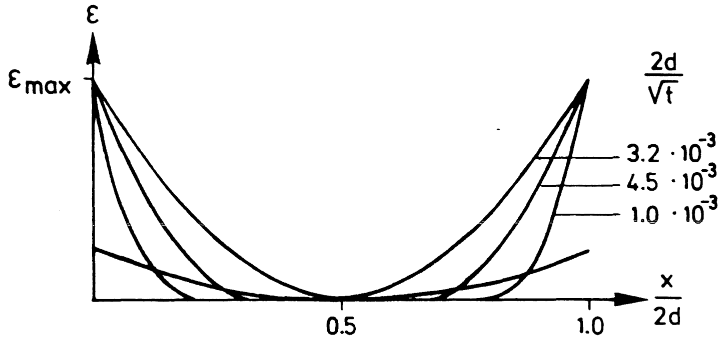


Figure 4. The initial strain as a function of depth in the specimen for different $2d/\sqrt{t}$.

Conclusions

The moisture distribution has been solved in one dimension and with a constant diffusivity. The moisture distribution, which is given in moisture content, is then converted into shrinkage or initial strain which is used as input load in further calculations. The final result from this chapter is shown in Figure 4. Here, the initial strain is presented as a function of depth in the specimen. It also shows curves for different ratio $2d/\sqrt{t}$, which shows the initial strain distribution for different geometry or at different times in the drying process.

CHAPTER 2 SHRINKAGE CRACKS - A FRACTURE MECHANICS PHENOMENON

When a piece of wood with a high relative humidity is put in a climate with a lower relative humidity, a drying process starts. This drying begins at the boundary of the material and propagates inwards the centre of the specimen, and a moisture differance between two adjacent points occurs. The moisture difference causes a shrinkage difference which develops shrinkage stresses in the material. If the stresses increase to the ultimate stress in any point of the specimen, failure occurs at this point or a fracture zone develops. The shrinkage is greatest at the boundary and therefore the crack propagation starts from the boundary. In this report all crack propagation starts from the boundary and is assumed to propagate into the material in a straight line at the symmetry line of the specimens, see Figure 5.

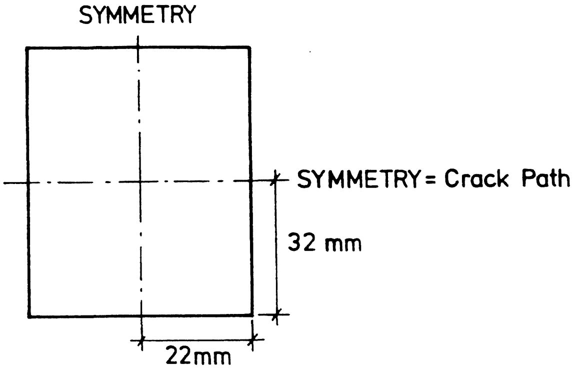


Figure 5. Geometry of specimen and the theoretical crack path.

To theoretically figure out how deep the cracks are which develop when wood is dried, it is obvious that fracture mechanics is the science to be preferred. The model used here is the Fictitious Crack Model which was first published by Hillerborg et al. in 1976. It is a non-linear strain-softening model. A comparison has also been made between Linear Elastic Fracture Mechanics (LEFM) and the fictitious crack model. This comparison is made to show that linear elastic fracture mechanics cannot be applied when calculations are made on shrinkage cracks in wood. Especially in the case of small specimens, where the fracture zone is relatively long compared to the length of the specimen.

Wood is an orthotropic and very complicated material, and therefore some approximations have been made. First of all, it is assumed that the material is isotropic and the mechanical properties are the properties in the weakest direction i.e. perpendicular to the grain, and also that they are independent of moisture content. Other approximations have already been made in the determinations of moisture distribution, see previous chapter. Of course it is possible to avoid these approximations to, but here it is of minor interest to find the true answers.

Fictitious Crack Model

The Fictitious Crack Model was developed to describe the fracture behavior of concrete and similar materials and in this report it is applied to wood. For further studies in the fictitious crack model Pettersson (1981) can be recommended.

In the fictitious crack model the whole stress-deformation curve in tension is used. This curve is divided into two curves, one describing the relationship between stress and strain outside the fracture zone and the other describing the relationship between stress and deformation in the fracture zone, see Figure 6. The area under the curve describing the fracture zone, i.e. the σ-w curve, divided by the fracture surface are equal to the fracture energy G_F.

