Determination of Mechanical Properties of the Bones of the Skull

Paper is concerned with experimental procedures and results obtained in tension, compression and shear tests carried out on human skull bone

by D. H. Robbins and J. L. Wood

ABSTRACT—This paper presents the initial results of a research project concerning the mechanism of head injury. In order to begin to define the mechanism, it is necessary to determine mechanical properties of the various skull bones, organize them into constitutive equations, and develop a structural model of the skull.

The material presented is concerned primarily with the development of experimental procedures and the results which have been obtained. The specimen-testing program has been split into four parts: (1) The procural of $^3/_4$-in. and $1^1/_2$-in.-diam plugs from human skulls at autopsy and the precise determination of specimen location and orientation; (2) the fabrication and strain gaging of small test specimens for basic tension, compression, tension-compression, and shear tests; (3) the conducting of tests; and (4) the correlation of experimental findings with microscopic structure by standard and nonstandard techniques of histology.

Introduction

A current research project at the Highway Safety Research Institute is concerned with the determination of material properties of the bones of the skull. This is part of an effort with the end objective of fabricating physical and analytical models which can be used to simulate head-injury mechanisms.

Several questions must be considered in developing a program for testing material of this type. What sources are available for obtaining material? How is a material stored which suffers physical and chemical changes with time? How are conventional or nonconventional material test procedures adapted for this material? Do the bones of the skull behave as an isotropic, linear, elastic material and, if not, what properties must be added to the list for consideration?

The published literature does not offer a complete set of answers to these questions. The review sources[1–4] which are concerned in total or in part with the mechanical properties of hard tissues refer only once to tests which have been carried out on the bones of the human skull. Evans and Lissner[5] have reported on the tensile and compressive strengths of embalmed human parietal bone. Dempster[6] has asserted on the basis of split-line analysis that a large portion of the skull possesses a random grain structure.

On the other hand experimental studies of the mechanical properties of other skeletal components have a long history dating back to the early studies of Wertheim[7] and Rauber[8] who used whole bones and pieces of bone, respectively. Most tests have been carried out statically with the exception of the compression tests of Bird[9] and McElhaney[10] where the effect of loading rate was studied. Techniques of histology have been used to study the microstructure of bone in relation to the physical properties by various investigators, some of whom are Dempster,[11, 12] who performed tests parallel and perpendicular to the orientation of the grain structure, Bird,[9] and Ascenzi[13] who has studied the properties of single osteons removed from bone. The only known attempts to define a stress–strain law other than Hookes' Law have been made by McElhaney[14] who proposes linear and logarithmic variations of stress with increasing strain rate and Sedlin[15] who proposes a Kelvin material in series with an elastic spring.

Material Acquisition, Storage and Processing

Before any extensive experimental program could be started, it was necessary to define sources for skull material. It was found that human material

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D. H. Robbins is Research Engineer and J. L. Wood is Graduate Research Assistant, Highway Safety Research Institute, University of Michigan, Ann Arbor, Mich.

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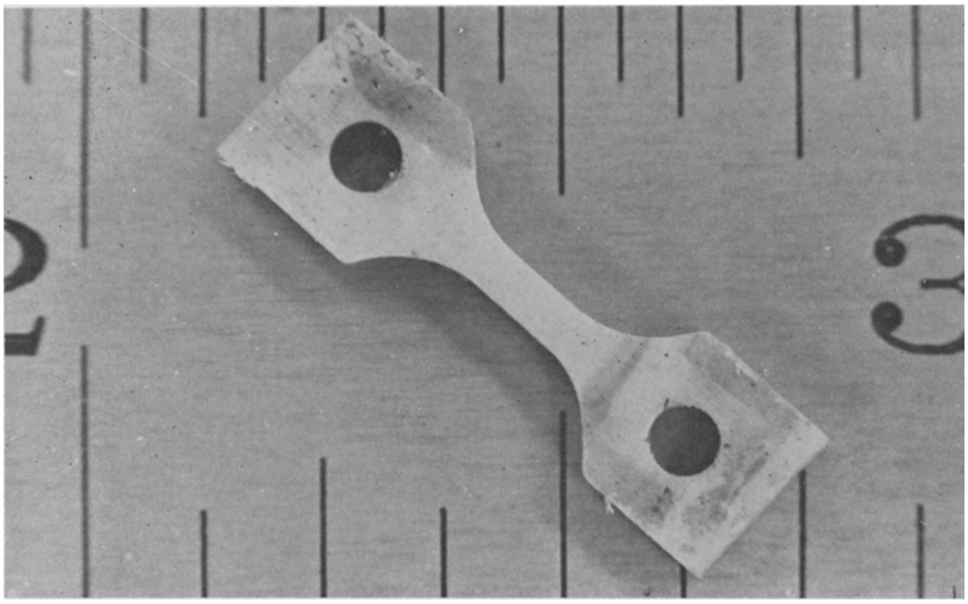

