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8) ABSTRACT

As a first attempt at identifying a tissue model for use in wound ballistic simulations a study of the wound profiles in soap during deceleration of spherical steel projectiles has been carried out. Experimental data were compared to numerical calculations using the AUTODYN-2D code.

We found that the AUTODYN-2D simulations show good agreement with experiment when a simple linear equation of state is used in conjunction with a Mieses strength model and a Pmin failure criterion. A detailed investigation using the numerical model showed that the deceleration of spherical steel projectiles were mainly dependent of the density of the soap, while the wound profiles were dependent of the mechanical strength material models used. We find that good material models of different tissues are important in order to do wound ballistic computations by using computer codes.

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CONTENTS

WOUND PROFILES IN SOAP CAUSED BY PENETRATION OF HIGH SPEED SPHERES

1 INTRODUCTION

In this article we focus on the ability to perform wound ballistic assessments using computer codes. Tissue simulants are usually defined as homogeneous materials that reasonably approximate the penetration resistance of soft tissue, but incapacitation from wounds is strongly dependent of the wound profiles in the tissue. It is therefore important to be able to model not only the penetration resistance in the tissue, but also the wound profiles.

Typical tissue simulants are soap and gelatin. A series of experiments where steel spheres were shot at soap targets have been carried out [1]. Comparison with AUTODYN-2D simulations[2] showed good agreement for projectile exit velocities. The simulations and the experiments gave an overall drag coefficient of 0.36. A detailed investigation using the numerical model showed that the deceleration of spherical steel projectiles were mainly dependent of the density of the soap.

In this report we show that the cavity profiles in soap are dependent of the material mechanical strength models used. Based on those results we foresee that wound profiles in a given tissue are dependent of the mechanical strength of the tissue. The mechanical strength of different tissues are different, and good material modelling is therefore important in order to perform wound ballistic computations by using computer codes.

2 THE EXPERIMENTAL SET-UP

In figure. 2.1 the experimental set-up used by Krogh and Omholt [1] is shown.

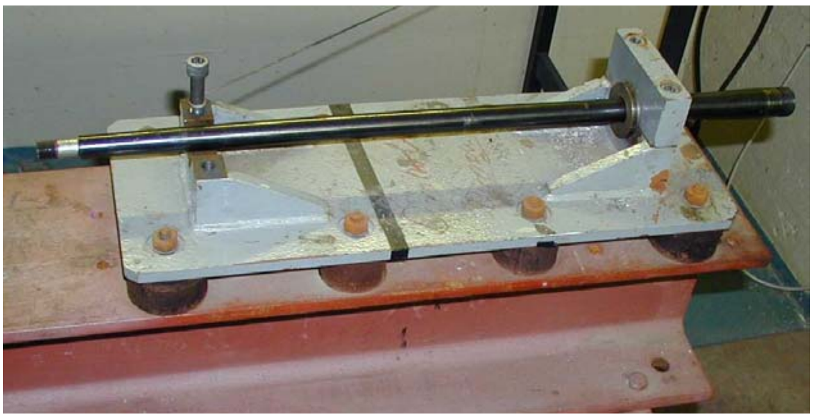

Figure 2.1 The experimental set-up (gun) used by Krogh and Omholt [1].

The velocity before and after penetration where measured by cross correlating signals from two coils in the front and in the back. Wound profiles where recorded afterwards by cutting the soap block in two.

