NIH Head Injury Model Construction Program
Special Report No. 1

RADIAL COMPRESSION TESTING OF A SINGLE HUMAN CALVARIUM

by

J. W. Melvin, Project Engineer

V. L. Roberts, Project Director

23 May 1969

Highway Safety Research Institute
The University of Michigan
Ann Arbor

INTRODUCTION

The work presented in this report was performed at the special request of the NIH Head Injury Model Construction Committee in the form of a letter of instruction dated January 6, 1969 from Eldon L. Eagles, M.D., Acting Associate Director, Collaborative and Field Research, National Institute of Neurological Diseases and Stroke. The required conditions of the test program, although not common practice in the Biomaterials Laboratory, were followed as closely as possible. The requested test protocol was:

1. Specimen: Skull, human cadaver, taken from a male Caucasian as near to age 60 as possible.
2. Test Specifications:
   - Compressive stress test
   - Composite specimens (3 layers intact)
   - Slow or static strain application (0.2 in/in/sec)
   - Test specimen from each point on the West Virginia University fine grid reference system (pp. 26-28, Fig. 1-2; twelve-month progress report).

TEST PROGRAM

An embalmed calvarium was obtained from the University of Michigan Anatomy Department. The calvarium was from a 55-year-old male Caucasian cadaver undergoing dissection in a gross anatomy class. The data on the cadaver and the test time schedule are summarized in Table 1. The calvarium was kept in a sealed plastic bag with moisture present until specimen preparation. The WVU fine grid was laid out on the calvarium (Figure 1) and then specimens were cored out of it at each available grid point (excepting the sutures) using a 3/8 inch diameter Stryker bone saw in a drill press. A simple tubular positioning fixture was employed to insure that the specimen was being taken normal to the surface of the skull (i.e. in the radial direction). The saw was advanced slowly and water was run continuously on the saw to avoid heat build-up in the bone. This procedure provided cylindrical specimens of 0.375 inch diameter with negligible cross-sectional area variation. Simple fixtures were made to clamp the specimens for the final machining step. Each specimen was placed in the fixture with a small amount of the inner or outer table layer of compact bone protruding. The fixture was then placed on the table of a Unimat SL set up as an end mill and the surface of the table material milled just enough to provide a flat surface perpendicular to the sides of the specimen. Both ends of the specimen were machined, thereby producing a finished test specimen in the form of a right circular cylinder of 0.375 inch diameter.

Since the milling operation removed a minimum of table material, each specimen had a different overall height. The next step, then, was to measure and record the overall height of each specimen and also to estimate and record the diploë layer thickness with dial calipers. Each specimen was then placed in individual bottles. Each bottle contained a short section of tygon tubing on which the specimen rested above the bottom of the bottle. A few drops of saline solution were added to each bottle to provide a high humidity atmosphere for the specimen. In a few cases capillary action between the tube and the bottle wall allowed water to contact the specimen. The specimens were then stored for one week at room temperature. Following the one week conditioning period, the specimens were weighed and tested.

The specimens were tested in radial compression using an Instron universal testing machine. A crosshead speed of 2 inches/minute was used to produce strain rates as close to the requested strain rate of 0.2 sec^{-1} as possible. A schematic of the test apparatus is shown in Figure 2. A cantilever strip deflectometer was used to measure the relative motion between the loading anvils, which is equivalent to specimen deflection when the specimen is in contact with both anvils. The load was transduced by a Kistler 937A piezoelectric load cell. The load signal and the deflection signal were both suitably modified by voltage dividers to allow direct recording of stress versus strain on an X-Y recorder, thereby minimizing data reduction time. Since the cross-sectional areas of all the specimens were the same, a single adjustment to electrically divide the load signal by the area was necessary to produce a stress output. However, each specimen had a different height and therefore each test required an adjustment in the deflection signal to electrically divide it by the specimen height to produce a strain output. This adjustment was done on a dial readout ten-turn potentiometer. To facilitate testing, the bottles of specimens were grouped according to height range in increments of 0.01 inches. The resulting group distribution is shown in Figure 3 and is effectively a specimen height distribution curve. Note that not all the specimen bottles are present in Figure 3 but the black capped bottles in those rows were moved up to indicate the total population at each interval.

Typical test results are shown in Figures 4 and 5. In all cases, the modulus of the elasticity of the specimen was taken to be the slope of the steep linear region of the curve prior to specimen crushing. The failure stress was read off the stress-strain curve directly in the case of specimens which exhibited a zero slope region during crushing as shown in Figure 4. In the case of a positive non-zero slope during crushing as shown in Figure 5, an offset method was used. In this method a line is drawn parallel to the linear modulus region but offset to the right by 2% strain. The intersection of the stress-strain curve and the offset line was taken to be the failure stress.

TEST RESULTS

A total of 143 tests were performed on embalmed human skull bone composite specimens subjected to radial compression. The complete summary of this data is in Table 2. Accompanying the fifteen copies of this report are five copies of an appendix containing all the stress-strain curves generated by this special test program. Figures 6 and 7 show the failure stress values and the modulus of elasticity values displayed on the fine grid position system. In addition to this form of data presentation an in-house computer program was used to produce a simulated three-dimensional display of diploë thickness, failure stress and modulus of elasticity as functions of skull position. These plots are shown in Figures 8, 9, and 10 respectively.

ACKNOWLEDGMENTS

The authors of this report wish to acknowledge the participation and assistance of the following persons in carrying out the work presented in this report: R. Hubbard, P. Fuller, S. Fisher, and J. Wood. The preparation of this report was aided by C. Shinn, C. Weston, S. Stewart, and P. Van Luven.

TABLE I

TEST SPECIMEN DATA AND TEST SCHEDULE

Calvarium Data:

Age:	55 years
Sex:	Male
Race:	Caucasian
Cause of Death:	Malnutrition and G. I. Bleeding
Date of Death:	10/19/68
Date of Embalming:	10/21/68

Test Time Schedule:

1. Calvarium obtained from cadaver bag 4/14/69.
2. Grid lay-out on calvarium.
3. Specimens cored from calvarium 4/25/69.
4. Specimens machined for parallel sides, height measured and inserted into moisture bottles.
5. Specimens allowed to equilibrate under high humidity conditions.
6. Began weighing and testing specimens 5/5/69.
7. Finished weighing and testing specimens 5/6/69.

