A numerical experimental analysis of a simple head model

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A numerical and experimental analysis of a simple head model

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Eindhoven, July 2000
Summary

At the University of Technology in Eindhoven a research project is set up with the title: "Determination of the dynamical behaviour of brain tissue during impact loading". To be able to determine the local response during an impact load a numerical head model has been developed in MADYMO. Partial testing of the numerical model occurs with a physical head model. In this physical head model the head is represented as a cup filled with a silicon gel that represents the brain (Michielsen, 1996, Roersma, 1998). The dynamical response of the cup filled with silicon gel can be made visible with the aid of markers and a high speed camera.

In this study the comparison of the numerical model with an experiment is done.

First three benchmark tests were done; omni-directional compression, simple shear and (un)-constrained tension. For omni-directional compression and constrained tension MADYMO shows no significant errors. For simple shear the shear strains were two times too small and the principal strains resulted in spikes. MADYMO prescribes the principal stresses in unconstrained tension not correct. This problem is related to the eigenfrequency of the system. From these tests can be concluded that the governing equations are solved correctly, but that the shear strain and principal strain output is incorrect.

In the experiment the physical head was rotated over 2.4 rad within 53 ms. The markers at the centre of the model show a larger delay in relative rotation, with respect to the cup, than the markers near the edge. The silicon gel deformed three dimensionally.

From the comparison between the numerical simulation and the experiment, it can be concluded that the trends were much alike. The tops in the relative rotation were almost on the same time and the same level. However at the end the simulation the markers shows an increase in delay of the relative rotation whereas the marker delay in the experiment still decreases. The maximum volume change was 26% despite a high bulk modulus of 1 GPa. The principal strains were at maximum 30%. This is a relevant strain for brain injury since from literature is known that brain-injury occurs when the strain in nerves is more than 20%.

It can be concluded that differences between simulation and experiment can be attributed largely to differences in numerical artefacts rather than to errors in material properties. Variations in material properties do not affect the trends in the simulation, only the level. Numerical variations influence in particular the decrease in slope after the tops of the relative rotation.
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<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>principal strain</td>
<td>[(-)]</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>strain rate</td>
<td>[(-)]</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>stretch ratio</td>
<td>[(-)]</td>
</tr>
<tr>
<td>( \rho )</td>
<td>density</td>
<td>[kg/m(^3)]</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Cauchy stress</td>
<td>[N/m(^2)]</td>
</tr>
<tr>
<td>( \tau )</td>
<td>time constants</td>
<td>[sec]</td>
</tr>
<tr>
<td>( \vec{v} )</td>
<td>velocity</td>
<td>[m/sec]</td>
</tr>
<tr>
<td>( G )</td>
<td>shear modulus</td>
<td>[Pa]</td>
</tr>
<tr>
<td>( K )</td>
<td>bulk modulus</td>
<td>[Pa]</td>
</tr>
<tr>
<td>( t )</td>
<td>time</td>
<td>[sec]</td>
</tr>
<tr>
<td>( V )</td>
<td>deformed volume</td>
<td>[m(^3)]</td>
</tr>
<tr>
<td>( V_0 )</td>
<td>original volume</td>
<td>[m(^3)]</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Cauchy stress matrix</td>
<td>[N/m(^2)]</td>
</tr>
<tr>
<td>( \mathbf{E} )</td>
<td>Green-Lagrange strain matrix</td>
<td>[(-)]</td>
</tr>
<tr>
<td>( \mathbf{F} )</td>
<td>deformation matrix</td>
<td>[(-)]</td>
</tr>
<tr>
<td>( \mathbf{I} )</td>
<td>unity matrix</td>
<td>[(-)]</td>
</tr>
<tr>
<td>( \mathbf{P} )</td>
<td>second Piola Kirchhoff stress matrix</td>
<td>[Pa]</td>
</tr>
</tbody>
</table>
1 Introduction

The head of the human is considered to be the most critical body part in crash situations. Up to now it is still unknown how an external load leads to head injury. Investigation is done to get insight in the relation between the mechanical load and the response of the head. The most ideal situation is directly measuring the response of the head when an external load is applied. However this is not possible and to solve this problem numerical head models are developed. The problem with these numerical head models is the validation. Physical head models are developed to test the quality of the numerical methods used in the numerical head models.

At the University of Technology in Eindhoven a research project is set up with the title: "Determination of the dynamical behaviour of brain tissue during impact loading". To be able to determine the local response during an impact load a numerical head model has been developed in MADYMO. Testing of the numerical model occurs with a physical head model. In this physical head model the head is represented as a cup filled with a silicon gel that represents the brain (Michielsen, 1996, Roersma, 1998). This silicon gel is visco-elastic and is described by a four mode Maxwell model. The dynamical response of the cup filled with silicon gel can be made visible with the aid of markers and a high speed camera.

In this research first three benchmark tests were done to investigate the reliability of MADYMO (chapter 2). Then two experiments are executed (chapter 3). The experiments are simulated in MADYMO and the comparison is made between the experiments and the simulation (chapter 4). Finally the differences between the experiments and the simulation are investigated by numerical variations and variations in material parameters (chapter 5).
2 Testing of MADYMO in simple loading conditions

During simulation of the physical model experiment, it is noticed \cite{1} that the volume change in some elements is larger than expected. Because of a great bulk modulus the material was expected to be almost incompressible. Another problem was that the shear strains were a factor two smaller as predicted theoretically. To investigate these problems, three benchmark tests were done: omni-directional compression, simple shear and (un)constrained tension. Theory and MADYMO are compared to each other in this chapter to investigate the reliability of MADYMO.

2.1 General material model description

Analytical

The analytical problem is solved with a linear elastic cube. The following relation between the second Piola-Kirchhoff stress $\mathbf{P}$ and the Green-Lagrange strain $\mathbf{E}$ was used:

$$
\mathbf{P} = (K - \frac{2}{3}G)\text{tr}(\mathbf{E}) + 2GE
$$

where

$$
\mathbf{E} = \frac{1}{2}(\mathbf{F}^C \cdot \mathbf{F} - \mathbf{I})
$$

and $\mathbf{F}$ is the deformation matrix.

