The Impact Properties of Bone

R.P. Dickenson, J.W. Wall and W.C. Hutton

Medical Engineering Unit,
Division of Engineering,
Polytechnic of Central London,
115 New Cavendish Street,
London W1M 8JS

Introduction

The mechanical properties of bone have been studied widely over the past 20 years for several reasons. Increasing interest in developing materials for skeletal support and replacement has stimulated an effort to determine the true mechanical properties of bone. Another area of interest is where the human body is subjected to high stresses. This occurs in passenger restraint systems in road vehicles. Here it is important to know the strength of the material which forms the framework of the human body. This factor is also important in jet aircraft, where the escape mechanism puts high loads on the body.

Reviews of the work in the field of mechanical properties of bone have recently been done by Currey (1970) and Reilly and Burstein (1974). Only recently has work been done under impact conditions. McElhaney (1966) found a maximum energy absorption to fracture at a loading rate of 1 per second. Crowninshield and Pope (1974) found similar results.

Wall et al (1974) noted increasing strength up to a rate of 1 s^{-1}.

In recent years increasing interest has been shown in energy absorption as an important parameter in bone fracture. Piekarski (1970), Pope and Outwater (1972) and Pope and Murphy (1974) all studied fracture energy though not under impact conditions.

In this study human, femoral cortical bone was tested in tension at a rate of 2 per second, producing a fracture in 20 to 30 milliseconds. Tensile testing was used because it has been shown by Brooks et al (1970) that the majority of fractures 'in vivo', in the femur, occur along planes of maximum tensile stress. To determine an impact loading rate is difficult. An idea of the order of magnitude of the impulsive load can be had from the work of Johnson et al (1975), who measured impulsive loads on the skull in boxing of 10 to 50 milliseconds. A theoretical impact of a projectile moving at 30 m.p.h. (as in a typical urban automobile accident) would result in a loading rate on the femur of about 15 per second. This figure would be considerably reduced also by the damping effect of the tissue surrounding the bone. Bearing these factors in mind using a rate of 2 per second (corresponding to a 20 millisecond fracture) seems reasonable. Another technique used to investigate bone fracture was high speed photography. The aim of this work then, was to investigate the impact properties of bone by examining energy absorption as a criteria for bone strength, as well as its relation to other properties, and to observe the mode of fracture by high speed photography.

Method

The specimens were prepared by removing the mid 100 cm of the femoral diaphysis at post mortem. They were sealed in plastic bags and stored at -20^{o}C until testing took place. Clinical histories were obtained and bone from persons with any possible skeletal defect was not used. Parallel strips of bone were removed from the lateral and medial quadrants using a horizontal milling machine for cutting. The bone was kept wet, in Hanks' Physiological Solution, throughout the fabrication and testing of the specimens. The strips were lapped to remove any cancellous bone or adherent tissue including the periosteum, so that only cortical bone remained.

Approximately 10 strips were obtained from each bone. The strips were then shaped into tensile test pieces using a hardened steel jig. The specimens produced were flat dumbbell shaped test pieces, 35 mm long with a central gauge length of 14 mm, the cross-sectional area being 4 sq. mm. The density of the test pieces was determined by a water displacement method, Wall et al (1972).

The testing was carried out on a Mayes Universal Hydraulic testing machine with a flat frequency response of 4 Hz $\pm$ 1 mm. An extensometer was built to measure bone strain directly. The extensometer output was fed through a carrier amplifer, a noise reduction system and displayed on an oscilloscope. The load cell output was also put through the noise reduction system before being displayed. The ram speed used was 1500 mm per minute.

Results and Discussion

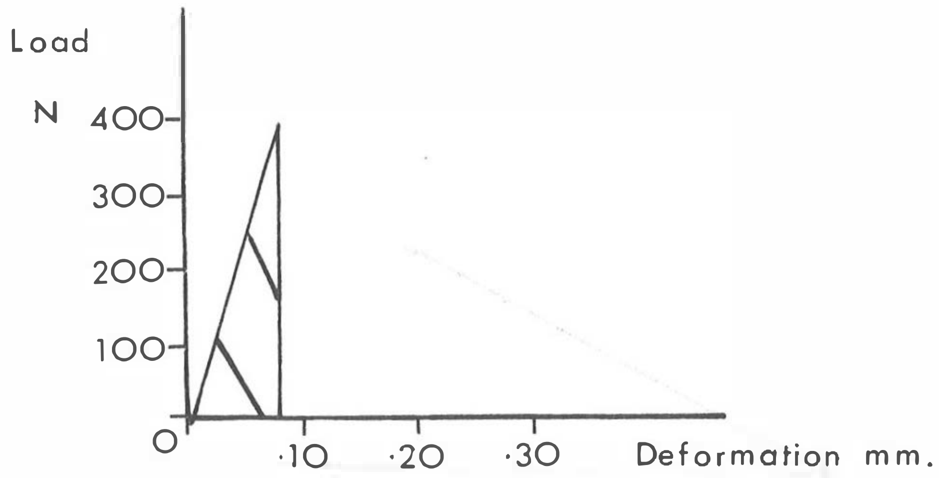
For the photographic analysis, a camera was used with a film speed of 5000 frames per second. This corresponds to a time interval between frames of 0.2 milliseconds. The films taken of the tensile tests, which will be shown at the conference, show that the crack propagation always took less than 1 frame. This meant that the minimum crack propagation speed was 10 m per second, although it obviously could have been much higher.

