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UNCONFINED COMPRESSION TESTS ON SNOW: A COMPARATIVE STUDY.(U)
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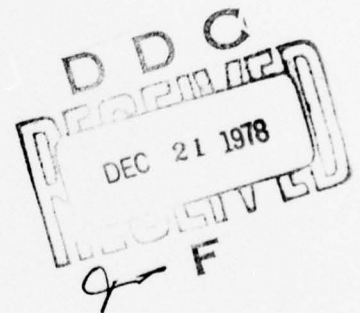
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UNCONFINED COMPRESSION TESTS ON SNOW A Comparative Study

A. Kovacs, F. Michitti and J. Kalafut

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20. Abstract (cont'd)

system are considered more representative of the unconfined compressive strength of the snow tested.

PREFACE

This report was prepared by Austin Kovacs, Research Civil Engineer, of the Foundations and Materials Research Branch, Experimental Engineering Division, CRREL, by Frank Michitti, a research civil engineer formerly with CRREL, and by John Kalafut, Electrical Engineer, of the Engineering Services Branch, Technical Services Division, CRREL. Funding was provided by DA Project 1T061101A91A, In-House Laboratory Independent Research.

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CONTENTS

Abstract-----	Page i
Preface-----	iii
Introduction-----	1
Samples-----	1
Test equipment-----	2
Test results-----	4
Discussion-----	6
Conclusion-----	7
Literature cited-----	8

ILLUSTRATIONS

Figure

1. Multi-degree of freedom self-aligning prototype platen assembly used to eliminate misalignment of unconfined compression test specimens-----	10
2. The new platen assembly enables self-alignment of unconfined compression test specimens by allowing the platen to shift laterally from a to b and to rotate if necessary-----	11
3. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-4-----	12
4. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-5-----	13
5. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-6-----	14
6. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-8-----	15
7. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-10-----	16
8. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-11-----	17
9. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-13-----	18
10. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-14-----	19
11. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-15-----	20
12. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-16-----	21
13. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-17-----	22
14. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-18-----	23

Figure		Page
15.	Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-21-----	24
16.	Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-22-----	25
17.	Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-22-----	26
18.	Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-26-----	27

TABLES

Table		
I.	Unconfined compressive strength data on firn from Camp Century, Greenland-----	3

UNCONFINED COMPRESSION TESTS ON SNOW

A Comparative Study

Introduction

In 1967 field tests were made (Kovacs et al. 1969) on the unconfined compressive strength of polar snow and ice. The study was performed at Camp Century, Greenland, where samples with densities varying from 0.340 to 0.890 g/cm³ were tested. In that report, the authors made reference to the significance of the scatter in the test results and put forth "that the primary cause of scatter in the test results data is associated with the singular or combined effects of nonaxially loaded and/or irregularly surfaced specimen ends, and to a lesser degree due to the inherent crystalline or structural flaws." If the scatter were related to nonaxially loaded specimens or to irregularly surfaced specimen ends, it was stated that the more realistic unconfined compressive strengths would be the highest ones. These strengths would have been "obtained from tests in which the samples had most careful preparation and alignment within the testing machine."

Further consideration was given to the alignment problem which resulted in the development of a new platen system designed to ensure nonaxial alignment of unconfined compression test specimens. A description of this platen system and some preliminary results obtained with its use in testing the unconfined compressive strength of freshwater ice are given in a Progress Report "On a Platen Concept for Use when Testing Brittle Materials" (Kovacs 1970). This report indicated that unconfined compression test specimens, no matter how carefully aligned on top of a conventional ball platen, were still misaligned. Therefore the specimens failed at an average load 30% lower than the apparently more perfectly aligned samples loaded on top of the new self-aligning platen system.

As a result of these findings it was decided to perform additional unconfined compression tests on Greenland snow for the purpose of determining if the use of the new platen system would result in strength values higher than those previously reported. It was anticipated that the new platen system would provide better sample alignment in the testing machine and, therefore, a more uniform stress field across the ends of the sample. If true, the expected higher strengths would support the reasoning advanced by Kovacs et al. (1969) quoted above. This report presents the findings of unconfined compression tests performed at CRREL on 0.600- to 0.625-g/cm³ density snow from Camp Century, Greenland - tests which do support the reasoning of Kovacs et al. (1969).

Samples

Samples of polar snow for this study were obtained from the Inclined Drift at Camp Century, Greenland (Kovacs et al. 1969). Test specimens were selected which had a density between 0.600 and 0.625 g/cm³. Their average density was 0.612 g/cm³. This density range was selected for comparison with 15 samples of the same snow tested by Kovacs et al. (1969), which had densities between 0.600 and 0.625 g/cm³ for an average of 0.617 g/cm³.

The samples for this study were prepared in a special jig mounted on a lathe. Each sample was prepared as a smooth-faced right cylinder with ends cut smooth and "flat." The length, diameter and density of each is shown in Table I. The average length and diameter were 20.7 and 7.5 cm, respectively, for a length to diameter ratio of ≈ 2.75 to 1. This ratio was selected to minimize the effects of end constraint, which becomes severe below a ratio of 2 to 1.

The samples of Kovacs et al. (1969) were cut to a standard length and planed smooth at the ends on a modified table sander. The ends were then hand-honed on fine-grained emery paper to remove minor surface irregularities. Extreme care was also taken to ensure that the side of each sample was perpendicular to the ends. Final samples averaged 7.6 cm in diameter and 21.0 cm long, which also gave a length to diameter ratio of ≈ 2.75 to 1.

Test Equipment

The press used in this study was the same one used by Kovacs et al. (1969) at Camp Century. The four-legged frame and cross heads of the press were made with thick steel components prestressed to ensure low compliance under load. A load cell was fixed to the bottom of the upper cross head and a hydraulic ram was built into the base assembly. For the Greenland tests, the ball platen hung from the bottom of the load cell. This rather standard platen configuration did not ensure axial alignment or proper seating of the test specimen. For the comparative test presented in this report, a prototype platen system was connected to the top of the ram piston. It is described by Kovacs (1970) as follows:

As shown in Figure 1, the platen system consists of a number of components. These include the often used platen and platen ball section with the platen ball fixed to the cap of the lower assembly. Highly polished and hardened steel inserts form the underside of the cap and upper face of the base. These inserts have a flatness better than 1/100,000 in. Between these inserts is a loose array of precision balls which give the cap, and therefore the platen, the unique and important feature of 360° of lateral translation as well as circular rotation on the plane of the base insert. The leaf springs, fixed to the cap, center the cap over the base. The tension springs between the cap and the platen collar help to keep the platen surface relatively level during raising of the test sample against the upper surface of the testing machine (i.e. the base of the load cell).

Besides providing anchorage for the tension springs, the platen collar supports three linear variable differential transformers (LVDTs). The LVDTs are used to measure sample deflection under load and indirectly provide a means of measuring press speed and time to failure. Signals from the LVDTs and the load cell are recorded at 60 in./sec on a high speed magnetic tape recorder and then played back at 1 7/8 in./sec into an X-Y plotter. The latter provides a graphic printout of the complete load vs deflection history of the test specimen up to failure.

