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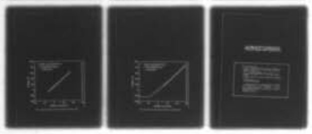

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DYNAMIC PROPERTIES OF MASS CONCRETE

by

Kenneth L. Saucier

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Dynamic direct tensile tests and stress-reversal tests were conducted on core samples from two concrete mixtures representative of mass concrete. Test procedures were developed for cyclical loading and loading to failure
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in 0.25 to 0.025 sec which represent one-fourth of a cycle having a frequency of 1 to 10 Hz. Stress-strain measurements were made on selected specimens. The procedures used could be modified to become American Society for Testing and Materials (ASTM) test methods for direct-tensile and stress-reversal tests of rock.

The tests indicated that there was no significant difference in tensile strength determined statically or dynamically on dry specimens. A 30 percent increase in strength was indicated for wet specimens tested dynamically. Very little hysteresis was evident in the tensile stress-strain curves. The results should be useful in studies conducted to determine the earthquake resistance of mass-concrete structures.

PREFACE

This paper was prepared for presentation in the Symposium on Soil and Rock Testing in the Field and Laboratory for Seismic Studies, sponsored by Committee D-18 on Soil and Rock for Engineering Purposes, held at the 80th Annual Meeting of the American Society for Testing and Materials, Denver, Colorado, June 1977.

The paper was approved for presentation and publication by the Technical Director of the US Army Engineer Waterways Experiment Station (WES). The information contained in the paper was developed through research done under Work Unit 31047, "Dynamic Material Properties of Mass Concrete," of the Civil Works Research Program of the Chief of Engineers. Mr. Lucien Guthrie was technical monitor.

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This paper was prepared by Kenneth L. Saucier, Acting Chief, Concrete and Rock Properties Branch, Engineering Mechanics Division, Concrete Laboratory. The Commander and Director and Technical Director of WES during the preparation of this paper were COL John L. Cannon, CE, and Mr. F. R. Brown.

DYNAMIC PROPERTIES OF MASS CONCRETE

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The tests indicated that there was no significnat difference in tensile strength determined statically or dynamically on dry specimens. A 30 percent increase in strength was indicated for wet specimens tested dynamically. Very little hysteresis was evident in the tensile stress-strain curves. The results should be useful in studies conducted to determine the earthquake resistance of mass-concrete structures.

KEY WORDS: concrete testing, tensile strength, dynamic tensile strength, mass concrete.

DYNAMIC PROPERTIES OF MASS CONCRETE

Introduction

Prediction of the dynamic response of a structure under loading such as could be caused by an earthquake requires a working knowledge of the mechanical properties of the material used in construction of the structure. Specifically, tensile strength, cyclic behavior, and stress-strain relationships appear to be of primary importance. Gravity dams are often constructed of mass concrete. A considerable amount of attention has been given to the compressive-stress parameter of concrete with the resulting recommendation[1] that the dynamic compressive strength used in an analysis be assumed as 125 percent of the static compressive strength, i.e., (f'_c) for dynamic loading conditions. Information on tensile strength, stress-strain relationships, and effects of cyclic loading in the range of seismic loading (1-10 Hz) appears to be meager.[2,3]

The objective of this study was to determine the tensile strength, cyclical behavior, and stress-strain relationships for concrete under seismic loading conditions (1-10 Hz).

Procedure

Mixtures

Two typical mass concrete mixtures were selected for study.

	Mixture 1	Mixture 2
Nominal maximum size aggregate, in. (mm)	3 (75)	3 (75)
Type of fine and coarse aggregate	Limestone	Limestone
Cement factor; lb/yd^3 (kg/m^3)	254 (151)	400 (237)
W/C ratio; by wt	0.80	0.51
S/A ratio; by vol	0.31	0.29
Air content, %	5	5
Slump, in. (mm)	2 (50)	2 (50)
Compressive strength, psi (MPa)	3000 (21)	6000 (41)
Test age	90 days	1 year

Fifteen-cubic-foot (0.76 m^3) batches of concrete were mixed from each mixture and used to cast blocks 16 in. (400 mm) high. The blocks were cured for 28 days and then cored to secure nominal 8- by 16-in. (200- by 400-mm) cores. The cores were stored in air until date of test.

Test Methods

The dearth of test data on the direct tensile strength of concrete indicated that equipment to conduct such tests would likely not be readily available. When this premise proved correct, plans were made to modify the equipment available at the Waterways Experiment Station (WES) to conduct dynamic monotonic (single stroke) and cyclical tensile-strength tests on mass-concrete test specimens. Contact with the US Bureau of Reclamation (USBR) revealed that a rapid-loading test machine at their Denver laboratory could possibly be used to conduct stress-reversal tests through the tensile-compressive range in question on large specimens. To assure that some reliable information was developed, the test schedule was formulated to use both machines. Also, if useful data were obtained using both machines, comparisons could be made between direct tensile tests and stress-reversal tests.

