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PENETRATION EXPERIMENTS AND 1D SIMULATIONS OF AIR RIFLE BB 4.5 MM STEEL SPHERE AND GAMO HUNTER 4.5 MM IMPACTING 10% GELATINE

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Abstract. *Gelatine of 10% concentration is often used as projectile target to simulate soft tissues of animals and humans. The 10% gelatine used in the tests fulfills the FBI standard protocol for penetration depth of BB 4.5 mm steel sphere impacting with 180 m/s. Here, experiments were conducted with BB 4.5 mm steel sphere and diabolo Gamo Hunter 4.5 mm pellets with varying impact velocity. The impact velocity was measured by chronograph. The deceleration and dynamic cavity size was studied by using high-speed camera with 10000 frames per second. Final penetration depth was manually measured. A 1D simulation model, considering the retardation force generated by drag and shear, was used to predict penetration depth in both 10% and 20% gelatine for projectiles with spherical nose shape. From the simulations it becomes evident that the drag force and static shear force alone can't explain the total retardation force to achieve the expected penetration depth. In the literature for experiments conducted on both 10% and 20% gelatine, there is confirmation that projectiles impacting with velocity above 100 m/s, the shear strength in the gelatine is increased by a factor 40 and 70 times for 10% and 20% gelatine, respectively. This concept was successfully used in the simulations by introducing a shear rate dependent shear force model which increases the static shear force of 10% and 20% gelatine. All experimental results, including high speed films and python simulation code of gelatine penetration, are publicly available, see [1], [2].*

1 INTRODUCTION

1.1 Background

To improve civil defence during crisis and war time, it is important to understand the effect of how splinter and debris of metals and concrete with high kinetic energy generated from explosions and how these would affect human body and its soft tissues during impact and penetration. To derive physical simulation models to include these effects, it is necessary to understand the physics of rapid penetration into soft body tissue. This paper has been conducted to broaden the civil defence knowledge and to be able to simulate the effects in physical experiments of penetration into soft tissue with 4.5 mm calibre air rifle. Here, the soft tissue is simulated by using 10% gelatine blocks. In simulation of hydrogels prepared from water solutions containing 10-20 mass % gelatine is generally acknowledged as muscle tissue simulants in terminal ballistic research [4]. As gelatine is a natural component of meat, made by the hydrolysis of collagen during processing and cooking. In [3] it is shown that extruded gelatine of microfibers mimics structural and biochemical characteristics of natural muscle tissues but is lacking surface layer which represents the effect of human skin and the density of bones. Gelatine is used to visualize both temporary and permanent impacts of which are conceived as providing a reasonable approximation to wounding in humans, as gelatines are used in both fatality and survivability studies, also comparison of ammunition effects [5]. Here, a simplified differential equation is formulated with drag force and shear force which is the result of the penetrator progressing into the gelatine block.

1.2 Definitions

The following definitions in italics are used in this paper:

10% gelatine block is a water-based solution containing 10% gelatine, developed according to Appendix 1.

Depth of Penetration (DOP) is the final penetration distance at rest that the penetrator travelled from entrance point to the tip of the penetrator, manually measured from entry point to tip of penetrator.

10% gelatine block *fulfilling the FBI standard protocol* is a block which have been initially shot with 4.5 mm steel sphere with impact velocity of 180±3 m/s having a DOP of 8.5±1 cm, see [7].

Dynamic Cavity Diameter (DCD) is the maximum expanded diameter observed in the 10% gelatine block with high-speed filming during the penetration process.

The type of 4.5 mm calibre penetrators used in this terminal ballistic study are defined in Table 1. The penetration results from *Sphere* and *Dome* are presented and discussed in this paper. Additional penetration results are omitted due to paper size, results for these penetrators are found in [1] and [2].

(a)		*Sphere*: ASG Blaster BB 4.5 mm – Baseline penetrator Nose shape: spherical Material type: steel mass: 0.35 g
(b)		*Dome*: Gamo Hunter Impact 4.5 mm Nose shape: half-sphere with small waist Material type: lead mass: 0.49 g mass increase to compared to Sphere: 40 %

Table 1: Different 4.5 mm calibre penetrator types are defined: *Sphere* and *Dome*.

2 EXPERIMENTS

2.1 Material specifications of used 10% gelatine block

The 10% gelatine blocks were manually mixed by using warm water and 100% gelatine powder a few days before the experiments presented in this paper, see Appendix I. The 100% gelatine powder used in the mixture is a commercially available product and is made from boiling the connective tissues, bones, and skins from cows.

2.2 Test arrangements

The experiments were conducted near Uleåborg/Oulu, Finland, during the summer months of July and August 2021. The test arrangements for the penetration experiments of 10% gelatine is shown in Figure 1. The experiments were conducted on a wooden table. Figure 1 shows the air rifle positioning and model type, Crosman and Hatsan, for the penetrators in calibre of 4.5 mm defined as Sphere and Dome, see section 1.2. The projectile’s impact velocity was measured with a chronograph. The 10% gelatine block of outer size 15 x 35,5 x 14,2 cm was fixated on a wooden block. The bottom surface of the wooden block had sandpaper attached for increased friction between wooden block and wooden table. The wooden block was also provided with a back stop to prohibit the gelatine to jump during the impact by the penetrator. The wooden block had a ruler mounted alongside below the gelatine block for digital measurements on films with the highspeed camera. The right side of the wooden table had natural day light. This is still not enough for the high-speed filming, see Figure 1 for camera positioning. The important flicker free LED lightning was added with a total of 720 W. The high-speed camera was set up to film a major part of the gelatine block with camera resolution 640x240 and 10 488 frames per second (FPS). This FPS was targeted to have enough film frames to capture the complete penetration process from impact the gelatine to standstill. Before and after each shot a photo was taken with mobile phone and the depth of penetration (DOP) was manually measured after each shot. All experimental results, including high speed films, are publicly available, see [1]. In [2], complete test series summary table is published together with key findings of experiments with different penetrator types in calibre 6.35 mm penetrating 10% gelatine blocks.

