DEFORMATION MEASURING SYSTEM FOR REPETITIVELY LOADED, LARGE DIAMETER SPECIMENS OF GRANULAR MATERIAL

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Research Report Number 99-4
Stress Distribution in Granular Masses
Research Study Number 2-8-66-99

Sponsored by

The Texas Highway Department
In Cooperation with the
U. S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

August, 1969

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

PREFACE

This is the fourth report issued under Research Study 2-8-66-99, Stress Distribution in Granular Masses, being conducted at the Texas Transportation Institute as part of the cooperative research program with the Texas Highway Department and U. S. Bureau of Public Roads.

The first three reports are:

"The Use of Particulate Mechanics in the Simulation of Stress-Strain Characteristics of Granular Materials," by James C. Armstrong and Wayne A. Dunlap, Research Report 99-1, Texas Transportation Institute, August, 1966.

"A Gyratory Compactor for Molding Large Diameter Triaxial Specimens of Granular Materials," by Lionel J. Milberger and Wayne A. Dunlap, Research Report 99-2, Texas Transportation Institute, October, 1966.

"Evaluation of the TTI Gyratory Compactor," by William M. Moore and Lionel J. Milberger, Research Report 99-3, Texas Transportation Institute, February, 1968.

The authors wish to thank all members of the Institute who assisted in this research. They would like to express special appreciation to Mr. Frank H. Scrivner whose advice and assistance throughout the study were particularly valuable. Special gratitude is also expressed to Mr. Ronnie Surovik for his assistance in the development of data reduction techniques, Messers. C. H. Michalak and Rudell Poehl for their assistance in data reduction and report preparation, and Mr. Gene Schlieker for his assistance during the test phase.

Thanks are also expressed to Mr. Kelsey Martin of Martin Research Associates for his initial concepts of the optical tracker used in this research and his advice and assistance in developing operational techniques to adapt the instrument to our research problem.

The authors also wish to thank Mr. James L. Brown, the Texas Highway Department Study Contact Representative, for his assistance and support in this research.

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

ABSTRACT

This report describes the design and evaluation of a deformation measurement system developed to observe the vertical and horizontal displacements of points on the surface of large diameter cylindrical specimens of granular material subjected to rapid, repeated load applications.

The system consists of a loading apparatus, triaxial cell, measurement transducers (including a newly developed optical tracker), and recording apparatus.

Because preliminary measurements made on specimens of granular materials were quite different than had been expected, a general evaluation of the system was undertaken. The evaluation was accomplished by loading 4 inch diameter by 8 inch high Lexan plastic cylinders and comparing specimen deformations, as measured with the entire system, against strain gage indications. The system was found to give satisfactory agreement with the known and observable characteristics of the plastic material, and it was concluded that the system would provide useful and valid deformation data on specimens of granular material.

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1. INTRODUCTION

Currently it is impossible to estimate, with any degree of confidence, the stresses and strains existing in granular type soils subjected to real loading conditions, for example, a moving wheel load over a gravel roadway. This conclusion is reached from laboratory studies made by numerous researchers into the peculiar behavior of these materials. So long as their behavior is not completely understood and until it can be represented by mathematical formulas of proven reliability, engineers will remain in ignorance of the internal stresses acting in these materials. The design of structures composed of these materials will continue to be based upon empiricism until this can be replaced by methods built upon fundamentally sound theoretical principles.

This paper describes a measurement system designed as an aid in determining the load-deformation characteristics of granular type soils subjected to both hydrostatic and uni-axial, dynamically applied, compressive loadings. Cylindrical test specimens, 6 inches in diameter by 8 inches high, are loaded hydrostatically from 10 to 30 psi in a pressure chamber (triaxial cell) with transparent walls, and loaded dynamically along the cylinder axis from 0 to 35 psi. The dynamic load is normally applied during a 0.2 second time interval and is repeated every 2 seconds. Permanent and dynamic deformations are observed at numerous points on the specimen to define the radial and axial deformations of the cylinder's surface.

Examination of the capabilities and limitations of existing motion sensors for this application indicated the need for a better non-contacting transducer. The prototype of a newly developed electro-optical transducer was obtained for use in the system. This transducer, an electro-optical displacement tracker developed by Martin Research Associates, Inc., senses the position of a small reflective target and resolves motion by supplying continuous electrical signals proportional to the X and Y components of the target displacement. Its resolution, for a 0.30 inch square target at 10 inch working distance, is below .000040 inch over a range of .070 inches, with response time of the order of 10 microseconds and stability better than .000040 inches per hour.

2. TEST EQUIPMENT

The test equipment consists of four basic components: (1) an apparatus for applying a repetitive load, (2) a triaxial cell, (3) an optical deformation measurement system, and (4) a recording system. These are described below.

1. Repetitive Loading Apparatus - The basic loading apparatus is the same as reported in Research Report 27-3 (1)* except that the loading station was constructed with its base embedded in concrete to provide a stable platform to minimize interference from vibrations. (See Figure 1). The apparatus was adjusted to provide a repetitive impulsive load of 0 to 35 psi to the specimen during 0.2 second. The impulsive load was repeated every 2 seconds. The load on the specimen is measured by a strain gaged cylindrical load cell incorporated between the hydraulic load piston and the triaxial cell loading rod. (See Figure 2).

2. Triaxial Cell - The triaxial cell follows conventional design and is the same as reported in Research Report 27-3 (1) except that the round lucite chamber was replaced with a specially fabricated square chamber to minimize optical path distortions. (See Figure 3). At the top of the triaxial cell is a strain gaged cantilever beam displacement transducer which measures the movement of the loading rod with respect to the top of the cell. (See Figure 4). The displacement measured by this transducer has been assumed in the past to represent the compression of the test specimen.

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*Numbers shown in parenthesis and underlined refer to reference numbers in Section 6.

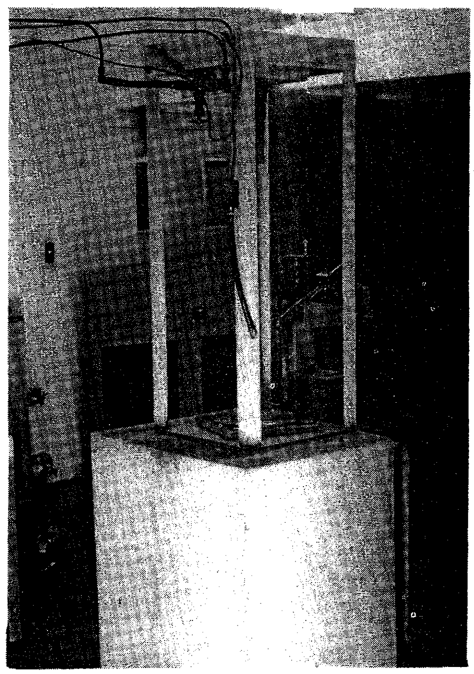

FIGURE 1 - The loading station used for the measurements is embedded in about 2200 pounds of concrete.

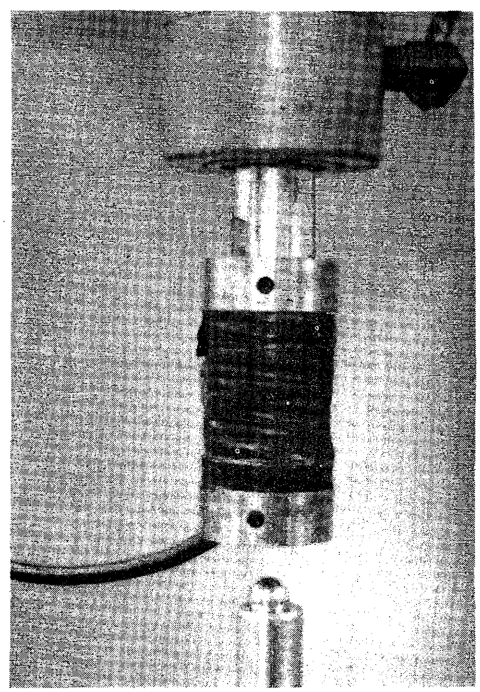

FIGURE 2 - The load cell is attached to the end of the hydraulic load piston.