The absence of a standard test led to the development and use of a method of test for direct tensile strength of concrete patterned after the ASTM Standard Method of Test for Direct Tensile Strength of Intact Rock Core Specimens (D 2936-71). Two diametrically opposed electrical-resistance strain gages were used on selected specimens to provide longitudinal stress-strain information. The test arrangement is shown in Figure 1. The procedure for the stress-reversal tests is similar to that for direct tensile strength. Specimens used were companion cores to those tested for direct tensile strength. Specimens were cut to proper length, gaged, and shipped to the USBR only after the concrete had reached 90-days age. The test configuration for the stress-reversal tests is shown in Figure 2. Preparation consisted of placing the specimen in the test frame with end pieces attached by epoxy. The epoxy was allowed to harden overnight. Prior to test the specimen was cycled statically to 700 psi (5 MPa) compression for the purpose of securing proper seating of all components. Rapid load tests were then conducted either through a cyclic phase or monotonically, both starting with a preload of 200 psi (1.4 MPa) compression. Figure 3 gives typical strain-time curves for a specimen undergoing cyclical loading.

Test Program

The large energy input to concrete gravity dams is to be most likely in the range of 1 to 10 Hz. The test program was thus established to include tests to failure within a time frame based on this frequency. Since there are four distinct parts of an earthquake loading pulse: (1) tension loading and (2) unloading, and (3) compression [illegible]ng and (4) unloading, the time to tensile failure should be one-fourth o[illegible]le time. Thus, the time to failure (rise time) for 1-, 5-, and 10-Hz tests would be 0.25, 0.05, and 0.025 sec, respectively. There is, of course, no way of knowing the strength of a specimen beforehand; the rise times achieved in the actual tests varied somewhat from those desired, generally ±20 percent.

In order to investigate the effects of monotonic stress reversal and cyclical loading and difference in moisture content on mass concrete, several types of loading conditions were used:

1. Direct tension tests cycled to either 60 percent or 80 percent of ultimate strength for approximately 25 cycles, then loaded to failure at the rate used during cycling.
2. Stress-reversal tests cycled to 80 percent of ultimate tensile strength for approximately 25 cycles, then loaded to tensile failure at the rate used during cycling.
3. Monotonic (single stroke) direct tension tests in which the failure load is applied so that the specimen fails during the first and only

pulse of a dynamic loader at a peak load occurring at one-fourth of the cycle time.

4. Monotonic stress-reversal tests in which the failure load is applied so that the specimen fails in tension during the first and only tensile pulse following the compressive portion of the cycle. The tensile failure stress is caused to occur at one-fourth of the complete cycle time.

5. Monotonic direct-tension static tests in which produce failure in approximately 60 sec of loading time.

Experimental Work (Results)

Cyclical Tests

Cyclical tests were conducted on 34 specimens from mixture No. 1 to determine the effect of repetitive loading on the ultimate strength of mass concrete. Specimens were loaded through approximately 25 cycles for a predetermined percentage of the estimated ultimate tensile strength at three different rates of loading. The specimens which did not fail during cycling were then loaded to failure monotonically. Results are given in Table 1. Seven of the 34 specimens failed during cycling:

Type Test	Specimen No.	Rate of Load, Hz	Failed on Cycle No.	Tensile Strength, psi	(MPa)
Direct Tension	18	1	5	200	(1.4)
Direct Tension	20	1	14	215	(1.5)
Stress Reversal	CE-2	1	1	210	(1.4)
Stress Reversal	3-10	5	5	230	(1.6)
Stress Reversal	CE-8	10	9	175	(1.2)
Stress Reversal	3-5	10	2	160	(1.1)
Stress Reversal	3-7	10	20	170	(1.2)

The ultimate monotonic tensile strength of virgin specimens from mixture No. 1 was found to be approximately 235 psi (1.62 MPa) (Table 2). Indications are, therefore, that some failures may be expected under cyclical loading at approximately 70 to 90 percent of the ultimate tensile strength.

Monotonic Tests

Monotonic (single stroke) tests were conducted on representative virgin specimens from each mixture and on specimens which did not fail during cycling. Both direct tension and stress reversal tests were conducted at different loading rates and results compared where feasible. Results of tests on the virgin specimens are given in Table 2. Although the data are somewhat limited, indications are that the rate of loading has no effect on the tensile strength for either mixture up to 10 Hz. Using the data from Table 3, it may be noted that the tensile strength of mixture No. 1 is approximately 8 percent of the compressive; however, for mixture No. 2, the tensile strength is only 5 percent of the compressive strength.

Those specimens which did not fail during cyclical loading (Table 1) were subsequently tested to failure monotonically. Twenty-seven specimens from mixture No. 1 were so tested. Results are given in Table 2. Again, no significant difference is indicated between rapid tensile strength and static tensile strength up to 10-Hz loading rate. The slight increase in average strength of the previously cycled specimens may be explained by the elimination of the weaker specimens during cyclical testing. Also of relevance is a comparison of the test methods. At the 1-Hz rate there is apparently no significant difference in the ultimate tensile strength obtained by the two methods, rapid direct and stress reversal.

Statistical treatment of the data developed for the two types of tests and various rates of loading would be desirable. Given below is the pertinent information for the failure tests of mixture No. 1.

Type Test	Rate of Load, Hz	No. of Specimens	Average Strength, psi	(MPa)	Standard Deviation, psi	(MPa)
Direct Tensile*	0.02	10	238	(1.64)	15	(0.10)
Direct Tensile*	1-5	10	241	(1.66)	20	(0.14)
Direct Tensile	1	8	254	(1.75)	17	(0.12)
Stress Reversal	1	7	269	(1.85)	40	(0.28)
Stress Reversal	5	7	249	(1.72)	38	(0.26)
Stress Reversal	10	5	267	(1.84)	25	(0.17)

*Virgin specimens, all others cycled specimens.