TABLE II

EMBALMED SKULL RADIAL COMPRESSION TEST

All Specimens 0.375 Inch Diameter

Specimen Location	Specimen Height Inches	Diploë Thickness inches	Specimen Weight grams	Modulus of Elasticity 10^5 lb/in^2	Failure Stress 10^3 lb/in^2
A- 2	.250	.105	.833	5.85	10.50
6	.270	.125	-	5.20	7.35
9	.270	.125	.942	4.98	10.00
10	.195	.120	.632	4.50	8.00
11	.190	.120	.594	3.52	5.92
12	.175	.070	.559	-	-
13	.255	.145	.778	3.45	6.20
14	.200	.160	.831	4.50	5.92
15	.320	.190	.879	2.12	4.77
16	.325	.165	.946	3.90	5.00
17	.335	.240	.968	3.20	5.50
18	.335	.170	.999	4.85	6.50
24	.350	.190	1.075	4.20	6.45
25	.310	.170	.974	4.78	7.70
26	.305	.160	.849	3.80	5.70
27	.320	.160	.967	3.00	5.40
28	.225	.110	.655	2.60	5.90
29	.240	.110	.686	3.20	6.30
30	.235	.125	.662	1.20	5.50
31	.240	.135	.725	3.70	6.30
32	.180	.080	.569	2.18	8.90
33	.260	.130	.795	2.45	7.22
B- 2	.335	.175	1.041	2.68	3.70
4	.285	.165	-	3.65	4.35
6	.285	.160	-	2.80	3.55
9	.310	.180	.903	2.62	4.05
10	.235	.140	.709	1.55	5.30
11	.200	.115	.593	3.10	6.25
12	.230	.130	.671	2.50	5.50
13	.265	.160	.777	3.30	6.10

Specimen Location	Specimen Height Inches	Diploë Thickness inches	Specimen Weight grams	Modulus of Elasticity 10^5 lb/in^2	Failure Stress 10^3 lb/in^2
14	.265	.145	.787	2.60	6.55
15	.275	.130	.801	2.95	5.95
16	.280	.130	.842	2.55	5.22
17	.280	.160	.847	2.90	6.20
18	.245	.125	.742	4.60	6.51
24	.305	.160	.939	3.48	6.32
25	.285	.175	.881	3.62	6.10
26	.295	.170	.898	3.58	5.40
27	.300	.160	.895	3.50	4.65
28	.285	.155	.861	2.82	5.75
29	.265	.150	.811	3.28	5.90
30	.265	.170	.763	3.20	5.00
31	.250	.130	.744	1.20	4.60
32	.225	.125	.667	2.52	6.10
33	.275	.120	.812	3.33	4.85
C- 1	.350	.200	1.033	3.35	3.80
2	.350	.185	1.016	2.75	3.25
3	.285	.135	-	3.50	4.55
4	.280	.125	-	4.40	4.65
5	.285	.130	-	2.25	3.40
6	.305	.170	-	1.65	3.00
7	.330	.180	-	2.50	3.30
9	.315	.180	.941	3.00	3.95
10	.305	.185	.848	3.18	4.50
11	.310	.190	.912	2.20	3.60
12	.275	.185	.795	2.10	4.00
13	.270	.180	.780	2.40	4.55
14	.275	.155	.789	2.52	3.50
15	.280	.160	.776	2.50	3.90
16	.280	.165	.773	2.26	3.70
17	.240	.150	.702	3.10	6.10
25	.265	.165	.783	3.05	6.00
26	.270	.175	.753	-	-
27	.290	.180	.868	2.70	4.60
28	.270	.170	.804	-	-

Specimen Location	Specimen Height Inches	Diploë Thickness inches	Specimen Weight grams	Modulus of Elasticity 10^5 lb/in^2	Failure Stress 10^3 lb/in^2
29	.255	.165	.739	3.50	4.70
30	.255	.135	.712	2.98	4.95
31	.280	.160	.798	2.40	4.50
32	.295	.165	.839	3.40	4.90
33	.300	.155	.892	2.90	4.10
D- 1	.345	.205	.951	2.30	3.20
2	.325	.175	.936	1.52	3.98
3	.285	.175	-	2.50	3.42
4	.255	.135	-	2.80	4.30
5	.315	.165	-	3.00	3.50
6	.345	.205	-	2.20	3.45
7	.370	.210	-	2.32	2.90
9	.285	.175	.821	2.70	4.50
10	.255	.185	.748	2.50	4.30
11	.270	.180	.745	2.15	3.60
12	.240	.190	.690	2.42	5.30
13	.260	.190	.717	1.75	3.25
14	.260	.185	.681	2.40	3.38
15	.285	.170	.753	2.48	3.78
16	.250	.125	.710	3.20	5.62
26	.280	.170	.830	3.05	5.60
27	.250	.160	.714	2.55	4.60
28	.235	.130	.640	1.90	3.50
29	.230	.135	.629	2.50	4.00
30	.235	.150	.656	3.10	5.02
31	.280	.200	.729	1.85	3.30
32	.310	.180	.890	3.28	4.25
33	.280	.180	.738	2.00	3.00
E- 1	.323	.200	-	2.45	3.10
2	.365	.230	1.013	1.35	3.02
3	.315	.200	-	2.30	3.35
4	.250	.140	-	3.35	4.05
5	.285	.170	-	2.10	3.22
6	.325	.210	-	2.20	3.15

Specimen Location	Specimen Height Inches	Diploë Thickness inches	Specimen Weight grams	Modulus of Elasticity 10^5 lb/in^2	Failure Stress 10^3 lb/in^2
7	.330	.255	-	1.50	2.61
9	.245	.130	.680	2.40	4.75
10	.265	.170	.725	2.40	5.02
11	.210	.150	.567	2.15	4.35
12	.200	.105	.550	1.50	4.60
13	.190	.125	.512	1.45	3.75
14	.205	.120	.558	1.62	3.90
15	.215	.135	.635	3.25	5.85
27	.215	.130	.649	3.18	6.34
28	.205	.130	.539	-	-
29	.210	.160	.517	1.00	2.90
30	.210	.150	.548	1.50	3.15
31	.230	.130	.628	2.10	5.10
32	.275	.195	.788	3.05	4.68
33	.285	.195	.712	1.85	3.25
F- 9	.240	.130	.698	2.60	4.25
10	.250	.150	.733	1.72	5.20
11	.240	.145	.708	2.68	5.00
12	.195	.140	.535	2.15	4.20
13	.185	.135	.500	0.91	3.32
14	.185	.120	.521	2.25	4.40
28	.185	.100	.521	2.30	4.40
29	.185	.110	.514	1.15	3.05
30	.185	.130	.507	1.80	3.85
31	.210	.135	.621	1.35	5.10
32	.250	.160	.740	2.95	4.90
33	.280	.200	.748	2.50	3.20
G- 9	.235	.135	.652	2.80	4.90
10	.210	.115	.655	3.40	8.00
11	.210	.150	.607	-	-
12	.210	.095	.598	1.48	3.45
13	.185	.105	.540	2.25	4.22
14	.190	.95	.594	2.40	6.30
28	.205	.115	.609	2.45	5.83

Specimen Location	Specimen Height Inches	Diploë Thickness inches	Specimen Weight grams	Modulus of Elasticity 10^5 lb/in^2	Failure Stress 10^3 lb/in^2
29	.140	.120	.550	1.15	3.80
30	.200	.140	.548	0.98	3.25
31	.170	.100	.487	1.75	4.70
32	.215	.130	.646	2.30	6.58
33	.245	.205	.764	1.93	3.60
H- 9	.210	.115	.608	2.30	5.70
10	.185	.075	.681	3.35	6.90
11	.180	.110	.604	1.75	6.00
12	.235	.110	.713	2.08	4.75
13	.240	.140	.724	2.75	4.92
29	.215	.110	.624	1.85	4.97
30	.265	.135	.736	2.05	4.20
31	.220	.145	.602	1.66	3.54
32	.190	.105	.569	2.85	5.62
33	.315	.180	.846	1.88	2.82