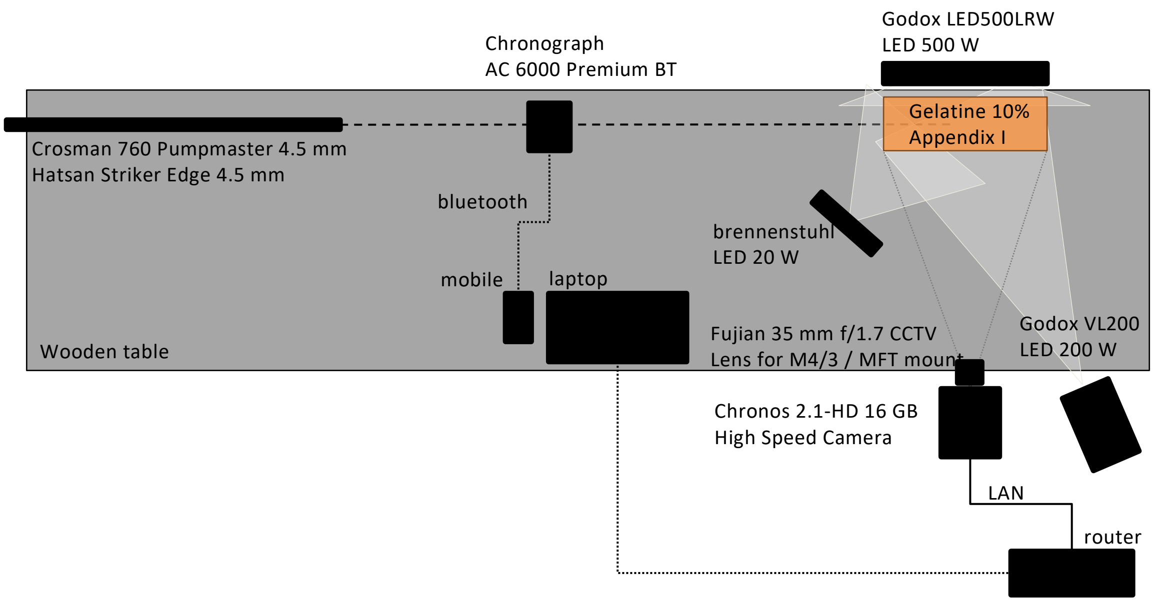


Figure 1: Principal sketch of test arrangement for 4.5 mm calibre gelatine 10% experiments.

3 EXPERIMENTAL RESULTS

The experiments are summarised in section 3.1 and section 3.2 shows the penetration depth and high-speed film experiment results of projectile penetration and estimation maximum dynamic cavity diameter. All experimental results including high speed films are publicly available, see [1]. In [2] the main experimental results from 6.35 mm calibre are shown with how different penetrator shapes affect the dynamic cavity diameter and DOP.

3.1 Experimental summary table

The penetrator Sphere 4.5 mm calibre terminal ballistics experiments in 10% gelatine are summarized in Table 2 for test series GB210827nr2 in format “Gelatine Block – Year Month Day – number”. This gelatine block fulfilled the FBI protocol requirements. For additional results from experiments, see [1]. The maximum impact velocity was 194.4 m/s with maximum penetration depth of 11.8 cm. The minimum impact velocity was 133.9 m/s with 7.8 cm DOP. The steel sphere penetrators were intact in shape, no signs of expansion, after each shot as seen in Figure 2 for three shots, where shot 1 is the bottom one, shot 2 is the middle one and shot 3 is the top one. The gelatine block is curved at the top which gives an absolute distance larger at the top, but the total penetration is measured from the gelatine block entry point to the tip of the Sphere penetrator.

Shot nr [nr]	Impact velocity [m/s]	Depth of Penetration [cm]	Film / Photo [id / time]	Penetrator [name]
1	179.6	9.4	GB210827nr2-1 /15:53	Sphere 4.5 mm
2	179.6	9.1	GB210827nr2-2 /16:01	Sphere 4.5 mm
3	181.3	9.1	GB210827nr2-3 /16:06	Sphere 4.5 mm
4	189.4	10.5	GB210827nr2-4 /16:12	Sphere 4.5 mm
5	192.5	10.5	GB210827nr2-5 /16:12	Sphere 4.5 mm
6	194.4	11.8	- /16:25	Sphere 4.5 mm
7	161.1	9.6	GB210827nr2-7 /16:32	Sphere 4.5 mm
8	135.0	8.2	GB210827nr2-8 /16:37	Sphere 4.5 mm
9	137.1	7.8	GB210827nr2-9 /16:46	Sphere 4.5 mm
10	135.9	7.5	GB210827nr2-10 /16:51	Sphere 4.5 mm
11	133.9	7.8	GB210827nr2-11 /16:56	Sphere 4.5 mm
12	134.0	7.7	GB210827nr2-12 /17:09	Sphere 4.5 mm

Table 2: Sphere Penetrator 4.5 mm calibre terminal ballistics on 10% gelatine, test series GB210827nr2.

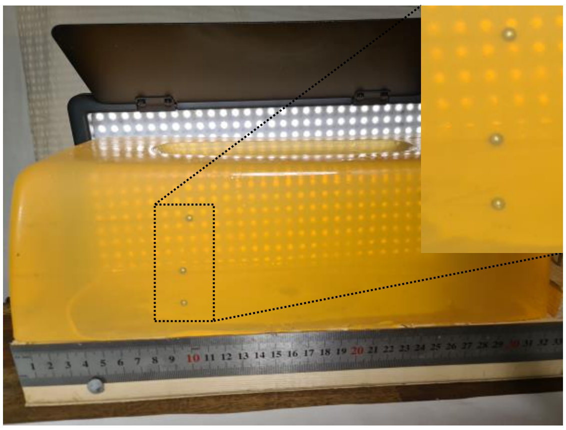


Figure 2: Terminal ballistic photo of GB210827nr2 after shot 3 at time 16:06 for Sphere 4.5 mm with 181.3 m/s impact velocity into gelatine 10%. DOP 9.1 cm, top, middle, and bottom sphere in the picture corresponds to shot 3, shot 2, and shot 1, respectively. All three shots fulfil the FBI protocol requirements of DOP range. Zoomed in area in figure shows all three shots.