TABLE 1
UNCONFINED COMPRESSIVE STRENGTH DATA ON FIRN FROM
CAMP CENTURY, GREENLAND

Sample	Length cm	Length in	Dia cm	Dia in	Specific Gravity	Press cm/min	Speed cm/min	Time To Fail. (Sec)	Strain At Failure	Strain Rate (Sec ⁻¹)	Stress At Failure kg/cm	Psi	Secant Modulus kg/cm ² X 10 ² Psi X 10 ³	Tangent Modulus kg/cm ² X 10 ² Psi X 10 ³	Test Temp C ^o	-25C Strength kg/cm ² Psi
GR-4	20.47	8.06	7.49	2.95	.602	6.50	2.56	0.75	.00372	.0050	23.7	337	63.3	221.5	-20	27.6 392
GR-5	20.73	8.16	7.47	2.94	.601	9.75	3.84	0.78	.00613	.0078	27.4	389	88.6	163.8	-22	29.7 422
GR-6	20.70	8.15	7.44	2.93	.610	5.51	2.17	0.84	.00372	.0044	30.7	437	82.3	117	-22	33.0 470
GR-8	20.68	8.14	7.47	2.94	.610	5.84	2.30	0.78	.00391	.0050	28.1	399	70.3	184.2	-22	30.4 432
GR-10	20.78	8.18	7.47	2.94	.605	3.68	1.45	0.69	.00205	.0030	27.7	394	129.4	184.6	-22	30.0 427
GR-11	20.76	8.18	7.49	2.95	.602	4.80	1.89	0.78	.00301	.0039	28.2	403	92.8	163.8	-22	30.7 436
GR-13	20.62	8.12	7.47	2.94	.612	6.15	2.42	0.75	.00373	.0050	25.0	356	64.7	178.6	-20	28.9 411
GR-14	20.55	8.09	7.42	2.92	.624	5.31	2.09	0.71	.00319	.0043	26.6	378	85.1	175.1	-20	30.4 433
GR-15	20.62	8.12	7.47	2.94	.606	4.80	1.89	0.71	.00374	.0039	27.2	387	96.3	158.9	-20	31.1 442
GR-16	20.73	8.16	7.47	2.94	.615	4.24	1.67	0.79	.00271	.0034	27.8	395	101.3	182.1	-20	31.6 450
GR-17	20.55	8.09	7.49	2.95	.615	4.39	1.73	0.76	.00270	.0036	29.2	416	110.4	173.0	-22	31.6 449
GR-18	20.78	8.18	7.47	2.94	.615	4.22	1.66	0.71	.00267	.0038	26.4	375	99.2	167.4	-20	30.2 430
GR-21	20.70	8.15	7.47	2.94	.622	4.09	1.61	0.70	.00274	.0039	21.9	312	80.9	145.6	-20	25.8 367
GR-22	20.73	8.16	7.52	2.96	.614	4.78	1.88	0.80	.00308	.0038	28.6	407	92.8	163.1	-20	32.5 462
GR-25	20.75	8.17	7.52	2.96	.617	4.22	1.66	0.69	.00234	.0034	23.7	337	69.6	169.5	-20	27.6 392
GR-26	20.80	8.19	7.52	2.96	.614	3.91	1.54	0.76	.00253	.0033	29.5	419	117.4	167.4	-20	33.3 474
AVG	20.68	8.14	7.47	2.94	.612	5.14	2.02	0.75	.00318	.0042	27.0	384	90.0	173.0		30.2 430

UNCONFINED COMPRESSIVE STRENGTH DATA ON FIRN TESTED AT CAMP CENTURY
(From Kovacs A., Weeks, Michetti, 1969)

1	NA	NA	NA	NA	.608	7.49	2.95	0.39	.00117	.0030	21.5	242	145.6	177.2	-25	252
2	"	"	"	"	.619	10.57	4.16	0.45	.00202	.0045	23.0	327	113.9	170.2	"	242
3	"	"	"	"	.611	9.02	3.55	0.40	.00168	.0042	19.6	279	116.7	173.0	"	246
4	"	"	"	"	.617	12.37	4.87	0.30	.00154	.0051	23.0	327	149.1	172.8	"	260
5	"	"	"	"	.620	16.51	6.50	0.19	.00147	.0077	20.0	287	137.1	172.3	"	245
6	"	"	"	"	.610	11.02	4.34	0.35	.00175	.0050	17.8	253	102.0	174.4	"	248
7	"	"	"	"	.623	12.80	5.04	0.40	.00237	.0059	22.5	320	94.9	147.7	"	210
8	"	"	"	"	.618	10.18	4.01	0.34	.00149	.0044	17.8	253	119.6	185.6	"	264
9	"	"	"	"	.615	12.22	4.81	0.38	.00242	.0064	20.1	286	83.0	138.5	"	197
10	"	"	"	"	.621	11.02	4.34	0.40	.00197	.0049	24.6	350	125.2	177.2	"	252
11	"	"	"	"	.616	9.09	3.58	0.39	.00148	.0038	20.2	287	136.4	174.4	"	248
12	"	"	"	"	.624	10.44	4.11	0.44	.00219	.0050	22.7	323	103.4	156.1	"	222
13	"	"	"	"	.622	10.16	4.00	0.45	.00229	.0051	25.0	356	109.0	163.2	"	232
14	"	"	"	"	.612	11.15	4.39	0.45	.00200	.0044	23.0	327	118.1	175.1	"	249
15	"	"	"	"	.614	9.24	3.64	0.42	.00175	.0042	21.8	309	124.5	185.6	"	264
AVG	20.96	8.25	7.6	3.0	.617	10.90	4.29	0.38	.00188	.0049	21.2	302	118.1	168.8		240

The above platen system can be used as follows. A test specimen is placed upon the platen, the ram is activated and the specimen is lifted upward against the rigid load cell. At contact the specimen automatically seats itself. This is possible because the cap is free to move laterally, allowing the platen to pivot the specimen into proper alignment. (This movement is illustrated in Figure 2.) The above technique is most desired when the test is to be performed at a set press speed. The automatic alignment feature allows the machine to come up to speed prior to specimen contact with the upper bearing surface.

When press speed is not important and lateral translation of the cap is not desired during the test, the test can be performed as follows. The specimen is brought into alignment by applying a very "low" seating load. The cap is then immobilized by seating the locking screws (shown in Figure 1). Loading is then continued.

A second generation platen system has been designed to eliminate the need to stop and lock the cap (Kovacs 1970). In this study the first generation platen assembly was not locked.

Test Results

It has been shown that when unconfined compression tests are performed on snow ice above -21.4°C at a strain rate faster than $0.0035/\text{s}$, there is no significant change in the failure stress (Carter 1970). Strain rates lower than $0.0035/\text{s}$ can have a significant effect upon the failure stress (Korzhevskiy 1962); therefore, to reduce the strain rate effect, for which there is no satisfactory correction, only samples which failed at rates higher than $0.0030/\text{s}$ were selected for use in this comparative study.

The time to failure and strain at failure for the unconfined compression test specimens used in this study (Table I) averaged 0.75 s and 0.00318 s , respectively. The average strain rate was $0.0042/\text{s}$ compared with $0.0049/\text{s}$ for the samples tested at Camp Century (see Table I). The fact that the average strain rate for this test program and the one made at Camp Century are above $0.0035/\text{s}$ and in close agreement with one another should eliminate bias in the failure stress due to strain rate effects and should make direct comparison between the tests possible.

The unconfined compressive strengths listed in Table I show that the specimens tested at Camp Century, Greenland, failed at an average unconfined compressive strength σ_c of 21.2 kgf/cm^2 (302 psi) while those tested on the new self-aligning platen system at CRREL failed at 27.0 kgf/cm^2 (384 psi), a 27% higher stress level. However, Table I also shows that the samples tested in Greenland were at -25°C while those tested at CRREL were 3° to 5°C warmer. There are numerous reports (e.g. Carter 1970, Bender 1957, Butkovich 1954, Kovacs 1967, Mellor and Smith 1966, Peyton 1966, Veinberg 1929, Vitman and Shandrikov 1938, Weeks and Assur 1969, and Wolfe and Thieme 1963) which discuss the σ_c dependence of snow or ice on temperature. Carter (1970), for example, shows that between -10° and -30°C the strength

of snow ice changes at approximately $2.2 \text{ kgf/cm}^2 \text{ } ^\circ\text{C}$ ($31 \text{ psi/}^\circ\text{C}$). This rate of strength increase is high in comparison to those found by most other investigators. The norm is perhaps best expressed by the σ_c vs temperature data of Butkovich (1954), Vitman and Shandrikov (1938) and Wolfe and Thieme (1963). Their data show that in the temperature range of -20°C to -40°C the unconfined compressive strength of ice changes at the rate of $\approx 0.75 \text{ kg/cm}^2 \text{ } ^\circ\text{C}$ ($\approx 11 \text{ psi/}^\circ\text{C}$). To conform with the Camp Century test temperature, the σ_c values obtained at -20° and -22°C have been adjusted to -25°C using the above correction. In so doing the average σ_c value for the laboratory tests becomes 30.2 kg/cm^2 (430 psi) and the difference between the average of the lower Camp Century σ_c values and that of the laboratory σ_c values increases to 42%.