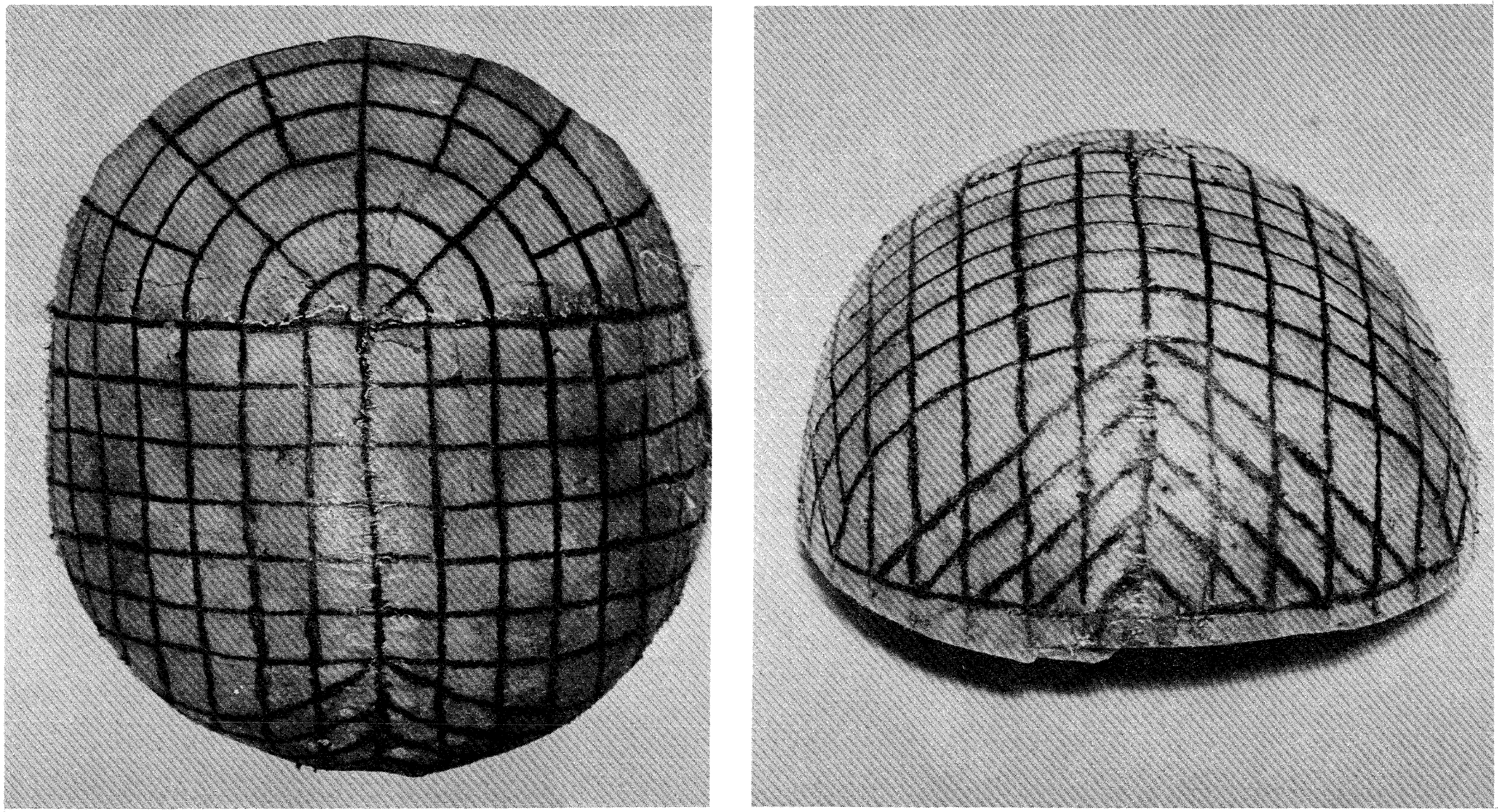


Figure 1. Fine Grid Reference System Lay-out on Skull.

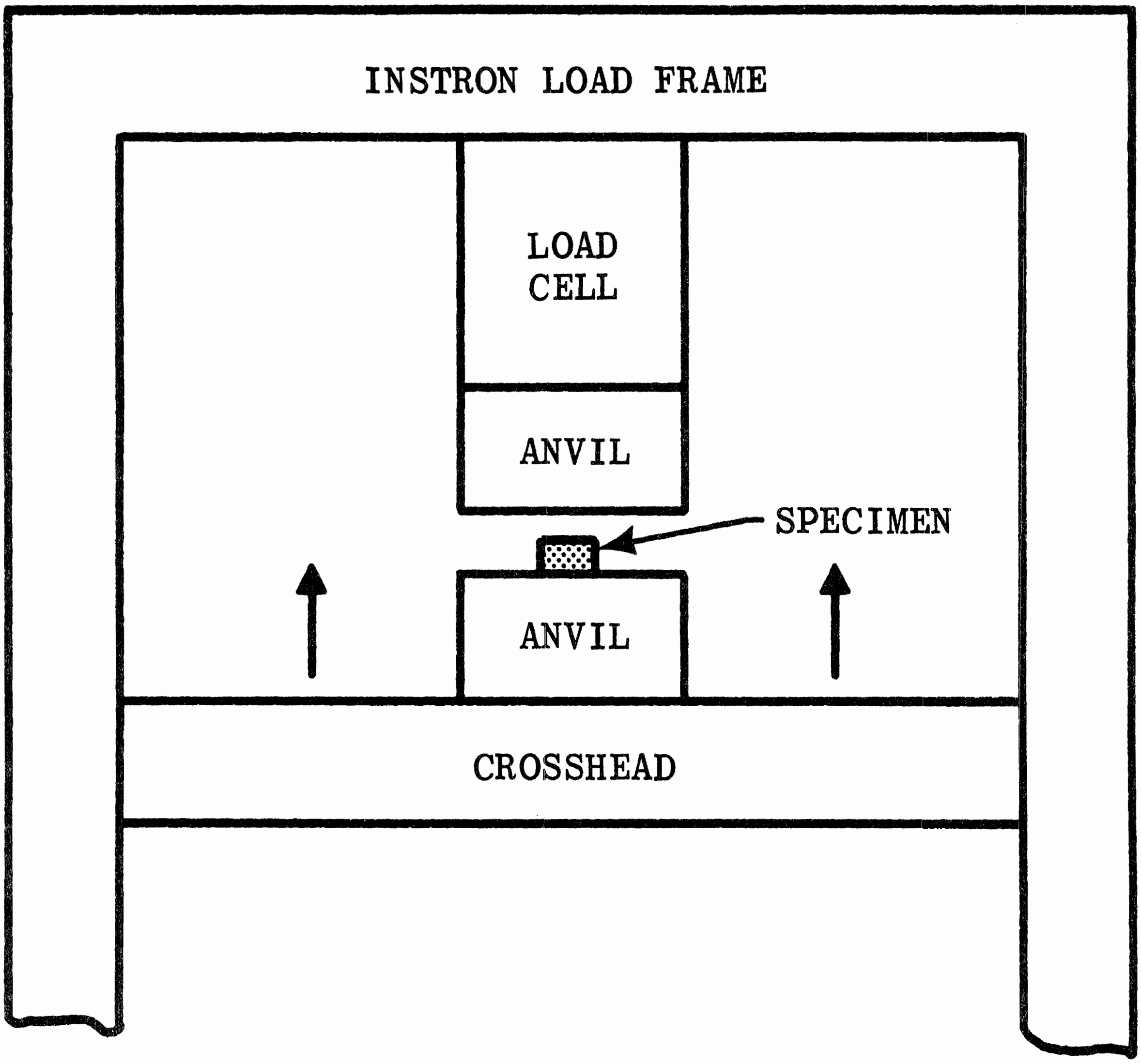


Figure 2. Schematic of Testing Configuration.

