APPLICATION OF THE SPLIT HOPKINSON BAR TO DETERMINE THE DYNAMIC RESPONSE OF BONE

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INTRODUCTION

A prerequisite in the design and analysis of a structural configuration is a knowledge of the material properties of the basic elements which comprise the structure under consideration. Thus, in order to study the response of the gross skeletal system or its components to external loading, both the static and dynamic material properties of the supporting connective tissues (primarily bone) must be investigated. Considerable effort has been expended to determine static properties using either conventional test equipment[1,2,3] or resonant frequency techniques[4,5]. In general, the static mechanical properties of bone have been well characterized as a function of fibre orientation in the specimen, temperature, post-mortem age and preserving treatment. However, little work has been done to determine the strain rate sensitivity of bone[6,7] under similar conditions. It would appear from the literature surveyed that previous methods used to determine the specimen strain and the applied strain rate were based on displacement-time data. Consequently, it was decided to analyse the dynamic response of bone directly using the split Hopkinson bar apparatus, thus reducing the errors associated with the computation of strain and strain rate. The following report briefly describes the split Hopkinson bar method and the theory required to interpret the output data. A discussion of the results obtained is then presented.

BASIC THEORY

The split Hopkinson bar test[8] has been used extensively to determine the dynamic response characteristics of materials under uniaxial compressive loading. The basic apparatus (Fig. 1) consists of input-output steel bars containing the bone sample sandwiched between them. Using a high pressure gas reservoir, a cylindrical projectile is fired down the barrel and impacted on the input bar. A one-dimensional strain pulse (ε_I) is then propagated along the input bar and recorded by a bonded foil electrical resistance strain gauge mounted a short distance (~1.0") from the specimen interface. Subsequently, the incident strain pulse (ε_I) is partially reflected (ε_R) and transmitted through the specimen with an intensity dependent upon the relative acoustic impedances of the materials. Again, at the second interface, the strain pulse is partially reflected and transmitted through the output bar (ε_o) and recorded by another strain gauge. For sufficiently short specimens, multiple reflections of the strain pulse occur within the specimen prior to the original wave fronts reaching the free ends of the input-output bars. It is assumed that a uniform state of stress and strain exists in the specimen. However, it must be noted in this simplified analysis that the effects of longitudinal inertia and radial motion (resulting in contact surface frictional forces) are neglected. It has been demonstrated that these effects are indeed negligible[9,10,11] providing that the short specimens have a length/diameter ratio of at least unity and the contact surfaces are coated with a lubricant. Of particular significance are the tests conducted by Tulk[11] to determine under what conditions an epoxy specimen containing an incapsulated foil strain gauge (1/8") would exhibit the same response as the split Hopkinson bar, assuming the strain is given by

$$\varepsilon(t) \simeq \int_o^t c\,\frac{(\varepsilon_I - \varepsilon_R - \varepsilon_o)}{L}\,dt$$

where L is the sample length and c is the one-dimensional elastic wave speed in the input-output bars. Thestrain rate can be determined directly from the relation

$$\dot{\varepsilon}(t) \simeq \frac{c}{L}\,\frac{(\varepsilon_I - \varepsilon_R - \varepsilon_o)}{L}$$

It was found that both strain-time profiles corresponded very closely except in the early stages of loading (<50 µsec). As a result, the split Hopkinson bar can be used with confidence to determine the strain-rate sensitivity of materials.

EXPERIMENT

All test specimens were fabricated from batches of beef femur bone taken from cattle nominally two years of age. Each bone sample was machined from the dense cortical material (Haversian bone) of the thick femoral mid diaphysis into cylinders 3/8" in diameter and 1/2" long, with the specimen axis aligned parallel to the long axis of the femur. All cutting and machining operations were performed with the specimens in a wet condition to minimize the effect of temperature[1]. During storage, specimens were immersed in an aqueous solution and refrigerated at 35°F. The primary objective of this programme was to determine the strain rate sensitivity of the compressive modulus of elasticity as a function of post-mortem age (PMA) for a statistically large sample of beef femurs. Thus, thirty test pieces were prepared from three different batches of femur bone. As many as eight femurs were required to yield sufficient

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specimens for testing at a given PMA. To date, elapsed post-mortem times of 14,21, 28 and 240 days have been considered. In order to determine the effect of dehydration on the dynamic material behaviour,a set of test specimens was refrigerated in a dry state.

Prior to inserting the bone sample into the split Hopkinson bar (Fig. 1), each polished face was coated with a silicone lubricant to reduce the frictional forces. The resulting dual strain-time oscilloscope traces were recorded on polaroid film and digitized at 1 ~ 2 µsec intervals commencing at the arrival time of the reflected and transmitted strain pulses monitored by the strain gauges on the input and output bars respectively. Typical results obtained for the compressive modulus of elasticity as a function of strain rate for a PMA of 21 days are shown in Fig. 2. A summary plot of the variation in the modulus as a function of both PMA and strain rate is given in Fig. 3.