Fig. 1—Tension specimen

was available at hospitals close to the Biomechanics Laboratories. Specimens have been removed at 100 autopsies with a $^3/_4$-in. or a $1^1/_4$-in.-diam Stryker bone plug cutter mounted in a Stryker autopsy saw. As many as four plugs have been taken from a single skull using the smaller cutter. The holes in the frontal bone are filled with dental acrylic. Embalmed skullcaps were available from the Department of Anatomy at the University. These offer a source which is useful in determining regional differences in skull physical properties.

When material is obtained, a complete specimen record is made. The location of a specimen of bone is specified by measuring the distances of the specimen from standard anatomical features such as suture lines. Orientation of a specimen in the skull, posterior–anterior and right–left, is indicated by making a cross directly on the skull before the specimen is removed. In addition, a circular paper spot representing each bone plug is placed on a reference skull kept in the laboratory to serve as a tally and also to indicate locations for future specimens.

Bone specimens are stored in glass vials in a freezer at $-10°$ C to prevent moisture loss. It is felt that enough evidence has become available in research at The University of Michigan and elsewhere to validate this technique for storage.

Tension–Compression Tests

There were multiple objectives in the development of this series of experiments. The first was the design of a tension test which could be conducted statically or dynamically. The results were to be static and dynamic elastic moduli or functional stress–strain relationships and failure stresses. It was necessary that this test could be carried out on the bones of the skull and the component inner and outer tables as well as the spongy diplöe layer. The second objective was development of a specimen and gripping system which would allow compressive as well as tensile forces to be applied to the specimen for the purpose of finding any transition modulus as a loading passes from tension to compression. An experimental design of this type allows cyclic testing and the measurement of hysteresis or energy absorbed by the bone as the loads are applied and released. The third objective of the program was the determination of the relation of the physical properties to the skull anatomy and, further, the relationship of the measured properties to the skull microscopic-structure properties through a series of histological studies.

The specimen and gripping system are shown in Fig. 1. The specimen is roughly $^1/_2$-in. long and the cross-sectional area of the test sections about 2×10^{-3} in.^{2} Small blocks are cut from the autopsy bone plugs, these blanks milled true and, finally, a finished specimen produced by mounting the blank in a template and using the Unimat lathe-mill as a routing table. Heat production is low. The solution to the problem of gripping a specimen for tension, compression, cyclic and dynamic loadings which was adopted involved applying a positive pressure to the specimen tabs as well as pinning the tab ends to prevent the specimen from slipping, bending or breaking in the grips.

In order to measure strain, it was decided that strain gages offered the greatest potential, although it was found that the mounting of gages on these small specimens was difficult. Epoxy-backed foil gages with grid sizes ranging from 0.015 to 0.04 in. have been used. After the gage is aligned and cemented to the bone with Eastman 910 adhesive,