Representative for the gel used in chapter 4 are the following values. The shear modulus, $G$, is 216.4095 Pa. It represents the equilibrium shear modulus which is extracted by a fit \cite{4} on data obtained by Brands \cite{121}. The bulk modulus, $K$, depends on the speed of sound \cite{3} and the density. The bulk modulus is calculated to be 1.0961, 10^9 Pa.

The Cauchy stress is defined as:

$$
\mathbf{\sigma} = \frac{1}{\text{det(\mathbf{F})}} \mathbf{F} \cdot \mathbf{P} \cdot \mathbf{F}^C
$$

For the analytical solutions equation 2.4 is solved.

$$
\mathbf{\nabla} \cdot \mathbf{\sigma} = 0
$$

(2.4)

MADYMO uses the overall equation:

$$
\mathbf{\nabla} \cdot \mathbf{\sigma} = \rho \dot{\mathbf{v}}
$$

(2.5)

Equation 2.4 and 2.5 are equal when $\rho \dot{\mathbf{v}}$ is small compared to $\mathbf{\nabla} \cdot \mathbf{\sigma}$. This has been achieved by applying the displacement in MADYMO slowly and keeping the system at rest afterwards so $\rho \dot{\mathbf{v}}$ is really zero.

Numerical

MADYMO test version 5.4 is used. The element that is used is SOLID 1; an eight node brick that can carry tensile, compression and shear loads. The element uses reduced integration with only one integration point, this reduces the CPU-time and prevents mesh locking but results in twelve hourglass modes. To eliminate the occurrence of hourglasses, MADYMO applies an Hourglass preventive algorithm that includes the hourglass stabilisation parameter that is set to default value. The material model that is used is linear visco-elastic (LINVIS). This is the same model as used for the silicon gel that represents the brain and that is used in the experiments. This LINVIS model is basically a four mode Maxwell model.
The parameters (see Table 2.1) used in this chapter are chosen such that the LINVIS model reduces to the linear elastic model (see equation 2.1). In this way MADYMO and theory can be compared.

Table 2.1 Four-mode Maxwell parameters

<table>
<thead>
<tr>
<th>i</th>
<th>$G_i$ [Pa]</th>
<th>$\tau_i$ [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\infty$</td>
<td>216.4095</td>
<td>-</td>
</tr>
</tbody>
</table>

The density of the material used is 970 kg/m³ and the volume of the cube is 1.

2.2 Omni-directional compression

Theory

A cube is omni-directional compressed, see Figure 2.1. The sides of the cube reduce from $l_0$ to $l$.

![Figure 2.1: omni-directional compression of a cube with original dimensions $l_0$ and deformed dimensions $l$](image)

For this experiment the deformation matrix $F$ and the Green-Lagrange strain $E$ equal:

$$F = \begin{bmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda \end{bmatrix}$$  \hspace{1cm} (2.6)

$$E = \frac{1}{2} \begin{bmatrix} \lambda^2 - 1 & 0 & 0 \\ 0 & \lambda^2 - 1 & 0 \\ 0 & 0 & \lambda^2 - 1 \end{bmatrix}$$  \hspace{1cm} (2.7)

Where $\lambda$ represents the stretch ratio ($l/l_0$), which is equal for all three directions.
Substitution of $E$ in the constitutive equation 2.1 yields:

$$P = \begin{bmatrix} p & 0 & 0 \\ 0 & P & 0 \\ 0 & 0 & p \end{bmatrix}$$

(2.8)

with $P = \frac{1}{2}K(\lambda^2 - 1)$

The Cauchy stresses that are also the principal stresses follow from equation 2.3 after substitution of $F$ and $P$.

$$\sigma_{xx} = \sigma_{yy} = \sigma_{zz} = \frac{1}{2}K \left( \frac{\lambda^2 - 1}{\lambda} \right)$$

(2.9)

The volume change is defined as

$$\Delta V = \frac{V - V_0}{V_0}$$

(2.10)

With $V_0$ is the original volume and $V$ the deformed volume. The ratio between $V$ and $V_0$ is described in equation 2.11.

$$V = \lambda^3 V_0$$

(2.11)

MADYMO

Omni-directional compression is applied using prescribed nodal displacements according to:

$$\lambda = 0.9 - 0.1 \cos(\pi + \pi/300t) \quad \text{for } t = 0 - 300 \text{ ms}$$

$$\lambda = 0.8 \quad \text{for } t = 300 - 480 \text{ ms}$$

Results

The results of the theory and MADYMO for the stress, strain and volume change can be seen in Figure 2.2. The strain, volume and the stresses of MADYMO follow the theory well. For the strain is the maximum difference $4*10^{-5} \%$. For the volume is the maximum difference $4.0*10^{-5} \%$. For the stress is the maximum difference also $4*10^{-5} \%$. The strain and the volume are prescribed by the boundary conditions, the stresses however are calculated by solving equation 2.5.
Conclusions

Differences between the theory and MADYMO can be neglected (maximum difference $4\times10^{-2}$ %). MADYMO represents the stress, Green-Lagrange strain and volume well. The volume changes as seen by Bax [1] are not an error of MADYMO.

2.3 Simple shear

Theory

This test compares MADYMO and theory for simple shear. Simple shear is visualised by Figure 2.3.

\[ \mathbf{F} = \begin{bmatrix} 1 & \gamma & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \]  

\hspace{3em}(2.12)
with $\gamma = \frac{s}{x}$, $s$ = displacement, $x$ = height of cube.