Due to the limited data, the closeness of the averages, and the relatively large standard deviations, detailed statistical analyses would serve no useful purpose. A cursory examination of the average strengths and standard deviations is sufficient to reveal that there is no significant difference in the various test methods or loading rates. There is less variation in results of the direct tensile tests than the stress reversal tests which, in the absence of other considerations, would provide a basis for selection of the direct tensile test as the standard method of test for evaluation of concrete under earthquake-type loading conditions.

The predominant effect in all the tensile tests was probably the alignment of the large aggregate with respect to the stress field. The interface of the aggregate and the paste was obviously the weakest portion of the concrete conglomerate. Large pieces of aggregate were exposed in most specimens after failure, as shown in Figure 4. The random alignment of these interfaces apparently determines the stress level at which a specimen will fail. Thus, one with a large critically positioned, smooth surface would fail at a much lower stress than one on which the bond interface was rough or was not required to resist a high tensile stress.

Moisture Effects Tests

A suite of tests was conducted on specimens from mixture No. 1 to determine the effects of moisture on the rapid loading strength of mass concrete. Half of the test specimens were inundated for 28 days prior to test while the other half remained in air storage. Direct tensile tests were conducted when the concrete was approximately one year old. Considerable difficulty was experienced in affixing the end caps to the wet cores; 18 tests were required to secure the 10 usable pieces of data for the wet specimens.

Results of the moisture effects tests are given in Table 3. Again, no difference is indicated in static and rapid loading-direct tensile strength of dry specimens. However, an appreciable increase, apparently 30 percent, in strength is indicated between the static and rapid loading strength of wet specimens. Thus the effect of rate of straining appears to be significant when moisture is present. Not unexpected is the decrease in static strength, both compressive and tensile, when test specimens are saturated. It should also be noted that no difference is indicated in the rapid loading direct tensile strength of concrete whether tested wet or dry.

Tests of Jointed Specimens

It is recognized that a massive unreinforced concrete structure will likely contain both joints and cracks due variously to construction requirements, temperature and volume changes in the mass, and foundation movement. These joints and/or cracks will have strength values varying between 0 and 100 percent of the mass. Obviously tests are not required to determine that direct tensile strength of an open discontinuity is nonexistent. Joints, however, can be tested for strength as intact specimens if jointed cores are secured without breakage. During the course of the investigation core specimens of both massive and jointed concrete taken from a gravity dam were received for test. The massive intact concrete compared favorably with that of mixture No. 2 (compressive strength, 6000 psi (41 MPa); rapid direct tensile strength, 300 psi (2 MPa)). Significantly, the strength of the construction joints was indicated to be approximately one-third (100 psi (0.7 MPa)) that of the concrete mass.

Stress-Strain Relationships

The stress-strain relationships were determined on selected specimens from 6 in. (152 mm) long electrical resistance strain gages affixed to the specimens. A typical strain-time, stress-time record for a stress reversal test is shown in Figure 3. Stress-strain curves were plotted from these results. A typical stress-strain curve for a specimen undergoing cyclical loading is given in Figure 5. Given in Figure 6 is a stress-strain curve for a test to failure. Significantly stress-strain relationships were essentially identical in tension and compression for the stress reversal tests. Very little hysteresis was noted in any of the tests. Apparently the compressive stress was not large enough to induce microfracturing with the resulting hysteresis. Tensile failure of a brittle material is usually the result of one crack rather than a series of small fractures which result in nonrecoverable deformation. Indications were that tensile cracking of dry specimens began at approximately 90 percent of ultimate strength and progressed very sharply during final failure loading.

Discussion

According to a recent review of the applicable literature,[3] significant gaps in knowledge remain relative to the earthquake resistance of mass concrete. The areas most in need of study were cited to be:

1. The effect of strain rate on dynamic properties, particularly tensile strength.

2. The effect of stress reversal on mechanical properties, including hysteretic behavior.

3. The effect of biaxial stress conditions.

The significant parameter is, of course, the tensile fracture mechanism of concrete. There are two predominant failure theories for concrete,[4,5] each of which has almost equal support: the Griffith theory and the strain-energy release theory. However, very few pure tension tests of concrete have been reported, and therefore the theories are of limited values for practical application. Hopefully, the information reported herein will help to narrow the gap between theory and practice.

The fact that approximately 20 percent of the tensile specimens failed during cycling at 70 to 90 percent of the indicated tensile strength is probably more the result of strength variation between specimens than fatigue effect. The fatigue effect at 25 cycles would likely not be great. Conversely, the failure of many specimens around large, critically oriented pieces of aggregate and the resulting high variability of the test results would account for some failures at lower than expected loads. Due to the heterogeneous composition of concrete, especially mass concrete, the large variation in test results might well be representative of the nature of the material.

The most significant information developed in the study related to the effect of rate of load on mass concrete specimens. Essentially, no significant difference in tensile strength was noted for concrete of two strength levels stressed to failure at times ranging between 60 sec (static) and 0.025 sec (10 Hz). In terms of dynamic testing, a time to failure of 0.025 sec is relatively slow. It is known that the more brittle a material the less the effect of rate of load. Apparently mass concrete in a dry condition is sufficiently brittle to escape the effect of load rate on strength in the range relevant to earthquake loading.

