

Parameter identification of the orthotropic material wood

Citation for published version (APA):

Campen, van, E. J. J. (1992). *Parameter identification of the orthotropic material wood*. (DCT rapporten; Vol. 1992.046). Technische Universiteit Eindhoven.

Document status and date:

Published: 01/01/1992

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

PARAMETER IDENTIFICATION
OF THE ORTHOTROPIC MATERIAL
WOOD

E.J.J. VAN CAMPEN

WFW 92.046

STAGE VERSLAG VAN EDGAR VAN CAMPEN, APRIL 1992.

BEGELEIDERS:

- dr.ir. C. OOMENS
- ir. M. VAN RATINGEN

PARAMETER IDENTIFICATION OF THE ORTHOTROPIC MATERIAL WOOD

By: Edgar van Campen
April 1992

CONTENTS:

SUMMARY

1. INTRODUCTION

2. THEORY

3. EXPERIMENTAL MODEL

4. FINITE ELEMENT MODELS

5. RESULTS

6. CONCLUSIONS

7. RECOMMENDATIONS

REFERENCES

SUMMARY

This paper describes a specific utilization of a numerical/experimental method for the characterization of materials, the identification method. The method is applied to the orthotropic material wood, using data from a three-point bending test. The conclusion is that only ratios of material parameters could be estimated, because of the local plastic deformation that occurred.

1. INTRODUCTION

The characterization of materials consists of determining the parameters of a chosen material model describing the material behaviour in an experiment. Applying traditional methods, for example a tensile test, prevents the strain field from being inhomogeneous. This means a considerable restriction in the scope of material characterization.

Hendriks [1991] describes the identification method which provides more freedom for experiments. In this method an inhomogeneous strain/displacement field on a test piece is measured. Also a finite element model, describing the experiment, with initial values for the material parameters, is used to compute a strain field. The measured strain data are compared with the calculated strain data. By means of feedback the values of the initial material parameters are modified. A new strain field is calculated based on the modified parameters. The resulting iteration process is repeated until the differences between the subsequent estimates for the material parameters are small enough, and the deflections between the calculated and measured strain field nears the measuring error. A flow chart of the identification method is presented in figure 1.1.

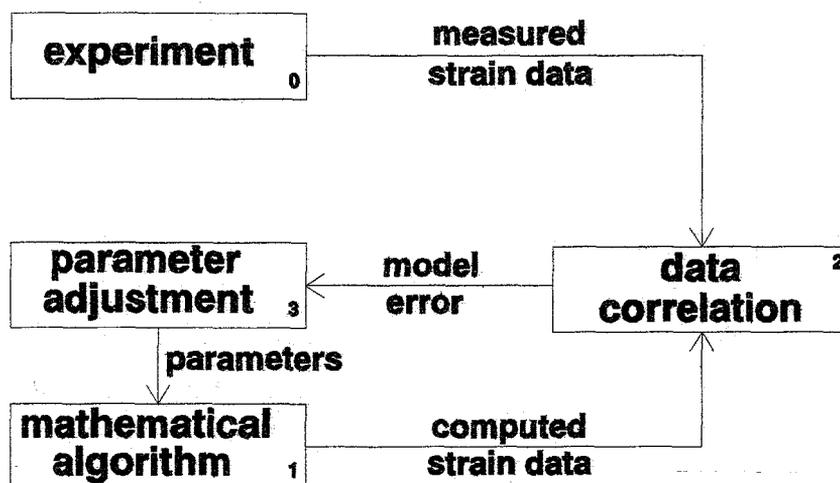


Figure 1.1. Flow chart for the identification method.

In this report the identification method is employed on the orthotropic material wood, using data from a three-point bending test. The material wood was examined because it can be described with a linear orthotropic model and because it has a high stiffness ratio, which is an interesting complication (J. de Jager [1991]). The three-point bending test causes an inhomogeneous strain field, with this strain field parameter estimations can be carried out.

