GA-A15400
UC-77

ANCHOR STUD MONOTONIC AND CYCLIC SHEAR TESTS
FINAL REPORT

by

J. LARRY PICKERING

Prepared under
Contract DE-AT03-76ET35300
for the San Francisco Operations Office
Department of Energy

GENERAL ATOMIC PROJECT 6400
DATE PUBLISHED: JULY 1979

GENERAL ATOMIC COMPANY

ABSTRACT

In a prestressed concrete reactor vessel (PCRV), the main cavity liner and other cavity liners with large diameter/thickness (D/t) ratios are anchored to the concrete by anchor studs. These anchor studs are subject to shear loading resulting from prestressing, pressurization, temperature, and creep of the PCRV. The test program discussed in this report consists of both monotonic and cyclic testing of models simulating the prototype anchor stud/concrete assembly. The tests determined the shear stiffness characteristics of the 3/4-in.-diameter, one-piece Nelson anchor stud embedded in concrete and established its low-cycle fatigue life under displacement-controlled loading. The previously obtained results of Phase I and Phase II tests on two-piece anchor studs, along with high-cyclic fatigue data taken from the literature, are discussed and are plotted with the current, Phase III, results to form a displacement versus cycles to failure curve covering a useful range of design applications.

CONTENTS

FIGURES

FIGURES (continued)

Figures (continued)

TABLES

Tables (continued)

1. INTRODUCTION

The cavities in a prestressed concrete reactor vessel (PCRV) are lined with a steel membrane which provides an impermeable barrier between the reactor primary coolant and the concrete structure. Anchor studs are welded to the concrete side of the liners with large D/t (diameter/thickness) ratios to guarantee displacement compliance between the liners and the concrete. These anchor studs are subject to shear loading from the following potential sources:

1. Non-cyclic loading

   a. PCRV prestressing - strain gradients that develop in the liner owing to cavity distortion.

   b. Time effects of the prestress loading - concrete creep causing additional liner strain gradients.

   c. Liner discontinuities - geometrical and yield strength differences between adjacent liner panels.

   The above loading does not relax during the life of the vessel and constitutes one-half of a full loading cycle. In the liner design analysis, the relative displacement between the cavity liner and concrete that results from the above loading is developed analytically. The stiffness characteristics of the 3/4-in.-diameter by 8-in.-long anchor stud embedded in concrete established from monotonic tests are needed as input to this analysis.

2. Cyclic loading

   a. PCRV pressurization and depressurization due to reactor operation.

   b. PCRV temperature variation due to reactor operation.

This report presents the results of tests performed to establish the monotonic and low-cycle fatigue characteristics of anchor studs used in a typical PCRV liner assembly. The tests represent the final phase, Phase III, of the General Atomic (GA) anchor stud test program. Similar tests were conducted in Phase I (Ref. 1) and Phase II (Ref. 2), the GA-funded portions of the program. However, the specimens in these two phases used two-piece anchor studs instead of the presently used standard one-piece anchor studs. The tests results of Phase I and Phase II are included in this report to permit comparison of the results for the two stud configurations. The results of cyclic tests in Phase II and of separate tests conducted in the high-cycle range, both presented originally in an S-N curve, are converted into a displacement range versus cycles to failure curve in this report. The combined low- and high-cycle fatigue results are presented in one figure in this report to form a useful piece of design information.

2. TEST PROGRAM DESCRIPTION

The purpose of the Phase III anchor stud test program is to provide design information on the one-piece, 3/4-in.-diameter by 8-in.-long, standard Nelson anchor stud for use in the PCRV liner design. The following items are included in the study:

1. Load/displacement curves are developed from the monotonic tests. These curves are used to establish the stiffness characteristics of the embedded anchor stud.

2. The monotonic tests are also used to develop the ultimate displacement characteristics of the studs. This information is used to establish the shear displacement allowables per Section III, Division 2 of the ASME Boiler and Pressure Vessel Code.

3. Displacement-controlled cyclic tests are performed to develop the low-cycle fatigue response of the tested geometry.

The anchor stud shear loading test program and specimen identification are outlined in Table 1.* The test sequence and test date are listed in Table 2.

*Tables appear in Section 9.

3. TEST SPECIMENS

Twelve specimens were tested in the Phase III test program (Ref. 3). Each specimen consisted of a single 3/4-in.-diameter by 8-in.-long Nelson stud welded on a 3/4-in.-thick steel plate with the anchor stud embedded in the concrete backing block. The anchor stud specimen is shown in Fig. 1.* As shown in this figure, two polyvinyl chloride (PVC) pipes were placed in the concrete to provide paths for the prestressing rods. A ball bushing was incorporated to provide flexibility at the test fixture/specimen interface. The steel portions in the specimens and the stud welding and qualifying procedures are described in Appendix A. Concrete properties and the casting details are described in Appendix B.

---

*Figures appear in Section 10.

4. SPECIMEN LOADING

The test fixture used for loading the specimens is shown in Fig. 2. A horizontal displacement transducer was used to limit the shear movement to the specified displacement range. Both the horizontal displacement and load data were recorded on chart drive units. The cyclic rate of the fatigue specimens varied approximately between 1 and 8 cycles/min. Details of the hydraulic system, controls, and instrumentation data center are described in Appendix C and Ref. 4.

To simulate the actual prototype condition, the concrete portion of each specimen was prestressed prior to loading. The specimen was placed in the test fixture, and two prestressing rods were inserted in the PVC pipes provided. The prestressing load was then applied on each of the rods by tightening the end nuts, using uniform loading increments up to the specified value of 24,000 lb each. This loading produced approximately 600-psi average stress in the concrete. After the prestressing load had been reached, the end plates in the test fixture were bolted in place to help keep the specimen prestress from relaxing (Fig. C-1, Appendix C). The "initial" and "after test" prestressing loads of each specimen are listed in Table 3.

One of the problems reported in the previous tests (Phase I, Phase II) was that failure detection in the cyclic tests was very difficult. This was primarily due to the geometry of the weld flashing around the stud (Figs. A-2 and A-3, Appendix A), which is characteristic of the welding procedure used. This flashing is capable of transmitting the shear load to the stud and/or concrete even after fatigue failure of the stud and therefore prevents stud failure detection from the usual drop in load. The procedure used in this test program was to apply a small normal tensile load on the anchor stud. The magnitude of this load was such that when failure did occur, the liner plate would lift off the concrete and activate a limit switch to shut down the test. The apparatus used to develop this loading on the specimen is also shown in Fig. 2. The spring was compressed to produce a constant normal load of approximately 100 lb.

5. TEST RESULTS

The specimen identification and corresponding displacement amplitude are given in Table 1. The load/displacement curves produced from the monotonic tests of specimens No. 2 and No. 3 are shown in Fig. 3. The data recording system malfunctioned during the first test on specimen No. 1, and no information was recorded. The Nelson "typical" load/shear displacement curve (Ref. 5) is also plotted for comparison. The ultimate shear displacements of the specimens were relatively consistent, with values of 0.253 in. and 0.242 in. for specimens No. 2 and No. 3, respectively. The load/shear displacement curves were replotted in Fig. 4 to obtain a better definition of the initial slopes. The two-piece anchor stud load/shear displacement curve developed in the Phase II program is also shown. The slope of a straight line connecting the origin and a point on the curve corresponding to 0.005-in. displacement (K_1) was arbitrarily chosen to represent the initial stiffness characteristic of the embedded stud. The slope of a chord connecting the points on the load/shear displacement curve corresponding to 0.005-in. and 0.01-in. displacement (K_2) was also calculated. The calculated stiffness values are listed in Table 4. The details of the failed stud of specimen No. 2 are shown in Figs. 5 and 6.

The cyclic tests were conducted in a displacement-controlled mode. The load relaxation as a function of cycles for each specimen is listed in Tables 5 through 13 and is plotted in Figs. 7 through 15. The load/shear displacement characteristics for the different displacement amplitudes and the details of the failed studs are shown in Figs. 16 through 24.

Loading anomalies were noted during the testing of specimens No. 11 and No. 12. The load developed in the first cycle of specimen No. 11 went off scale and therefore was not recorded. The load magnitude apparently exceeded the expected load, which was based on the statically loaded specimens at a shear displacement of 0.025 in. (approximately 22,000 lb per Fig. 3). The scale factor on the instrumentation equipment was changed on the second cycle, and the recorded load was 13,875 lb - advance and 27,870 lb - retract (Table 13). It is not clear, however, whether there actually was an overload in the anchor stud or whether the load was reacted elsewhere in the test setup. The recorded stud load magnitude is in question because the recorded load for the second cycle is again higher than the ultimate stud load developed in the static tests (Fig. 3), and the recorded displacement did not show any deviation from the specified value (±0.025 in.). The third cycle and all subsequent cycles behaved as expected; i.e., the recorded load stayed within the load range predicted by the static load/displacement curve (Table 13). The fatigue lives of specimens tested at the ±0.025-in. displacement range (Tables 11 through 13) indicate, however, that specimen No. 11 may have been more severely loaded than specimens No. 6 and No. 10.

Specimen No. 12 was also overloaded. This was the result of the failure of a limit switch during a restart, which allowed the stud to be deflected beyond the specified value (±0.012 in.). The event occurred at 12,874 cycles in the retract direction and at 13,891 cycles in the advance direction (Fig. 15). This overload in both directions may have blunted the existing fatigue crack, resulting in a larger number of cycles to failure than for two similarly loaded specimens (Tables 5 through 7). The operating procedure was changed for subsequent specimens to prevent this problem from reoccurring.

6. DISCUSSION

The shear stiffness of prototype anchor studs is difficult to establish analytically because of the concrete/anchor stud interaction. The anchor stud stiffness is dependent upon the type of concrete, the concrete prestress level, and the stiffness of the liner. The type and strength of the concrete used in this test program were modeled to represent the prototype (Appendix B). The models were also prestressed to the same level expected in the prototype near the liner/concrete interface. Therefore, both the property of concrete and the level of prestress are eliminated as parameters in applying the test results to the prototype anchor studs.

The liner modeled in the test program is representative of flat surface regions of the prototype vessel. This configuration offers little support in the out-of-plane direction and does not resist liner/concrete separation. The recorded separations for the monotonically loaded tests of specimens No. 2 and No. 3 are shown in Fig. 3. A cylindrical liner presses against the backing concrete under prestress loading and therefore represents a stiffer geometry. This stiffening effect is dependent upon the diameter/liner thickness (D/t) ratio of the geometry and could change the anchor stud stiffness characteristics. The prototype cavity liners presently under consideration have relatively large D/t ratios, and the test results developed in this program are assumed to apply conservatively.

In Fig. 3, the load/shear displacement curves developed in the monotonic tests for specimens No. 2 and No. 3 appear to bound the comparable curve for a "typical" Nelson 3/4-in.-diameter stud, indicating a variation that may be expected in stud stiffness. However, the "typical" Nelson stud shows a higher ultimate load than the two test specimens. This difference could be attributable to the difference in the degree of restraint modeled into each specimen and test fixture, which limits the steel/concrete separation. Data on vertical separation between the liner and concrete are not available for the "typical" Nelson stud. The initial stiffness for each specimen is defined up to 0.010-in. displacement as slopes of a bilinear curve as shown in Table 4 and Fig. 4. The stiffness values as defined are used as a means to numerically describe the load/displacement curves.

For the cyclic tests, the test matrix incorporated nine specimens tested at displacement amplitudes of 0.025, 0.018, and 0.012 in. The displacement control mode was selected in order to represent the strain-controlled loading imposed on the prototype liner. The magnitudes of the displacement range were selected to define the behavior of the test specimens in the low-cycle fatigue regime. The load relaxation resulting from the fixed displacement testing for each specimen was quite significant, as shown in Tables 5 through 13 and Figs. 7 through 15.

The tests reported here represent Phase III of the GA anchor stud testing program. While the specimens in Phase III used one-piece anchor studs, the specimens in both Phase I and Phase II used two-piece anchor studs. The cyclic tests in Phase I were performed in a displacement-controlled mode. The results of Phase I cyclic tests, however, did not reveal with sufficient accuracy the number of cycles to failure due to test fixture/specimen constraint problems. In Phase II, 11 specimens, each with two two-piece studs, were cyclically tested in a load-controlled mode. A description of Phase II cyclic tests is given in Appendix D. The results of the Phase II cyclic tests were presented in the form of an S-N curve in Ref. 2. It was found that the data variation from test to test is larger than would normally be expected. In addition, data presented in the form of an S-N curve are not directly applicable to the prototype condition in which the anchor stud is subject to displacement-controlled shear loading. For application to displacement-controlled loading cases, the Phase II fatigue data were replotted in this report using an estimated displacement range (selected at half life) as the ordinate (Fig. 25). It is interesting to note that the replotted curve showed a smaller test to test variation than the original S-N presentation. As shown in Fig. 25, one specimen out of the total of 22 specimens failed at a much lower life (two orders of magnitude lower) than the rest of the specimens. The stud used in this specimen went through the same qualification program (tensile pull of 17,000 lb and a visual check) as the rest of the specimens, which rules out material weakness as the obvious explanation.

The cyclic tests conducted in Phase III provide a comparison between the load- and the displacement-controlled testing. They also provide a larger data base to permit discounting the significance of the unusually low life of one specimen in Phase II. It is noted that Fig. 25 shows a good agreement between the results of Phase II and Phase III tests. The cyclic test data produced in Phase II and Phase III of the GA anchor stud test program cover the low-cycle range. No high-cycle fatigue test has been performed for specimens simulating the anchor stud/concrete assembly as used in PCRV cavity liners. Reference 6 reported the results of high-cycle shear fatigue tests performed on specimens in which the 3/4- or 7/8-in.-diameter Nelson studs were welded to a wide flange beam and embedded in a 6-in. concrete slab. Although the geometries of the specimens are different, the test data in Ref. 6 are used to obtain a displacement range versus number of cycles to failure curve in the high-cycle fatigue range as discussed in Appendix E.

In Fig. 25, the data from Phase II and Phase III of the GA program and those from Ref. 6 are plotted. The combined data set covers the entire useful range of fatigue cycles and constitutes the best available design information at present on shear fatigue of liner/anchor stud assemblies.

7. SUMMARY AND CONCLUSIONS

1. The shear load/displacement curves obtained from the monotonic tests are generally similar to that for a "typical" Nelson stud (Fig. 3). However, the "typical" Nelson stud shows a higher ultimate load than test specimens No. 2 and No. 3. This difference could be attributable to the degree of restraint modeled into the specimen and test fixture, which limited the steel/concrete separation (the vertical separation deflection was not listed for the "typical" Nelson stud).

2. The ultimate displacements obtained from the two monotonically loaded tests are 0.253 in. and 0.242 in.

3. The initial stiffness (K_1) values for test specimens No. 2 and No. 3 are 1.95×10^6 lb/in. and 1.18×10^6 lb/in., respectively. The average of these two stiffness values is essentially the same as the "typical" Nelson stud value (Table 4). Thus, the two test specimens illustrate the possible stiffness variation from the average response.

4. Significant load relaxation was observed for each specimen subject to constant displacement cyclic loading.

5. The results of the cyclic test agreed well with the results of the Phase II tests (load-controlled cyclic testing with two-piece anchor stud) when the half-life displacements were plotted against the number of cycles to failure (Fig. 25).

6. The anchor stud monotonic and cyclic test results presented in this report may be applied directly to the prototype liner.

8. REFERENCES

1. Foglesong, L., "1100 MW(e) PCRV Liner R&D Anchor Stud Test Interim Report," General Atomic unpublished data, May 10, 1971.
2. Griffin, R., "Liner Anchor Stud Shear Fatigue Tests - Phase II," General Atomic unpublished data, February 20, 1973.
3. Pickering, J. L., "PCRV Liner Anchor Stud Shear Fatigue, Phase III," General Atomic unpublished data, April 5, 1977.
4. Morrill, W., "Test Procedure for PCRV Liner Anchor Stud and Cooling Tube Shear Fatigue, Phase III," General Atomic unpublished data, April 24, 1978.
5. Nelson Stud Welding Company, "Embedment Properties of Headed Studs," Nelson Stud Document Design Data 10, October 31, 1975.
6. Slutter, R. G., and J. W. Fisher, "Fatigue Strength of Shear Connectors," Highway Research Record, Number 147, Bridges and Structures Report No. 9, 1966.
7. Nicolayeff, F., "PCRV Liner Specimens for Shear Test," General Atomic unpublished data, August 23, 1978.

9. TABLES

TABLE 1

ANCHOR STUD SHEAR LOADING TEST PROGRAM[a]

Type of Test	Test Specimen Number	Controlled Displacement (in.)	Remarks
Monotonic	1	Pull to failure	Apply a unidirectional static shear load on each test specimen until anchor stud failure or gross slippage occurs.
	2	Pull to failure	
	3	Pull to failure	
Cyclic	4	+0.012 to -0.012	Apply a cyclic, displacement-controlled shear load on each test specimen until anchor stud failure.
	5	+0.012 to -0.012	
	12	+0.012 to -0.012	
	7	+0.018 to -0.018	
	8	+0.018 to -0.018	
	9	+0.018 to -0.018	
	10	+0.025 to -0.025	
	11	+0.025 to -0.025	
	6	+0.025 to -0.025	

[a] Ref. 3.

TABLE 2

ANCHOR STUD TEST SEQUENCE

Type of Test	Test Specimen	Test Sequence	Date Tested
Monotonic	1	1	No data
	2	2	8/29/78
	3	3	8/29/78
Cyclic	4	11	11/15/78
	5	12	12/ 5/78
	6	7	10/24/78
	7	8	10/30/78
	8	9	11/ 2/78
	9	10	11/ 6/78
	10	4	9/19/78
	11	5	9/21/78
	12	6	9/27/78

TABLE 3

CONCRETE PRESTRESSING LOAD VALUES BEFORE AND AFTER TESTING

Specimen ID	Initial Prestress Load Cell Reading (lb)		After Test Load Cell Reading (lb)		Comments
	L4	L6	L4	L6	
Monotonic Tests					
1	24,065	23,934	--	--	--
2	--[a]	--	16,826	23,737	--
3	20,674	23,606	--	--	--
Cyclic Tests					
4	24,000	24,033	--	--	--
5	23,935	23,967	--	--	--
6	23,935	24,131	23,413	23,705	At end of test
7	24,163	24,000	--	--	--
8	23,967	24,164	--	--	--
9	23,935	24,164	--	--	--
10	23,804	24,000	22,891	20,356	At 800 cycles
11	24,000	24,131	22,207	22,654	At end of test
12	24,033	24,098	22,957	22,982	At 115,988 cycles

[a] Not recorded.

TABLE 4

ANCHOR STUD STIFFNESS

Anchor Stud	Anchor Stud Stiffness ($\times 10^6$ lb/in.) K_1[a]	K_2[a]
Specimen No. 2	1.95	1.06
Specimen No. 3	1.18	1.10
Average	1.57	1.08
Nelson "Typical" 3/4-in.-dia. stud	1.60	1.06
Two-piece anchor stud, average of two specimens (Appendix E)	1.46	1.29

[a] See Fig. 4 for definition of slopes.

TABLE 5

ANCHOR STUD CYCLIC TEST
SPECIMEN NO. 4 (±0.012-IN. CONTROLLED DISPLACEMENT)

Cycle	Load (lb)		Cycle	Load (lb)	
	Advance	Retract		Advance	Retract
1	17,982	13,572	100	14,056	10,663
2	17,352	12,311	200	13,814	10,324
3	16,964	12,021	400	13,135	10,276
4	16,625	11,827	600	13,959	8,967
5	16,383	11,633	800	13,765	9,112
6	16,262	11,730	1,000	13,475	8,773
7	16,092	11,633	2,000	12,651	8,822
8	16,092	11,633	4,000	11,633	7,998
9	15,995	11,439	6,000	10,469	8,240
10	15,995	11,390	8,000	10,179	7,513
20	15,510	11,148	10,000	7,513	8,725
40	14,783	11,051	12,000	8,725	7,512
60	14,541	10,809	14,000	7,610	6,301
80	14,444	10,566	14,363	Failure	

TABLE 6

ANCHOR STUD CYCLIC TEST
SPECIMEN NO. 12 (±0.012-IN. CONTROLLED DISPLACEMENT)

Cycle	Load (lb)		Cycle	Load (lb)	
	Advance	Retract		Advance	Retract
1	16,480	14,300	1,000	11,830	7,170
2	15,560	14,060	2,000	10,880	7,510
3	15,270	13,810	4,000	10,660	6,380
4	14,930	13,570	6,000	10,180	7,760
5	14,830	13,430	8,000	9,690	7,610
6	14,540	13,180	10,000	10,080	7,800
7	14,400	13,090	12,874	--	Overload[a]
8	14,350	12,990	12,875	13,960	240
9	14,250	12,890	13,000	11,590	240
10	14,060	12,870	13,891	18,420[a]	--
20	13,180	12,360	13,892	2,710	3,200
54	12,600	11,630	20,218	3,080	2,130
80	12,990	11,050	49,942	2,790	2,420
100	12,890	10,910	60,344	3,296	1,840
200	12,750	9,690	96,518	3,390	1,550
400	11,197	10,760	103,897	3,199	1,357
600	11,150	10,180	108,672	2,520	1,360
800	11,630	7,510	115,988	1,406	1,188
			122,068	1,454	194
				Failure	

[a]Overload condition was due to the malfunction of the displacement control apparatus; load magnitude was off scale.