Also of significance is the effect of rate of load on strength of wet concrete specimens. Although the data are somewhat limited, there appears to be an increase of approximately 30 percent in tensile strength of wet concrete between static testing and rapid loading to failure at a rate of 5 Hz. This indication agrees substantially with the results of the only two studies discovered which dealt with dynamic tensile strength of concrete, by Hatano[6] and Takeda.[7] Hatano's tests were conducted on wet specimens, but the moisture condition of Takeda's specimens was not defined. Apparently wet concrete, being less brittle than dry, is susceptible to strain rate effects in the range of earthquake loading.

The indication that the ratio of tensile to compressive strength decreases as the concrete strength increases is not surprising. Previous work[8,9] on the static test range supports this finding. The information secured from tests of jointed cores is significant. The joints tested appeared to be excellent construction joints, yet developed only one-third the tensile strength of comparable mass concrete. Reversal of stresses within test specimens apparently had no effect on the tensile strength or stress-strain relationships of dry concrete. Compared to the stress reversal test, the direct tension test is easier to conduct and would appear to be acceptable for use as a method of determining the relevant properties of earthquake susceptible concrete.

Several important aspects of the stress-strain relationships were developed; (a) the linearity of the stress-strain ratio up to approximately 80 percent of the ultimate strength; (b) the similarity of the stress-strain curves in tension and compression; (c) the noneffect of stress reversal; and (d) the lack of applicable hysteresis. Yerlici[10] has reported substantiating data for point (a) above and Hughes and Chapman[11] for point (b). The lack of effect of stress reversal (point c) may be new but not surprising information. The aforementioned points are related and should be useful in analyzing the stress-strain relationships for concrete under earthquake-type loading conditions.

Probably the most significant point is the almost perfect elasticity and consequent absence of hysteresis in the stress-strain curves. The interest in the hysteresis loop arises from the fact that its area represents an irreversible energy of deformation. The loop may be used to calculate a value of hysteretic damping. Obviously the deformability of a material such as the concrete tested herein will be nominal.

The effect of biaxial stress conditions on the strength or durability of mass concrete was not addressed in this study. Reportedly the parameter of biaxial tension is of importance in earthquake analysis.[3] Of interest is some recent work on the area of biaxial tension given in reference 12. Indications are that concrete strength in biaxial tension is essentially equal to, but no greater than, the uniaxial tensile strength. It follows then that the rapid loading biaxial strength of dry concrete should approximate the direct tensile strength as determined in this investigation. Biaxial tension tests may be required to determine the effect of multiaxial stresses on the strength of wet concrete.

Conclusions

Based on the results of this investigation, the following conclusions appear warranted:

1. Some failures may be expected under cyclical tensile loading of mass concrete specimens at 70 to 90 percent of the indicated ultimate tensile strength.
2. Rate of loading has no effect on the tensile strength of dry, virgin, mass concrete specimens up to a loading rate of 10 Hz.
3. For conventional concrete the tensile strength is approximately 7.5 percent of the compressive strength; for high strength concrete the tensile strength is 5 percent of the compressive strength.

4. No difference is indicated between static tensile strength and rapid tensile strength up to 10 Hz loading rate for previously cycled specimens.
5. There is apparently no significant difference in the results obtained, and therefore the two test methods used herein, rapid direct and stress reversal are equally useful.
6. The effect of alignment within the test specimens of large aggregate pieces is critical and probably contributes to the high variability of the test results.
7. An increase in tensile strength of approximately 30 percent is indicated between static and rapid loading tests of wet concrete specimens.
8. The strength of representative construction joints in direct tension may be only about one-third that of the concrete mass.
9. Stress-strain relationships for dry mass concrete are essentially identical in tension and compression, and the tensile curve is linear up to approximately 80 percent of ultimate strength.
10. Very little hysteresis is evident in stress reversal tests of mass up to 30 percent of the compressive stress and 80 percent of the tensile stress.

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TABLE 1 - Results of Cyclical Tensile Tests

Mixture No. 1

Type Test	Specimen No.	Rate of Load, Hz	No. of Cycles	Cycled to Tension psi (MPa)	Broke During Cycling	Remarks
Direct Tension 60% level	4	1	22	160 (1.1)	No	
	10	1	24	140 (1.0)	No	
	11	1	24	140 (1.0)	No	
	12	1	25	140 (1.0)	No	
	13	1	26	160 (1.1)	No	
Direct Tension 80% level	2	1	20	200 (1.4)	No	
	14	1	24	185 (1.3)	No	
	15	1	26	200 (1.4)	No	
	18	1	5	200 (1.4)	Yes	Failed 5th Cycle
	20	1	14	215 (1.5)	Yes	Failed 14th Cycle
Stress Reversal	CE-1	1	25	200 (1.4)	No	
	CE-2	1	1	210 (1.4)	Yes	Failed 1st Cycle
	CE-3	1	25	160 (1.1)	No	
	CE-4	1	25	170 (1.2)	No	
	CE-6	1	25	170 (1.2)	No	
	3-11	1	50	180 (1.2)	No	
	3-12	1	25	190 (1.3)	No	
	3-13	1	25	200 (1.4)	No	
Stress Reversal	CE-13	5	25	200 (1.4)	No	
	CE-14	5	12	160 (1.1)	No	
	CE-15	5	25	180 (1.2)	No	
	CE-16	5	25	180 (1.2)	No	
	CE-17	5	25	180 (1.2)	NO	
	3-8	5	27	110 (0.8)	No	
	3-9	5	28	180 (1.2)	No	
	3-10	5	5	230 (1.6)	Yes	Failed 5th Cycle
Stress Reversal	CE-7	10	25	150 (1.0)	No	
	CE-8	10	9	175 (1.2)	Yes	Failed 9th Cycle
	CE-9	10	25	180 (1.2)	No	
	CE-10	10	25	180 (1.2)	No	
	CE-11	10	25	170 (1.2)	No	
	3-5	10	2	160 (1.1)	Yes	Failed 2nd Cycle
	3-7	10	20	170 (1.2)	Yes	Failed 20th Cycle
	3-14	10	25	180 (1.2)	No	