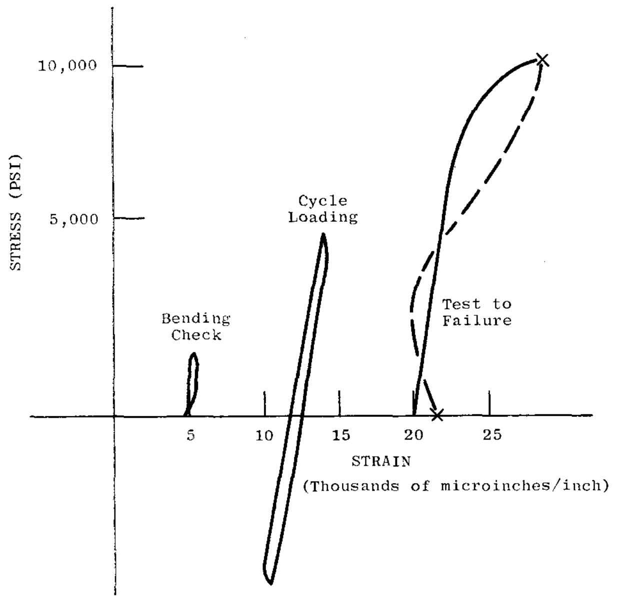

Fig. 2—Stress vs. strain for tension–compression test

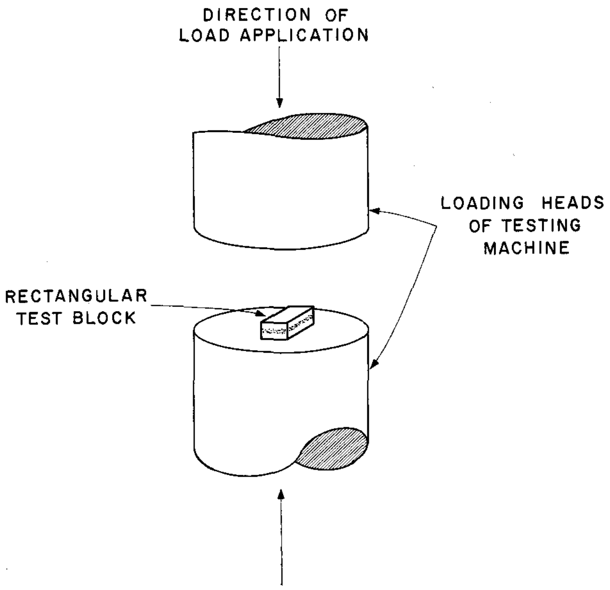

Fig. 3—Compression-test setup

the tabs are tinned and the lead wire is attached. Overheating results in crazing of the cement under the gage, in damage to the bone, and in a failure of the gage to adhere. Microscopic examination of strain-gaged specimens reveals that there is no profusion of the bone with cement.

The testing machines being used are a 10,000-lb-capacity Instron floor-model testing machine with reversible-loading design and a PlasTech testing machine capable of inducing a strain rate of about 5000/sec for specimens of this size. For the static tests, load vs. strain curves are obtained by running the load and strain signals through Honeywell bridge - excitation - balance units into an X-Y recorder. For the limited number of dynamic tests which have been carried out, load, deformation rate and strain are recorded on a storage oscilloscope and photographed.

A drawing of a typical plot of a test is shown in Fig. 2. A series of three tests is actually performed on each specimen. A bending test which is carried out first shows whether the specimen is properly lined up in the gripping system. If alignment is perfect, no strain appears.

The next series of tests involves performing a series of cycles from tension to compression for the purpose of finding energy-absorption properties of bone, tension elastic modulus, compression modulus, and the modulus which exists as loading proceeds from tension to compression and back. It has been found that the hysteresis properties of bone seem to be large, i.e., a relatively large amount of energy is absorbed during cyclic loading from tension to compression.

Finally, the specimens are loaded in tension to failure. The curves seem nearly linear for about two-thirds of the load range indicating that a