TABLE 7

ANCHOR STUD CYCLIC TEST
SPECIMEN NO. 5 (±0.012-IN. CONTROLLED DISPLACEMENT)

Cycle	Load (lb)		Cycle	Load (lb)	
	Advance	Retract		Advance	Retract
1	20,879	18,212	100	15,569	14,897
2	19,438	17,011	200	14,704	14,512
3	19,077	16,579	400	14,320	13,936
4	18,789	16,579	600	14,416	13,840
5	18,597	16,555	800	14,416	13,119
6	18,357	16,506	1,000	13,936	13,263
7	18,212	16,458	2,000	11,821	13,215
8	17,924	16,242	3,000	12,254	11,437
9	17,972	16,242	4,000	9,899	12,494
10	17,780	16,194	5,000	10,428	10,284
20	17,011	15,666	6,035	9,515	10,812
40	16,340	15,473	7,733	3,748	6,199
60	16,194	15,089	7,817	Failure	
80	15,954	15,041			

TABLE 8

ANCHOR STUD CYCLIC TEST
SPECIMEN NO. 7 (±0.018-IN. CONTROLLED DISPLACEMENT)

Cycle	Load (lb)		Cycle	Load (lb)	
	Advance	Retract		Advance	Retract
1	20,580	18,905	80	13,475	14,227
2	19,195	18,420	100	13,185	13,863
3	18,420	18,032	200	12,264	12,942
4	18,177	17,693	400	11,003	11,634
5	17,693	17,256	600	9,064	11,149
7	17,256	17,062	800	7,756	10,276
8	17,256	16,966	1,000	6,714	9,695
9	16,869	16,675	1,500	4,605	8,240
10	16,675	16,578	1,800	3,223	5,720
20	15,826	16,045	1,990	1,357	4,023
40	14,954	15,030	2,000	485	3,781
60	14,542	14,445	2,049	193	1,939
				Failure	

TABLE 9

ANCHOR STUD CYCLIC TEST
SPECIMEN NO. 8 (±0.018-IN. CONTROLLED DISPLACEMENT)

Cycle	Load (lb)		Cycle	Load (lb)	
	Advance	Retract		Advance	Retract
1	19,839	20,480	80	12,845	17,353
2	17,935	19,632	100	12,506	16,966
3	17,644	19,486	200	10,906	16,189
4	17,305	19,244	400	10,373	14,445
5	16,869	19,147	600	9,695	13,621
6	16,529	19,050	800	8,386	12,845
7	16,384	19,050	1,000	7,441	12,118
8	16,142	18,904	1,200	6,253	10,809
9	15,996	18,808	1,350	4,532	9,355
10	15,899	16,529	1,360	4,120	8,774
20	14,542	18,614	1,370	3,442	7,659
40	14,300	18,274	1,380	Failure	
60	13,185	17,644			

TABLE 10

ANCHOR STUD CYCLIC TEST
SPECIMEN NO. 9 (±0.018-IN. CONTROLLED DISPLACEMENT)

Cycle	Load (lb)		Cycle	Load (lb)	
	Advance	Retract		Advance	Retract
1	25,521	21,860	60	19,389	15,996
2	24,212	20,019	80	18,468	15,899
3	23,752	19,486	100	17,499	15,511
4	23,703	19,341	200	15,027	14,057
5	23,316	19,050	400	14,736	12,991
6	22,928	18,953	600	12,799	11,924
7	22,734	18,905	800	11,149	10,906
8	22,540	18,808	900	10,082	10,470
9	22,346	18,565	1,000	8,628	9,792
10	22,104	18,323	1,110	5,817	6,544
20	20,989	17,596	1,195	Failure	
40	19,922	16,529			

TABLE 11

ANCHOR STUD CYCLIC TEST
SPECIMEN NO. 6 (±0.025-IN. CONTROLLED DISPLACEMENT)

Cycle	Load (lb)		Cycle	Load (lb)	
	Advance	Retract		Advance	Retract
1	23,752	22,419	90	15,172	15,221
2	22,831	21,522	100	14,881	14,784
3	22,200	20,843	200	12,167	13,088
4	21,667	19,971	300	10,179	11,924
5	21,231	19,389	400	6,568	9,937
6	20,940	19,098	440	4,556	8,579
7	20,601	18,808	450	2,714	7,610
8	20,359	18,565	500	533	6,786
9	20,068	18,420	600	533	6,301
10	19,922	18,420	700	388	6,205
20	18,565	17,305	800	291	6,160
30	17,887	16,820	900	290	5,720
40	17,208	16,335	1,000	387	5,720
50	16,578	15,996	2,000	194	4,605
60	16,142	15,802	2,370	194	4,460
70	15,754	15,608	3,000	194	3,880
80	15,317	15,221	3,400	194	3,102
			3,448	0	1,503
				Failure	

TABLE 12

ANCHOR STUD CYCLIC TEST
SPECIMEN NO. 10 (±0.025-IN. CONTROLLED DISPLACEMENT)

Cycle	Load (lb)		Cycle	Load (lb)	
	Advance	Retract		Advance	Retract
1	22,690	19,150	100	11,780	14,200
2	18,080	18,710	200	10,280	12,800
3	17,450	18,320	300	8,970	12,120
4	17,450	18,180	400	8,090	11,880
5	16,720	18,030	500	6,980	11,250
6	16,480	17,840	600	5,820	11,290
7	16,340	17,740	900	4,020	11,540
8	16,000	17,550	1,233	3,050	10,910
9	15,800	17,450	1,287	2,810	10,180
10	15,710	17,350	1,341	2,670	10,420
27	13,890	16,090	1,400	2,080	9,600
50	12,850	15,270	1,425	870	7,510
			1,449	0	5,330
				Failure	

TABLE 13

ANCHOR STUD CYCLIC TEST
SPECIMEN NO. 11 (±0.025-IN. CONTROLLED DISPLACEMENT)

Cycle	Load (lb)		Cycle	Load (lb)	
	Advance	Retract		Advance	Retract
1	15,750	Off scale	150	12,550	11,246
2	13,875	27,870	160	12,120	11,540
3	21,425	18,230	170	12,200	11,630
4	19,680	16,580	180	11,780	11,440
5	19,490	16,430	190	11,830	11,250
6	19,240	16,340	200	11,390	10,810
7	19,000	16,350	210	10,760	10,660
8	18,760	15,900	220	10,660	10,470
9	18,600	15,850	230	10,230	9,790
10	18,470	15,660	240	9,690	9,210
20	17,450	14,540	250	8,820	8,290
40	16,240	13,430	260	7,320	7,170
60	15,120	12,600	268	3,390	2,760
80	14,540	12,260		Failure	

10. FIGURES

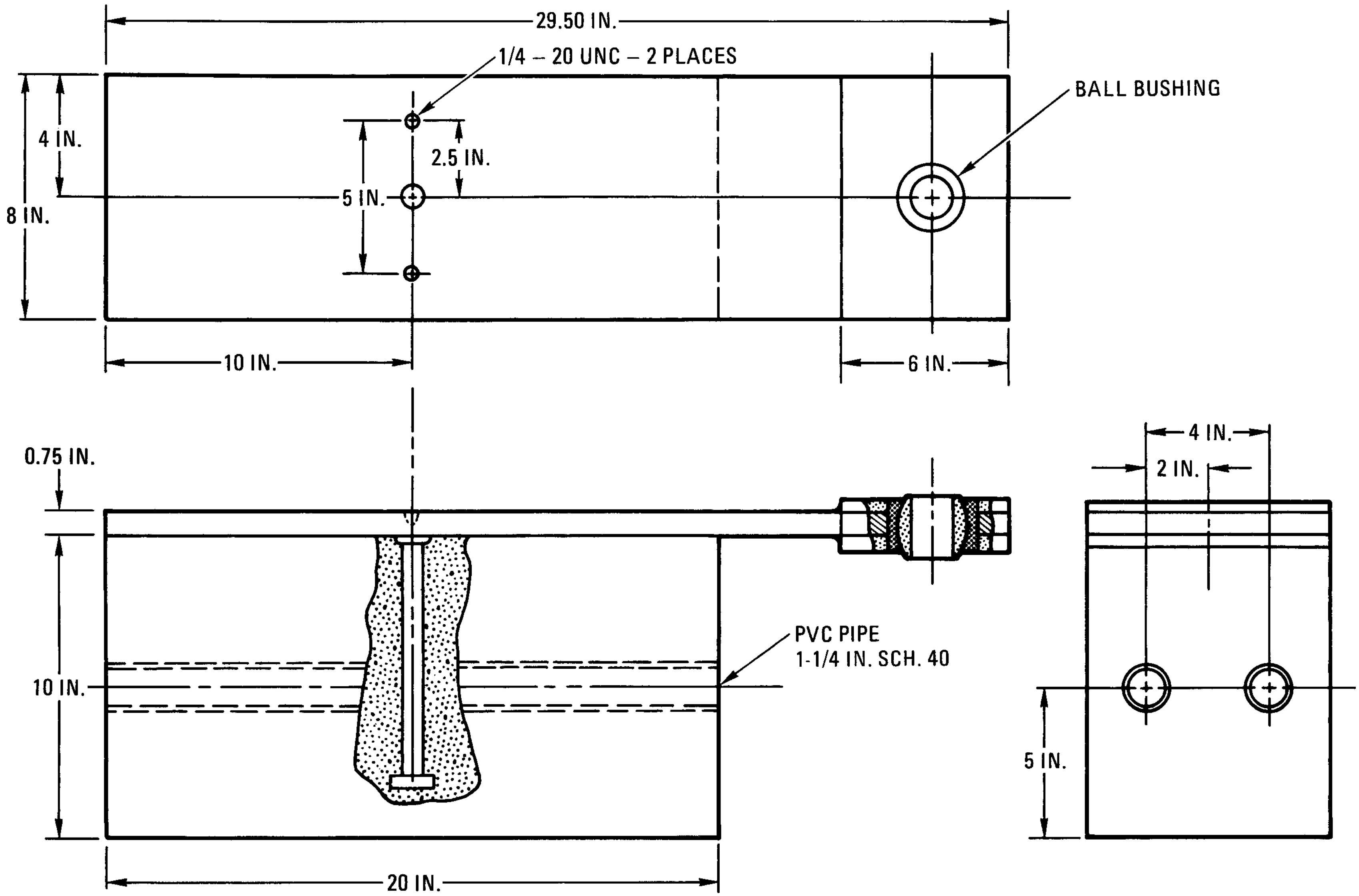


Fig. 1. Anchor stud test specimen

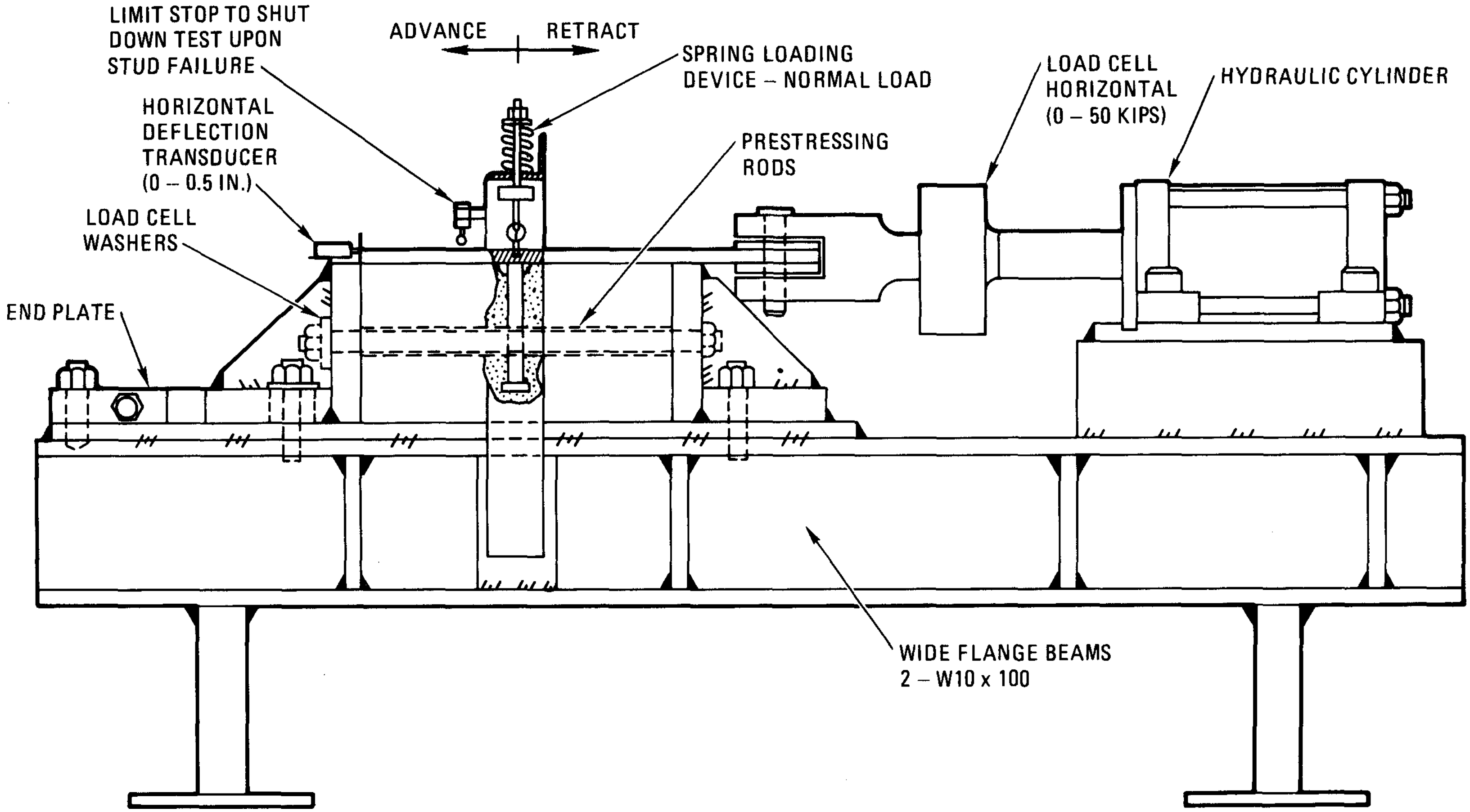


Fig. 2. Loading frame assembly and instrumentation - side view

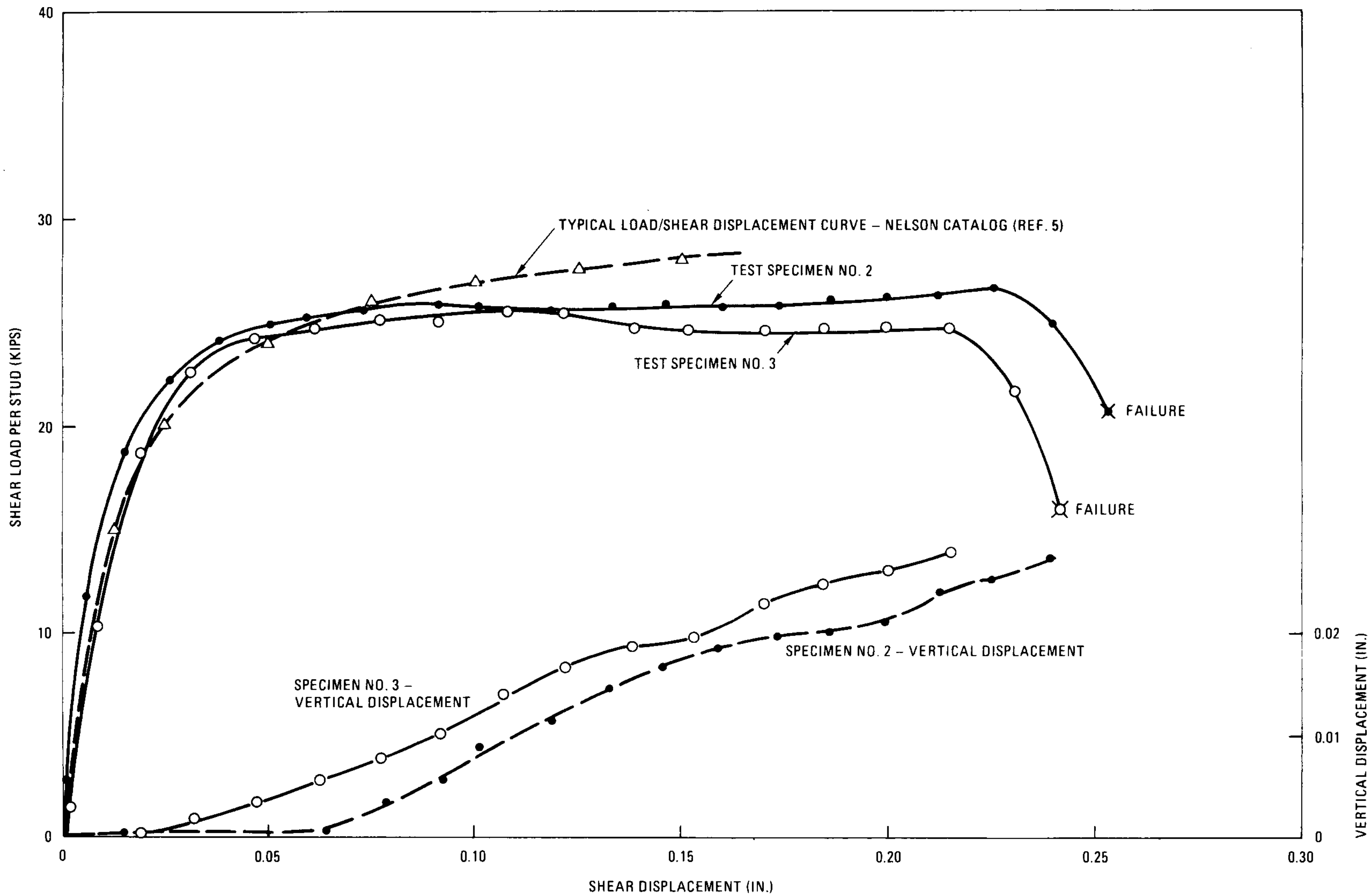


Fig. 3. Shear load/displacement curve for monotonic load - specimen No. 2 and No. 3

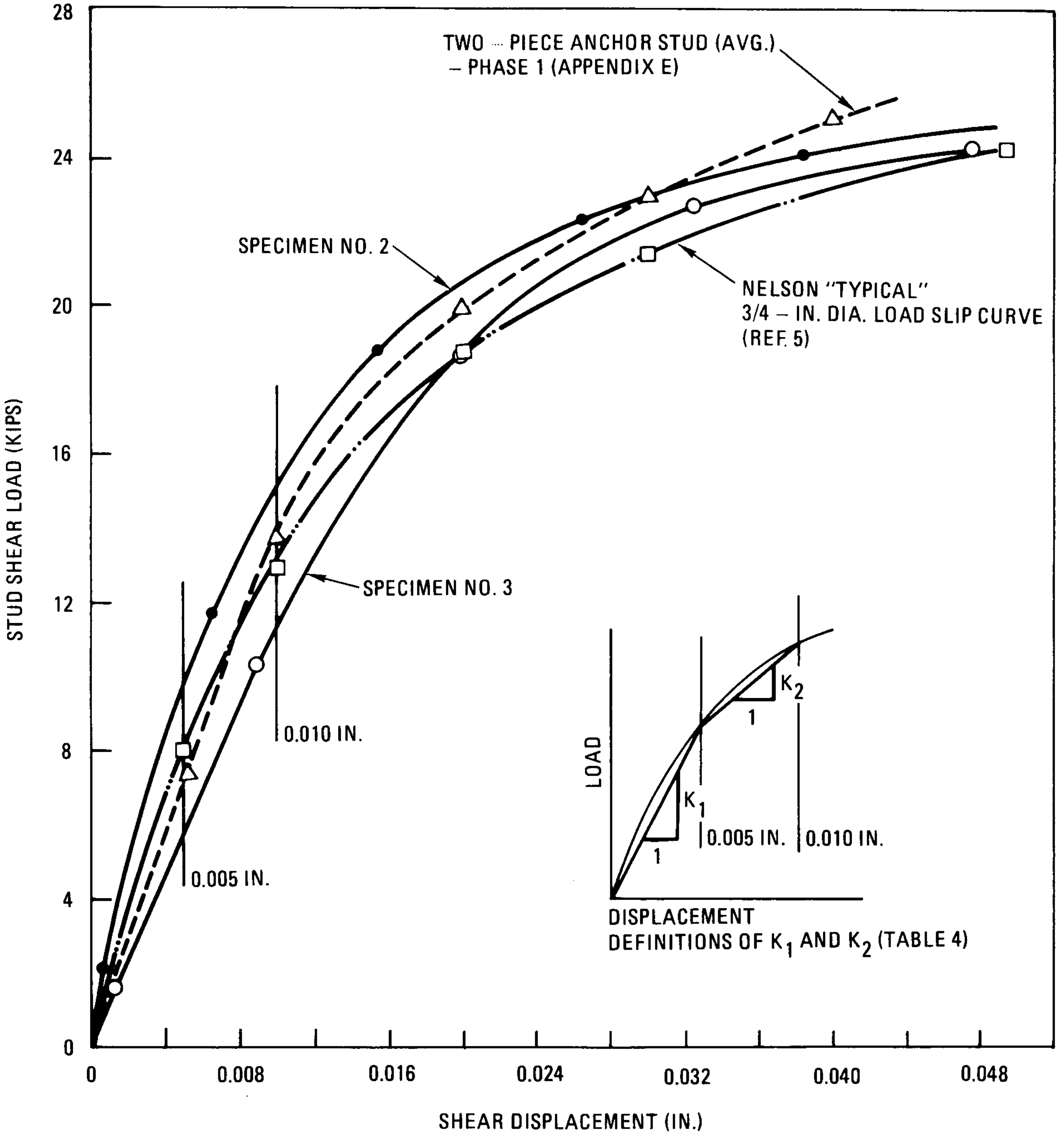


Fig. 4. Replotted shear load/displacement curve for monotonically loaded specimens No. 2 and No. 3; two-piece anchor stud curve from Phase II is shown for comparison.

