THE DYNAMIC BEHAVIOUR OF BALLISTIC GELATIN

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Abstract. In order to characterise the effect of projectiles it is necessary to understand the mechanism of both penetration and resultant wounding in biological systems. Porcine gelatin is commonly used as a tissue simulant in ballistic tests because it elastically deforms in a similar manner to muscular tissue. Bullet impacts typically occur in the 350-850 m/s range; thus knowledge of the high strain-rate dynamic properties of both the projectile and target materials are desirable to simulate wounds. Unlike projectile materials, relatively little data exists on the dynamic response of flesh simulants. The Hugoniot for a 20 wt.% porcine gelatin, which exhibits a ballistic response similar to that of human tissues at room temperature, was determined using the plate-impact technique at impact velocities of 75-860 m/s. This resulted in impact stresses around three times higher than investigated elsewhere. In U_S-u_P space the Hugoniot had the form $U_S = 1.57 + 1.77u_P$, while in P-u_P space it was essentially hydrodynamic. In both cases this was in good agreement with the limited available data from the literature.

Keywords: Plate-impact, Shock, Hugoniot, Ballistic gelatin, Biological materials.
PACS: 43.25.Cb, 43.40.Ng, 43.80.Cs, 62.50.Ef.

INTRODUCTION

Human muscle is c.75% water. Gelatin provides a method of suspending water in a solid, castable form. The resultant similarity in ballistic response to muscular tissue has led to the use of porcine gelatin dissolved at 20 wt.% in water as a flesh penetration simulant. While much previous work on this material has involved validation against low velocity penetration data [1,2], surprisingly little high strain-rate data beyond a limited U_S-u_P Hugoniot [3] exists in the literature. In this paper a novel "cup" system is used to allow plate-impact experiments on as-cast 20 wt.% gelatin targets, establishing a U_S-u_P equation-of-state in order to inform comparison of the simulant and actual tissue materials at high strain rates. This material equation-of-state provides useful information to aid the development of future hydrocode models to simulate tissue damage.

EXPERIMENTAL PROCEDURE

Material properties

A 250 bloom porcine gelatin (Weishardt International, France) mixed in water to 20 wt.% at c.60 ºC, and subsequently allowed to set at room temperature, was employed in all tests. Density was measured to be slightly greater than water at 1.06 ± 0.01 g/cm^3. Sound speeds were measured ultrasonically using a Panametrics 5077PR pulse receiver in the pulse-echo configuration combined with appropriate Panametrics 1.0 MHz transducers. A longitudinal sound speed (c_L) of 1.48 ± 0.06 mm/µs was established, in good agreement with c_L for water (1.49 mm/µs [4]). During plate-impact experiments gelatin acts hydrodynamically – i.e. as a fluid. It possesses negligible stiffness and is therefore unable to support a shear wave [4].

Plate-impact experiments

Plate-impact experiments [5-7] at 75-860 m/s were conducted using a ∅50-mm bore single-stage gas gun [8]. Target material was cast into level cup containers, with a base comprising a c.1 mm thick cover plate of the same material as the flyer plate. Careful measurement of the final as-cast thickness (3-10 mm) was made. Longitudinal manganin gauges (type LM-SS-125CH-048, manufactured by Vishay Micro-Measurements® & SR-4® and calibrated according to [6]) were encapsulated within 25/50-μm thick mylar layers as required and introduced either side of the target to monitor shock propagation. Shock velocity was subsequently determined based on the spatial separation of the two gauges. The rear surface gauge was backed by a 12-mm thick PMMA block, sized to allow mounting within the cup where the depth of gelatin was insufficient to reach the cup rim. The rear surface gauge package was adhered to the back face of the as-cast gelatin using a compatible fast-setting epoxy, before being bonded to the structural elements of the cup to enhance target package rigidity. All other elements of the target package were bonded using slow curing Loctite 0151 HYSOL® Epoxi-Patch® Adhesive. Gauge analysis was performed according to the impedance matching technique [5-7]. A typical experimental setup is shown in Fig. 1. Impact velocities were measured by shorting a series of spatially separated velocity pins, while the target package was mounted on a target ring, itself mounted on a sacrificial barrel extension.