The second Piola-Kirchhof stress can be calculated according to equation 2.1.

$$\mathbf{E} = \frac{1}{2} \begin{bmatrix} \gamma^2 & \gamma & 0 \\ \gamma & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

(2.13)

The Cauchy stresses are then (see also equation 2.3).

$$\mathbf{P} = \begin{bmatrix} \left(K - \frac{2}{3}G\right)\frac{1}{2}\gamma^2 + Gy^2 & Gy^2 & 0 \\ Gy^2 & \left(K - \frac{2}{3}G\right)\frac{1}{2}\gamma^2 & 0 \\ 0 & 0 & \left(K - \frac{2}{3}G\right)\frac{1}{2}\gamma^2 \end{bmatrix}$$

(2.14)

The principal strains are the roots of the characteristic equation that follows from the determinant.

$$\det(\mathbf{E} - \alpha\mathbf{I}) = \begin{vmatrix} \frac{1}{2}\gamma^2 - \alpha & \frac{1}{2}\gamma & 0 \\ \frac{1}{2}\gamma & -\alpha & 0 \\ 0 & 0 & -\alpha \end{vmatrix} = 0$$

(2.18)

The characteristic equation is then:

$$\alpha^2 \left(\frac{1}{2}\gamma^2 - \alpha\right) + \alpha \left(\frac{1}{2}\gamma\right)^2 = 0$$

(2.19)

It follows that the principal strains are:

$$\alpha_1 = \frac{1}{4}\gamma^2 + \frac{1}{4}\sqrt{\gamma^2 + 4}$$
$$\alpha_2 = \frac{1}{4}\gamma^2 - \frac{1}{4}\sqrt{\gamma^2 + 4}$$
$$\alpha_3 = 0$$

(2.20)

**MADYMO**

The cube is deformed under simple shear, this means in MADYMO that the upper face is moved with a sinuslike movement. The simple shear is applied using prescribed nodal displacement according to: $y = 0.01 \times \sin(\omega t)$.

**Results**

The results of MADYMO and the theory are shown in Figure 2.4 (strain), Figure 2.5 (stresses) and Figure 2.6 (principal strains).

The maximum difference between theory and MADYMO for the strain in XX-direction is $1 \times 10^{-4}$% with respect to the peak value. The difference between theory and MADYMO for the strain in XY-direction is 50 %.

The maximum difference in stress between theory and MADYMO is 0.3 % in XX- and YY-direction and 2 % in XY-direction.
The first and the third principal strains are zero except for some spikes. The second principal strain is negative with some spikes to zero. The spikes occur at random. More insight in the occurrence of the spikes is gained by comparing the sum of the principal strains obtained with MADYMO and theory in Figure 2.7.

Figure 2.4: Green-Lagrange strain for a cube in simple shear. MADYMO results, directly from output

Figure 2.5: Cauchy stresses for a cube in simple shear. MADYMO results, directly from output
Figure 2.6: principal strains in simple shear. Theory results sorted to magnitude where $\frac{1}{2}$ theory means that the XY-component of the Green-Lagrange strain is divided with 2 by calculating the principal strains. MADYMO results, directly from output.

Figure 2.7: adding the principal strains for a cube in simple shear for the theory and MADYMO

From Figure 2.7 can be concluded that the difference is not caused by arranging the principal strains.

Conclusions

The Green-Lagrange shear strain is a factor 2 too small. The other strains are represented with little difference. The maximum difference is then $1\times10^{-4}$%. The maximum difference for the stress is 2%. MADYMO predicts
the principal strains not good. Spikes occur and the values are not correct. To investigate the source of this error, the principal strains have been recalculated but now with the XY-component of the Green-Lagrange strain divided by 2. The principal strain, calculated in this way, coincides with the spikes obtained using MADYMO (see Figure 2.5). Further differences between the principal strains can also be contributed to different arranging of the principal strains in theory and MADYMO. However apart from the spikes and rearranging, MADYMO predicts two of the principal strains to be zero, whereas theory predicts only one. The non-zero MADYMO result coincides with the theory, adjusted as explained above. The arranging of the principal strains is not the cause of the difference between theory and MADYMO.

2.4 Unconstrained and constrained tension

Theory

A single cube element is deformed in x-direction under tension (see also Figure 2.8).

![Diagram of constrained and unconstrained tension for a cube with original dimensions $x_0$, $y_0$, and $z_0$, and with the changed dimensions $x$, $y$, and $z$.](image)

Unconstrained

Constrained

Figure 2.8: constrained and constrained tension for a cube with original dimensions $x_0$, $y_0$, and $z_0$, and with the changed dimensions $x$, $y$, and $z$

A difference is made between the constrained and the unconstrained case. When the cube is deformed under constrained tension no movement occurs in $y$ and $z$ directions, under unconstrained tension the movement in $y$ and $z$ directions is free.

**Constrained tension**

For the constrained case, the deformation-matrix $\mathbf{F}$ is:

$$
\mathbf{F} = \begin{bmatrix} \lambda & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}
$$

(2.21)

where $\lambda$ represents the stretch ratio.

And the Green-Lagrange strain is then (see equation 2.2):

$$
\mathbf{E} = \frac{1}{2} \begin{bmatrix} \lambda^2 - 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}
$$

(2.22)

The second Piola-Kirchhoff stress tensor is (see equation 2.1):
The Cauchy stresses are also the principal stresses.

**Unconstrained tension**

For the unconstrained case, the deformation-matrix $F$ is:

$$F = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_2 \end{bmatrix}$$  \hspace{1cm} (2.28)

where $\lambda_1$ represents the stretch ratio and $\lambda_2$ is the stretch ratio due to the movement in $y$ and $z$.

And the Green-Lagrange strain is then (see equation 2.2):

$$E = \frac{1}{2} \begin{bmatrix} \lambda_1^2 - 1 & 0 & 0 \\ 0 & \lambda_2^2 - 1 & 0 \\ 0 & 0 & \lambda_2^2 - 1 \end{bmatrix}$$  \hspace{1cm} (2.29)

The second Piola-Kirchhoff stress tensor is (see equation 2.1):

$$P = \begin{bmatrix} P_1 & 0 & 0 \\ 0 & P_2 & 0 \\ 0 & 0 & P_2 \end{bmatrix}$$  \hspace{1cm} (2.30)

Where

$$P_1 = (K - \frac{2}{3} G)\left(\frac{1}{2}(\lambda_1^2 - 1) + (\lambda_2^2 - 1)\right) + G(\lambda_1^2 - 1)$$  \hspace{1cm} (2.31)

$$P_2 = (K - \frac{2}{3} G)\left(\frac{1}{2}(\lambda_1^2 - 1) + (\lambda_2^2 - 1)\right) + G(\lambda_2^2 - 1)$$  \hspace{1cm} (2.32)