In section 2 the constitutive behaviour of wood and a short description of the parameter estimation algorithm are mentioned. Section 3 describes the experiment that has been carried out. Section 4 describes the finite element model. In section 5 results of the experiment and of the parameter estimation are presented. In section 6 some conclusions are given. Section 7 describes some recommendations.

2. THEORY

2.1. Constitutive behaviour of wood

Wood is a material which, up to a certain degree, can be considered as orthotropic. A characteristic feature of wood is the high degree of anisotropy, up to a ratio of the largest and the smallest Young's moduli of 20. Wood also has a certain degree of dependency on time, moisture content, humidity and pressure. However, it can be shown that if these quantities do not alter too much, their contribution to the material properties can be neglected (J.M. Dinwoodie [1989]).

The material then can be described by a linear elastic orthotropic model, if the displacements are not too large. If the size of the used specimen is small in comparison to the cross-sectional dimensions of the tree and it is obtained far enough from the centre of a cross-section, a Cartesian co-ordinate system can be used to describe the model. Figure 2.1 defines the material directions that will be used. Direction 1 is the longitudinal heading, parallel to the axis of the tree. Direction 2 is the radial direction and heading 3 is the tangential heading.

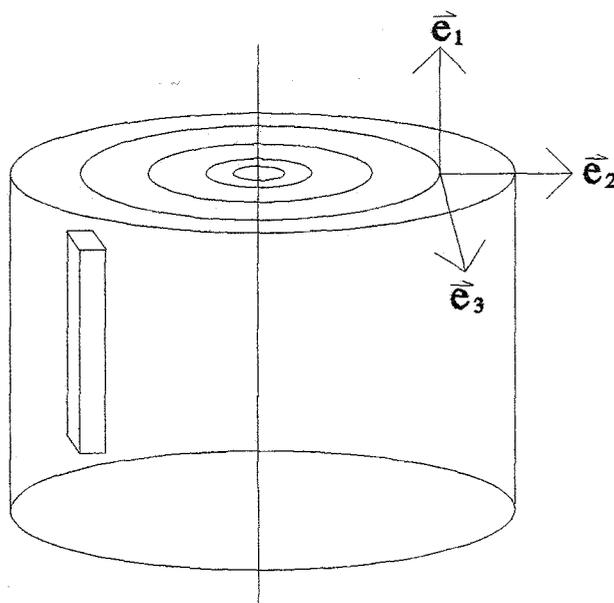


Figure 2.1. Definition of the co-ordinate system.

The specimen will be loaded in a three-point bending test (figure 3.3). The problem can be reduced to a quasi-two dimensional case by assuming a plane stress condition. Further the assumption is made that, under elastic deformation, the Young's moduli in tension, compression and bending are identical. With these simplifications the elastic behaviour can be described with Hooke's Law as follows (Oomens [1991]):

$$\varepsilon = \underline{\mathbf{C}} \sigma \quad (2.1)$$

With the following compliance matrix:

$$\underline{\mathbf{C}} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \quad \text{with} \quad \nu_{21} = \nu_{12} \frac{E_2}{E_1} \quad (2.2)$$

From the above it is evident that there are four independent material parameters: two Young's moduli (E_1 and E_2), one Poisson's ratio (ν_{12} or ν_{21}) and one shear modulus (G_{12}). These parameters are to be estimated.

2.2. Parameter estimation

Hendriks [1991] presents a method by which the parameter estimation can be carried out by means of the method of least squares.

The problem is represented by:

$$\mathbf{y}_k = \mathbf{h}_k(\mathbf{x}) + \mathbf{v}_k \quad (2.3)$$

In this equation the column \mathbf{y}_k contains the displacements of material points of the **k-th** measurement. The column \mathbf{x} contains the parameters that are to be estimated. It is assumed that an algorithm is available to calculate \mathbf{y}_k when \mathbf{x} is known; this function is symbolized by the nonlinear column $\mathbf{h}_k(\mathbf{x})$. The column \mathbf{v}_k contains observation errors.