The parameters measured in the mechanical tests were Ultimate Tensile Strength, Modulus of Elasticity, Percentage Elongation of the specimen, energy absorbed to fracture.

Two typical load-extension curves are shown in figures 1(a) and 1(b). The energy absorption is the shaded area under the line. The results obtained to date are shown in figures 2 and 3. The statistical analysis utilised a program to do a non-linear regression analysis via orthogonal polynomials and to compute a correlation coefficient from this line; the significance level being determined from this.

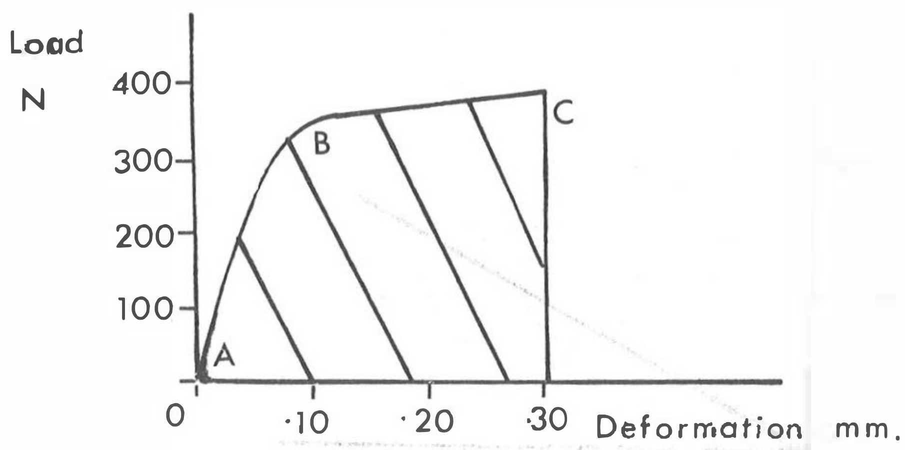
In figure 2 the correlation between Percentage Elongation and Energy Absorption is significant at the 5% level. Percentage Elongation is the total extension divided by the original length expressed as a percentage. The correlation can be explained by reference to figure 1. Figure 1(a) shows a brittle fracture and 1(b) shows a pull-out failure of bone in tension. These two sypes of failure were studied by Pierkarski (1970). The flat part of the line in 1(b), BC, is believed to be due to a pull out of the osteons from the surrounding matrix, resulting in a large extension before failure. This explains the correlation since the area under BC accounts for the majority of the energy absorbed during the test.

The correlation between Ultimate Tensile Strength and Energy Absorption in figure 3 is significant at the 5% level. This can again be explained by reference to 1(b). It can be seen that the ultimate strength increases the further along BC the fracture occurs and as mentioned above the area under BC is the main factor affecting the energy absorption. This establishes that, to a certain extent, energy absorption is a criteria for bone strength. Further work is at present being done to determine the relative importance of this factor as opposed to other factors which are known to affect ultimate strength, for instance density. This work will be discussed at the conference.



Load
N
400
300
200
100
O
·10
·20
·30
Deformation mm.

Fig 1a.



Load
N
400
300
200
100
A
B
C
0
·10
·20
·30
Deformation mm.

Fig 1b.