And according to equation 2.3 the Cauchy stresses are.

$$\sigma_{xx} = \frac{\lambda_1}{\lambda_2} \left[ (K - \frac{2}{3} G)\left(\frac{1}{2}(\lambda_1^2 - 1) + (\lambda_2^2 - 1)\right) + G(\lambda_1^2 - 1) \right]$$  \hspace{1cm} (2.33)

$$\sigma_{yy} = \sigma_{zz} = \frac{1}{\lambda_1} \left[ (K - \frac{2}{3} G)\left(\frac{1}{2}(\lambda_1^2 - 1) + (\lambda_2^2 - 1)\right) + G(\lambda_2^2 - 1) \right]$$  \hspace{1cm} (2.34)
These Cauchy stresses are also principal stresses. Since unconstrained tension is considered the cube is in planars perpendicular to y and z 'stress-free'. This holds that the stresses $\sigma_{yy}$ and $\sigma_{zz}$ in are zero.

$\lambda_2$ can now be separated in equation (2.34) following:

$$\lambda_2 = \sqrt{\frac{1}{2} (K - \frac{2}{3} G) (\lambda_1^2 - 1)} \quad \left( K + \frac{1}{3} G \right) + 1$$

(2.35)

MADYMO

The cube has ribs with initial length 1. Tension is realised by nodal displacement following the next steps.

$\lambda_1 = 0.1 \times \cos(\pi + \pi / 300 \times t) + 1.1$ for $t = 0-300 \text{ ms}$

$\lambda_1 = 1.2$ for $t = 300-480 \text{ ms}$

Results

In Figure 2.9 are the strains of the constrained tension plotted. Maximum difference between theory and MADYMO is $3 \times 10^{-5}$%.

![Graph of Green-Lagrange strain in XX-direction in constrained tension, MADYMO results, directly from output](image)

In Figure 2.10 are the stresses of the constrained tension plotted. Maximum difference between theory and MADYMO is $3 \times 10^{-5}$%. The stress in YY-direction is equal to the stress in ZZ-direction as predicted in theory.
Figure 2.10: principal stresses in constrained tension. MADYMO results, directly from output

Figure 2.11: Green-Lagrange strain in XX and YY-direction in unconstrained tension. MADYMO results, directly from output

In Figure 2.11 are the strains plotted for the unconstrained case. The strain in YY-direction is equal to the strain in ZZ-direction. These results show a maximum difference of $3 \times 10^{-5}$ % and 0.2 % in XX- and YY-direction respectively. In Figure 2.12 the stresses of the unconstrained tension are plotted. The stress in YY-direction is equal to the stress in ZZ-direction. The Cauchy stresses fluctuate all the time.
To find out what the cause is of this behaviour the following numerical actions are taken:
1. the time step in MADYMO is divided by 10
2. the strain is divided by 10
3. reduced integrated SOLID 1 element is replaced by a fully integrated SOLID 8
4. the block is represented by 8 elements instead of 1

Non of the actions had any effect on the fluctuations.

To find out what else could cause the fluctuations also physical parameters were looked at. The density and the bulk modulus were changed, this was done to find out what the influence is of these parameters on equation 2.5.

The eigenfrequency, $f$, is proportional to the square root of $\frac{K}{\rho}$. Firstly the bulk modulus is decreased from $1.0961 \times 10^9$ Pa to $1.0961 \times 10^6$ Pa and secondly the density is increased from $970$ kg/m$^3$ to $970 \times 10^3$ kg/m$^3$. The results are plotted in Figure 2.13.

The fluctuations are less but they still occur. The frequency of the fluctuations is reduced with a factor 30 that is equal to the square root of 1000 (the bulk-modulus decreases and the density increases 1000 times). This indicates that the problem of the fluctuations in the stresses has something to do with the eigenfrequency. When the density is increased, the amplitude of the main stress is much higher. When however the bulk modulus is decreased the amplitude is lower. When the results of the decreased bulk modulus are multiplied with 1000 this gives almost the same results as the decreased density.
Conclusions

In case of the constrained tension MADYMO can produce correct answers with an error of $3 \times 10^{-5}$ % at maximum. For unconstrained tension MADYMO produces good results for the strains, however for the stresses MADYMO produces errors which cannot be explained. The density and the bulk modulus do affect the errors.

2.5 Chapter conclusions

For omni-directional compression MADYMO shows no significant errors. For simple shear MADYMO produces errors: the shear strain is two times too low and the principal strains result in spikes. The stresses show no significant differences. For tension MADYMO shows no significant errors for the constrained case. For the unconstrained case, problems occur for the stresses. These problems are related to the eigenfrequency of the system.

During these experiments MADYMO version 5.4.1 was released. To find out whether this version was improved the same tests were done. However the new version gave the same results. MADYMO 5.4.1 shows the same errors.
3 Experiment

The aim of the experiment is to apply traffic impact related loading conditions on a material representative for brain tissue. This material is a silicon gel (Dow Corning, Sylgard 527 A&B). A cup and the gel are a simplification of the sagittal head cross-section. The cross-section splits the head in 2 symmetric parts and therefore a head rotation results in a two dimensional motion. This experiment is done to get information about the dynamic response of the material.

3.1 Experimental set up

A cup filled with gel is subjected to a fast rotation. To rotate the cup, the same set up is used as by Bax [1]. A spring is chosen as loading device for the cup. The spring is connected to the cup with a ratchet wheel. The ratchet wheel is used to elongate the spring. The wheel is fixed after the load is applied. The elongation of the spring will be described as ticks of the ratchet wheel. Once the cup is released, it starts to rotate due to the spring force. On the top of the gel and the cup there are markers that begin to move when the cup begins to rotate. The motion of the markers is recorded by a high speed camera, the optical axis of which is oriented along the cup axis (see Figure 3.1). The images recorded during the experiment are post-processed in Matlab. This results in data about the two dimensional rotation of the markers. The rotation of the markers can be presented with respect to the rotation of the cup. For more details see Bax [1]. The experiment is done with 2 and 4 ticks of the ratchet wheel.

