Modeling the application of fluid filled foam in motorcycle helmets

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Chapter 1

Introduction

Each year a lot of motorcyclists are killed in traffic accidents. For instance, in 1999, 2470 motorcyclists were killed in traffic accidents in the United States [10]. Wearing a helmet prevents brain injury, the primary cause of death in motorcycle accidents, in 67% of the accidents [9]. In the United States however, where wearing a helmet is not compulsory in all states, many motorcyclists do not wear a helmet because of their size and weight. Decreasing the weight of the helmet might lead to a substantial increase in the utilization of helmets.

A lot of research is being done to improve helmet designs [7, 11, 12, 13]. Most of these studies focus on improving the foam liner, the primary energy absorbing component of a helmet, to decrease the weight of the helmet. In the recent study by Shuaeib et al. [13] a promising design was developed, however, this design required a relatively large thickness.

In a recent study it was shown by Dawson [5] that replacing part of the foam liner by a composite layer consisting of high density polyurethane and low density polyurethane impregnated with glycerol leads to a significant decrease in the weight of the helmet compared to commercially available helmets. This study, however, was completely experimental and it is expected that even more improvement can be made in a time efficient way by using a numerical optimization. To this end first the behavior of the proposed layer of polyurethane needs to be described.

In this report a first step is made towards the modeling of the behavior of the polyurethane layer. The model of Dawson et al. [4] which describes the behavior of a single column of impregnated foam under dynamic compression is extended to describe the behavior of the composite layer. Using the developed model simulations of a motorcycle crash are performed.
Chapter 2

Earlier work

In the experimental work done by Dawson [5] it was found that commercially available motorcycle helmets can be significantly improved. The commercially available helmet, from here on referred to as standard design, consists of the shell, the foam liner and a layer of comfort foam, see figure 2.1. The shell is primarily meant to prevent penetration of objects through the helmet. The foam liner is the primary energy absorption layer and often consists of polystyrene.

Dawson found that replacing part of the polystyrene layer by a composite layer consisting of high density polyurethane and low density open cell polyurethane impregnated with glycerol can lead to significant weight reductions. The improved design is depicted in figure 2.2, where figure 2.2(a) shows a side view of the new design and figure 2.2(b) shows a cross sectional view of the composite layer.
In his work, Dawson used a more or less trial and error method to come up with an optimal design. It is expected that improvement is possible over Dawson’s results by using numerical optimization techniques. To this end the behavior of the composite layer under dynamic compression needs to be described.

As a starting point for the description of this behavior the model of Dawson et al. [4] is used. This model is capable of describing the stress-strain relation for low density, open cell foam impregnated with glycerol under dynamic compression. It was verified experimentally for strain rates of $2.5 \times 10^{-4} \text{s}^{-1}$ to $10 \text{s}^{-1}$. There are two issues with this model that need to be resolved.

First, the strain rates that occur in the foam in a typical crash are well above $10 \text{s}^{-1}$. It needs to be examined whether the model is also applicable to these higher strain rates.

Secondly, the model is only capable of describing the behavior of a single cylindrical specimen, whereas the composite layer may consist of more than one cylindrical column of fluid filled foam. More important than the number of the columns, however, is the fact that each column is embedded in a layer of dry foam. In the experiments of Dawson the fluid could flow freely out of the specimens into the air. In the composite layer this is not the case and therefore the model of Dawson needs to be extended to account for this.

In the next chapter the model of Dawson is tested for higher strain rates and in chapter 4 the extension to account for the dry foam surrounding the column of fluid filled foam is made.
Chapter 3

High strain rate behavior

In this chapter the model of Dawson [4] will be briefly described. Next, the experimental procedure used to test at both low and high strain rates is explained.

3.1 Fluid filled foam model

3.1.1 Stress-strain response of foam

Gibson and Ashby previously developed a model for the compressive stress-strain response of reticulated foam where no fluid was assumed to be present in the foam. The equations are given by [6]

\[ \sigma^* = \epsilon E^* , \quad 0 < \epsilon < \epsilon_{el}^* \] (3.1)

\[ \sigma^* = \sigma_{el}^* , \quad \epsilon_{el}^* < \epsilon < \epsilon_D \left(1 - \frac{1}{D}\right) \] (3.2)

\[ \sigma^* = \frac{\sigma_{el}^*}{D} \left(\frac{\epsilon_D}{\epsilon_D - \epsilon}\right)^m , \quad \epsilon > \epsilon_D \left(1 - \frac{1}{D}\right) \] (3.3)

where \( \sigma^* \) is the average, uniform stress response of the foam, \( E^* \) is the effective modulus of the foam, \( \epsilon \) is the strain, taken to be positive in compression, \( \epsilon_{el}^* \) is the elastic buckling strain, \( \sigma_{el}^* \) is the elastic buckling stress, and m and D are constants associated with the microstructure of the foam. For polyurethane foams the constant m was given as 1. The fully densified strain \( \epsilon_D \) is given by

\[ \epsilon_D = 1 - 1.4 \left(\frac{\rho_0}{\rho_s}\right) \] (3.4)

where \( \rho_0 \) is the initial density of the foam and \( \rho_s \) is the density of the solid from which the foam is made. The constant D is given by

\[ D = \frac{\epsilon_D}{\epsilon_D - \epsilon_p^*} \] (3.5)
where $\epsilon_p^*$ is the strain at the end of the plateau, where the stress becomes higher than the elastic buckling stress $\sigma_{cl}^*$. 

It is known that polyurethane foams exhibit a strong strain rate dependent behavior. To account for this, Dawson et al. proposed a new relation for the effective modulus, based on a finite element simulation. Dawson found the effective modulus to be well described by the relation [4]

$$E^* = X \ln(\dot{\epsilon}/\dot{\epsilon}_0) + Y$$

where $X$ and $Y$ are constants determined from the finite element simulation and $\dot{\epsilon}_0$ is taken to be $1s^{-1}$.

### 3.1.2 Microstructure of foam under compression

To describe the evolution of the microstructure of the foam under compression the model of Dawson et al. [4] is used. In this model it is assumed that the cells of the foam under compression remain elastic up to the elastic buckling strain $\epsilon_{cl}^*$. 

For strains higher than the elastic buckling strain layers of cells buckle and collapse without expanding laterally, resulting in a Poisson’s ratio of approximately zero. As the first layer of cells collapses, the other cells remain in the elastic regime. The strain in these cells is approximately equal to the elastic buckling strain $\epsilon_{cl}^*$. When the specimen is compressed further the layer of cells next to the collapsed layer will also collapse, forming a band of collapsed layers of cells. The strain in this band of collapsed layers is assumed to be uniform and equal to the densified strain $\epsilon_d$. The densified strain is the strain at which further densification of the cells starts to occur. For the type of foam considered in this analysis the densified strain was found by Dawson to be $\epsilon_d = 0.60$ [4].

