Bachelor End Project:
Characterization of the constitutive behavior of polymer foams

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Abstract

The predictive capabilities of the commercial crash simulation codes that are used in the design process are limited by the quality of the available constitutive models for foam. The objective of this project is to improve the current constitutive models for polymeric foams.
This report consists of two chapters. In the first chapter the macroscopic behavior of polymeric foams will be researched by imposing only small deformations. Using Hooke’s law the Young’s modulus of the foam is calculated. Also the influence of the volume percentage of voids is discussed.
In the second chapter the behavior will be researched using large deformation. The model used to describe the constitutive behavior is the Leonov model. First a global representation of the model is given. Then the macroscopic constitutive behavior of polymeric foam in 2-D is given. Finally the implementation of the Leonov model in MARC® is used to simulate compression tests on the polymeric foam and the results are discussed.
## List of symbols

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<th>Symbol</th>
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<tr>
<td>$E$</td>
<td>Young’s modulus</td>
<td>GPa</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Engineering stress</td>
<td>Pa</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Engineering strain</td>
<td>[-]</td>
</tr>
<tr>
<td>$F$</td>
<td>Load</td>
<td>N</td>
</tr>
<tr>
<td>$A_0$</td>
<td>Original cross sectional area</td>
<td>m²</td>
</tr>
<tr>
<td>$\Delta l$</td>
<td>Deformation elongation</td>
<td>m</td>
</tr>
<tr>
<td>$l_0$</td>
<td>Original length</td>
<td>m</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Poissons ratio</td>
<td>[-]</td>
</tr>
<tr>
<td>$G$</td>
<td>Elastic shear modulus</td>
<td>MPa</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Bulk modulus</td>
<td>MPa</td>
</tr>
<tr>
<td>$G_r$</td>
<td>Strain hardening modulus</td>
<td>MPa</td>
</tr>
<tr>
<td>$\eta$</td>
<td>Viscosity</td>
<td>Pa·s</td>
</tr>
<tr>
<td>$\bar{\sigma}$</td>
<td>Equivalent stress</td>
<td>MPa</td>
</tr>
<tr>
<td>$p$</td>
<td>Hydrostatic pressure</td>
<td>MPa</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>$S$</td>
<td>Softening variable</td>
<td>[-]</td>
</tr>
<tr>
<td>$A$</td>
<td>Deformed cross sectional area</td>
<td>m²</td>
</tr>
<tr>
<td>$\sigma_T$</td>
<td>True stress</td>
<td>Pa</td>
</tr>
<tr>
<td>$S_0$</td>
<td>Initial softening variable</td>
<td>[-]</td>
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</table>
**Introduction**

Foam materials are known for their good energy-absorbing and ergonomic properties. That’s the reason why they are used by the automotive industry. The foam materials are used in safety applications; examples are dashboards, bumper systems and seats. Another advantage of the use of foam materials is their low density. This results in a reduction in weight and the gas consumption and pollution are reduced.

The quality of the available constitutive models for foam is limited. Therefore the automotive industry is not able to optimize their products in a reliable manner using commercial crash simulations. That is why there’s a need for the characterization of the constitutive behavior of polymeric foams.

The energy-absorbing and ergonomic properties are a result of the macroscopic constitutive behavior of polymeric foams. This behavior is the result of an interplay between the intrinsic material behavior of the polymer basis-material and the complex microstructure that is present in the foams.

The outline of this report is as follows: polymeric (in this case polycarbonate) foam material is scanned using a CT-scanner. Then the scans are meshed using automatic 3D mesh generations, as developed in the world of bone-biomechanics. A compression test will be simulated with the use of a finite element code in this case MSC.MARC 2003® using the 3D mesh. Two different sort of tests are simulated: small deformation and large deformation. The used models are briefly explained and the results of the simulations are presented. Finally remarks will be placed and conclusions will be drawn.
Chapter 1

Small deformation

1.1 Hooke’s law

If the material is deformed with a compression test, the degree to which a material deforms or strains depends on the magnitude of an imposed stress. If the material is stressed at a relatively low level, stress and strain are proportional to each other through the relationship:

\[ \sigma = E \varepsilon \]  \hspace{1cm} (1.1)

This is known as Hooke’s law and the constant of proportionality \( E \) [GPa] is the modulus of elasticity, or Young’s modulus. The engineering stress \( \sigma \) and the engineering strain \( \varepsilon \) in Hooke’s law are defined by the following relationships:

\[ \sigma = \frac{F}{A_0} \] \hspace{1cm} (1.2)

and

\[ \varepsilon = \frac{\Delta l}{l_0} \] \hspace{1cm} (1.3)

In which \( F \) is the load applied perpendicular to the material cross section, \( A_0 \) is the original cross sectional area before any load is applied, \( l_0 \) is the original length of the specimen and \( \Delta l \) is the deformation elongation [1].