![Figure 3.1: top view of the cup](image)

3.2 Results

A qualitative impression of the deformation of the gel in the 4 ticks experiment is shown in Figure 3.2

![Figure 3.2: side view of the cup 4 ticks at ± 25 ms, the black dots are the markers](image)

The cup rotation and the movement of the markers can now be described by means of marker trajectories that are plotted in Figure 3.3. The total experiment lasted 78 ms.
The cup stops rotating when it hits an end-stop, this is the end of the motion range. The stop of the cup causes the loop at the end of the marker rotation. It can be seen that the marker motion is predominately angular, not radial.

In Figure 3.4 the angular rotation of the markers is plotted as the relative displacement as function of the angular cup rotation.

At t=0 ms the cup begins to move. The markers have a delay in rotation with respect to the rotation of the cup. Marker 3 in Figure 3.4 is the last marker that begins to rotate. Marker 1 is the first marker that follows the rotation of the cup. All the tops of the markers occur from t=24-27 ms. At t=43 ms the movement is abruptly stopped because the cup hits the end-stop and this causes the negative tops, i.e. the marker rotation exceeds the cup rotation. The motion of the gel was three dimensional when the elongation of the ratchet wheel was 4 ticks.
(see Figure 3.2). To reduce this effect also an experiment is done with an elongation of the spring of 2 ticks of the ratchet wheel.

The deformation with 2 ticks is still three dimensional but less than the four ticks (see Figure 3.5).

In Figure 3.6 the trajectories of the markers are plotted as the relative displacement as function of the angular cup rotation. At $t=0$ the cup begins to move. The markers have a delay in rotation with respect to the rotation of the cup. Marker 3 in Figure 3.5 is the last marker that begins to rotate. Marker 1 is the first marker that follows the rotation of the cup. All the tops of the markers occur from $t=20-24$ ms. The end-stop is reached at $t=56$ ms.

![Figure 3.5: side view of the cup 2 ticks at ±20 ms, the black dots are the markers](image1)

![Figure 3.6: relative displacement of the markers 2 ticks](image2)
3.3 Discussion/Conclusion

The three dimensional effects are still present at the 2 ticks experiment although the effects were less compared to the 4 ticks. The experimental set up is a simplification of the sagittal head cross-section and to keep this experiment realistic the three dimensional effects are not wanted. The markers show a delay in rotation compared to the cup.

Now the experiment with an elongation of 4 ticks and that of Bax [1] are compared to each other (see also Figure 3.7). Bax noticed two tops, the first top is probably a result of releasing the spring a little due to lifting a handle which locks the ratchet wheel. The second top is due to the release of the spring's energy. Bax's first top is not considered for the comparison and only the top from \(t=23\) to \(t=54\) ms is noticed.

The rotation of the cup in both experiments is almost equal, 2.4 rad. The relative rotations of the markers in this experiment are less than that of Bax. The amplitude of the relative rotation is reduced with \(\pm 25\%\) for all the markers. This can be explained by the ageing of the gel. The gel used in this experiment is the same as Bax used. The gel then was 4 days old while at the day of testing now the gel was 4 months of age. The maximum amplitudes of each marker are on the same time.

Figure 3.7: relative displacement of the markers, 4 ticks as seen by Bax [1]
4 Simulation of the experiment in MADYMO

A numerical model of the experiment is developed in MADYMO. MADYMO is a combined program, multi-body and finite element. The experiment of previous chapter was done to check the results of a Finite Element, FE, model in MADYMO. An advantage of such model is that output parameters can be generated which can not be measured with an experiment.

It is hypothesised that brain damage is caused by strains in the brain of 20% and more [1]. After a check whether MADYMO describes the experiment accurately, the strains are presented. In chapter 2 is concluded that there are no substantial differences between MADYMO 5.4 test version and MADYMO version 5.4.1. The test version is used because existing post-processing programs were used and they were written for the test-version.

4.1 Numerical model

In chapter 2 a material model was introduced for a linear elastic material. In that case most of the parameters were zero (see Table 2.1). The gel in chapter 3 was a visco-elastic material and the shear-properties of this gel were investigated by Brands [2] for frequencies ranging from 1 to 8086 rad/sec. The behaviour of the gel was described using a 4-mode Maxwell-model. Material parameters were obtained using the Levenbergh-Marquardt algorithm in the fit procedure implemented in MATLAB by Zoetelief [4]. Results of this fit procedure are shown in Table 4.1 and Figure 4.1.

<table>
<thead>
<tr>
<th>Table 4.1</th>
<th>Four-mode Maxwell parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>$G_i$ [Pa]</td>
</tr>
<tr>
<td>1</td>
<td>2.7599.10^4</td>
</tr>
<tr>
<td>2</td>
<td>1.1712.10^2</td>
</tr>
<tr>
<td>3</td>
<td>3.7879.10^2</td>
</tr>
<tr>
<td>4</td>
<td>1.2232.10^-1</td>
</tr>
<tr>
<td>$\infty$</td>
<td>216.4095</td>
</tr>
</tbody>
</table>

Figure 4.1: the loss- and elastic-modulus of the gel and the fit made with the parameters of Table 4.1
The geometry of the model consists of the silicon gel only. The cup was modelled as a boundary condition. It is sufficient to prescribe the movement of the outer nodes since it is assumed that no slip occurs between cup and the gel. The gel is modelled with 1104 elements and has a radius of 0.015 m and a height of 0.013 m. The mesh is plotted in Figure 4.2. For more details see Bax [1].

To compare MADYMO with the experiment the trajectories of nodes in MADYMO must be followed. Bax [1] uses points that have almost the same radii as the markers in the experiment. Because, in the FE-model, the relation between two nodal displacements is linear, the displacements of nodes were interpolated so they could be compared to the markers with the same radii in the experiment, without losing accuracy. To investigate the strains, first the volume-change was measured of elements along radial cross-section A-A in Figure 4.2. Next, the principal strains were investigated in the element where the volume change was largest.