790124

Fig. 5. Detail of failed stud, liner side - monotonic test on specimen No. 2

790123

Fig. 6. Detail of stud, concrete side - monotonic test on specimen No. 2

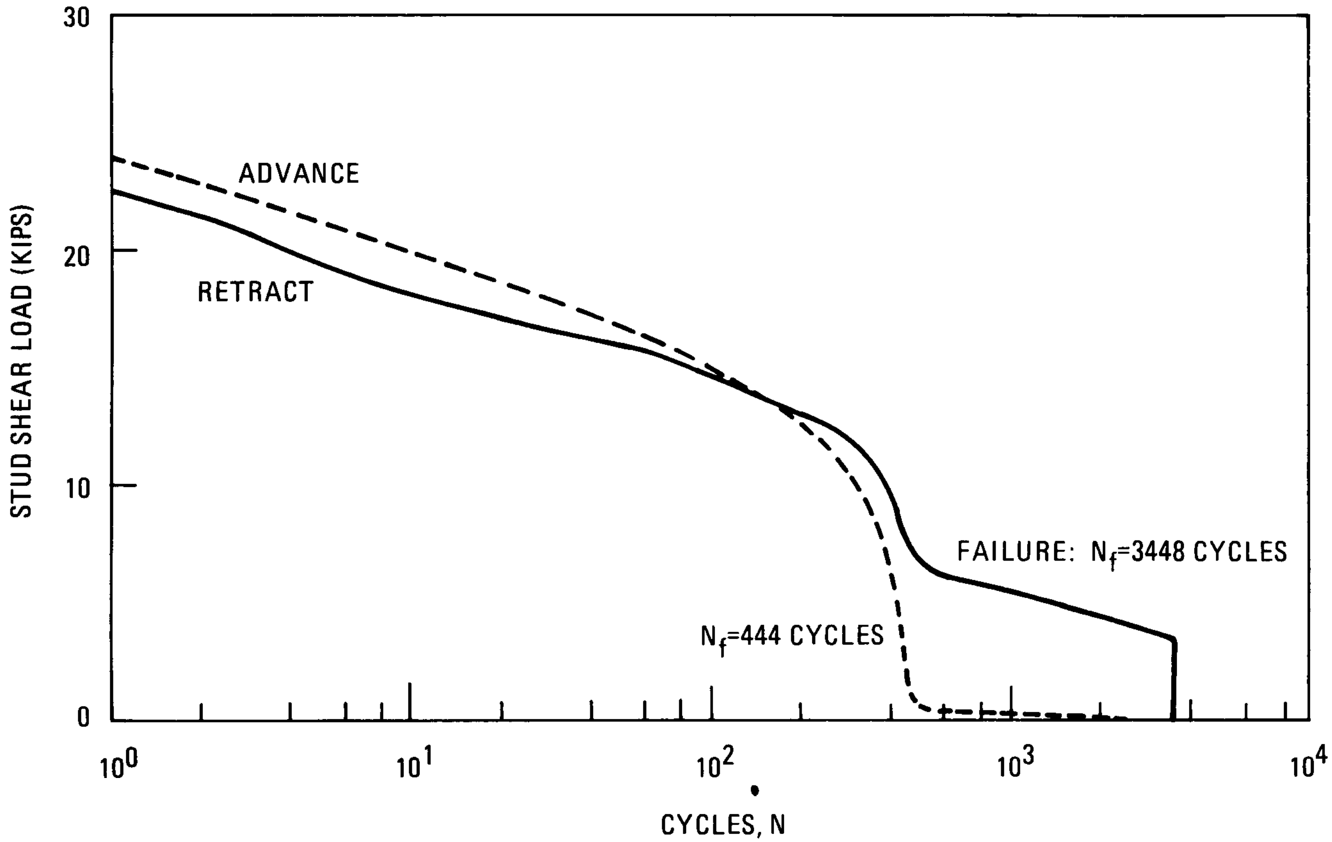


Fig. 7. Load relaxation curve for specimen No. 6 (±0.025 in.) controlled displacement

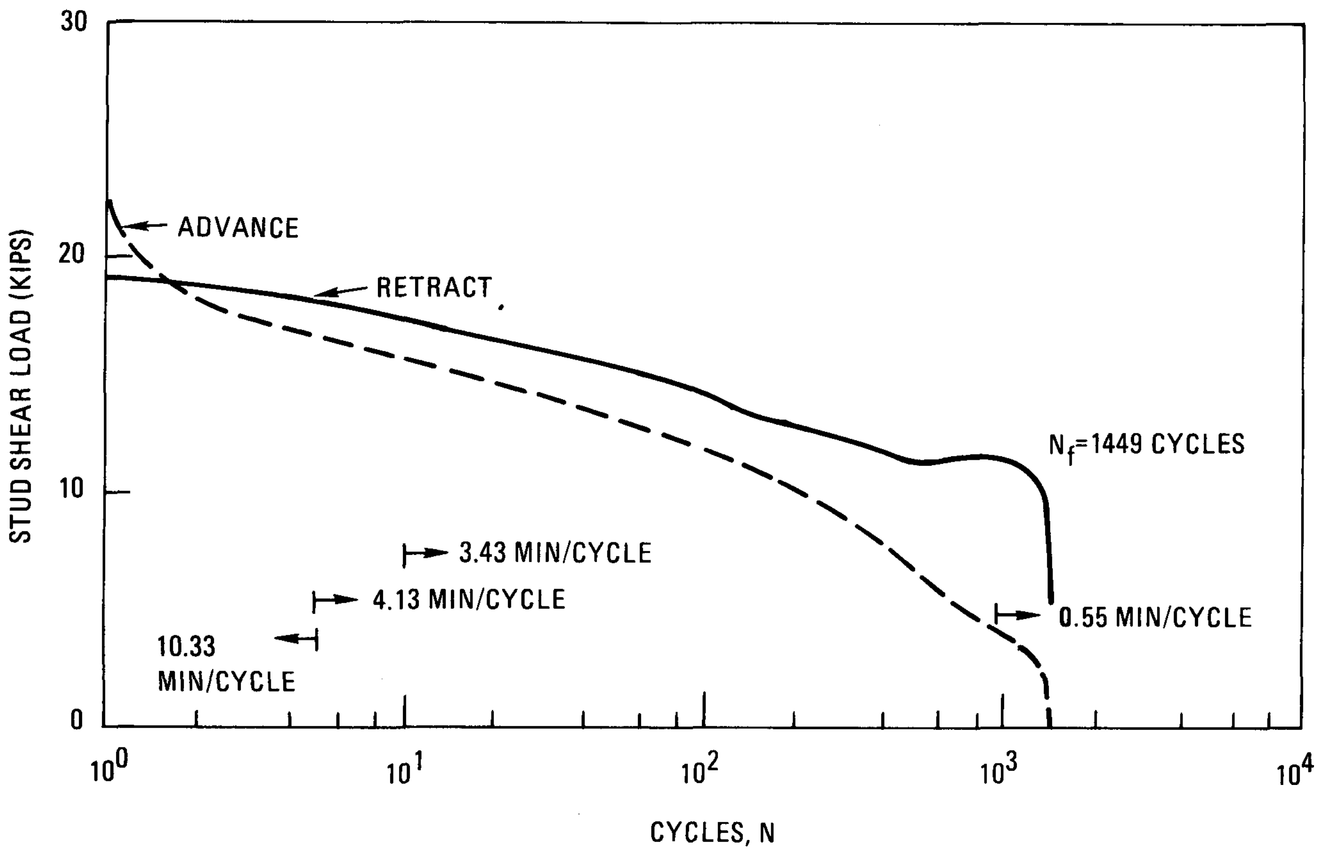


Fig. 8. Load relaxation curve for specimen No. 10 (±0.025-in. controlled displacement)

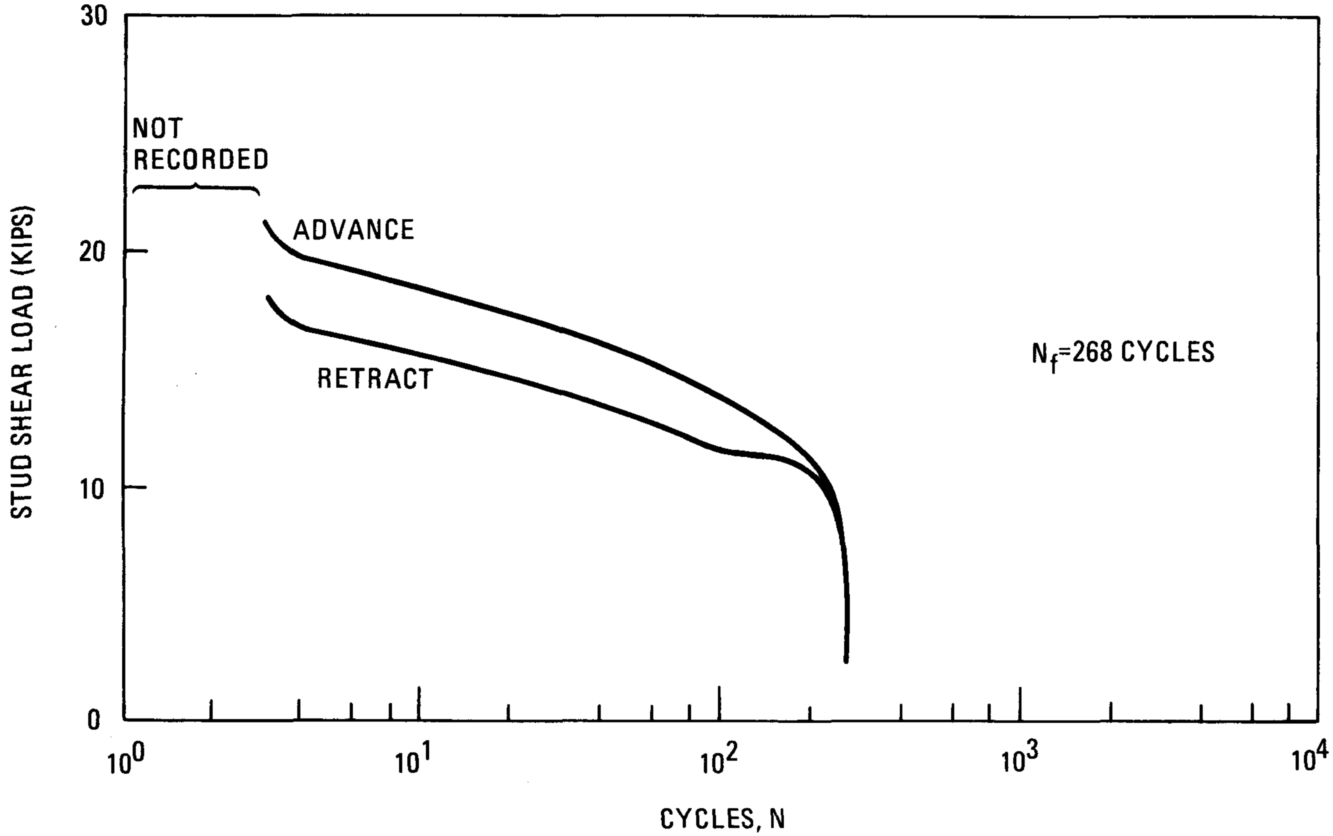


Fig. 9. Load relaxation curve for specimen No. 11 (±0.025-in. controlled displacement)

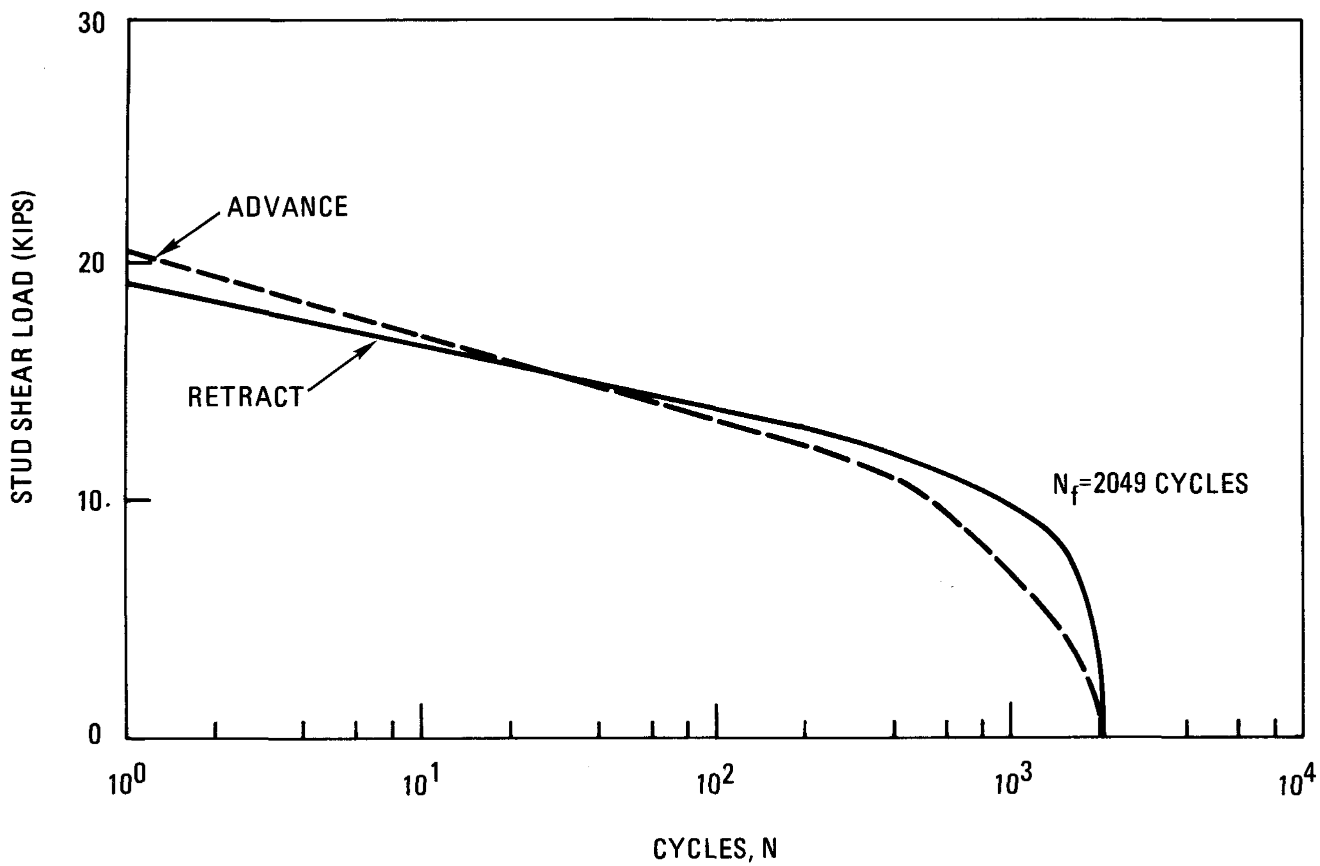


Fig. 10. Load relaxation curve for specimen No. 7 (±0.018-in. controlled displacement)

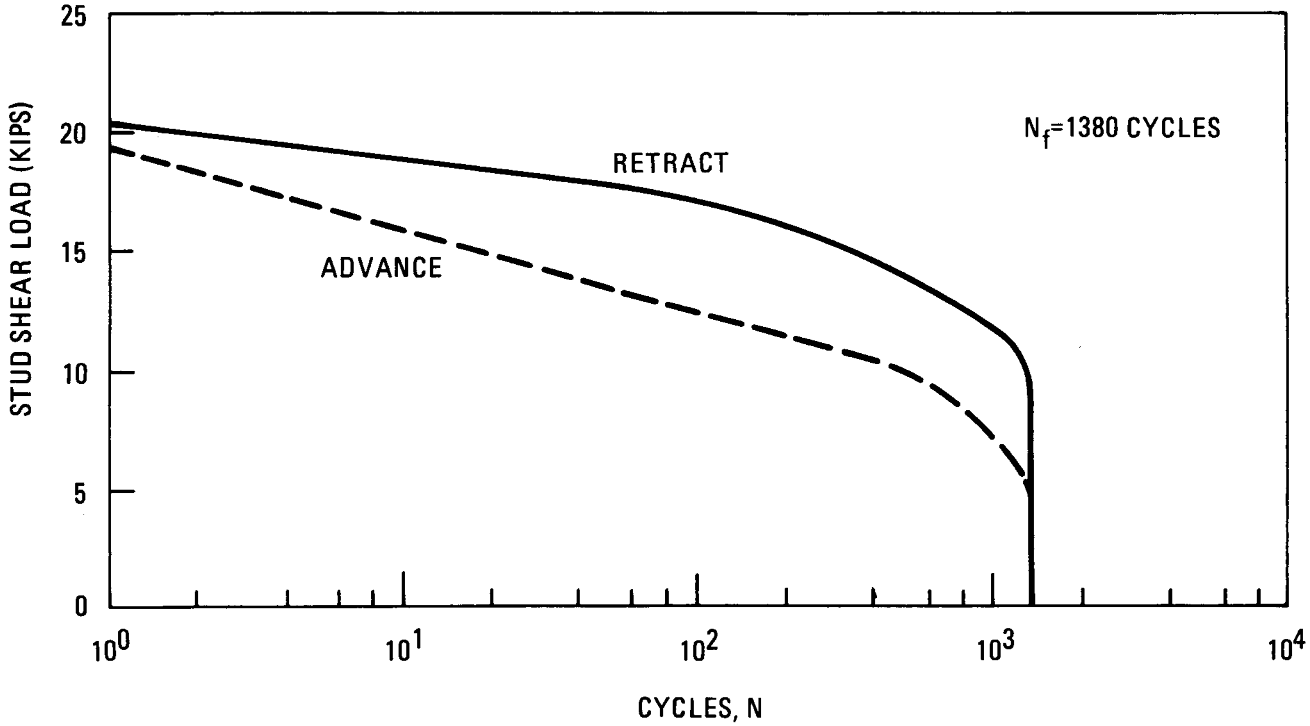


Fig. 11. Load relaxation curve for specimen No. 8 (±0.018-in. controlled displacement)

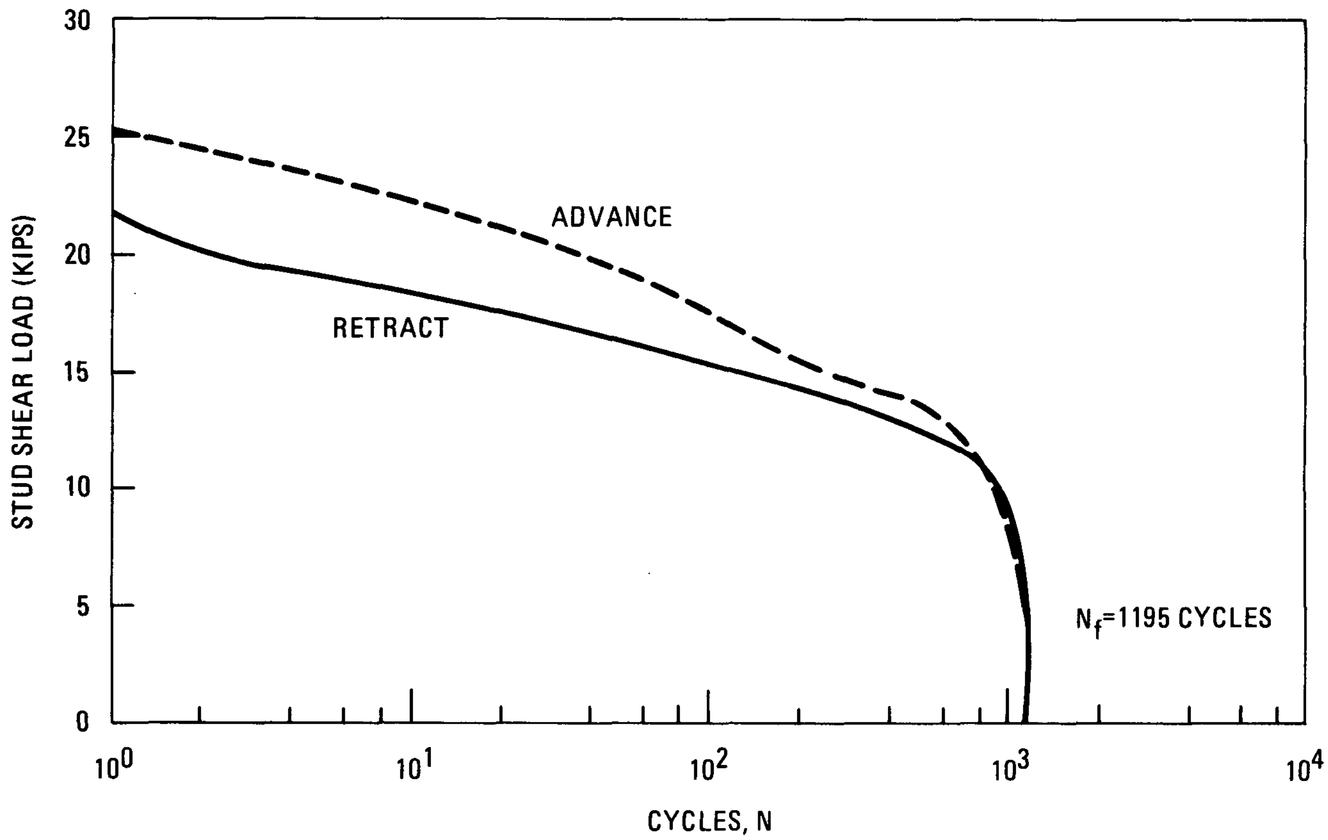


Fig. 12. Load relaxation curve for specimen No. 9 (±0.018-in. controlled displacement)