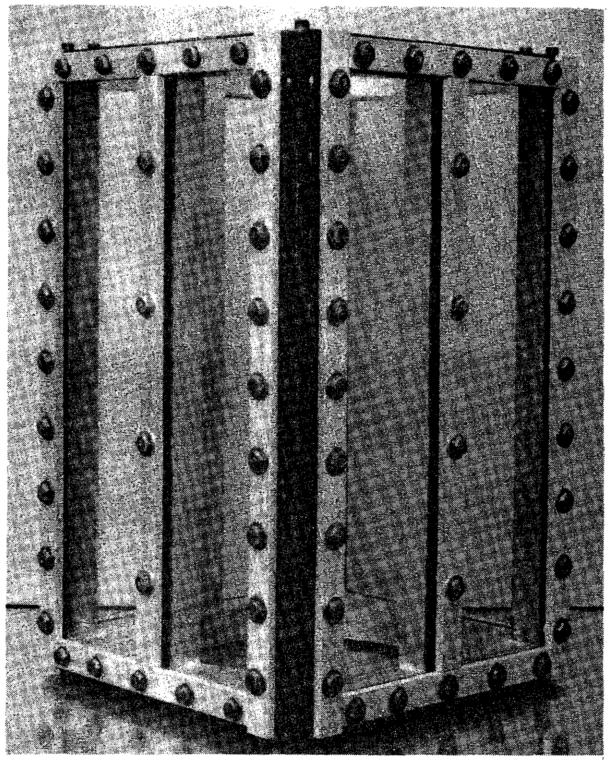

FIGURE 3 - A square triaxial cell was fabricated to minimize optical path distortions.

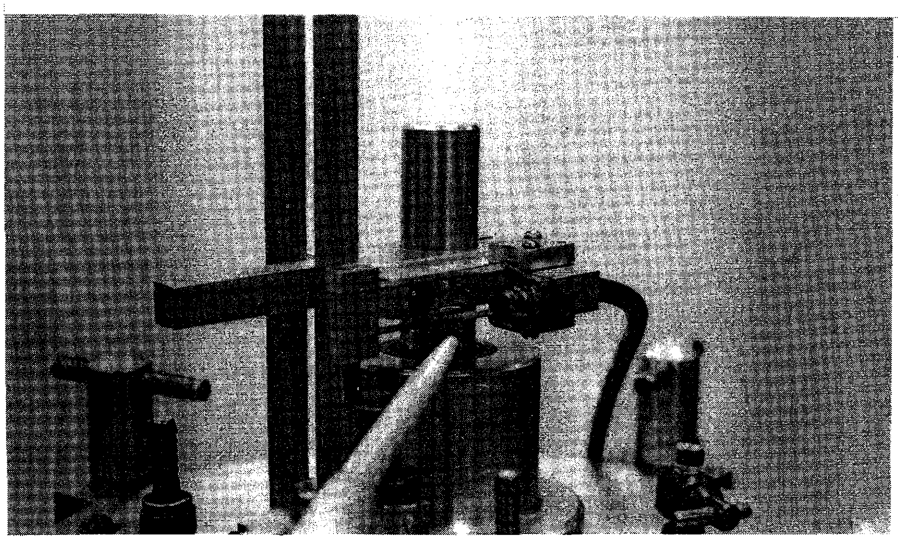

FIGURE 4 - The displacement of the loading rod with respect to the top of the triaxial cell is measured with strain gaged cantilever beam.

3. <u>Optical Deformation Measurement System</u> - Prior to testing, several 0.3 inch (±0.002 inch) square reflective targets are glued to the curved surface of the test specimen. (See Figure 5). To provide a uniform reflective surface, 3M Scotchlite Reflective Sheeting Number 3280 is placed on the targets. The targets are located so that changes in the horizontal and vertical dimensions of the specimen due to loading can be observed optically. (See Figure 6). When a target is observed with the optical tracker, the motion of the target, relative to the optical axis of the tracker, produces two output signals. One of the signals is proportional to the horizontal and the other to the vertical movement of the target.

The optical tracker and its accompanying projection lamp, which illuminates the targets, are placed on an X-Y slide assembly. (See Figure 7). The projection lamp is a modified 35mm slide projector operated from a regulated 120 volt DC power supply. The projector is mounted on the slide assembly and focused so that it illuminates an area in the object plane of the tracker approximately 0.6 inch in diameter.

The X-Y slide assembly is equipped with precision micrometer screws that are accurate to 0.001 inch in 12 inches and has dials graduated in 0.001 inch increments. (See Figure 8). The optical axis of the tracker is centered on a target by using the micrometer screws to move the tracker until two meters mounted on the tracker control box read zero. (See Figure 9). One meter registers horizontal and the other vertical relative distance between the target center and the optical axis of the tracker.

The final zeroing of the meters is accomplished in the interim (approximately 1.8 seconds) between dynamic load impulses. After alignment,

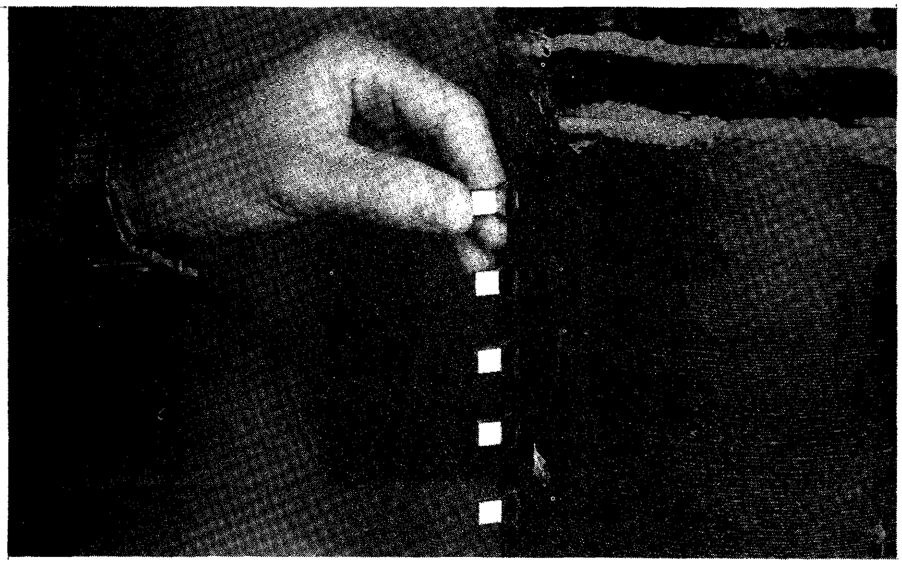

FIGURE 5 - Several reflective targets, glued to the curved surface of the test specimen, are spaced on one inch centers in two vertical, diametrically opposed lines.

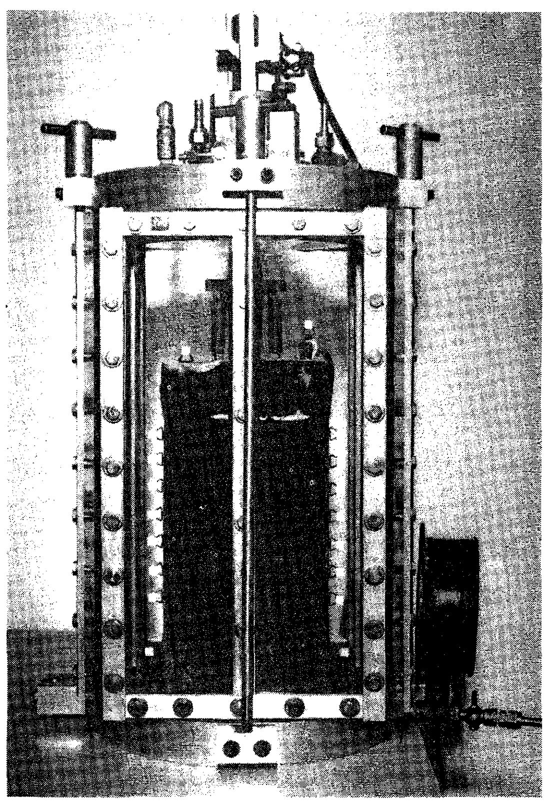

FIGURE 6 - A specimen ready for testing.