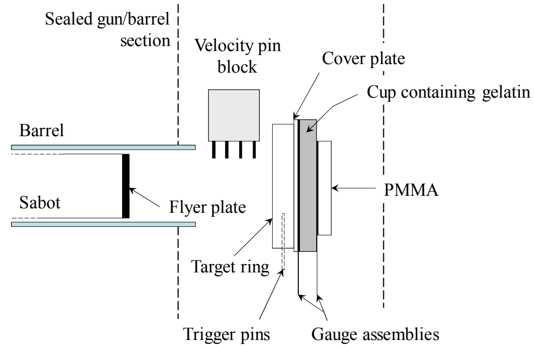

Figure 1. Plate-impact experimental setup.

RESULTS AND DISCUSSION

Nine shots using either PMMA, Dural or Cu flyers were undertaken according to the configuration shown in Fig. 1. Experimental results are summarised in Table 1. In one case front gauge failure prevented a U_S-u_P point from being determined and, in another, insufficient confidence in the measured Hugoniot stress led to its exclusion from the results. Typical front and rear unfiltered gauge traces are presented for a 604 m/s shot in Fig. 2. The rear surface trace has been rescaled to represent the approximate stress in the gelatin target based on the known Hugoniot of PMMA according to [7],

TABLE 1. Summary of experimental results.

v_{impact} (m/s)	Flyer material	Flyer thickness (mm)	u_P (mm/μs)	U_S (mm/μs)	σ_X (GPa)
75	PMMA	10	0.050	1.68	0.11
112	Dural	10	0.091	1.68	----
170	Cu	5	0.163	1.76	0.34
199	Dural	10	0.166	1.95	0.24
367	Dural	5	0.310	2.16	0.62
546	Cu	10	----	----	1.26
604	Cu	10	0.561	2.60	1.58
804	Cu	10	0.746	2.67	2.33
857	Cu	10	0.785	3.13	2.34

$$\sigma_{gelatin} = \frac{1}{2}\frac{(Z_{gelatin} + Z_{PMMA})}{Z_{PMMA}}\sigma_{PMMA}, \qquad (1)$$

where $\sigma_{gelatin}$ is the stress in the gelatin, σ_{PMMA} is the stress in the PMMA, $Z_{gelatin}$ is the impedance of the gelatin and Z_{PMMA} is the impedance of the PMMA. Where, $Z = \rho_0 U_S$, ρ_0 is the material density and U_S the shock velocity in the material measured from the shock transit time (Δt in Fig. 2).

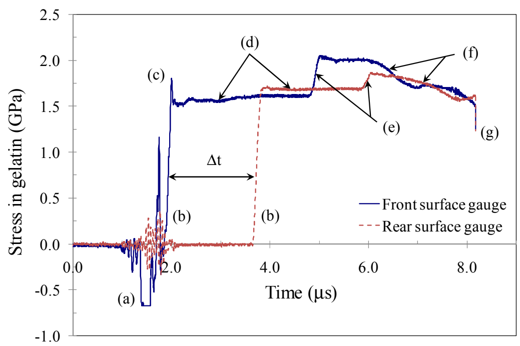

Figure 2. Front/rear gauges traces generated following impact of a 10-mm thick Cu flyer at 604 m/s onto a 4.6 mm thick gelatin target following Fig. 1.

Both traces in Fig. 2 showed a rapid rise (b) to a Hugoniot stress (d) followed by a reloading (e) and subsequent elastic release (f) before gauge failure (g). An initial undershoot on the front surface gauge just before shot arrival at (a) has been linked elsewhere [9] to an increase in capacitance between the gauge and cover plate as the cover plate is accelerated towards the gauge. Gauge rise times (b) were relatively slow compared to a typical longitudinal gauge response [7] at 144 and 170 ns on the front and rear gauges respectively. This was due to the difficulty of ensuring an intimate contact with the as-cast gelatin. Nevertheless, these rise times were comparable and sufficiently sharp to indicate a good impedance match between the manganin gauges and their encapsulation. Further, rise durations were small compared to the temporal shock lifetime. Following the rise on the front surface gauge, ringing within the gauge encapsulation just before the Hugoniot plateau resulted in an overshoot above the Hugoniot stress (c). Good correlation between the constant Hugoniot stress values on both gauges (d) followed reduction of the rear surface data using Equation (1). A consequent difference in stress magnitude of <5% between the two plateaus confirmed the validity of the stress measurements. Finally, reloading above the original Hugoniot stress on both gauges at (e) is due to shock reverberation [10,11] – i.e. ringing between the higher impedance Cu cover and PMMA backing which encapsulated the lower impedance target gelatin.