It was pointed out that the output from the three LVDT's, which recorded sample deflection and the output from the load cell, were recorded on a high-speed magnetic tape recorder. These signal data were then played back at a much slower speed into an X-Y plotter. Load vs deflection, load vs time, and deflection vs time plots could thus be obtained. Work sheets with the load-deflection and load-time curve for each specimen are shown in Figures 3-18. Electrical noise within the CRREL laboratory picked up by the tape recorder caused the saw-tooth microrelief on the curves. Various filtering techniques were tried in an attempt to eliminate the noise and smooth the curves but they were abandoned when it was noted that the data were adversely affected. The curves nevertheless are exceedingly interesting, for they provide a new insight into the stress-strain behavior of firn and, as Kovacs (1970) has shown for ice up to failure, a load history which can only be observed through the use of a high-speed recorder.

Examination of the load-deflection curves (i.e. stress-strain curves) shows that there was very little curvature prior to Hookian behavior and that the load-deflection curves show one or more steps. The strain adjustment events were not the record of LVDT seating. This is clear from the load vs time curves, which show that each step in the load-deflection curve was accompanied by a sudden decrease in load. This would suggest that stress concentrations were being released by some dilatatory event, perhaps one associated with the movement of line defects or the formation of microcracks. This phenomenon was observed in the Camp Century test data (see, for example, stress-strain curves 30 V-2 and 30 V-3 of Fig. 10 in Kovacs et al. 1969) but was not referred to in Kovacs et al. (1969) due to an uncertainty of the reality of such a phenomenon. Experiments by Hudson et al. (1971) indicate that dilatatory adjustments also occur in the stress-strain curves of marble, sandstone and concrete tested in unconfined compression.

With some tests the tangent moduli E_T increased after dilation (see Fig. 16) while in others there was a decrease (see Fig. 4). However, for the majority of the tests there was no significant change in E_T as a result of dilation. This was surprising as it infers that no "hardening or stiffening" nor structural weakening occurred during this stress-strain readjustment.

The tangent and secant moduli for each test are listed in Table I. No temperature adjustment has been made in moduli from the laboratory tests to conform to the temperature of the Camp Century tests. The reason is that

Nakaya (1959) has shown that between -10° and -30°C there is only a 2.0% change in the dynamic modulus per $^{\circ}\text{C}$. One may assume that the same would be true for the static modulus. Table I shows that the average tangent modulus obtained from the laboratory tests ($17,300 \text{ kgf/cm}^2$ or $246,000 \text{ psi}$) and from the Camp Century tests ($16,880 \text{ kgf/cm}^2$ or $240,000 \text{ psi}$) are nearly the same. The slight difference which does exist is probably related to the method used to analyze the data from Camp Century, i.e. masking dilation steps in the stress-strain curves. Therefore, for all intents and purposes the tangent moduli are within experimental error and show, as expected, that the two studies were performed on firm with the same structural properties.

In a number of tests following the last dilation recorded the load did not immediately drop to zero but held momentarily or even tried to increase. This may be seen in Figures 7, 12, 15, and 17.

Discussion

The strength of snow varies not only with its density and structure but also with external conditions which change its internal nature and stress distribution. In this respect snow and ice exhibit a complexity of poly-phases which makes determination of their physical and mechanical properties directly related to the external conditions existing at the time of each determination. Although experiments have been performed on snow and ice during which certain external conditions have been held constant (e.g. temperature, strain rate, load rate, stress, specimen size, etc.), the physical nature of the deformation and strength properties of snow is still not clearly understood. Attempts to develop theories related to snow deformation or collapse under load have therefore lacked agreement with fact. This difficulty is related to the physical nature of snow or ice whose strength and structure change directly with external conditions which have not been adequately determined or taken into consideration.

In this comparative study every effort was made to limit the variables known to affect unconfined compression test results. This included the use of snow samples of virtually the same size, shape and density obtained from the same location. The hydraulic testing machine used for the Camp Century tests was also used at CRREL. The strain rate was nearly the same for both studies but most importantly averaged above $0.0035/\text{s}$, the rate below which the failure strength of ice increases rapidly and above which no apparent increase in failure strength occurs. The temperature was warmer for the CRREL tests but this effect could be corrected for.

Two variables did exist which made the samples tested and the test apparatus used at CRREL different from those used in the Camp Century study. First, while careful sanding and hand honing of specimen ends was performed on each Camp Century specimen to ensure that the ends were flat, parallel, and perpendicular to the sample axis, it must be considered that the samples prepared on the lathe at CRREL were more nearly perfect right cylinders with flatter ends. Secondly, the platen assembly used at CRREL was, of course, significantly different from that used at Camp Century. Determining the exact contribution of these two variables to the net gain in the σ_c values noted in the CRREL tests is not possible; however, the relative contribution

is. Kovacs (1970) performed unconfined compression tests on freshwater ice samples of the same size and shape as those used in this study. The samples were made into right cylinders on the same lathe and tested on the same hydraulic press. The significance of these tests is that the samples tested on the new platen assembly failed at an average 30% higher stress level than similar samples tested on a conventional platen-ball assembly. It may thus be reasoned that of the 42% increase in the average failure stress of the firm samples tested at CRREL over those tested at Camp Century, 30% is the result of better alignment on the new platen assembly and 12% is due to better specimen preparation.

While the noted increase in failure stress is significant and represents the highest σ_c values obtained to date on 0.60-0.625 g/cm³ density snow at these strain rates, the scatter in the data has not been reduced. It is speculated that the scatter is not that associated with imperfect sample preparation or imperfect sample alignment but is the result of inherent crystalline or structural flaws.

The load-deflection curves all show that strain dilation accompanied by load reduction occurred during each of the unconfined compression tests made at CRREL. These adjustments characteristically occurred in 8 ms, during which the highest load decrease noted was 208 kg (460 lb) and the highest deflection measured was 0.025 cm (0.01 in.). The cause of this dilation phenomenon may be associated with strain adjustment around internal dislocations or microfractures (Savage and Mohanty 1969) or with initial splitting of the test specimen into a columnar structure prior to failure. Kovacs (1970) has explained the dislocation as follows:

Whatever the cause, it can be postulated that failure may be brought on prematurely by the elastic-response of the testing machine during this strain adjustment. The reasoning here is that during strain-adjustment the machine is suddenly unloaded and elastically tries to return to its fully unloaded state. The sample, in the process of adjusting to receive additional load, is suddenly overloaded by the "onrushing" machine and fails. If this is what happened at failure then the test specimens could have sustained even greater loads. At the least it points out the desirability of performing unconfined compression tests with a stiff machine, i.e. one with "little" compliance, to ensure against premature failure (Kovacs 1970).

For a description of stiff testing machines see, for example, Bieniawski (1966, 1967, 1968 and 1969), Hawkes and Mellor (1970), Hudson et al. (1971), and Rummel and Fairhurst (1970).