TABLE 2 - Results of Monotonic Tests

Type Test	Mixture No.	No. of Specimens	Rate of Load, Hz	Tensile Strength psi	Tensile Strength (MPa)	Std Deviation psi	Std Deviation (MPa)
Virgin Specimens							
Static Direct Tensile	1	5	0.02	235	(1.6)	13.5	(0.09)
Rapid Direct Tensile	1	5	1	230	(1.6)	23.6	(0.16)
Static Direct Tensile	2	5	0.02	305	(2.0)	29.5	(0.20)
Rapid Direct Tensile	2	5	5	315	(2.2)	19.5	(0.13)
Stress Reversal	2	5	10	310	(2.1)	32.5	(0.22)
Previously Cycled Specimens							
Rapid Direct Tensile	1	8	1	255	(1.8)	17.5	(0.13)
Stress Reversal	1	7	1	270	(1.9)	39.8	(0.27)
Stress Reversal	1	7	5	250	(1.7)	37.9	(0.26)
Stress Reversal	1	5	10	265	(1.8)	25.4	(0.18)

TABLE 3 - Moisture Effects Tests - Monotonic Loading - 5 Hz

Static Compressive			Static Direct Tensile			Rapid Load Direct Tensile		
Specimen No.	Strength		Specimen No.	Strength		Specimen No.	Strength	
	psi	(MPa)		psi	(MPa)		psi	(MPa)
Dry Cores								
M1	3630	(25.02)	M7	225	(1.55)	M17	250	(1.72)
M2	3410	(23.51)	M8	265	(1.83)	M18	260	(1.79)
M3	3200	(22.06)	M9	220	(1.52)	M19	230	(1.59)
			M10	235	(1.62)	M20	265	(1.83)
			M11	240	(1.65)	M21	245	(1.69)
Avg	3410	(23.51)		235	(1.62)		250	(1.72)
Inundated Cores								
M4	2760	(19.03)	M12	185	(1.28)	M22	270	(1.86)
M5	2790	(19.24)	M13	195	(1.34)	M23	280	(1.93)
M6	2890	(19.93)	M14	180	(1.24)	M24	260	(1.79)
			M15	220	(1.52)	M25	255	(1.76)
			M16	190	(1.31)	M26	240	(1.65)
Avg	2810	(19.37)		195	(1.34)		260	(1.79)