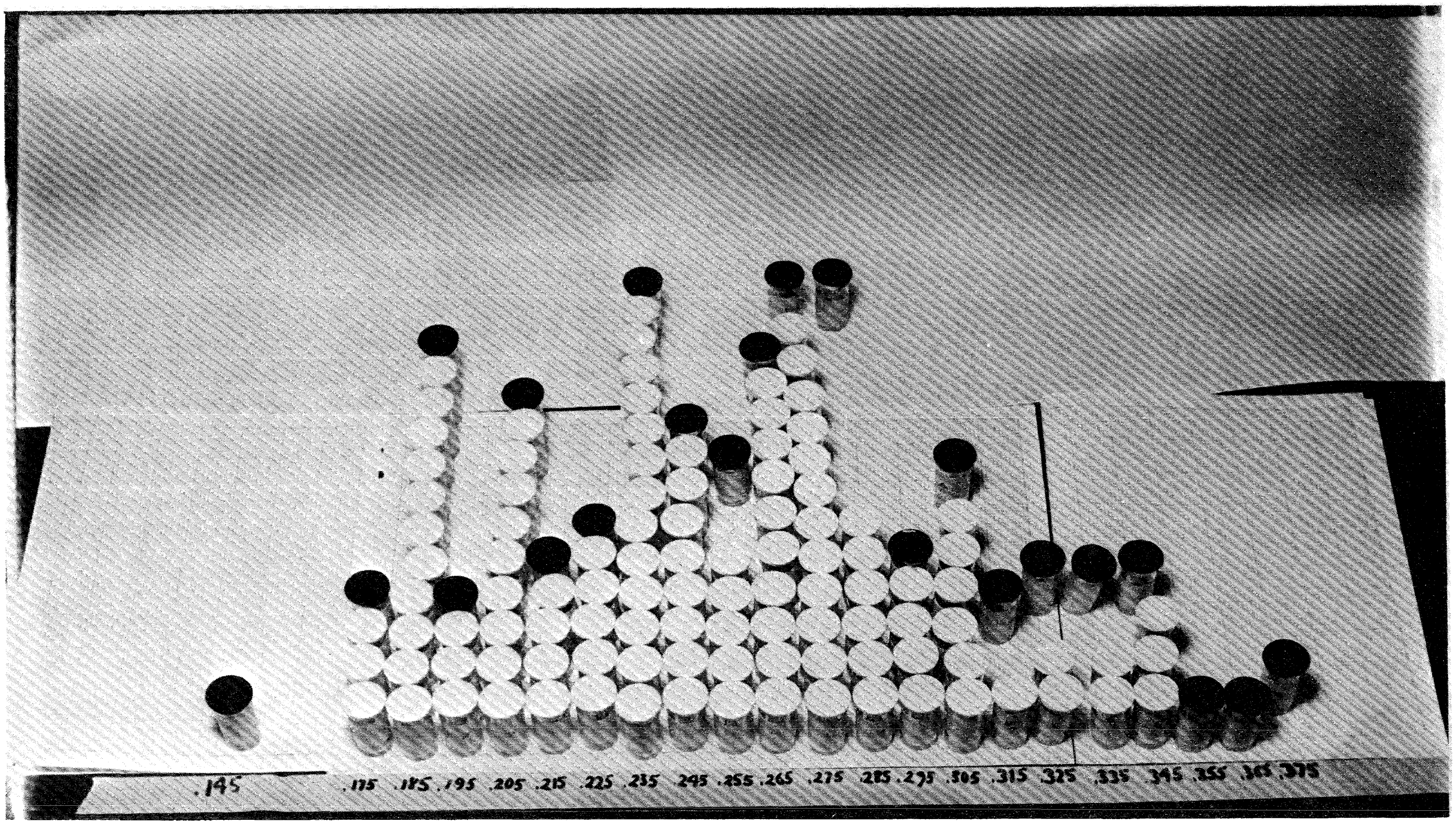


Figure 3. Test Specimen Storage Bottles Grouped According to Specimen Height Ranges.

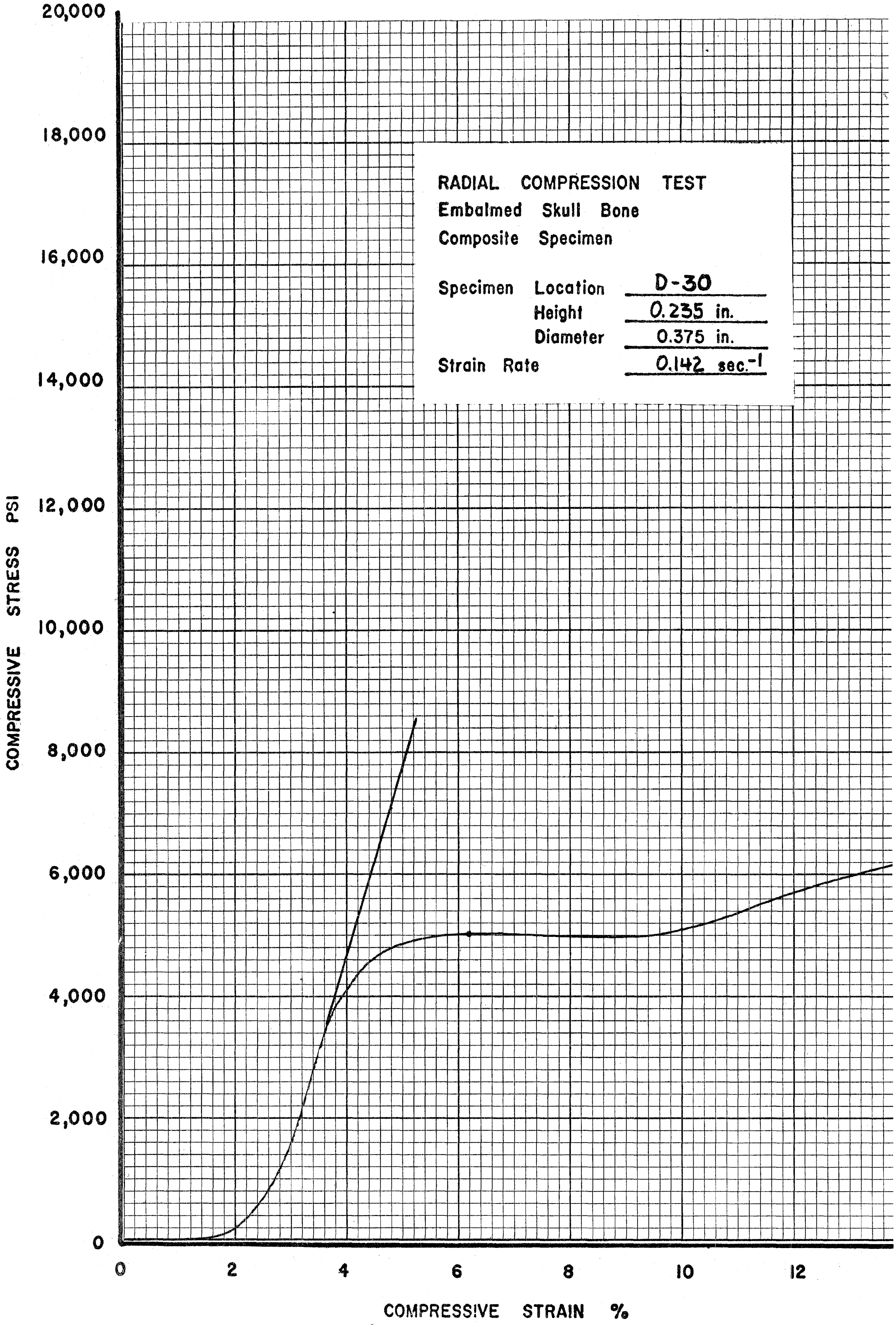


Figure 4. Typical Compressive Stress-Strain Curve Exhibiting Zero Slope Crushing Failure.