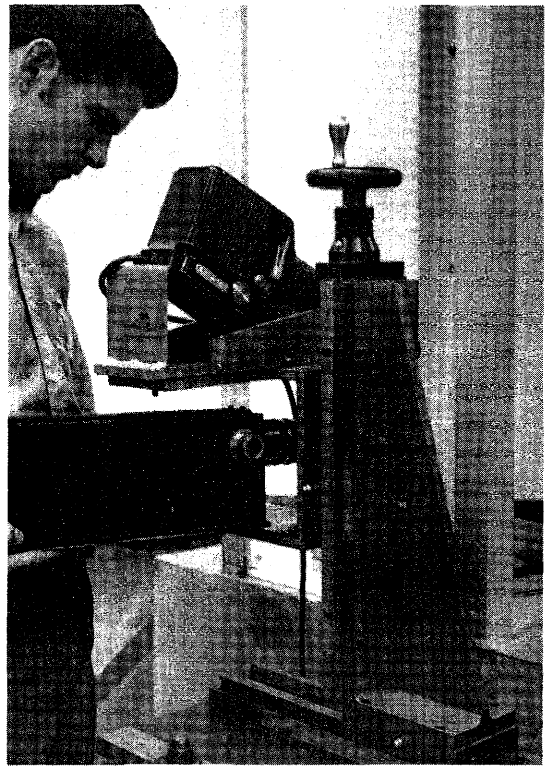

FIGURE 7 - The optical displacement tracker and the projection lamp are mounted on a micrometer X-Y slide assembly.

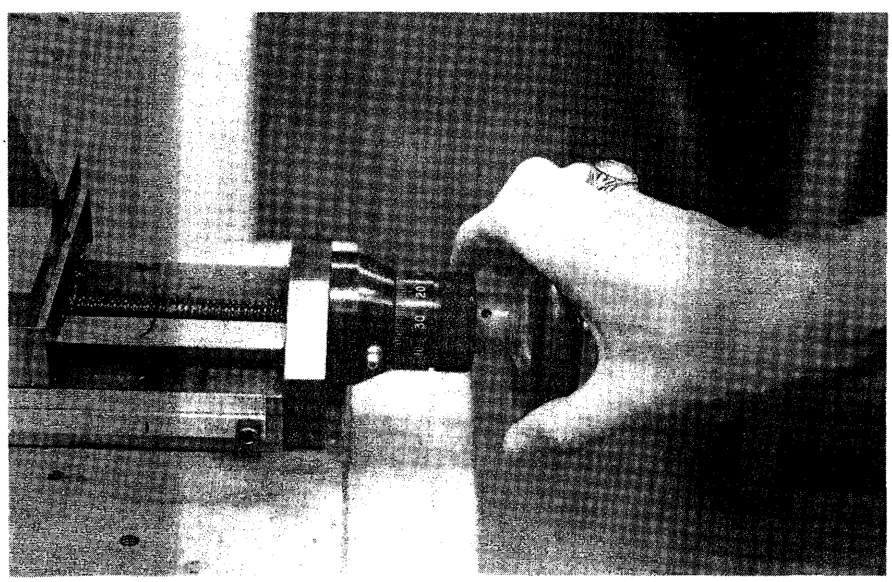

FIGURE 8 - The tracker is aligned on a target by manual operation of the micrometer screws.

the micrometer screw settings are recorded and long term creep can be measured by observing changes in the micrometer readings; however, the accuracy is limited by the readability of the dials to about ±0.0005 inch. Dynamic deformations up to ±0.030 inch accurate to within one percent (±0.00004 inch) are measured by observing the output signals from the tracker during the period of dynamic load (approximately 0.2 second). If only one target is involved, creep can be measured with similar accuracy, up to 0.030 inch by leaving the micrometer screw settings untouched.

4. Recording System - The recording system consists of a Honeywell 1508 Visicorder, a 130C Hewlett-Packard Oscilloscope, together with appropriate bridge balance units for the strain gaged transducers. There are four inputs to the recording system: (1) the vertical component of target displacement, (2) the horizontal component of target displacement, (3) the magnitude of the load and (4) the vertical displacement of the loading rod. The oscilloscope is preceded by a switching unit which allows any of the four signals to be displayed on either the horizontal or vertical input of the scope. Also, any one of the four signals can be displayed vertically on the scope versus time horizontally. This switching allows, for example, (a) the viewing of a plot of X versus Y motions of a given target, (b) load versus rod displacement or (c) load versus time. In addition, four inputs are continuously recorded by galvanometer traces on the light sensitive paper of the visicorder. Figure 10 shows a typical visicorder record with the four traces for one cycle of loading.

Before usable data can be taken with the optical tracker, it must first be calibrated on each individual target along both the vertical and

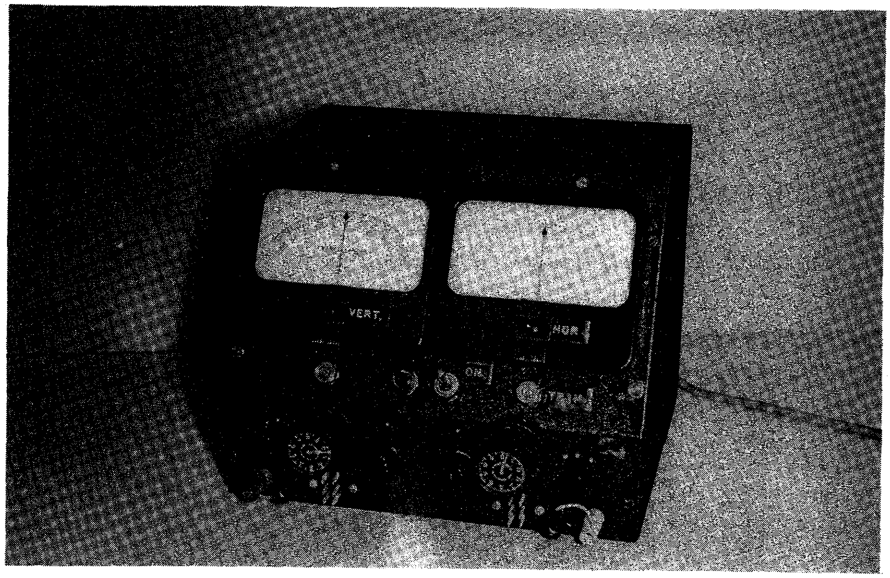

FIGURE 9 - When the meters on the tracker control box are zeroed, the optical axis of the tracker is aligned on a target.

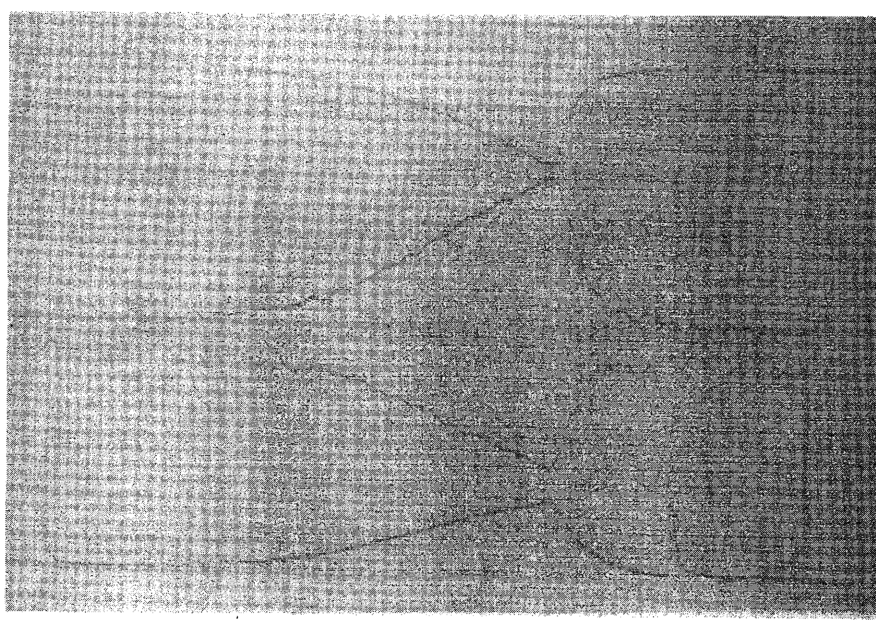

FIGURE 10 - A typical visicorder record obtained for one target during an impulsive load. From top to bottom the four traces represent: a) load, b) horizontal displacement, c) vertical displacement, and d) rod displacement.

horizontal axes. This calibration is accomplished after the tracker is aligned on a given target by moving the tracker with the micrometer screw for one axis to the extreme of its visicorder range. The micrometer screw is then turned back in incremental steps (for example, five mil increments) through center, to the other extreme of the range. A short visicorder recording is made at each incremental step. (See Figure 11). This procedure is followed for both the vertical and horizontal axis on each target. For each individual target a calibration curve for each axis is prepared by plotting chart divisions on the record versus micrometer screw movements, in mils. (See Figure 12). If all targets were of identical size and reflectance, the calibration curves for all targets would be alike.