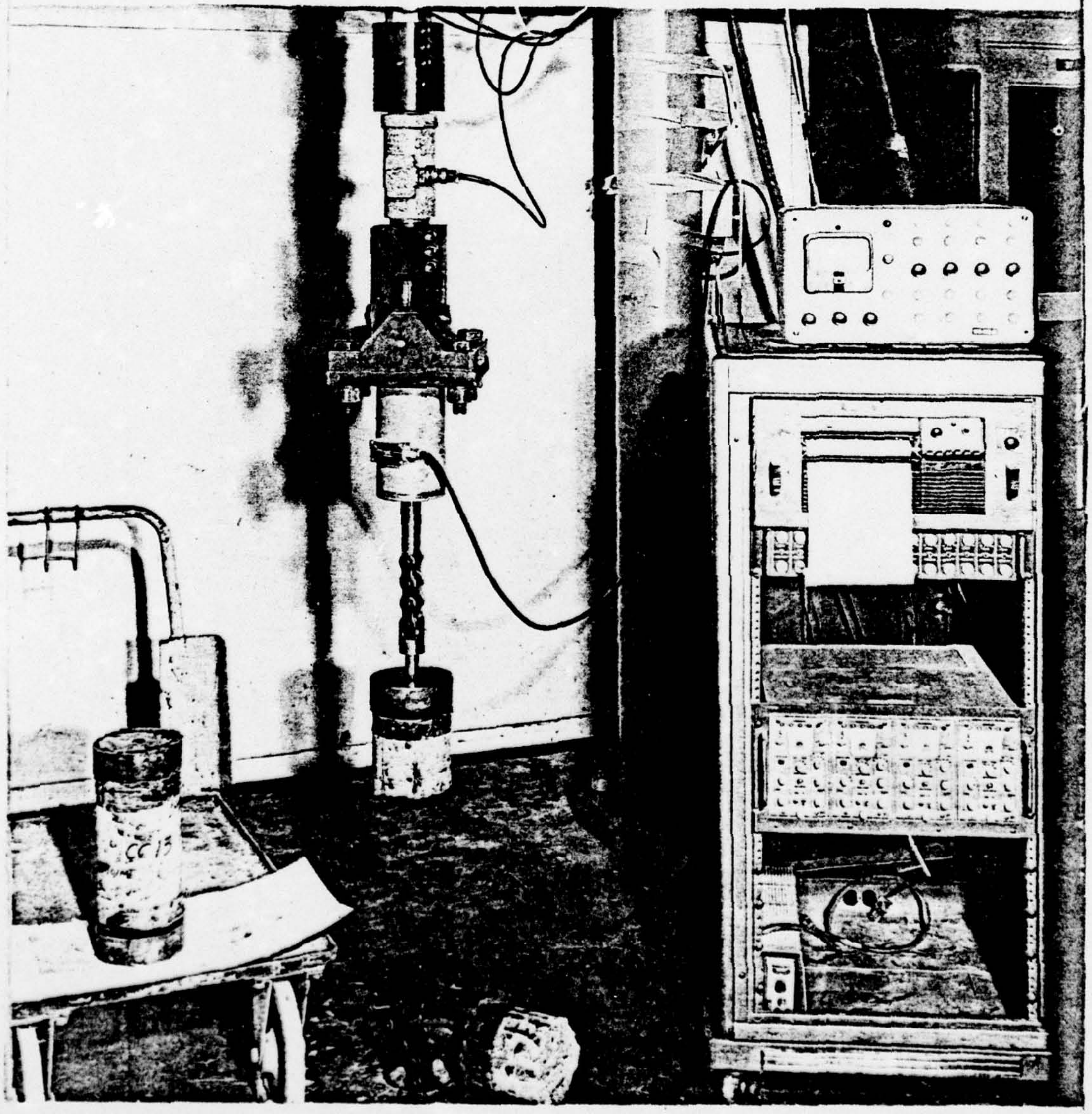

FIG. 1--Direct Tension Test Apparatus

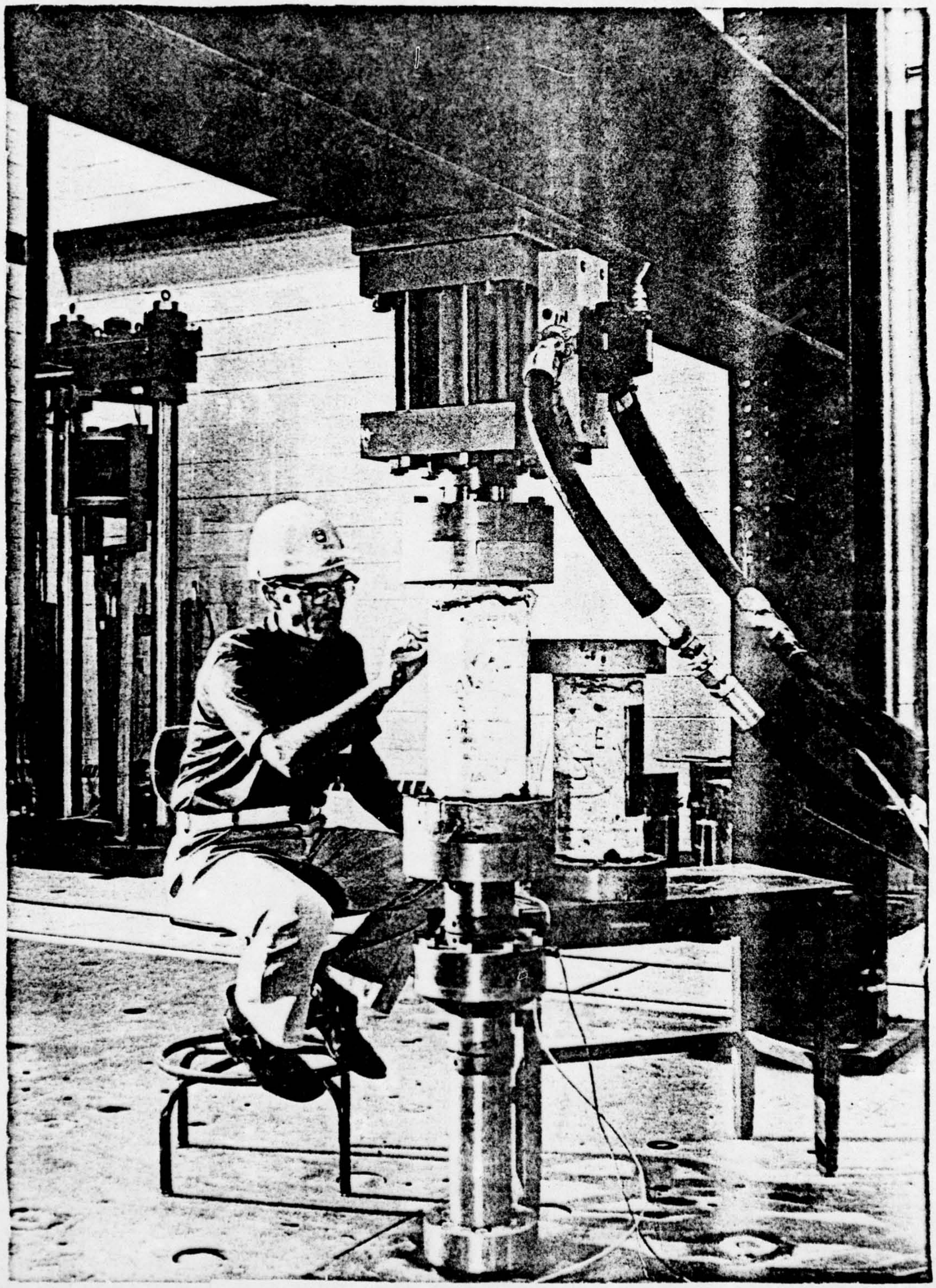

FIG. 2--Test Configuration Stress Reversal Tests

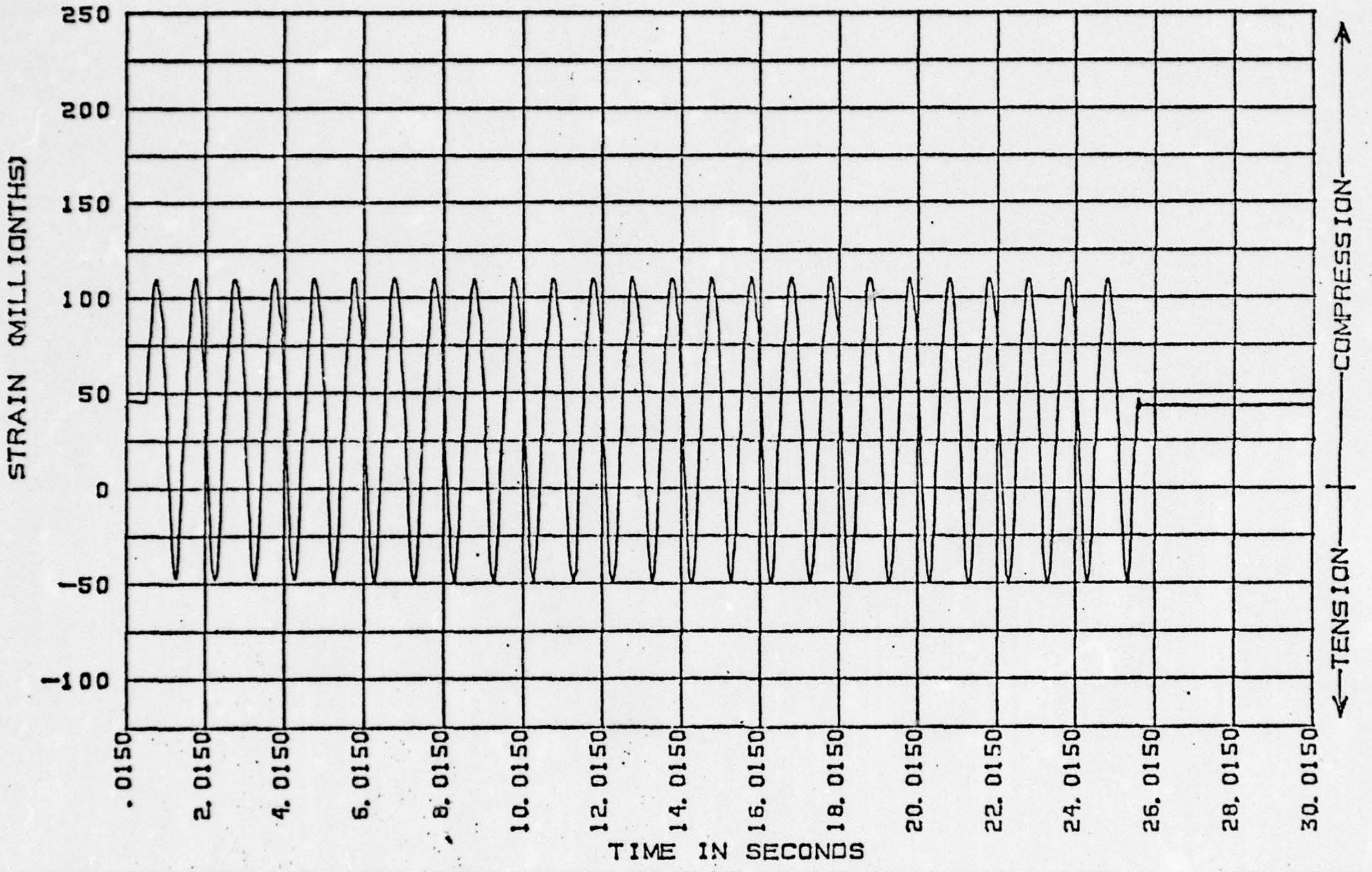