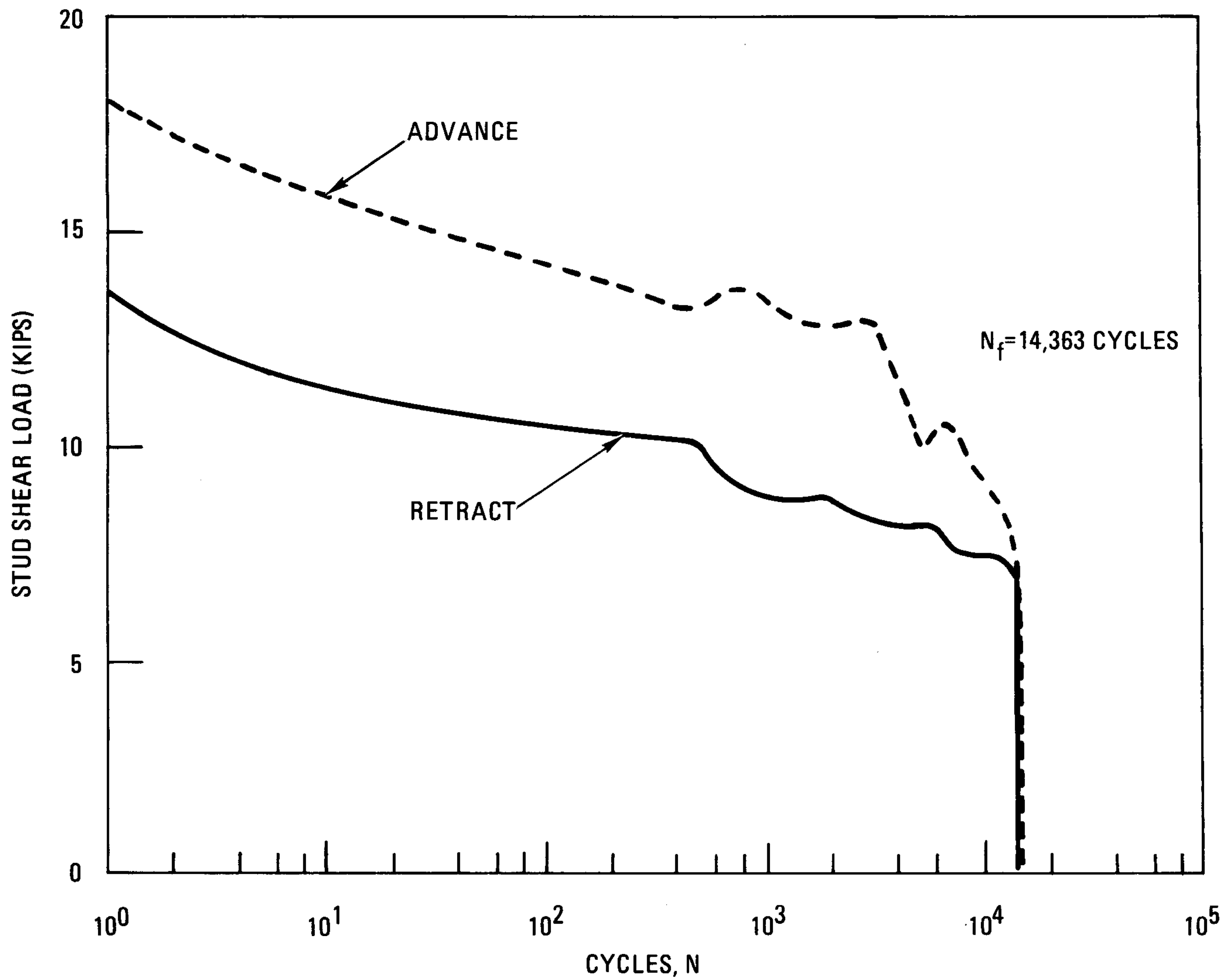


Fig. 13. Load relaxation curve for specimen No. 4 (±0.012-in. controlled displacement)

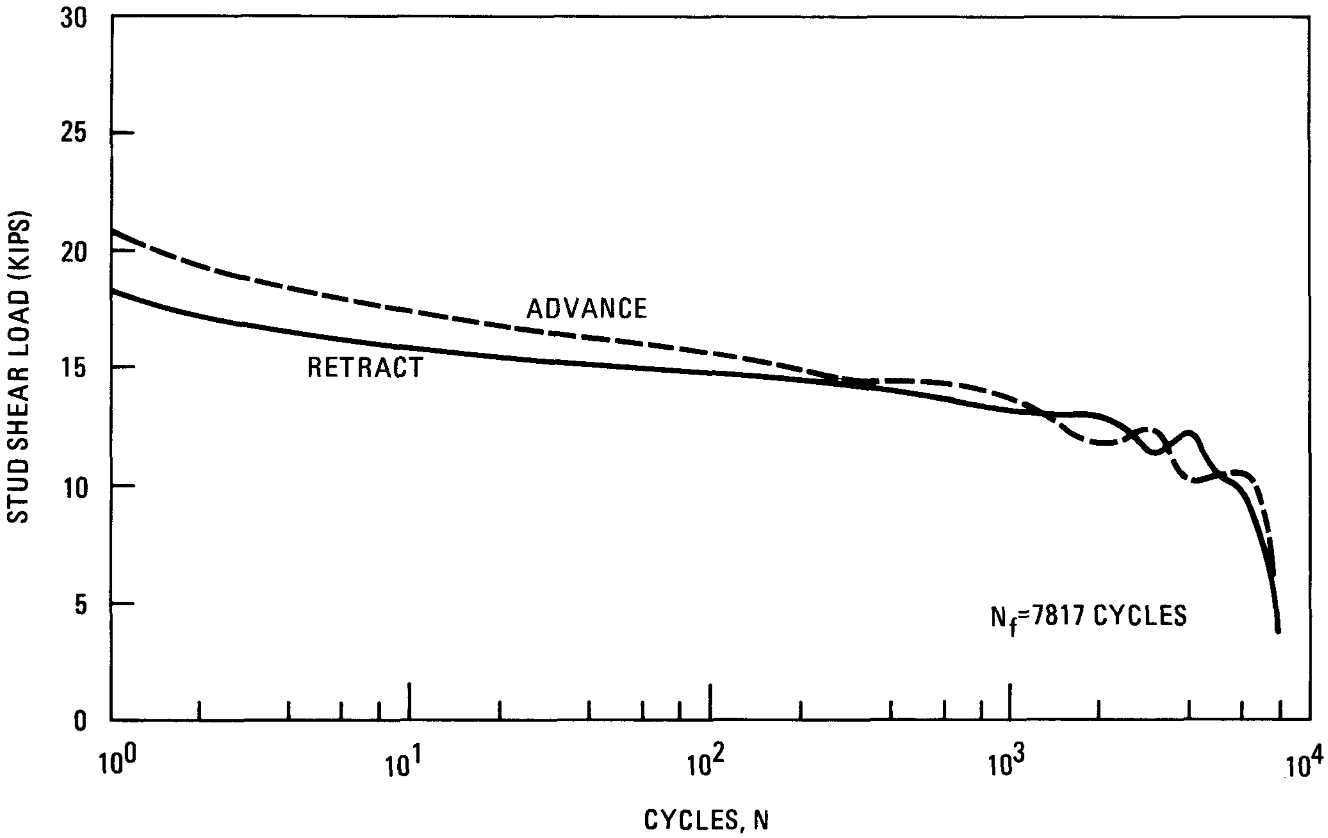


Fig. 14. Load relaxation curve for specimen No. 5 (±0.012-in. controlled displacement)

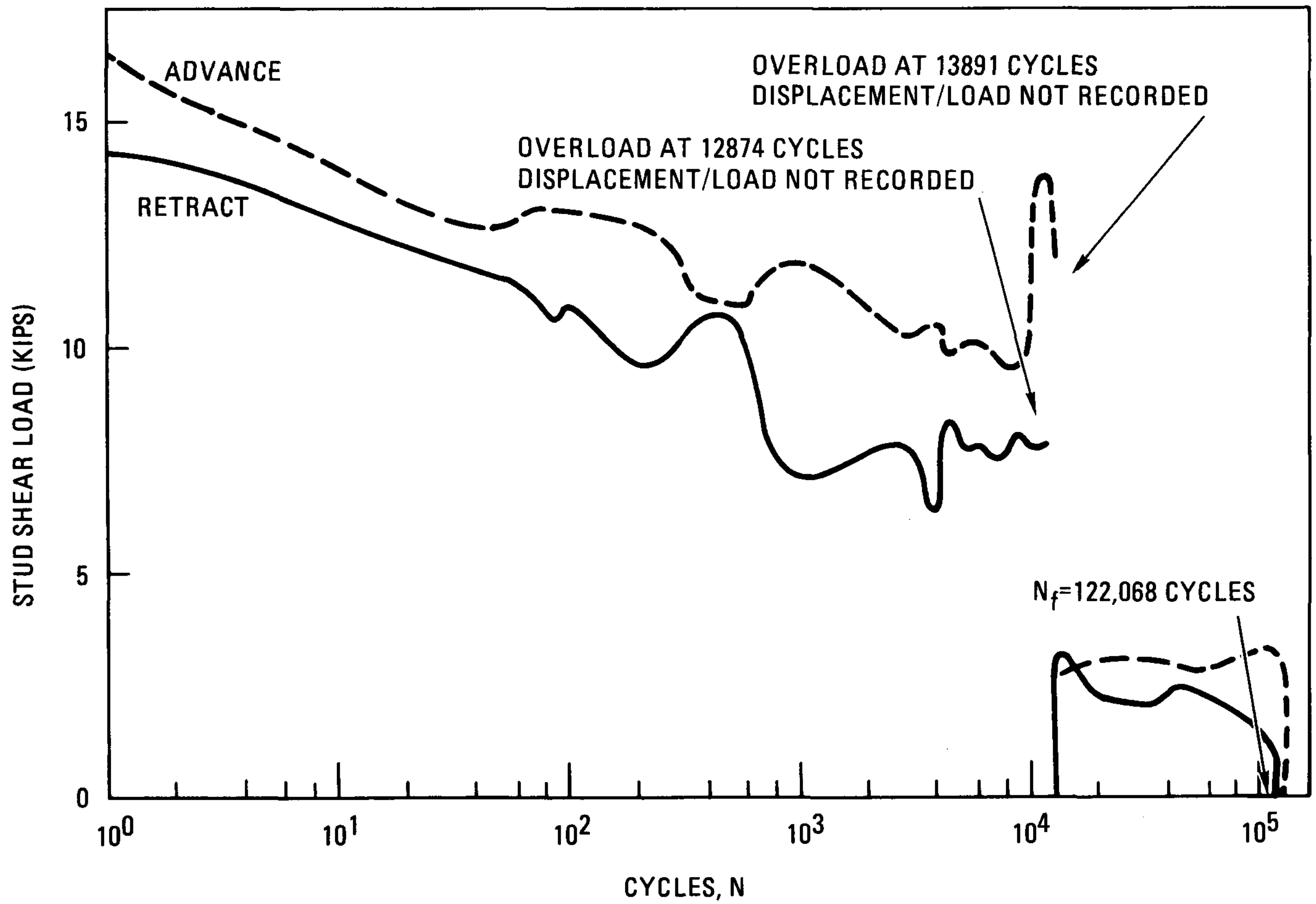


Fig. 15. Load relaxation curves for specimen No. 12 (±0.012-in. controlled displacement following overload)

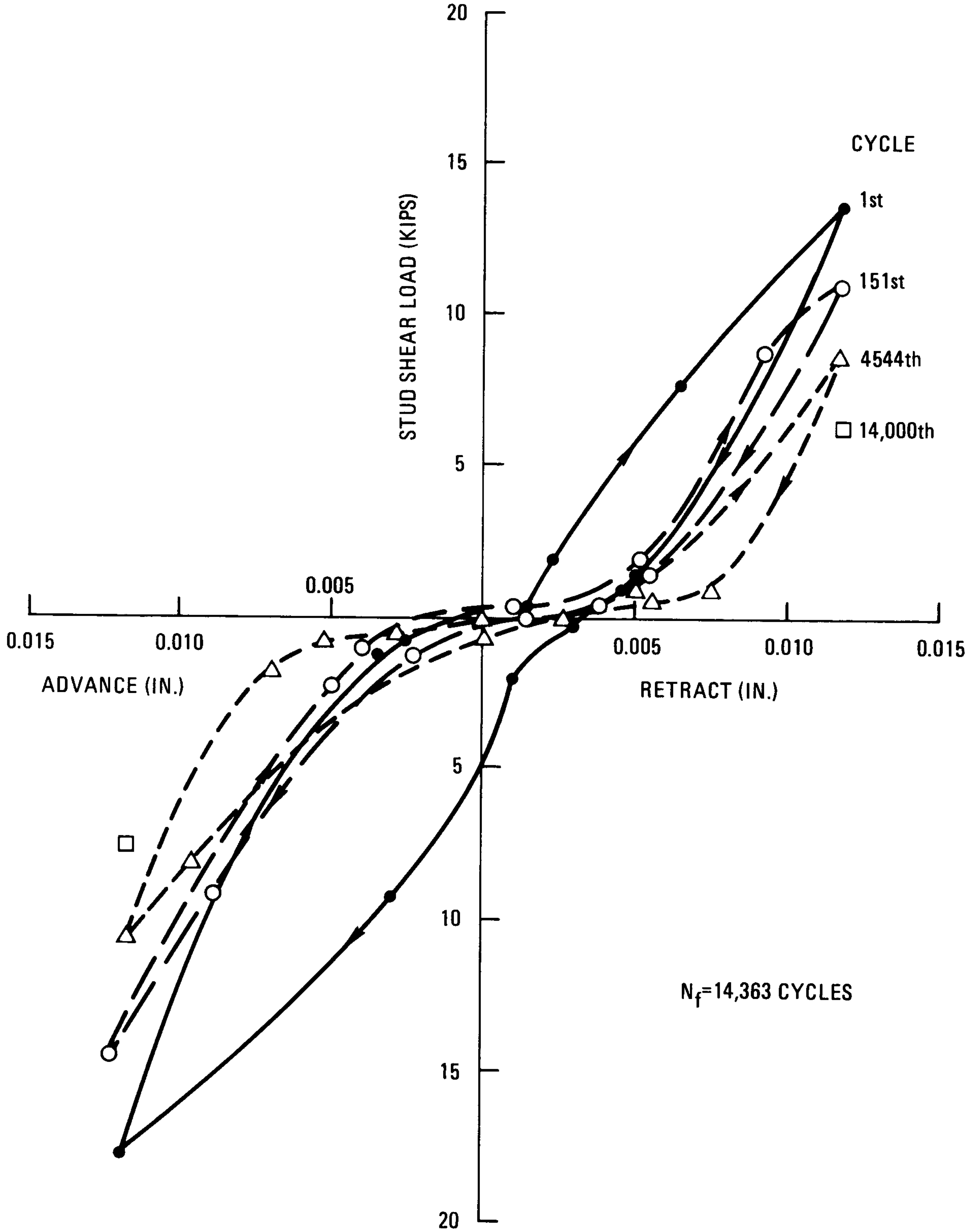


Fig. 16. Sheer load/displacement curve for specimen No. 4 (±0.012-in. controlled displacement)

790127

Fig. 17. Detail of failed stud, concrete side - specimen No. 4 (±0.012-in. controlled displacement)

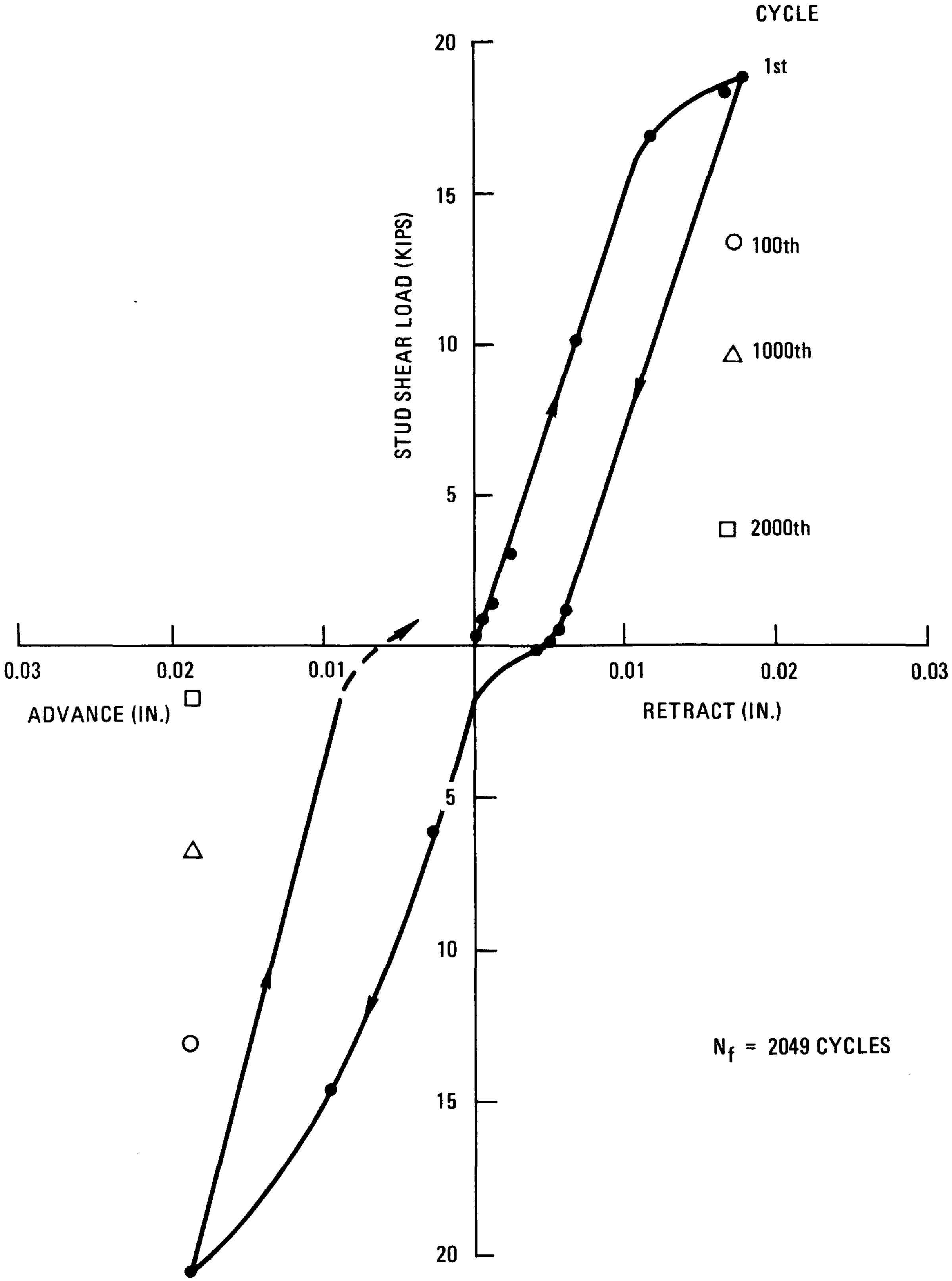


Fig. 18. Shear load/displacement curve for specimen No. 7 (±0.018-in. controlled displacement)

790130

Fig. 19. Detail of failed stud, liner side - specimen No. 7 (±0.018-in. controlled displacement)

790129

Fig. 20. Detail of failed stud, concrete side - specimen No. 7 (±0.018 – in. controlled displacement)