The Dome 4.5 mm calibre terminal ballistics experiments in 10% gelatine are summarized in Table 3 for test series GB210828nr3. The first shot though, as standard, even in this test series was a shot with a Sphere 4.5 mm with impact velocity of 182 m/s, which fulfils the FBI standard protocol requirement of DOP with 9.2 cm. The maximum impact velocity was 317.6 m/s with maximum DOP of 19.2 cm. Table 3 shows that shots 9, 10 and 11 have similar initial impact velocities with an average of 149.2 m/s and an average DOP of 10.1 cm. This indicates that the DOP is fairly similar Dome and Sphere when the impact kinetic energy (around 5.5-5.7 J) is equal, compare with shot 1 in Table 3. The Dome has 40 % increased mass compared to the Sphere, see Table 1.

Shot nr [nr]	Impact velocity [m/s]	Depth of Penetration [cm]	Film / Photo [id / time]	Penetrator [name]
1	182.0	9.0	GB210828nr3-1/14:54	Sphere 4.5 mm
2	132.7	7.8	GB210828nr3-2/14:59	Dome 4.5 mm
3	67.2	2.5	GB210828nr3-3/15:06	Dome 4.5 mm
4	71.0	3.4	GB210828nr3-4/15:11	Dome 4.5 mm
5	67.9	2.8	GB210828nr3-5/15:18	Dome 4.5 mm
6	97.3	5.0	GB210828nr3-6/15:24	Dome 4.5 mm
7	95.6	4.5	GB210828nr3-7/15:30	Dome 4.5 mm
8	97.4	5.2	- / -	Dome 4.5 mm
9	148.3	9.5	GB210828nr3-9/15:46	Dome 4.5 mm
10	149.3	10.4	GB210828nr3-10/15:51	Dome 4.5 mm
11	149.9	10.5	- / 15:55	Dome 4.5 mm
12	193.5	14.0	GB210828nr3-12/16:00	Dome 4.5 mm
13	193.5	13.2	GB210828nr3-13/16:05	Dome 4.5 mm
14	191.9	13.3	GB210828nr3-14/16:11	Dome 4.5 mm
15	298.0	18.2	GB210828nr3-15/16:20	Dome 4.5 mm
16	317.6	19.2	GB210828nr3-16/16:26	Dome 4.5 mm
17	280.1	19.1	GB210828nr3-17/16:26	Dome 4.5 mm

Table 3: Dome penetrator 4.5 mm calibre terminal ballistics on 10% gelatine, test series GB210828nr3.

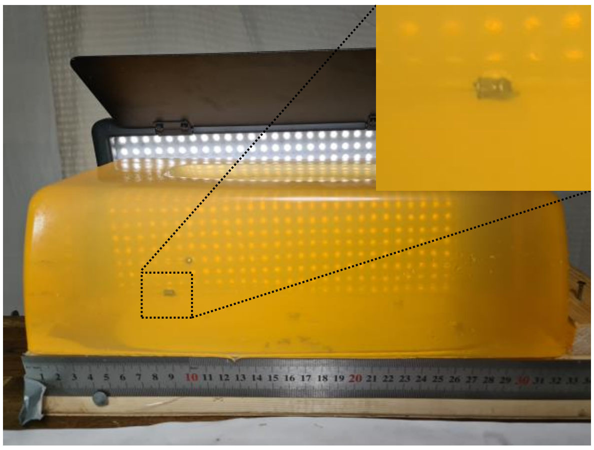
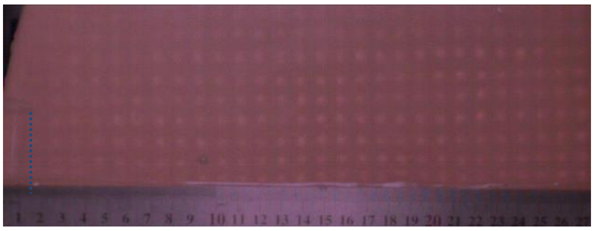


Figure 3: Terminal ballistic photo of GB210828nr3 after shot 1 and shot 2 at time 14:59 for Sphere and Dome mm with shot 1 and shot 2 having 182.0 and 132.7 m/s in impact velocity resulting in DOP 9.0 and 7.8 cm, respectively. Zoomed in area in figure shows shot 2.

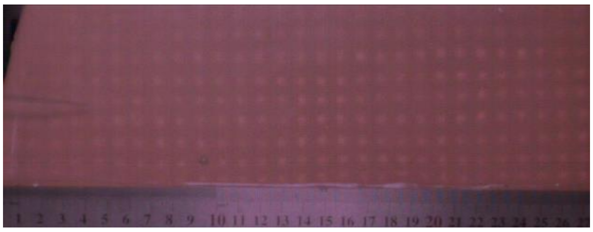
3.2 Penetration depth and high-speed camera results

The high-speed camera results were processed by using the VSDC Video Editor version 6.9.5.382, and screen shots from the original film frames are shown in Figure 4 and 5 (short keys ctrl+F12) without any adjustments of colour, brightness, contrast, or sharpness.

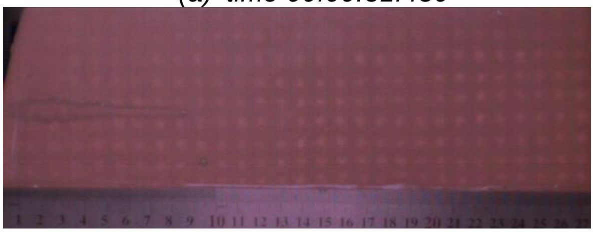
The high-speed camera results for Sphere 4.5 mm GB210827nr2-2 for shot 2 are shown in Figure 4 at four times, and the impact velocity was 179.6 m/s. The vertical blue dashed line in Figure 4(a) shows the penetration progress at time 00:00:31.450 ms. The maximum dynamic cavity diameter is about 9-10 mm and the DOP was 9.1 cm. Before the penetrator came to a complete stop, it elastically penetrated about 1 cm deeper before bouncing back to the final DOP of 9.1 cm.