As the foam is compressed, the average cell diameter also changes. Dawson et al. [3] found an expression for the average cell diameter and based on this expression a model for the permeability of the foam was developed.
This model gives the permeabilities of the foam in the linear elastic regime $k_{el}$, in the elastic buckling regime $k_{el}^*$ and in the densified regime $k_d$ as

$$k_{el} = A d_0^2 (1 - \epsilon) \left(1 - \frac{\rho_0}{\rho_s} \frac{1}{(1-\epsilon)}\right)^3 0 \leq \epsilon \leq \epsilon_{el}^*$$  (3.9)

$$k_{el}^* = A d_0^2 (1 - \epsilon_{el}^*) \left(1 - \frac{\rho_0}{\rho_s} \frac{1}{(1-\epsilon_{el}^*)}\right)^3 \epsilon = \epsilon_{el}^*$$  (3.10)

$$k_d = A d_0^2 (1 - \epsilon_d)^2 a \left(1 - \frac{\rho_0}{\rho_s} \frac{1}{(1-\epsilon_d)}\right)^3 \epsilon = \epsilon_d$$  (3.11)

where $A$ is an empirical constant given by Brace as 0.025 [1], $a$ is an empirical constant given by Dawson as 0.85 for the foam considered in this report, and $d_0$ is the initial average pore diameter.

### 3.1.3 Fluid flow

For most achievable strain rates the flow of highly viscous fluid through foams as considered in this analysis is dominated by viscous forces. Therefore it is assumed that Darcy’s law is applicable to describe the flow. To test this assumption the Reynolds number can be used. It was found by Comiti et al. [2] that the transition from the viscous dominated regime to the inertial dominated regime occurs at a critical Reynolds number of $Re = 0.83$ in the type of material considered in this analysis.

### 3.1.4 Fluid contribution

The model of Dawson et al. [4] considers cylindrical specimens of fluid filled under dynamic axial compression between two flat plates. The lower plate is fixed and the upper plate is moving downwards with a velocity $|\dot{h}|$. The initial height and radius of the specimen are taken to be $h_0$ and $R$ respectively. When the foam is compressed the actual height is given by $h(t)$ and the radius is assumed to remain unchanged.

For strains smaller than the elastic buckling strain $\epsilon_{el}^*$ the entire specimen is assumed to be in the linear elastic regime. For strains larger than the elastic buckling strain but smaller than the densified strain $\epsilon_d$ part of the specimen is still in the linear elastic regime and part of the specimen is in the densified regime.

### 3.1.5 Single regime model

In the single regime, where $\epsilon \leq \epsilon_{el}^*$, it is assumed that the foam deforms uniformly; see figure 3.1
Neglecting gravitational effects and assuming that the relative velocity of the fluid with respect to the foam in z direction is zero it can be seen that the pressure gradient in z direction is equal to zero. Therefore the velocity of the fluid in radial direction $V_e$ is uniform in the z direction and given as

$$V_e = -\frac{hr}{2h\phi}$$

Darcy’s law gives the pressure gradient as

$$\frac{\partial P}{\partial r} = -\frac{\mu V_e}{k_e}$$

where $\mu$ is the dynamic viscosity of the fluid. The free surface boundary condition reads

$$P = 0 \quad \text{on } r = R$$

where P is the local pressure in the fluid minus the atmospheric pressure. Using the expression for the fluid velocity the pressure in the fluid can be found to be

$$P = \frac{\mu h}{4\phi hk_e} (r^2 - R^2)$$

Neglecting inertial effects the force applied by the top compression plate can be found by using a force balance

$$F_f = \int_0^R P|h|2\pi rdr$$
\[ F_f = -\frac{\mu h R^4}{8\phi h k_e} \]  
(3.17)

To account for the tortuous and anisotropic foam microstructure an empirical constant \( C \) is introduced

\[ F_f = -\frac{C\mu h R^4}{8\phi h k_e}, \text{ for } \epsilon \leq \epsilon_{el}^\ast \]  
(3.18)

where \( C \) is a single constant to be determined from experimental data. In earlier work [4] this constant was found to be \( C = 0.59 \) for the type of foam used in this analysis. \( C \) was also found to be independent of foam grade and strain rate.

### 3.1.6 Two regime model

To be able to describe the fluid flow through the foam in the two regime model, where \( \epsilon_{el}^\ast < \epsilon < \epsilon_d \), the behavior of the foam must be known. As is described in section 3.1.2 layers of cells buckle and collapse under compression forming a band of densified layers of cells. It is assumed that this band initiates in the center of the specimen and symmetrically propagates towards the compression plates as the specimen is further compressed. Because of symmetry there is no fluid flow across the center of the specimen and only the top half of the problem needs to be analyzed. The problem is depicted in figure 3.2

![Two regime model](image)

(a) Two regime model for strains \( \epsilon_{el}^\ast < \epsilon < \epsilon_d \)
(b) Top symmetrical half of two regime model. Velocity of fluid (solid arrow). Relative velocity of fluid with respect to the foam (dotted arrow).

Figure 3.2: Two regime model [4].

In the analysis of the top half the height of the elastic regime is \( 1/2 h_e \).
and the height of the densified regime is $1/2 \ h_d$ where

$$h_e = \chi_e h$$  
$$h_d = \chi_d h$$  \hspace{1cm} (3.19)  
\hspace{1cm} (3.20)

The boundary conditions at the free surface are that the pressure in both regimes is equal to the atmospheric pressure. Furthermore, the pressure gradient in $z$ direction is zero at the foam plate interface. Since no fluid can flow across the center of the specimen due to symmetry there is also a no flux condition at $z = 0$. The pressure field is taken to be continuous between the linear elastic and densified regime and the pressure gradient is discontinuous due to the change in permeability. The last boundary condition corresponds to the fluid exiting the layer undergoing elastic buckling. It is assumed that the fluid exiting this layer flows either into the linear elastic regime or into the densified regime.