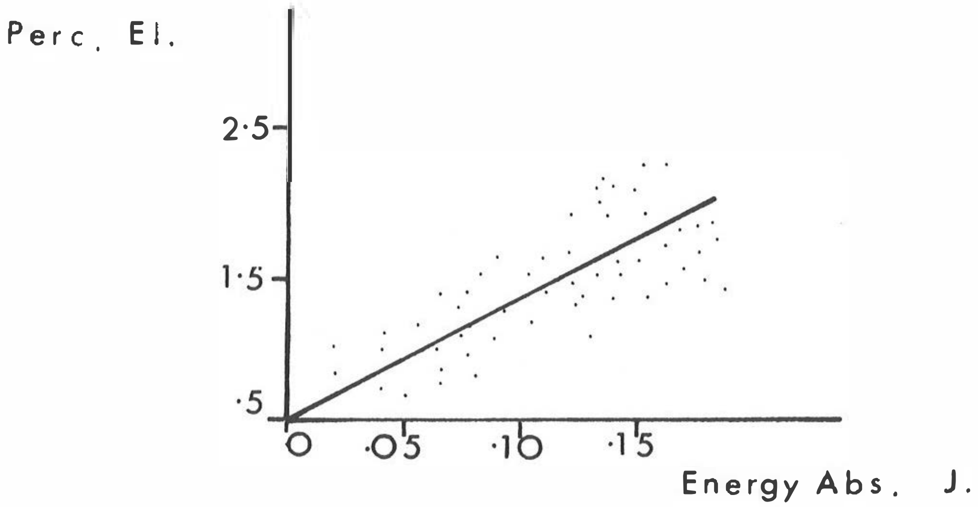

Perc. El.
2·5
1·5
·5
0
·05
·10
·15
Energy Abs. J.

Fig 2

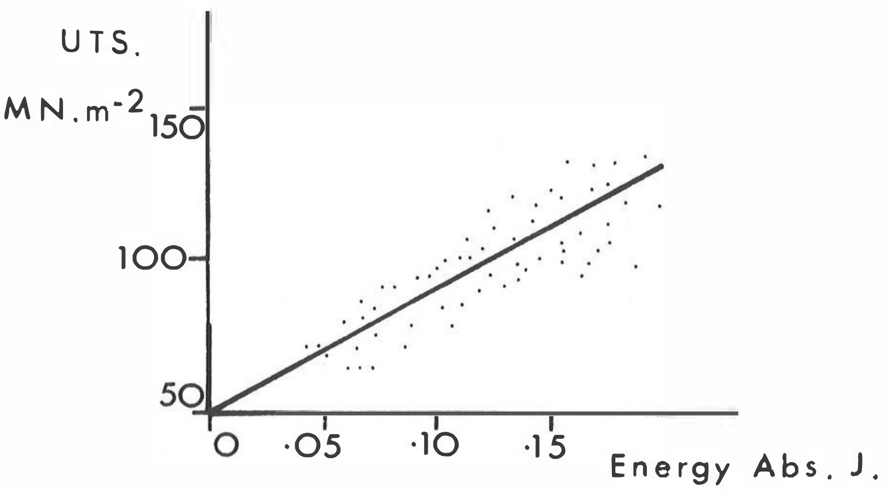

UTS.
MN.m-2
150
100
50
0
·05
·10
·15
Energy Abs. J.

Fig 3

Bibliography

Currey, J.D.
The mechanical properties of bone. Clinical Orthopaedics and Related Research, 73, 1970, 210-213.

Reilly, D.T. and Burstein, A.H.
The mechanical properties of cortical bone (Review article). Journal of Bone and Joint Surgery, 56A (5) 1974, 1001-1021.

McElhaney, J.H.
Dynamic response of bone and muscle tissue. Journal of Applied Physiology, 21, 1966, 1231-1236.

Crowninshield, R.D. and Pope, M.H.
The response of compact bone in tension at various strain rates, Annuals of Biomedical Engineering, 2, 1974, 217-225.

Wall, J.C., Hutton, W.C. and Cyron, B.M.
The effects of age and strain rate on the mechanical properties of bone (In Proceedings of the International Meeting on Biomechanics of Trauma in Children, Lyon, France, September 1974).

Piekarski, K.
Fracture of bone. Journal of Applied Physics, 41(1), 1970, 215-223.

Pope, M.H. and Outwater, J.O.
The fracture characteristics of bone substance. Journal of Biomechanics 5, 1972, 457-465.

Pope, M.H. and Murphy, M.C.
Fracture energy of bone in a shear mode. Medical and Biological Engineering, 12(b), 1974, 763.

Brooks, D.B., Burstein, A.H. and Frankel, V.H.
The biomechanics of torsional fractures: the stress concentration of a drill hole. Journal of Bone and Joint Surgery, 52A, 1970, 507-514.

Johnson, J., Skorecki, J. and Wells, R.P.
Peak accelerations of the head experienced in boxing. Medical and Biological Engineering, 13(3), 1975, 396.

Wall, J.C., Chatterji, S. and Jeffery, J.W.
Human femoral cortical bone. A preliminary report on the relationship between strength and density. Medical and Biological Engineering, 10, 1972, 673.