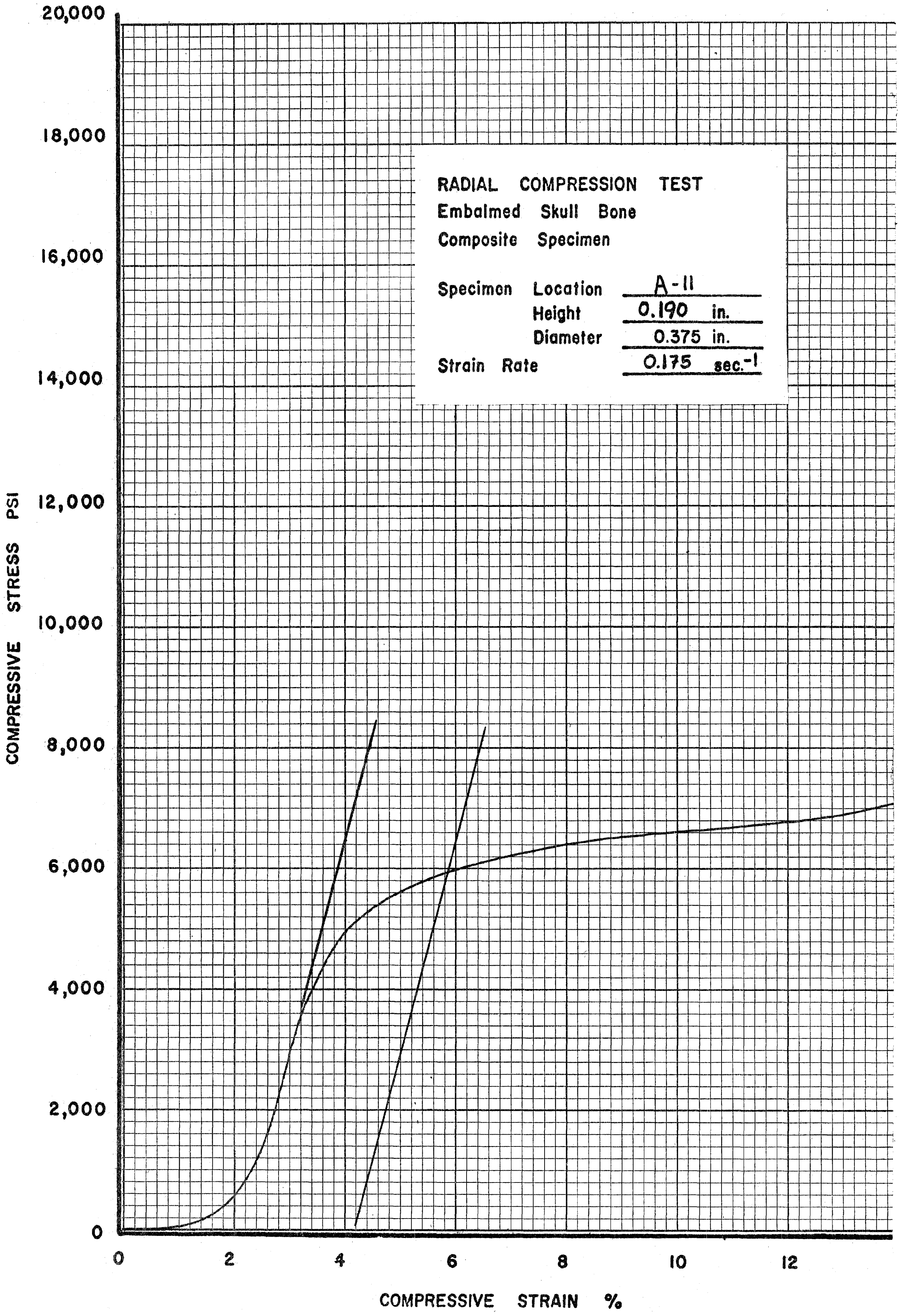


Figure 5. Typical Compressive Stress-Strain Curve Requiring a 2% Offset to Determine the Failure Stress.