These relationships will be used to calculate the ratio between \( E_{\text{foam}} \) (Young’s modulus of the polymeric foam, in this case polycarbonate) and \( E_{\text{material}} \) (Young’s modulus of the basis material).

1.2 Numerical

To predict the macroscopic response of the polymeric foam the 3D mesh based on the CT-scans has to be incorporated in a finite element method. The finite element code used is MSC.MARC 2003®. The CT-scans are based on voxels. The term voxel is used to characterize a volume element; it is a generalization of the notion of pixel that stands for a picture element.

Two different 3D meshes of the same piece of polycarbonate were made, one with eight-noded linear hexagonal elements (136400 elements and 153973 nodes) and the other one with four-noded linear tetrahedral elements (790582 elements and 172218 nodes). They will be called hexmesh and tetmesh respectively from now on. The files resulting from the 3D mesh generation can be imported in MSC.Mentat® if the mesh
doesn’t contain too many elements (see figure 1.1). When the number of element used is too large some problems arise when importing the CT file in MSC.Mentat®. Therefore it is necessary to rewrite the CT meshfiles so that Marc can read them in as an input file [2], in this way MSC.Mentat® doesn’t have to visualize the 3D mesh.

To rewrite the CT mesh file into an input file for MSC.MARC® an m-file is made in MATLAB® (see tetmesh.m). First the information from the 3D mesh generation file is reordered so it can be used in an inputfile. Then the actual inputfile can be written that contains all the material properties, geometry information, boundary conditions, nodal ties etc. For the tetmesh it is also necessary to check if the mesh contains any elements that are inside out. The m-file does this and if there are any elements inside out they will be flipped. Another advantage of writing input files in this way is the possibility to change the size of the 3D mesh with the m-file.

Figure 1.1: Hexmesh in MSC.Mentat® with size 0.57*0.55*0.5 [mm].

Figure 1.2: Chosen boundary conditions.
The simulations in MARC® are based on a compression test. A compression test has a particular set of boundary conditions so it’s important that the simulation has the same boundary conditions. The boundary conditions are chosen as follows:
On the left side of the block (see figure 1.2) one node is fixed in space at the left lower angular point, the right lower angular point is fixed in the y-direction for anti-rotation and the whole left side is fixed in the x-direction. A displacement in the negative x-direction is acting on the right side of the block. The other nodes on the right side are linked to the node where the displacement acts on (so they will follow the displacement of the node they are tied to), simulating a compression test. For the simulation of compression tests in other directions other boundary conditions have to be chosen.

1.3 Results

The compression test will be simulated in the x, y and z-direction and with tetmeshes of different sizes, this is done with the m-file (see figure 1.3). The meshes have a different volume percentage of voids.

![Figure 1.3: The different sizes of tetmeshes used with (a) being the smallest and (d) being the largest mesh.](image)

(a) 27 vol. % voids; 57634 elements and 13815 nodes
(b) 23 vol. % voids; 169400 elements and 38815 nodes
(c) 21 vol. % voids; 373698 elements and 83584 nodes
(d) 19 vol. % voids; 701661 elements and 154223 nodes
The simulations are done with tetrahedral elements of type 134 (full integration). The material properties used are a Young’s modulus of 1.0 GPa and a poisson ratio of 0.3. A displacement of 1.0e-5 m is imposed in negative x, y or z-direction. The solver used is of the type iterative sparse.

To calculate E-foam the reaction force \( F \) has to be known. If \( F \) is known the modulus of elasticity can be calculated using equations (1.2), (1.3) and (1.1) because \( A_0 \), \( l_0 \) and \( \Delta l \) are known. All the nodes on the side of the block where the displacement acts on are tied to one node with the so-called nodal ties. Only one variable is tied at a time (x, y or z-direction). In this way the total reaction force \( F \) that applies perpendicular to the block’s cross section will be obtained from one node, otherwise all the reaction forces of the different nodes have to be added individually.