$$\frac{\partial P^*_d}{\partial z} = \frac{\partial P^*_e}{\partial z} = 0 \quad , \quad \text{on} \quad r = R$$  
$$\frac{\partial P^*_d}{\partial z} = 0 \quad , \quad \text{on} \quad z = 0$$  \hspace{1cm} (3.21)  
\hspace{1cm} (3.22)

$$\frac{\partial P^*_d}{\partial z} = \alpha \mu \frac{\dot{h}}{k} \quad , \quad \text{on} \quad z = 1/2 h_d$$  \hspace{1cm} (3.23)

$$\frac{\partial P^*_e}{\partial z} = \mu h \frac{\dot{h}}{k} \quad , \quad \text{on} \quad z = 1/2 h_d$$  \hspace{1cm} (3.24)

$$P^*_d = P^*_e \quad , \quad \text{on} \quad z = 1/2 h_d$$  \hspace{1cm} (3.25)

where $\alpha$ is a numerically determined constant representing the fraction of the flux exiting the layer undergoing elastic buckling into the linear elastic regime, $P^*_e$ is the pressure in the linear elastic regime and $P^*_d$ is the pressure in the densified regime. The flow in either of the regimes is assumed to be described by Darcy’s law

$$\nabla P^* = -\frac{\mu V}{k}$$  \hspace{1cm} (3.27)

where $V$ is the relative velocity of the fluid with respect to the foam and $k$ is the permeability which is assumed to be isotropic for each regime. Applying continuity for an incompressible Newtonian fluid and taking the divergence of both sides of equation 3.27 gives

$$\nabla^2 P^* = -\frac{\mu \nabla \cdot V}{k} = 0$$  \hspace{1cm} (3.28)

The solution for the pressure field as well as the constant $\alpha$ can be determined by solving the boundary value problem. The numerically determined
constant $\alpha$ is found to be a function of the permeabilities $k$, the radius $R$ and the height of both the regimes

$$\alpha = \alpha(k^*_e, k^*_d, R, h_e, h_d)$$  \hspace{1cm} (3.29)

An example of how $\alpha$ might look like can be seen in figure 3.3.

The pressure field in the linear elastic regime is given by

$$P_e^* = \sum_{n=1}^{\infty} \frac{\alpha \mu k R (e^{k_n(z-1/2h_d)} + e^{k_n(h_e-z+1/2h_d)} J_0(k_n r))}{k^*_e(k_n R)^2(1 - e^{k_n h_e}) J_1(k_n R)}$$  \hspace{1cm} (3.30)

where $k_n$ are numerical terms involving $R$, $J_0$ is a zero order Bessel function and $J_1$ is a first order Bessel function. Neglecting inertial effects the force on the top compression plate can be found by integrating

$$F_f = \int_0^R P_e^* |_{h/2} 2\pi r dr$$  \hspace{1cm} (3.31)

$$F_f = -\frac{2\pi \alpha \mu k^* R^3}{k^*_e} \sum_{n=1}^{\infty} \frac{1}{(k_n R)^3 \sinh(1/2k_n h_e)}$$  \hspace{1cm} (3.32)

Just as in the single regime model, in the two regime model the constant $C$ is also used to account for the tortuous and anisotropic foam microstructure

$$F_f = -\frac{2C\pi \alpha \mu k^* R^3}{k^*_e} \sum_{n=1}^{\infty} \frac{1}{(k_n R)^3 \sinh(1/2k_n h_e)}$$  \hspace{1cm} (3.33), for $\epsilon^*_e < \epsilon < \epsilon_d$

As in the single regime mode, $C$ was found by Dawson et al. [4] to be $C = 0.59$ for the type of foam used in this analysis and independent of foam grade and strain rate.
3.2 Materials

The tests were done using open cell, flexible, polyester based polyurethane foam with nominal cell diameter of 175 µm, corresponding to a foam grade of 90 pores per inch. Based on manufacturer’s values, the relative density of the foam was taken to be $\rho_0/\rho_s = 0.03$. Cylindrical specimens with radius $R = 12.7 mm$ and height $h = 12.5 mm$ were cut from the foam.

The fluid used in the experiments is glycerol. The density of the glycerol was measured to be 1260 $kg/m^3$. The viscosity of glycerol depends quite strongly on the amount of time the fluid has been exposed to air and was measured to be $\mu = 0.79 Pas$ for the conditions of the test. To verify the expression for the effective modulus, equation 3.6, air filled foam was also tested. The dimensions of these specimens were the same as for the fluid filled specimens.

3.3 Experimental procedure

Each sample was saturated with glycerol prior to testing. To this end each sample was submerged in a bath of glycerol and compressed and uncompressed at 1 mm/s. Since glycerol is a highly viscous fluid at room temperature the glycerol was heated to 40°C to temporarily decrease the viscosity and therefore simplify the saturation process. It was found earlier that compressing polyurethane foam to a strain of $\epsilon = 0.75$ for a short period of time causes almost no permanent damage to the material [8]. Therefore the samples were compressed to a strain of $\epsilon = 0.75$ and uncompressed. This process was repeated four times. After saturating the samples the foam was put in an oven at 23°C for two hours to completely recover from the damage done to the foam by the saturation process. For the air filled foam the saturation process was skipped.

The stress strain response of each sample was measured from 0 to 0.60 strain for test velocities from 5 $mm/s$ to 3 $m/s$. For test velocities of 5 $mm/s$ an Instron 4201 was used at a constant loading velocity. The data acquisition unit used was capable of a data acquisition rate of 1000 Hz. For test velocities of 25 $mm/s$, 100 $mm/s$, and 250 $mm/s$ an Instron 1321 testing machine was used at constant velocity. The data acquisition for this machine was the same as for the Instron 4201. For test velocities of 2 $m/s$ and 3 $m/s$ an Instron drop tower was used. The drop tower impacts the samples with a flat plate weighing just over 7 kg. Because the impact energy is substantially greater than the energy absorbed by the foam the experiments were at nearly constant velocity. The data acquisition rate for these experiments was selected to be 250 kHz. To prevent overloading the drop tower load cell the highest impact velocity used was 3 m/s.
3.4 Results

3.4.1 Air filled foam

The results for the tests on the air filled foam are shown in figure 3.4.

Figure 3.4: Air filled foam response at different strains. Model (solid line) and experimental data (errorbars)
Each image shows the data for a single value of the strain over a range of strain rates for both the model presented in section 3.1.1 and for the experimental results. Equations 3.2-3.3 and 3.6 are used to plot the response for the model.

For test velocities of 250 mm/s and higher the data acquisition turned out to be problematic and therefore no data is presented for these test conditions. For 250 mm/s heavy oscillations in the force, especially at low strains, were observed in the measurements. For lower velocities oscillations were also present, but not as pronounced as for 250 mm/s.

In the drop tower experiments the load cell was not able to detect the loads resulting from the impacting of the foam, since the loads were too low. Therefore no data is presented for these strain rates.

