



Impact of steel spheres on ballistic gelatin at moderate velocities

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ABSTRACT

We study experimentally and computationally the penetration of a steel sphere into a block of ballistic gelatin for developing an improved understanding of the damage caused to human soft tissues when impacted by a blunt object moving at a moderately high speed. The gelatin is modeled as an isotropic and homogeneous elastic–plastic material that exhibits linear strain-hardening and obeys a polynomial equation of state. Pictures taken by a high speed camera help construct the tunnel formed in the gelatin that is found to compare well with the computed one. Furthermore, computed time histories of the pressure at a point agree well with the corresponding experimentally measured ones for small times. The computed time histories of the temporary cavity size agree well with the corresponding experimental ones. These agreements between test findings and computed results imply that the computational model can reasonably well predict significant features of the impact event. Effects of impact velocity and sphere diameter on damage caused to the gelatin have also been studied.

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1. Introduction

The massive statistical data indicates that, in the modern warfare, fragments cause 75% of injuries to soldiers and the remaining 25% are caused by the bullet and the shock wave [1]. It is, therefore, important to understand deformation mechanisms in soft tissues due to the impact of fragments. Ballistic gelatin (hereafter referred to as gelatin) is commonly used as a representative simulant to evaluate the damage induced by the impact of blunt objects and blast loading on soft tissues [2–4]. Gelatin, a protein derived from skin or bone [5], is produced by submitting collagen to an irreversible process that renders it water-soluble. There are two common gelatin formulations, 10% at 4 °C and 20% at 10 °C, based on the mixture by mass fraction [3,6,7]. These are known as Fackler and NATO gelatin, respectively. In order to simulate the impact of an object into gelatin one ideally needs its high strain-rate and temperature-dependent material properties but they are not available in the open literature over the range of strain-rates and temperatures likely to occur in an event involving moderately high impact speeds.

Cronin and Falzon [7] studied effects of temperature, aging time and strain-rate on 10% gelatin, and found that upon increasing

strain-rate to 1/s the failure stress increased by a modest amount. Salisbury and Cronin [8] employed a polymer split Hopkinson pressure bar (PSHPB) to test gelatin at a wide range (up to 1500/s) of strain rates. Their test results suggest that the 10% gelatin is a highly strain-rate dependent hyperelastic material. Kwon and Subhash [9] studied the uniaxial compressive stress–strain response of 10% gelatin under quasi-static and dynamic (strain-rate range of 2000–3200/s) loading using an MTS machine and the PSHPB, respectively. They found that the gelatin strength remained essentially constant in the quasi-static regime but at high strain-rates the compressive strength increased from 3 kPa at a strain-rate of ~0.0013/s to 6 MPa at a strain-rate of ~3200/s. Kwon and Subhash's [9] results agree with those of Salisbury and Cronin at low strain-rates but differ at strain-rates greater than 1000/s. Moy et al. [10] tested gelatin in uniaxial tension and found that the response also exhibited strain-rate dependence and the failure stress increased with an increase in the strain-rate.

Aihaiti and Hemley [11] have shown that Poisson's ratio of 10% gelatin increases from 0.34 to about 0.37 when the pressure is increased from 0 to around 3 GPa, and stays at 0.37 for pressures between 3 and 12 GPa. Parker [12] has found that the 10% gelatin transforms to solution at 30.5 °C, and from solution to gelation at 24.4 °C.

Nagayama et al. [13] have presented shock Hugoniot compression data for several bio-related materials by using flat plate impact experiments. They proposed the following shock Hugoniot function

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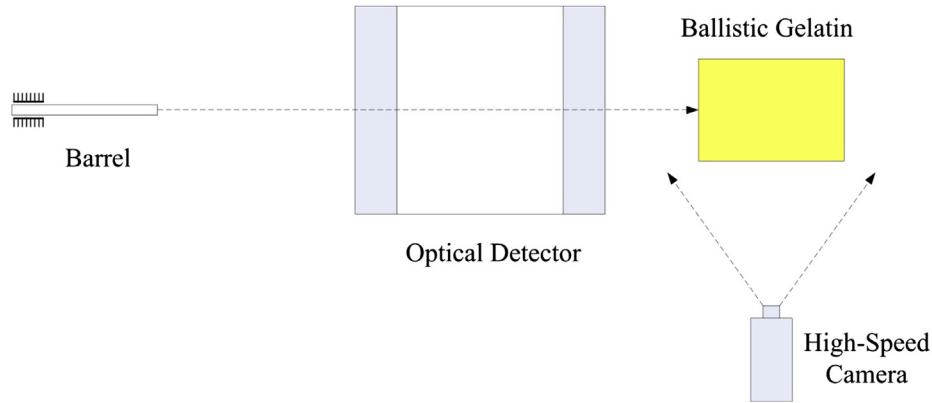


Fig. 1. Schematics of the experimental set-up.

$$U_s = 1.52 + 2v_p \quad (1)$$

for the 10% gelatin. In Eq. (1) U_s and v_p are the shock and the particle speed, respectively. Appleby-Thomas et al. [14] also employed plate-impact experiments to study the dynamic response of 25% gelatin, ballistic soap and lard. All three materials exhibited linear Hugoniot $U_s - v_p$ relations. Whereas the gelatin behaved hydrodynamically under shock, the soap and the lard appeared to strengthen under increased loading.

Mechanisms dominating deformations of solids during impact generally vary with the impact speed. Wilbeck [15] has classified deformations of some low strength materials (birds, gelatin and RTV rubber) in five regions: elastic, plastic, hydrodynamic, sonic and explosive. There is no single constitutive relation for gelatin that can well describe its mechanical behavior in all these five regimes. For low velocity impact a rate-dependent hyperelastic constitutive model is expected to describe well the mechanical behavior of gelatin. However, for high velocity impact the hydrodynamic response that considers possible phase transformations may be more suitable [16] at least in the initial phase of the penetration event. The strength of the gelatin may play a role once the penetrator has considerably slowed down. In the absence of test data for characterizing the material response at high strain rates and temperatures, we adopt an elastic–plastic model for the gelatin and use a polynomial equation of state (EoS) to describe its hydrodynamic response. It is hard to quantify the improvement in the computed results by considering strain-rate and thermal softening effects at this time.