![Figure 1.4: Ratio between E-foam and E-material against the height of the tetmesh in different directions.](image)

In figure 1.4 the ratio between the Young’s modulus (E-foam) that is a result of the simulations and the Young’s modulus (E-material) that is used as input in MARC® is plotted against the height of the tetmesh. The graph shows that an increasing height of the mesh results in a higher E-foam. It is expected that at a certain height the value will not change anymore. That certain height isn’t reached yet in the scans that were used in this simulation.

In figure 1.4 it is seen that with larger heights the volume percentage of voids decrease. That’s not always the case because if the mesh was reduced to a region that didn’t contain any voids E-foam and E-material would be the same. In figure 1.5 the influence of the vol. % of voids is seen. The graph shows that an increasing vol. % voids result in a lower value of E-foam. If the foam has a low vol. % of voids E-foam will go to the same value of E-material. For lower percentages the graph is linear, then E-foam can be predicted. It is also seen that E-foam has different values in different directions. So the difference in vol. % of voids isn’t the only reason for the E-foam values to differ. The boundary conditions used in the different directions differ from each other. The area of the mesh that is fixed by the boundary conditions differ for the simulations in different directions. For example in figure 1.3(d) it is seen
that the right side of the mesh contains voids. So on that side less area of the mesh has a pre-described boundary condition than if that side of the mesh wouldn’t contain any voids. These boundary conditions have an influence on the value of $E_{\text{foam}}$, so the values of $E_{\text{foam}}$ in the different directions can differ. Boundary conditions result in more stress in the mesh so it is expected that the boundary conditions result in a larger $E_{\text{foam}}$.

The two different 3D meshes contain different elements so the foam is meshed differently. In figure 1.6 it is seen that a void is meshed differently and as a result the two different meshes have a different volume percentage of voids. It is also seen that the foam is meshed more realistic in the tetmesh. In table 1.1 the volume percentage of voids for the two meshes are given. Figure 1.8 shows that a lower vol. % of voids result in a lower value of $E_{\text{foam}}$.

Figure 1.5: Ratio between E-foam and E-material against the volume percentage of voids of the tetmesh in different directions.

Figure 1.6: Void meshing for hexmesh and tetmesh respectively.
Table 1.1: Volume percentage of voids for the tetmesh and the hex mesh

<table>
<thead>
<tr>
<th>Size of the mesh</th>
<th>Tetmesh</th>
<th>Hexmesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig 1.3(a)</td>
<td>27 %</td>
<td>26 %</td>
</tr>
<tr>
<td>Fig 1.3(b)</td>
<td>23 %</td>
<td>23.3 %</td>
</tr>
<tr>
<td>Fig 1.3(c)</td>
<td>21 %</td>
<td>21.5 %</td>
</tr>
<tr>
<td>Fig 1.3(d)</td>
<td>19 %</td>
<td>19.3 %</td>
</tr>
</tbody>
</table>

If the difference of $E_{\text{foam}}$ is only the result of the volume percentage of foam, the value of $E_{\text{foam}}$ would be the same for the different meshes if the vol. % of voids is the same. In figure 1.8 it is seen that this is not the case. The resulting $E_{\text{foam}}$ for simulations using a tetmesh are higher than using a hexmesh. So the use of different elements has influence on the value of $E_{\text{foam}}$.

Figure 1.7: Ratio between $E_{\text{foam}}$ and $E_{\text{material}}$ against the height of the different meshes.

Figure 1.8: Ratio between $E_{\text{foam}}$ and $E_{\text{material}}$ against the vol. % of voids for different meshes.
Chapter 2

Large deformation

2.1 Elastic deformation

In a compression test a specimen will be exposed to large deformations. Besides elastic deformation there will be plastic deformation too. Because elastic-plastic simulations are more complex it is wise to look what happens if the mesh is exposed to large deformations using the theory of linear elasticity.