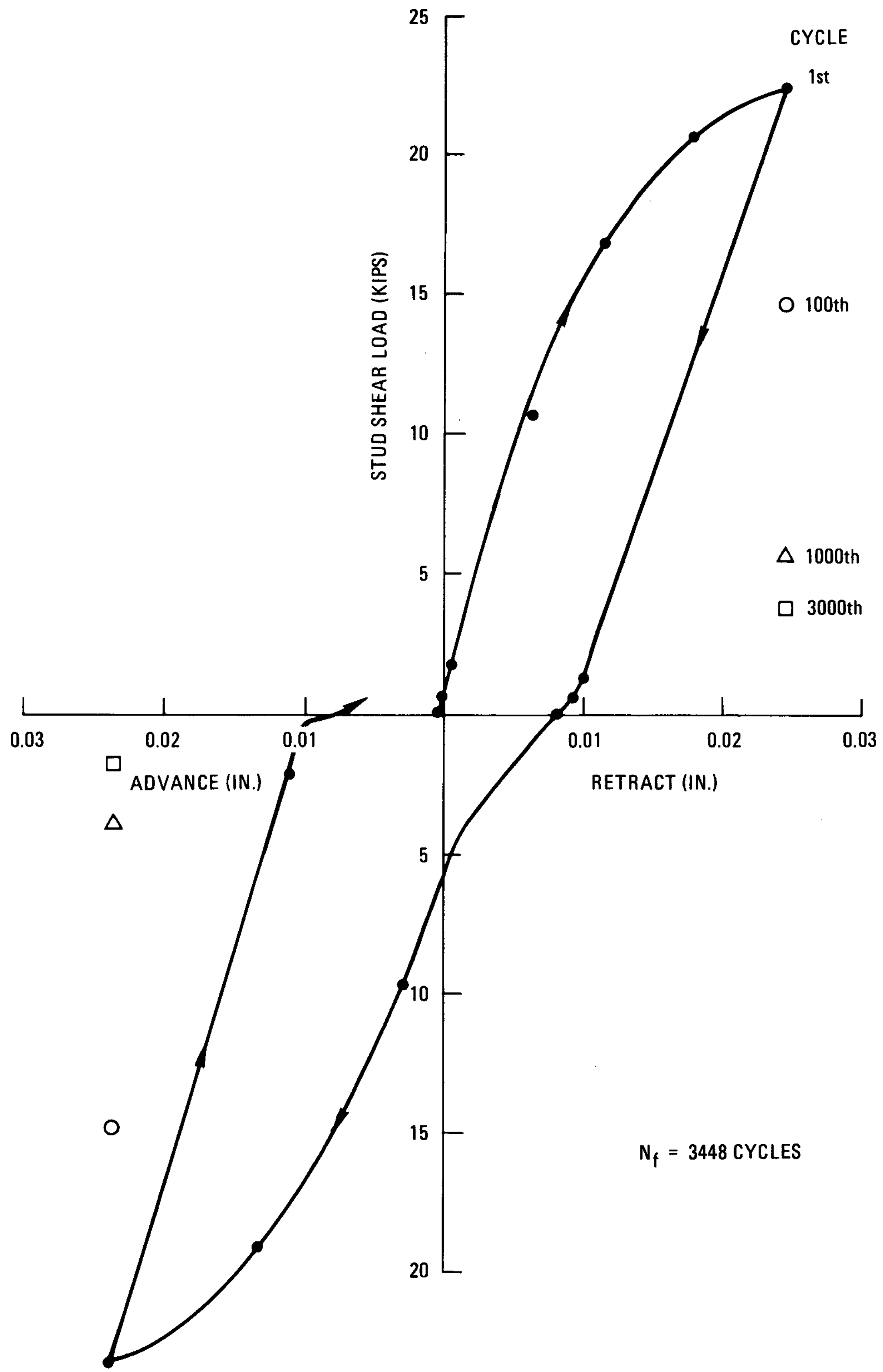


Fig. 21. Shear load/displacement curve for specimen No. 6 (±0.025-in. controlled displacement)

790132

Fig. 22. Detail of failed stud, liner side - specimen No. 6 (±0.025-in. controlled displacement)

790121

Fig. 23. Detail of failed stud, concrete side - specimen No. 6 (±0.025-in. controlled displacement)

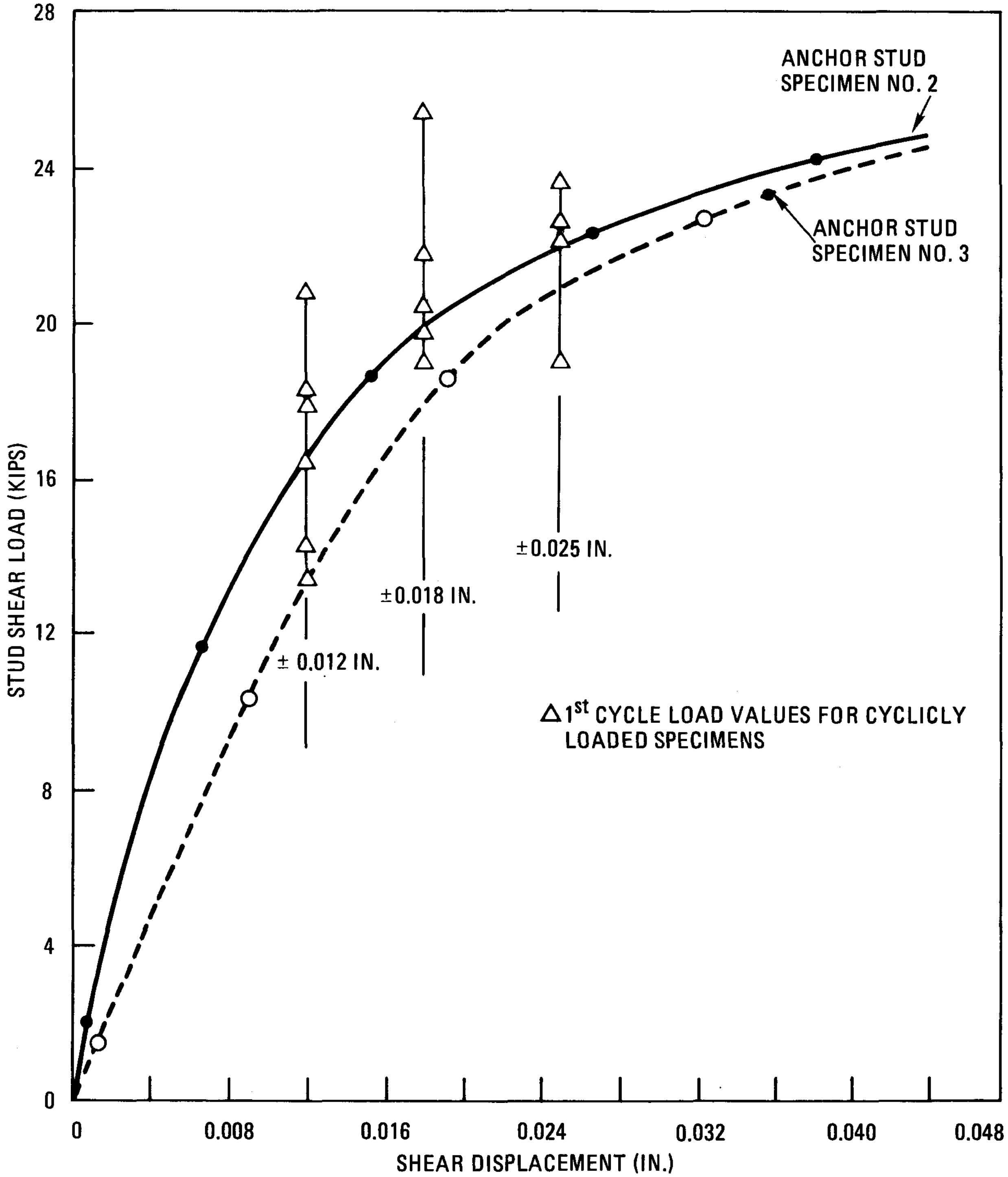


Fig. 24. Shear load/displacement results from cyclic tests

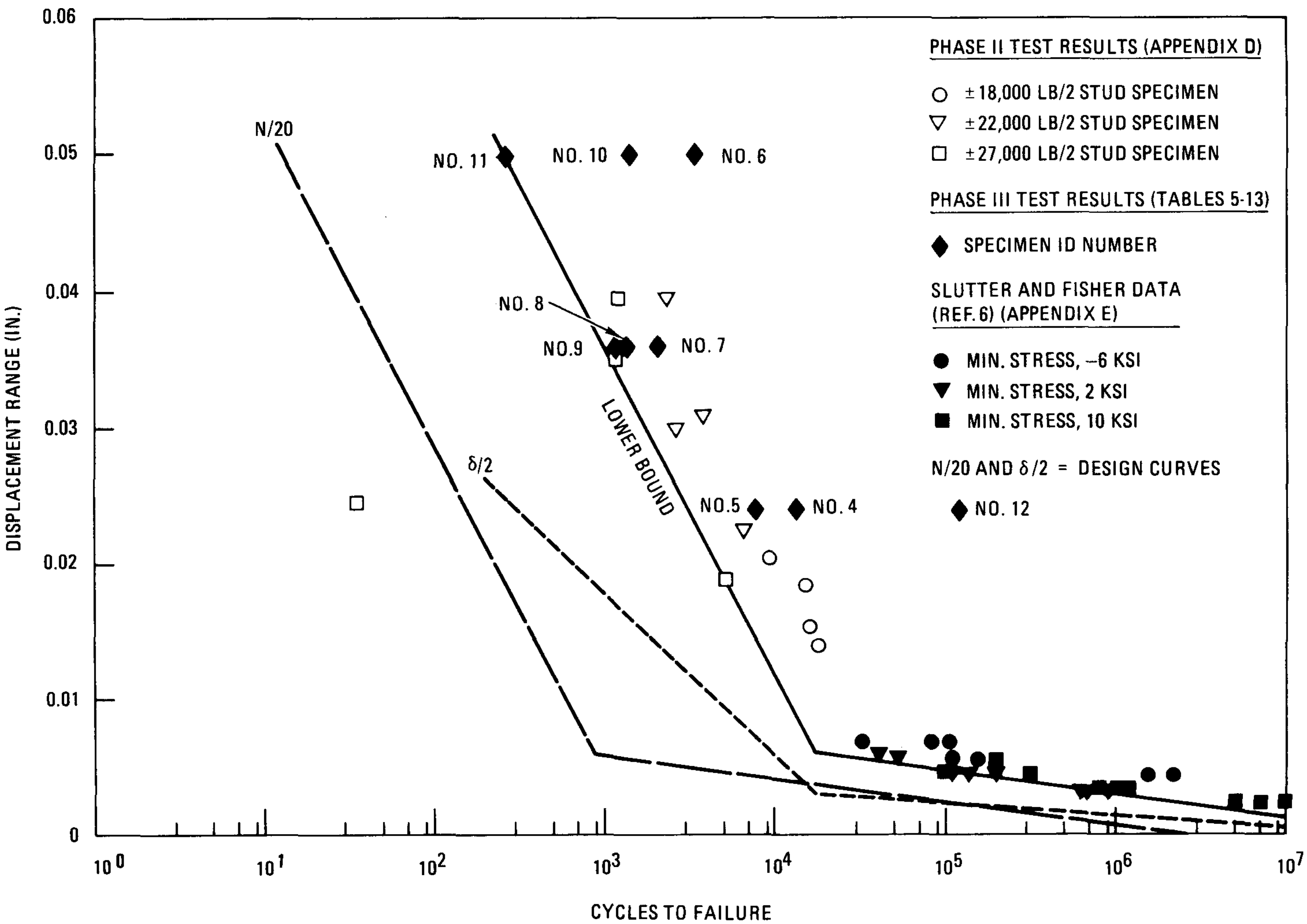


Fig. 25. Cycles to failure versus displacement range curve

APPENDIX A
STUD WELDING

All anchor studs were welded in the downhand position according to the AWS Structural Welding Code D1. 1-75, Section 4.25-4.31, and General Atomic Procurement Requisition No. 650127. The welding was performed by the TRW Nelson Division (Los Angeles).

Materials and equipment used in the welding consist of:

1. Nelson NS-20A HD stud welding system (799-340-000*).
2. RT-1800A power source (750-256-000).
3. Nelson time current analyzer (512-182-000).
4. 3/4 x 8-3/16 shear connector (101-098-023).
5. 3/4 F-305 ferrules (100-101-043).

Weld settings are as follows:

Lift - 0.093	Tranquil arc setting - 3.5
Plunge - 0.187	Polarity - straight
Time - 0.83 sec	Current - 1500 amp

In addition to the 12 test specimens, six studs were welded onto 6 in. by 12 in. sample plates (Fig. A-1). Three of these sample plates were sectioned for weld detail examination (Fig. A-2), and three were tensile tested to failure (Fig. A-3, Table A-1). The tensile test of the three anchor stud samples was conducted with an MTS 810 material test machine. The anchor stud samples were coupled to the machine with mounting fixtures as shown in Fig. A-3.

---

*Part number.

Details of the stud and plate materials are as follows:

Stud Material Description

Part No. 101-098-023, 3/4 x 8-3/16 S3L

HT #L-44918

ASTM A108 - 73

Chemical composition:

Carbon 0.16% Manganese 0.48%

Phosphorus 0.005% Sulphur 0.019%

Mechanical properties:

Yield strength: 72,634 psi Ultimate strength: 75,114 psi

Reduction of area: 58.3% Elongation: 24.3%

Plate Material Description

3/4-in. thickness

SA 537 Class 2, quenched and tempered

Chemical composition:

Carbon 0.24% Manganese 0.65%

Phosphorus 0.035% Sulphur 0.04%

Mechanical properties:

Yield strength: 60,000 psi min.

Ultimate strength: 80,000 psi min.

Elongation: 22%

TABLE A-1

TENSILE TEST RESULTS ON ANCHOR STUD SAMPLES[a]

Specimen No.	Ultimate Load (lb)	Location of Failure
1	28,900	Shank, $\sim$2 in. above weld
2	29,400	Shank, $\sim$2 in. above weld
3	29,600	Shank, $\sim$2 in. above weld

[a]Tensile test loading fixture and hold-down apparatus are shown in Fig. A-3.

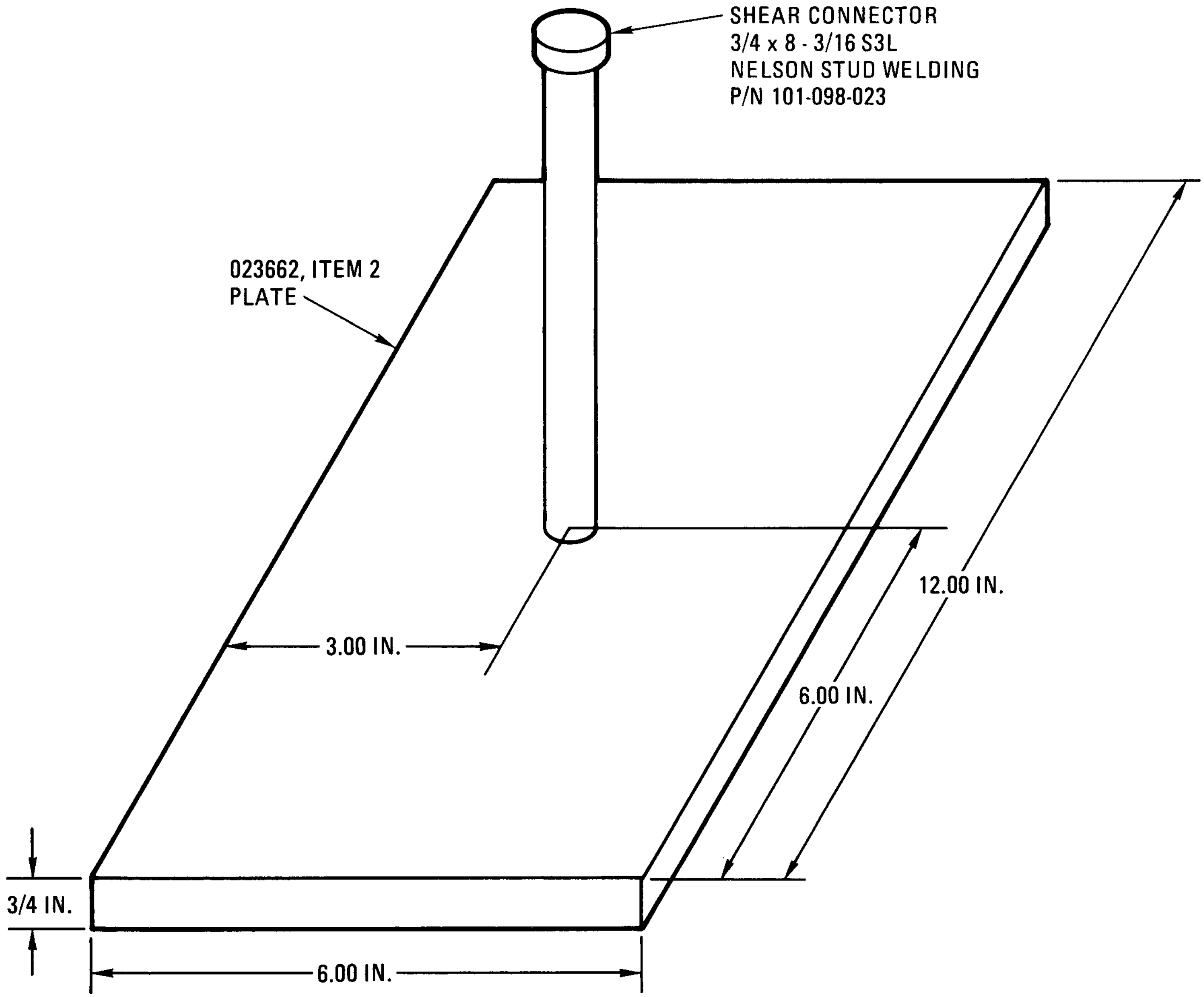
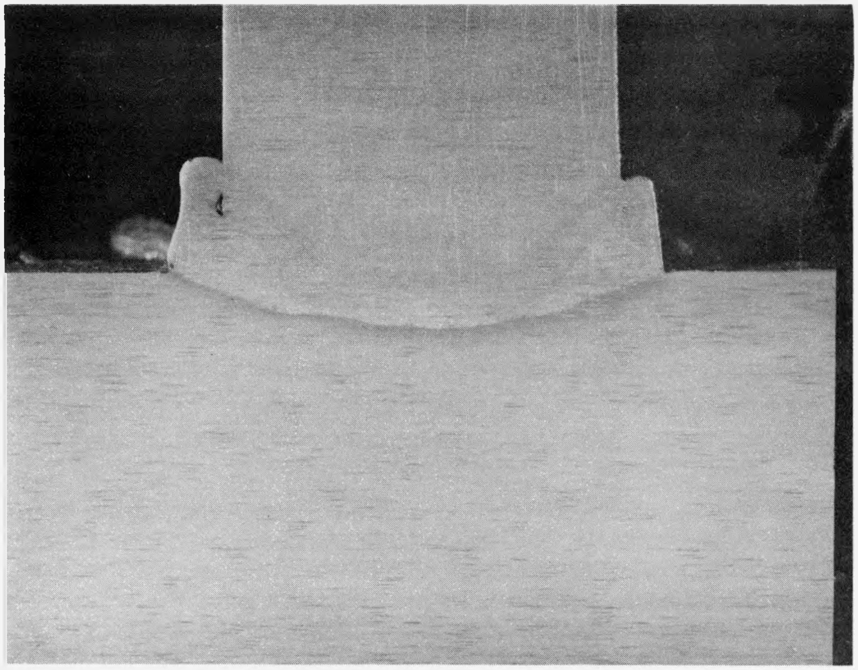
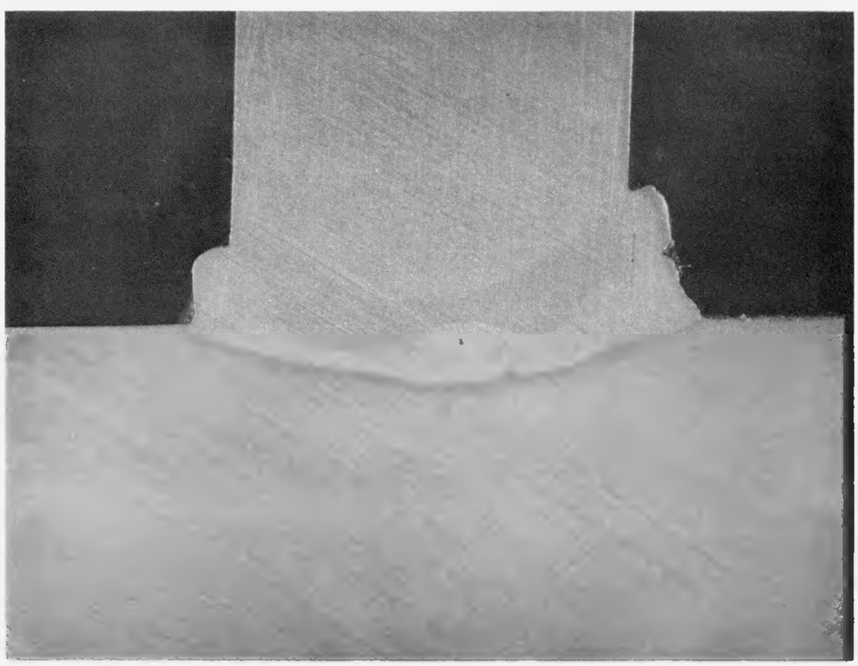