FIG. 3--Typical Strain-Time Record

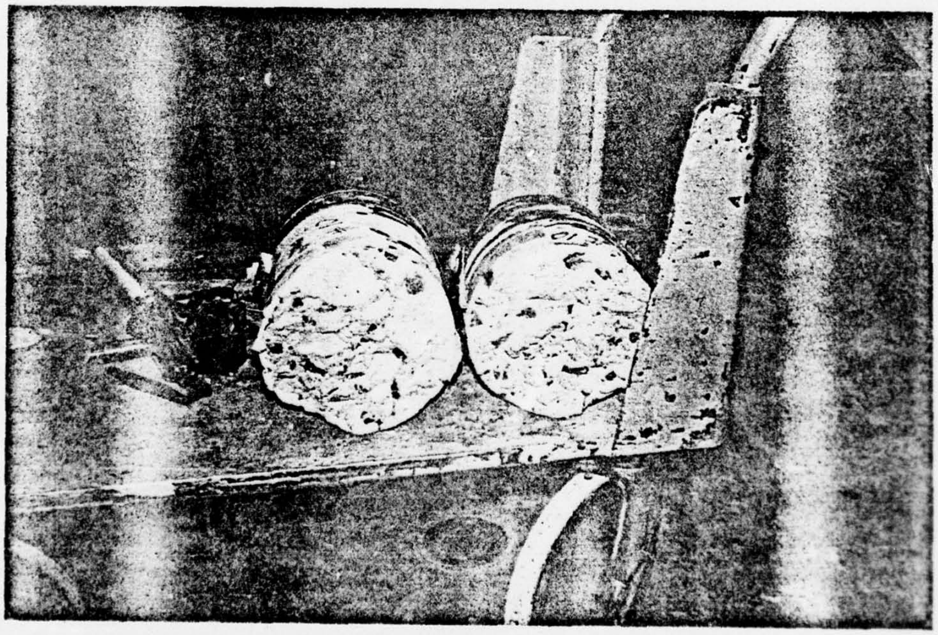

FIG. 4--Typical Failure Surface of a Tensile Test Specimen

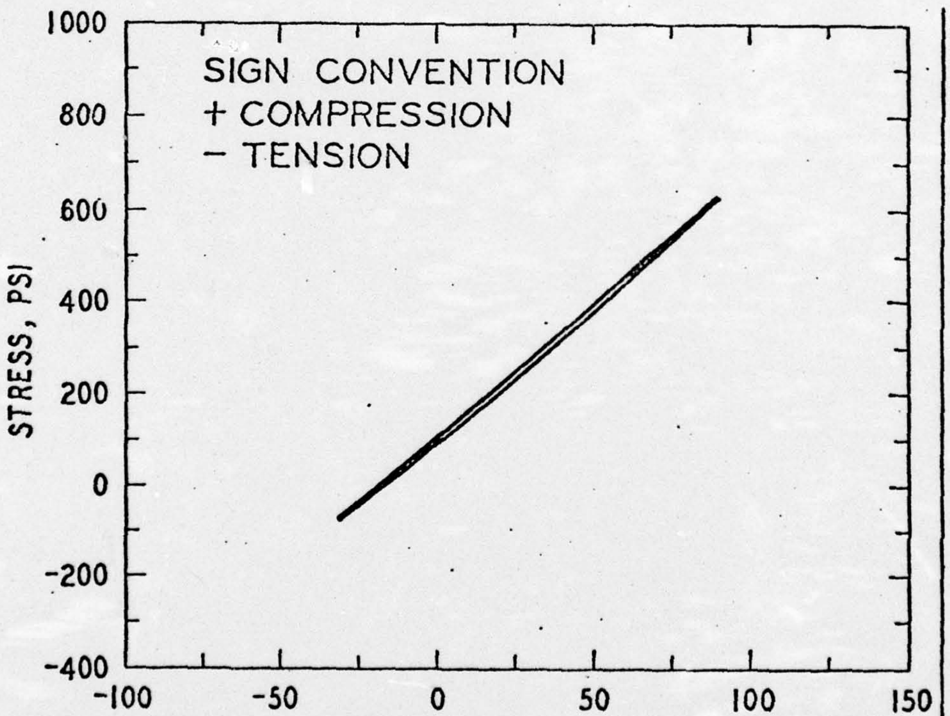

FIG. 5--Dynamic Stress Reversal Studies, Cyclical Test