For the sequential estimations based on prior knowledge of the parameters, the following equation is found:

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \underline{\mathbf{K}}_{k+1}(\mathbf{y}_{k+1} - \underline{\mathbf{H}}_{k+1}\mathbf{x}_k) \quad (2.4)$$

\underline{H}_k represents the measurement matrix (also called design matrix). The term $\underline{H}_{k+1}\underline{x}_k$ represents the expected observation measurements, based on the a priori estimate \underline{x}_k . Since the term \underline{y}_{k+1} contains the actual observed value, the difference $(\underline{y}_{k+1} - \underline{H}_{k+1}\underline{x}_k)$ gives new information. This difference is multiplied by a weighting matrix \underline{K}_{k+1} and forms the innovation for the new estimate \underline{x}_{k+1} .

The weighting matrix is computed according to:

$$\underline{K}_{k+1} = (\underline{P}_k + \underline{Q}_{k+1})\underline{H}_{k+1}^T(\underline{R}_{k+1} + \underline{H}_{k+1}(\underline{P}_k + \underline{Q}_k)\underline{H}_{k+1}^T)^{-1} \quad (2.5)$$

The update of the covariance of the estimation error in \underline{x}_{k+1} can be calculated with:

$$\underline{P}_{k+1} = (\underline{I} - \underline{K}_{k+1}\underline{H}_{k+1})(\underline{P}_k + \underline{Q}_{k+1}) \quad (2.6)$$

The matrix \underline{R}_{k+1} is the covariance matrix of the observation error \underline{v}_{k+1} . \underline{Q}_k is a nonnegative symmetric matrix. The introduction of this matrix \underline{Q}_k makes it possible to put less weight to the a priori estimate \underline{x}_k , and more weight to the new data.

The above is an outline of the theory described in Hendriks [1991].

3. EXPERIMENTAL MODEL

On a wooden bar (dimensions: 300 mm X 30 mm X 30 mm) 80 retro reflective markers were placed. They reflect incoming light very strongly in comparison to the background. This offers the possibility to observe the displacements of the markers, and thus of the bar, with a video tracking system (Hentschel GmBh, Hannover). These markers can be placed at random, but they should have at least 7 mm spacing.

The 80 markers were placed for different purposes; 14 markers were placed to mark the surroundings of the bar, 21 markers were used to deal with boundary conditions (e.g. to take into account the local plastic deformation at the supports), and 45 markers were actually used to measure the displacements of the bar at different locations. Figure 3.1 shows the initial position of the 45 markers that were used to measure the displacements of the bar. Figure 3.2 shows the 21 markers that were used to deal with boundary conditions.

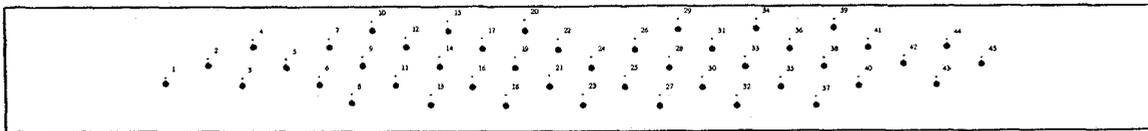


Figure 3.1. Initial position of the markers used for measuring displacements.

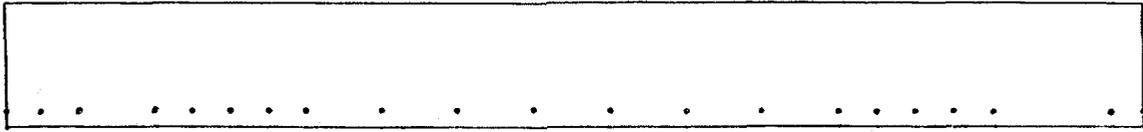


Figure 3.2. Initial position of the markers used to deal with boundary conditions.

The three-point bending test was carried out on a Zwick 1484 200 kN tensile machine. The force was applied in the middle of the bar. The displacement of the thrust was raised in steps of 0.3 mm. Each measurement was followed by a relaxation time of 3 minutes. After those 3 minutes all marker positions were measured.