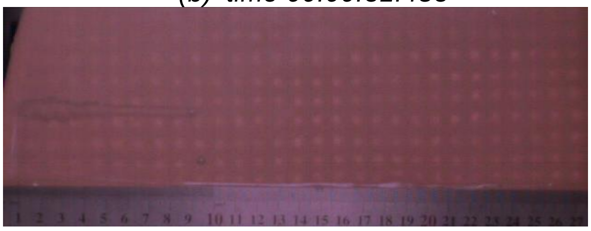
(a) time 00:00:31.450



(b) time 00:00:31.483



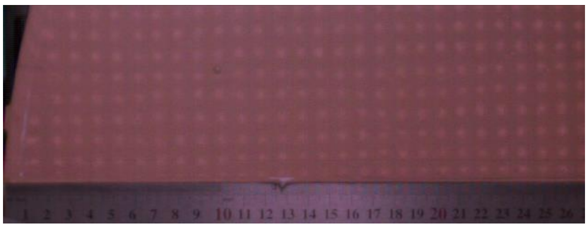
(c) time 00:00:31.583



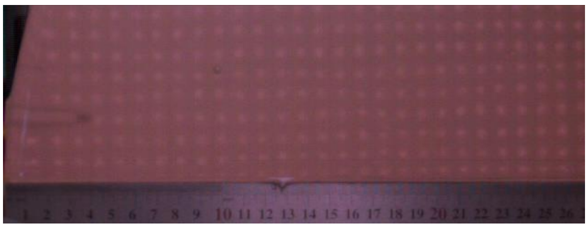
(d) time 00:00:41.433

Figure 4: Chronos 2.1 camera capturing 10 000 FPS of dynamic cavity and penetration at different times (a) to (d) for Sphere 4.5 mm with 179.6 m/s impact velocity into gelatine 10%. Test series GB210827nr2, shot 2. The unit of the metallic ruler below gelatine is in [cm].

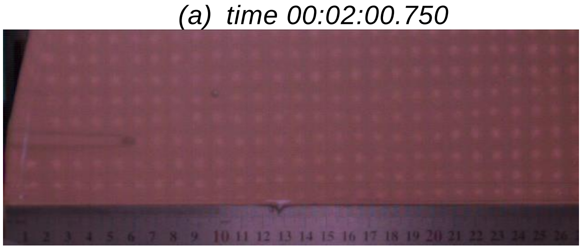
For Dome 4.5 mm in test series GB210828nr3, shot 2, had 132.7 m/s as impact velocity and resulted in 7.8 cm DOP, see Table 3. In Figure 5 the dynamic cavity and DOP progress are shown. The dynamic cavity diameter is about 10 mm at maximum expanded state. The dome is having a very stable and straight penetration progress when penetrating the gelatine as can be seen in Figure 5. The stable penetration behaviour was also seen in the high-speed penetration cases with the higher impact velocity shots 15, 16, and 17, see Table 3. The impact velocity was 298.0, 317.6, 280.1 m/s with final DOP of 18.2, 19.2, and 19.1 cm. In all films for the Dome penetrator stable straight penetration progress was evident.



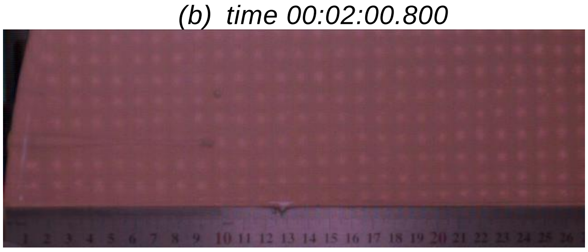
(a) time 00:02:00.750



(b) time 00:02:00.800



(c) time 00:02:00.850



(d) time 00:02:01.150

Figure 5: Chronos 2.1 camera capturing 10 000 FPS of dynamic cavity and penetration at different times (a) to (d) for Dome 4.5 mm with 132.7 m/s impact velocity into gelatine 10%. Test series GB210828nr3 shot 2. The unit of the metallic ruler below gelatine is in [cm].

4 1D SIMULATION OF PENETRATOR RETARDATION IN GELATINE

4.1 Modelling of governing equations for penetration

The force equilibrium for the penetrator can be stated as

$$F_{inertial} = F_{shear} + F_{drag} \tag{1}$$

where the inertial mass force $F_{inertial}$ is defined as

$$F_{inertial} = m_{penetrator} \cdot a_{penetrator} \tag{2}$$

where $m_{penetrator}$ is the fixed mass of the penetrator and $a_{penetrator}$ is its acceleration during the penetration of the gelatine block. The drag force F_{drag} in equation (1) is defined as

$$F_{drag} = -\frac{1}{2}\rho_{gelatine} \cdot C_{drag}(Re) \cdot A_{penetrator} \cdot v_{penetrator}^2 \tag{3}$$

where $\rho_{gelatine}$ is the density of the gelatine, $C_{drag}(Re)$ is the drag coefficient of the penetrator, which is a function of Reynolds number *Re.* $A_{penetrator}$ is the fixed reference area related to the penetrator, for a sphere it is the cross-sectional area $A_{penetrator} = \pi d^2/4$, and the $v_{penetrator}$ is the velocity of the penetrator. The following function was used for the drag coefficient $C_{drag}(Re)$

$$C_{drag}(Re) = A + B + C + D \tag{4}$$

$$A = 24/Re \tag{5}$$

$$B = (2.6 \cdot (Re/5.0))/(1 + (Re/5.0)^{1.52}) \tag{6}$$

$$C = 0.411 \cdot (Re/2.63 \cdot 10^5)^{-7.94}/(1 + (Re/2.63 \cdot 10^5)^{-8.0}) \tag{7}$$

$$D = 0.25 \cdot (Re/1 \cdot 10^6)/\ (1 + (Re/1 \cdot 10^6)) \tag{8}$$

where this is correlated with experimental data for flow around a sphere, see p. 625 in [9]. The Reynolds number, *Re,* for both sphere and dome penetrator are defined as

$$Re = \frac{\rho_{gelatine} \cdot d_{eq} \cdot v_{penetrator}}{\eta_{gelatine}} \tag{9}$$