The solid lines represent the model and the errorbars, connected by the dashed line, represent the data points. Each errorbar represents the mean of two experiments and the length of each errorbar corresponds to two standard deviations.

3.4.2 Fluid filled foam

For the fluid filled foam, the solid model, equations 3.2 - 3.3 and 3.6, and the fluid model, equation 3.33, are combined to plot the response. To this end however, the parameters used in the model 3.33 are needed. Since the foam used in this analysis is the same as Dawson et al. [4] used in their experiments the values measured or determined by Dawson were used [4]. Since Dawson determined the constant C to be independent of foam grade or strain rate, the value Dawson found, C = 0.59, is used in the model.

The results are plotted in figure 3.5, where the solid lines represent the model and the errorbars, connected by the dashed lines, represent the experimental data. Again, each experimental data point corresponds to the mean of two experiments and the errorbars are of length two standard deviations.

It should be noted that the model is not valid at exactly the densified strain $\epsilon_d$, therefore the model is plotted at a strain of $\epsilon = 0.599$ instead of $\epsilon = 0.6$.

The maximum Reynolds number in these experiments is calculated to be approximately $Re = 0.55$ at a strain of $\epsilon = 0.6$ for a test velocity of 3 m/s.
Figure 3.5: Fluid filled foam response at different strains. Model (solid line) and experimental data (errorbars)

For the fluid filled foam all the results of the experiments are usable, also the results at loading velocities of 250 mm/s and higher. The oscillations observed for the air filled foam at 250 mm/s were not so prominent for the fluid filled foam. In the drop tower experiments, because of the significantly
higher loads compared to the dry foam, the load cell was able to record the data properly for the fluid filled foam.

It should be mentioned, however, that in the drop tower results, all variables, except for the load, are calculated based on the load-time signal. This means that the strain, for example, may not be as accurate as in the tests at lower velocities, since in the machines used for the lower velocity tests the displacement is measured instead of calculated.

### 3.5 Discussion

For the air filled foam the results indicate that, for the strain rates presented in the figures, the model gives lower values for the force than are experimentally obtained. This can be understood by the fact that the foam model 3.2 - 3.3 combined with 3.6 assumes an almost uniform plateau where the experiments show an increasing force in the plateau regime.

Furthermore the results for low strains ($\epsilon = 0.1$ and $\epsilon = 0.2$) seem to be less reproducible than for the higher strains. The large standard deviations for $\epsilon = 0.1$ can be explained by the fact that the experimentally obtained data shows large oscillations. These oscillations of two identical specimens were found not to be in phase therefore causing the standard deviation to be quite large compared to the standard deviation for higher strains at the same strain rate. The oscillations are also the cause of the decrease in force in the result for $\epsilon = 0.2$.

The results for the fluid filled foam seem to correspond to the model quite well for strain rates up to $10\,\text{s}^{-1}$. For higher strain rates the model gives significantly higher forces than are measured. It is not expected that the solid model, equations 3.2 - 3.3, has a significant influence on these differences. The forces given by the solid model, even for high strain rates, are small compared to the fluid contribution. Since the load cell of the drop tower was not able to detect the forces in the air filled foam experiments it is assumed these forces are indeed small compared to the fluid contribution.

The discrepancy between the model and the experimental results at higher strain rates might have several causes. It was found by Dawson [5] that for foams impregnated with non Newtonian fluids the force exerted on the foam by the fluid flowing through the foam causes the struts of the foam to fracture, destroying the complete microstructure of the foam. This enables the fluid to flow more easily and thus lowers the force needed to compress the sample. To check whether this happened in the experiments samples were examined with a SEM after being tested. In figure 3.6 the SEM image of a fluid filled sample tested at 3 m/s is shown.
Figure 3.6: SEM image of fluid filled sample after being tested at 3 m/s. The fractured struts are a result of the preparation of the sample for the SEM, not from the compression test.

It can not be concluded from this image that the struts have fractured. Apparently the force of the Newtonian fluid used in these experiments flowing through the foam is not high enough to fracture the struts.

It is however possible that the force of the fluid flowing through the foam causes the struts to deform elastically thereby temporarily increasing the cell diameter and thus effectively increasing the permeability of the foam. The permeability model, 3.10 - 3.11, that was used in the model 3.33 was verified with water flowing at low rates through the foam. The forces of the water on the foam are assumed to have been considerably smaller than the forces exerted by the glycerol on the foam. However, since the struts did not fracture, it is not expected that this explains all of the difference, since the permeability would need to increase by a factor of 10 compared to Dawson’s values [4] to properly describe the behavior at high strain rates.

One more explanation is the fact that the foams seems to expand radially during compression at high strain rates. The model assumes the free surface to be fixed at position $r = R$ but in the high strain rate experiments it was observed that the foam expanded radially. It is possible that at high rates the glycerol flowing through the foam exerts a viscous drag force on the foam high enough to drag the foam along instead of flowing through the foam. Because of this fact the velocity of the fluid with respect to the foam is lower than expected and thus the pressure gradient in the fluid is lower. This will lead to a lower compression force, as can be observed from equations 3.16 and 3.31. It is needed to gain more knowledge on this behavior, for example for which strain rates the drag force becomes important enough to take it into account. Using a high speed camera more information could be gained on this behavior.
Furthermore the maximum Reynolds number in the high strain rate tests is calculated to be approximately $Re = 0.55$ which rises the question whether the assumption of viscous flow is reasonable. It might be needed to account for inertial forces in the model to properly describe these tests. It is not expected, however, that incorporating inertial forces in the model would give a better description since this would lead to higher pressure drops and therefore to even higher forces in the model. A note on the Reynolds number is that the actual Reynolds number might be substantially lower than the one calculated since it was discussed that the actual fluid velocity might be lower than assumed because of the radial expansion of the foam.
Chapter 4

Extended model

4.1 Extension of model

In the helmet experiments performed by Dawson [5], part of the polystyrene layer was replaced by a composite layer consisting of fluid filled columns embedded in air filled foam. In the experiments by Dawson the air filled foam was a high density polyurethane foam and the fluid filled foam was a low density foam. The behavior of a fluid filled column embedded in a dry foam needs to be described. As a first step towards a description for this behavior this analysis considers the case of a fluid filled low density foam embedded in the same low density air filled foam, see figure 4.1, where the plate mentioned in the experimental procedure, section 4.2, is already shown in the cross sectional view.