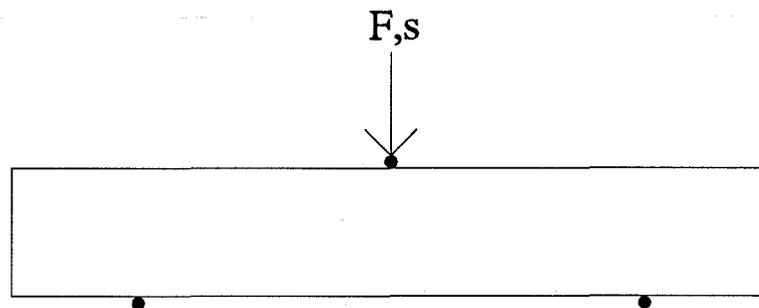


Figure 3.3. The three-point bending test.

During the experiment diagrams of strains and stresses in the bar were made with raw data. The displacements appeared to produce strains that are large enough to run a parameter estimation. The strains have to be larger than the measurement error, and strains in different directions have to be present.

Table 3.1. Experimental results from the three-point bending test.

measurement	displacement* [mm]	force [N]
15	4.502	3143.7
19	5.702	3712.5

* These are the displacements of the thrust.

Figure 5.2 shows the principal strains that occurred in the bar, at places where markers were used to measure displacements. The highest strain was 0.39% and the lowest strain was 0.06%.

4. FINITE ELEMENT MODELS

After carrying out the measurements, two finite element models were developed. The meshes were generated with the finite element program IDEAS [IDEAS User Guide]. The elements used for this mesh were linear quadrilateral elements. (4 nodes and 4 integration points) The completion of the model and the calculations were done with DIANA [DIANA Finite Element Analysis]. The mesh was generated with IDEAS because this program offers more sophisticated features than DIANA with respect to mesh generation. Figure 4.1.a and b show the two meshes that were used. One model contains 430 elements; the other has 135 elements. Figure 4.1.a shows that the shape of the elements of the first mesh is not well. Some elements have already a strong deformed configuration in their initial position. This is the result of the fact that markers that were used for boundary conditions, must have the same location as nodes of the model.

The second mesh looks good.

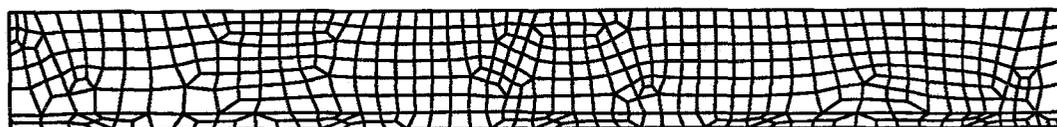


Figure 4.1.a. Mesh with 430 elements.

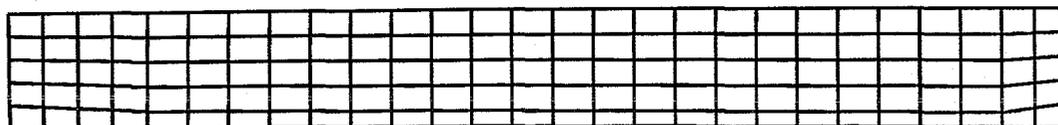


Figure 4.1.b. Mesh with 135 elements.

It is not necessary that the markers in the experimental set-up are located on element nodes, except for markers that are used for boundary conditions.

To deal with the rigid motion of the bar, which occurs through the local plastic deformation at the supports and which does not contribute to the strains in the bar, use is made of boundary conditions. In the area just above the local plastic deformation the displacement is prescribed as a boundary condition. To get these displacements, 21 markers were used in the experiment. To prescribe those displacements it was necessary for the markers to have the same location as the corresponding nodes in the finite element model.

For the first model (figure 4.1.a) 21 nodes were used to describe the boundary conditions. In one node the displacement was prescribed in two directions, in the other 20 nodes the displacement was described only in one direction.

For the second model (figure 4.1.b) only two nodes were used: one was used to describe the displacements in two directions, the other was used to describe the displacement in only one direction.

