Obtaining the High Strain Rate Properties of Bone Using the Image-Based Inertial Impact (IBII) Test

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Abstract. While there is a large body of work addressing the mechanical properties of bone at quasi-static strain rates, there are comparatively few studies that investigate the high strain rate behaviour of bone. The high strain rate data that currently exists for bone is generally obtained using the compressive split Hopkinson pressure bar (SHPB) technique. However, *in-vivo* failure of bone will generally occur in a loading state in which the bone is mostly subjected to bending. This makes the high strain rate tensile strength an important parameter for predicting failure in bone under impact loading. The Image-Based Inertial Impact (IBII) test is an alternative to the SHPB that is particularly well suited for testing quasi-brittle materials (*e.g.* bone) in tension. The IBII test method uses full-field kinematic measurements coupled with the Virtual Fields Method to identify material properties for a sample that is indirectly loaded in tension by a reflected stress wave. Therefore, the aim of this study is to use the IBII method to investigate the high strain rate properties of bone including stiffness and tensile strength.

Introduction

Most existing data for the mechanical properties of bone is obtained at quasi-static loading rates. However, bone fracture events tend to occur at higher rates due to impact loads. For example at moderate loading rates, a fall or physical trauma; at high strain rates, a car accident; or at extremely high rates due to explosive loading/ballistic trauma. Therefore, there is a need to obtain data at a variety of strain rates in order to develop material models that can predict bone fracture due to impact loads. Current high strain rate data for bone has mostly been obtained with the split-Hopkinson pressure bar (SHPB) technique using compressive loading [1]. Bone fracture events that occur due to impact loading do not usually occur due to purely compressive loading and are generally the result of bending loads at the whole bone level. Therefore, the tensile strength of bone is also an important parameter for predicting fracture due to impact loading. Obtaining the tensile strength of a quasi-brittle material like bone using the SHPB is extremely difficult. The reason for this is that the low strain to failure under tensile loading for quasi-brittle materials leads the sample to fail before inertial effects have damped out [2]. Recently, the image-based inertial impact (IBII) test has been developed as an alternative to the SHPB technique. The IBII technique is specifically designed for testing brittle and quasi-brittle materials at high strain rates and does not rely on the assumption of quasi-static equilibrium [3,4]. The IBII method uses full-field measurements coupled with the virtual fields method to identify material properties at high strain rates. Therefore, the aim of this study is to use the IBII test method to investigate the high strain rate properties of cortical bone.

The Virtual Fields Method (VFM) for IBII Tests

The IBII test uses a plate-like sample impacted in an edge-on configuration as shown in Fig. 1. Here, ultra-high speed imaging is coupled with a full-field displacement measurement technique (*e.g.* the grid method) to measure kinematics during the impact. The full-field displacement measurements are used to obtain strain fields through spatial differentiation and acceleration fields through double temporal differentiation. The simplest method of analysing data from an IBII test using the VFM is to use rigid body virtual fields [3,4]. The use of rigid body virtual fields generates ‘stress-gauge’ equations which relate the measured acceleration fields to stress averages. Here we consider two cases, the standard axial stress gauge and a shear stress gauge:

$$\overline{\sigma_{xi}}^{y} = \rho x_0 \overline{a_i}^{S}, \quad i = x, y \tag{1}$$

where $\overline{\sigma_{xi}}^{y}$ is the average stress over the line at x_0 (see Fig. 1 (a)), $\overline{a_i}^{S}$ is the surface average of the acceleration field over the area S (from the free edge to x_0) and ρ is the density of the material. Combining the average stress with the average strain allows for stress-strain curves to be constructed over the duration of the test. For the IBII configuration shown in Fig.1 (a) a perfectly aligned impact produces no shear stress. However, slight projectile misalignments can cause enough shear to allow the shear modulus to be obtained.

Experimental Method

Bone Samples. Two bovine femurs and two bovine tibias were obtained from a local butcher. The samples were stored at -20ºC soaked in Phosphate Buffered Saline (PBS) during all stages of the preparation. Rectangular samples with a nominal geometry of 20x12x2mm were wet machined from cortical shaft of the bones. Half the samples were cut aligned to the longitudinal axis of the bone and the other half were cut transverse. Samples were paired based on location with one sample being allocated for quasi-static testing and one sample allocated to IBII testing. A grid pattern with a pitch of 0.337mm was printed directly onto the sample surface using the procedure described in [5]. Prior to testing the samples were soaked in PBS at room temperature for several hours.