DISCUSSION OF RESULTS

For the thirty beef femur specimens subjected to strain rates ranging from 10 ~ 500 sec^{-1}, it is evident that the compressive modulus of elasticity varies with the applied strain rate much in the same manner as a viscoelastic material. Since a large sample of femur bones was investigated, expected variations in the moduli were observed, although the scatter about a median value was nominally ± 20%. Hence, it would appear that the statistical variation in the compressive modulus of elasticity for a wide range of strain rates is not sufficiently great to prevent an assessment of the strain rate sensitivity of femur bone, as shown in Fig. 2.

For the range of elapsed post-mortem times considered, some effect on the strain rate behaviour was observed (Fig.3) after a period of approximately one month. However, substantial increases in the moduli were found for the specimens which were refrigerated in a dry state, indicating that dehydration does in fact tend to alter the material properties of bone.

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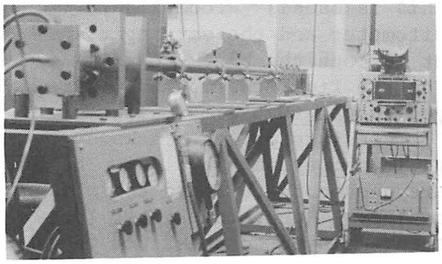
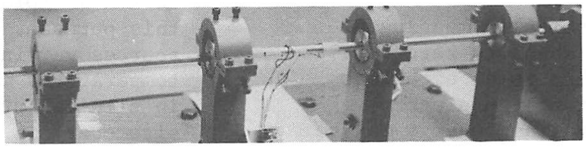


FIG. I



INPUT-OUTPUT BARS WITH BONE SPECIMEN

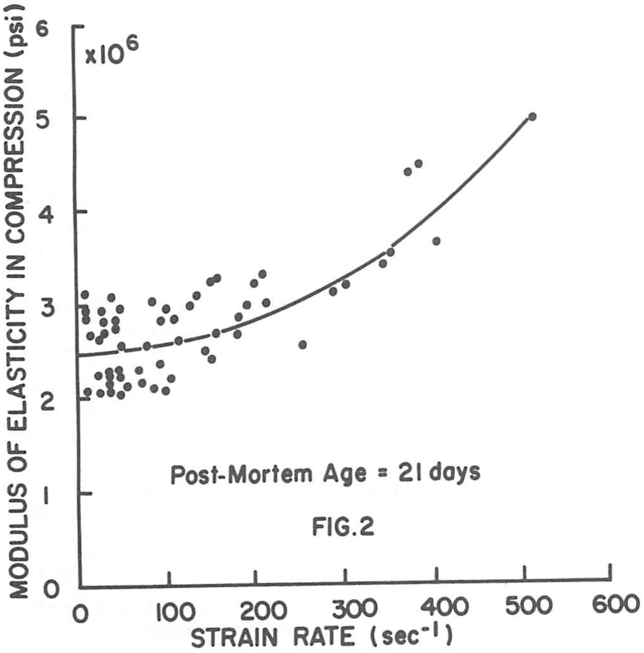


FIG.2

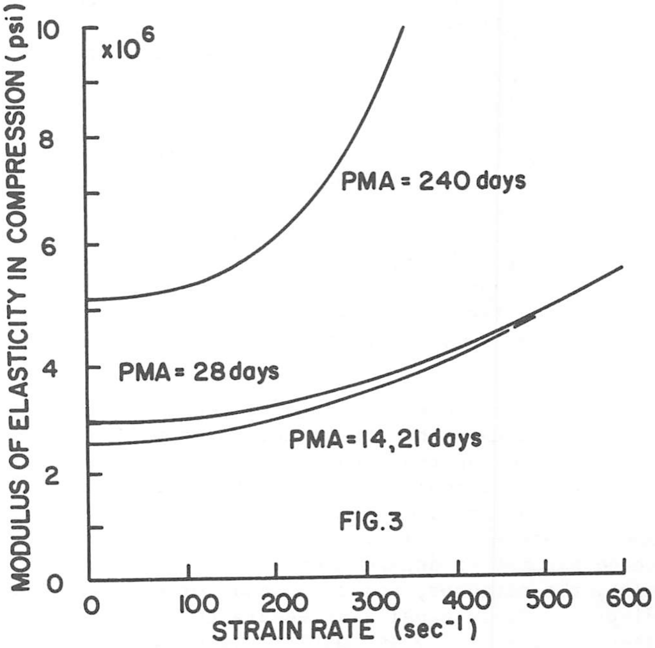


FIG.3