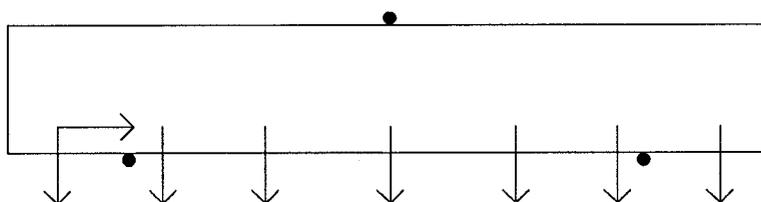


Figure 4.2. Kinematic boundary conditions.

The assumed situation is one of a linear elastic deformation. In fact local plastic deformation occurs at the supports (above the supports and below the force). This problem is met by taking boundary conditions into consideration. This causes a difference for E_1 , E_2 and G_{12} , because the actual deformed situation (local plastic and elastic deformation, see figure 4.3) is not equal to assumptions that are made in the model (only linear elastic deformation, see figure 4.4).

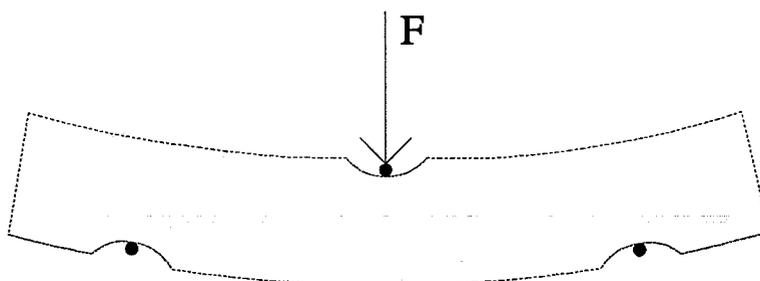


Figure 4.3. Actual deformation in the bar.

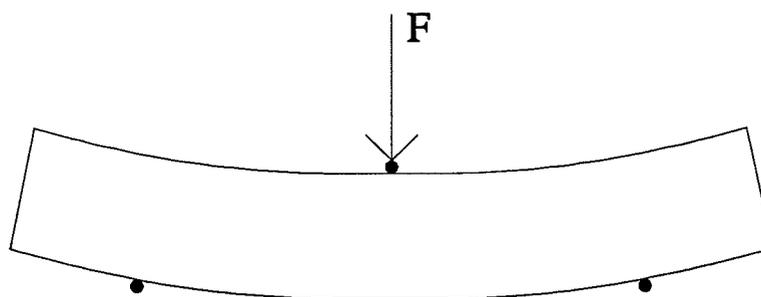


Figure 4.4. Deformation in the bar assumed in the model.

5. RESULTS

The measurement of the displacements was done in pixels. In this case 1 mm corresponds to 789 pixels. The displacements in figure 5.1 are measured in pixels.

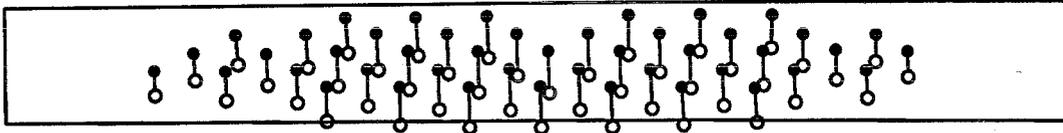


Figure 5.1. Marker displacements of the 15th measurement, in pixels, 10 times enlarged.

The strains in the bar are about 100 times larger than the corresponding measurement errors. Also the distribution for the principal strains is not homogeneous (figure 5.2).