4.2 Results

In Figure 4.3 the relative marker rotation is plotted as seen in the experiment and in the simulation for two ticks.
The delay in angular rotation in the simulation is larger than in the experiment. In comparison to the experiment, in the simulation the decrease after the top is faster for point 3 and slower for point 1. Point 2 follows the experiment after the top. At $t=42$ ms the delay in angular rotation for all three points begins to increase in contrary to the experiment where delay still decreases slowly.

In Table 4.1 the amplitudes of the tops and the times when they occur are presented.

<table>
<thead>
<tr>
<th>Number of marker</th>
<th>Amplitude: top [rad]</th>
<th>% difference amplitude</th>
<th>Time: top [ms]</th>
<th>% difference time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Experiment</td>
<td>0.1318</td>
<td>+8 %</td>
<td>0.0202</td>
<td>+9 %</td>
</tr>
<tr>
<td>MADYMO</td>
<td>0.1423</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Experiment</td>
<td>0.2434</td>
<td>+1 %</td>
<td>0.0222</td>
<td>+1 %</td>
</tr>
<tr>
<td>MADYMO</td>
<td>0.2470</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Experiment</td>
<td>0.3160</td>
<td>+5 %</td>
<td>0.0238</td>
<td>-6 %</td>
</tr>
<tr>
<td>MADYMO</td>
<td>0.3316</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At the end of the simulation the relative marker rotation is too high compared to the experiment. These differences are presented in Table 4.2

<table>
<thead>
<tr>
<th>Number of marker</th>
<th>% difference amplitude</th>
<th>100% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>128 %</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>82 %</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>56 %</td>
<td></td>
</tr>
</tbody>
</table>

The differences increase with increasing radius of the markers.

The maximal volume change for the elements on cross-section A-A is to be seen in Figure 4.4. The volume change differs from $-0.7\%$ to $-26.3\%$. The maximum volume change occurs in an element that lies on the outside of the model. For this element the volume change in the time is plotted in Figure 4.5.

Figure 4.4: maximal volume change for 2 ticks, direct MADYMO output used
The volume change for this element shows 2 fast decreases and is relatively constant from $t=18$ to 43 ms.

To get an idea of the strains that occur for this element, the cartesian strains and principal strains are plotted in Figure 4.6 and Figure 4.7. The shear strains are corrected with a factor 2, this because MADYMO produces shear strains which are a factor 2 too low. The principal strains are calculated from the cartesian strain output, provided by MADYMO because the principal strains that follow out of MADYMO are not correct (see chapter 2).
MADYMO produces cartesian strains while cylindrical strains are easier to interpret. This is the reason that the principal strains are also plotted. At $t=22$ ms the tops in Figure 4.3 occur and at this time the maximum shortening is order $30\%$ (principal strain 1, figure 4.7)). The shortening increases slowly after this time. The maximal lengthening is order $30\%$ and is also slowly increasing. The maximal volume change and maximal principal strains are at $t = 55$ ms just before the cup hits the end-stop. The volume change is checked by multiplying the principal strains with the original volume (see equation 2.1), the volume change is represented well.

For the 4 ticks simulation the relative angular rotation is less than in the experiment (see Figure 4.8). The maximum delay is earlier than the experiment. The decrease after the top is in the simulation faster for point 2 and 3. Point 1 decreases slower than the experiment. Top 1 is wide compared to top 2 and 3. At $t=36$ ms the relative rotation of the simulation seems to stay relatively constant.
4.3 Discussion/Conclusion

For 2 ticks are the differences, between experiment and simulation, for a range from t=0 to 40 ms pretty good (see Table 4.2). After this time MADYMO and the experiment begin to diverge (see Table 4.3). The differences can be an effect of numerical aspects or of some material parameters. Figure 4.9 shows that the mesh is not as fine as it should be, there are edges were a smooth line is expected. The maximum in volume change and principal strains occurs at t=55 ms. From Figure 4.3 follows that at this time the simulation and the experiments begin to diverge. At t=23 ms the strains and principal strains that occur are in the range where brain damage is expected. For 4-ticks the tops of the simulation are too low and only for the first 20 ms the simulation describes the experiment well.

The volume changes up to 26% under this loading condition may be caused by the ‘open’ top of the cup. The changes are considered to be smaller when the top of the cup is covered.
5 Parametric study

In chapter 4 differences can be seen between experiment and simulation. These differences can be caused by the material parameters or numerical artefacts due to mesh and other input parameters used for the simulation. In this chapter the numerical artefacts and the material parameters are varied and their effect is studied by comparing the simulation results obtained using the varied parameter with a reference situation presented in chapter 4 and Table 4.1. The influence of these variations is analysed in terms of the change of the relative rotation of the markers. The variations of this chapter are summarised in Table 5.1.

Table 5.1: different variations in chapter 5

<table>
<thead>
<tr>
<th>Type of variation</th>
<th>Name:</th>
<th>What is changed:</th>
<th>How is it changed:</th>
<th>§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numerical</td>
<td>8 times refinement</td>
<td>Mesh</td>
<td>Mesh is refined 8 times</td>
<td>5.1.1</td>
</tr>
<tr>
<td></td>
<td>64 times refinement</td>
<td>Mesh</td>
<td>Mesh is refined 64 times</td>
<td>5.1.2</td>
</tr>
<tr>
<td></td>
<td>Solid 8</td>
<td>Type of the elements</td>
<td>Type is change from SOLID 1 in SOLID 8</td>
<td>5.1.3</td>
</tr>
<tr>
<td></td>
<td>Hourglass</td>
<td>Hourglass parameter</td>
<td>Hourglass parameter is divided by 10</td>
<td>5.1.4</td>
</tr>
<tr>
<td>Material</td>
<td>G change</td>
<td>Shear moduli</td>
<td>All shear moduli are increased/decreased 10% compared to Table 4.1</td>
<td>5.2.1</td>
</tr>
<tr>
<td></td>
<td>τ change</td>
<td>Time constants</td>
<td>All time constants are increased/decreased 10% compared to Table 4.1</td>
<td>5.2.2</td>
</tr>
<tr>
<td></td>
<td>G&lt;sub&gt;0&lt;/sub&gt; zero</td>
<td>Fit procedure</td>
<td>A new fit is done with G&lt;sub&gt;0&lt;/sub&gt; is set to zero. Parameters are in Table 5.2</td>
<td>5.2.3</td>
</tr>
</tbody>
</table>

5.1 Numerical variations

To investigate the influence of the mesh in the simulation, the mesh is refined 8 times and 64 times. Also the element type is changed from SOLID1 into SOLID8. Next the hourglass parameter, which reduces the risk of hourglassing, is reduced.