Using water as proxy material for soft tissue, An et al. [17] used the commercial finite element (FE) software LS-DYNA to simulate the evolution of a temporary cavity and the pressure developed during high velocity impact of a rigid sphere into a body of water. Dyckmans et al. [18] measured material parameters of ballistic soap using the split Hopkinson pressure bar (SHPB), and simulated the impact of steel spheres in a soap block using the commercial software AUTODYN.

Koene and Papy [19] used AUTODYN to study deformations induced by the penetration of ABS (Acrylonitrile–Butadiene–Styrene) plastic spheres into gelatin at velocities up to 160 m/s. For simulating tests of armor impacting gelatin, Shen et al. [20] modeled gelatin as nearly incompressible rubber. Cronin employed a viscoelastic material model [21], and a rate-dependent hyperelasticity model using tabulated values of stresses and strains [22] to simulate the mechanical behavior of gelatin. It was found that the viscoelastic material model could adequately capture only the low strain-rate response of gelatin, and the tabulated hyperelasticity model provided an accurate representation of the gelatin at low and intermediate strain rates. However, high strain rates of the order of 1000/s were not considered. Minisi [23] simulated the projectile–gelatin interaction at high impact velocities with the 10% gelatin modeled as a hydrodynamic material with the Mie–Grüneisen equation of state at high strain rates and a Mooney–Rivlin material at low strain rates. However, when to transition between the two material models and values of material parameters are not listed in the report.

Here we experimentally and numerically study deformations induced by a steel sphere moving at a moderate speed and impacting at normal incidence a rectangular gelatin block. The steel is modeled as a rigid material and the gelatin as an elastic–plastic material with linear strain-hardening and a cubic polynomial relation between the hydrodynamic pressure and the change in



Fig. 2. Photo of the experimental set-up.

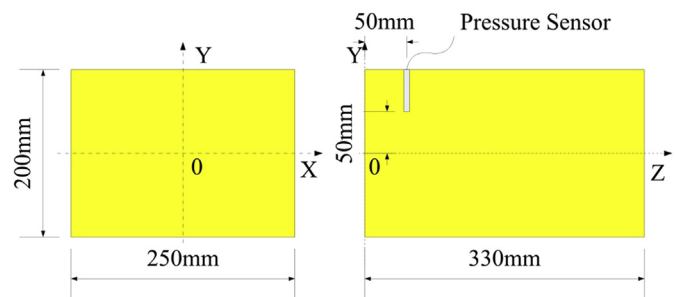


Fig. 3. Location of the pressure sensor embedded in the gelatin block.

Table 1
Experimental values of the impact speed and the maximum cavity diameter.

Diameter (mm)	Impact speed (m/s)	Kinetic energy (J)	Maximum temporary cavity diameter (mm)	Time of maximum temporary cavity (ms)	Perforation
4.8	721	118	62.1	2.1	No
4.8	728	120	63.7	2.2	No
4.8	731	121	63.9	2.2	Yes
4.8	947	203	76.2	2.7	Yes
4	717	67	48.7	1.7	No
3	659	24	37.5	1.4	No

mass density. Time histories of the temporary cavity and of the hydrodynamic pressure for small times computed using the commercial software LS-DYNA are found to agree well with the corresponding experimental findings.

2. Experimental results

A 250 mm × 200 mm × 330 mm gelatin (10% at 4 °C) block resting on a table was impacted by 4.8, 4 and 3 mm diameter steel spheres using a rifle with its muzzle 15 m from the front face of the gelatin. The gelatin was prepared using the same procedure as that outlined in Refs. [3,6,7]. The speed of the sphere just before impacting the gelatin was measured with a double base optical detector. The size and position of temporary cavity, and speed of the steel sphere in the gelatin were determined using a high-speed camera (Figs. 1 and 2) capable of taking 20,000 frames per second with a resolution of 512 × 512 pixels, and located 6 m from the gelatin. A pressure sensor (PCB 113B24 with a range of 0–7 MPa) was embedded in the gelatin to measure the change of pressure (Fig. 3). The appropriate lighting was used to increase block's transparency and clearly visualize the ballistic phenomenon.

The experimentally determined penetration depth and the maximum temporary cavity size (diameter) for the six tests performed are listed in Table 1. Of course, additional tests need to be conducted to determine a better estimate of the ballistic limit. However, for understanding the penetration phenomenon, observations from these six tests should suffice since tests are rather expensive. For the 4.8 mm diameter sphere impacting at normal incidence the gelatin block at 728 m/s and 947 m/s, time histories of the experimentally determined pressure are compared in Fig. 4 with those found from numerical simulations. Furthermore, experimental and computed shapes of the temporary cavities are exhibited in Fig. 5. These results will be discussed in Section 3.

3. Numerical simulations

3.1. Material model and verification

We used the commercial FE software, LS-DYNA, to simulate the impact experiment described above. The gelatin was modeled as an elastic–plastic material with the polynomial EoS (Eq. (5)) and the yield strength σ_y given by [24]

$$\sigma_y = \sigma_0 + E_h \bar{\epsilon}^p \quad (2)$$

where σ_0 is the initial yield strength, $\bar{\epsilon}^p$ the effective plastic strain,

$$E_h = \frac{E_t E}{E - E_t} \quad (3)$$

the plastic hardening modulus, E Young's modulus, and E_t the tangent modulus. The material is assumed to obey the von Mises yield criterion

$$\phi = \frac{1}{2} s_{ij} s_{ij} - \frac{\sigma_y^2}{3} = 0 \quad (4)$$

where $\mathbf{s}$ is the deviatoric stress tensor.