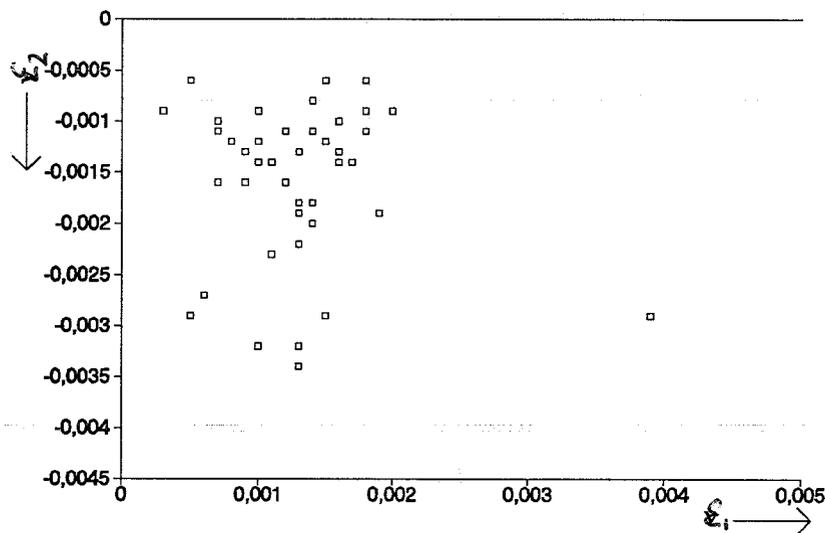


Figure 5.2. Principal strains in the bar for the 15th measurement.

The parameter estimation was carried out with the marker displacements of the 15th measurement. The values for E_1 , E_2 and G_{12} were estimated and with those values the ratios of E_1/E_2 and E_1/G_{12} were calculated. Table 5.1 shows the parameter estimations for E_1/E_2 and E_1/G_{12} after 8 iteration steps. Figures 5.3.a and b show the undeformed meshes and the deformed meshes with the estimated parameters at the 8th iteration step.

With the estimation process ν could not be estimated as its value did not convergence.

Table 5.1. Parameter estimations, 135 elements, 8 iteration steps.

Parameter		Expected Value *	Initial Value		Estimated Value	
x_i	unit	$x_{\text{expected},i}$	$x_{0,i}$	st.dev	$x_{8,i}$	st.dev
E_1/E_2	[-]	12.93	10	62.9	7.47	1.47
E_1/G_{12}	[-]	16.79	10	62.9	23.74	1.47

* These values hold for spruce.

Also a parameter estimation process was carried out for the 19th measurement. The results obtained after this process were not reliable.

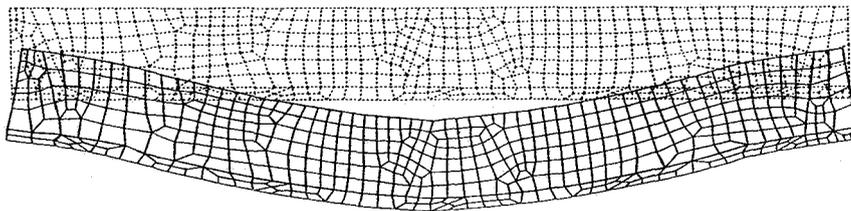


Figure 5.3.a. Undeformed and deformed mesh for the model with 430 elements.

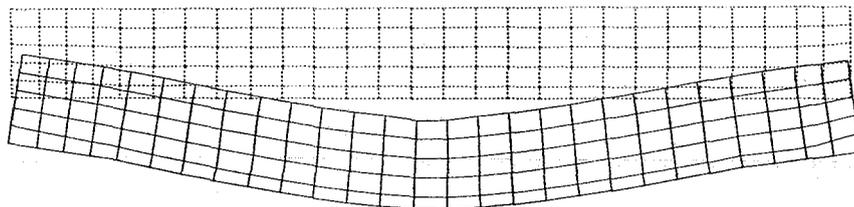


Figure 5.3.b. Undeformed and deformed mesh for the model with 135 elements.

Figure 5.4 shows the residual displacement field in the bar after 8 iteration steps. The massive circles present the measured marker displacements, the open circles present the calculated marker displacements. The differences between measured and calculated marker displacements appear to be very small, and at random.