The accuracy attained by this calibration procedure is limited principally by the readability of the micrometer dials. It is estimated that the calibration curve obtained from a sequence of ten steps using the 0.001 inch dial graduations is valid within one percent or better.

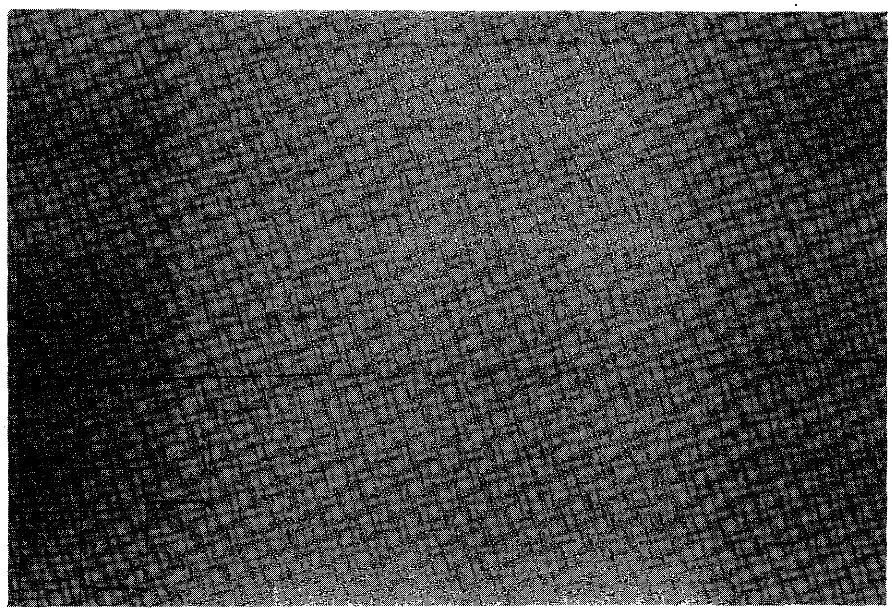

FIGURE 11 - A typical visicorder record made for the calibration of one axis of motion for one target.

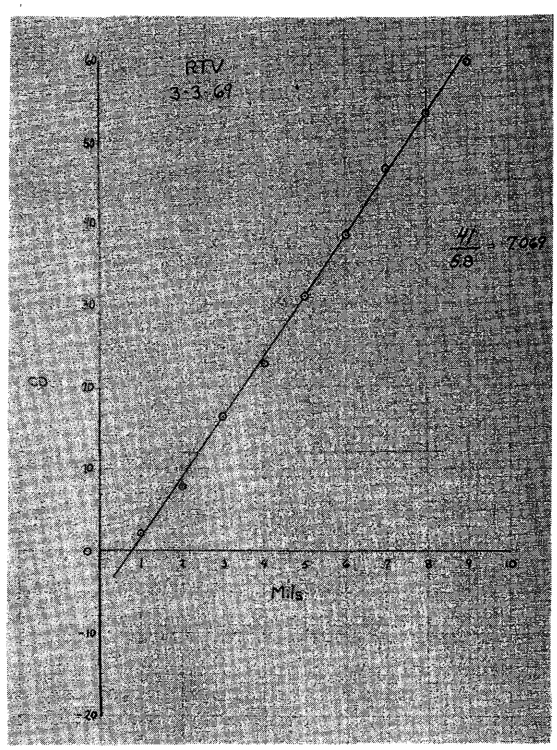

FIGURE 12 - A typical calibration plot for one axis of motion for one target.

3. MEASUREMENTS AND DATA REDUCTION

Eighteen targets are used for a single test. (See Figure 13). On each side of the specimen, seven of the targets are glued to the specimen's surface, one to the top loading plate and one to the base of the triaxial cell. The seven targets on the side of the specimen are spaced vertically on one inch centers, beginning one inch from each end of the eight inch high specimen.

For a single test, two complete sets of readings are made. The first set of readings consists of 18 visicorder records, one for each target. The first set is obtained by beginning at the top right target, then testing each target in turn in a clockwise direction and ending at the top left target. The second set is obtained similarly, except that the order of target testing is reversed. As previously mentioned, a single visicorder record consists of four continuous galvanometer traces plotted against time during one load impulse, namely, a) horizontal target displacement, b) vertical target displacement, c) rod displacement and d) load. The scale along the length of the record represents time.

Though it requires approximately two hours to make the two complete sets of visicorder records representing one test, the first set of data is normally in very close agreement with the second set. In other words, the specimen evidently undergoes no significant change during the testing period, and the load and rod displacement traces shown on all 36 records are almost identical.

The 36 visicorder records are digitized by measuring the height of each trace at regular time increments (normally 0.01 second). This

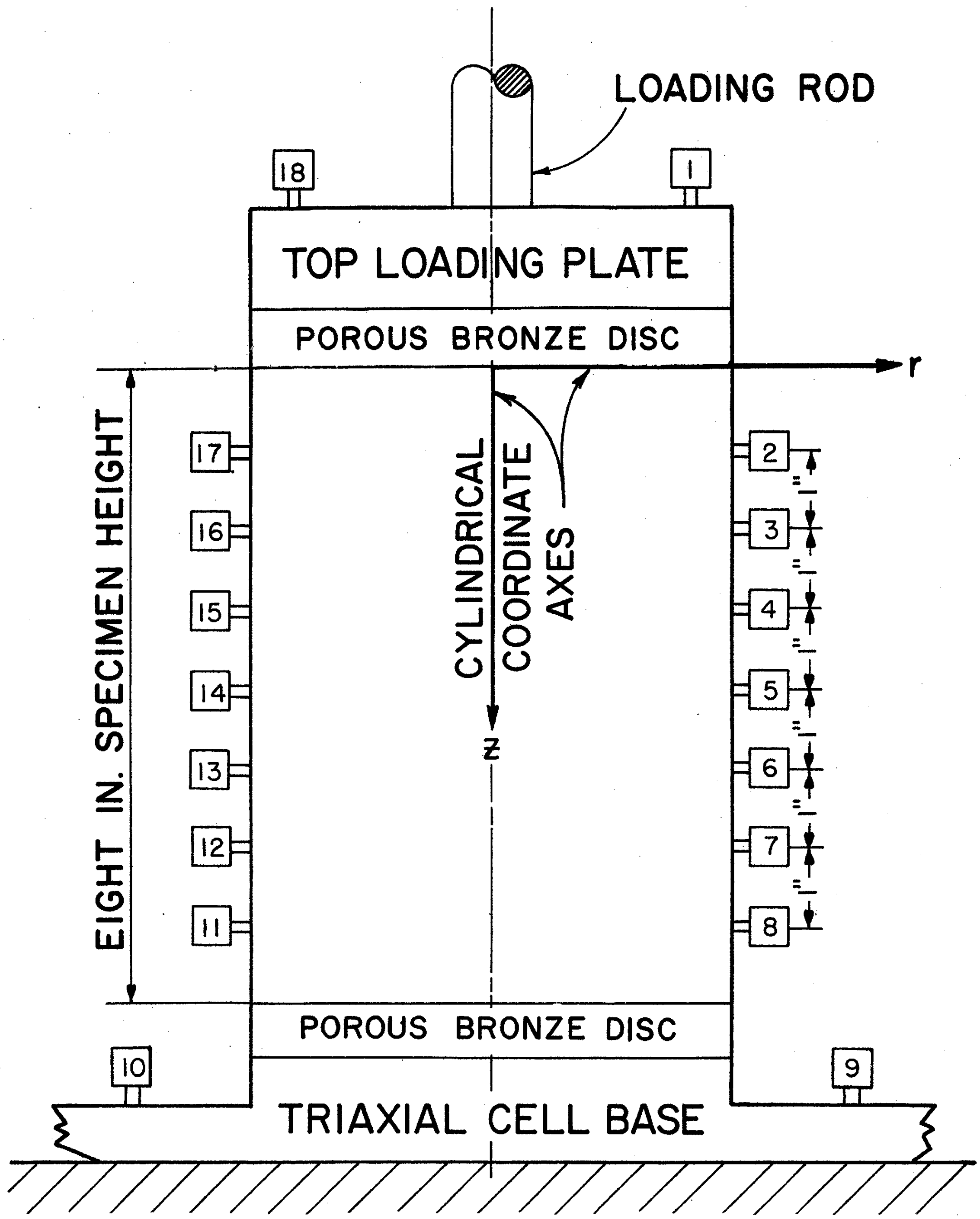

FIGURE 13 - Schematic showing target positions on a test specimen and the coordinate system used for representation of displacements.

information, along with appropriate scale factors, is punched on IBM computer cards. Thus, the four measurements versus time are available for computer data processing. Through standard techniques of interpolation and data processing, each visicorder record is reduced to the following four records versus regular load increments (normally 200 lbs.):

a) horizontal target displacement for 18 targets (averages of data from 2 records).

b) vertical target displacement for 18 targets (averages of data from 2 records).

c) rod displacement (average of data from 36 records).

c) loading rate (average of data from 36 records).