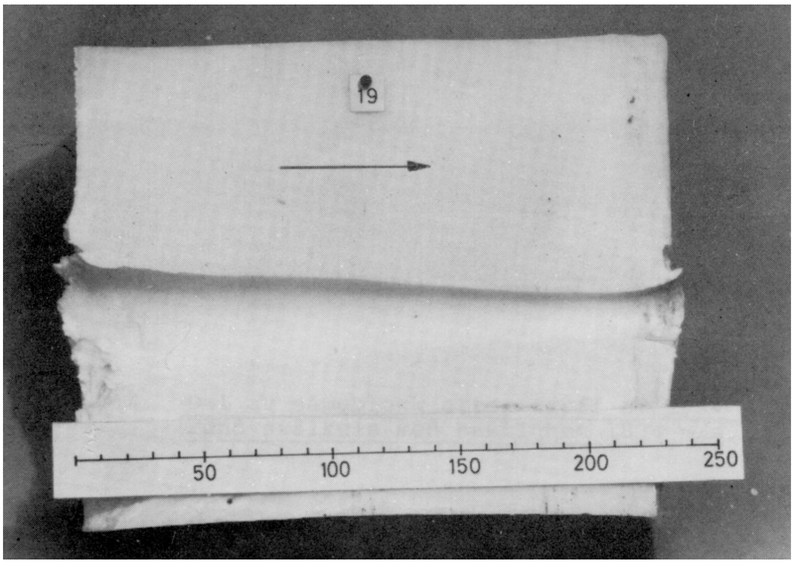

Figure 2.2 Soap block after being penetrated by a steel sphere at an initial velocity of 1258 m/s (the length scale is in mm). Length=25 cm, width=19.5cm, quadratic.

3 THEORETICAL BACKGROUND-THE WOUND PROFILE

This section gives a short description of the cavity created by a penetrating stiff projectile.

The standard cavity expansion theory predicts that the dimension of the cavity in a semi-infinite target is roughly equal to the calibre of the penetrator. Our experimental result does not support this prediction. Generally we can write that the force F working on the projectile is given as

$$\mathrm{F} \overset{\mathrm{def}}{=} F_p + F_s \tag{3.1}$$

$$F_p \overset{\mathrm{def}}{=} 1/2\, Cd_p \mathrm{A} \rho_0 \mathrm{v}^2 ,\ F_s \overset{\mathrm{def}}{=} A r_t \ r_t \overset{\mathrm{def}}{=} 1/2\, \mathrm{Cd_s Y}\ (1+\mathrm{Log}[2\ \mathrm{G/Y}]) \tag{3.2}$$

F_p : force caused by inertial forces
F_s : force caused by material strength
R: radius of the spherical nose
A: πR^2, projected area of the spherical nose
ρ_0: density of the target
Y: yield limit for the target
G: shear modulus for the target
v :penetration velocity

Cd_p : pressure drag coefficient
Cd_s : deviatoric drag coefficient

According to the cavity expansion the theory the force acting on a spherical projectile is given by[3]

$$\mathrm{F_{pc}} = 2\pi \mathrm{R}^2 \int_0^{\theta_c} \rho_0 \mathrm{v}^2 \frac{3}{2} \cos^2(\theta)\cos(\theta)\sin(\theta)\mathrm{d}\theta = \frac{3}{4}\mathrm{A}\rho_0 \mathrm{v}^2 \left(1-\cos^4(\theta_c)\right) \qquad (3.3)$$

and

$$\mathrm{F_{sc}} = 2\pi \mathrm{R}^2 \int_0^{\theta_c} \frac{2}{3}\mathrm{Y}\left(1+\log\left(\frac{2\mathrm{G}}{\mathrm{Y}}\right)\right)\cos(\theta)\sin(\theta)\mathrm{d}\theta = \frac{1}{3}\mathrm{AY}\left(1+\log\left(\frac{2\mathrm{G}}{\mathrm{Y}}\right)\left(1-\cos(2\theta_c)\right)\right) \qquad (3.4)$$

$\theta_{c,}$ is the slip angle. In the initial phase of the penetration this quantity depends on the degree of penetration, and is given by:

$$\theta_c = \theta_{cc} \overset{\mathrm{def}}{=} Min\left(\frac{\pi}{2}, \arccos\left(1-\frac{\mathrm{x}}{\mathrm{R}}\right)\right) \qquad (3.5)$$

where

x: penetration depth

The part of the drag coefficient that is due to the inertial (dynamic) forces, will then be given by:

$$\mathrm{Cd_{pc}}(\theta_c) \overset{\mathrm{def}}{=} \frac{\mathrm{F_{pc}}}{\frac{1}{2}\rho_0 \mathrm{v}^2 \mathrm{A}} = \frac{3}{2}\left(1-\cos^4(\theta)\right) = 3\theta_c^2 - \frac{1}{4}\theta_c^4 + O\left(\theta_c^6\right) \qquad (3.6)$$

and the part that is due to the strength of the material (the deviatoric part) is given by:

$$\mathrm{Cd_{sc}}(\theta_c) \overset{\mathrm{def}}{=} 2\frac{\mathrm{F_{sc}}}{\mathrm{AY}\left(1+\log\left(\frac{2\mathrm{G}}{\mathrm{Y}}\right)\right)} = \frac{2}{3}\left(1-\cos(2\theta_c)\right) \qquad (3.7)$$