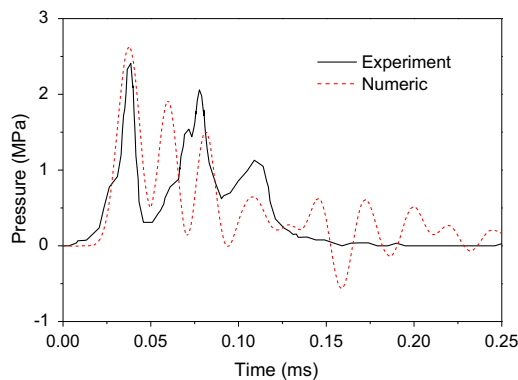
Constitutive relations (2)–(4) are supplemented with the following polynomial EoS relating the pressure, P , with the change in the specific volume or the mass density ρ [15,25]:

$$P = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 \quad (5)$$

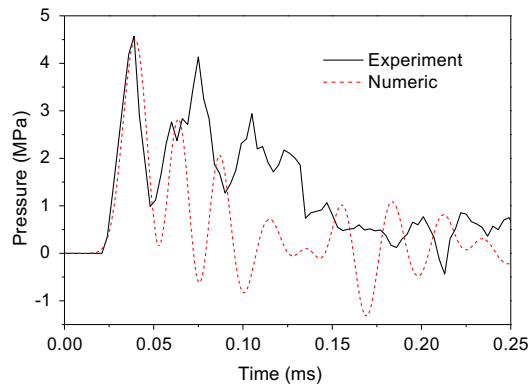
where $\mu = \rho/\rho_0 - 1$ is a dimensionless parameter defined in terms of the ratio of the current mass density ρ to the initial mass density ρ_0 , and C_0 , C_1 , C_2 and C_3 are material constants. Wilbeck [15] has shown that the pressure–density relation across a shock can be written as

$$P = \frac{\rho_0 c_0^2 \eta}{(1 - k\eta)^2}, \quad \eta = 1 - \frac{\rho_0}{\rho} = \frac{\mu}{1 + \mu}, \quad (6)$$

where the Hugoniot parameter k is a constant. For small and moderate values of μ it can be shown [16,26], that Eq. (6) reduces to Eq. (5) with $C_0 = 0$, $C_1 = \rho_0 c_0^2$, $C_2 = (2k - 1)C_1$ and $C_3 = (k - 1)(3k - 1)C_1$. Thus if we know values of the bulk modulus C_1 or the sound speed c_0 and the Hugoniot parameter k then constants C_2 and C_3 can be evaluated [16]. Values of material parameters for the gelatin used in this work are listed in Table 2. The value 850 kPa of Young's modulus E is obtained by using our data



(a) Impact speed = 728 m/s



(b) Impact speed = 947 m/s

Fig. 4. Time histories of the computed and the experimental pressures at the point (0, 50 mm, 50 mm) for the 4.8 mm diameter sphere impacting at normal incidence the gelatin block at 728 m/s (left) and 947 m/s (right).