![Extended model](image.png)

Figure 4.1: Extended model.
In this case, where the fluid filled and air filled foam are the same foam, it is assumed that both the fluid filled and air filled foam deform in exactly the same way. The permeabilities are assumed to be the same at any time during compression. If the assumption is made the fluid remains in a cylindrical shape during compression and flows directly from the fluid filled foam into the initially air filled foam, see figure 4.2, the governing equations and boundary conditions for both the single regime and two regime model remain unchanged, except for the position of the free surface.

![Figure 4.2: Cross sectional view of sample during compression. The dashed lines indicate the initial position of the fluid in the fluid filled foam.](image)

4.1.1 Single regime model

For the single regime model, $\epsilon \leq \epsilon^*_e$, the free surface boundary condition now reads

$$P = 0, \text{ on } r = \sqrt{\frac{h_0}{h}} R_0$$

(4.1)

where $R_0$ is the initial radius of the fluid filled foam, $h_0$ is the initial height of the foam, and $h$ is the actual height of the foam. The pressure field now reads

$$P = \frac{\mu}{4\phi h k_e} (r^2 - \frac{h_0}{h} R_0^2)$$

(4.2)

The force on the top compression plate caused by the compression of the sample is given by

$$F_f = -C_{\mu} \pi \dot{h} \left( \frac{h_0}{h} \right)^2 R_0^4$$

(4.3)

4.1.2 Two regime model

For the two regime model, $\epsilon^*_e < \epsilon < \epsilon_d$, the free surface boundary condition now reads

$$P_d^* = P_e^* = 0, \text{ on } r = \sqrt{\frac{h_0}{h}} R_0$$

(4.4)
The solution for the pressure field remains almost unchanged, except the radius in the pressure field is no longer the initial radius of the fluid filled foam but the actual radius of the fluid column.

\[
P^*_{e} = \sum_{n=1}^{\infty} \frac{\alpha \mu \dot{h} \sqrt{\frac{h_0}{R_0}} R_0 \left( e^{k_n (z - 1/2d)} + e^{k_n (h_e - z + 1/2d)} J_0(k_n r) \right)}{k_{el}(k_n \sqrt{\frac{h_0}{R_0}} R_0)^2 (1 - e^{k_n h_e}) J_1(k_n \sqrt{\frac{h_0}{R_0}})}
\]

(4.5)

The compressive force needed to compress the sample is now given by

\[
F_f = -2C \pi \alpha \mu \dot{h} \left( \frac{h_0}{R_0} \right)^{3/2} R_0^3 \sum_{n=1}^{\infty} \frac{1}{(k_n \sqrt{\frac{h_0}{R_0}} R_0)^3 \sinh(1/2k_n h_e)}
\]

(4.6)

4.1.3 High strain rate correction

In the experiments on the fluid filled foam, section 3.4.2, it was shown that for high strain rates the model of Dawson does not provide an accurate description of the response of the foam. Since it was not clear what caused the discrepancy between the model and the data no attempt was made to improve the behavior of the model for high strain rates. Since basically the same model is used in these experiments it is not expected the extended model will give a good description of the experiments at high strain rates either.

Because this section mainly focuses on checking the assumptions made in the extension of the model, it is necessary to have the model of section 3.1.6 describe the data at high strain rates well. Therefore the model of section 3.1.6 was fitted to the experimental data for the original model for test velocities of 2 m/s and 3 m/s. To this end the parameter C (equations 3.18 and 3.33) was used to obtain a good description of the data at high strain rates. For a schematic overview, see figure 4.3.

![Figure 4.3: Overview of fitting procedure. C is fitted to experimental high strain rate data from chapter 3. The newly obtained C is used to describe the experimental data obtained for the extended model.](image-url)
It is important to note that $C$ is actually not meant for this kind of fitting. The discrepancy between the data and the model is most likely not caused by a change in either tortuosity or anisotropy of the foam and $C$ was introduced into the model to account for these two factors. Furthermore, in earlier work $C$ was found to be independent of the strain rate, still, in this procedure it is used to account for a discrepancy between data and the model which seems to be strain rate dependent. To fit $C$, the experimental data at strains of $\epsilon = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6$ from the tests at 2 m/s and 3 m/s of section 3.4.2 was used. For each data point the mean of two experiments was used. A single value for $C$ was determined using a least squares fit type.

4.2 Materials and experimental procedure

Cylindrical specimens were cut from low density, open cell polyurethane foam, the same as described in section 3.2. The radius and height of these specimens were respectively 25.4 mm and 12.5 mm. From the center of each specimen a cylindrical part having radius 12.7 mm was cut. The dimensions were chosen such that, for $\epsilon = \epsilon_d$, the fluid does not flow out of the initially air filled foam. The center part was then impregnated with glycerol as described in section 3.3. After saturating the sample it was not directly put into the oven. Instead, the fluid filled part was press fitted into the larger air filled part. However, to make sure the permeabilities of the fluid filled foam and air filled foam are the same, before putting the two parts together, the air filled foam was also compressed and uncompressed to a strain of $\epsilon = 0.75$ at 1 mm/s for four times. It was noted by Dawson that the permeability before and after the saturating process are somewhat different [3] and therefore this process was necessary to make sure the permeabilities of the fluid filled foam and the initially air filled foam are the same at all times during deformation. Because of the contact between the glycerol and the epoxy the viscosity of the glycerol decreased a bit and was measured to be $\mu = 0.77 \text{Pas}$ for the test conditions.

After putting the parts together the specimens are ready to be used. However, it is expected the composite layer of fluid filled foam columns embedded in air filled foam will most likely be attached to another layer in real life applications. For example, in the helmet design the composite layer was glued to the ABS shell on one side and to the polystyrene layer on the other side. Because of this, and to make sure the assumption that all fluid flows directly from the fluid filled foam into the air filled foam is met, the assembled specimens were bonded to thin ABS plates. To this end a high strength, water proof epoxy was used. After assembly the specimens were put into the oven at 23°C and allowed to recover for 2 hours.
4.3 Results

4.3.1 High strain rate fit

Fitting the model 3.33 to the data of section 3.4.2 for the tests at 2 m/s and 3 m/s gave the parameter $C$ as $C = 0.063$. A goodness of fit parameter $R^2$ was calculated as

$$R^2 = 1 - \frac{SS_{err}}{SS_{tot}}$$

(4.7)

where

$$SS_{err} = \sum (y_i - f_i)^2$$

(4.8)

$$SS_{tot} = \sum (y_i - \bar{y})^2$$

(4.9)

where $y_i$ are the values of the experimentally obtained data, $\bar{y}$ is the mean of the experimentally obtained data, and $f_i$ are the modeled values. The goodness of fit parameter for the data at 2 m/s was calculated to be $R^2 = 0.88$ and for 3 m/s it was determined to be $R^2 = 0.90$. Using $C = 0.063$, the model of section 3.33 represents the data at high strain rate, to which the model was fitted, quite well, as can be seen in figure 4.4.
Figure 4.4: Response of fluid filled column at different strains using parameter fitted to high strain rate date, $C = 0.063$. Model, equation 3.33 (solid line) and experimental data (errorbars)

4.3.2 Extended model

The results from the experiments on the fluid filled foam embedded in air filled foam are shown in figure 4.5. The model, equation 4.6, is plotted
using the fitted value for C, C = 0.063. To compare the low strain rate experimental data with the model, the results using C = 0.59 are shown in figure 4.6.