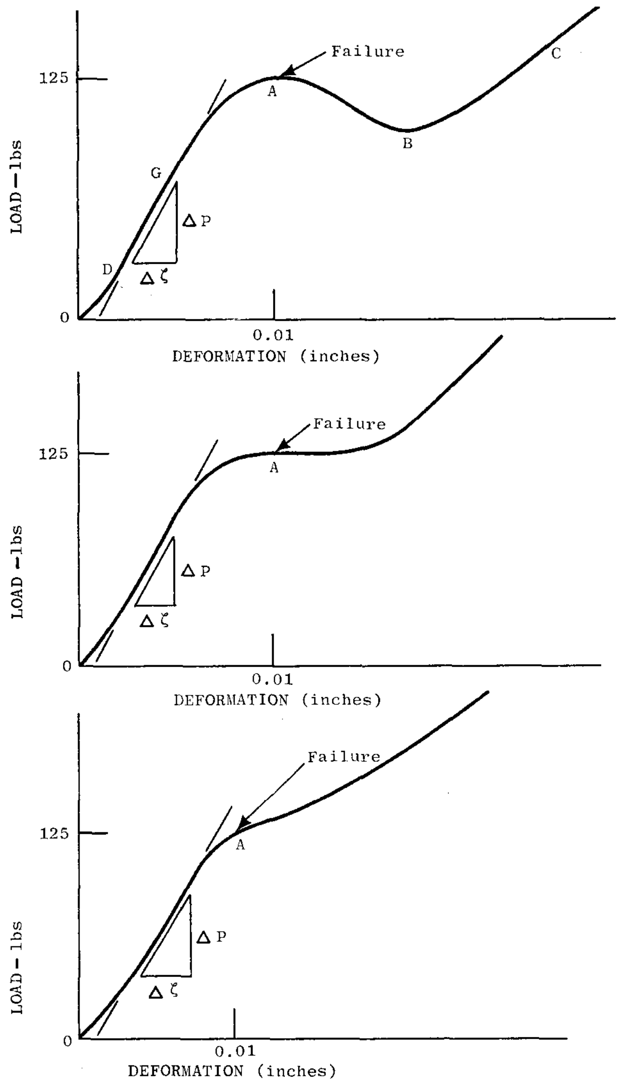

Fig. 4—Load vs. deformation for compression test

Young's modulus defining a linear material is a good approximation in the case of skull bone. Also, it has been noted that bone is a brittle material as there is little yielding or permanent deformation induced before failure. A final property, which is observed when the specimen does not fracture through a strain gage destroying the electrical circuit, is the recovery which takes place in the material when the load is released. The amount of strain induced is large, indicating the viscoelastic behavior of bone. Observations have shown that the bone assumes its initial strain level in about 15 min after the test has concluded.

The average Young's modulus of 2.11 × 10^6 psi and failure stress of 9500 psi are based on about 50 tests and are in line with other published figures for static tests on other types of bone. The fact that the tension-compression loop closes upon itself and that it is linear for a large portion of both the tension and compression sections indicates that tension and compression moduli are the same and that there is a smooth transition when loading passes from tension to compression.

Variations in breaking stress seem to be related to the homogeneity of the bone. Low breaking stresses occur when there is some spongy bone, blood vessels, etc., present to initiate early failure. These same features probably have something to do with the variation in values obtained for the tension modulus. Thus far, no differences in physical properties have been identified which correlate well with the observed osteon directional patterns or with specimen location and orientation in the skull. This is not surprising due to the more random pattern of microstructure found in many parts of the skull.

A few dynamic stress–strain tests have been carried out. Preliminary results indicate that there is a small increase in elastic modulus with no increase in breaking stress which is common for brittle materials.

Structural Compression Tests

The objective of this test series was the determination of the crush failure characteristics of the diplöe layer of the skull and the measurement of an average structural compression modulus of elasticity for rectangular blocks of skull bone. The compressive load was applied to the block in a direction perpendicular to the surface of the skull. A schematic of the test setup is shown in Fig. 3. A series of seventy tests has been carried out to date on bone removed at autopsy and frozen until the test date.

The test specimens were made from bone plugs removed at autopsy by first machining the circular disks flat on a milling machine while using a jig for clamping the specimen. This piece was then sawed into smaller pieces and finished specimens were in the shape of very small blocks with all planes mutually perpendicular to each other. Specimen widths were 0.20 in. or smaller and height varied from 0.16 to 0.23 in.

The testing of the specimens was done on a 10,000-lb capacity Instron floor-model testing machine. The specimens were placed between a compression load cell and the traveling crosshead and the rate of loading adjusted to the desired level. Load was recorded on a strip chart.

The most typical curves obtained are shown in Fig. 4. The first curve was the most frequent. After the specimen was judged to have failed, the test was stopped. There were several criteria for failure. Whenever the curve looked like the portion ABC in Fig. 4, it was inevitable that the specimen had failed cataclysmically. All the failures were in the diplöe. When no cataclysmic failure was observed, then either the failure was indicated by a sharp rise in the loading curve or by a constant horizontal loading curve as shown in the last two drawings in Fig. 4.

A structural modulus was obtained by comparing axial deformation with load. The mean value was 2.02 × 10^5 psi with high and low values being 5.3 × 10^5 psi and 0.104 × 10^5 psi. A range of values this large contrasts greatly with the moduli obtained in the tension–compression tests where the bone was compact. Failure stresses are also much lower indicating the collapse of the weblike structural network of the diplöe layer. The mean value is 5300 psi with high and low values of 15,700 psi and 768 psi.

Shear Tests

The purpose of the shear test is to measure the shear strength of the diplöe in human skull bone when it is subjected to a simple shear force. Embalmed human skullcaps are being used for this test because of ready availability and the desire to determine any regional variation of properties with specimen location in the skull.