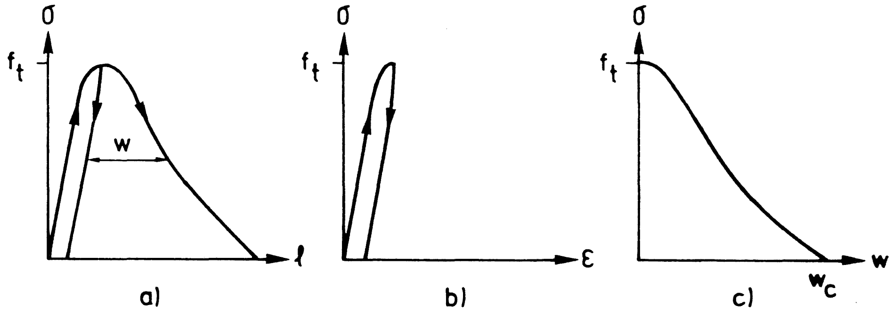


Figure 6. Stress-deformation curve and the two curves when the the stress-deformation curve is divided.

The $\sigma-\varepsilon$ curve is valid only until the tensile strength f_t is reached in any point of the material. When f_t is reached, a fracture zone starts developing at this point and the stress starts decreasing. The $\sigma-w$ curve is now used at this point. In the region outside the fracture zone the $\sigma-\varepsilon$ curve is used.

The fracture zone is assumed to have a length of zero in the direction of the main stress before the tensile stress is reached, and a length of w after the fracture zone has begun to develop. The fracture zone can thus be visualized as a fictitious crack, able to transfer tensile stress, hence the name fictitious crack model. The tensile stress in the fracture zone is a function of the fictitious crack width w according to an $\sigma-w$ curve.

FCM for calculations on shrinkage cracks in wood

Before any calculations can be made, it is necessary to find the whole stress-deformation curve for wood. This kind of test must be made in a very stiff testing machine, or a machine with closed-loop facilities. Tests have been made in both types of machine and these tests have disclosed great difficulties in finding the complete stress-deformation curve. These difficulties are due to insufficient stiffness in the stiff testing-machine, and in the testing system with closed-loop we have had difficulties with a machine which does not want to listen to our commands. Also, the successful tests show a great spread in the results. All the tests were made perpendicular to the grain, with the fracture surface in the LT-plane. The geometry of the specimens is shown in Figure 7. In the results two types of curves can be found for Swedish pine, one with behaviour similar to concrete, see Figure 8, and one elastoplastic, see Figure 9. In the calculations made here the former is used, i.e. Figure 8. This curve is divided into an $\sigma-\varepsilon$ curve and an $\sigma-w$ curve, see Figure 10. These curves can be approximated to straight lines in many different ways and here the $\sigma-w$ curve has been approximated to one straight line, see Figure 11. This makes the calculations much easier. The approximation is made so we have the right fracture energy, i.e. we assume a critical fictitious crack width. The fracture energy has been measured by three-point bending tests, Helmerson (1978).

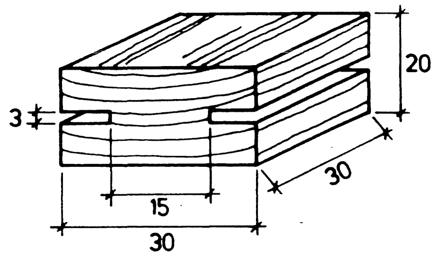
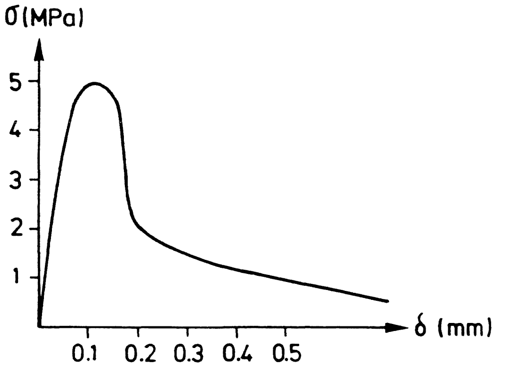
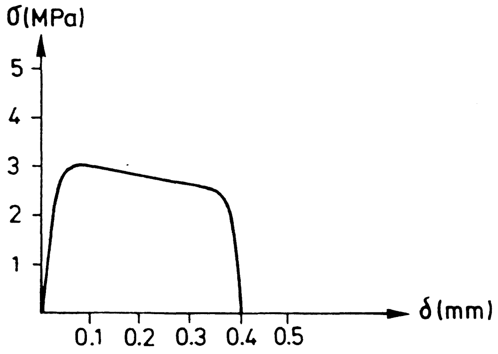


Figure 7. Geometry of test specimen.