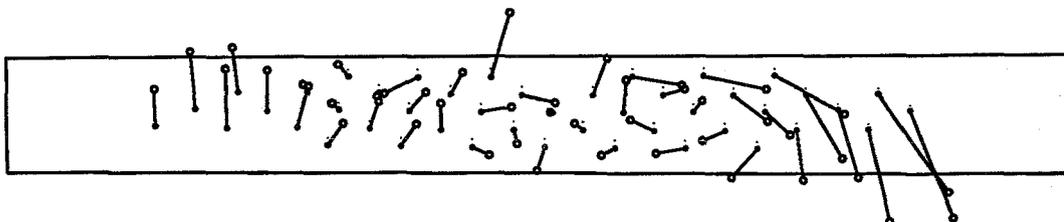


Figure 5.4. Residual displacement field in the bar, in pixels, 500 times enlarged.

The development of the estimated ratios throughout the iteration process is presented in figure 5.5.

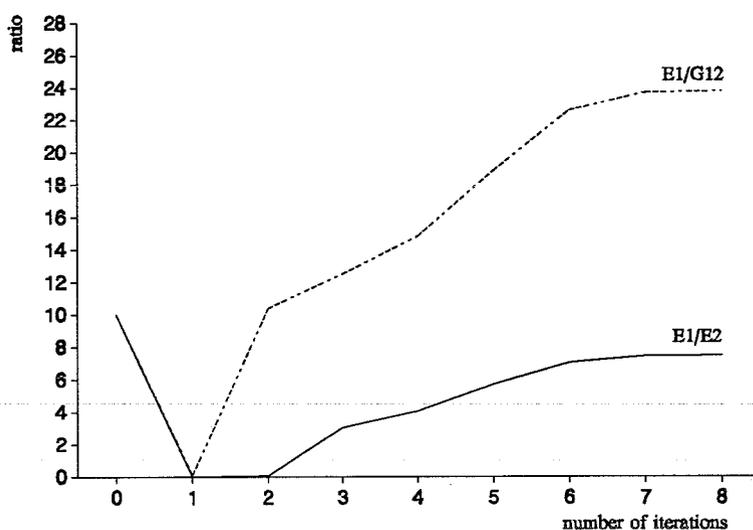


Figure 5.5. Development of estimates for E_1/E_2 and E_1/G_{12} .

The parameter estimation program calculates an error for every set of parameters. For the successive iteration steps the square root of this error is shown in figure 5.6.

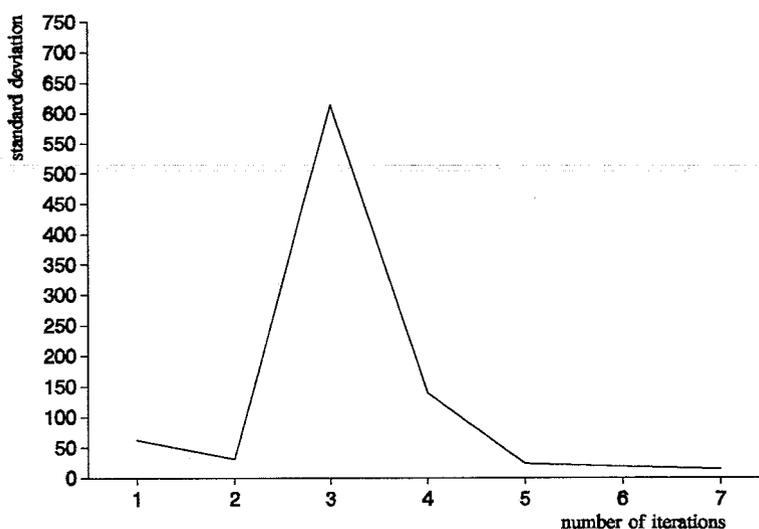


Figure 5.6. Development of the estimation error.

As mentioned previously, the parameter ν could not be estimated with the parameter estimation program. Figure 5.7 shows the calculated error for different values of ν . It appears that the error almost does not change. If it was possible to estimate ν well, there would be an evident minimum in the error for the right value of ν .