where d_{eq} is the diameter of a sphere with the same volume as the penetrator, $\rho_{gelatine} = \rho_{gelatine10\%} = 1020\,\frac{\text{kg}}{m^3}$ is the gelatine's density, and $\eta_{gelatine} = 10^{-2}$ Pa s is the gelatine's viscosity. The viscosity is the measure of a fluid's resistance for deformation at a given rate. The gelatine's viscosity is an order of magnitude larger than of water [10], [11]. The calculation of resistance forces and Reynold's number, Equations (3) and (9), respectively are also found in [8]. Fig. 6 shows the drag coefficient of a sphere as a function of Reynold's number. The flow below $Re \ll 10^{-1}$ is called creeping flow or Stoke's regime, where there is no wake behind the sphere, see Fig. 6 illustration of flow around the sphere [8]. In this creeping flow regime, the Stoke's equation for a sphere describes the pure drag force by multiplying the sphere's area with the stress vector which results in $F_{drag} = 6\pi\eta d_{eq} v_{penetrator}$, which is a linear relationship with velocity [9], [12]. In the opposite limit $Re \gg 10^{-1}$, the sphere ploughs through the fluid and leaving the fluid in turbulent state behind the sphere. In the regime of $10^3 < Re < 10^5$ called Newton's regime wakes behind the sphere is fully turbulent while the boundary layer of the front wet surface is still laminar flow. In this Newton's regime equation (3) with stagnation pressure increase represents the drag force quite well [8],[12]. In between Stoke's and Newton's regime there is an intermediate regime $10^{-1} \leq Re \leq 10^3$. In the intermediate regime flow remains attached to the sphere when $Re \leq 20$ [8]. In $20 \leq Re \leq 130$ circular wakes behind the sphere grow but remain steady and attached to the sphere. As Reynold's number increases from 130 to 1000 vortex shedding begins and slowly becomes instable and unsteady until fully turbulent [8]. To make the drag force equation (3) valid throughout the different regimes, the drag coefficient $C_{drag}(Re)$ needs to be updated depending on the current Reynold's number as shown in equation (4).

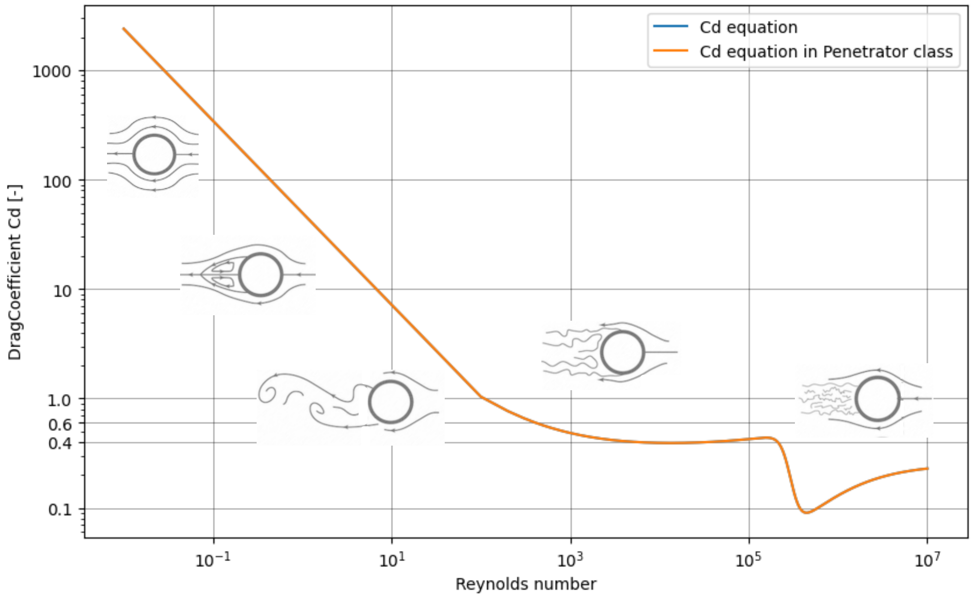


Figure 6: Drag Coefficient as a function of Reynolds number, equation (4), including illustration of different flow regimes, illustrations from [8].

The resistance forces, drag- and shear force or internal friction force are supported by many penetration studies, especially penetration into gelatine [13]-[16]. However, the penetration equations (1)-(2) are initially formulated in 1820s by Poncelet [17] and are well summarized by Bulson, see page 142 in [18]. Poncelet assumes the force resisting penetration would be given by $F = -A(C_1 + C_2 * v_{penetrator}^2)$, where *F* is the resisting force, *A* is the cross-sectional area of the penetrator, $v_{penetrator}$ is the impact velocity, and C_1, C_2 were constants to be determined by experiments. Poncelet suggests that the internal resistance C_1 or here named shear strength of a material is constant and independent of the velocity of the penetration. The constant value C_1 has been challenged by Wijks et.al [19] where Poncelet's model was used for matching experimental results of final penetration of steel/tungsten sphere penetration into 10% and 20% gelatine, respectively. To match the calculations with experimental results, the apparent shear strength value of C_1 where needed to be increased with 40 times and 70 times the quasi-static dog bone tensile strength of 10% and 20% gelatine, respectively. Therefore, in this paper the following shear force equation is proposed for gelatine

$$F_{shear} = -\tau_{yield,gelatine} \cdot A_{wet,penetrator} \cdot (1 + (2 \cdot v_{penetrator}/d_{eq})^{P_{shearRate}}) \tag{10}$$

where $\tau_{yield,gelatine}$ is the static shear strength of the gelatine, $A_{wet,penetrator}$ is the wetted area of the penetrator which is the half front surface are of a sphere, $2 \cdot v_{penetrator}/d_{eq}$ is the shear strain rate, $\frac{d_{eq}}{2}$ is the characteristic length of shearing strain [15]. $P_{shearRate}$ is the proposed gelatine's shear rate power (SRP) factor.