Fig. A-1. Anchor stud tensile test specimen

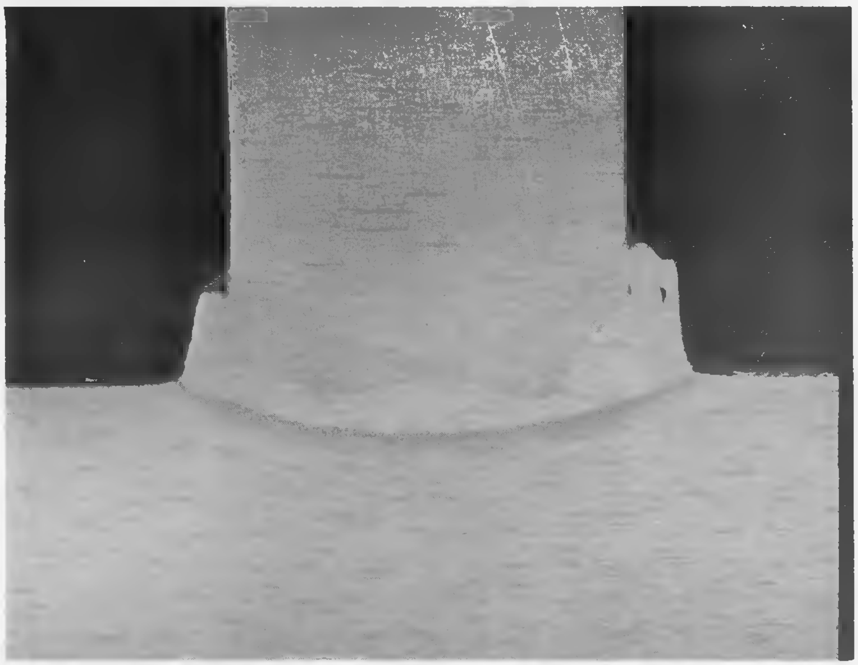


(a) Cross section of anchor stud weld No.1s



(b) Cross section of anchor stud weld No. 2s

Fig. A-2. Cross section of anchor stud welds (sheet 1 of 2)



(c) Cross section of anchor stud weld No. 3s

Fig. A-2. Cross section of anchor stud welds (sheet 2 of 2)

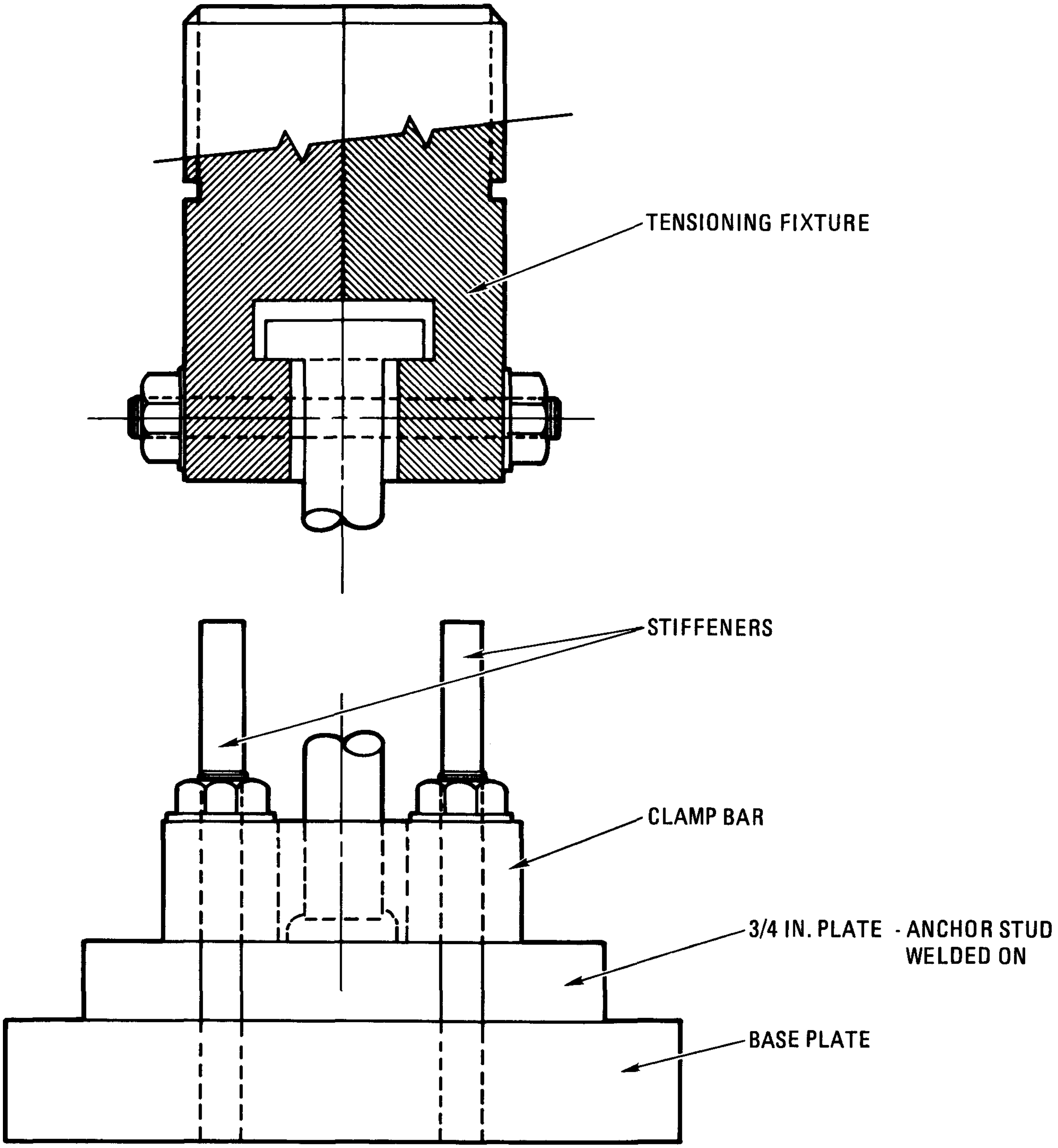


Fig. A-3. Anchor stud tension test setup

APPENDIX B
CASTING OF SPECIMENS

The 12 shear test specimens were cast at Southern California Testing Laboratory (San Diego) according to GA Specification (Ref. 7). Steel forms were used in the casting operation to assure one-dimensional control of the concrete block.

The concrete mix was designed on a one-cubic-yard basis with proportions as follows:

Cement	700 lb
Water	260 lb
Fine aggregate	1207 lb
3/8-in. fine aggregate	387 lb
3/4-in. fine aggregate	580.5 lb
1-1/2-in. fine aggregate	967.5 lb
Admixture	6 fluid oz/100 lb of cement

The casting operation was performed on four days, with two batches cast each day (Table B-1). The batch sizes varied depending upon the size and number of shear specimens and test cylinders to be cast. The specimens were stored outside beneath soaked burlap sacks and plastic covering until the last compressive cylinder test was conducted. The cylinder test results for each specimen and the specimen age at testing are given in Table B-2.

TABLE B-1

ANCHOR STUD SPECIMEN CASTING

Casting No.	Batch No.	Cubic Yards	Specimen Cast	No. Cyl's	Date Cast
1	1	0.059	1	2	5/8/78
	2	0.085	2&3	2	5/8/78
2	1	0.061	4	2	5/10/78
	2	0.080	5&6	1	5/10/78
3	1	0.061	7	1	5/12/78
	2	0.080	8&9	1	5/12/78
4	1	0.061	10	2	5/16/78
	2	0.080	11&12	1	5/16/78

TABLE B-2

CASTING COMPRESSIVE STRENGTH TEST RESULTS FOR ANCHOR STUD SPECIMENS

Specimen No.	Age (Days)	Compressive Strength[a] (psi)
1	7	6230
	28[b]	7570
2&3	14	6970
	28	7780
4	7	5801
	28	6620
5&6	14	7030
7	7	6320
8&9	14	7330
10	7	6410
	28	7230
11&12	14	6740

[a] Specified minimum compressive strength of concrete was 6500 psi at 28 days per GA Specification (Ref. 7).

[b] Modulus of elasticity at 28 days = 3.9×10^6 psi.

APPENDIX C
TEST SETUP

The PCRV liner anchor stud structural test was conducted in the Experimental Engineering and Advanced Materials test facilities of General Atomic Company (Ref. 4).

Shear tests of anchor stud test specimens, part number 023662 (Table C-1), were conducted with a hydraulic-cylinder-operated test rig, part number EE-2517-2, as shown in Figs. C-1 and C-2. Air-operated hydraulic pumps (Fig. C-3) supplied pressurized oil to actuate the cylinder. Figure C-4 shows the test control and instrumentation setup. Details of the test equipment configuration are given in the following diagrams:

Fig. C-5, Hydraulic Load System Schematic
Fig. C-6, Test Control Circuit Schematic
Fig. C-7, Instrumentation for Anchor Stud Test
Fig. C-8, Test Instrumentation Block Diagram

TABLE C-1

DRAWING PACKAGE OF TEST FIXTURE AND SPECIMENS

Dwg. No.	Issue	Title
EE-2517 (2 sheets)	A	Test Rig Assembly
EE-2536	A	Frame Assembly
EE-2519	A	Clevis
EE-2520	A	Clevis Pin
EE-2530	A	Clevis - Anchor Stud
EE-2531	A	Pin Anchor Pin
EE-2538	A	Plate - Anchor Stud
EE-2542	A	Test Specimen Assembly - Anchor Stud
EE-2559	A	Jam Nut
0243662	C	Test Specimen - Anchor Stud
EE-2547	A	Mold Assembly 8-in. Anchor Stud
EE-2593	A	Test Coupon - Anchor Stud
EE-2597	A	Tensioning Fixture - Anchor Stud
EE-2598	A	Clamping Assembly - Anchor Stud

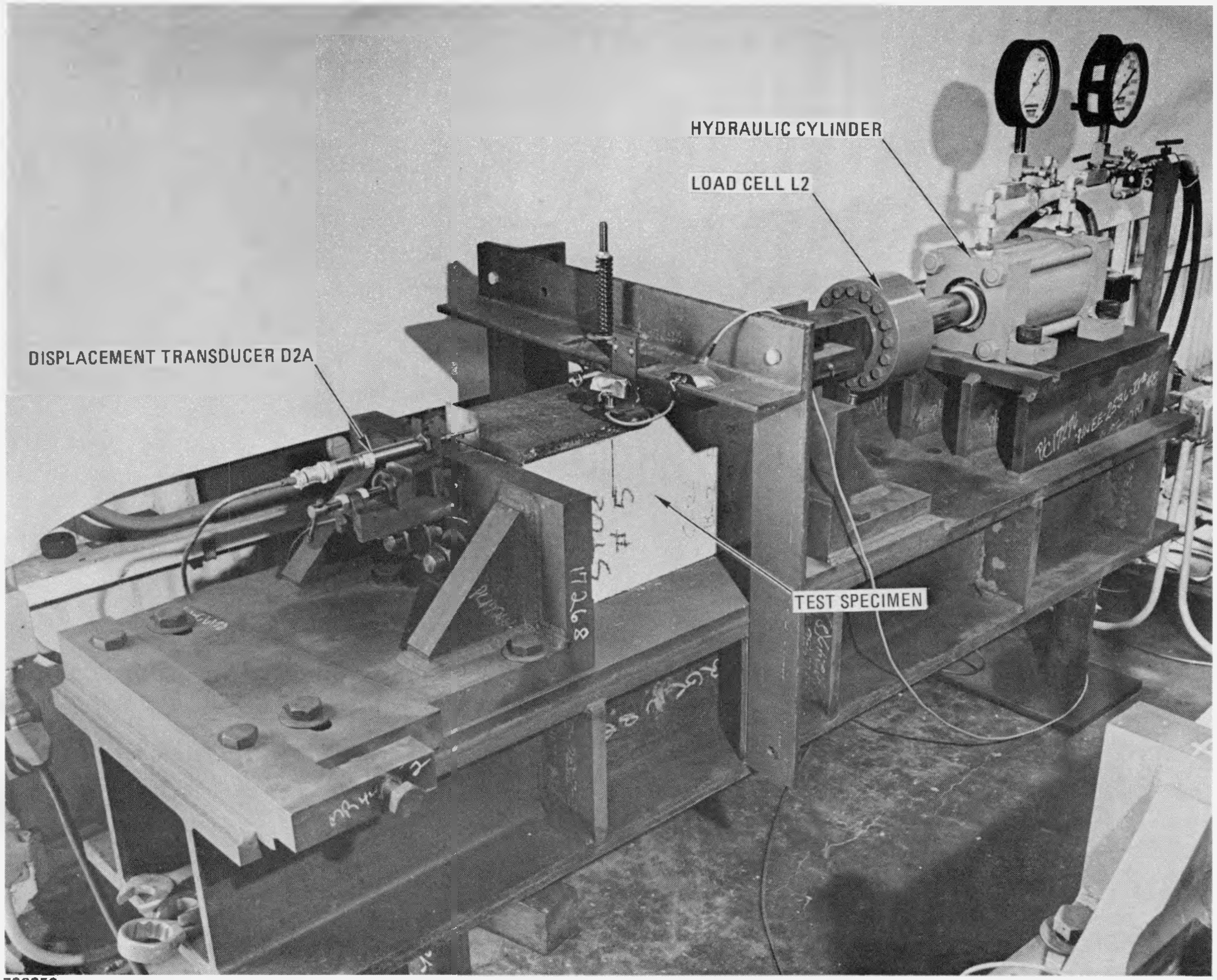
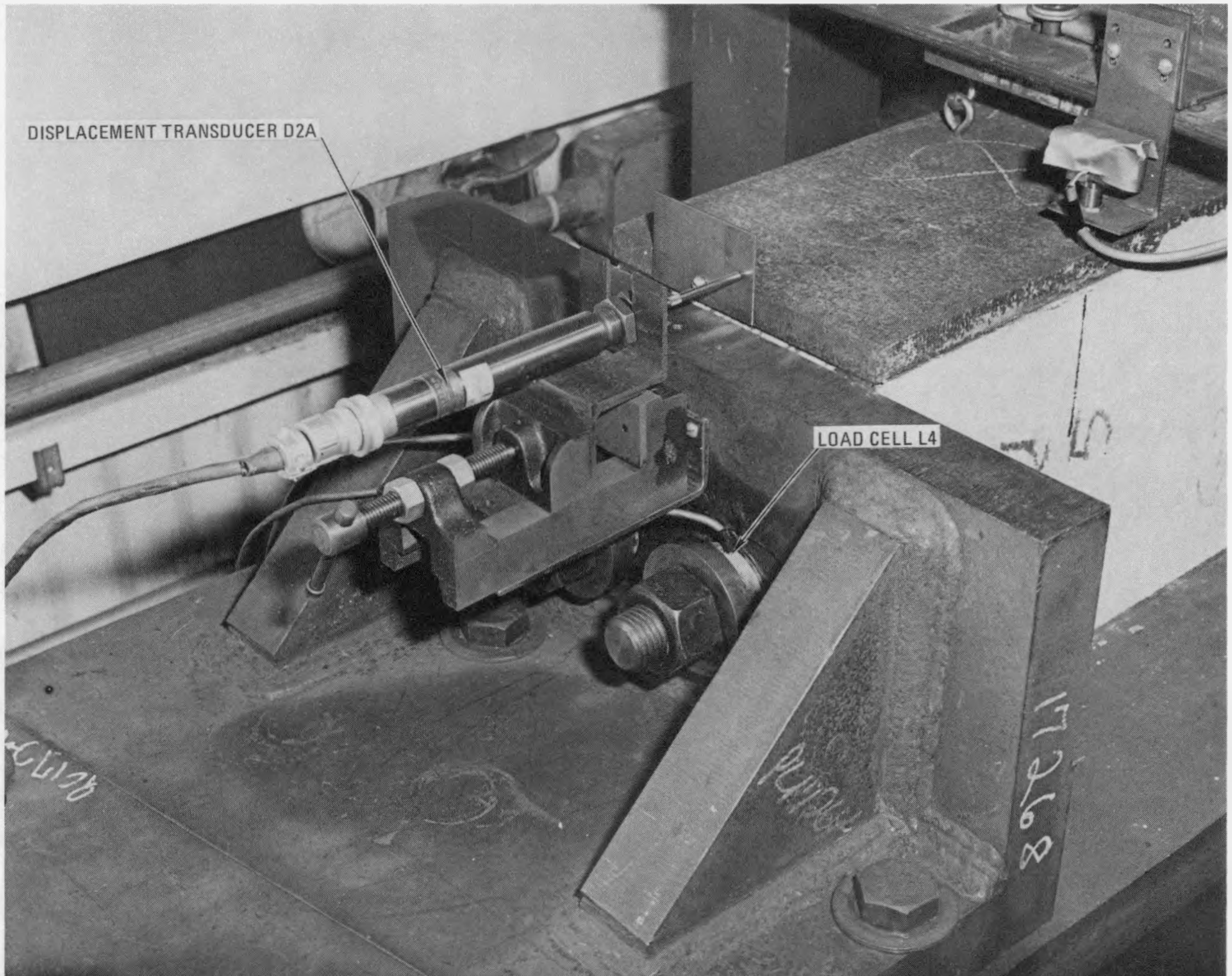
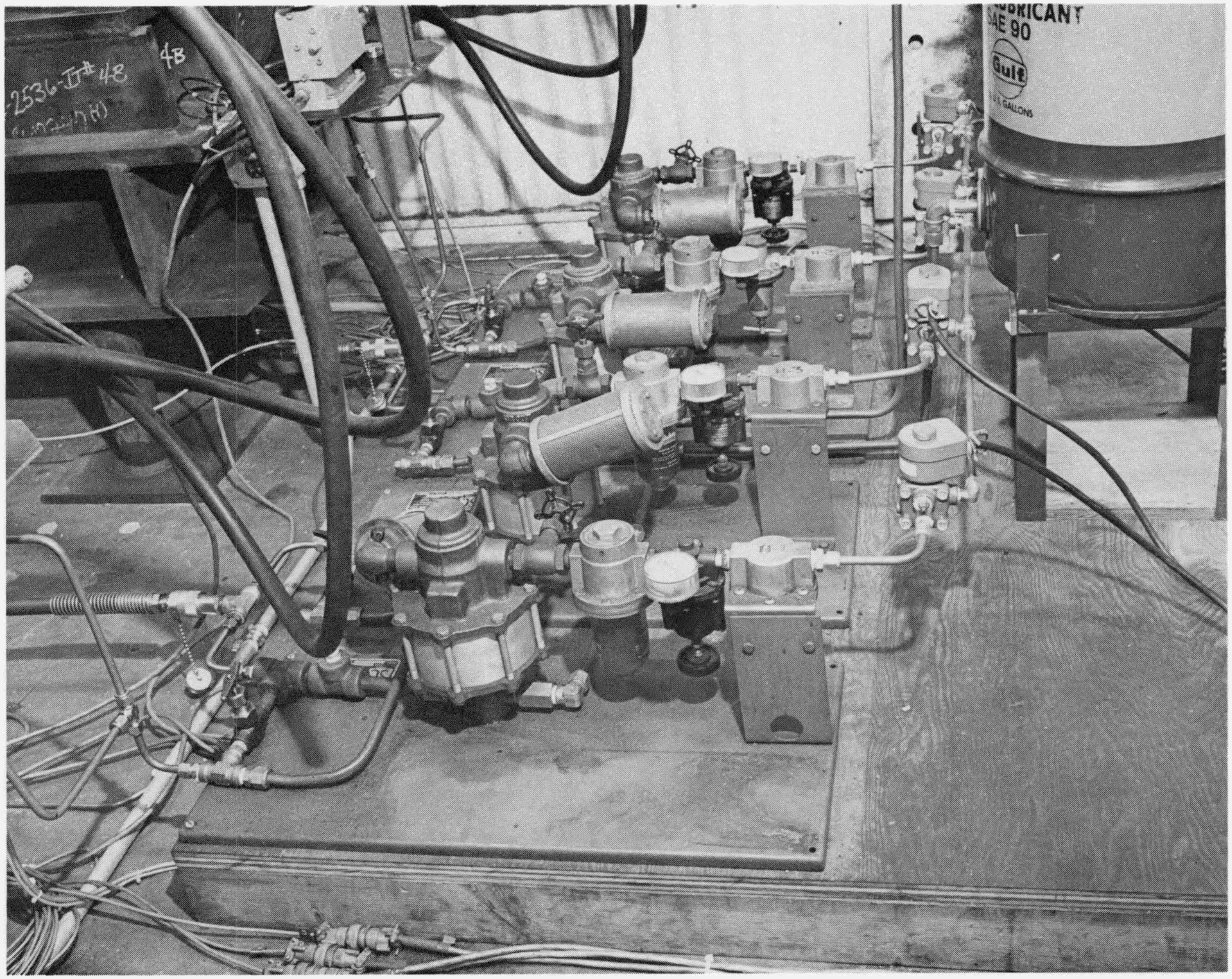