Stress-deformation curves for wood

Figure 8. Figure 9.

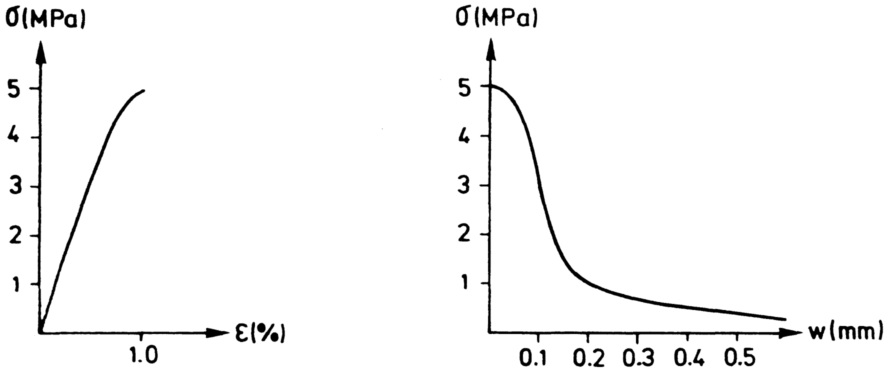


Figure 10. σ- ε curve and σ-w curve

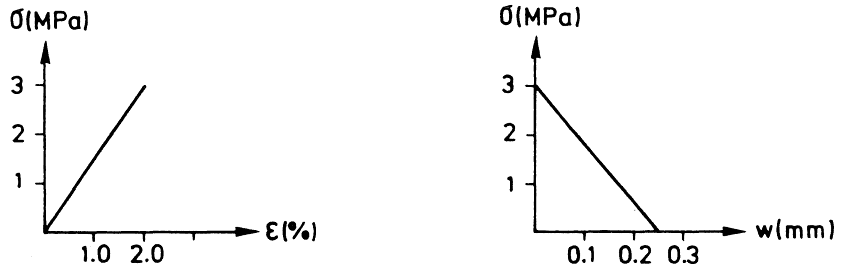


Figure 11. Approximated σ-ε curve and σ-w curve

An FEM-mech according to Figure 12 has been used in the computations and the properties for the material are as follows

f_t = 3 MPa
E = 460 MPa
Poisson's ratio = 0.015
Thickness = 1 m
G_F = 360 N/m
$w_c = 240*10^{-6}$ m
ε_{max} = 5 %
Specimen dried from w_0 to w_1
Geometry see Figure 5

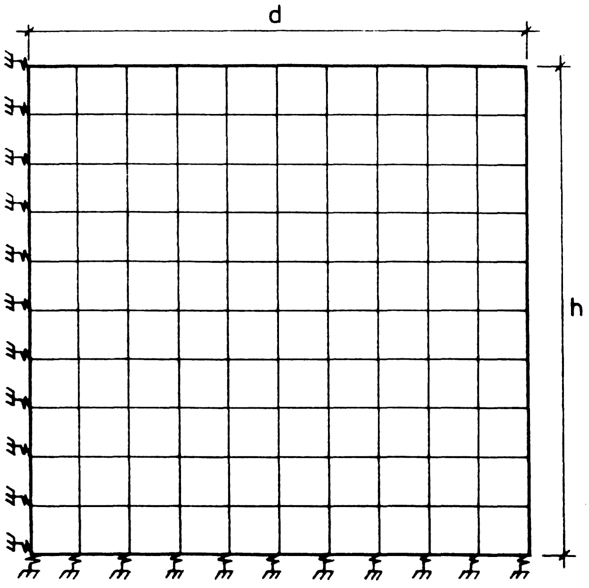


Figure 12. FEM-mesh

In the FEM-computations the σ-w curve are modelled with springs that have a negative stiffness. Thus when the tensile strength is reached at any node in the specimen, a fracture zone starts to develop. In this node a spring is coupled with a negative stiffness that describes the σ-w curve, see Figure 11 and Figure 13b. This spring is then able to transfer stress until the deformation in the fictitious crack has reached the critical fictitious crack width w_c, see Figure 13c. When the deformation has reached w_c in the fracture zone the stress in the spring is zero, the spring disconnects from the node and a open crack with no stress transferring abilities has appeared, Figure 13d.