5.1.1 8 times refinement

For the 8 times refinement each element of the reference simulation was divided in 2 layers of 4 elements. The gel is then simulated with 8832 elements. The CPU-time, the effective time the computer uses to solve the simulation, is increased from 567.9 to 11933.6 seconds. This is an increase of 2101%. The results are plotted in Figure 5.1.

![Graph showing relative rotation of markers for reference simulation and 8 times refinement](image)

Figure 5.1: Relative rotation of the markers for the reference simulation and the 8 times refinement. Centre marker is the lowest line, in between marker is the mid-line, edge marker is the top-line.
As compared to the reference simulation, in this simulation the onset of the marker rotations is similar. However, maximum rotations are higher and occur later. The subsequent decrease of the rotation occurs less fast. Finally, the increase of rotation, occurring in the reference simulation after 40 ms, is absent in the present simulation.

5.1.2 64 times refinement

For the 64 times refinement each element of the reference simulation was divided in 4 layers of 16 elements. This resulted in 70656 elements. Due to a bug in MADYMO, the computer used at the TUE, a SGI ORIGIN 200, could not be used solve the simulation.

5.1.3 Solid 8

For the reference simulation a SOLID1 element is used. In a SOLID1 element, element integrals are evaluated numerically using only one integration point. In MADYMO is also a SOLID8 element available, this type solves the element integrals using eight integration points. The results are plotted in Figure 5.2.

![Graph showing relative rotation of the markers for the SOLID1 and the SOLID8 element](image)

*Figure 5.2: Relative rotation of the markers for the SOLID1 and the SOLID8 element. Centre marker is the lowest line, in between marker is the mid-line, edge marker is the top-line.*

The relative rotation of the SOLID8 element is zero except for some little vibrations. This means that this element type "locks" and equation 2.2 can not converge to a correct solution.

5.1.4 Hourglass parameter

The hourglass parameter is divided by 10 from 0.1 to 0.01. The results are interpreted by looking at the relative rotation, Figure 5.3 and by plotting the total internal energy and the hourglass energy, Figure 5.4.
Figure 5.3: Relative rotation of the markers for the reference hourglass parameter and the 10\% hourglass parameter. Marker 1 is the lowest line, marker 2 the mid-line, marker 3 is the top-line.

Figure 5.4: Total internal and hourglass internal energy for the reference hourglass parameter and the 10\% hourglass parameter.
The changes with respect to the reference simulation are similar to those obtained in the refined mesh; peak rotations are larger and occur later and rotation decays slower.

The total internal energy is increased with decreasing the hourglass parameter. The total internal energy is the sum of the internal energy and the hourglass internal energy. In the reference simulation \( \frac{1}{4} \) of the total internal energy is caused by the hourglass energy. With the reduced hourglass parameter this ratio decreases to \( \frac{1}{10} \). As expected, the total energy was almost zero in both simulations. The total energy is calculated by:

\[
\text{Total energy} = \text{kinetic energy} + \text{dissipate energy} + \text{internal energy} - \text{external energy}.
\]

The energy dissipation was, unexpectedly, zero, this means that no energy is dissipated in the simulations. The type of energy are not specified in the manual of MADYMO.

### 5.2 Variations in material properties

Another explanation for the differences in chapter 4 can be searched for in the material properties. It is possible that these material parameters are not accurate due to measurements inaccuracy of the material behaviour [2] and due to potential fit errors. To investigate this, the shear moduli, \( G \), and the time constants, \( \tau \) as used in chapter 4 are varied with \( \pm 10\% \). Also the effect of \( G\infty \) is investigated.

#### 5.2.1 Variations of the shear moduli

The material model is described in chapter 4 and now only the shear moduli in Table 4.1 are decreased/increased with 10%. In Figure 5.5 the loss- and elastic modulus are plotted.

![Graph showing loss and elastic modulus](image)

Figure 5.5: Loss and elastic modulus for the experimental data [2] and the increased/decreased \( G \)

According to Figure 5.5 the increasing/decreasing of all shear moduli has effects on the level of both the loss and elastic modulus. In Figure 5.6 and Figure 5.7 the results of the simulation are shown.
Figure 5.6: Relative rotation of the markers for the reference simulation and the increased G simulation.

Centre marker is the lowest line, in between marker is the mid-line, edge marker is the top-line.

Figure 5.7: Relative rotation of the markers for the reference simulation and the decreased G simulation.

Centre marker is the lowest line, in between marker is the mid-line, edge marker is the top-line.
The changes in $G$ do not affect the character of the relative rotations. However with the increased $G$ the tops occur earlier and are lower than the reference simulation. The decay and increase of the relative rotation at the end of the simulation still occur. The level of the relative rotation is lower.

For the decreased $G$ the effect is the reverse to the increased $G$: the tops are higher and later. The level of the relative rotation is higher after the tops.

5.2.2 Variations of the time constants

Now the time constants of Table 4.1 are decreased/increased with 10%. In Figure 5.8 the loss- and elastic modulus are plotted.

From Figure 5.8 follows that increasing/decreasing of all shear modulus has effects on the level of both the loss and elastic modulus.

In Figure 5.9 and Figure 5.10 the results are plotted.
Figure 5.9: Relative rotation of the markers for the reference simulation and the 10% more $\tau$
Marker 1 is the lowest line, marker 2 the mid-line, marker 3 is the top-line.