After penetrating a distance R, critical angle is according to equation (3.5), given by $\theta_c = \pi/2$. Then we have from (3.6) and (3.7) that

$$\mathrm{Cd_{pc}}(\pi/2) = 3/2 \qquad (3.8)$$

$$\mathrm{Cd}_{sc}\left(\pi/2\right)=4/3 \tag{3.9}$$

According to the results in reference [2], the pressure drag coefficient is 0.36 instead of 3/2. We use 0.36 in this paper.

Let s(t) be the position of the projectile inside the soap. The equation of motion is then $m\,\dot{s}(t)= F_p+F_s$, where m is the mass of the projectile. Inserting the relations in (3.1) we have

$$\dot{v}(t) \overset{\text{def}}{=} -\alpha/m\ v(t)^2-\beta/m,\alpha \overset{\text{def}}{=} (1/2)\rho_0\, Cd_p A,\beta \overset{\text{def}}{=} r_t A,\ v(t)\geq 0 \tag{3.10}$$

where $\dot{s}(t) \overset{\text{def}}{=} v(t)$. Assuming that the drag coefficients are constant , the solution is

$$v(t)=(\beta/\alpha)^{1/2} Tan[c-t\,\alpha/m\,(\beta/\alpha)^{1/2}],c \overset{\text{def}}{=} ArcTan[v(0)(\alpha/\beta)^{1/2}],t_{\max}=c\,m/(\alpha\beta)^{1/2} \tag{3.11}$$

where t_{max} is the time when the projectile stops in the target. For a large part of the penetration process $F_s/F_p \ll 1$. Expansion of equation (3.11) gives

$$v(t)\approx v(0)/(1+v(0)(\alpha/\beta)t)\,. \tag{3.12}$$

There is a one to one relation between the time t and the position s, let's say t= T(s). Now, defining $v(s) \overset{\text{def}}{=} v(T(s))$, the equation of motion becomes

$$\dot{v}(s)=-\alpha/m\,v(s)-(\beta/m)/v(s) \tag{3.13}$$

The solution is

$$v(s)=[(v(0)^2+\beta/\alpha)Exp[-2(\alpha/m)s]-\beta/\alpha]^{1/2},s_{\max}=1/(2\alpha)\ m\ Log[1+v(0)^2(\alpha/\beta)] \tag{3.14}$$

where s_{max} is the maximum penetration length. Again, using the fact that the pressure force is much larger that the strength force for a large part of the penetration process, equation (3.14) can be approximated as

$$v(s)\approx v(0)Exp[-(\alpha/m)s] \tag{3.15}$$

During penetration the energy lost by the projectile is converted to heat. Assuming that the heat is generated by plastic deformation of the target we can write

$$F_p v + F_s v = v(t) 2\pi \int_0^a (F_s / A) r dr \quad (3.16)$$

This relation says that the work done by the projectile pr unit time is used to open a cylindrical cavity of radius a. Equation (3.16) gives the important relation

$$a(s) = R(1 + F_p / F_s)^{1/2} \quad (3.17)$$

This relation tells that when the mechanical strength force is much smaller that the dynamic pressure force, the deceleration of the projectile is controlled by the dynamic force, while the cavity radius is controlled by the square root of the ratio of those to forces, i.e.

$$a(s) \approx R(F_p / F_s)^{1/2} \quad (3.18)$$

Using the relations in (3.1) we have

$$a(s) = R(1 + 1/2\, C d_p \rho_0 v(s)^2 / r_t)^{1/2} \quad (3.19)$$

In the next section we will compare equation (3.19) with both experimental and simulated values.