In Table 4 the material properties for target and penetrator material are summarized. The Gelatine's SRP factor was calibrated three times, once for meeting a generic FBI protocol standard with a 4.5 mm steel sphere with density of 7900 kg/m^3 and impact velocity of 180.2 m/s resulting in DOP of 8.5 cm, see Table 4 column 2 for target SRP. The second calibration of SRP, see Table 4 column 3 for target SRP, was done after adjusting the steel sphere to correct total mass of these experiments and the average DOP 9.2 cm of shots 1 2 and 4 in GB210827nr2. The final SRP is for 20% gelatine was calibrated to meet the NATO protocol with DOP 4.4 cm, see Table 4 column 3 for target SRP. The NATO protocol is explained in [7]. The 20% gelatine material properties are stated here only for completeness, any simulation results on it are omitted in this paper.

Target material				
Material Property [unit]	**10% Gelatine FBI Protocol**	**10% Gelatine Experiment calibrated**	***20% Gelatine Nato Protocol***	**Comment / Reference**
Density [kg/m^3]	1020	1020	*1060*	10% gelatine, see [19]. 20% gelatine, see [19]-[21].
Viscosity [Pas]	0.01	0.01	*0.01*	[8] and [10].
ShearYieldStress [Pa]	30000	30000	*50000*	[19].
ShearRatePower(SRP) [-]	0.335	0.306	*0.38*	These values are calibrated in this paper.
Penetrator material				
Material Property [unit]	**Sphere FBI Protocol**	**Sphere Experiment Calibrated**	**Dome Experiment Calibrated**	**Comment / Reference**
Density [kg/m^3]	7900	7335.5	10269.75	Calibrated for total mass of sphere, see Table 1.
Diameter [m]	$4.5*10^{-3}$	$4.5*10^{-3}$	$4.5*10^{-3}$	

Table 4: Material properties for target and penetrator.

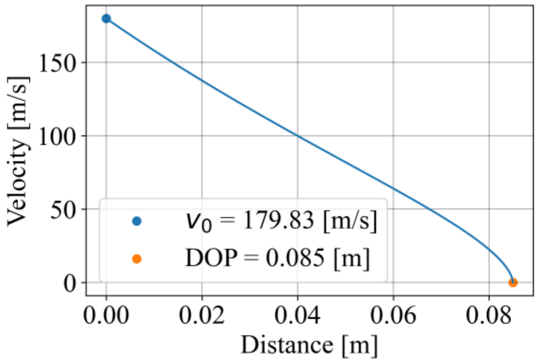
4.2 Programming of the simulation code

The Python language version 3.10.0 was used for the simulations [22]. The Spyder Integrated Development Environment (IDE) version 5.3.2 was used for programming, pre-, and post-processing of the simulation results [23]. Spyder was installed as a python package (pip install spyder). In addition, the following packages were installed and used in the software developed "from collections import defaultdict", "import numpy", "import pandas", "import matplotlib.pyplot as plt", and "import csv". The python language and the Spyder IDE are all open source and freely downloadable. The simulation code for this paper is available in [1].

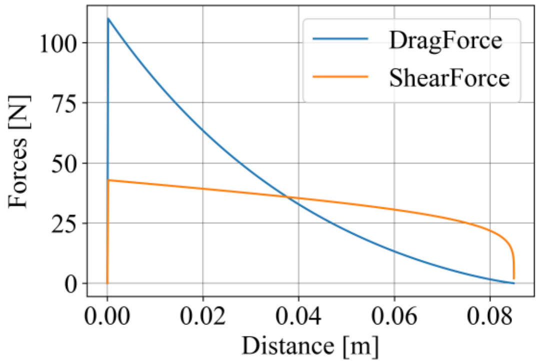
4.3 The simulation results

The differential equation stated in (1)-(2) were solved with forward Euler method with a time step size, $dt = 1 \cdot 10^{-6}$, that is small enough to not influence the DOP more than on 4th decimal, i.e., smaller than a millimetre. The velocity and distance of the penetrator were updated with time step size multiplied with their current timestep's derivative, respectively.

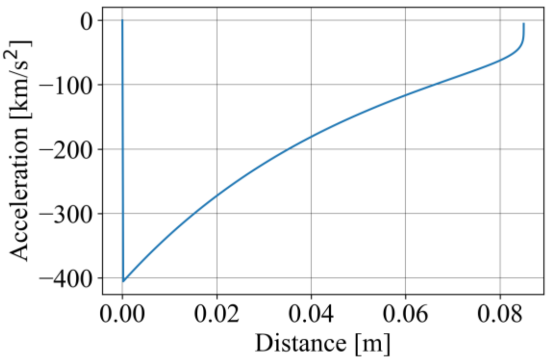
The FBI protocol simulation is shown in Fig. 7, in which the Sphere's velocity as a function of distance is shown. The final DOP is 8.5 cm, which was used for fitting the SRP = 0.335 value for the ideal 10% gelatine according to FBI protocol, see Table 4. In Fig 7b the resistance forces are shown, the drag force is initially the largest force, approximately 100 N, compared to the shear force which is estimated to be around 50 N initially. The drag force is reduced more than half of the initial value at impact, after the penetrator penetrated about 0.04 m into the gelatine. After the 0.04 m distance, the shear force is the largest resistance force until DOP is reached. In Fig 7c the acceleration is shown, which shows large deceleration, initially approximately -400 km/s^2. In Fig. 7d the C_{drag} value is shown as a function of penetration. The C_{drag} value varies from initially 0.42 to a minimum of 0.39 at distance 0.077 m and then the C_{drag} value increases again until standstill. This is due to that the Reynold's number is initially about 82 500 and the Reynold's number remains above 1000 until a penetration depth of 0.0849 m is reached, which is 99.88% of DOP. According to Fig. 6 which shows C_{drag} value for a sphere as function of Reynold's number, this is the Newton Regime, when the wake behind sphere is fully turbulent.



