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Short Communication

A constitutive model for ballistic gelatin at surgical strain rates

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ABSTRACT

This paper describes a constitutive model for ballistic gelatin at the low strain rates experienced, for example, by soft tissues during surgery. While this material is most commonly associated with high speed projectile penetration and impact investigations, it has also been used extensively as a soft tissue simulant in validation studies for surgical technologies (e.g. surgical simulation and guidance systems), for which loading speeds and the corresponding mechanical response of the material are quite different. We conducted mechanical compression experiments on gelatin specimens at strain rates spanning two orders of magnitude ($\sim$0.001–0.1 s^{-1}) and observed a nonlinear load–displacement history and strong strain rate-dependence. A compact and efficient visco-hyperelastic constitutive model was then formulated and found to fit the experimental data well. An Ogden type strain energy density function was employed for the elastic component. A single Prony exponential term was found to be adequate to capture the observed rate-dependence of the response over multiple strain rates. The model lends itself to immediate use within many commercial finite element packages.

1. Introduction

In this paper we propose a constitutive modelling framework for ballistic gelatin at low (quasi-static) strain rates. Based on observed experimental results (both here and in previous studies), we aim in particular to capture the strong strain rate-dependence of the material, which is not possible with elastic models only. A combined experimental and analytical approach is used to determine a suitable form for the constitutive equations. Experiments and models are then linked via a parameter fitting routine that combines an optimisation algorithm with a computational model of compression experiments.

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Organically-derived gels, hydrogels, silicon-gels, etc. have been used in a variety of biomedical applications (Juliano et al., 2006; Trexler et al., 2011; Drury and Mooney, 2003; Sun et al., 2012; Pervin and Chen, 2011). Soft tissue substitutes like these are favoured over native soft tissue for many applications due to the ease of sourcing such materials, the ability to control the sample preparation processes (e.g. composition and shape), and ethical implications. Ballistic gelatin in particular has frequently been employed as a soft tissue substitute (Kwartowitz, 2012; Malekzadeh et al., 2011; Mendez-Probst et al., 2010) as it is biologically-derived and has favourable properties such as biodegradability and ease of manufacture and preparation. Moreover, its mechanical properties and response to a variety of mechanical tests have been found to be similar to those of soft tissues (Breeze et al., 2013; Kalcioglu et al., 2010), further enhancing its suitability as a substitute. Its primary use has been in forensic and military applications (Liu et al., 2014a), most notably ballistic impact (Alley et al., 2011), wound profiling, and projectile wounding/penetration studies (Liu et al., 2014b; Swain et al., 2014). But, it has also found important application as a phantom material in medical imaging and surgical-guidance studies (e.g. simulating breast, prostate and other tissues) (Lawrentschuk et al., 2011; Lindner et al., 2010; Maier-Hein et al., 2009; Miranda et al., 2013; März et al., 2014; Sutcliffe et al., 2013), wherein it has been found to emulate soft tissue properties with satisfactory fidelity. It is these latter applications, in which loading speeds (that we loosely call 'surgical speeds') are several orders of magnitude lower than in ballistics studies, that motivate the present work. In this context, availability of a reliable constitutive model will allow *in silico* simulation of experimental scenarios to be undertaken, and correlated with experimental observations themselves.

This study is concerned with modelling the time- and rate-dependence of the gelatin's mechanical response at quasi-static loading speeds. The majority of past studies have focused on characterisation at 'dynamic' (~ 1000–$3000\ \text{s}^{-1}$) strain rates, reflecting its primary application area (Kwon and Subhash, 2010; Subhash et al., 2012; Salisbury and Cronin, 2009). Test configurations such as Hopkinson bar impact (Cronin and Falzon, 2009), uni-axial tension (Moy et al., 2008), indentation (Juliano et al., 2006), and others have been used for this purpose. But, it is widely recognised that the material's constitutive behaviour is distinctly different under these two loading speed regimes, possibly due to microstructural re-organisation of the material at higher rates (Kwon and Subhash, 2010). Typically, the material appears much stiffer at higher speeds, though rate-dependence can indeed be observed across all speeds studied so far. As a result it is difficult to formulate general constitutive models that capture the gelatin response at *both* quasi-static and dynamic loading rates, nor indeed may this be an efficient approach if only a narrow envelope of speeds is of interest in any single application.

Characterisation at lower speeds, similar to here, was considered in Cronin and Falzon (2011) and Cronin (2011). Both finite strain behaviour and strain rate-dependence were studied. In Cronin and Falzon (2011), compression tests at various loading speeds were performed and the responses were modelled with a simple Neo-Hookean type hyperelastic constitutive model. Such models, however, are unable to capture strain rate-dependence, and it was therefore separately fit to the data for each strain rate. Improved models aimed at addressing this deficiency were proposed in Cronin (2011) in the form of quasi-linear viscoelasticity and tabulated hyperelasticity, both of which are able to capture strain rate-dependence, though using quite different approaches. Viscoelastic models are formulated in terms of a convolution integral that imbues a dependence on the entire strain history of the material, naturally including, for example, temporal patterns of strain magnitude and rate. This is coupled with relaxation functions, usually of exponential decay form, that reflect viscous phenomena. Many important physical manifestations of these mechanisms, such as stress relaxation, creep and rate-dependence therefore naturally emerge from such models. In contrast, tabulated models, which were favoured in Cronin (2011), simply incorporate an ensemble of elastic response curves at different strain rates, and provide a numerical mechanism for switching between them according to the imposed loading characteristics (Kolling et al., 2007). The approach is general in the sense that quite varied phenomena can be included (for example, a wide range of loading speeds was considered in Cronin, 2011, as well as material damage), but it relies on provision of a sufficiently rich set of constituent curves to cover the desired range of loading conditions. Instabilities may also be introduced when transitioning between certain loading regimes, meaning additional care must be taken in those regions (Kolling et al., 2007).

In this work, we revisit the viscoelastic approach, which, though more complex in its functional form, offers a more compact overall representation of the key response features. It also provides a continuous and smooth prediction of mechanical response across its range of validity. We couple the basic viscoelastic formulation with a suitable hyperelastic strain energy function to accommodate not only the time- and rate-dependence, but finite deformation features also. The resulting model can be efficiently solved in any finite element (FE) framework. Compression testing of cylindrical gelatin specimens at a range of loading speeds was also undertaken, on the basis of whose results suitable model parameters for this material were identified. A curve fitting scheme based on a FE model of the compression experiments was developed for this purpose. Finally, a sensitivity analysis on the model

Fig. 1 – Liquid gelatin cast into the mould after dissolving the gelatin powder in water. Scum is visible on the top layer of the material.