4 AUTODYN SIMULATION AND EXPERIMENTAL RESULTS

In this section simulations in AUTODYN-2D will be compared to the experiments. Figure 4.1 shows the Euler grid of the soap and the Lagrange grid of the spherical steel projectile.

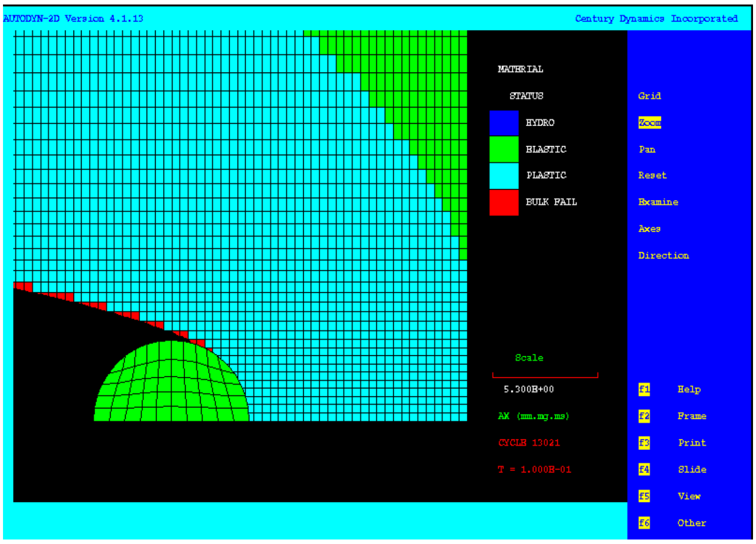

Figure 4.1 The grid of the target and projectile after 0.1 milli second.

The first step is to calibrate the value of Cd_s . In figure 4.2 the cavity diameter given from equation (3.19) is shown together with Autodyn simulations as a function of penetration depth for shots with initial velocities of 1258m/s. The shear modules and the yield strength are chosen arbitrarily as a first guess. In order to achieve a match between those two curves Cd_s is found to be 1.73, while Cd_p is chosen as the standard value of 0.36. Next, in order to find the material parameters, we compare solutions from (3.19) with experimental results for a cylindrical projectile with a spherical nose. We choose the same drag coefficients, and search for values of the yield strength and shear modulus that fit the experimental results for this cylindrical projectile. The curves are shown in figure 4.3. The material parameters are given in appendix A, and they are in agreement with quasi static compression tests. Lastly, in figure 4.4 we compare experimental and theoretical values for the steel sphere using the material parameters and the drag coefficients. The curves fit nicely together.

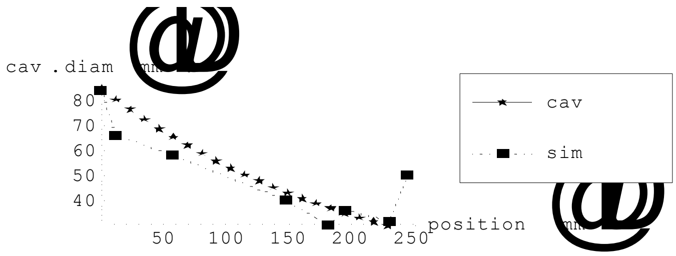

Figure 4.2 Cavity expansion theory compared with experimental diameters for a sphere.

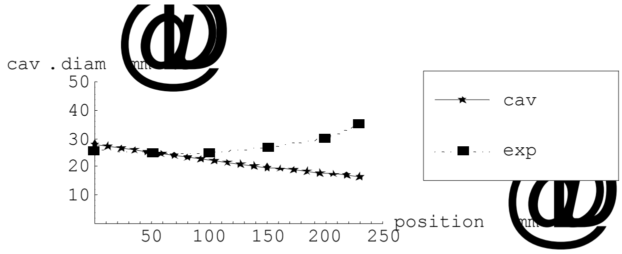

Figure 4.3 Cavity expansion theory compared with experimental diameters for a cylindrical projectile.