Figure 4.5: Response of fluid filled foam column embedded in air filled foam at different strains using parameter fitted to high strain rate data, C = 0.063. Model, equation 4.6 (solid line) and experimental data (errorbars)
It can be seen in figure 4.5 that the model, using C = 0.063, for strain rates up to approximately 100s$^{-1}$ gives a lower force than experimentally determined. For higher strain rates the model gives higher forces than the experimental data. This effect seems to increase with increasing strain, except for the results for $\epsilon = 0.1$. At $\epsilon = 0.1$ the drop tower results show substantial oscillations, resulting in a decreasing mean and increasing standard deviation.
Figure 4.6: Response of fluid filled foam column embedded in air filled foam at different strains using parameter found by Dawson, C = 0.59. Model, equation 4.6 (solid line) and experimental data (errorbars)

In figure 4.6 the results using C = 0.59 are shown. At high strain rates the model overestimates the force significantly. At lower strain rates the the model seems to correspond to the data quite well, however, at higher strains the agreement between data and model can be seen to get less.
4.4 Discussion

In the figures for $C = 0.59$ it can be seen that the model is in good agreement with the data up to a certain strain for low strain rates. For higher strains the model overestimates the data. One reason for this might be the fact that the assumption of the fluid flowing directly from the fluid filled foam into the initially air filled foam is not met. It is possible that, at higher strains, a small gap forms between the two foams. This means that not all the fluid flows through the foam but some of the fluid remains in this gap. This means that, for the same compression, less fluid has to flow through the foam and therefore the pressure drop and thus the compressive force will be lower than for the case where there is no gap between the two foams, as is assumed in the model.

For high strain rates, figure 4.5, the same phenomenon can be observed. At higher strains the model overestimates the experimental data by a significant amount. One reason for this could be again the formation of a gap between the two foams at higher strains.

Another cause for the discrepancy at all strains could be the fact that the parameter $C$ was fitted to the experimental data for the fluid filled foam without air filled foam surrounding it. In those experiments the maximum fluid velocity in the foam was lower than in the experiments of this section at the same global strain rate. Since the influence of a higher fluid velocity in the model is stronger than experimentally observed (as was seen in the results of section 3.4.2 where the model severely overestimated the compressive force) this could explain some of the difference. The maximum Reynolds number was calculated to be $Re = 0.79$ which is considerably higher than the maximum Reynolds number in the experiments of chapter 3 and makes the assumption of viscous flow more questionable.

Furthermore the assumption of the fluid remaining in a cylindrical shape during deformation might not be completely met, although the influence of this assumption being met or not is not completely clear.

Lastly it should be noted that the parameter $C$ was fitted to the data of section 3.4.2. One of the reasons mentioned in the discussion on the discrepancy between the model and the data was radial expansion of the foam. In the experiments of this section, however, the samples were glued to plates on both sides thereby limiting the radial expansion. It was expected to see no radial expansion in the experiments but even with the top and bottom of the sample constrained the foam expanded radially. Not to the same extent as the samples of section 3.4.2 but radial expansion of the sample might still be a explanation for poor agreement between data and model using $C = 0.59$. 

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Chapter 5

Helmet tests

In this section an attempt is made to use the model developed in chapter 4 to develop a model that describes the impact of a motorcycle accident. The aim is to develop a way to determine the maximum load on the head for a given helmet design. As previously described, currently commercially available motorcycle helmets consist of three layers: the shell, the foam liner, and the comfort foam. The shell is primarily meant to prevent objects to penetrate the helmet. The primary energy absorbing layer is the foam liner. Usually the foam liner is made of polystyrene beads. The comfort foam is used to allow the helmet to comfortably fit a range of head sizes.

To improve helmets much of the focus is on improving the foam liner. In the work by Dawson [5] it was found that replacing part of the polystyrene layer by a composite layer consisting of columns of fluid filled foam embedded in air filled foam could result in a significant decrease in weight of the helmet while still providing a sufficient level of protection.

5.1 Helmet model

Whereas several different motorcycle helmet testing methods exist, in this analysis the Peak Limit Acceleration (PLA) criterion is used. Most international standards require the maximum acceleration of the head does not exceed 300g under a direct impact of a 5 kg mass traveling at 6 m/s to 7.5 m/s [7, 13]. The resulting impact energies range from 90 J to 140 J. Based on a head mass of 5 kg, an acceleration of 300g corresponds to a maximum load on the head of 15 kN.

In this analysis the improved helmet design as described in section 2, figure 2.2 is considered. Variations in the number and radius of fluid filled columns in the polyurethane layer are considered.

Although in real helmets the curvature of the helmet improves the impact resistance and energy absorbing capabilities, for the purpose of comparing different designs, flat plates are used. The plates have an area of 100 mm
x 100 mm since this is assumed to accurately represent the cross-sectional area of the helmet used to absorb most of the impact energy under standard testing conditions [7].

A rather simple dynamical model is used to describe the forces resulting from the impact of the striker. The dynamical model can be seen in figure 5.1.

![Dynamical model of the helmet](image)

**Figure 5.1:** Dynamical model of the helmet

In this figure PS is the polystyrene and PU is the composite fluid filled / air filled polyurethane layer. The polystyrene and polyurethane layers are both modeled as point masses, where the (nonlinear) springs and damper connecting them represent the stress - strain behavior of each layer. The springs and damper are taken to be massless. The strain in each layer is taken to be uniform. The shell is taken to be made of ABS.