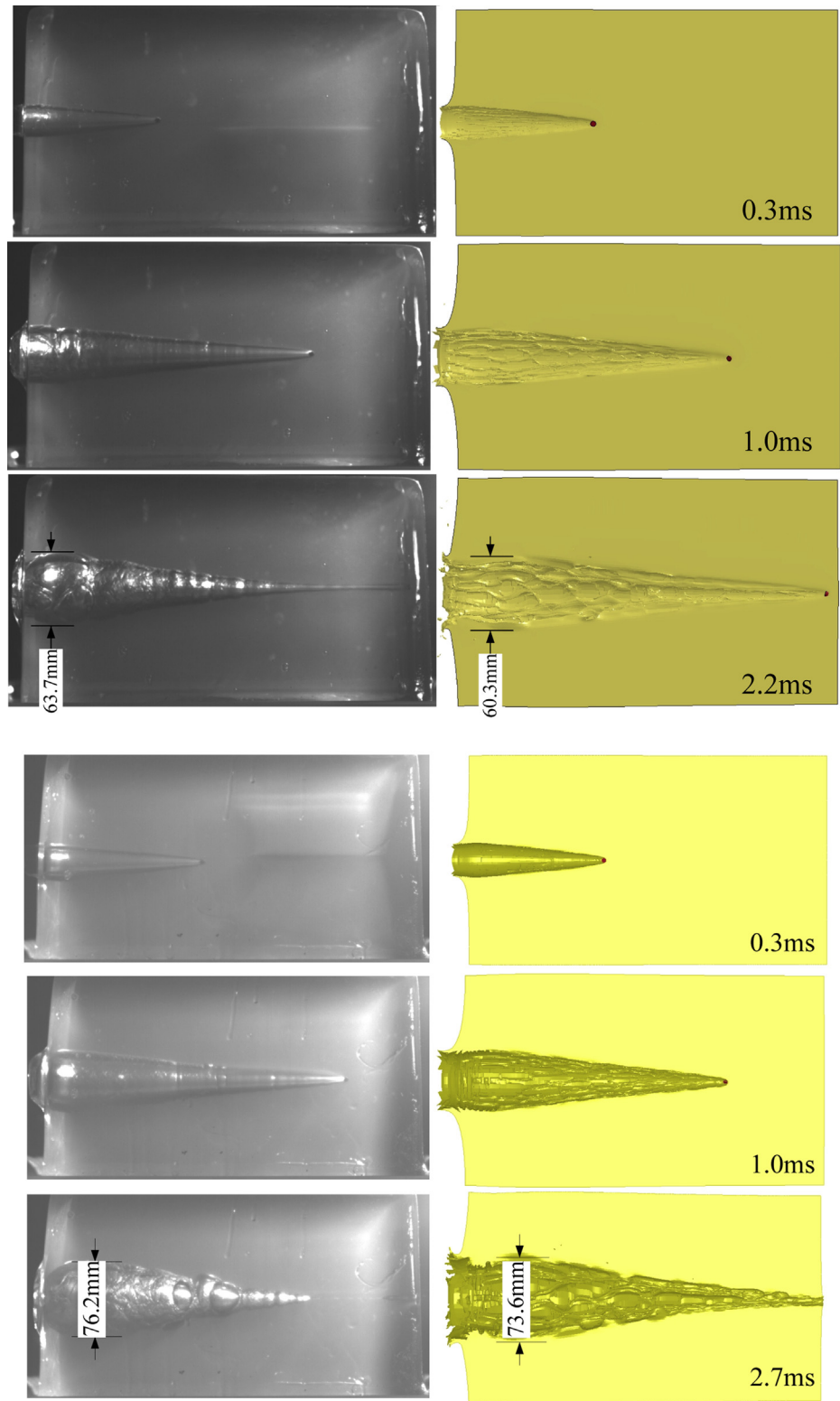


Fig. 5. Computed (left) and experimentally (right) observed temporary cavity profiles for impact velocity of 728 m/s (top) and 947 m/s (bottom).

Table 2
Values of material parameters for the gelatin.

ρ (kg/m ³)	E (kPa)	E_t (kPa)	σ_0 (kPa)	C_0 (GPa)	C_1 (GPa)	C_2 (GPa)	C_3 (GPa)
1030	850	10	220	0	2.38	7.14	11.9

Table 3
Values of material parameters for the steel sphere.

Mass density (kg/m ³)	Young's modulus (GPa)	Poisson's ratio
7830	211	0.27

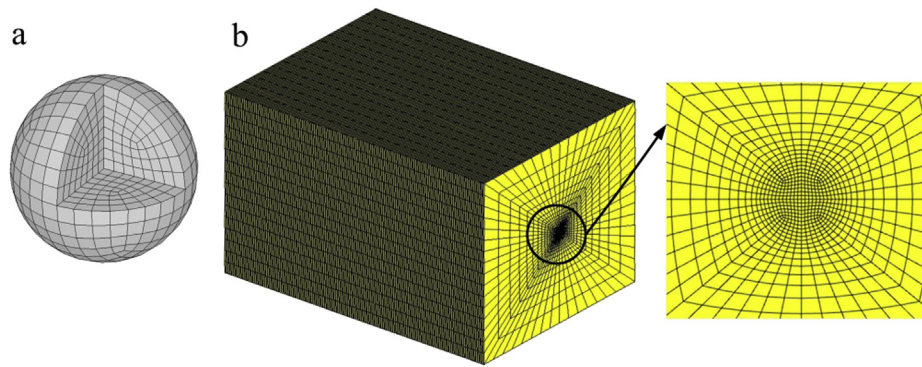


Fig. 6. Discretization of the sphere and the gelatin block into 8-node brick elements. (a) Sectioned view of steel sphere, (b) FE grids on surfaces of the gelatin block, and enlarged view of the FE mesh in the impacted area.

for quasistatic uniaxial compression tests and finding the secant modulus for the point (296 kPa, 0.349). The value of E_t is estimated.

It was noticed that the impacting spheres underwent very little deformations during the penetration process. We thus assume the sphere to be rigid during numerical simulations and use for it the material model (MAT_RIGID) in LS-DYNA. Even though values of material parameters for the steel are listed in Table 3, only the value of mass density is needed for the numerical work.

The 3-dimensional (3-D) geometries of the sphere and the gelatin were discretized into 1048 and 595,200 8-node brick elements, respectively. One such discretization is exhibited in Fig. 6. The gelatin has small elements ($0.31 \text{ mm} \times 0.31 \text{ mm} \times 0.6 \text{ mm}$) in the cylindrical region encompassing the impacted area, and the element size increases as one moves away from this zone. The element size in the sphere is less critical for computing the penetration depth provided that the sphere geometry can be adequately reproduced. Two other FE meshes, shown in Fig. 7, with element sizes of $0.63 \text{ mm} \times 0.63 \text{ mm} \times 0.6 \text{ mm}$ and $0.42 \text{ mm} \times 0.42 \text{ mm} \times 0.6 \text{ mm}$ were used to study the dependence of computed results upon the FE mesh used. Results computed with the three discretization of the gelatin region should help delineate the effect of the FE mesh size on the computed results.

The ERODING_SURFACE_TO_SURFACE contact definition was used to simulate the interaction between the sphere and the gelatin. The viscous hourglass control algorithm with hourglass coefficient = 0.01 was employed. All bounding surfaces of the gelatin block and the steel sphere except those contacting each other are taken to be traction free. The contacting surfaces are taken to be smooth. The block is assumed to be initially at rest and stress free. An element of the gelatin is assumed to fail when the effective plastic strain in it equals a critical value, and the failed element is deleted from the analysis domain.

Using the finest FE mesh, it can be concluded from values listed in Table 4 that for critical values of the effective plastic strain equal to 0.7, 0.9 and 1.1, the computed penetration depths and the maximum cavity diameters differed from each other by less than 3% and 12%, respectively. Subsequently, we use 0.9 as the critical value of the effective plastic strain. We note that Cronin and Falzon [7] analyzed an axisymmetric problem and found the optimized value of the erosion strain to be between 0.738 and 0.755 which increased with a decrease in the mesh size. Assuming that all of the plastic working is converted into heating and deformations are locally adiabatic, temperature rise in an element just before it is deleted equals approximately 45°C . We realize that neglecting thermal softening and strain-rate dependence in the material model makes the analysis approximate. However, we neither could find test data in the open literature nor we could generate it ourselves to determine values of material parameters for quantifying these effects. There may be phase transformations induced because of the temperature rise and accounting for the latent heats of phase transformations will complicate the analysis. Effects of phase transformations have been considered by Zhu and Batra [27]. In a commercial code these effects are usually incorporated in the EoS. However, no such EoS is available for the gelatin in the open literature.