Conclusion

The results of this study support the contention of Kovacs et al. (1969) that their unconfined compressive strengths of Camp Century snow and ice may be low due to possible irregularities on the specimen ends and/or non-axially loaded samples. Either of these conditions would cause a nonuniform stress field to exist across the sample ends and cause samples to fail at a lower stress level than if a uniform stress field existed. The combined effect of preparing cylindrical firm samples on a lathe and testing them on

a new multi-degree-of-freedom, self-aligning platen assembly at CRREL was a significant increase (42%) in the average unconfined compressive strength of 0.600- to 0.625-g/cm³ density snow over that of samples tested at Camp Century, Greenland. These results coupled with those of Kovacs (1970) show the advantage of using a self-aligning platen system to ensure nonaxial loading of unconfined compression test specimens. It is hoped that other investigators will make similar comparative unconfined compression tests to further document the merit of self-aligning platen systems. With guarded optimism the author believes that such tests will show higher strength values consistently obtained with the use of a self-aligning platen assembly.

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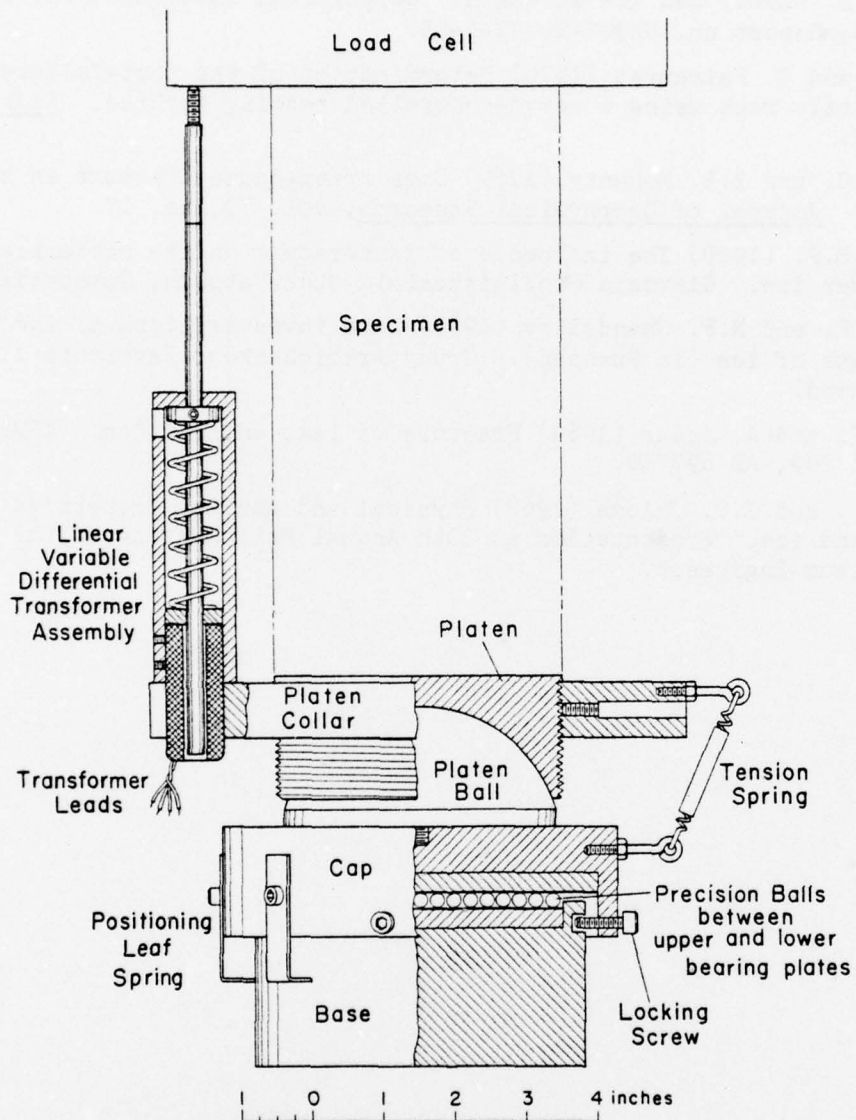


Figure 1. Multi-degree of freedom self-aligning prototype platen assembly used to eliminate misalignment of unconfined compression test specimens.

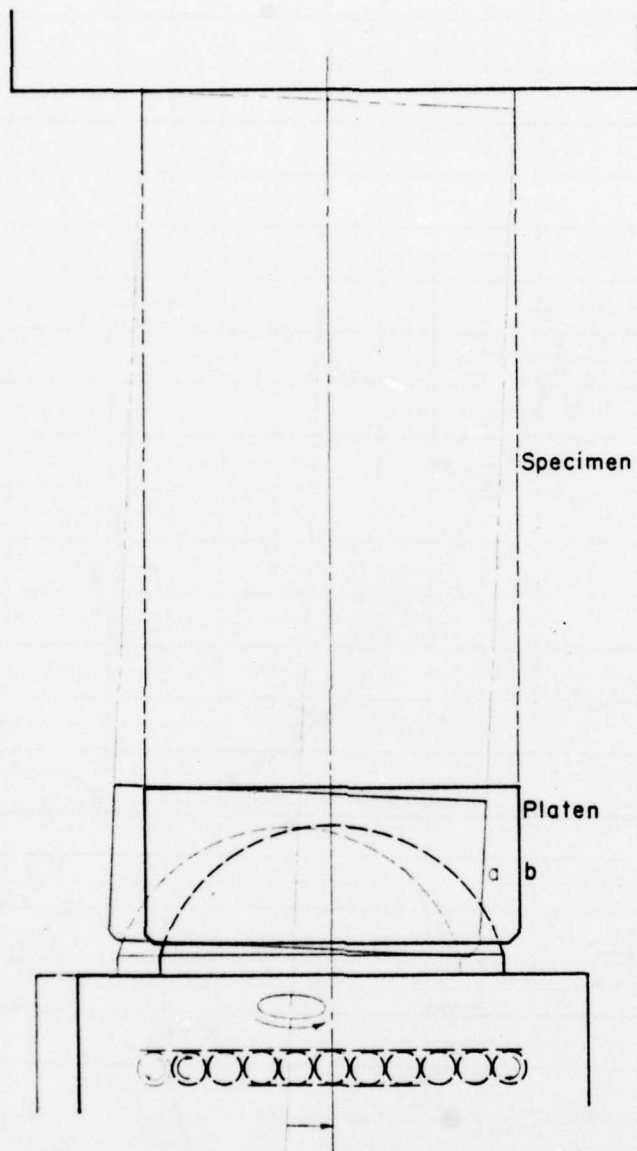


Figure 2. The new platen assembly enables self-alignment of unconfined compression test specimens by allowing the platen to shift laterally from a to b and to rotate if necessary.