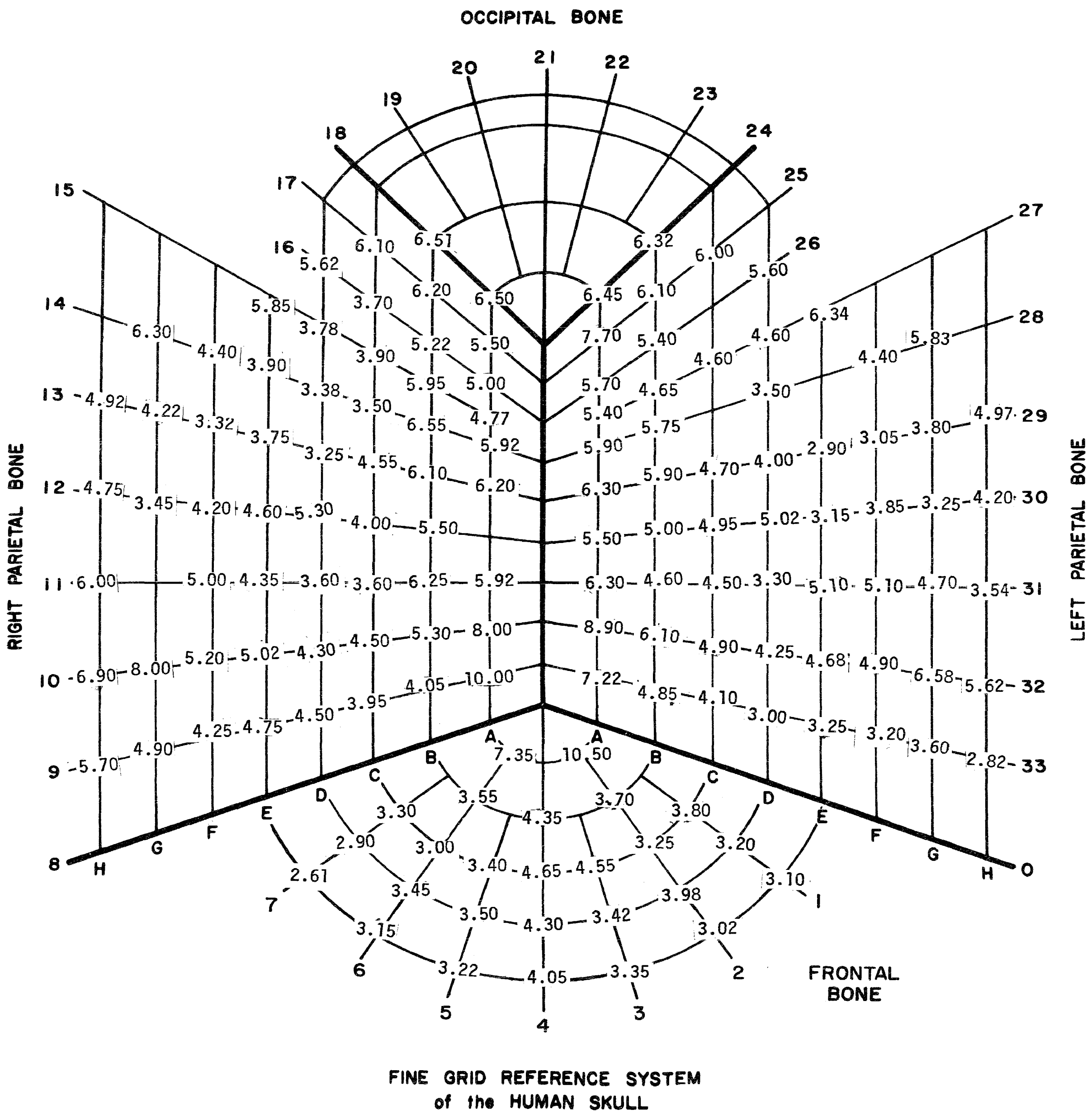
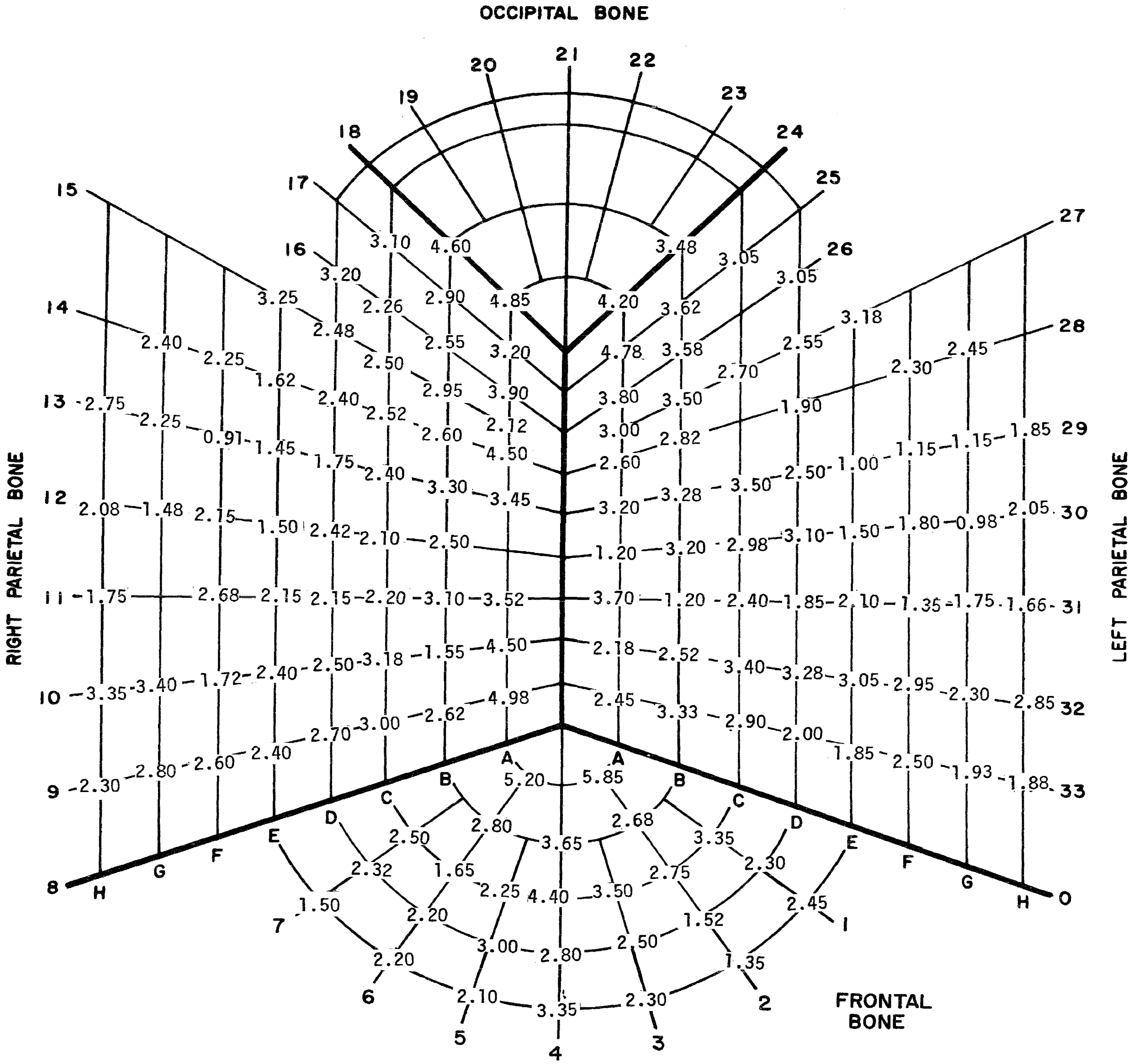
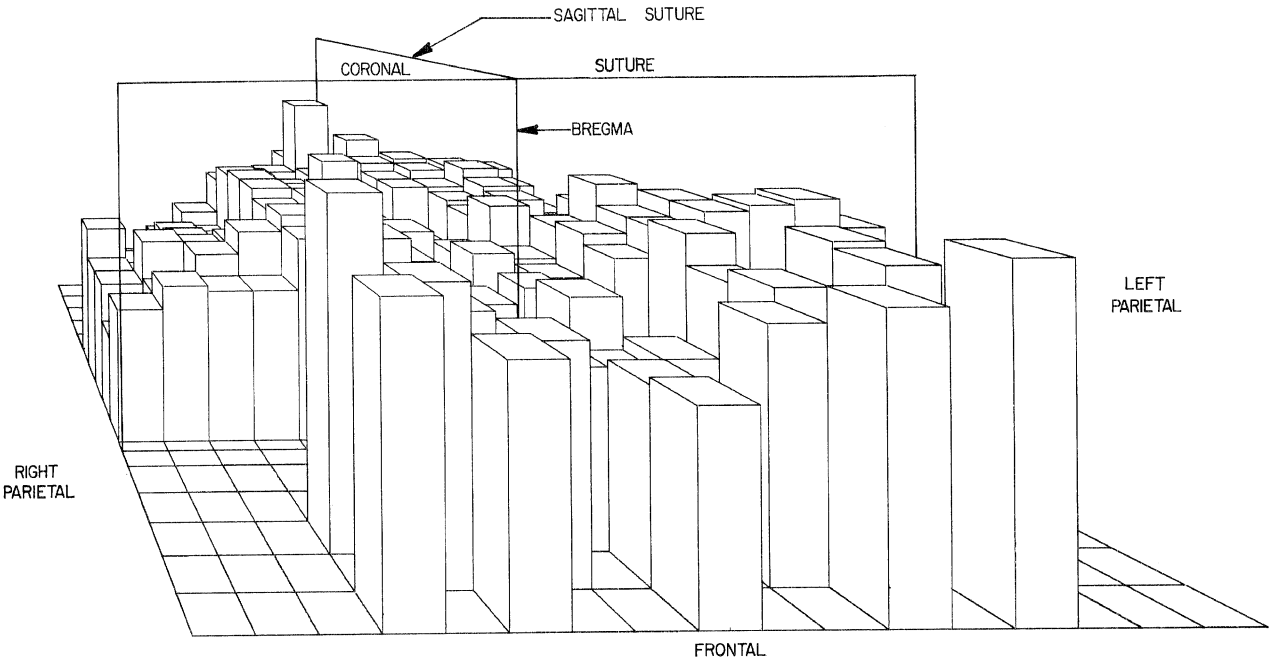


Figure 6. Compressive Failure Stress in 10^3 psi units Displayed on the Fine Grid System.

