Identification of the mechanical properties of dog skin

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Identification of the Mechanical Properties of Dog Skin

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September 1994
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Chapter 1

Introduction

To determine the material parameters of the biological tissue skin, a mixed numerical/experimental method, as described by Hendriks (1991), is used. This method includes three elements:

1. measuring the displacements of markers, attached to the material, with a video tracking system (Hentschel, Zamzow, 1990)
2. creating a finite element model of the specimen
3. estimating the material parameters with an identification algorithm, that uses the differences between the measured displacements and the displacements, calculated with the finite element program

Here an experiment as described by Van Ratingen (1994) was repeated. In this experiment dog skin was used, that was taken out of a sheepdog. This dog had been used before as a test object at the university of Limburg. At a biaxial testing system equibiaxially constant-rate-of-stretching tests and an equibiaxial quasi-static extension test were performed. The data from the video tracking system, measured at the equibiaxial quasi-static extension test, were used in the DIANA finite element package to estimate the material parameters.

The objective of this exercise was to improve the experimental protocol as used by Van Ratingen (1994) and to get more experimental data and insight.
Chapter 2

Experiment

With the use of a plastic thin plate frame (figure 2.1) a specimen of about $120 \times 120$ mm$^2$ was taken out of the dog. The material was not frozen like it was done by Van Ratingen (1994). Instead, it was transported in a cooled box and tested after about 4 hours.

![Figure 2.1: Plastic thin plate frame](image)

The specimen was tested in a biaxial testing system, schematically shown in figure 2.2. With this system the applied forces in both $x$ and $y$ directions were measured as function of the extension. Because of the different sizes of the clamps, these forces were divided by the clamp width to obtain the load intensities in both directions.

The following tests were carried out:

- First, the specimen was submitted to five successive equibiaxially constant-rate-of-stretching tests at a rate of 0.1 mm/s, up to 5 mm extension and back.

- Then an equibiaxial quasi-static test was done, in which the specimen was extended up to 6 mm, in steps of 0.25 mm at a constant rate of 0.025 mm/s.
After each step the material was relaxed for about 90 s before the marker displacements were measured. The measurements of this test were used to estimate the parameters.

In figures 2.3 and 2.4 the load intensities in $x$ and $y$ direction, respectively, are shown as function of the extension, for all tests. From these figures the following remarks can be made:

- From the curves of the equibiaxially constant-rate-of-stretching tests a preconditioning effect is observed. These curves converge to a stable solution.
- The superposed sines on the load intensity curves in the $y$ direction are caused by a defect in the testing system.
- It can be seen, that the material $x$ direction is less stiff than its $y$ direction. It is therefore assumed that the fibres are mainly directed at the $y$ direction.
- The quasi-static measurements lie below the curves of the constant-rate-of-stretching tests. This shows that the material has visco-elastic properties.
- In comparison to the results found by Van Ratingen (1994), no significant differences are noticed between freezing and not freezing the material.

Figure 2.2: Biaxial testing system
Figure 2.3: Load intensity in z direction

Figure 2.4: Load intensity in y direction
A finite element analysis was done with the DIANA finite element package. A part of the specimen was modelled as a flat membrane with linear elastic, orthotropic properties. The marker area was divided into $20 \times 20$ Q8MEM elements. These are 4-node, isoparametric, plane stress elements.

The local approach was used to model the experiments. That is, the displacements of the boundary markers were used as kinematic boundary conditions. Since with the local approach no dynamic boundary conditions (i.e. forces) are used, only ratios between stiffness parameters could be estimated.

The orientation of the material symmetry 1-axis in each element was described by the bilinear function:

$$\alpha = b_0 + b_1x + b_2y$$  \hspace{1cm} (3.1)

In this equation $x$ and $y$ are the global coordinates, given in pixels.

The parameter column $\xi$ can now be written as:

$$\xi^T = [ \begin{array}{cccc} b_0 & b_1 & b_2 & \bar{E}_2 & \nu_{12} & \bar{G}_{12} \end{array} ]$$  \hspace{1cm} (3.2)

Where $\bar{E}_2 = E_2/E_1$ and $\bar{G}_{12} = G_{12}/E_1$. 


Chapter 4

Parameter estimation

4.1 Theory

In the module PAREST (Courage and Hendriks, 1993), that is part of the DIANA finite element package, a sequential minimum variance estimator is implemented. In this module a set of observation columns $y_k, k = 1, \ldots, N$, is introduced. Here only one column $y$, containing averaged displacement components of markers, is used. An algorithm, based on the finite element method, is applied to calculate the displacements at the marker positions, for a known $x$. This is represented by a function $h$. With this, the following can be written:

$$ y = h(x) + \nu $$

(4.1)

Where $\nu$ is a column of observation errors. To combine the experimental data and a priori information on $x$, the following quadratic form $S_k$ is minimized with respect to $x$:

$$ S_k = (y - h(x))^T R^{-1} (y - h(x)) + (\hat{x}_k - x)^T P_k^{-1} (\hat{x}_k - x) $$

(4.2)

The measurements provide knowledge on the errors in the displacements in $y$. These errors are expressed in the choice for $R$. The error covariance matrix $P_k$ is given by:

$$ P_k = E\{(\hat{x}_k - E\{\hat{x}_k\})(\hat{x}_k - E\{\hat{x}_k\})^T\} $$

(4.3)

A small, diagonal, nonnegative matrix $Q$ is added to $P_k$ to prevent it from becoming too small or singular, leading to convergence problems.