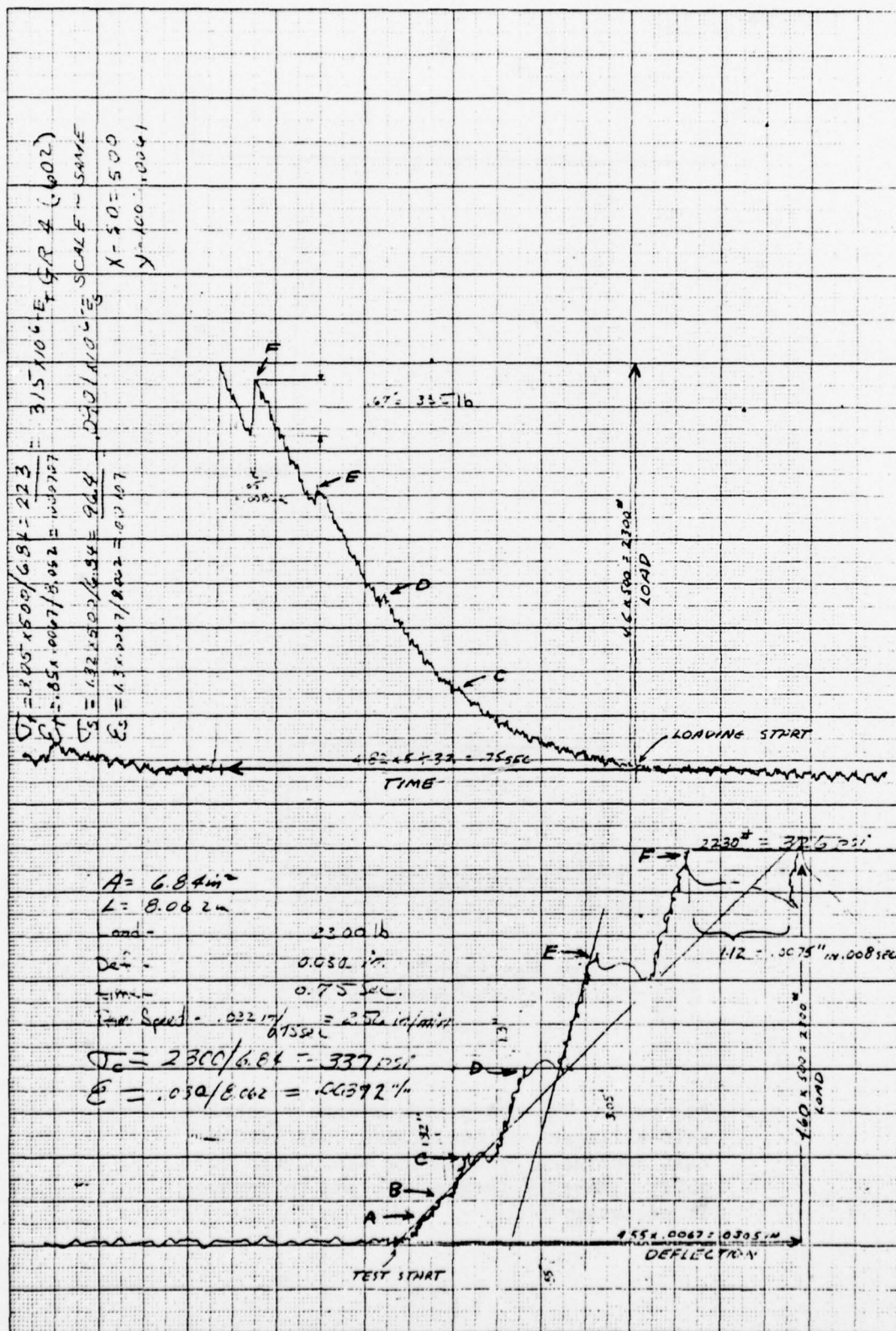


Figure 3. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-4.

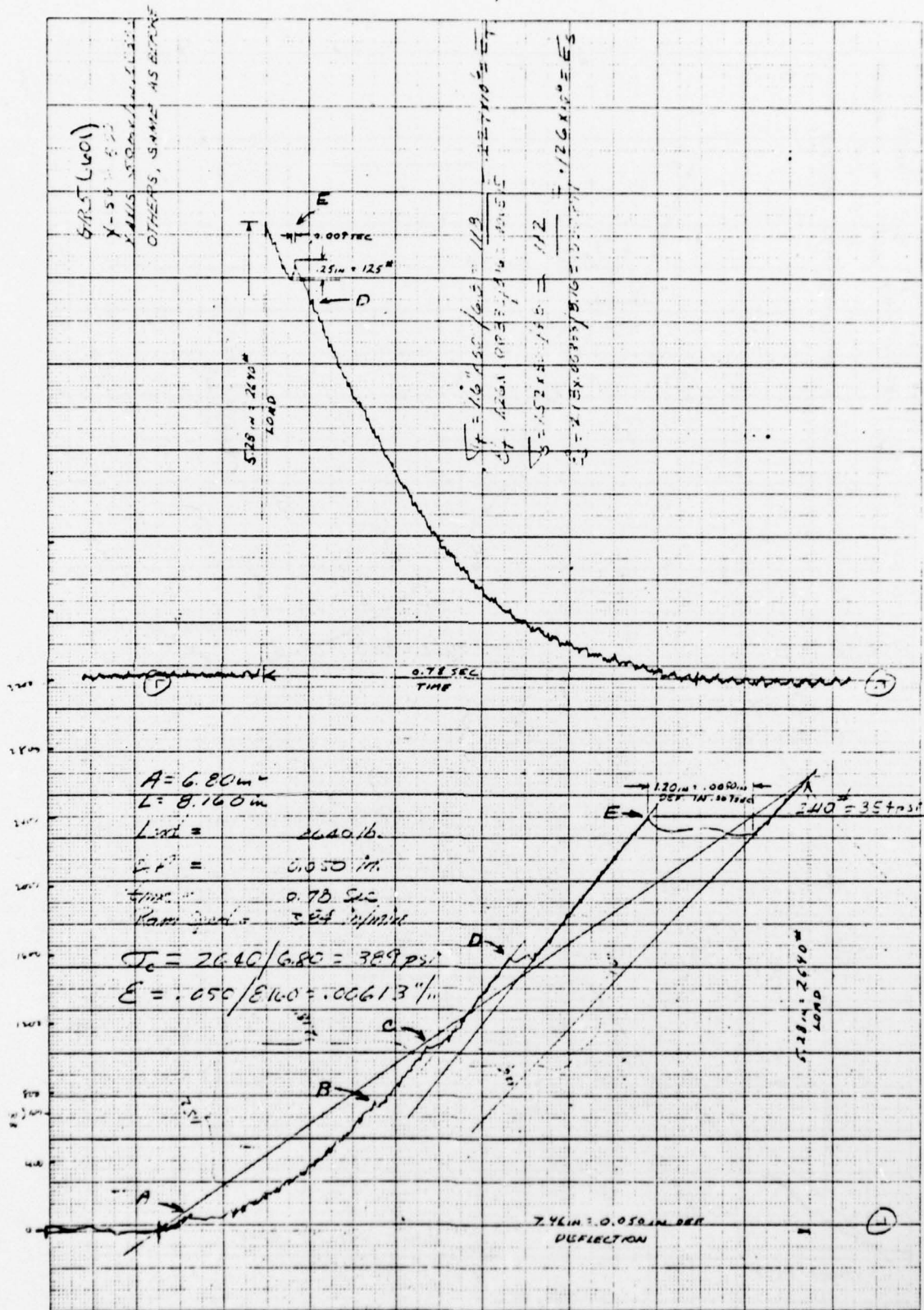
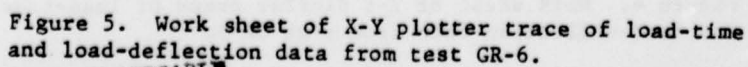


Figure 4. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-5.