A typical set of data reduced from a test is shown in Tables 1 and 2. The data shown were obtained while testing a low modulus plastic for equipment evaluation purposes as explained in more detail in the next section. In Tables 1 and 2 cylindrical coordinate sign convention is used for presentation of displacements. From the data given, one can observe that the displacements measured are not axially symmetrical. This is due to a) imperfectly aligned load, b) imperfections in both material and dimensions of the test cylinder, and c) imperfections in top and bottom loading plates. Displacements of like kind measured on opposite sides of the cylinder were averaged and these averages were assumed to represent the displacements for an axially symmetrical test specimen. The radial and vertical displacements are represented by the conventional symbols, u and w, respectively.

TABLE 1: TYPICAL VERTICAL TARGET DISPLACEMENT, W, VERSUS LOAD (TEST NO. 6)

Vertical Displacements (mils) in Body of Table Are
The Average of Two Measurement Records Made on Each Target

TGTS	LOAD (POUNDS)									
	200	400	600	800	1000	1200	1400	1600	1800	2000
1	0.569	1.121	1.583	2.050	2.505	2.930	3.331	3.723	4.049	4.332
2	0.474	0.915	1.290	1.683	2.083	2.417	2.715	3.140	3.552	3.800
3	0.413	0.804	1.125	1.448	1.832	2.085	2.399	2.749	3.019	3.264
4	0.375	0.738	1.053	1.362	1.701	1.915	2.154	2.442	2.715	2.954
5	0.355	0.621	0.898	1.157	1.413	1.607	1.805	2.021	2.258	2.466
6	0.293	0.542	0.804	1.006	1.216	1.385	1.578	1.744	1.900	2.079
7	0.261	0.472	0.635	0.818	0.976	1.125	1.230	1.364	1.523	1.602
8	0.194	0.341	0.502	0.593	0.708	0.790	0.885	0.994	1.067	1.144
9	0.017	0.061	0.084	0.109	0.125	0.149	0.170	0.188	0.207	0.235
10	0.065	0.096	0.136	0.179	0.221	0.276	0.328	0.368	0.404	0.455
11	0.240	0.413	0.534	0.643	0.726	0.856	0.971	1.049	1.138	1.229
12	0.221	0.437	0.623	0.774	0.917	1.072	1.219	1.327	1.449	1.599
13	0.300	0.511	0.771	0.960	1.126	1.331	1.559	1.727	1.889	2.100
14	0.335	0.587	0.867	1.074	1.263	1.515	1.769	1.978	2.177	2.407
15	0.364	0.653	0.955	1.213	1.475	1.755	2.030	2.310	2.544	2.774
16	0.372	0.749	1.119	1.370	1.680	2.025	2.352	2.633	2.917	3.249
17	0.370	0.783	1.220	1.563	1.920	2.318	2.722	3.045	3.364	3.790
18	0.723	1.273	1.843	2.216	2.652	3.214	3.741	4.056	4.336	4.862

TABLE 2: TYPICAL HORIZONTAL TARGET DISPLACEMENT, U, VERSUS LOAD (TEST NO. 6)

Horizontal Displacements (mils) in Body of Table Are
The Average of Two Measurement Records Made on Each Target

TGTS	LOAD (POUNDS)									
	200	400	600	800	1000	1200	1400	1600	1800	2000
1	0.000	0.042	0.083	0.107	0.118	0.100	0.064	0.016	-0.030	-0.088
2	0.049	0.098	0.136	0.173	0.184	0.193	0.198	0.199	0.200	0.199
3	0.048	0.080	0.109	0.127	0.136	0.143	0.149	0.153	0.150	0.150
4	0.032	0.063	0.096	0.116	0.123	0.129	0.135	0.140	0.147	0.156
5	0.044	0.082	0.101	0.129	0.144	0.153	0.165	0.174	0.183	0.200
6	0.044	0.069	0.092	0.108	0.119	0.132	0.147	0.158	0.164	0.174
7	0.020	0.043	0.059	0.069	0.080	0.091	0.101	0.113	0.128	0.140
8	0.028	0.041	0.047	0.062	0.080	0.095	0.106	0.119	0.133	0.144
9	0.000	-0.013	-0.012	-0.015	-0.027	-0.032	-0.032	-0.039	-0.050	-0.051
10	0.003	0.007	0.030	0.040	0.042	0.047	0.054	0.060	0.068	0.075
11	0.022	0.066	0.112	0.159	0.196	0.241	0.287	0.333	0.373	0.405
12	0.020	0.068	0.131	0.186	0.231	0.300	0.365	0.422	0.479	0.537
13	0.051	0.105	0.155	0.216	0.259	0.317	0.377	0.440	0.504	0.561
14	0.038	0.063	0.101	0.156	0.202	0.247	0.301	0.372	0.441	0.499
15	0.025	0.067	0.103	0.155	0.216	0.269	0.334	0.409	0.474	0.541
16	0.032	0.053	0.070	0.127	0.172	0.223	0.284	0.352	0.424	0.494
17	0.035	0.036	0.039	0.063	0.089	0.128	0.187	0.261	0.336	0.400
18	-0.065	-0.137	-0.222	-0.262	-0.293	-0.310	-0.304	-0.283	-0.257	-0.224

4. EVALUATION TESTS

Because preliminary measurements made on soil specimens were quite different than had been expected, an evaluation of the system was made utilizing two 4 inch diameter by 8 inch high Lexan* thermoplastic cylinders. The setup for testing the plastic cylinders was similar to the schematic shown in Figure 13 except that 6 inch diameter aluminum spacers, with machined 4 inch diameter depressions for centering the cylinders, were used in lieu of the 6 inch porous bronze discs shown in the figure. The thermoplastic material was selected because of its reported temperature stability and its fairly low modulus of elasticity; the reported average modulus is 345,000 psi (2).

On the periphery of each cylinder at mid-height 2 Micro Measurements EA13-062TH-120, 90° rosette gages were placed 180° apart. The gages on the 2 cylinders were wired to form 2 wheatstone bridges, one for measuring vertical strain and the other for measuring circumferential strain. Each bridge consisted of two active and two dummy gages. To insure maximum temperature compensation, one cylinder was tested utilizing its gages as the active arms of the bridge while the gages on the other cylinder served as the dummy arms.

Strain gage signal conditioners were used to amplify the bridge output signals and to excite the bridges with approximately 0.3 volts RMS, at 400 Hz. These low excitation voltages were used to minimize local heating around the gages. Both bridges were calibrated by

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*Registered trade mark, General Electric measuring the bridge unbalance with a digital strain indicator when the active gages were shunted with an appropriate precision calibration resistor. Just prior to testing, the calibration resistor was used to shunt the active gages to obtain a scale factor for the visicorder recorder.

Targets were placed on the test cylinder and measurements were made as described in Section 3, Measurement and Data Reduction. The outputs from the two strain gage bridges (gages were used only for the evaluation tests) were put on the 36 visicorder records. As would be expected, all 36 records of circumferential and vertical strain were approximately alike. Using the same procedure described for reducing the rod displacement data, these strain records were digitized and processed to yield strain versus load data (average of 36 records).

Values of vertical and radial displacement, loading rate and rod displacement -- reduced as described in Section 3 -- are given in Tables 3 and 4. In these tables, the motions of the top loading plate and the base of the triaxial cell are shown at z equal to 0 and 8 inches respectively. The circumferential and vertical strains measured with the strain gages are also given. The data in these tables represent two tests which differ only in the loading pattern that was used for testing.

Plots of vertical and radial displacements versus z from the two tests are shown in Figures 14 and 15. From these curves vertical and circumferential strains were computed. The vertical strain, ε_z, was taken as the slope of the w versus z curves, and the circumferential strain, ε_θ, as the radial displacement, u, divided by the original radius of the specimen.