Figure 5.10: Relative rotation of the markers for the reference simulation and the 10% less $\tau$
Centre marker is the lowest line, in-between marker is the mid-line, edge marker is the top-line.
Again the changes in $\tau$ do not affect the rotation pattern of the relative rotation. However, for the increased $\tau$, the top values are less than the reference simulation. Maximum changes occur around the tops.

The tops for the decreased $\tau$ are higher than the reference simulation and again the maximum changes occur around the tops.

### 5.2.3 Fit with $G_\infty$ zero

In the fit procedure [4] the $G_\infty$ can be set to zero. This affects the fit-procedure and a new set of material parameters can be obtained. These parameters are in Table 5.2 and the corresponding loss and elastic modulus are in Figure 5.11.

<table>
<thead>
<tr>
<th>Table 5.2: New parameters for new fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>parameter with $G_\infty$ is zero</td>
</tr>
<tr>
<td>$G_1$</td>
</tr>
<tr>
<td>$2.4449 \times 10^{-4}$</td>
</tr>
<tr>
<td>$G_2$</td>
</tr>
<tr>
<td>$1.4531 \times 10^{-3}$</td>
</tr>
<tr>
<td>$G_3$</td>
</tr>
<tr>
<td>$2.9164 \times 10^{-2}$</td>
</tr>
<tr>
<td>$G_4$</td>
</tr>
<tr>
<td>$2.6720 \times 10^{-2}$</td>
</tr>
<tr>
<td>$G_\infty$</td>
</tr>
<tr>
<td>$0$</td>
</tr>
<tr>
<td>$\tau_1$</td>
</tr>
<tr>
<td>$1.1927 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tau_2$</td>
</tr>
<tr>
<td>$3.3817 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\tau_3$</td>
</tr>
<tr>
<td>$5.6603 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\tau_4$</td>
</tr>
<tr>
<td>$4.3211$</td>
</tr>
</tbody>
</table>

The difference with the reference simulation is that both the elastic- and the loss modulus are higher for low frequencies. The time constant $\tau_4$ is large, compared to the time scale of the simulation, and that makes $G_\infty$ the new $G_\infty$. The new $G_\infty$ is larger than the reference $G_\infty$ this causes the difference. The result of the simulation is plotted in Figure 5.12.
Figure 5.12: Relative rotation of the markers for the reference simulation and the fit with $G_0$ zero. Marker 1 is the lowest line, marker 2 the mid-line, marker 3 is the top-line.

From Figure 5.12 it follows that the first top is not as high as the reference simulation. The times when they occur are not changed. The minimum round $t=42$ ms is also lower. The end level of the relative rotations is equal to the reference simulation.

5.3 Discussion/Conclusion

The differences that occur in chapter 4 can be explained by numerical and material parameters. Therefore in this chapter a parametric study was done.

From the numerical variations were the mesh refinement and the variation of the hourglass parameter the most useful. These two changes gave similar responses in the simulation. Changing the SOLID1 element to a SOLID8 element was not useful because the elements were locking and so this can not explain the differences in chapter 4. A refinement of 64 times resulted in so many elements that the computer was not capable to solve the problem.

Variations in the material parameters did not affect the character of the relative rotations. For increased $G$ and $\tau$ the tops of the relative rotations decreased and reverse. The tops occur later for the decreased $G$ and $\tau$ and reverse. The effects were less for the increased/decreased $\tau$ than for the $G$. Setting $G_0$ to zero in the fit procedure, mainly affect the decay behaviour of the marker rotations. The affect is small although.

The overall conclusion is that the numerical variations have more effect on the simulation than the material parameters. The numerical variations influenced the trend of the relative rotation most. This is not wanted since numerical variations must not influence the simulation. The variations in material parameters are ideal to fit the level of the simulation on the experiment, the variations do not have effect of the trend of the simulation. To refine the numerical simulation more investigation must be done.
6 Conclusions and recommendations

In chapter 2 three benchmark tests were done; omni-directional compression, simple shear and (un)-constrained tension. For omni-directional compression and constrained tension MADYMO shows no significant errors. For simple shear the shear strains were two times too small and the principal strains resulted in spikes. MADYMO prescribes the principal stresses in unconstrained tension not correct. This problem is related to the eigenfrequency of the system. From these tests can be concluded that the governing equations are solved correctly, but that the shear strain and principal strain output is incorrect.

In the experiment (chapter 3) the physical head was rotated over 2.4 rad within 53 ms. The physical head is represented by an open cylindrical cup in which a silicon gel was present. The markers at the centre of the model show a larger delay in relative rotation, with respect to the cup, than the markers near the edge. The silicon gel deformed three dimensionally. The strains that occur in the silicon gel were 30% whereas 20% strain in nerves can lead to serious head injury. This indicates the response in the open cup to be too severe to mimic the closed head behaviour of brain tissue inside a closed head. The gel showed an ageing effect since the response on the mechanical load applied by Bax [1] was different than occurred in this study.

From the comparison between the numerical simulation and the experiment (chapter 4), it can be concluded that the trends were much alike. The tops in the relative rotation were almost on the same time and the same level. However at the end the simulation the markers shows an increase in delay of the relative rotation whereas the marker delay in the experiment still decreases. The maximum volume change was 26% in an element on the outside of the mesh, despite a bulk modulus of 1 GPa.

From chapter 5, it can be concluded that the differences between simulation and experiment can be attributed largely to numerical artefacts rather than to errors in material parameters. Variations in material properties do not affect the trends in the simulation, only the level. Numerical variations influence in particular the decrease in slope after the tops of the relative rotation. The simulation locks when the element type is changed from ‘SOLID 1’ in ‘SOLID 8’.

Some aspects are investigated in the last chapter, but to eliminate the influence of numerical aspects in the simulation further investigation of the numerical variations must be done. When numerical artefacts are reduced sufficiently, further investigation can be done on the material aspects. The occurrence of large three dimensional effects at the top of the gel in the physical head model is not representative for the behaviour of brain in the skull during impact. To avoid these three dimensional effects in the gel, a cup with a cover at the top could be used.
References