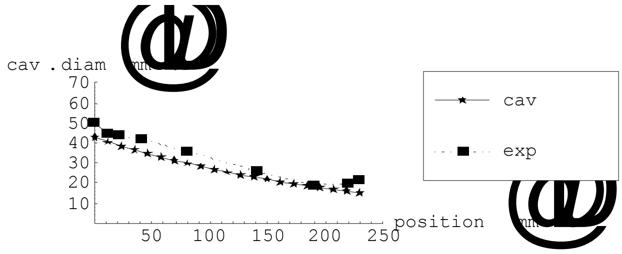

Figure 4.4 Cavity expansion theory compared with experimental diameters for a sphere.

Let's say that the energy of the projectile is given initially as e(0). What calibre should we use for a projectile in order to achieve a maximal cavity surface in the target given that the initial energy is constant for all calibres? Taking a steel sphere as an example, we have

$$m(R)=(4/3)\pi R^3,\ \alpha(R)=(1/2)\mathrm{Cd_p}\rho_0\ \pi \mathrm{R}^2,\ \beta(R)=rt\pi R^2,\ \mathrm{v}_0(\mathrm{R})=(\mathrm{e}(0)\ 3/2/\pi/\rho_s/\mathrm{R}^3) \quad (4.1)$$

$$\mathrm{v(R,s)}=[(\mathrm{v}_0(\mathrm{R})^2+\beta/\alpha)\mathrm{Exp}[-2(\alpha(\mathrm{R})/\mathrm{m(R)})\mathrm{s}]-\beta/\alpha]^{1/2},$$

$$a(R,s)=R(1+((1/2)Cd_p\rho_0/rt)v(R,s)^2)^{1/2},\ \mathrm{s_{max}(R)}=(1/2/\alpha(R))m(R)Log[1+v_0(R)^2(\alpha/\beta)]$$

The total area is then given by

$$\mathrm{Area(R)}=\int_0^{\mathrm{s_{max}(R)}} 2\pi \mathrm{a(R,u)udu} \quad (4.2)$$

In figure 4.5 we see a plot of $\mathrm{Area(R)/Area(R}=3.97\ 10^{-3}\mathrm{m})$ as a function of the relative dimension R/(3.97 10^-3). Observe that there is an optimal dimension of the sphere. It is easy to show the following relation analytically;

$$\mathrm{Area(R)}\to 0,\ \text{when } \mathrm{R}\to\infty, \mathrm{Area(R)}\to 0,\ \text{when } \mathrm{R}\to 0 \quad (4.3)$$

According to Rolle's theorem if follows that the continuous function Area(R) has an optimum.

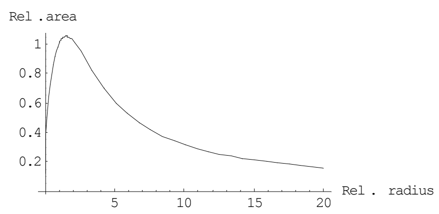

Figure 4.5 Relative area as a function of relative radius.

5 CONCLUSION/DISCUSSION

We have found that the AUTODYN-2D simulations show good agreement with experiment when a simple linear equation of state is used in conjunction with a Mieses strength model and a P_{min} failure criterion. A detailed investigation using the numerical model shows that the deceleration of spherical steel projectiles were mainly dependent of the density of the soap, while the wound profiles were very dependent of the material mechanical strength model used. We find that good material models are very important in order to do wound ballistic computations using computer codes.

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[1] Krog T., Omholt L., FFI/Notat-81/4008.

[2] Martinussen S. M., Moxnes J. F., FFI/Report-02/03293

[3] Bishop R. F., Hill R., Mott N. F., The Theory of Indentation and Hardness Tests, Proc. Phys. Soc. Vol. 57, Part 3, No. 321, pp. 147-159, May 1945.

A APPENDIX

The following material parameters were used:

Steel Sphere: Radius: 3.97mm. Mass::2.04 g, Yield stress: 1.6 10^9 Pa
Soap: Length: 23cm,width: 19.5cm, quadratic, density:1034 kg/m^3,
Yield stress: 3.2 10^6PaYoung's modulus: 1.82 10^8 Pa, Bulk modulus:2.65 10^9Pa,Pmin=-infinite.

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