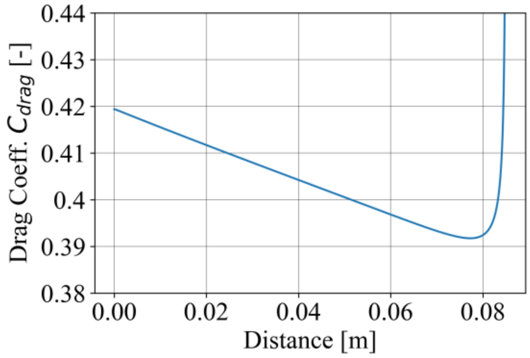
(a) Penetrator velocity as a function of distance



(b) Resistance forces as a function of distance



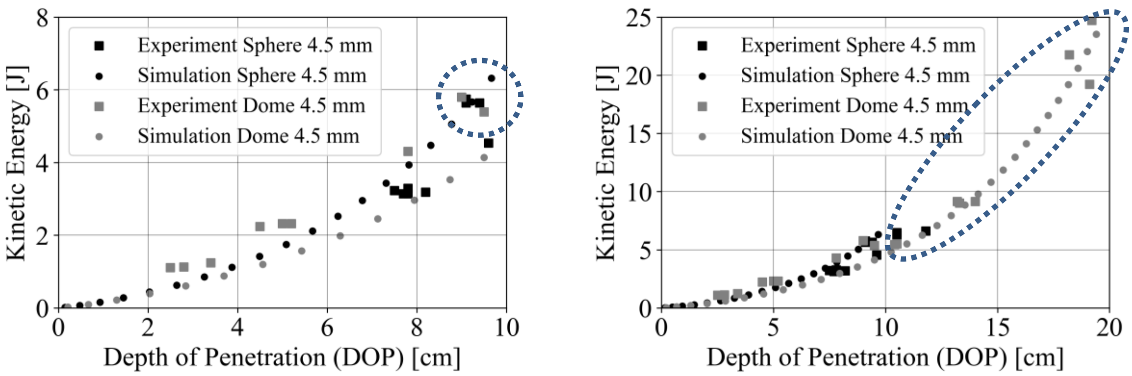
(c) Penetrator acceleration as a function of distance



(d) Drag coefficient as a function of distance

Figure 7: Simulation of FBI protocol requirement in gelatine block 10% with v_0 = 179.83 m/s resulting in DOP 8.5 cm.

Simulations were conducted for impact velocities of 10 to 200 m/s and 10 to 320 m/s in steps of 10 m/s for the Sphere and Dome, respectively. The simulated ranges of impact velocities fits the experimental data ranges that were conducted for the Sphere and the Dome. Simulations were conducted with the 10 % Gelatine Experiment calibrated version, see Table 6, with SRP = 0.306. Similar plots as shown in Fig.7 are omitted for each simulation, these can instead be produced by the simulation code [1]. The results are instead summarised in Fig. 8, which shows the impact kinetic energy as a function of the DOP. In Fig 8a, the plot range for kinetic energies up to 8.0 J and DOP up to 10 cm are shown. The dotted circle line in Fig. 8a shows the fitting of the three experimental FBI protocol shots that was used for calibrating the SRP value. For the Dome simulations, only the mass of the penetrator was adjusted, which then can be seen as another data set. In Fig 8b, shows the experimental results of Dome which had higher impact kinetic energy, up to 25 J, see elliptic dotted line, see also Table 3, test series GB210828nr3, shots 12-17. The correlation is good between experiments and simulations for the complete range of experimental data of Dome shots conducted. Considering that the calibration of the SRP value for the gelatine was done for the Sphere and for lower kinetic energy impact level, i.e. the FBI standard protocol with 5.7 J.



(a) Plot range max 8 J and max DOP 10 cm.

(b) Plot range to fit all presented experimental results.

Figure 8: Maximum Kinetic Energy as a function of DOP for Experimental data of Sphere and Dome compared with simulations.

5 CONCLUSIONS

The experiments showed that the manually manufactured 10% gelatine blocks fulfilled the FBI protocol requirements of DOP range allowed. The experiments were able to visualize the penetration process into 10 % gelatine blocks for different penetrator shapes by using mainstream high-speed camera with a resolution of 640x240 pixels and minimum of 10000 FPS. The used high-speed camera captured the whole penetration process from impact to final DOP inside the gelatine block including dynamic cavity diameter. Important take away is to have enough flickering free LED lighting power to make films bright enough due to the high FPS rate. To conduct the FBI protocol verification of the 10% gelatine blocks it is essential to have an appropriate air rifle to adjust the impact speed close to 180 m/s for the required BB 4.5 mm steel sphere. In these experiments with 4.5 mm the Crosman 760 Pumpmaster was used which is an accurate and reliable solution which has been produced for over 40 years. For the higher impact velocities of 300 m/s the Hatsan Striker Edge 4.5 mm was succesfully used for the Dome shots.

A good correlation between simulations and experiments were governed by introducing a shear rate dependent shear force instead of a constant material dependent shear force as the original Poncelet equation suggests. The proposed shear rate power factor, SRP, for modelling shear force in gelatine fulfils the quasistatic tensile dog bone tests and the increased apparent shear strength increase of 40 and 70 times for 10% and 20% gelatine, respectively, that were found from experimental data fitting to Poncelet equation [19].

5 FUTURE WORK

The high-speed filming reveals that the final measured DOP is smaller than maximum penetration depth seen in the films. This suggests that an elastic part should be included in the gelatine force resistance modelling. Additionally, the dynamic cavity captured from the high-speed films can be used to confirm dynamic cavity modelling as in e.g. Liu et. Al. [10].

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REFERENCES

[1] L. Laine, "Open dataset of 10% gelatin penetration experiments and simulation code for 4.5 and 6.35 mm caliber", DOI: 10.5281/zenodo.7655010, (2023).

[2] L. Laine, "Penetration experiments of air rifle projectiles with caliber 6.35 mm and different nose shapes impacting 10% gelatine", *in Proceedings of 14th Shock and Impact Loads on Structures, Singapore, (2023)*

[3] L. A. MacQueen, C. G. Alver, C. O. Chantre, S. Ahn, L. Cera, G. M. Gonzalez, B. B. O'Connor, D. J. Drennan, M. M. Peters, S. E. Motta, J. F. Zimmerman, and K. K. Parker, "Muscle tissue engineering in fibrous gelatin: implications for meat analogs", Journal of npj Science of Food volume 3:20, https://doi.org/10.1038/s41538-019-0054-8, (2019).