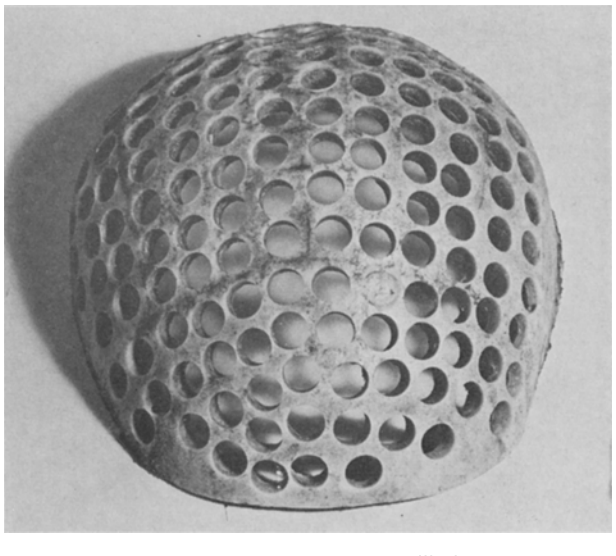

Fig. 5—Skullcap with shear specimens drilled out

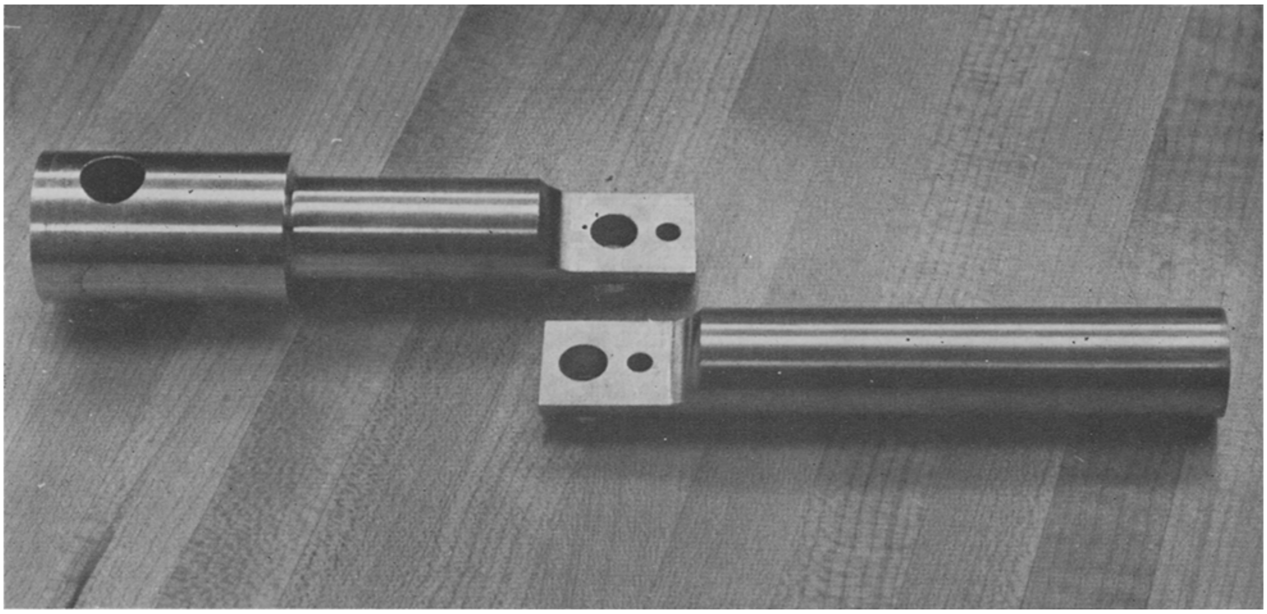

Fig. 6—Shear-test fixture

For each of the three skullcaps used so far, circular plugs are cut using a $^3/_8$-in. bone-plug cutter. Water is generously applied to the blade of the cutter during the drilling procedure to act as a lubricant and to prevent burning of the plug.

A reference system was designed to identify the location of bone plugs removed from the calvarium. This system is an adaptation of McElhaney[16] based on the coronal and sagittal suture lines of the skullcap. A cut skullcap is shown in Fig. 5.

A total of 370 tests have been carried out on the Instron testing machine using the shear grips shown in Fig. 6. The failure load is recorded in order to determine the simple shear-failure stress, the average value of which is 1900 psi. It should be observed that this value is lower than the failure stresses obtained in the compression tests. No clearly defined relation between strength and location or between strength and rate of loading has yet been determined.

Conclusions

Based on the above results, the following conclusions may be drawn:

1. Skullcap compact bone has a static elastic modulus in tension and compression on the average of 2.1×10^6 psi.
2. The breaking stress in tension is about 9500 psi.
3. The large hysteresis loop and the large amount of recoverable strain induced in a specimen stressed to failure points out that skull bone is a highly viscoelastic, brittle material.
4. The nature of the compression test results indicates that the skull can be thought of as a sandwich shell possessing transverse orthotropy, the middle layer being an energy absorber.
5. When the diplöe layer of the skull is subjected to a shearing force, the failure stresses are lower than those developed in tension or compression.

Acknowledgments

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