TABLE 3: TEST NO. 5 - DISPLACEMENTS, STRAINS AND LOADING RATES VERSUS LOAD
(4" DIAMETER BY 8" HIGH LEXAN PLASTIC CYLINDER - SLOW LOADING RATE)

	LOAD (POUNDS)									
	200	400	600	800	1000	1200	1400	1600	1800	2000
z (in)	Vertical Displacement (Mils)									
0*	0.631	1.155	1.653	2.140	2.583	3.000	3.442	3.893	4.296	4.664
1	0.429	0.876	1.235	1.616	1.988	2.351	2.725	3.108	3.485	3.837
2	0.377	0.756	1.081	1.424	1.745	2.048	2.346	2.658	2.980	3.305
3	0.351	0.674	0.984	1.260	1.549	1.839	2.098	2.363	2.638	2.914
4	0.321	0.594	0.853	1.071	1.318	1.574	1.791	1.998	2.215	2.428
5	0.265	0.520	0.751	0.948	1.136	1.349	1.545	1.720	1.888	2.061
6	0.236	0.455	0.618	0.771	0.936	1.081	1.213	1.348	1.468	1.576
7	0.197	0.347	0.476	0.596	0.707	0.811	0.923	1.010	1.088	1.158
8*	0.031	0.061	0.098	0.141	0.179	0.214	0.249	0.280	0.309	0.334
	Radial Displacement (Mils)									
0*	-0.009	-0.021	-0.057	-0.075	-0.082	-0.100	-0.122	-0.138	-0.147	-0.165
1	0.022	0.050	0.081	0.107	0.140	0.174	0.202	0.225	0.252	0.284
2	0.030	0.059	0.085	0.116	0.150	0.183	0.216	0.250	0.285	0.319
3	0.038	0.077	0.117	0.143	0.182	0.217	0.249	0.285	0.323	0.360
4	0.037	0.068	0.109	0.146	0.182	0.218	0.254	0.287	0.320	0.352
5	0.031	0.066	0.102	0.137	0.171	0.206	0.239	0.274	0.309	0.342
6	0.032	0.064	0.098	0.136	0.172	0.207	0.241	0.276	0.306	0.336
7	0.016	0.044	0.070	0.100	0.132	0.158	0.185	0.214	0.244	0.272
8*	0.006	0.015	0.011	0.009	0.007	0.006	0.005	0.006	0.007	0.009
Loading Rate (lbs/sec)	6950	15800	23500	31500	39850	44850	47300	49900	52650	52000
Rod Displacement (Mils)	0.783	1.604	2.233	2.878	3.482	4.063	4.646	5.253	5.832	6.393
Circumferential Strain** (Mils/in)	0.013	0.026	0.040	0.055	0.069	0.083	0.098	0.113	0.128	0.144
Vertical Strain** (Mils/in)	-0.032	-0.066	-0.101	-0.137	-0.171	-0.205	-0.242	-0.279	-0.316	-0.351

*Displacement shown for z = 0 and 8 inches is the displacement for the top loading plate and triaxial cell base respectively.

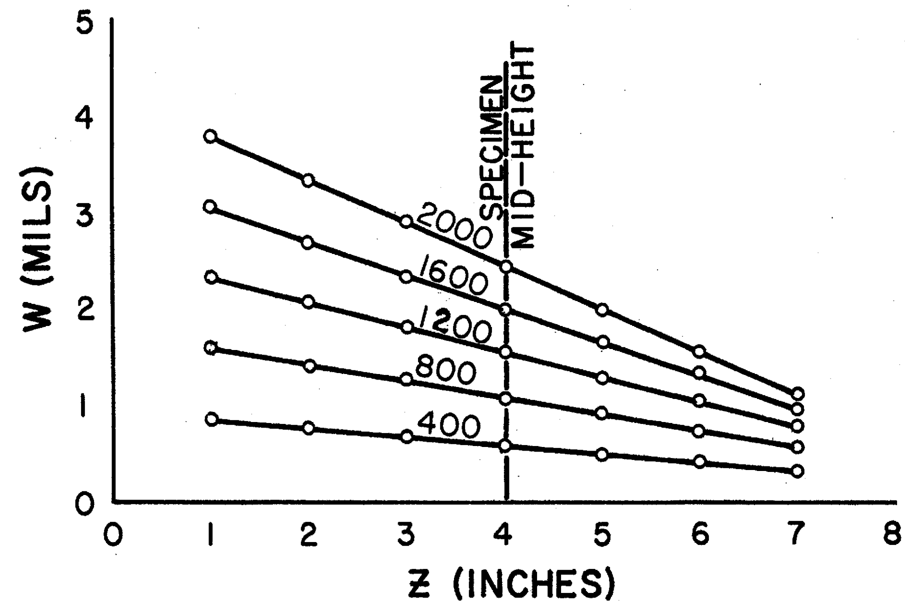
**Measured by strain gage.

TABLE 4: TEST NO. 6 - DISPLACEMENTS, STRAINS AND LOADING RATE VERSUS LOAD
(4" DIAMETER BY 8" HIGH LEXAN PLASTIC CYLINDER - SLOW LOADING RATE)

	LOAD (POUNDS)									
	200	400	600	800	1000	1200	1400	1600	1800	2000
z (in)	Vertical Displacement (Mils)									
0*	0.646	1.197	1.713	2.135	2.579	3.072	3.536	3.890	4.193	4.597
1	0.422	0.849	1.254	1.619	1.993	2.356	2.707	3.081	3.449	3.784
2	0.393	0.777	1.122	1.409	1.756	2.055	2.376	2.691	2.968	3.257
3	0.370	0.696	1.004	1.288	1.588	1.835	2.092	2.376	2.630	2.864
4	0.345	0.604	0.883	1.116	1.338	1.561	1.787	2.000	2.218	2.437
5	0.297	0.527	0.788	0.983	1.171	1.358	1.569	1.736	1.895	2.090
6	0.241	0.455	0.629	0.796	0.947	1.099	1.225	1.346	1.486	1.601
7	0.217	0.377	0.518	0.618	0.717	0.823	0.928	1.022	1.103	1.187
8*	0.041	0.079	0.110	0.144	0.173	0.213	0.249	0.278	0.306	0.340
	Radial Displacement (Mils)									
0*	-0.033	-0.048	-0.070	-0.078	-0.088	-0.105	-0.120	-0.134	-0.144	-0.156
1	0.042	0.067	0.088	0.118	0.137	0.161	0.193	0.230	0.268	0.300
2	0.040	0.067	0.090	0.127	0.154	0.183	0.217	0.253	0.287	0.322
3	0.029	0.065	0.100	0.136	0.170	0.199	0.235	0.275	0.311	0.349
4	0.041	0.073	0.101	0.143	0.173	0.200	0.233	0.273	0.312	0.350
5	0.048	0.087	0.124	0.162	0.189	0.225	0.262	0.299	0.334	0.368
6	0.020	0.056	0.095	0.128	0.156	0.196	0.233	0.268	0.304	0.339
7	0.025	0.054	0.080	0.111	0.138	0.168	0.197	0.226	0.253	0.275
8*	0.002	-0.003	0.009	0.013	0.008	0.008	0.011	0.011	0.009	0.012
Loading Rate (lbs/sec)	6900	14600	21850	28250	32150	35700	36300	36100	34100	31250
Rod Displacement (Mils)	0.989	1.737	2.445	3.112	3.736	4.333	4.924	5.495	6.041	6.570
Circumferential Strain** (Mils/in)	0.014	0.029	0.045	0.061	0.076	0.092	0.108	0.125	0.141	0.157
Vertical Strain** (Mils/in)	-0.032	-0.066	-0.099	-0.134	-0.167	-0.201	-0.235	-0.269	-0.303	-0.336

*Displacement shown for z = 0 and 8 inches is the displacement for the top loading plate and triaxial cell base respectively.