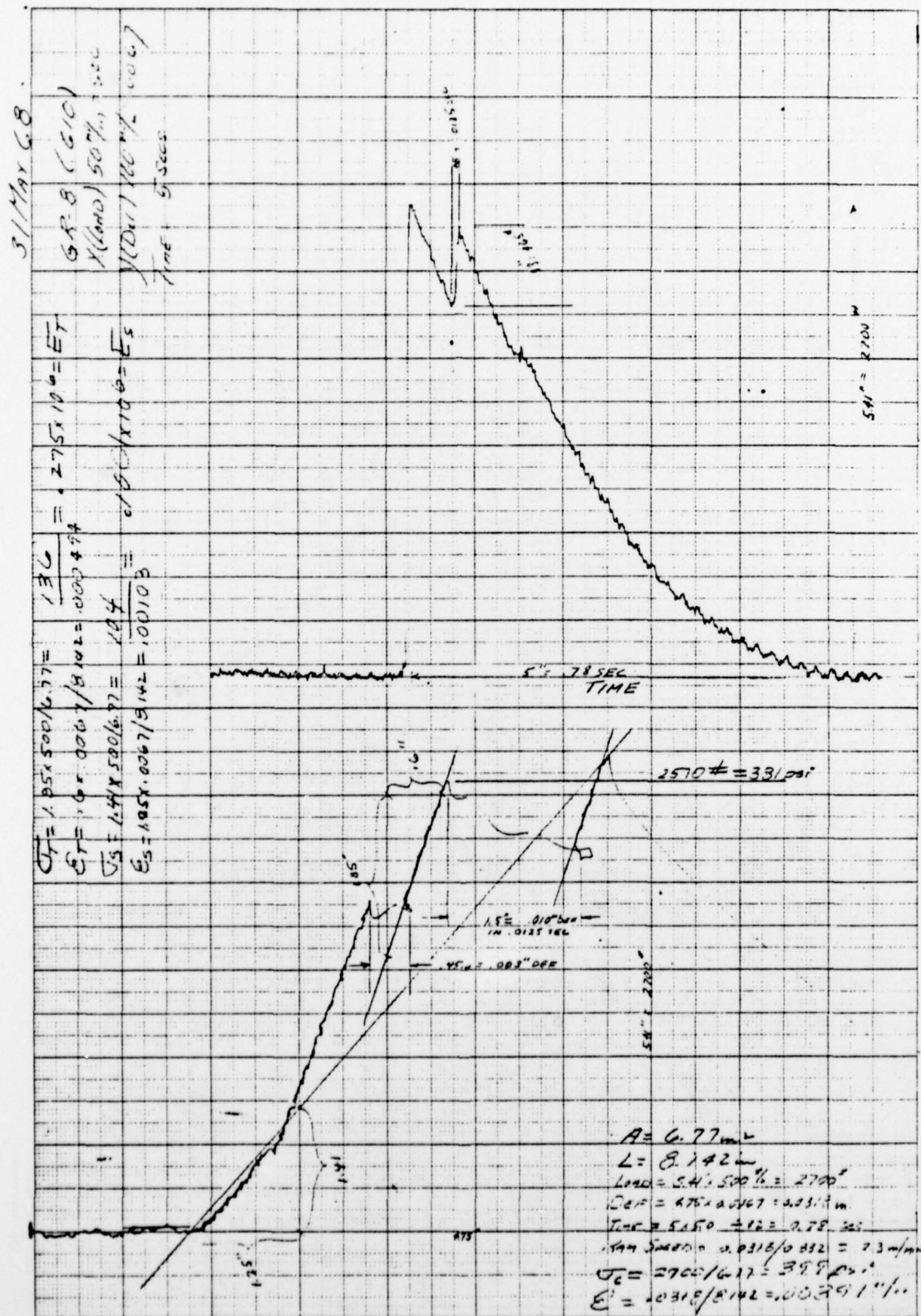
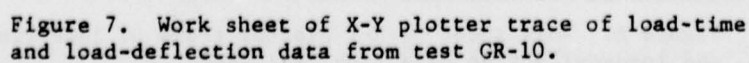


Figure 6. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-8.



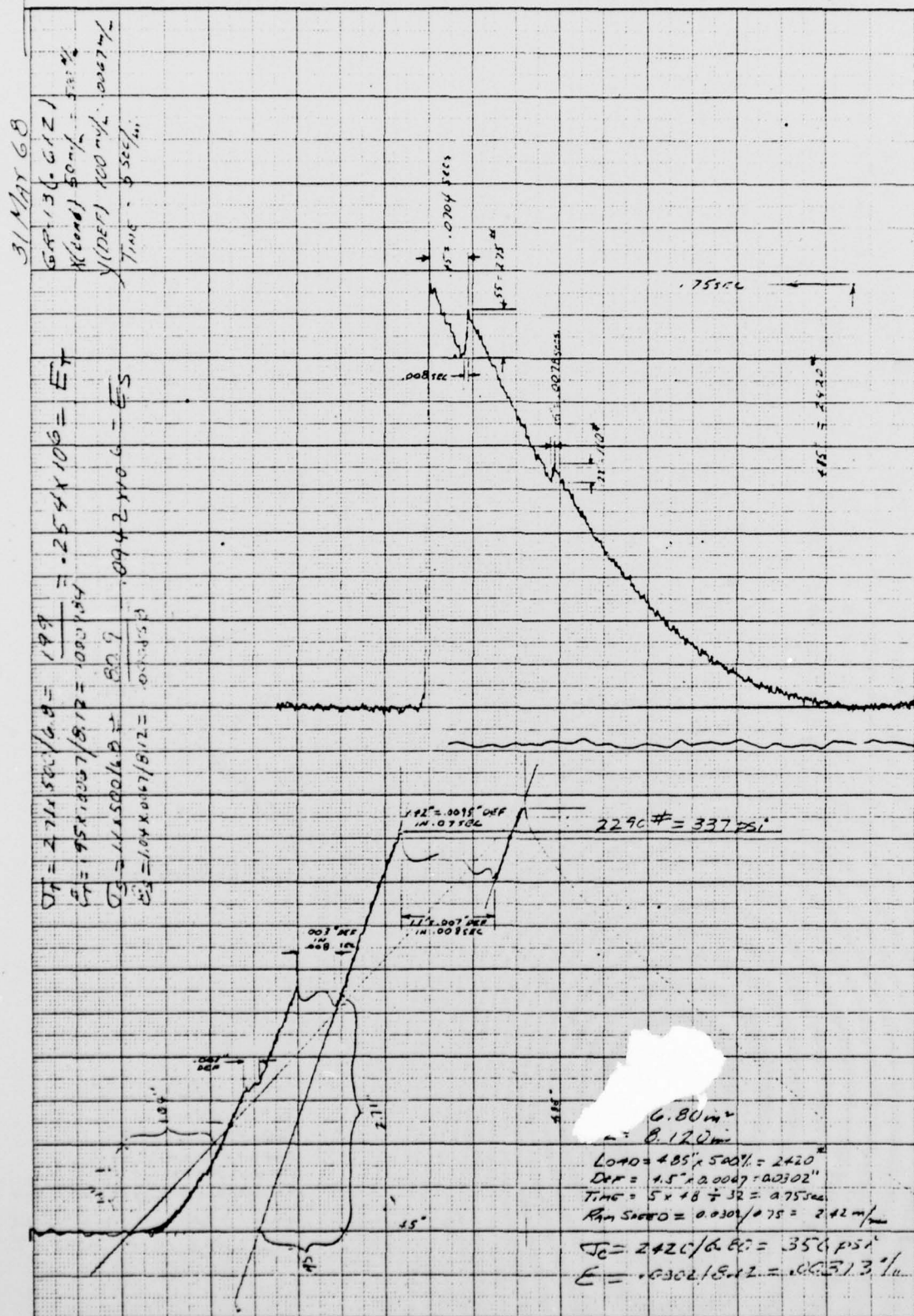
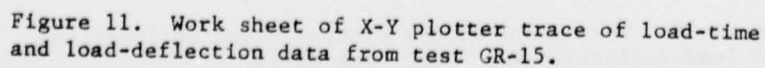
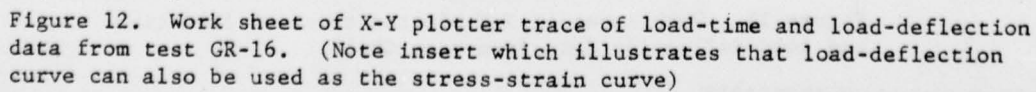


Figure 9. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-13.