The simulations will be done with a reduced hexmesh. The hexmesh is chosen because it has fewer elements then the tetmesh, so the simulating time will be shorter. The simulations are done with hexagonal elements of type 7 (full integration). The value of $E$ and the poisson ratio $\nu$ of polycarbonate are 2.0 GPa and 0.3 respectively. They will be used as the material parameters in MARC®. During the simulations some problems arise. Because the deformations are large some elements deform too much and they will be “pushed” inside out. If the tetmesh is used the same problem occurs at approximately the same strains. A solution for the simulation problems is to remesh the mesh when the element deformation is too large or the use of quadratic elements instead of linear.

2.2 Leonov model

For the simulation of elastic-plastic behavior of polycarbonate the Leonov model is used. The Leonov model is a nonlinear viscoelastic model. In figure 2.1(b) a one-dimensional representation of the constitutive model is presented.

![True stress-strain curve with corresponding graphical representation](image)

*Figure 2.1: True stress-strain curve with (b) corresponding graphical representation [3].*

The constitutive model consists of two parallel parts: the part describing the yield and strain softening and the other describing the strain hardening part. Physically this can be interpreted as the part of weak secondary forces and the part of network entanglements. The first is described with a generalized Maxwell spring-dashpot element including an Eyring viscosity, the second as a neo-Hookean spring.
The Cauchy stress tensor $\mathbf{\sigma}$ is additively decomposed in an effective/driving stress tensor $\mathbf{\sigma}_e$ and a hardening stress tensor $\mathbf{\sigma}_h$ (see figure 2.1), according to

$$\mathbf{\sigma} = \mathbf{\sigma}_e + \mathbf{\sigma}_h$$

(2.1)

The effective/driving stress tensor can be split in two parts: the deviatoric and the hydrostatic part. So $\mathbf{\sigma}_e$ is given by the relation:

$$\mathbf{\sigma}_e = \mathbf{\sigma}_h^d + \mathbf{\sigma}_d^d$$

(2.2)

and (2.1) becomes

$$\mathbf{\sigma} = \mathbf{\sigma}_h^d + \mathbf{\sigma}_d^d + \mathbf{\sigma}_h$$

(2.3)

Where $\mathbf{\sigma}_h^d$ is the hydrostatic stress and $\mathbf{\sigma}_d^d$ is the deviatoric stress. Assuming only small volumetric deformations, $\mathbf{\sigma}_d^d$ is related to the deviatoric part of the elastic isochoric left Cauchy Green deformation tensor $\mathbf{\tilde{B}}^d_e$ through the generalized Hookean relation

$$\mathbf{\sigma}_d^d = G\mathbf{\tilde{B}}^d_e$$

(2.4)

where $G$ represents the shear modulus. The hydrostatic stress $\mathbf{\sigma}_h^h$ is coupled to the volume change by

$$\mathbf{\sigma}_h^h = \kappa(J - 1)\mathbf{I}$$

(2.5)

with $\kappa$ the bulk modulus, $J$ the volume change ratio and $\mathbf{I}$ the unity tensor. The Leonov model is completed by expressing the plastic deformation rate tensor $\mathbf{D}_p$ in the effective stress. $\mathbf{D}_p$ is related to the effective deviatoric stress tensor $\mathbf{\sigma}_d^d$ by a non-Newtonian flow rule with an Eyring viscosity $\eta$

$$\mathbf{D}_p = \frac{\mathbf{\sigma}_d^d}{2\eta(\mathbf{\sigma}, p, T, S)} = \frac{G}{2\eta}\mathbf{\tilde{B}}^d_e$$

(2.6)

Where $\mathbf{\sigma}$ is the equivalent Von Mises stress, $p$ the hydrostatic pressure, $T$ the temperature and $S$ the softening variable.

For additional information about the Leonov model concerning kinematics, balance laws and stress calculation is referred to van Breemen [2].

If the Leonov model is compared with experimental data (figure 2.2) it can be seen that the model can be used for a good description of the softening and hardening of the material. But it has its shortcomings in the elastic region.
Figure 2.2: True stress-strain curve of a compression test; experiment (---), Leonov model with classic softening function [5] (- -) and Leonov model with inverted softening function [6](---) [3].

2.3 2-D macroscopic constitutive behavior

Before simulating in 3D, the macroscopic constitutive behavior of polymeric foam in 2-D is given as studied by Smit [4]. The darker areas in figure 2.3 represent yielded zones. The corresponding stress-strain curve is depicted in figure 2.4. Point f and h correspond with the stage of deformation figure 2.3 is in.