**Measured by strain gage.



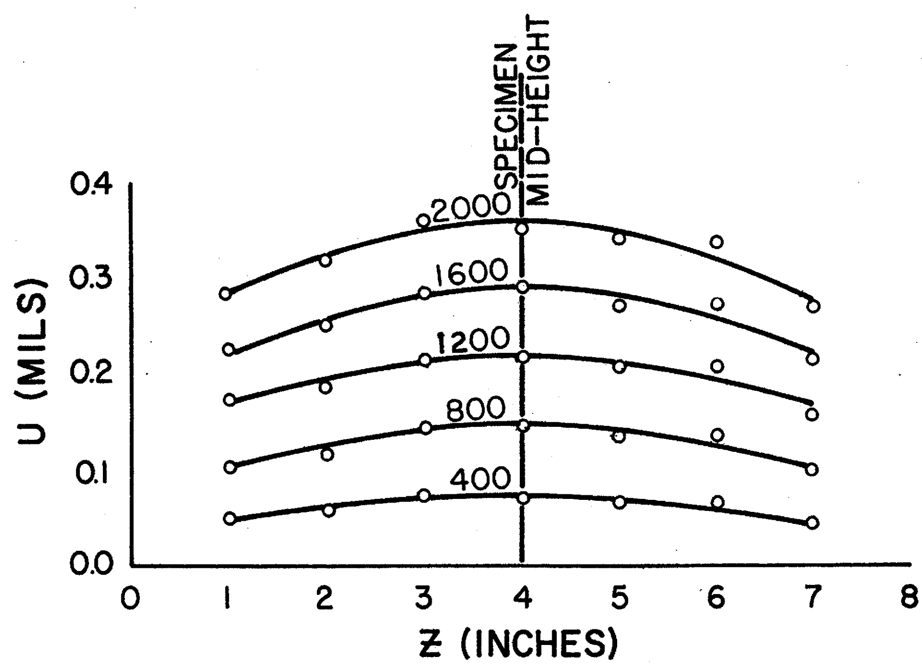


FIGURE 14 - Test No. 5 - Vertical displacement, w, and radial displacement, u, versus z (4" diameter by 8" high Lexan plastic cylinders - fast loading rate).

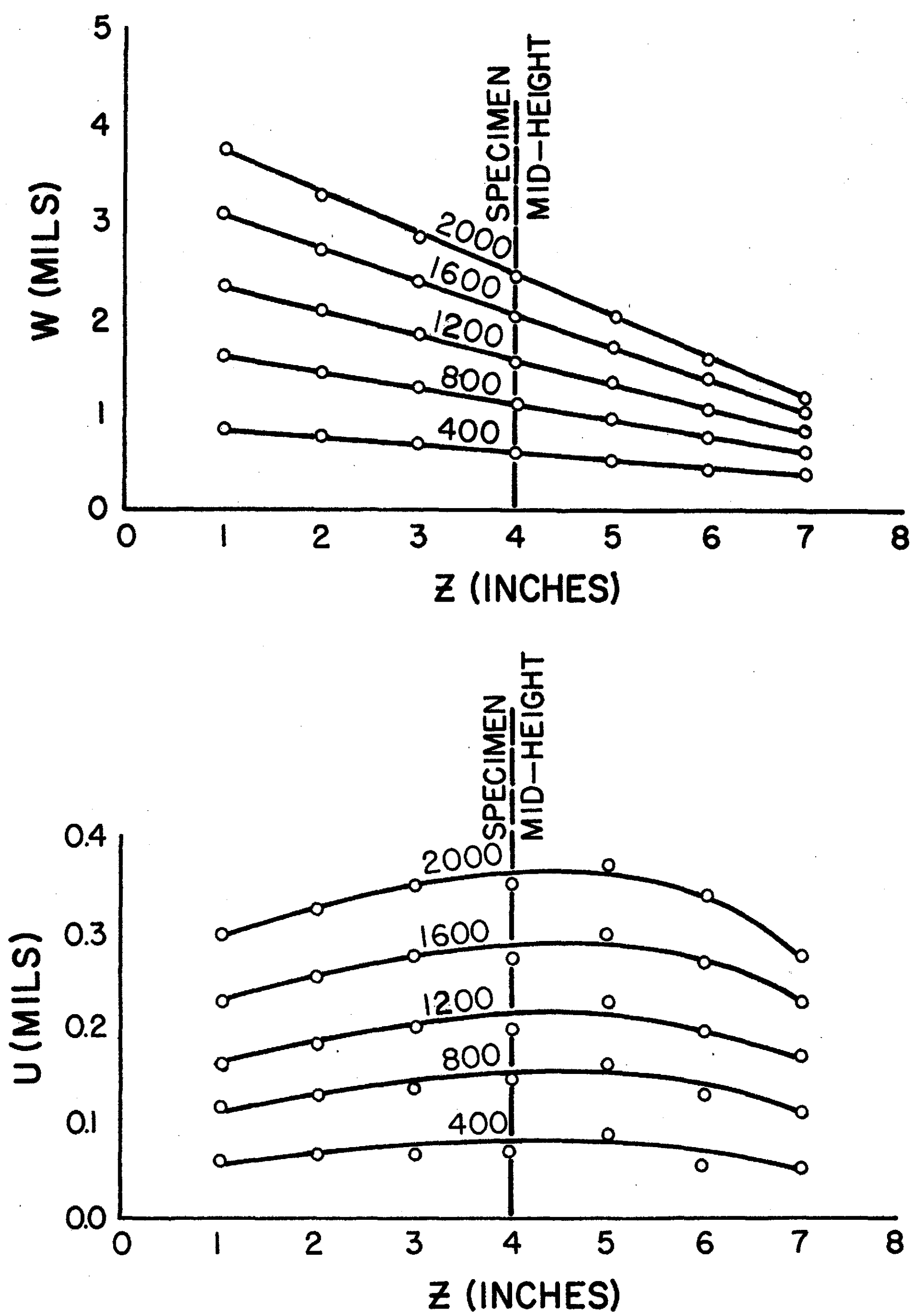


FIGURE 15 - Test No. 6 - Vertical displacement, w, and radial displacement, u versus z (4" diameter by 8" high Lexan plastic cylinders - slow loading rate).

Plots of load versus vertical strain for the two tests are shown in Figures 16 and 17. The strains given are as follows:

a) Change in specimen height measured by the rod displacement, divided by the specimen height.

b) Change in specimen height measured by the difference in the vertical displacement of the top loading plate and the base of the triaxial cell, divided by the specimen height.

c) The vertical strain computed from the tracker data -- the slope of the w versus z curves (Figures 14 and 15).

d) Direct strain gage measurement.

From Figures 16 and 17 it is clear that the determination of vertical strain is highly dependent on the measurement method used. The vertical strain indicated by the tracker, believed to be the actual strain in the boundary of the specimen is less than that computed from the loading rod displacement. It is also less than that computed from the difference in the vertical displacement of the top loading plate and the base of the triaxial cell. These disparities must be due to strains resulting from the seating of the loading rod, top plate, specimen ends, etc. It is also clear that the strains measured with the tracker are about 25 to 30 percent higher than those measured with the strain gages.

A difference of this magnitude is attributable to the reinforcement effect of the strain gages when used on low modulus materials. Effective gage factors were reported (3) to differ less than one percent from manufacturer's gage factor for conventional gages attached to material of modulus 10^6 psi but to become 5 to 15 percent less when attached to materials of modulus $6.5 + 10^5$ psi. Accordingly, it appears reasonable to expect