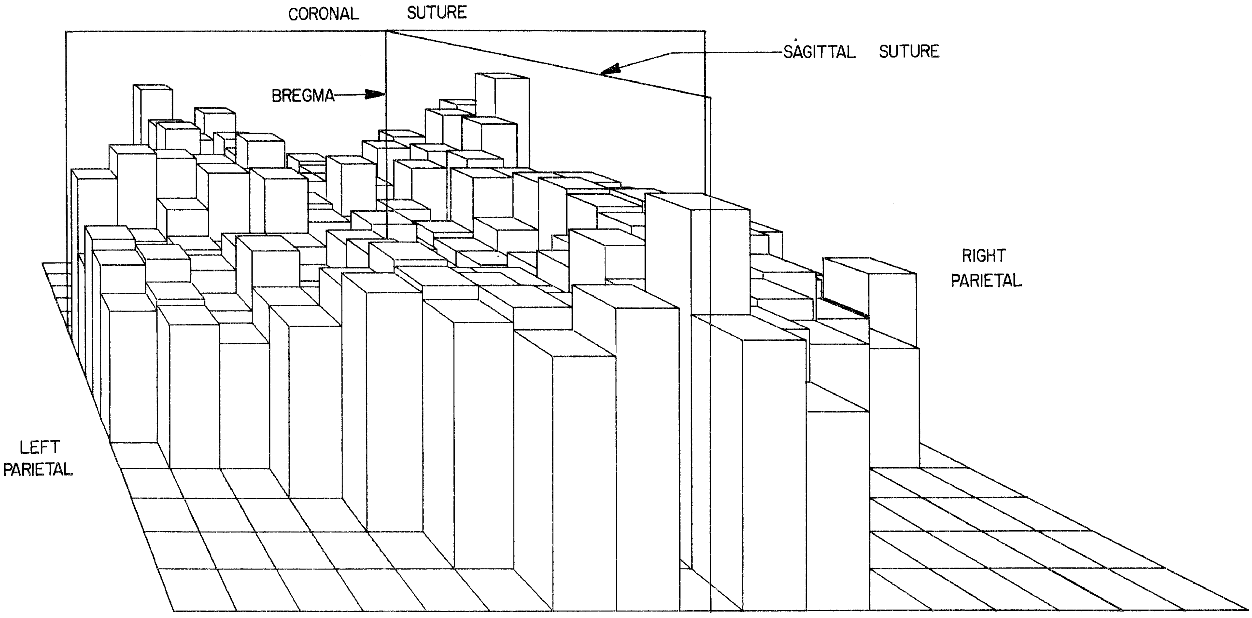


FINE GRID REFERENCE SYSTEM
of the HUMAN SKULL

Figure 7. Compressive Modulus of Elasticity in 10^5 psi units Displayed on the Fine Grid System.