For the impact speed of 728 m/s, time histories of the numerically computed penetration depths with the three FE meshes are compared with the corresponding experimental one in Fig. 8. Penetration depths computed with the coarse mesh have large deviations from those found experimentally. The difference between the computed and the test values of penetration depth decreases with a decrease in the size of smallest element in the FE mesh for the gelatin. At $t = 2 \text{ ms}$, the penetration depth with the finest FE mesh differs from the test value by less than 7%. Results presented below are with the finest FE mesh.

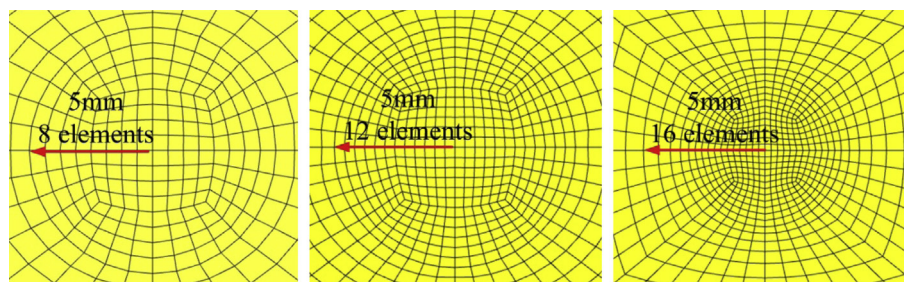


Fig. 7. Partial enlarged views of the coarse (left), medium (center) and fine (right) FE mesh for the gelatin.

Table 4

For the impact velocity of 728 m/s, computed penetration depth and the maximum cavity diameter for three values of the critical effective plastic strain.

Critical value of the effective plastic strain	Penetration depth (mm)	Maximum cavity diameter (mm)
0.7	234.3	58.7
0.9	231.7	60.3
1.1	227.6	66.3
Experiment	236.7	63.7

3.2. Numerical results and discussion

A phenomenon of interest in the penetration of gelatin is the formation of the temporary cavity. The kinetic energy of the sphere transferred to the gelatin accelerates the medium surrounding the path of the sphere and moves gelatin away from the sphere both radially and axially thereby creating a tunnel, called temporary cavity, behind the sphere. As should be clear from time histories, exhibited in Fig. 9, of the computed and the experimental depths of penetration for impact speeds of 728 and 947 m/s, the numerical results agree well with the experimental data and the computed penetration depth is less than that measured experimentally by at most 10%.

For the two impact speeds, Fig. 5 exhibits the numerically computed and experimentally observed cavity profiles at 0.3, 1 and either 2.2 or 2.7 ms after impact. For the impact speed of 728 (947) m/s, the numerically computed maximum diameter of 63.7 (76.2) mm compares well with the experimental value of 60.3 (73.6) mm with the difference between the computed and the measured values being 5.5 (3.5)%. The temporary cavity looks like a slender cone that with the passage of time expands in both radial and axial directions. After reaching the maximum size it begins to collapse as elastic deformations of the gelatin are recovered.

Upon impact a very high pressure is generated in the region around the impacted face that propagates both radially and axially. This initial phase of the pressure pulse can be divided into two parts: penetration shock wave and pressure fluctuations. For the two impact speeds, the time histories exhibited in Fig. 4 of the computed and the experimentally measured pressure at the location (0, 50 mm, 50 mm) of the pressure gauge in the gelatin suggest that initially the two sets of results are very close to each other. However, after 0.05 ms the experimental results show more

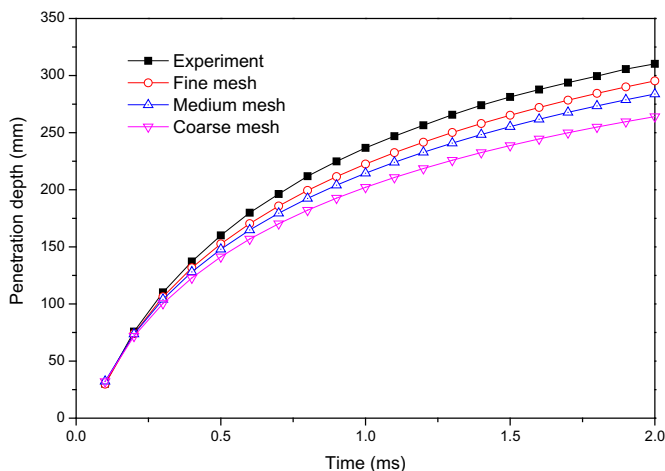


Fig. 8. Comparison of computed and experimental time histories of the penetration depths.

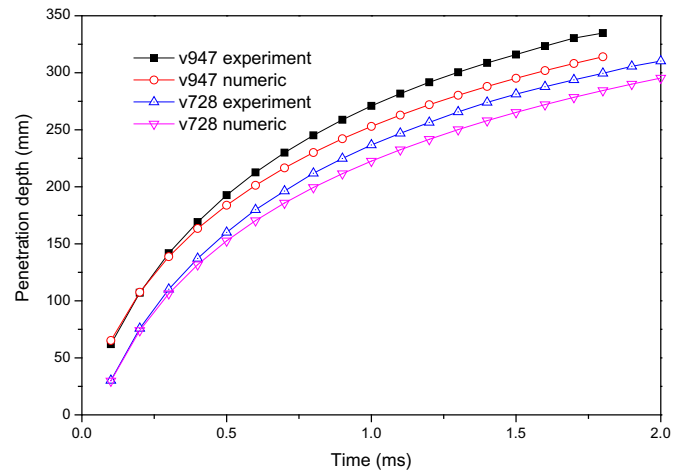


Fig. 9. Time histories of the computed and experimentally determined penetration depth.

dissipation than that evidenced by the computed results. The difference between the numerical and the experimental results for later times is more for the 947 m/s impact speed than that for the 728 m/s impact speed. It seems that a strain-rate dependent material model for the gelatin may be more appropriate for capturing this dissipation in the gelatin.