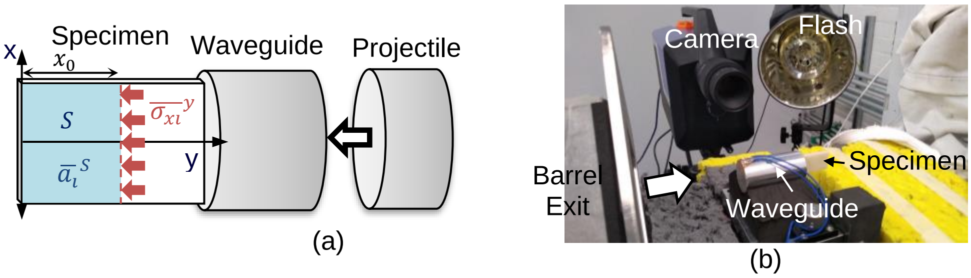

Figure 1: (a) Schematic of the IBII test and (b) photograph of the test set-up

Impact Rig and Imaging Set-up. The IBII testing procedure followed the general procedure outlined in [5]. A purpose-built gas gun was used to perform the IBII tests with the aluminium projectile and waveguide combination described in [4]. A Shimadzu HPV-X camera was used to image the samples at 5 Million fps and the grid method was used to perform the full-field displacement measurements (sampling of 6 pixels/period). Other relevant experimental and data processing parameters are summarised in [5].

Results and Discussion

Initial results for a longitudinal bone sample are presented in Fig. 2 where Eq. 1 is used to reconstruct the stress-strain response. Here we observe that the longitudinal stress-strain curve is much less noisy than the shear one as the deformation is predominantly axial (the shear only results from slight projectile misalignment). Linearly fitting the stress-strain curves in each case gives a longitudinal stiffness of Q_{11} = 27.8 GPa and a shear stiffness of Q_{66} = 7.7 GPa. The strain rates observed in this test are on the order of 1000/s.

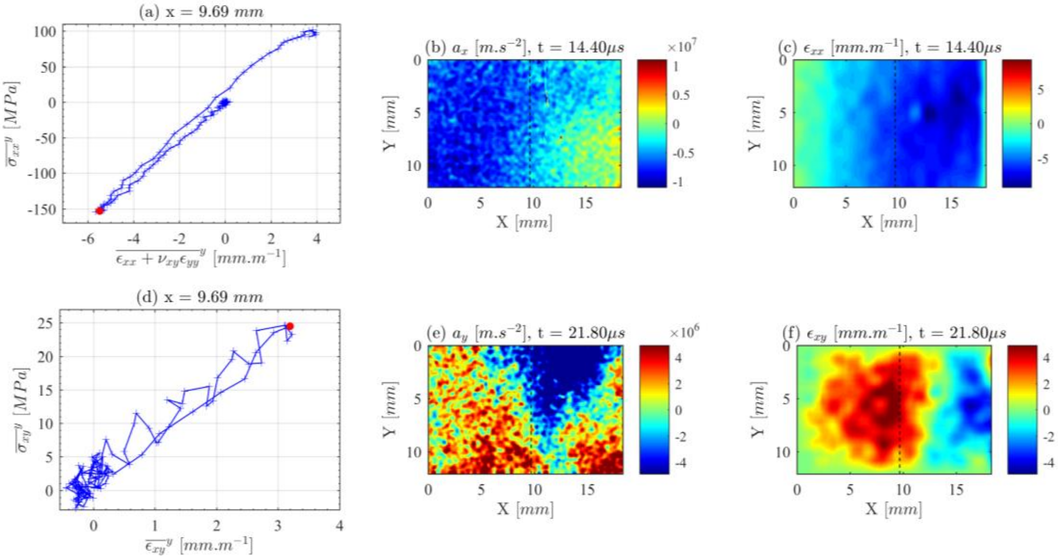

Figure 2: Stress-strain curves and kinematic fields for the axial and shear stress components of an example longitudinal bone sample

Conclusion

The preliminary results of this study show that the IBII test method can be used to obtain a range of material properties for bone under high strain rate loading. Future work will focus on developing more heterogenous test cases that will allow for the identification of all stiffness components in single test or failure stress under combined loading states. This could be achieved by impacting the test sample over half its height or by introducing geometrical stress concentrators.

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