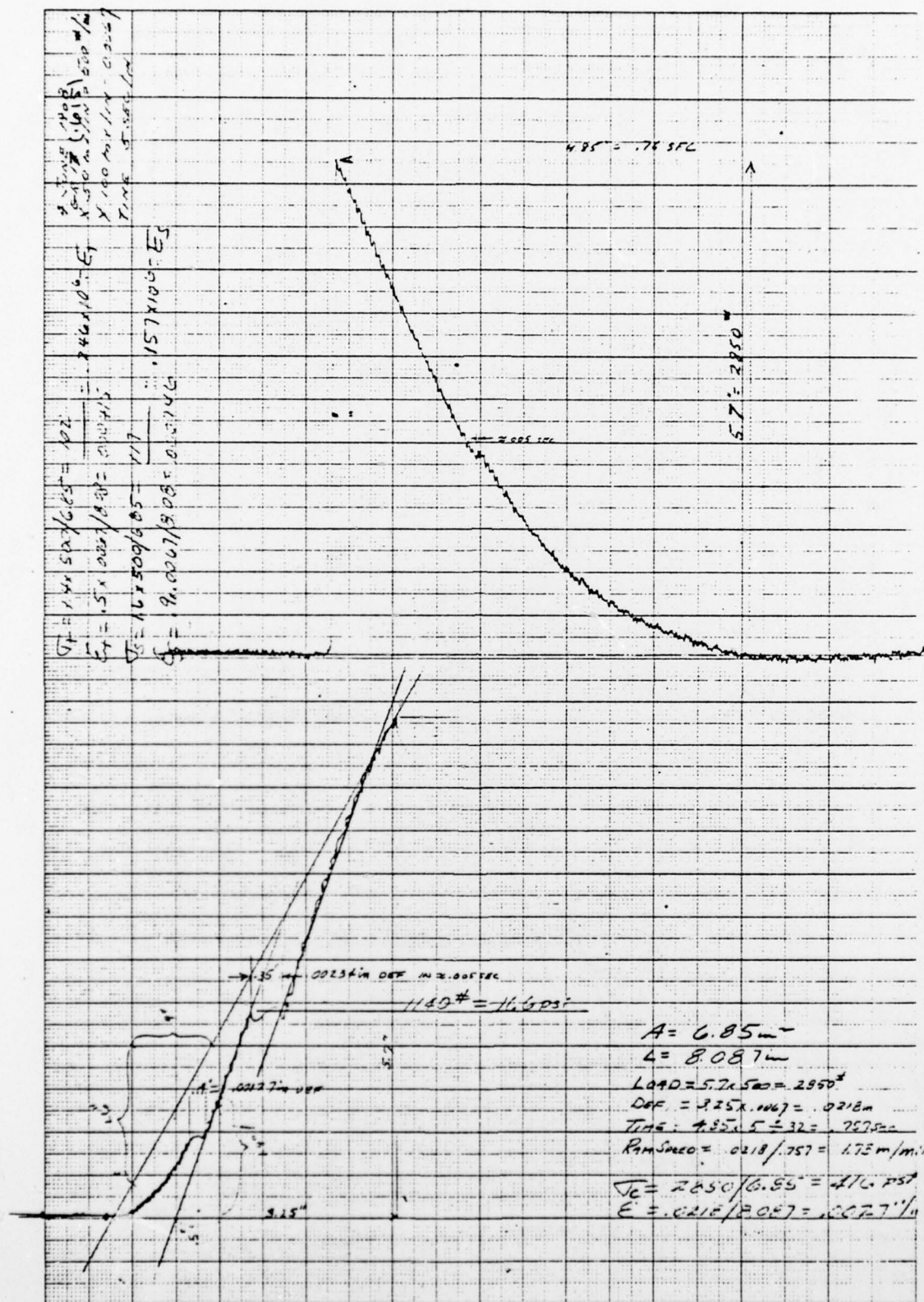


Figure 13. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-17.

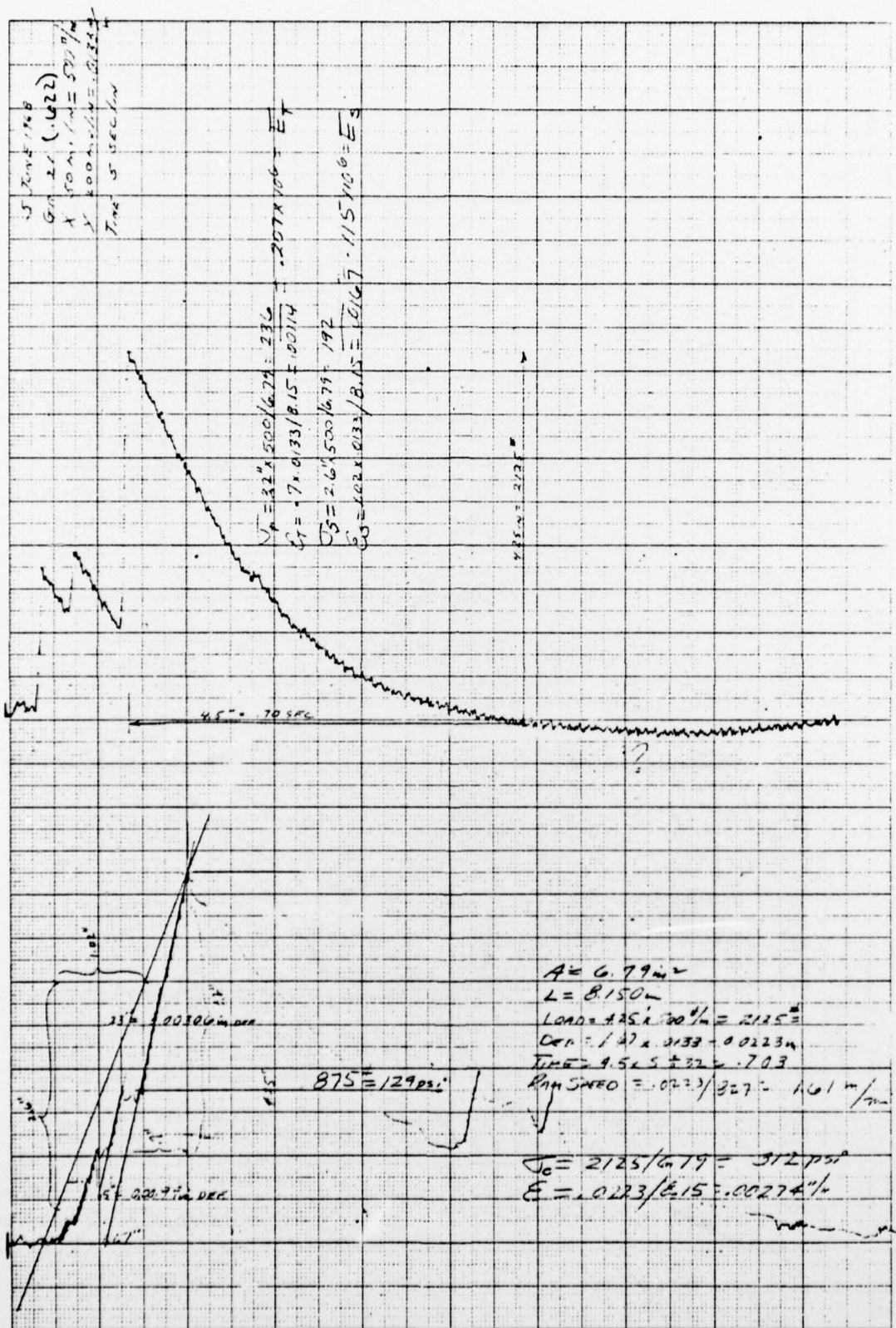
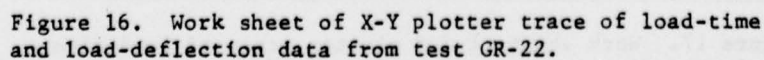


Figure 15. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-21.