In earlier work it was noted the shell absorbs little of the total impact energy [12]. Therefore the ABS shell is assumed to be rigid in this analysis. Furthermore it is assumed the striker collides completely inelastically with the ABS shell on impact. It is assumed the ABS shell and the mass of the polyurethane are rigidly connected to each other. The layer of comfort foam is omitted from the model since its energy absorption capabilities are negligible compared to the other layers.
The equations describing the model are given by
\begin{align}
(m_{\text{striker}} + m_{\text{ABS}} + m_{\text{PU}}) \ddot{x}_{\text{PU}} &= -F_{\text{PU}} \tag{5.1} \\
m_{\text{PS}} \ddot{x}_{\text{PS}} &= F_{\text{PU}} - F_{\text{PS}} \tag{5.2}
\end{align}
Here, $F_{\text{PU}}$ is the compressive force resulting from the deformation of the polyurethane layer, and $F_{\text{PS}}$ is the compressive force resulting from the deformation of the polystyrene layer.

The initial velocity of the combination of striker, ABS and PU is determined by conservation of momentum. The initial conditions are given by
\begin{align}
x_{\text{PU}}(t = 0) &= 0 \tag{5.3} \\
\dot{x}_{\text{PU}}(t = 0) &= \frac{v_{\text{striker}} m_{\text{striker}}}{m_{\text{striker}} + m_{\text{ABS}} + m_{\text{PU}}} \tag{5.4} \\
x_{\text{PS}}(t = 0) &= h_{0_{\text{PU}}} \tag{5.5} \\
\dot{x}_{\text{PS}}(t = 0) &= 0 \tag{5.6}
\end{align}
in this model $v_{\text{striker}}$ is the impact velocity of the striker, $m_i$ is the mass of object $i$, and $h_{0_{\text{PU}}}$ is the initial height of the polyurethane layer.

To calculate the force in the polyurethane layer, the model developed in section 4 is used. Since it is expected the strain rates in the helmet test are high, $C = 0.063$ is used as found in section 4.3 for the high strain rate experiments. The force in the polyurethane is based on the number and size of the fluid filled columns.

The model was run for 1, 4, and 9 columns where the radius of each column ranged from 0.01 m to 0.03 m, 0.01 m to 0.02 m, and 0.0075 m to 0.015 m respectively. It is assumed the fluid flow from each column is unaffected by the fluid flow from the other columns.

Because the model described in section 4 shows a discontinuity in the force at $\epsilon^*_{el}$ numerical difficulties are to be expected. Therefore the single regime model was adapted in such a way the force - strain relation is continuous. The influence of this adaption on the force - strain relation is small.

To determine the parameters describing the response of the polystyrene layer several experiments were done and the parameters of the model (equations 3.2 - 3.3) were fitted to the data. The response of the polystyrene was found to be approximately independent of the strain rate, therefore the strain rate dependent expression for the effective modulus does not need to be used.

The maximum force on the head is taken to be the maximum force in the polystyrene.

5.2 Materials and experimental procedure

Experiments were performed on samples made of square cross sections of 100 mm x 100 mm. The outer shell was made of ABS with a density of
Table 5.1: Overview of configurations used in the experiments

<table>
<thead>
<tr>
<th>Number of columns</th>
<th>Radius of each column (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0127</td>
</tr>
<tr>
<td>1</td>
<td>0.0191</td>
</tr>
<tr>
<td>1</td>
<td>0.0254</td>
</tr>
<tr>
<td>4</td>
<td>0.0127</td>
</tr>
<tr>
<td>9</td>
<td>0.0127</td>
</tr>
</tbody>
</table>

1.12 g/cm$^3$ and a thickness of 6.25 mm, which is slightly thicker than the shells used in commercially available helmets due to practical issues. The polystyrene used has a density of 0.055 g/cm$^3$ and a thickness of 25 mm. The open cell polyurethane foam used in the fluid filled / air filled layer is the same as used in the earlier experiments. The total design is slightly thicker than commercially available helmets but for the purpose of testing the model this configuration can be used.

A 100 mm x 100 mm section of polyurethane foam was cut. From this layer cylindrical specimens were cut. The size and number of columns used were varied in the experiments. An overview of the used configurations is given in figure 5.2 and table 5.1.

(a) Single fluid filled column. (b) Four fluid filled columns. (c) Nine fluid filled columns.  

Figure 5.2: Overview of configurations used in the experiments

The cylindrical specimens were impregnated with glycerol, as described in section 3.3. After saturating, the columns were press fit in the 100 mm x 100 mm section. Next, the polyurethane layer was attached to the polystyrene layer on one side and to the ABS layer on the other side, using water resistant epoxy.

After allowing the samples to completely cure at 23° C, the samples were loaded in a drop tower and impacted using a striker with a diameter of $D = 35$ mm. The impact mass used was 7.2 kg, which was the lowest mass possible. The impact velocity was set to 6 m/s, resulting in an impact
energy of approximately 130 J. The load versus time signal was recorded for
each test using a load cell connected to the striker at a rate of 250 kHz.

5.3 Results

![Figure 5.3: Results of impact simulations on helmet](image)

The results from the model are shown in figure 5.3. On the x axis the weight
of the fluid in each configuration is given. This is also a measure for the
radius of the fluid filled columns, since, for each line, only the radius of the
fluid filled columns was varied. On the y axis the maximum load on the
head is given. Since for each configuration the weight of the samples is the
same except for the mass of the fluid, the mass of the fluid is an indication
for the weight efficiency of each design. Each of the three lines corresponds
to a different number of fluid filled columns, as can be seen in the legend of
the figure.

From the figure it is clear that the best performing design is the one
using only a single column, since for each fluid mass the single column design
results in a lower maximum load than the designs involving more columns.

The experimental results are shown in table 5.2. Each experiment was
carried out twice and the mean and standard deviation of these experiments
are shown in the table. Also shown in table 5.2 are the results from the
model for each design.

It can be seen that the trend of the model is not supported by the data.
Where the model indicated the single column would be the most favorable,
the experimental results tell otherwise. Although the differences are small
the configuration using nine columns can be seen to be the best performing
Table 5.2: Overview of results

<table>
<thead>
<tr>
<th>Number of columns</th>
<th>Radius of each column (m)</th>
<th>Fluid mass [kg]</th>
<th>Experimental mean [kN]</th>
<th>Standard deviation [kN]</th>
<th>Model [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>8.97</td>
<td>0.15</td>
<td>10.43</td>
</tr>
<tr>
<td>1</td>
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<td>8.74</td>
<td>0.26</td>
<td>9.35</td>
</tr>
<tr>
<td>1</td>
<td>0.0254</td>
<td>0.0319</td>
<td>8.51</td>
<td>0.11</td>
<td>8.67</td>
</tr>
<tr>
<td>4</td>
<td>0.0127</td>
<td>0.0319</td>
<td>8.00</td>
<td>0.11</td>
<td>9.56</td>
</tr>
<tr>
<td>9</td>
<td>0.0127</td>
<td>0.0718</td>
<td>7.79</td>
<td>0.13</td>
<td>9.11</td>
</tr>
</tbody>
</table>

one. In the model the configuration using a single column with a radius of $R = 0.0254$ m resulted in the lowest load on the head.