U_S-u_P and P-u_P Hugoniot relationships based on Table 1 are presented in Figs. 3 and 4 respectively. Errors were calculated in different ways. For U_S and u_P they were based on the range of possible shock arrival times (Δt in Fig. 2) and were typically < 0.4 and 0.01 mm/μs respectively. For σ_X, the errors represented variations across the measured Hugoniot plateaus and were consistently < 0.1 GPa. For comparison, the limited available literature data on 20 wt.% gelatin is also included in Fig. 3 [3].

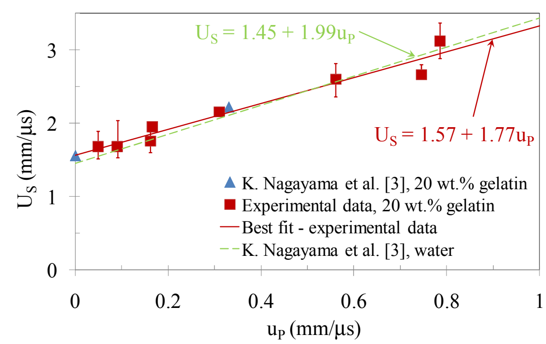

Figure 3. U_S-u_P Hugoniot, 20 wt.% gelatin.

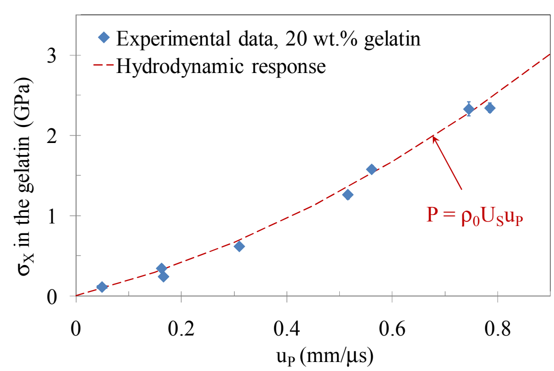

Figure 4. P-u_P Hugoniot, 20 wt.% gelatin.

The U_S-u_P Hugoniot in Fig. 3 is in good agreement with the two available data points for 20 wt.% gelatin from Nagayama et al. [3]. Further, within the error bars the experimental Hugoniot for 20 wt.% gelatin and that for water from [3] are extremely similar. This implies that gelatin behaves entirely hydrodynamically under shock loading. Unlike strong materials where U_S-axis intercept normally occurs at the bulk sound speed [5], with gelatin, the intercept occurs at a similar velocity to the longitudinal sound speed (e.g. 1.45 mm/μs, compared to a measured c_L of 1.48 ± 0.06 mm/μs). Fig. 4 includes a theoretical curve, based on the U_S-u_P Hugoniot set out in Fig. 3, which predicts the behaviour of the gelatin assuming that it behaves hydrodynamically [9]. Good agreement is observed between the experimental data and the hydrodynamic response.

CONCLUSIONS

A novel technique which allows 1D plate-impact experiments to be carried out on gel-based materials has been successfully implemented using 20 wt.% porcine gelatin. U_S-u_P and P-u_P Hugoniot relationships have been established for this material. Good agreement between the measured U_S-u_P relationship and the limited literature data available enhanced confidence in the technique. The importance of this result was emphasised by the fact that the type of gelatin employed is well defined, whereas the source of the material described in the literature is unclear. Comparison of the measured Hugoniot to that for water as well as ultrasonic measurements of elastic properties indicated that under high strain rates the as-cast gelatin behaves hydrodynamically (e.g. it exhibits no significant shear strength).

Overall, the equations-of-state set out in this paper greatly enhance the availability of materials data for hydrocode models designed to compare the response of ballistic penetration simulants with actual biological tissues. When combined with a knowledge of ballistic tests (to allow calibration of strength elements of material models), this data should minimise the requirement for testing on biological tissues.

ACKNOWLEDGEMENTS

The authors wish to thank both Gary Cooper for experimental support and ARUP for provision of both funding and support.

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2009-12-31T00:00:00Z

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AIP American Institute of Physics

hepherd CJ, Appleby-Thomas GJ, Hazell PJ, Allsop DF. The dynamic behaviour of ballistic gelatin, AIP Conference Proceedings, Volume1195, 2009, pp. 1399-1402

http://dx.doi.org/10.1063/1.3295071