For the impact speed of 728 m/s, results plotted in Fig. 4 reveal that the first three wave peaks with pressures of nearly 2.54, 1.8 and 1.6 MPa occur at the gage location. The second and subsequent peaks are caused by the interaction between the incident wave and waves reflected from boundaries of the gelatin including from the free surface of the cavity formed in the wake of the sphere. Computed pressure profiles at 0.1 and 0.2 ms after impact are exhibited in Fig. 10.

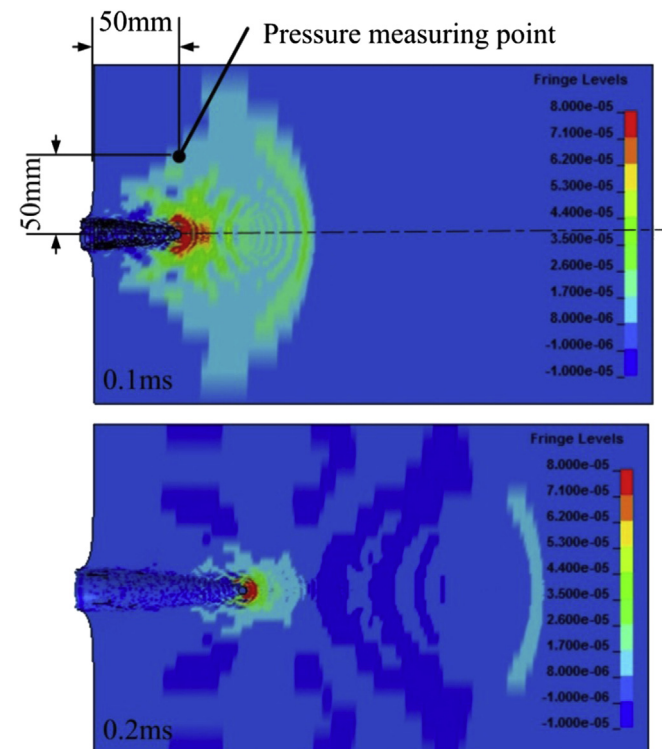


Fig. 10. Contours of pressure (10^5 MPa) in gelatin at 0.1 (top) and 0.2 ms (bottom) after impact (contour level 2.6-05 means pressure of 2.6 MPa).