5.4 Discussion

The results of the model show that for increasing fluid mass (or column radius) the maximum load on the head decreases. This can be understood by the fact that for a larger fluid mass the polyurethane layer is able to absorb more energy. For a very low fluid mass the polyurethane layer does not absorb a significant amount of energy and all the energy needs to be absorbed by the polystyrene layer, resulting in higher maximum loads on the head.

As shown in table 5.2 the results from the experiments and from the model differ in a couple of ways. This may be because of several reasons.

The first important point is the fact that the tests are at high strain rate. The maximum Reynolds number in these tests was calculated to be approximately $Re = 0.80$, so the assumption of the flow being in the viscous regime is questionable. It was concluded in section 4.3 that the high strain rate description of the model was not accurate. Using $C = 0.063$ the model corresponded better to the data at test velocities of 2 m/s and 3 m/s. However, the helmet experiments are at 6 m/s. Therefore it is expected that, using $C = 0.063$, the forces in the polyurethane as calculated with the model for the helmet tests are higher than in reality. Since there is no experimental data for test velocities higher than 3 m/s it is uncertain how large the difference is. Furthermore all the experiments in chapter 4 were done on samples having the same radius, $R = 12.7mm$. The model was not verified for other dimensions of the samples. It was noted by Dawson [5] that the model does describe tests on larger samples too, but those experiments were all done at low strain rates. It is expected that for larger samples at high strain rates the difference between model and data gets even bigger than for the samples considered in chapter 4.
The second point which makes it hard to compare the experimental data to the model are the assumptions made in the model. The assumption of uniform strain in each layer is not met. Since the stiffness of the fluid filled part and the air filled part of the polyurethane layer are significantly different from each other the strain in both the polyurethane and the polystyrene is not uniform. Only the fluid filled part of the polyurethane foam transfers load to the polystyrene. The other parts of the polystyrene layer are not directly loaded. This observation is supported by the experimental data. The larger the initial area of the fluid filled columns, the larger the area of the polystyrene that is loaded and therefore the maximum load decreases since the energy is absorbed in a larger volume.

Continuing this reasoning it would be expected that the load as given by the model is lower than in the experiments, since the model assumes the total volume of polystyrene to aid in absorbing the energy. However, this expectation is not supported by the data. This difference might be caused by the fact that the ABS will in fact absorb a small amount of energy. Furthermore the polystyrene in the experiments shows a significant amount of bending because of the localized loading. This energy absorption mechanism is not accounted for in the model. It is also not clear whether the assumption that the fluid flow from one column does not affect the flow from other columns is met in the experiments, especially in the configuration with nine columns. Next to these three explanations the earlier mentioned high strain rates are a possible cause for the discrepancies observed.

On a more general note the modeling as point masses connected by massless springs and dampers may not be very accurate. Since the mass of the polystyrene is small the forces in the polystyrene and polyurethane layer are approximately in equilibrium. This means that this model calculates the force on the head and the force on the striker to be approximately the same. However, it was shown that the head force and striker force are not the same in helmet impact tests [7]. This is also a shortcoming of this experimental procedure since in these tests the load cell is connected to the striker and not to the place where the head would normally be.

Another disadvantage of the dynamical model used is the fact that, at some point, the polyurethane layer will get loaded in tension. Since the model does not describe tension the simulations could not be continued beyond the point where the polyurethane is loaded in tension. It is, however, not expected that the maximum load in this model would change significantly since almost all the impact energy is absorbed at the moment the polyurethane gets loaded in tension.
Chapter 6

Conclusions and Recommendations

In this report the model of Dawson et al. [4] was tested at high strain rates. It turned out that the model did not represent high strain rate data quite well. In this work a fit was used to obtain a better agreement between data and model, however, this type of fit does not provide insight in the behavior at other strain rates. Several possible causes for the lack of agreement between data and model have been proposed. The inertial forces were neglected in this analysis but may be significant at the high strain rates used in the experiments. In future work the high strain rate behavior of fluid filled foams needs to be studied closer.

The model of Dawson et al. [4] was extended to account for air filled foam surrounding the fluid filled foam. This extension was shown to correspond to experimental data quite well for low strain rates and up to a certain strain. For high strain rates the model does not agree with the data. Using a fit the model corresponded better to the data but again this does not provide insight in the physical processes playing a role. More tests should be done to estimate the possible influence of the gap forming between the fluid filled foam and air filled foam, and the influence of the radial expansion of the foam.

Further work can be done on the air filled foam surrounding the air filled foam. In this analysis both foams were taken to be the same but to get full flexibility in optimizing designs it is needed to be able to use a different foam for the air filled foam than for the fluid filled foam. Extending the model to account for this might prove to be hard since the assumption of both foams deforming in exactly the same way and having the same permeability can not be made anymore in that case.

The fluid used in this analysis was glycerol. The viscosity of glycerol is influenced strongly by temperature, making the use of it in carefully designed helmets impractical. On a hot day the helmet might react differently to a
crash than on a cold winter day. Therefore the use of other fluids might be a better option. Especially non Newtonian fluids look promising since the properties of these fluids can be tuned and thus enable even further design optimization. The model of Dawson [5] which describes the flow of non Newtonian fluids through open cell foams can be used as a starting point to explore the possibilities of using non Newtonian fluids.

The developed model was used to come to a dynamical model describing the impact of a motorcycle helmet. Several configurations of the polyurethane player were tested and compared with the model. The trend of the experimental data did not correspond to the model. The assumption of uniform strain in each layer was not met. Furthermore the strain rates in the simulations were beyond the strain rates of the experiments done to test the extended model. This once again shows the importance of a description of the high strain rate behavior of fluid filled foams. The dynamical model used needs to be improved.

To obtain more geometrical flexibility in modeling the response of fluid filled foams it might be useful to adapt the model in such a way that it is able to describe other than cylindrical shapes of fluid filled foams. This might again prove to be hard and for applications where flexibility in the shape of the fluid filled foam is needed computational methods might prove to be a better choice. However, in applications where such flexibility is not needed the use of the developed model, once fully capable of describing high strain rate behavior, is most likely an easier and computationally less expensive way to go.
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cell foams under compressive strain. Int. J. Solids Struct. 44, pp. 5133-5145