Figure 2.3: Shear zones in a uniaxially stretched polycarbonate with 30 vol.% voids [4].

The change in strain softening behavior originates from the irregularity of the microstructure. This is reflected in the yield process, which occurs as a sequence of isolated shear events distributed over the whole microstructure. A shear process involves the development of shear bands. The material inside a shear band will first strain soften (unstable deformation zone) and after that it will strain harden (stable deformation zone). Since the overall mechanical response is the averaged behavior over both stable and unstable deformation zones, the temporary unstable behavior of the yield zone is evened out in the global macroscopic response. In figure 2.3 is seen that the yielding of one ligament invokes ligaments in the neighborhood to yield also. In this way the plastic deformation is spread out over the whole microstructure.
Figure 2.4: True stress-linear strain curve of a tensile test. The material used is polycarbonate [4].

2.4 Numerical

The Leonov model was already implemented in MSC.MARC 2003® by van Breemen [2]. This was done using the user-subroutine HYPELA2. First a compression test was simulated using a one-element block, the displacement was imposed at a constant velocity. The simulation results in the following characteristic graph:

Figure 2.5: Compression test simulation of one hexagonal element showing the equivalent von mises stress and the softening variable against the total equivalent strain.

In figure 2.5 it is also seen that when the material starts yielding, the initial softening variable $S_0$ with a value of 30 (characteristic for polycarbonate foam) starts to decrease. So this parameter can be used to represent the plastic deformation in the material. This parameter can be visualized in the results of MARC®. Then it can be seen were plastic deformation starts and how it develops in the material.
The implemented Leonov model will be used to simulate a compression test for a homogeneous block, a block with different sizes of voids and a block with two voids. Finally the implementation is used to simulate a compression test using a reduced hex and tetmesh.

2.5 Results

When a material is exposed to large deformation, the cross-sectional area will change over time. Therefore the engineering stress $\sigma$ can’t be used anymore and the true stress $\sigma_T$ is used. True stress $\sigma_T$ is defined as the load $F$ divided by the instantaneous cross-sectional area $A$ over which deformation is occurring [1], or

$$\sigma_T = \frac{F}{A}$$  \hspace{1cm} (2.7)

Various simulations were done with blocks with different voids and different numbers of voids. All the simulations were done with blocks of dimension 1*1*1 [m] and a displacement of 0.5 m is imposed in negative x-direction. The displacement is subdivided in 200 increments and is imposed at constant velocity of 0.005 m/s so the strain rate is not constant. The solver used is of the type multifrontal sparse.

In figure 2.6 and 2.7 it can be seen how the plastic deformation develops using the softening variable. The darker areas represent areas with the most plastic deformation. The plastic deformation starts above and under the void (figure 2.6) and develops in the direction of the corners (figure 2.7). While the material left and right of the void is still in its elastic region.

In figure 2.8 the compressive true stress for different sizes of voids are shown. The strain softening for the block with 1 vol. % voids is smaller than for the homogenous one, the same counts for the Young’s modulus (a void means less material). The reduction in strain softening can be explained in the same way as was done for the 2-D tensile test simulation: the overall mechanical response is the averaged behavior over both the stable (elastic and hardening) and unstable deformation (softening) zones. Because the volume percentage of the voids is low strain softening is still present.

Larger voids result in a lower Young’s modulus and the material will yield at a lower stress. Larger voids also result in earlier simulation problems so not much can be said on its influence on the strain softening. As was stated before a solution for the simulation problems is to remesh the mesh when the element deformation is too large or the use of quadratic elements instead of linear.
Figure 2.6: Value of the softening variable $S$ in a block with one void; early stage with strain $\varepsilon = 0.0875$

Figure 2.7: Value of the softening variable $S$; Further stage with strain $\varepsilon = 0.125$
Figure 2.8: The compressive true stress versus the engineering strain using blocks with different vol. % of voids.

Figure 2.9 represents the plastic deformation developing for a block with two voids. The plastic deformation develops in the same way as for the block with one void. The only difference is the region between the two voids. The deformation develops from one hole to another.