The optimization problem can be solved iteratively, applying the following scheme:

- Parameter update

$$ \hat{x}_{k+1} = \hat{x}_k + K_{k+1} (y - h(\hat{x}_k)) $$

(4.4)
• Weighting matrix $K_{k+1}$

$$K_{k+1} = (P_k + Q)H_{k+1}^T(H_{k+1}(P_k + Q)H_{k+1}^T + R)^{-1} \quad (4.5)$$

• Estimate error covariance matrix update

$$P_{k+1} = (I - K_{k+1}H_{k+1})(P_k + Q)(I - K_{k+1}H_{k+1})^T + K_{k+1}KK_{k+1}^T \quad (4.6)$$

• With initial conditions

$$\begin{cases} \hat{x}_0 = \bar{x}_0 \\ P_0 = \bar{P}_0 \end{cases} \quad (4.7)$$

The nonlinear function $h$ is linearized with respect to $\hat{x}$:

$$H_{k+1} = \left( \frac{\partial h_k(x)}{\partial \hat{x}} \right)_{\hat{x}=\hat{x}_k} \quad (4.8)$$

### 4.2 Case 1

In figures 2.3 and 2.4 it can be seen, that in the range from 0 to about 3 mm extension the material may be characterized with a linear model. Therefore the reference state was chosen at 0 and the loaded state at 2 mm extension in both $x$ and $y$ directions. The initial values of the parameters were chosen:

$$\hat{x}_0^T = [0 \ 0 \ 0 \ 1 \ 0.3 \ 1] \quad (4.9)$$

Refer to Eq. 3.2 for the parameters in $\bar{x}$.

In the estimation process, the error covariance matrix $P_k$ is updated, which slows down convergence. As noted before, this is compensated by using a matrix $Q$, that is added to $P_k$. Convergence can also be speeded up by restarting the process after a number of iterations. In this way the initial matrix $P_0$ will be used each time the process is restarted, with initial values for the parameters that are equal to the estimates of the previous iteration step.

The following diagonal matrices were chosen for $P_0$ and $Q$:

$$P_0 = [10^{-4}, 10^{-4}, 10^{-4}, 10^{-4}, 10^{-4}, 10^{-4}] \quad (4.10)$$

$$Q = [10^{-8}, 0, 0, 10^{-8}, 10^{-8}, 10^{-8}] \quad (4.11)$$

Now estimation was done by using three methods with restarts, by doing

• subsequently 5, six times 15 and again 5 iterations,

• four times 50 iterations and

• two times 100 iterations.
These three methods delivered the following results:

<table>
<thead>
<tr>
<th></th>
<th>method 1</th>
<th>method 2</th>
<th>method 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_0$</td>
<td>1.280</td>
<td>1.278</td>
<td>1.204</td>
</tr>
<tr>
<td>$b_1$</td>
<td>$6.825 \cdot 10^{-5}$</td>
<td>$6.840 \cdot 10^{-5}$</td>
<td>$7.211 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$b_2$</td>
<td>$-8.159 \cdot 10^{-5}$</td>
<td>$-8.160 \cdot 10^{-5}$</td>
<td>$-7.994 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$E_2$</td>
<td>$4.024 \cdot 10^{-1}$</td>
<td>$4.024 \cdot 10^{-1}$</td>
<td>$4.234 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>$1.000 \cdot 10^{-3}$</td>
<td>$1.000 \cdot 10^{-3}$</td>
<td>$1.289 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>1.056</td>
<td>1.061</td>
<td>1.074</td>
</tr>
</tbody>
</table>

In figures 4.1 to 4.3 the parameter estimates are plotted against the iteration. The first two methods lead approximately to the same numerical values for the parameters. It can be seen from these figures, that with the first method the parameters are converged after about 80 iterations and after about 180 iteration for the second. With the third method however, the parameters are still not converged after 200 iterations. From these results it can be concluded, that method 1 is preferred.

In figure 4.4 the directions of the local material symmetry 1–axes are plotted, as estimated with method 1. The remark, made in chapter 2, that the fibres would mainly be directed at the $y$ direction does not hold, thoug the direction field looks acceptable.

### 4.3 Case 2

In case 1 $\nu_{12}$ tended to go to a negative value, but it was restricted to values of $10^{-3}$ and higher, because a negative Poison's ratio is improbable for skin. This error may be caused by two reasons. First, it is possible that the reference state was not well defined. Secondly, the displacements in the loaded state could be too small and/or there was a lack of information on the Poisson’s ratio’s value.