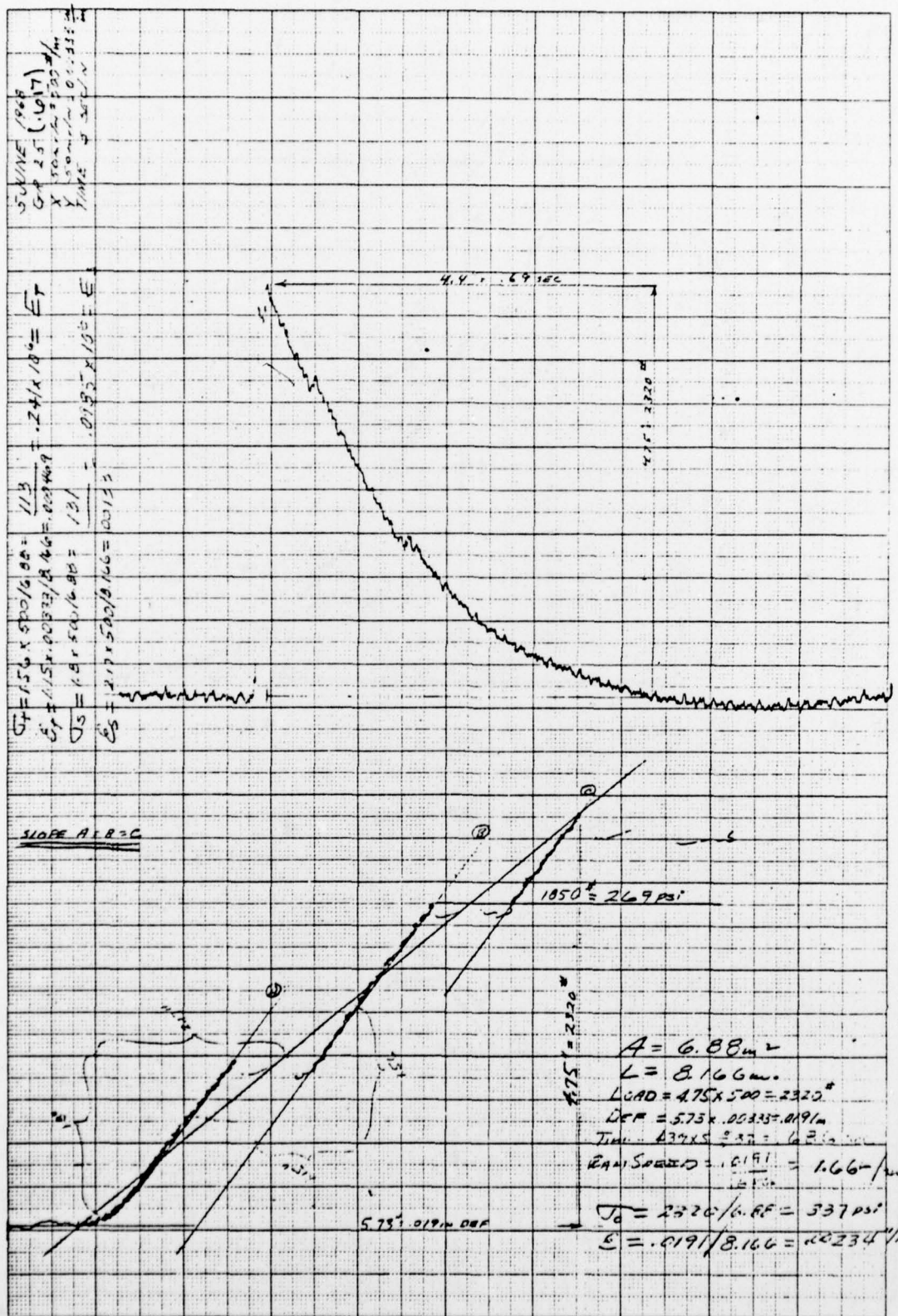


Figure 17. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-25.

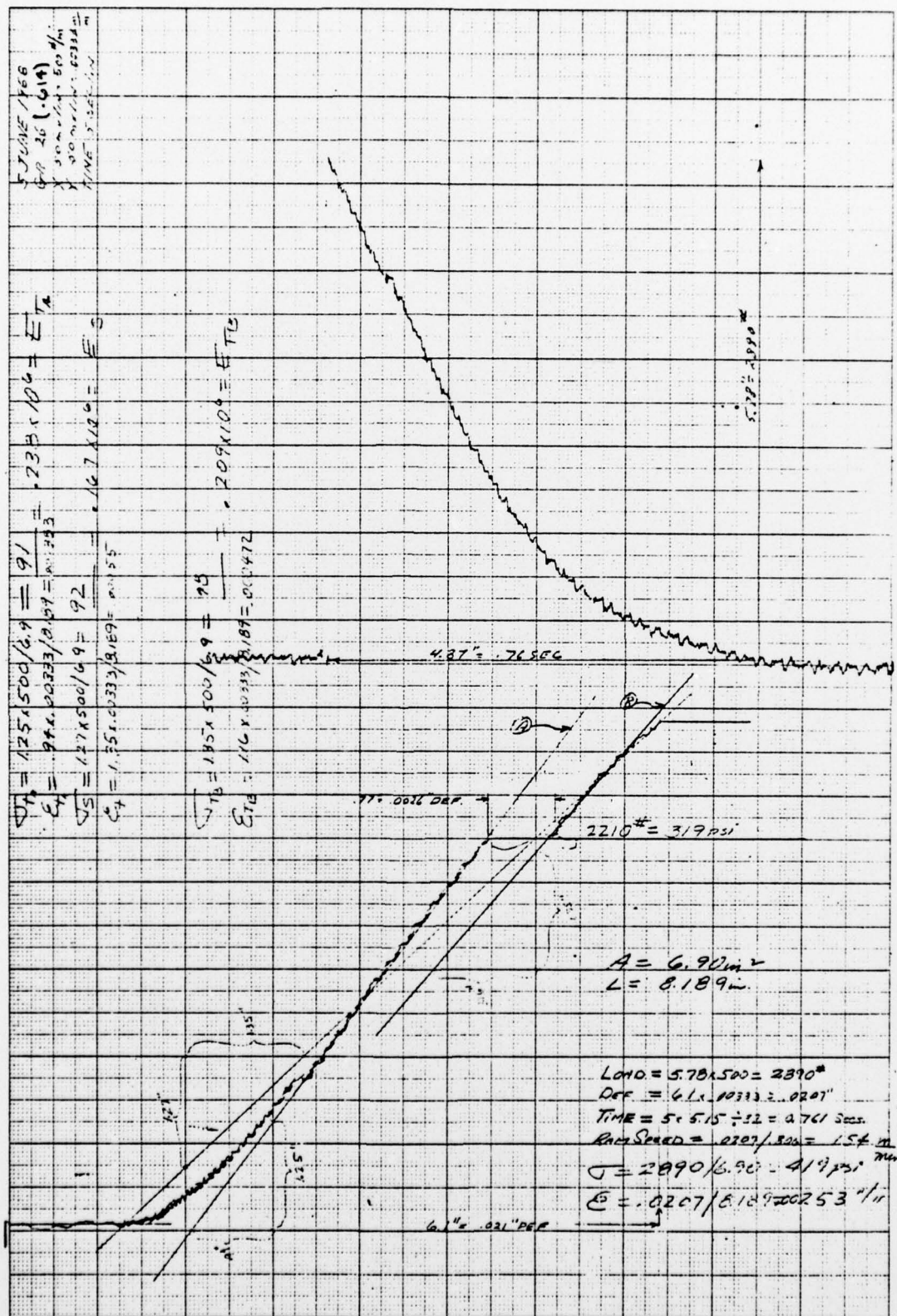


Figure 18. Work sheet of X-Y plotter trace of load-time and load-deflection data from test GR-26.