The results for the Leonov implementation are as predicted. The implementation is now used to describe the behavior of polymer foams. For the simulations of a compression test on the scanned polymeric foam a reduced hexmesh is used (27 vol. % voids, 4371 elements and 5682 nodes). All the simulations were done with blocks of dimension 0.21*0.19*0.14 [mm] and a displacement of 0.1 mm is imposed in negative x-direction. The displacement is subdivided in 500 increments of the same size and is imposed at constant velocity of 0.001 mm/s. The solver used is of the type multifrontal sparse.

In figure 2.10 the development of plastic deformation in the reduced hexmesh is presented. The plastic deformation is present in some parts of the hexmesh. But the biggest part of the mesh is still deformed in its elastic region. This is a result of the simulation with MARC®, because the deformation of some elements were too large in an early stage of the simulation.
Figure 2.9: Value of the softening variable $S$. With strain $\varepsilon = 0.125$

Figure 2.10: Value of the softening variable $S$ for a reduced hexmesh. With strain $\varepsilon = 0.0457$
In figure 2.11 the result of the simulation is plotted. As a reference the result of a simulation of a homogeneous block of the same size as the reduced hexmesh is plotted in the same figure. It can be seen that the deformation is still in its elastic region because there are not enough shear bands present to initiate the yielding in the global macroscopic response.

![Figure 2.11: The compressive true stress versus the engineering strain for a homogeneous block and a reduced hexmesh (same size).](image)

Finally a simulation using a reduced tetmesh was done (27.8 vol. % voids, 23780 elements and 5928 nodes). In this simulation there are even less shear bands present when simulation problems occur than with the simulations using a reduced hexmesh. This is seen in figure 2.12. In contrast to the results of the simulations with small
deformation, the Leonov model predicts the same value of $E_{\text{foam}}$ (slope of the graph) in spite of the difference of vol. % of voids between the two meshes and the different elements used.
Conclusions and recommendations

- The size of the scans of the polycarbonate foam isn’t large enough to predict the Young’s modulus $E$ of the polymeric foam. This is seen in fig. 1.4. The value of the ratio between $E$-foam and $E$-material still increases when the height of the mesh gets larger. It is expected that with larger meshes $E$-foam will go to a constant. The value of $E$-foam also differ in the different directions, this can be the result of the different boundary conditions used. The influence of the boundary conditions wasn’t researched in this project.

- In figure 1.5 it is seen that lower vol. % of voids result in a lower value of $E$-foam. For lower percentages the graph is linear, then $E$-foam can be predicted.

- The two 3D meshes have a different vol. % of voids. This is a result of the different meshing of the foam (see fig. 1.6). The difference in volume percentage of the voids (see table 1.1 and figure 1.7) result in different values of $E$-foam. The tetmesh reproduces the voids in a more realistic way. So when using a scanned piece of polymer foam for simulations it is preferred that the mesh consists of tetrahedral elements.

- The difference in $E$-foam isn’t only the result of the vol. % of voids in the mesh (see figure 1.8). The different elements also used have an influence on the value of $E$-foam.

- The Leonov model is used to give a description of the macroscopic constitutive behavior of polymer foams. It was implemented in MSC.MARC 2003® by van Breemen [2]. The results from the simulations on blocks with different sizes and numbers showed a reduce in strain softening (see figure 2.8).

- In contrast to the results of the simulations with small deformation, the Leonov model predicts the same value of $E$-foam for the two different 3D meshes in spite of the difference of vol. % of voids and the different elements used.

- When simulating a compression test on the polymer foam meshes some problems occur. Some elements are under such a large deformation that they are pushed inside out. This happens with both meshes. So the deformation that acts on the meshes is too low to result in significant plastic deformation (see fig. 2.10). Use of the tetmesh in simulations result in simulation problems at $\varepsilon = 0.047$ and for the hexmesh at $\varepsilon = 0.037$ (see fig. 2.12). A solution for this is to remesh the mesh when the element deformation is too large or the use of quadratic elements instead of linear. The solutions will result in an increase of simulation time.

- The simulation using the Leonov implementation were done by imposing a displacement at constant velocity. It is recommended that the loading rate used is a constant logarithmic strain rate because the Leonov model is time dependant (see figure 2.1(b)).
Bibliography


[2] MARC user manuals A and C.