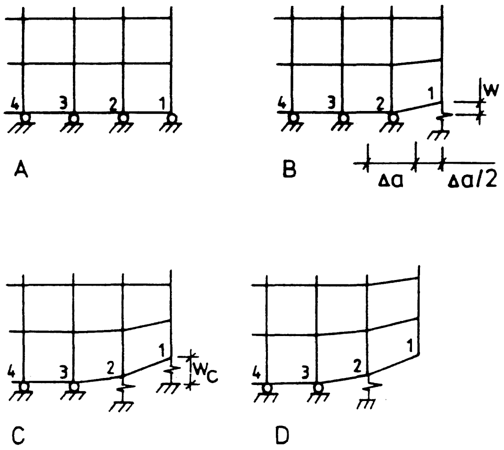


Figure 13. Calculations by fictitious crack model.

FEM-computations have to be done for different times in the drying process, if we are to follow the crack propagation. Such calculations have been done, leading to a curve describing the depth of the cracks which develop in certain degrees of drying. This is shown in Figure 14. In the diagram are ε defined as the shrinkage needed for a certain crack depth. In the diagram two curves are shown, the dotted curve describes how deep in the material the fracture zone has reached when the material is subjected to shrinkage. The second curve describes how deep in the material there is a real crack with no stress transferring abilitis. The crack depth shown in Figure 14 is the maximal crack depth through the whole drying process.

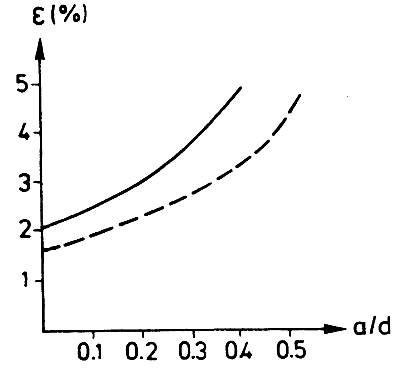


Figure 14. Shrinkage as a function of crack depth. The dotted curve shows how deep the fracture zone develops.

Calculations have also been done using Linear Elastic Fracture Mechanics, (LEFM). In the calculations have the critical stress intensity factor been assumed to

$$K_c = \sqrt{EG_F} \qquad \text{Eq. 6}$$

A comparison between the two models can be found in Figure 15. Here one can see one of the problems with LEFM, the singularity that occurs when there is no crack in the material. This problem is well-known but even when there is a crack one can see a great difference between FCM and LEFM. This difference can be explained by the relatively long fracture zone in the specimen. When a material has a long fracture zone a non-negligible part of the potential energy is stored in the fracture zone.

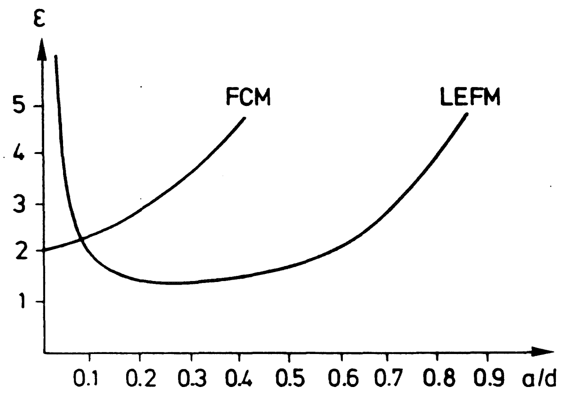


Figure 15. Comparison between FCM and LEFM.

The curves in Figure 14 can be used to determine cracks when a specimen is dried from equlibrium with one relative humidity to another relative humidity, by the use of a sorption isoterm for the material, see Figure 16. The dotted curve can be used to determine a drying process with no fracture zone developing in the material, i.e. the stresses developed by shrinkage have never reached the tensile strength, and there is no damage to the material. It is possible to make this calculation without FCM, it is only to calculate linear elastic. If the other curve is used a drying process can be determined where some damage has occurred in the material, but there are no open cracks. In Figure 17 is a curve which describes a drying process for a specimen that does not give any open cracks.