[4] E. J. Wolberg, "Perfomance of the Winchester 9mm 147 Grain Subsonic Jacketed Hollow Point Bullet in Human Tissue and Tissue Simulant", Journal of the International Wound Ballistics Associations, pages 11-13 winter, (1991).

[5] D. J. Carr, T. Stevenson, and P. F. Mahoney, "The use of gelatine in wound ballistics research", International Journal of Legal Medicine132:1659–1664 pp, https://doi.org/10.1007/s00414-018-1831-7, (2018).

[6] Haendler & Natermann Sport Gmbh, https://www.hn-sport.de/en/air-gun-hunting, (2022).

[7] Clear Ballistics, FBI Protocol definition, https://www.clearballistics.ca/pages/faqs, (2022).

[8] G. Bagheri and C. Bonadonna, "On the drag of freely falling non-spherical particles", in arxiv https://arxiv.org/pdf/1810.08787.pdf, (2018).

[9] A. Morrison, *An Introduction to Fluid Mechanics*, Cambridge University Press, New York, (2013).

[10] L. Liu, Y. Fan, W. Li, and H. Liu, "Cavity dynamics and drag force of high-speed penetration of rigid spheres into 10wt% gelatin", *Int. J. of Impact Engineering.* 50, 68–75. http:// dx.doi.org/10.1016/j.ijimpeng.2012.06.004. (2012)

[11] D. Veysseta, S. E. Kooia, A.A. Mazneva, S. Tang, A. S. Mijailovicd,Y. J. Yang, K. Geisere, K. J. Van Vliete, B. D. Olsena, and K. A. Nelson, "High-velocity micro-particle impact on gelatin and synthetic hydrogel", *Journal of the Mechanical Behavior of Biomedical Materials*, Vol. 86, Pages 71-76 (2018).

[12] B Lautrup, *Physics of Continuous Matter Exotic and Everyday Phenomena in the Macroscopic World*, IOP Publishing Ltd, Book 581 pages. (2005).

[13] L. M. Sturdivan, *A mathematical model for assessing weapons effects from gelatin penetration by spheres*, Report nr. EB-TR-73022, National Technical Information Service, Edgewood Arsenal, Aberdeen Proving ground, MD, USA, (1972).

[14] L. M. Sturdivan, *A mathematical model of penetration of chunky projectiles in a gelatine tissue simulant*, Report nr ARCSL-TR-78055, Chemical Systems Laboratory, Aberdeen Proving Ground, MD, USA, (1978).

[15] G. W. Stone, Projectile penetration into representative targets, Report nr. SAND94-1490, Sandia National Laboratories, NM, USA, (1994).

[16] S. B. Segletes, Modeling the penetration behavior of rigid spheres into ballistic gelatin, Report nr. ARL-TR-4393, Army Research Laboratory, Aberdeen Proving Ground, MD, USA, (2008).

[17] J. V. Poncelet, *Introduction a la mécanique industrielle, physique ou expérimentale, 3rd edition,* http://books.google.com, (1838),

[18] P. Bulson, Explosive Loading of Engineering Structures, ENFN SPON, London, England, (1997).

[19] G. Wijk, Å Collin, and R. Amiree, "Sphere penetration into gelatine and board", *19th International Symposium of Ballistics*, proceedings 1019-1026 pp, 7–11 May, Interlaken, Switzerland, (2001).

[20] J. Winter and D. Shifler, *The material properties of gelatine gels,* Report nr 217, USA Ballistics Research Laboratories, Aberdeen Proving Ground, MD, USA,, (1975).

[21] C. J. Shepherda, G. J. Appleby-Thomasa, P. J. Hazella, and D. F. Allsopa, "THE DYNAMIC BEHAVIOUR OF BALLISTIC GELATIN", *AIP Conference Proceedings 1195*, 1399, https://doi.org/10.1063/1.3295071, (2009).

[22] Python language, version 3.10.0 , https://python.org/, (2022).

[23] The Scientific Python Development Environment ("Spyder") version 5.3.2, https://www.spyder-ide.org/, (2022).

APPENDIX I – RECIPE FOR PRODUCING GELATINE 10%

Ingredients needed and the process is described for producing 5 litre gelatine 10% concentration are given in this appendix. Important notice is to use gloves that are water and heat resistant while processing the gel.

Ingredients
4.5 litre water (clear and drinkable)
500 gram Pure Gelatin (in experiments the producer Nyttoteket Sweden was used).
5 drops of cinnamon oil (1 drop per litre for gelatine clarity)

Process

- Heat the water up to +80 degrees Celsius, use digital thermometer to check temperature.
- Pour the water into dough mixer with bucket minimum capacity of five litre. Pour the gelatine powder slowly into the dough mixer while the mixer is running on even speed.
- Add 5 drops of cinnamon oil, let mixer run for five minutes and check that all gelatine powder has desolved into the heated water.
- Use suitable mold shapes for the intended penetration experiments, here molds of plastic material with lid and with outer size of 15 x 35,5 x 14,2 cm and total volume of five litre was used.
- Coat inside the mold with a cooking oil to help the release the gel when it is ready.
- Pour the warm gel into the mold, use duct tape to seal the lid and secure the mold for transport.
- Cool the mold in +2 degrees Celsius refrigrator for about 24-48 hours.
- Before use, check the temperature initial +2 degrees temperature with a digital food themometer that can penetrate the gelatine. Document each gelatine, water concentration, gel concentration, refrigrator cooling time and initial gelatine temperature.
- Check the produced gelatine 10% penetration qualities by using FBI standard protocol by manual measurement of the penetration depth. The FBI standard protocol requires maximum penetration depth of 8.5 ± 1 cm for a 4.5 mm BB steel sphere impacting with 180 ± 3 m/s. If Crosman 760 pumpmaster rifle used, the impact velocity of 180 m/s is achieved with approximately 8 pumps. Use at least one FBI protocol verification per mold.
- If the mold is not fulfilling the penetration requirements, try to adjust the gelatine water ratio and the cooling time.