Fig. C-1. Anchor stud test rig (EE-2517-2)



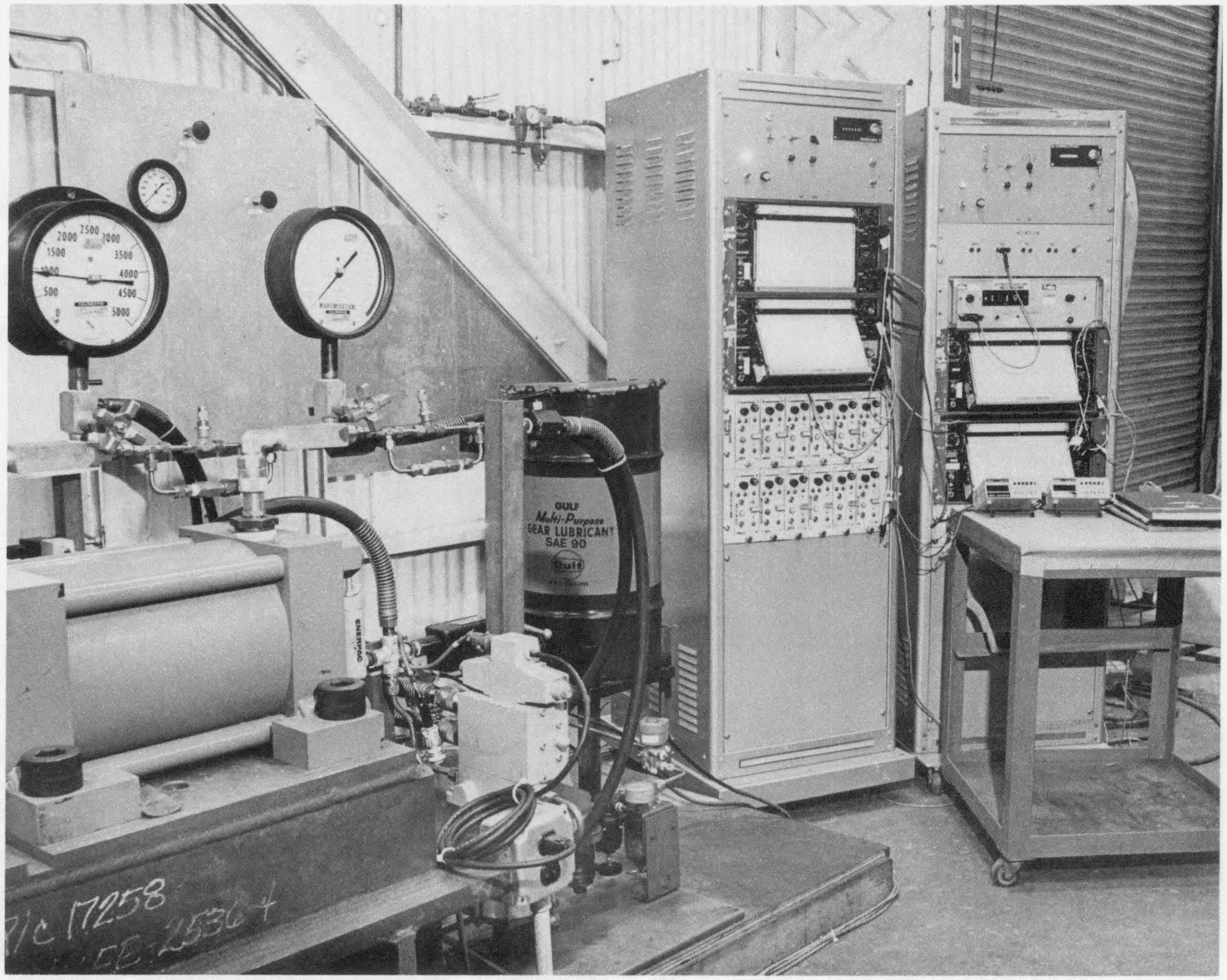
790060

Fig. C-2. Anchor stud test rig instrumentation (EE-2517-2)



781866

Fig. C-3. Air-operated hydraulic pumps



781863

Fig. C-4. Anchor stud test controls and instrumentation

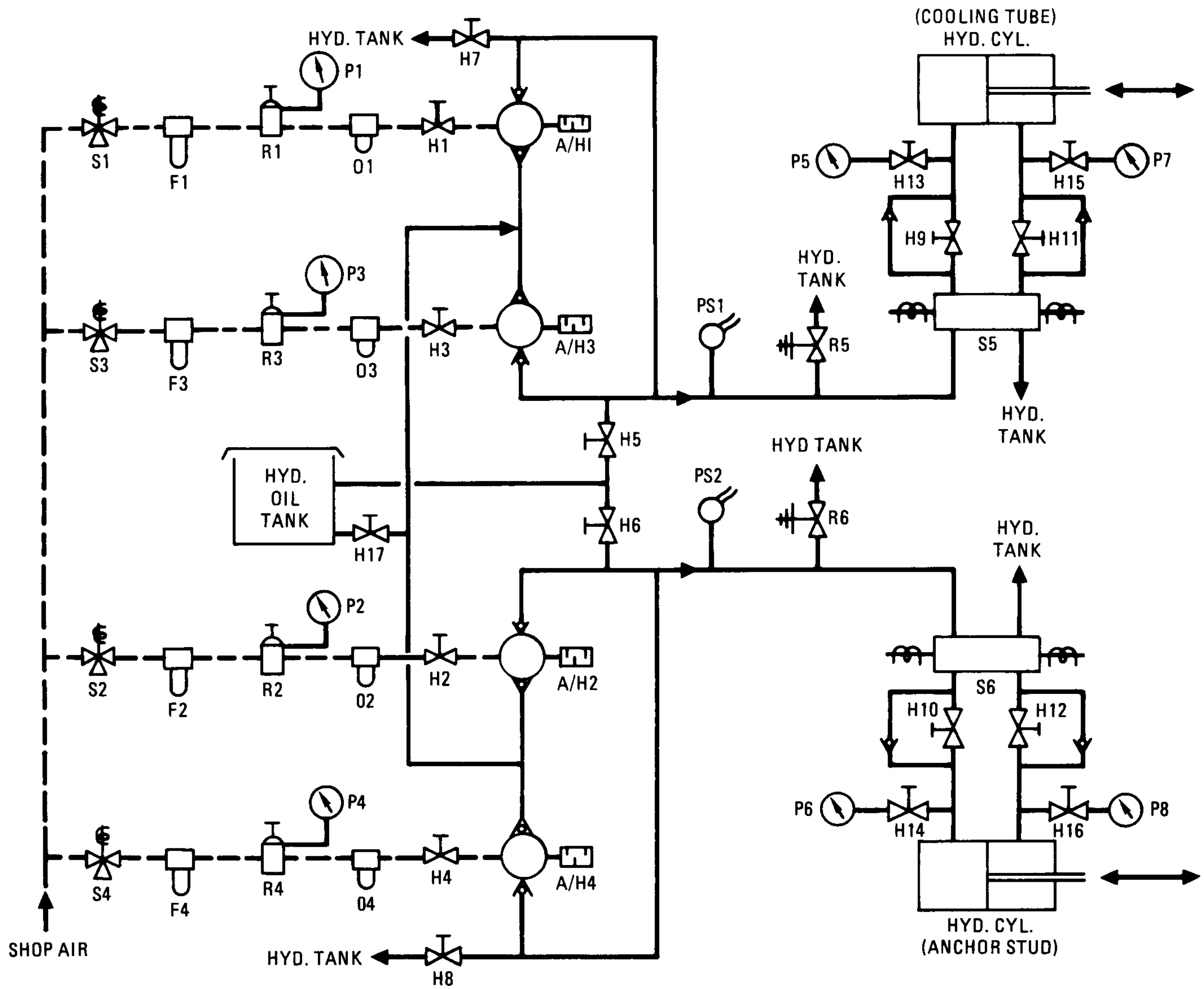


Fig. C-5. Hydraulic load system schematic

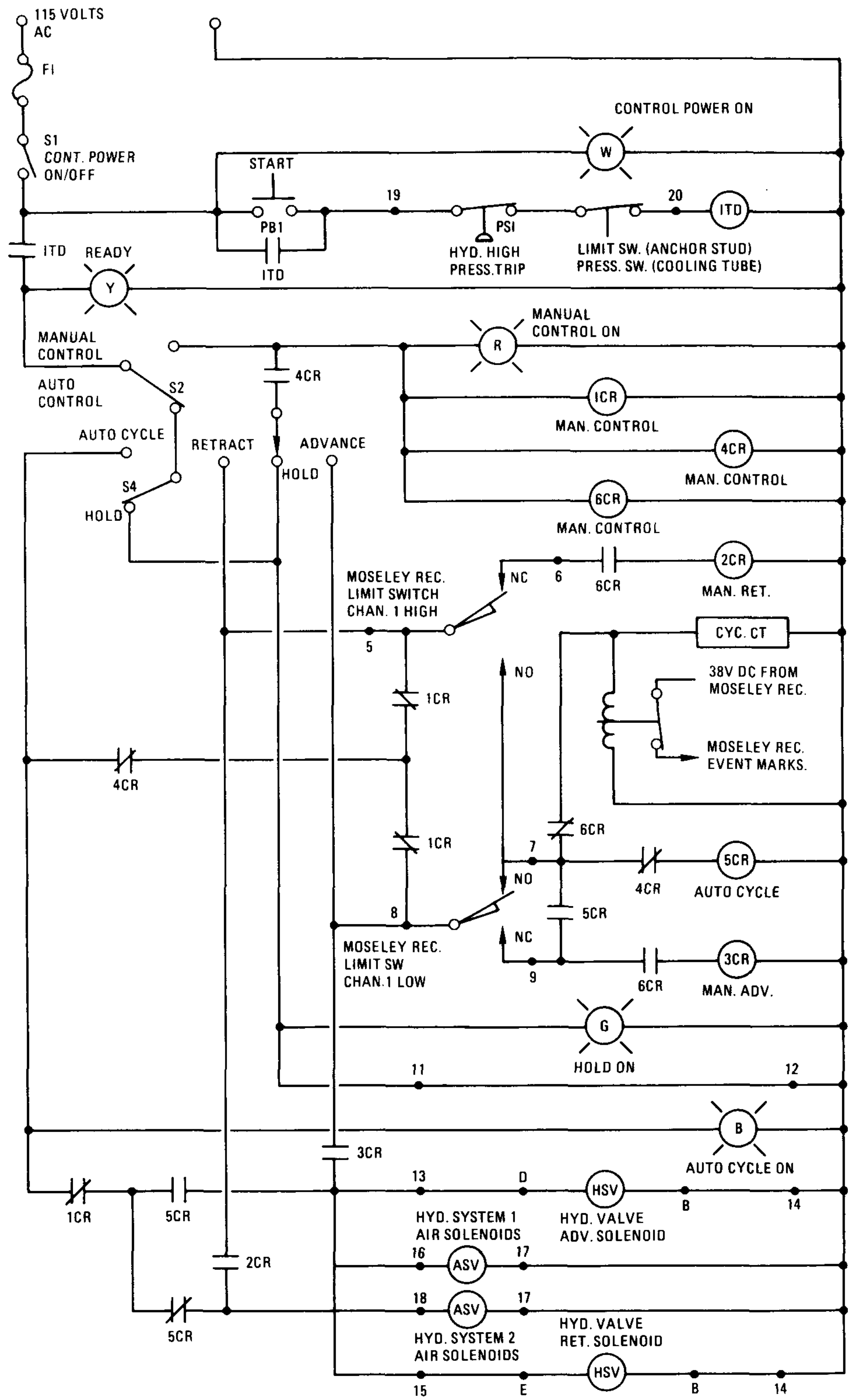


Fig. C-6. Test control circuit schematic

INSTRUMENTATION LIST - PCRV LINER ANCHOR STUD AND COOLING TUBE SHEAR TESTS (PHASE III)						
TEST RIG	MEASUREMENT TYPE	SYMBOL	TRANSDUCER MFG.	NOMINAL RANGE	RECORDER/ INSTRUMENT	REMARKS
EE-2517-2	DISPLACEMENT	D2	AMETEK	0.6 IN.	MOSELEY	STATIC TEST
ANCHOR	DISPLACEMENT	D2A	DAYTRONICS	0.5 IN.	MOSELEY	FATIGUE TEST
STUD	LOAD	L2	INTERFACE	50K LB	MOSELEY	
	LOAD	L4	SABER	50K LB	METER (DVM)	
	LOAD	L6	SABER	50K LB	METER (DVM)	
	PRESSURE	P6		5000 PSI	GAUGE	
	PRESSURE	P8		5000 PSI	GAUGE	

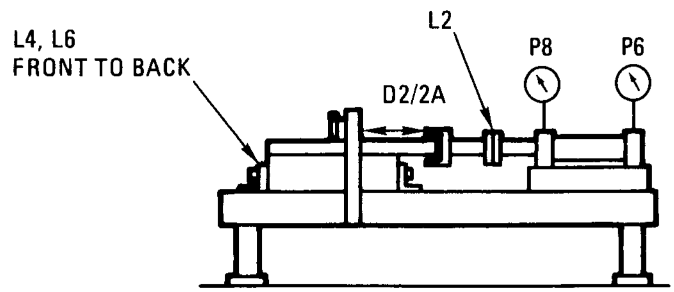


Fig. C-7. Instrumentation for anchor stud test

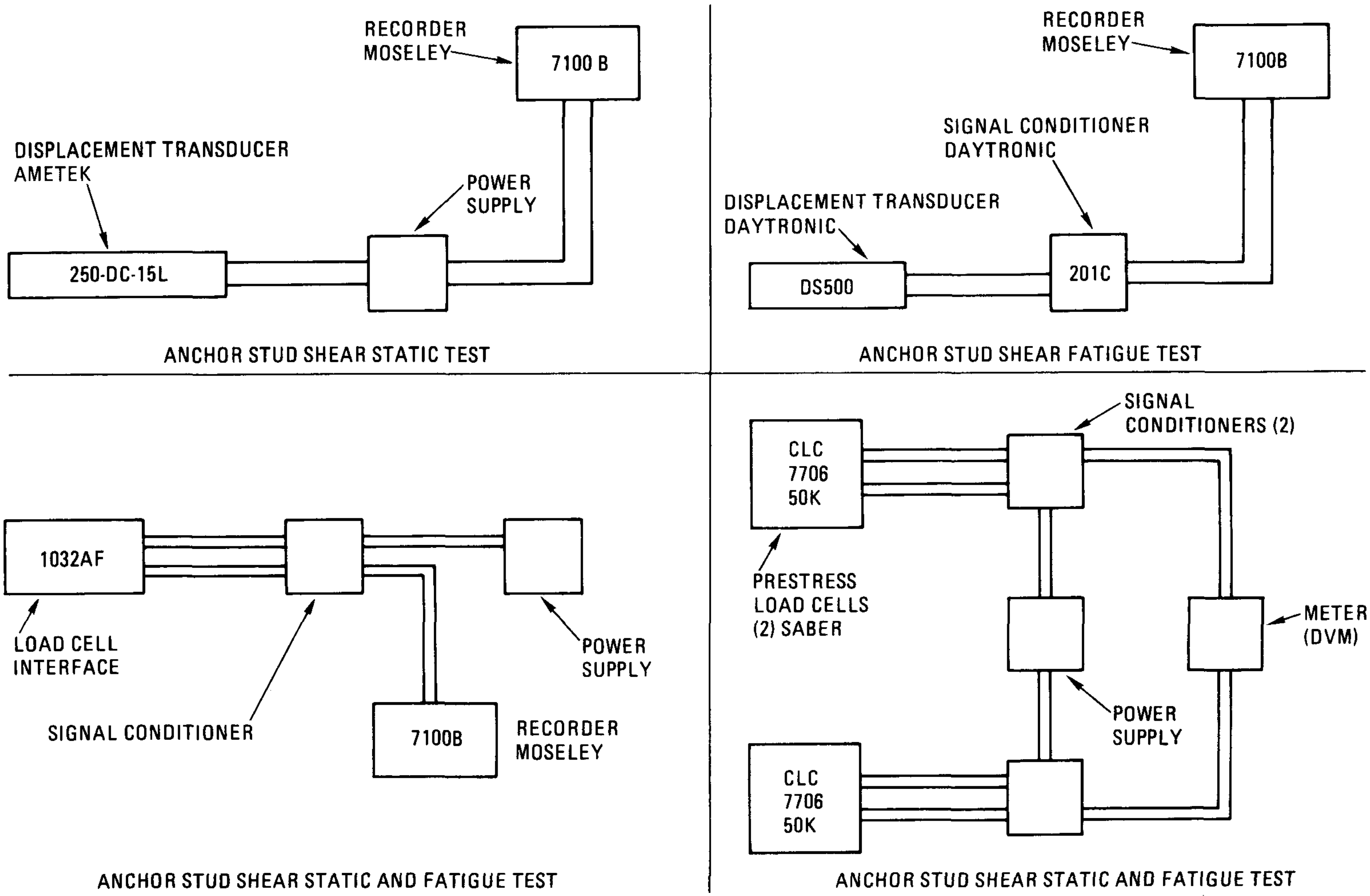


Fig. C-8. Test instrumentation block diagram

APPENDIX D

PHASE I AND PHASE II TEST RESULTS

Phase I and Phase II of General Atomic's anchor stud test program were performed using double plate test specimens with two-piece anchor studs. The stud configuration and the test specimen are shown in Fig. D-1. Both monotonic and displacement-controlled cyclic tests were conducted in Phase I. The monotonic load/displacement curves for specimens No. 13 and No. 14 are shown in Fig. D-2. For the cyclic tests, problems were encountered in detecting when fatigue failure occurred due to excessive fixture/specimen restraint, and the testing was discontinued. In Phase II, the test specimen and the test fixture were modified to reduce the restraint, and the testing mode was changed from displacement controlled to load controlled. The test results from Phase II are shown in Table D-1 and Fig. D-3 in terms of initial, half-life, and failure (or end of test) displacement ranges developed during the load-controlled cyclic testing. The results of these tests are also discussed in earlier sections of this report in conjunction with other test results (see Fig. 25).