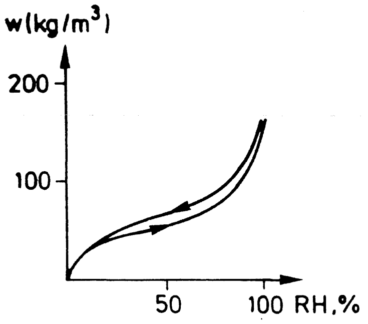


Figure 16. Sorption isoterm

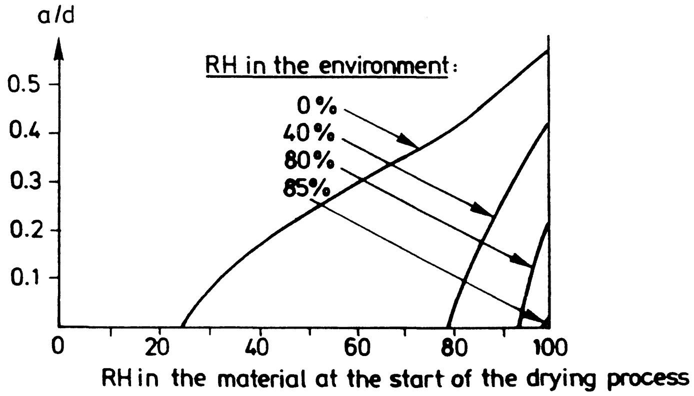


Figure 17. Crack depth at different relative humidity in the environment.

It is important to see how the size of the specimen influences the crack depth. Calculations have been done for some different specimen size and these calculations show that size is an important factor, see Figure 18. The relative depth of the crack increases with increasing size of the specimen, especially with small and normal dimensions.

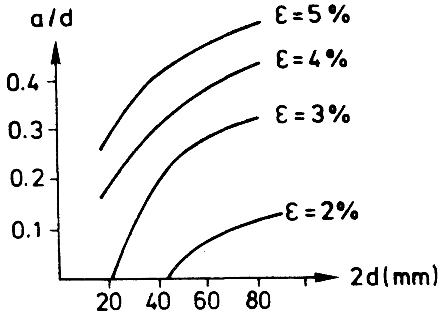


Figure 18. Influence of size of specimen.

Conclusions

It is possible by means of the Fictitious Crack Model to simulate crack propagation in wood subjected to drying. The problem in this type of calculation is to find relevant material data. As the whole stress-deformation curve is used in the calculations it is thus necessary to find this curve - a task which has proved to be difficult. A very stiff testing machine is needed to find the descending branch in the working curve. Some successful tests have been done, and these tests show a great scatter not only in the form of the stress-deformation curve, but also in tensile strength and fracture energy. There is no significance in the tests but they show at least a possible appearance of the stress-deformation curve.

A comparison has been made between FCM and LEFM. This comparison shows a great difference between the two models. Primarily LEFM is not applicable when there is no crack. The difference in results can be explained by the relatively long fracture zone which can hold energy.

The dependency on size has been examined and has shown to be considerable, especially with specimens of small dimensions.

CHAPTER 3 CONCLUSIONS AND FURTHER RESARCH

It is possible by means of the Fictitious Crack Model to simulate a crack growing through a piece of wood when it is exposed to a drying process. There is one difficulty with the method, the problem of finding the whole stress-deformation curve, which is needed for the calculations. Calculations have been made on a small piece of wood applied to a drying process. The results of these computations are considerably different to those obtained via Linear Elastic Fracture Mechanics. Not only in the singularity which occurs in LEFM but also in the numerical results. This difference is due to the relatively long fracture zone in the specimen. The fracture zone stores a non-negligible part of the potential energy in the specimen.

From the numerical results a curve has been obtained describing a possible way to dry wood without getting any cracks. It is a great problem to find a good method by which to dry wood, but application of FCM makes this theoretically possible. Calculations have also been done on the influence of specimen size, and these calculations show a great influence of size on the relative crack depth. The relative depth of the crack increases with increasing size of the specimen, especially at small and normal dimensions on construction beams.

In the research project "Fracture Mechanics Applied to Wood" we hope to find the complete stress-deformation curve, hopefully in both Mode 1 and Mode 2. We are then going to work with mixed mode. There is also a theoretical part to the project, involving a great deal of work on computer programmes for calculations in mixed mode. Such calculations are particulary important for wood, its orthotropic qualities often leading to large shearing stresses.

Calculations will be made on beams with longitudinal cracks, different types of holes and section changes. The influence of shrinkage stresses on strength are also going to be investigated. The validity of these calculations will then be tested in the laboratory on the above mentioned types of beams.

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