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Research Paper

The high strain-rate behaviour of selected tissue analogues

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ABSTRACT

The high strain-rate response of four readily available tissue simulants has been investigated via plate-impact experiments. Comparison of the shock response of gelatin, ballistic soap (both sub-dermal tissue simulants), lard (adipose layers) and Sylgard® (a potential brain simulant) allowed interrogation of the applicability of such monolithic tissue surrogates in the ballistic regime. The gelatin and lard exhibited classic linear Hugoniot equations-of-state in the U_S–u_P plane; while for the ballistic soap and Sylgard® a polymer-like non-linear response was observed. In the P/σ_X–v/v_0 plane there was evidence of separation of the simulant materials into distinct groups, suggesting that a single tissue simulant is inadequate to ensure a high-fidelity description of the high strain-rate response of complex mammalian tissue. Gelatin appeared to behave broadly hydrodynamically, while soap, lard and Sylgard® were observed to strengthen in a material-dependent manner under specific loading conditions at elevated shock loading pressures/stresses. This strengthening behaviour was tentatively attributed to a further polymeric-like response in the form of a re-arrangement of the molecular chains under loading (a steric effect). In addition, investigation of lateral stress data from the literature showed evidence of operation of a material-independent strengthening mechanism when these materials were stressed above 2.5–3.0 GPa, tentatively linked to the generically polymeric-like underlying microstructure of the simulants under consideration.

1. Introduction

Protection against ballistic attack is an area of on-going interest. Development of ballistic protection solutions – as well as understanding of post-event phenomena from a forensics standpoint – requires knowledge of both body tissue behaviour and associated damage mechanisms. Tissue damage can arise from a variety of different routes including blast waves in air/water, penetration from projectiles and fragments, blunt-trauma and rapid acceleration/deceleration during impact events. Typically, data regarding tissue response during such events is derived from ballistic trials.

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However, these are expensive in both time and resources. Numerical simulations provide a more economic route to interrogate ballistic events. Material property and calibration data for such simulations requires experimental derivation. Further, due to a combination of availability and ethical considerations, such experiments normally involve tissue analogues.

A relatively small range of materials are typically employed as tissue surrogates for ballistic testing purposes; in particular, ballistics gelatin (Nicholas and Welsch, 2004; Appleby-Thomas et al., 2011) and ballistic soap (Appleby-Thomas et al., 2011; Dyckmans et al., 2003; Nsiampa et al., 2008). However, the complexity of mammalian tissue means that relatively simple and largely homogeneous simulants do not fully represent true tissue behaviour under given impact conditions. Further, it is well known that tissues exhibit a high degree of strain-rate sensitivity (McElhaney, 1966). Consequently, in order to provide high-fidelity materials data for forensics-linked simulations, a detailed knowledge of a variety of tissue analogues representative of differing tissue elements will be required.

The complexity of mammalian tissue is reflected in its laminated structure which involves – in addition to the underlying bone (McElhaney, 1966; Ural et al., 2011) – numerous extended (and often structurally anisotropic) layers; principally the epidermis, dermis, subcutaneous fat (adipose tissue) and muscle (Comley and Fleck, 2010; Jussila et al., 2005).

There is a relatively wide body of work investigating the low-medium strain-rate (typically $<10^4$/s) response of both tissue and simulant materials. For example, McElhaney (1966) investigated the response of (both bovine and human femur) bone loaded along its axis and bovine muscle tissue to impact at strain rates of up to 4000/s. A change in the failure mechanism of bone was observed at a relatively low strain rate of 1/s; below this threshold shear failure was observed, while above brittle fracture appeared to dominate. With muscle, however, McElhaney tentatively linked stress-strain behaviour to the cellular nature of the tissue. At stresses of around 0.7 MPa and for strain rates up to ca. 10^2/s a change in behaviour (in the form of a "humped" region in the measured stress-strain curves) was observed. This behaviour was attributed to the inability of the fluid both within the muscle cells (sarcomeres) and in the interweaving 'myofibrillar' spacings (filled with sarcoplasm) to move as the loading rate increased. Interestingly, this phenomenon dissipated as strain-rates approached 10^3/s. This was attributed to the viscoelastic properties of the muscle tissue becoming more homogenous in this loading region. Such results highlight the complex nature of muscle tissue—which is not only inherently anisotropic in terms of structure, but also demonstrates a clear strain-rate dependent response to impulsive loading.