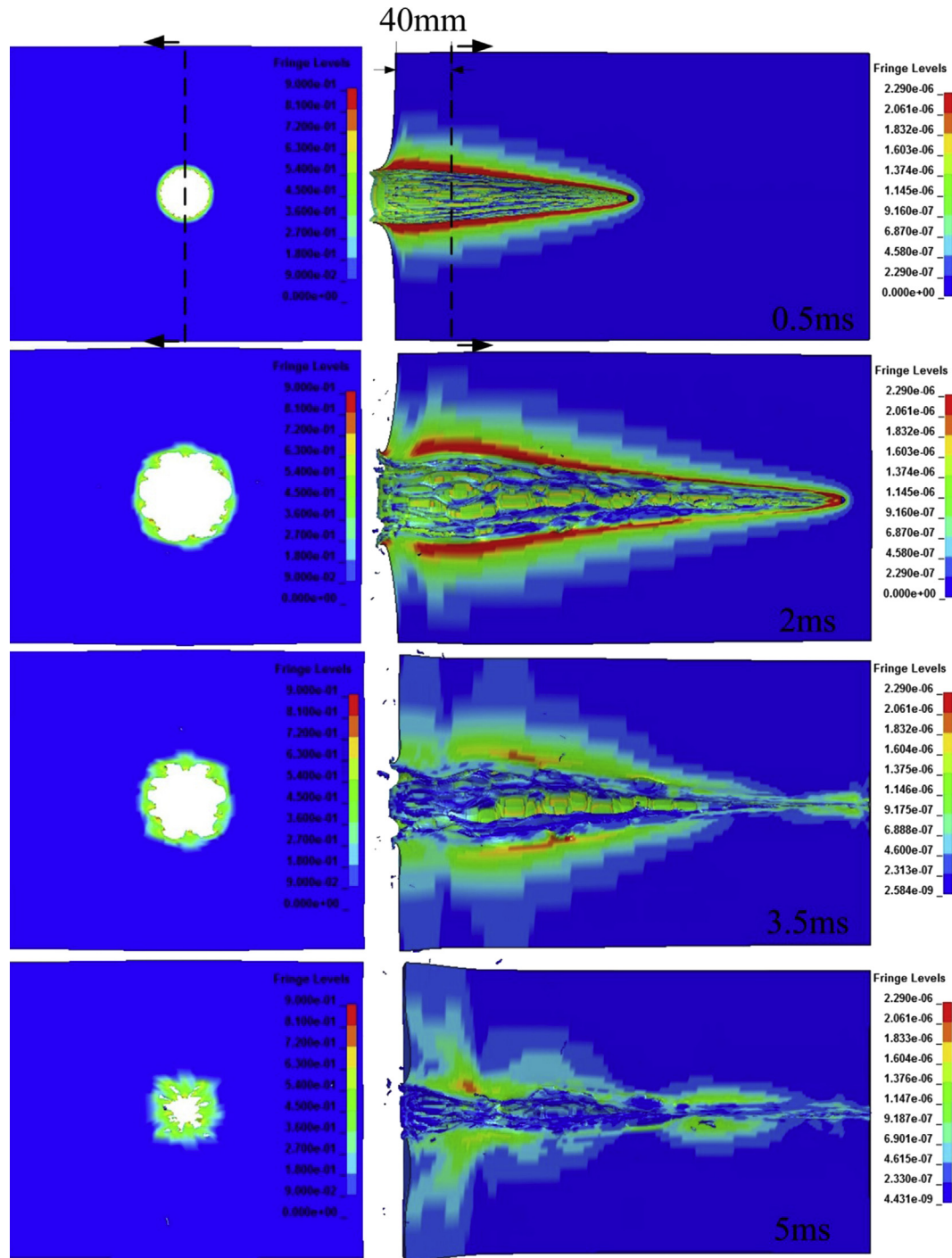


Fig. 11. At $t = 0.5, 2, 3.5$ and 5 ms after impact, contours of effective plastic strain in the impacted face (left) and of effective stress in 10^5 MPa (right) in the gelatin around the temporary cavity.

We have displayed in Fig. 11 contours of the effective plastic strain and the effective stress in the gelatin. The size of the plastically deformed region increases around the cavity surface irrespective of whether the cavity expands or contracts as the kinetic energy of the gelatin is converted into the plastic energy of deformation. About 0.2% of the gelatin mass was lost due to erosion of elements.

Pictures taken by the high-speed camera displayed in Fig. 12 reveal that for the 728 m/s impact speed the cavity expands and contracts about seven to eight times until all of the kinetic and the

stored energy in the gelatin has been dissipated. However, we could not numerically reproduce this pulsation of the cavity surface due to the use of the Lagrangian formulation of the problem, and not being able to adaptively refine the FE mesh in the gelatin.

3.3. Effect of impact parameters of steel sphere

The numerical results computed with three different sphere diameters and several different impact velocities are listed in Table 5. Three simulations labeled A, B and C in Table 5 employed

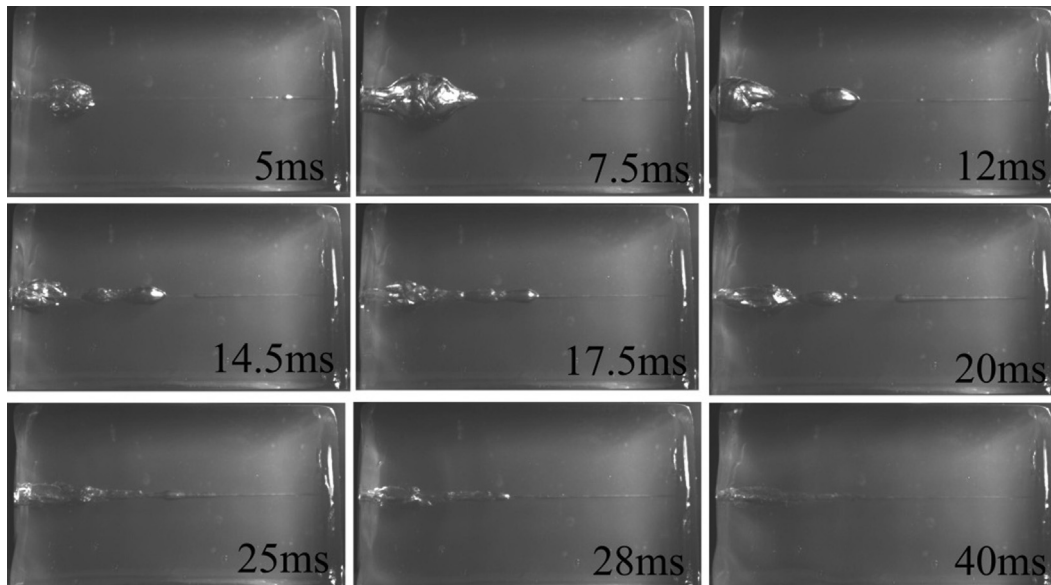


Fig. 12. Cavity pulsation captured by the high-speed camera.

Table 5

Numerical results with different impact velocities and sphere diameters.

No.	Diameter of steel sphere (mm)	Impact velocity (m/s)	Kinetic energy (J)	Maximum temporary cavity size (mm)	Time of temporary cavity (ms)	Maximum penetration resistance (N)	Initial expansion velocity of temporary cavity (m/s)
A	4.8	1200	326	95	3	5763	20
B	4.8	1000	227	83	2.8	4107	16
C	4.8	800	145	73	2.6	3091	13
D	4	800	84	60	2.3	2194	14
E	3	800	35	43	1.7	1161	13
F	4	1052	145	70	2.5	3178	14
G	3	1630	145	65	1.9	3829	19

the same sphere that has different initial velocities and hence different initial kinetic energies. Computed results show that the maximum temporary cavity size, maximum impact resistance and the initial expansion velocity of the cavity monotonically decrease with a decrease in the initial kinetic energy of the impacting sphere. Taking results for simulation B as the reference, +20% and –20% change in the impact speed alters, respectively, the maximum penetration resistance by +40% and –22% and the maximum temporary cavity size by +13% and –12%.

In simulations C, D and E, the impact speed is kept constant at 800 m/s but the sphere diameter is varied. Taking results for simulation D as the reference, +20% and –25% change in the sphere diameter affects, respectively, the maximum penetration resistance by +42% and –45% and the maximum temporary cavity size by +20% and –30%.

Simulations C, F and G have the same initial kinetic energy of the sphere. The maximum temporary cavity sizes for the three simulations are within 12% of each other. The maximum penetration resistances for simulations C and F are close to each other, whereas for simulation G it is considerably higher than that for the other two simulations.