Therefore new experiments were done with the reference state at 1 mm extension in $x$ and $y$ directions and the loaded one at 3 mm. The initial conditions were chosen equal to those in case 1. In figure 4.5 the parameters are plotted against the iteration number. After 5 and three times 15 iterations, the estimates were given by:

<table>
<thead>
<tr>
<th></th>
<th>$-1.289$</th>
<th>$3.460 \cdot 10^{-4}$</th>
<th>$-2.746 \cdot 10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_0$</td>
<td>$b_1$</td>
<td>$E_2$</td>
<td>$\nu_{12}$</td>
</tr>
<tr>
<td>$b_2$</td>
<td>$G_{12}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$-1.289$</td>
<td>$3.460 \cdot 10^{-4}$</td>
<td>$-2.746 \cdot 10^{-4}$</td>
<td>$1.000 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>$6.098 \cdot 10^{-1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Again $\nu_{12}$ becomes $10^{-3}$ and now $E_2 > 1$, making the 2–axis the stiffest direction. Also, the parameters $b_0$, $b_1$ and $b_2$ describe a physically impossible
direction field. So with an unacceptable direction field, the other parameters should also be distrusted.

Now the initial values of $b_0$, $b_1$ and $b_2$ were chosen to be equal to the estimates, found with the first iteration method in case 1. The initial values of $E_2$, $\nu_{12}$ and $G_{12}$ and the matrices $P_0$ and $Q$ were again chosen as before, giving:

$$\hat{x}_0^T = [1.280 \; 6.825 \cdot 10^{-5} \; -8.159 \cdot 10^{-5} \; 1 \; 0.3 \; 1] \quad (4.12)$$

After three times 15 iterations the parameters converged to acceptable values, as seen in figure 4.6, given by:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_0$</td>
<td>1.596</td>
</tr>
<tr>
<td>$b_1$</td>
<td>$3.649 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$b_2$</td>
<td>$-7.715 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$E_2$</td>
<td>$1.493 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>1.157</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>$6.801 \cdot 10^{-1}$</td>
</tr>
</tbody>
</table>

Van Ratingen (1994) found the following results for his specimen B:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_2$</td>
<td>$1.6 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>1.0</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>$3.1 \cdot 10^{-1}$</td>
</tr>
</tbody>
</table>

In figure 4.7 the direction field is plotted.

Finally matrix $Q$ was enlarged to investigate the effect on convergence, in comparison with using restarts:

$$Q = [10^{-4}, 0, 0, 10^{-4}, 10^{-4}, 10^{-4}] \quad (4.13)$$

The initial conditions were chosen as before, with the estimated values of $b_0$, $b_1$ and $b_2$ from case 1. In figure 4.8 it can be seen that, though the enlarged matrix $Q$ causes oscillations in the estimates, the parameters still converge. Also, convergence is approximately as fast as with the use of restarts. However, as expected, the final estimates contain some small differences, compared to those found with restarts in figure 4.6. The estimated parameters were given by:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_0$</td>
<td>1.620</td>
</tr>
<tr>
<td>$b_1$</td>
<td>$4.095 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$b_2$</td>
<td>$-8.152 \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$E_2$</td>
<td>$1.673 \cdot 10^{-1}$</td>
</tr>
<tr>
<td>$\nu_{12}$</td>
<td>1.147</td>
</tr>
<tr>
<td>$G_{12}$</td>
<td>$7.839 \cdot 10^{-1}$</td>
</tr>
</tbody>
</table>
Figure 4.1: Estimation with method 1 in case 1

Figure 4.2: Estimation with method 2 in case 1
Figure 4.3: *Estimation with method 3 in case 1*

Figure 4.4: *Direction field with $\alpha = 1.280 + 6.825 \cdot 10^{-5}x - 8.159 \cdot 10^{-5}y$*
Figure 4.5: *Estimation with old initial values in case 2*

Figure 4.6: *Estimation with new initial values in case 2*
Figure 4.7: Direction field with $\alpha = 1.596 + 3.649 \cdot 10^{-5}x - 7.715 \cdot 10^{-5}y$

Figure 4.8: Estimation with larger $Q$
Chapter 5
Conclusions and recommendations

- No significant differences are noticed between freezing and not freezing the specimen.

- A pre-conditioning effect is observed from the experimental data.

- The fact that the material shows only a small linear area is probably caused by a large in vivo pre-stress or pre-strain.

- Good correspondence is noticed between estimates found here and those found by Van Ratingen (1994).

- Because of the fact, that only one column \( y \) is used in the sequential minimum variance estimator, matrix \( P_k \) loses its effect after a number of iterations and convergence is slowed down. To compensate this, both updating \( P_k \) by using restarts, as adding matrix \( Q \) to \( P_k \) are used. The final estimates contain some small differences, because in both cases a slightly different quadratic form \( S_k \) is minimized.
References