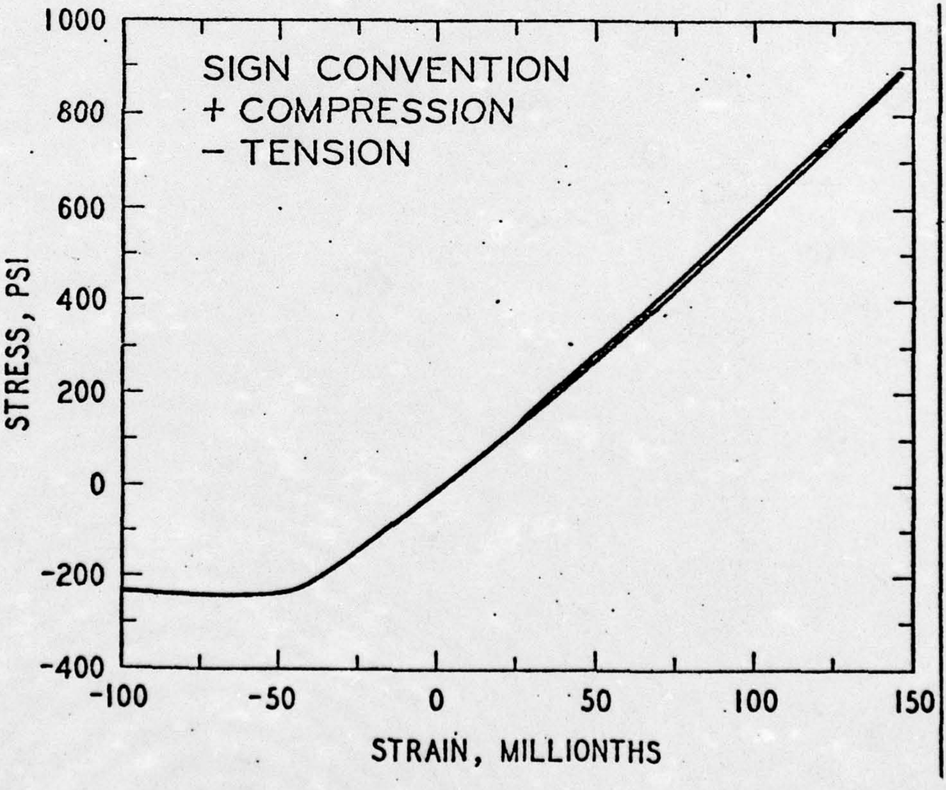

FIG. 6--Dynamic Stress Reversal Studies, Failure Test

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

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