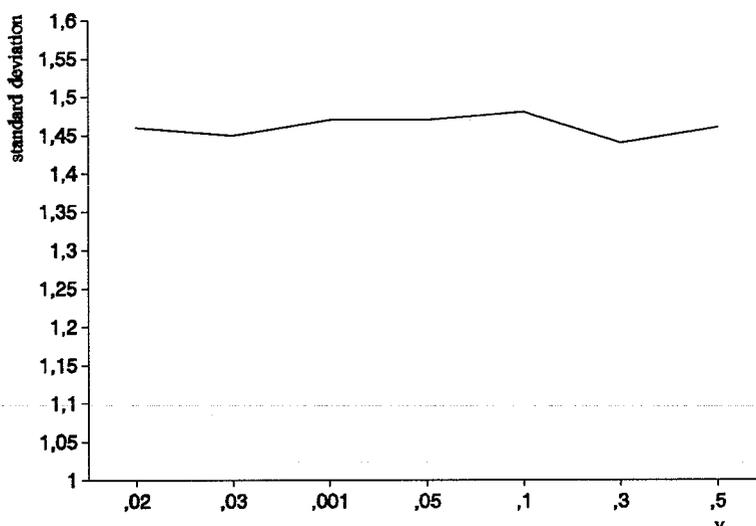


Figure 5.7. The error for different values of ν .

6. CONCLUSIONS

The major conclusion is that the three-point bending test is not a suitable test to determine material characteristics.

The discrepancies between the estimated and the expected parameter values may have the following reasons:

- The assumed situation is one of a linear elastic deformation. As has been mentioned already at the end of section 4, local plastic deformation occurs at the supports. This problem is met by taking boundary conditions. This causes an overestimation for E_1 , E_2 and G_{12} .
- The actual values for the material parameters are unknown. This has the following reasons:
 - It is not exactly known what kind of wood is used for the performed test. Hence exact values for the parameters are unknown. The most likely values are those of spruce. It is most likely that the expected values are not equal to the real values.
 - Not every piece of wood is identical. There is a difference between different trees, but also within one tree differences occur. These circumstances can cause the differences between the estimated and the expected values.

After removing the force the shape of the bar took its original configuration (except for the local plastic deformation at the supports). Hence it is not likely that any plastic deformations occur elsewhere in the material.

The assumption that the bar material is homogenous is a good approximation. This can be concluded from the residual displacement field. The residual displacements are very small in comparison to the measured displacements.

To make a good estimation of parameters it is necessary for the strains to be large enough. Also strains should occur in different directions. All these demands were met.

7. RECOMMENDATIONS

It is recommended to use for the finite element computation at least 2 meshes with different numbers of elements, thus offering the possibility to get an impression about the reliability of the estimation.

Also for the same reason it is recommended to make more parameter estimations with the same test piece by carrying out more measurements at several loadings. It is possible to make use of more measurements in one parameter estimation run. This is recommended.

Better results can be obtained by an investigation of the local plastic deformation. If local plastic deformation is implemented in the finite element model, better estimates for the material parameters can be made.

Also use can be made of the local approach, only look at the places where elastic deformation occurs.

It is recommended to investigate the possibility to avoid local plastic deformation by a number of cyclic reloadings.

It is clear that making use of kinematic boundary conditions only, excludes the possibility of estimating the exact parameter values. However the ratios E_1/E_2 and E_1/G_{12} can be estimated well. If E_1 is determined, e.g. by a compression-test, E_2 and G_{12} can be determined from the estimated ratios.

REFERENCES

Jager, J. de

"Application of a numerical/experimental method for the mechanical characterization of wood". WFW 91.097, November 1991

Dinwoodie, J.M.

"Wood: nature's cellular, polymeric fibre-composite". J.M. Dinwoodie, London: Institute of Metals, 1989.

Oomens, C.W.J.

"Constitutieve Modellen". Lecture Notes, Eindhoven University of Technology, Department of Mechanical Engineering, January 1991.

Hendriks, M.A.N.

"Identification of the mechanical behaviour of solid materials". PhD thesis, Eindhoven University of Technology, 1991.

IDEAS User Guide, Engineering Analysis, Pre- and Postprocessing, SDRC.

DIANA Finite Element Analysis, Release 4.1, July 1, 1991 TNO Building and Construction Research.