More recently Van Sligtenhorst et al. (2006) discussed the use of polymeric (PMMA) bars in a split Hopkinson pressure bar (SHPB) arrangement (Field et al., 2004) to interrogate the high-strain-rate properties of soft tissue. While largely focused on the application of this experimental technique to such materials, bovine semimembranosis muscle (located at the back of the thigh) tissue samples were examined at strain-rates in the range 0.3/s to 2300/s. Tissue was primarily cut with the fibres running parallel to the loading direction; however, tests with fibres perpendicular to the bars showed no significant difference in response under these loading conditions. Again, a highly strain-rate sensitive response was observed. In addition, for given loading conditions, stresses were found to be consistently higher than those measured by McElhaney (1966); a result which led the authors to surmise that the samples investigated by McElhaney may have been subject to non-uniform deformation. Finally, tests on post-rigor tissue showed that after 24 hours, tissue response gradually reverted to that of fresh material—suggesting that such material (which is more easily sourced than fresh tissue) might provide an adequate simulant in certain circumstances.

At lower rates of strain (>1/s), Comley and Fleck (2010) employed a Universal Testing machine with crosshead speeds of 0.01–10 mm/s to conduct "trouser tear tests" – interrogating material toughness – on porcine adipose tissue. This material was investigated due to its potential for use as a human adipose tissue simulant. A collagen-based reinforcement membrane surrounding lipid-filled cells (adipocytes) was identified as the source of the material's toughness. Further, a secondary network of surrounding collagen (known as interlobular septa) were observed to provide an additional (albeit) minimal contribution to the material's ability to absorb energy before failure. Other low strain-rate studies include that by Jussila et al. (2005), in which ⌀ 4.5 mm lead spheres were projected into gelatin blocks faced by skin simulants using an air rifle. Different simulants were compared to literature data on the performance of human skin from cadavers. Based on a comparison of key human skin/simulant properties including penetration threshold velocity, tensile strength and elongation at break, the optimal skin simulant was found to be ca. 1 mm thick chrome-tanned leather. Further, this material was also found to produce exit wounds similar to those of human tissue when impacted with 5.56 mm × 45 mm Federal Tactical rounds.

While the studies outlined above have demonstrated similarities in the impact response of materials such as bovine muscle to human tissue, there is a clear driving force from both the practical acquisition and ethical standpoints towards employing synthetic tissue analogues. For example, Jussila et al. (2005) considered various polymer-based skin simulants. However, as discussed, they found that leather provided the best experimental fit in terms of material properties.

Despite this, synthetic tissue simulants have been extensively employed for ballistic-testing purposes. Both 10–20 wt% gelatin (Appleby-Thomas et al., 2011; Dyckmans et al., 2003; Nsiampa et al., 2008; Shepherd et al., 2009) and ballistic soap (Appleby-Thomas et al., 2011; Shepherd et al., 2011) have been widely employed in this role. Gelatin's viscoelastic behaviour mimics the response under impact of human tissue, with temporary cavities forming. However, these cavities oscillate and decay, preventing post-impact visualisation. Consequently, ballistic soap is often employed in tandem with gelatin; under impact it plastically deforms, creating a permanent cavity whose extent is broadly equivalent to the peak extent of deformation in gelatin. Both gelatin and ballistic soap have been characterised at relatively high rates of strain. For example, the impedance-matching technique (Zel′dovich et al., 2002; Meyers, 1994) was employed by Shepherd et al. (2009) to investigate the response of 20 wt% porcine gelatin to 1D impact for strain-rates $>10^5$/s.