In Fig. 13 we have plotted the variation of the maximum temporary cavity size versus the initial kinetic energy of the impacting sphere. It is clear that the maximum cavity diameter is an affine function of the initial kinetic energy of the sphere at least in the range of parameters studied. The data for the initial kinetic energy of the impacting sphere between 25 J and 250 J lie on the straight line whose equation is listed in the figure.

The temporary cavity profiles at $t = 0.1, 0.5, 1.5, 3.0$ and 4.5 ms for different diameters of the impacting sphere but having the same initial kinetic energy (simulations C, F and G) impacting gelatin are compared in Fig. 14. The 4.8 (3) mm sphere produces the maximum (minimum) penetration depth although its impact velocity is the lowest of the three spheres. It suggests that the sphere mass is the primary factor that determines the penetration depth.

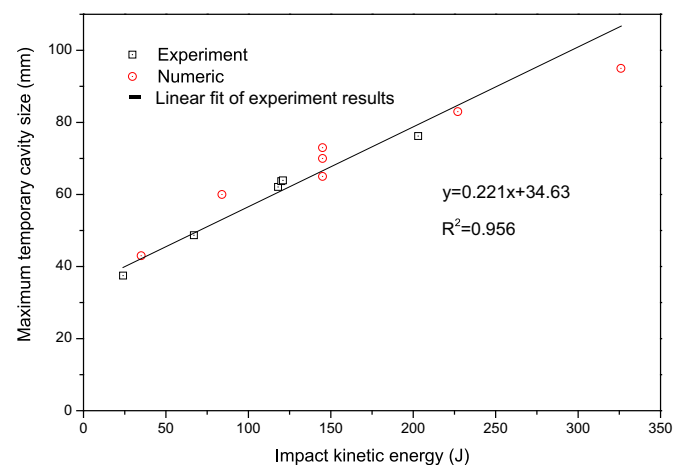


Fig. 13. Maximum temporary cavity size versus the initial kinetic energy of the impacting sphere.

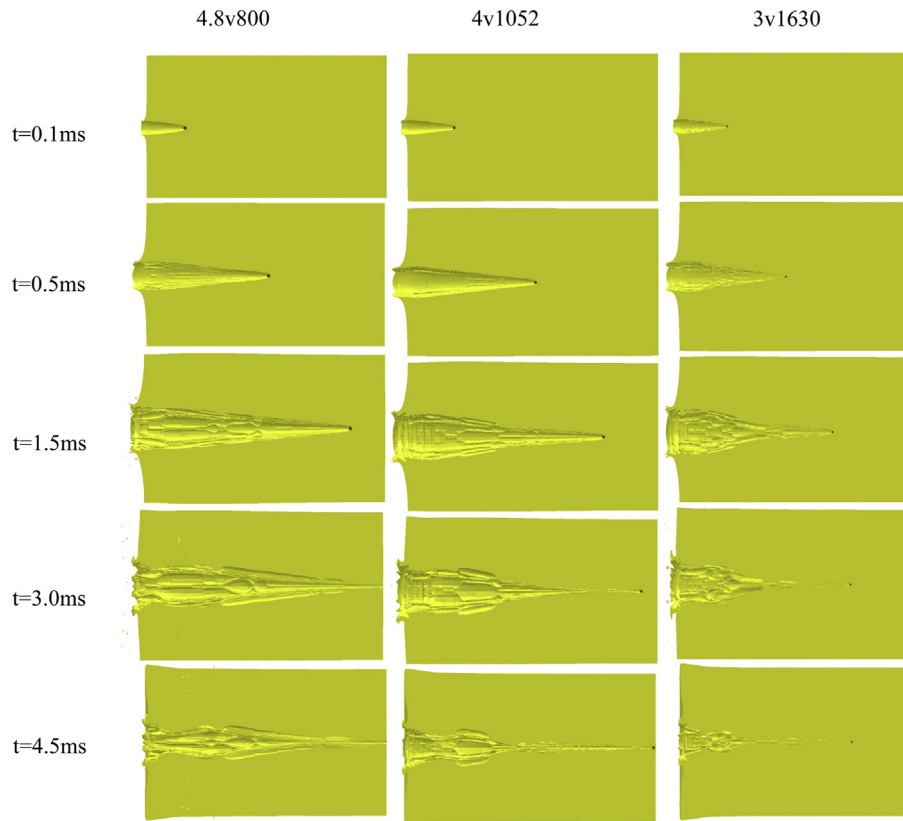


Fig. 14. Comparison of temporary cavity profiles for three spheres of different diameters but having the same initial kinetic energy (the first number in 4.8v800 stands for the sphere diameter in mm, and v800 implies sphere velocity = 800 m/s).

4. Conclusions

We have conducted ballistic experiments involving the impact and penetration of a steel sphere into a rectangular block of ballistic gelatin, and have used the commercial finite element software, LS-DYNA, to simulate the test configurations. Images recorded with a camera capable of taking 20,000 frames/s are used to visualize the tunnel shape. The impacting sphere has been modeled as rigid, and the ballistic gelatin as an elastic–plastic linearly strain hardening material for which the equation of state expresses the pressure as a polynomial of degree 3 in the relative volume change. The computed time histories of the penetration depth are found to be close to those observed experimentally. At a point close to the point of impact between the sphere and the gelatin, the computed time history of the pressure agrees well with that measured for small times but differences between the two sets of values grow after the first full cycle of pressure at the gage location. The shape of the computed temporary cavity is very close to the experimentally observed one and the computed peak diameter of the cavity near its mouth at 2.2 ms after impact differs by 5% from the measured one. Thus the material model used to simulate the response of the ballistic gelatin provides good results for the penetration of a steel sphere into the ballistic gelatin. The computed results suggest that the sphere mass rather than its kinetic energy determines the penetration depth.

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