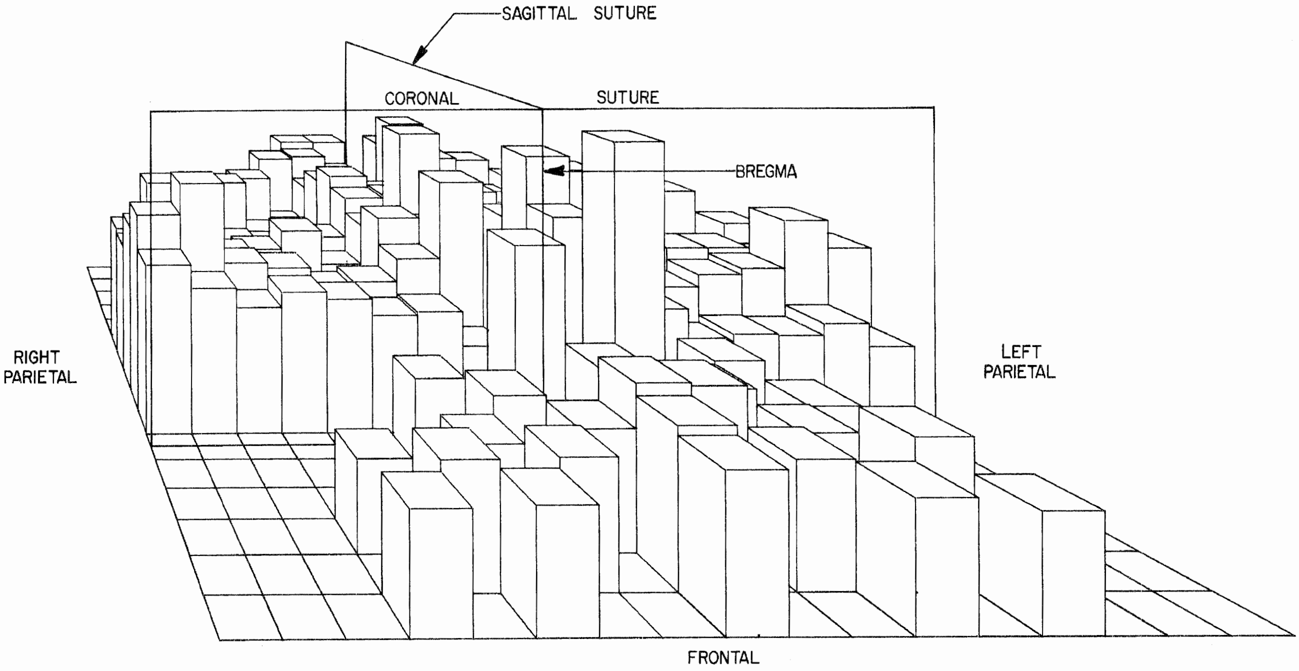
FRONT VIEW



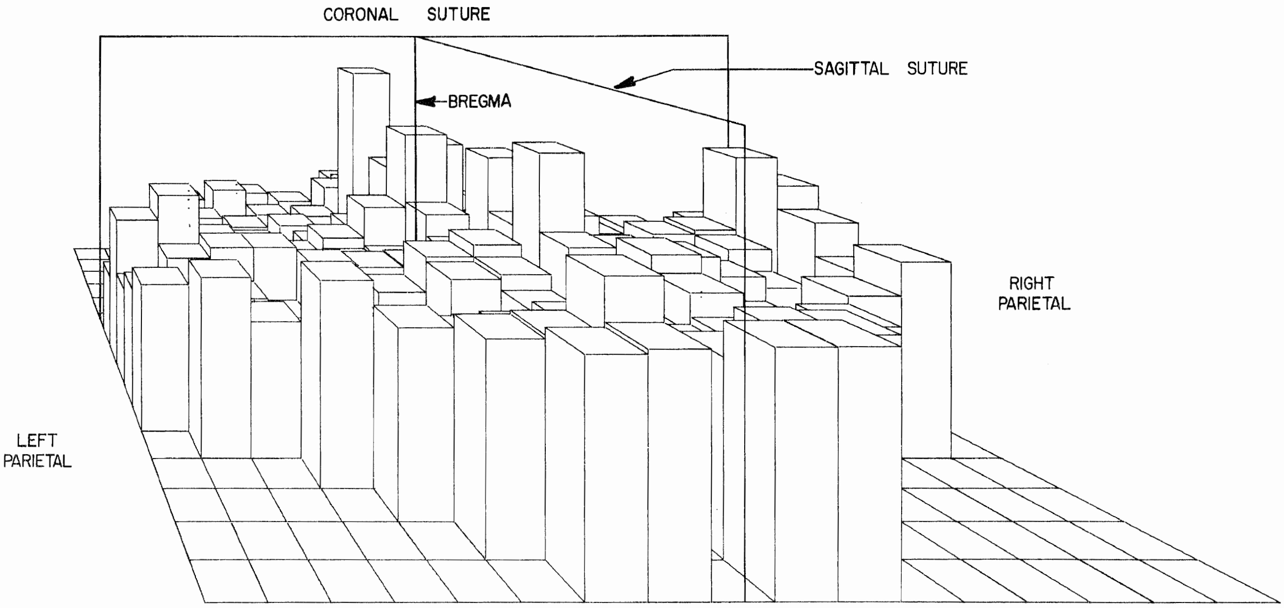
REAR VIEW

3-D DIPLOË THICKNESS

Figure 8. 3-D Representation of Diploë Layer Thickness as a Function of Grid Position.



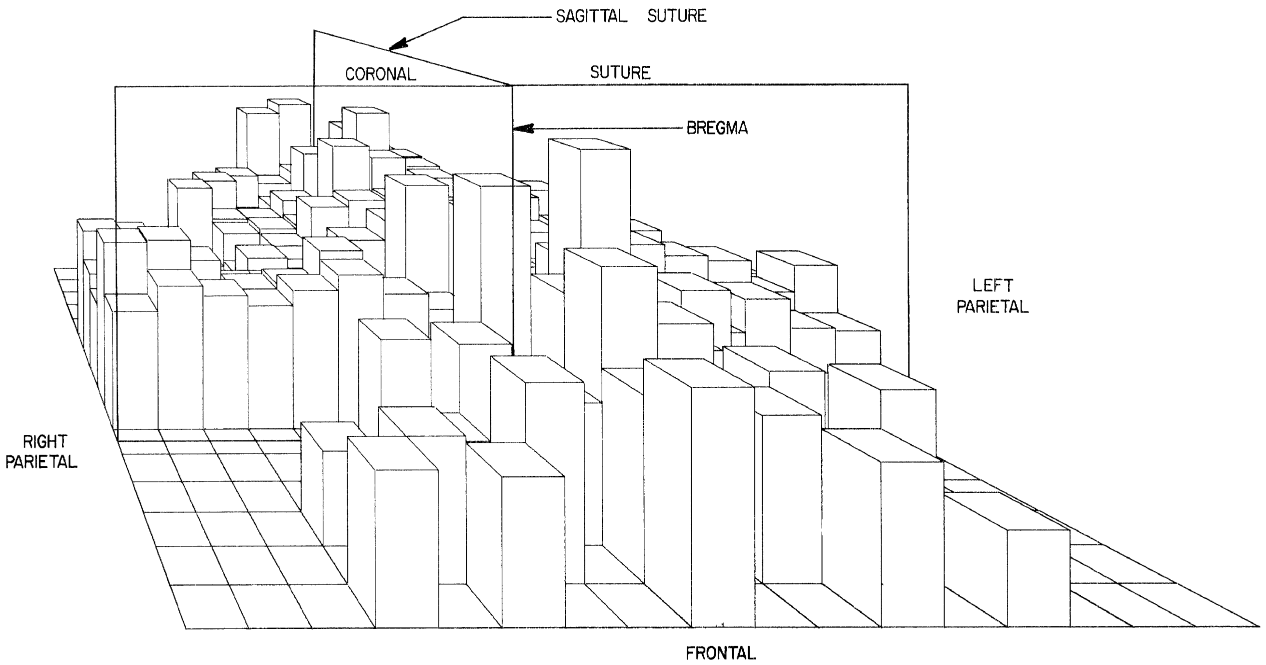
FRONT VIEW



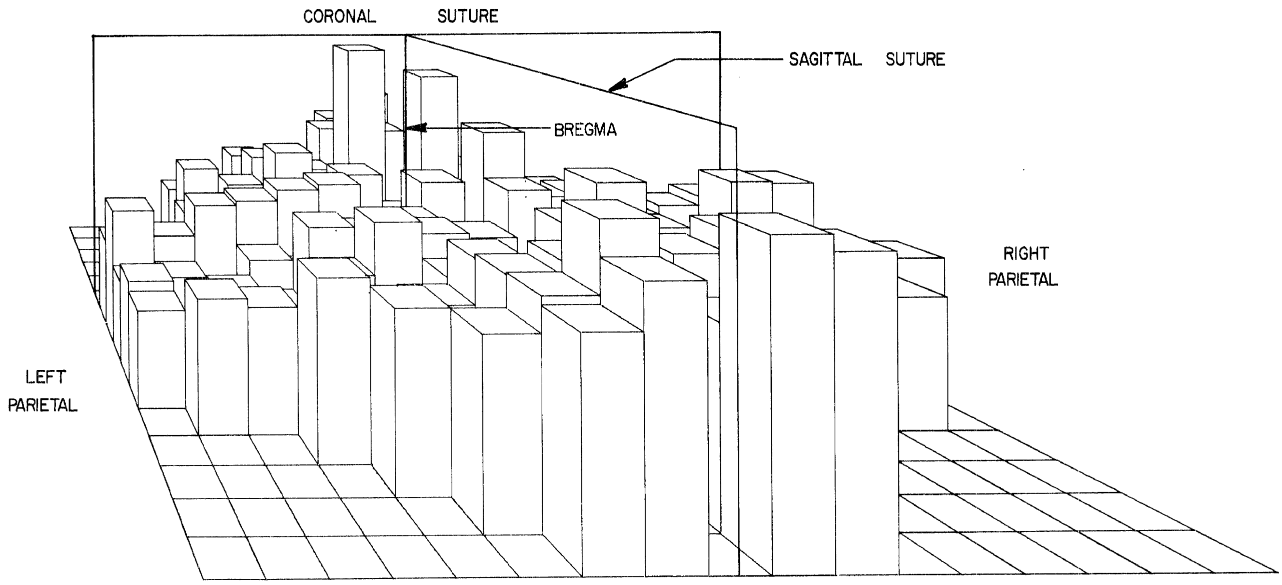
REAR VIEW

3-D FAILURE STRESS

Figure 9. 3-D Representation of Compressive Failure Stress as a Function of Grid Position.



FRONT VIEW



REAR VIEW

3-D MODULUS of ELASTICITY

Figure 10. 3-D Representation of Compressive Modulus of Elasticity as a Function of Grid Position.