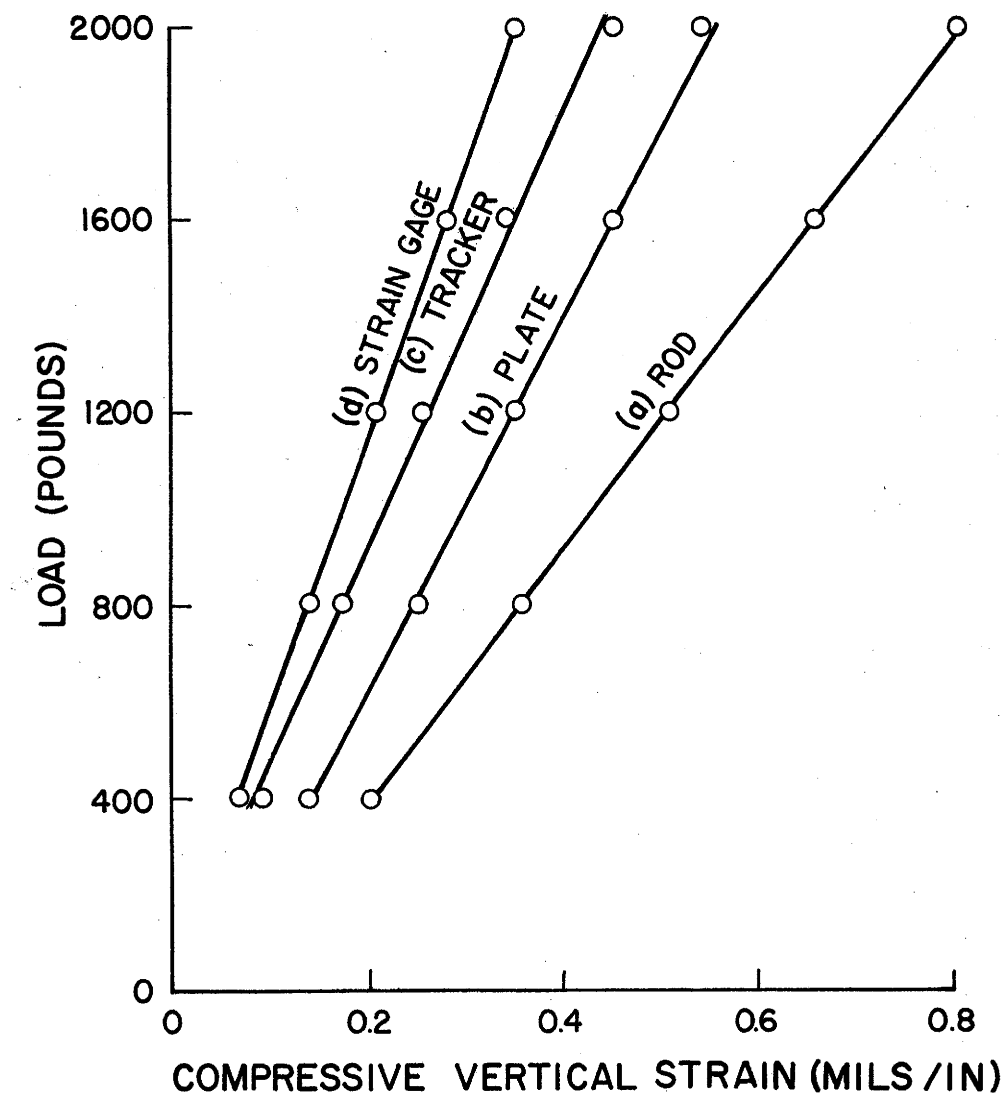


FIGURE 16 - Test No. 5 - Load versus comparative vertical strains computed from a) rod displacement, b) relative motion of loading plates, c) w versus z curves (Figure 14) and d) direct strain gage measurements.

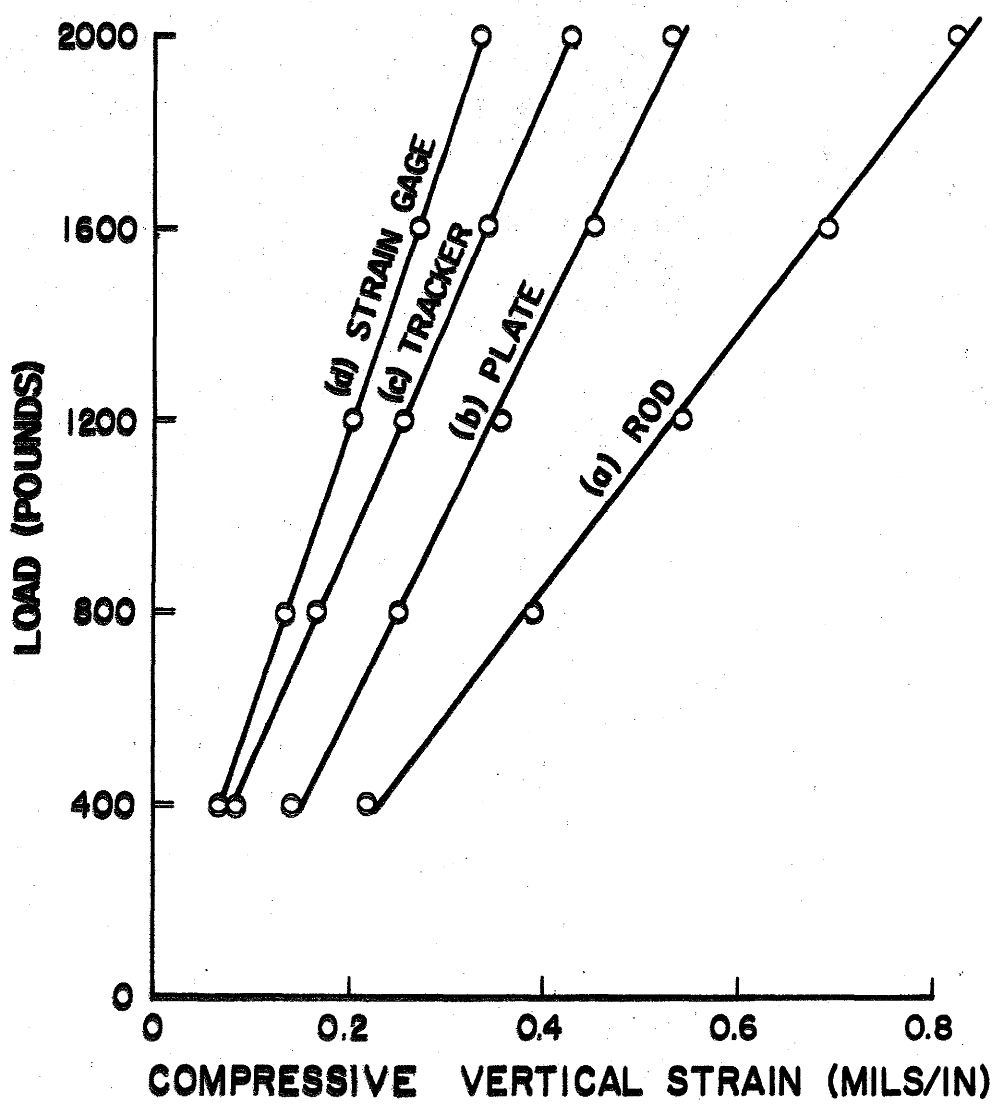


FIGURE 17 - Test No. 6 - Load versus comparative vertical strains computed from a) rod displacement, b) relative motion of loading plates, c) w versus z curves (Figure 14) and d) direct strain gage measurements.

25 to 30 percent lower than normal gage factor on a material whose modulus is 3.5 $+$ 10^5 psi.

Thus, it is concluded that serious errors can be incurred with low modulus materials through the use of conventional strain gages which are not subject to direct calibration procedures.

Table 5 contains comparisons of strain determinations at mid-height made from tracker data -- w and u versus z curves -- with those from direct strain gage measurements. Again it is clear that the strain gage determinations are about 25 percent low. Table 5 also contains comparisons of elastic modulii computed from the slopes of the lines in Figures 16 and 17.

TABLE 5: MEASUREMENT COMPARISONS

Comparative Strains At Specimen Mid-Height

Test No.	Load (Pounds)	ε_z (Mils): w Vs z Curves	ε_z (Mils): Strain Gage	ε_θ (Mils/in): u Vs z Curves	ε_θ (Mils/in): Strain Gage
5	400	-0.089	-0.066	0.037	0.026
	800	-0.171	-0.137	0.074	0.055
	1200	-0.254	-0.205	0.110	0.083
	1600	-0.341	-0.279	0.146	0.113
	2000	-0.452	-0.351	0.180	0.144
6	400	-0.079	-0.066	0.040	0.029
	800	-0.164	-0.134	0.077	0.061
	1200	-0.254	-0.201	0.108	0.092
	1600	-0.341	-0.269	0.143	0.125
	2000	-0.425	-0.336	0.182	0.157

Comparative Determinations of Elastic Modulii

Method of Strain Measurement	Elastic Modulii (Psi): Test 5	Elastic Modulii (Psi): Test 6
a) Rod Displacement	210,000	210,000
b) Relative Plate Motion	310,000	325,000
c) w Versus z Curves	355,000	365,000
d) Strain Gages	450,000	470,000
e) Manufacturers Avg. Value (2)	345,000	

NOTE: Test Nos. 5 and 6 represent two tests made on a 4" diameter by 8" high Lexan plastic cylinder. The two tests differ only in the loading pattern that was used for testing.

5. CONCLUSIONS

Listed below are the more significant conclusions which were reached as a result of the development and evaluation of the measurement system described in this report.

1. Vertical displacement of the loading rod or of the end plates is always greater than the test specimen deformation.

2. General purpose foil strain gages, when used on low modulus materials, introduce errors by effectively reinforcing the specimen in the region of gage attachment.

3. Tracker data appears to represent more reliably the deformation of low modulus test specimens than any other method known to the authors.

4. Measurements made with the tracker are adversely affected by the inability to achieve axially symmetrical specimens and load distribution. The average of observations made on opposite sides of a test specimen is believed to approximate an axially symmetrical case.

6. REFERENCES

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3. Webb, L. D., Harris, R. W., and Cook, E. E., III, "Study and Literature Survey of Stress State Transducer Development", Technical Report AFRPL-TR-69-74, Volume II, Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California, pp 139-143, March, 1969.