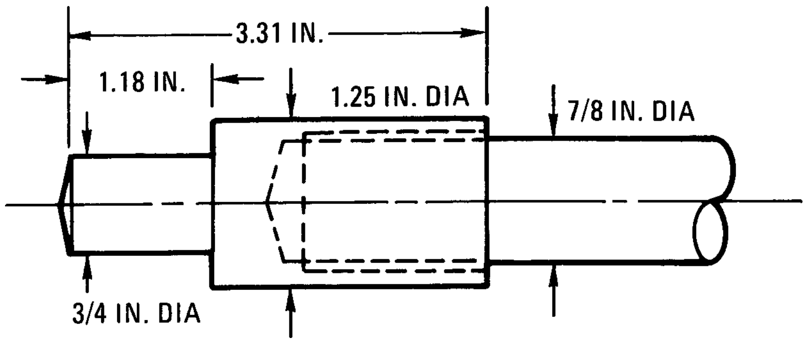
TABLE D-1

ANCHOR STUD SHEAR FATIGUE TEST RESULTS
PHASE II[a] (TWO-PIECE ANCHOR STUD CONFIGURATION)

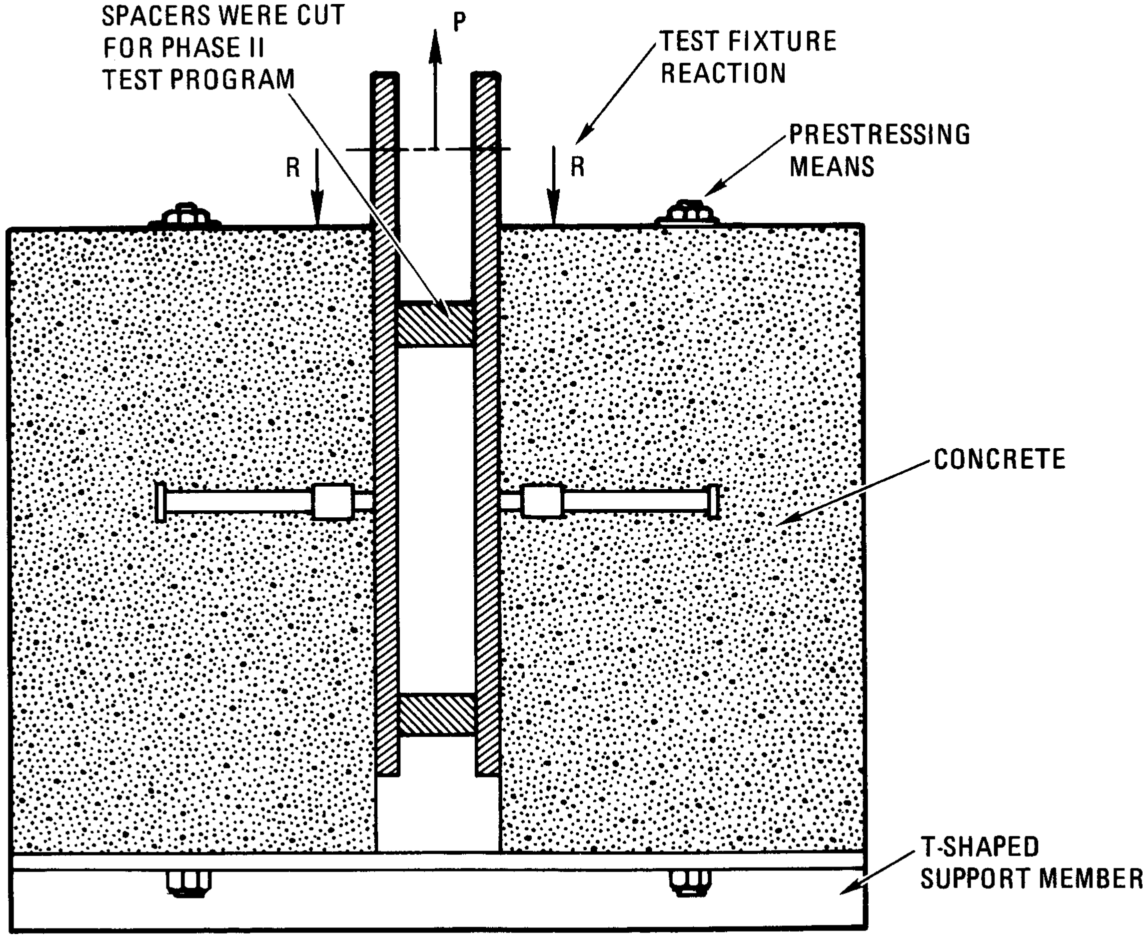
Specimen No.	Stud	Test Load /2 Studs (lb)	Displacement Range (inch)			Cycles to Failure
			Initial	1/2 Life	At Failure or End of Test	
4	1	±18,000	0.011	0.013	0.0155	19,856 - no failure
	2	±18,000	0.012	0.014	0.0165	18,500
5	1	±18,000	0.015	0.0155	0.025	16,368
	2	±18,000	0.0175	0.0185	0.0215	15,000
19	1	±18,000	0.018	0.023	0.029	9,355 - no failure
	2	±18,000	0.017	0.0205	0.022	9,355
12	1	±22,000	0.014	0.0175	0.020	6,879 - no failure
	2	±22,000	0.018	0.0225	0.027	6,400
16	1	±22,000	0.0205	0.027	0.032	2,396 - no failure
	2	±22,000	0.031	0.0395	0.048	2,300
17	1	±22,000	0.025	0.031	0.0335	3,926
	2	±22,000	0.026	0.335	0.041	3,926 - no failure
20	1	±22,000	0.023	0.032	0.039	3,174 - no failure
	2	±22,000	0.026	0.03	0.034	2,750
6	1	±27,000	0.0135	0.019	0.022	5,000
	2	±27,000	0.013	0.017	0.02	6,337 - no failure
10	1	±27,000	0.016	0.0175	0.019	48 - no failure
	2[b]	±27,000	0.022	0.0245	0.025	35
15	1	±27,000	0.029	0.0395	0.047	1,200
	2	±27,000	0.028	0.039	0.062	1,330 - no failure
18	1	±27,000	0.023	0.035	0.042	1,109
	2	±27,000	0.0225	0.034	0.037	1,109 - no failure

[a] Ref. 2.

[b] This specimen went through the same tensile pull (17,000 lb) qualification test as the other specimens. There is no explanation for the low number of cycles to failure.



(a) TWO-PIECE ANCHOR STUD



(b) DOUBLE PLATE TEST SPECIMEN

Fig. D-1. Test specimen and anchor stud used in Phase I and Phase II test program

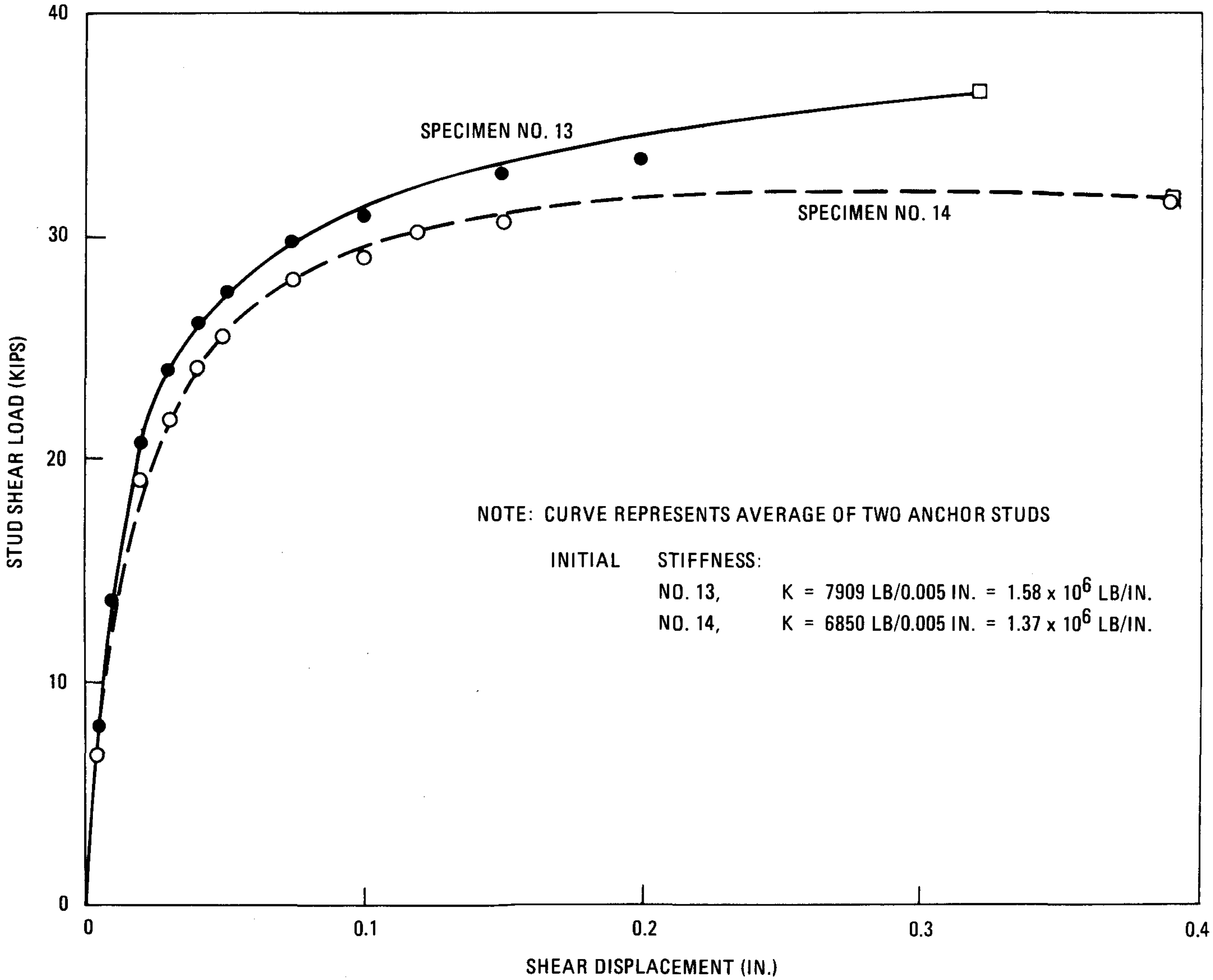


Fig. D-2. Shear load/displacement curve for two-piece anchor stud (Phase I)

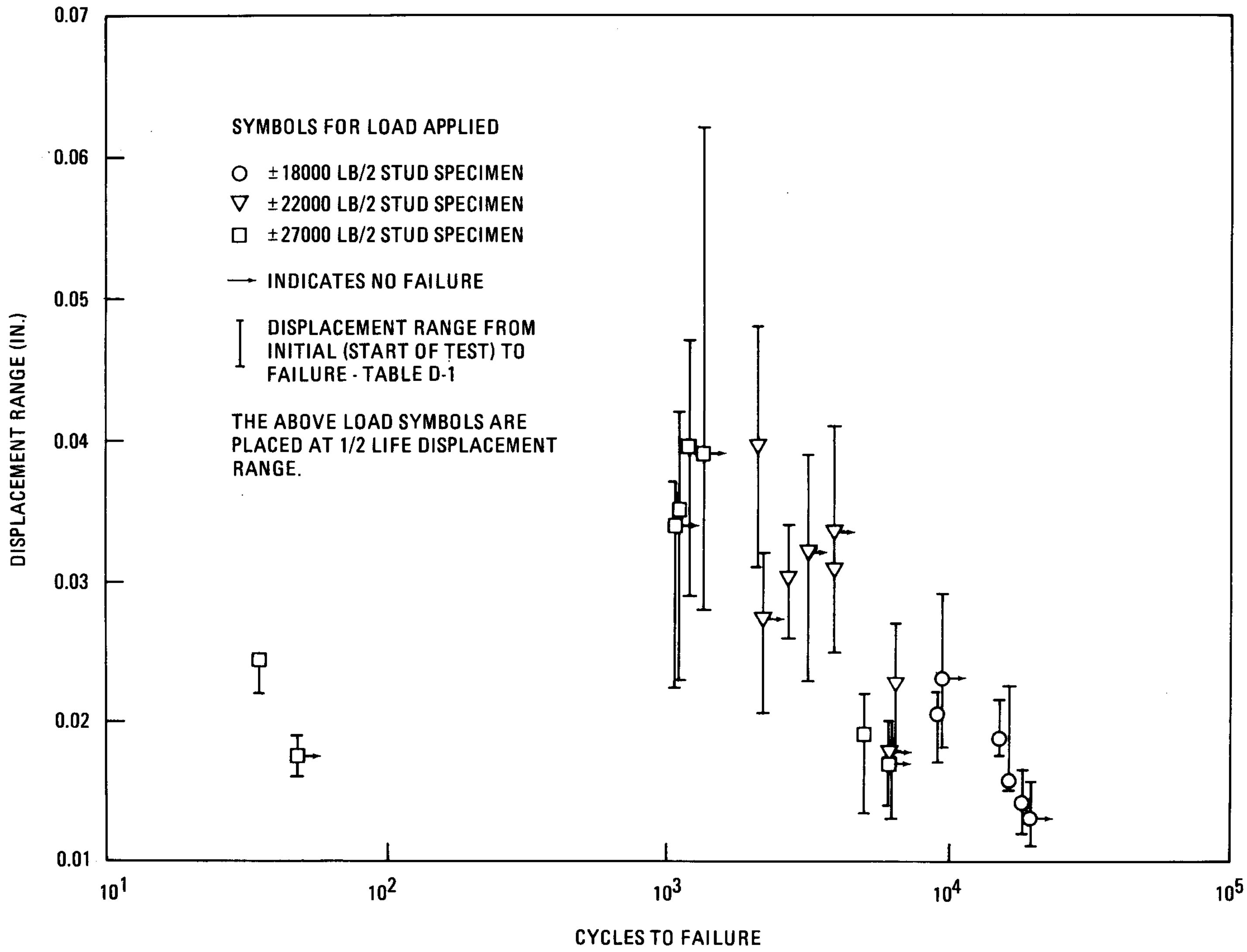


Fig. D-3. Cycles to failure versus displacement range values - Phase II

APPENDIX E

ANCHOR STUD HIGH-CYCLE SHEAR FATIGUE TEST

The test program resported in this appendix (Ref. 6) was designed to provide information on the effect of stress range and minimum stress level on the cyclic life of various shear connectors. Included in the test program were 35 push-out specimens with 3/4-in.-diameter stud connectors. Each specimen consisted of a 20 x 26-3/4 by 6 in. reinforced-concrete slab attached by four 3/4 by 4 in. anchor studs to a W8 x 40 beam section as illustrated in Fig. E-1. The mean compressive strength of the concrete cylinders tested was 4300 psi, and the standard deviation was 335 psi. The push-out specimens were tested by applying a load to the edge of the reinforced-concrete slab. The average shear stress on the studs caused by the applied load was computed on the basis of the nominal cross-sectional area of the studs. Stress range was defined as the maximum horizontal shear stress minus the minimum horizontal shear stress in ksi on the cross-sectional area of studs.

The main experiment was designed to evaluate two controlled variables, the stress range and the minimum stress. Five levels of maximum stress and three levels of minimum stress were selected in order to establish the fatigue characteristics of the connectors. Each minimum stress level was combined with three levels of maximum stress, as illustrated in Fig. E-2, in order to obtain data on the effect of minimum stress on the maximum stress and minimum stress on the stress range. Of the 35 specimens tested, 27 constituted the main experiment, with 8 specimens being added to the program to obtain additional data. These added specimens were cast at a different time and thus had a different concrete strength. The mean compressive strength of all cylinders for this series was 3320 psi, and the standard deviation of the concrete strength was 110 psi. The results indicated that concrete strength did not significantly influence the high-cyclic fatigue strength of the connectors.

The test results reported in Ref. 6 were converted from stress basis into displacement basis (Table E-1) and were then plotted as shown in Fig. E-3. The following conclusions can be derived from Fig. E-3:

1. For the three minimum stress levels used, the stress range (and the corresponding displacement range) affected the cyclic life at each minimum stress level to the same degree.

2. The stress reversal load cycle (S_{min} = -6 ksi) had significantly longer lives for the same stress (displacement) range than those cycles without stress reversal (S_{min} = 2 ksi, 10 ksi).

TABLE E-1

CONVERSION OF TEST RESULTS REPORTED IN REFERENCE 6
FROM STRESS BASIS TO DISPLACEMENT BASIS

I. P_{min} = -2,651 lb[a] (-6 ksi),[b] $\delta_{min}^{(c)}$ = -0.0017 in.

Max. Load (lb)	$\delta_{max}^{(c)}$	δ_{range}	Cycles to Failure, N
4,417 (10 ksi)	0.0029	0.0046	$1.6x10^6$, $2.1x10^6$, $2.2x10^6$
6,185 (14 ksi)	0.004	0.0057	$1.05x10^5$, $1.05x10^5$, $1.6x10^5$
7,952 (18 ksi)	0.0052	0.0069	$3.1x10^4$, $8x10^4$, $1.05x10^5$

II. P_{min} = 883 lb (2 ksi), δ_{min} = 0.00058 in.

Max. Load (lb)	δ_{max}	δ_{range}	Cycles to Failure, N
6,185 (14 ksi)	0.004	0.0034	$6.4x10^5$, $6.4x10^5$, $9.0x10^5$
7,952 (18 ksi)	0.0052	0.0046	$1.1x10^5$, $1.4x10^5$, $2.0x10^5$
9,719 (22 ksi)	0.0064	0.0058	$4.0x10^4$, $5.1x10^4$, $5.1x10^4$

III. P_{min} = 4,417 lb (10 ksi), δ_{min} = 0.0029 in.

Max. Load (lb)	δ_{max}	δ_{range}	Cycles to Failure, N
7,952 (18 ksi)	0.0052	0.0023	$5x10^6$, $7x10^6$, 10^7
9,719 (22 ksi)	0.0064	0.0035	$8x10^5$, 10^6, $1.2x10^6$
11,486 (26 ksi)	0.0075	0.0046	$9.5x10^4$, $2x10^5$, $3.1x10^5$

(a) All load values represent the average load per stud developed by dividing the total load applied to the specimen by the number of studs in the specimen.

(b) All stress values represent the average stress developed by dividing the total load applied to the specimen by the total stud area in the specimen.

(c) Estimated displacement developed using the monotonic stiffness of the 3/4-in.-diameter anchor stud (K_1 = $1.57x10^6$ lb/in., Table 4 of this report).

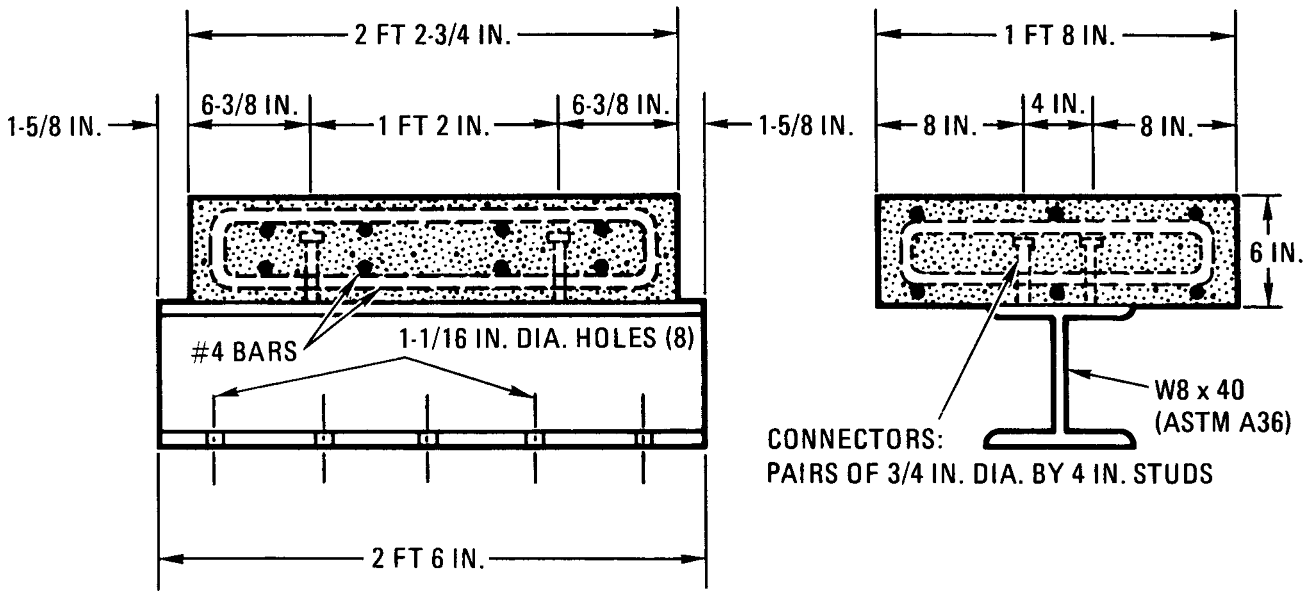


Fig. E-1. Details of high cyclic shear fatigue test specimen

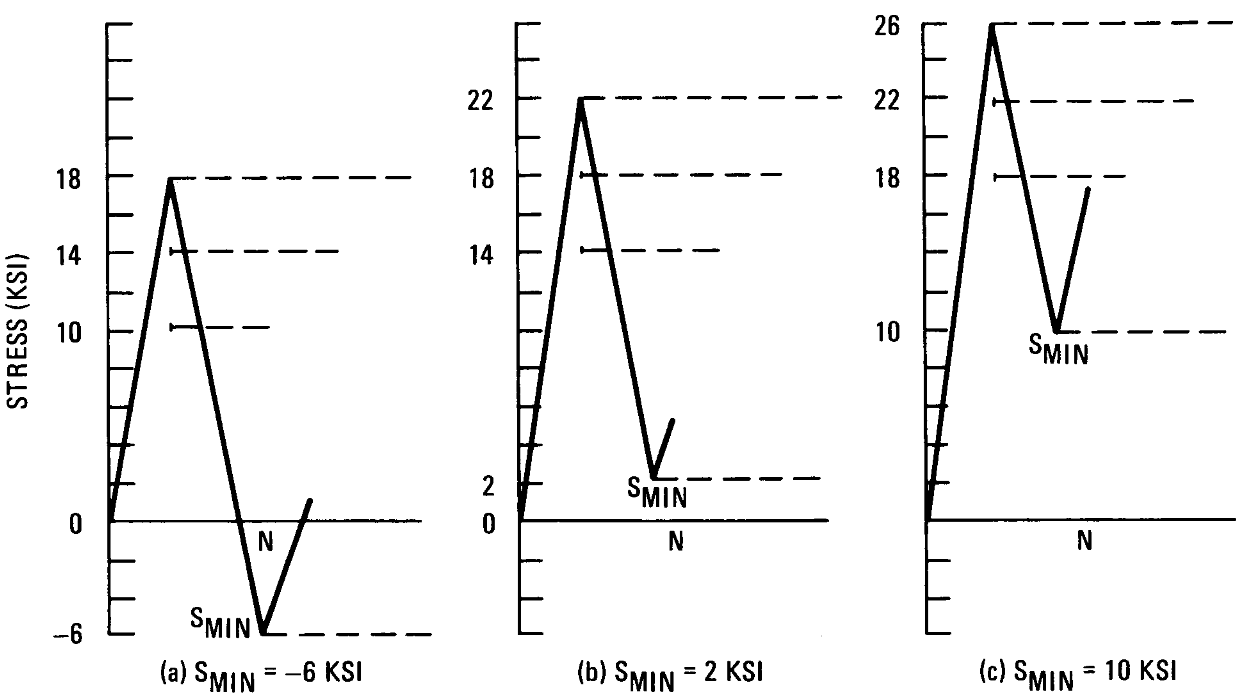


Fig. E-2. Stress (load) cycles used in high cyclic shear fatigue test program

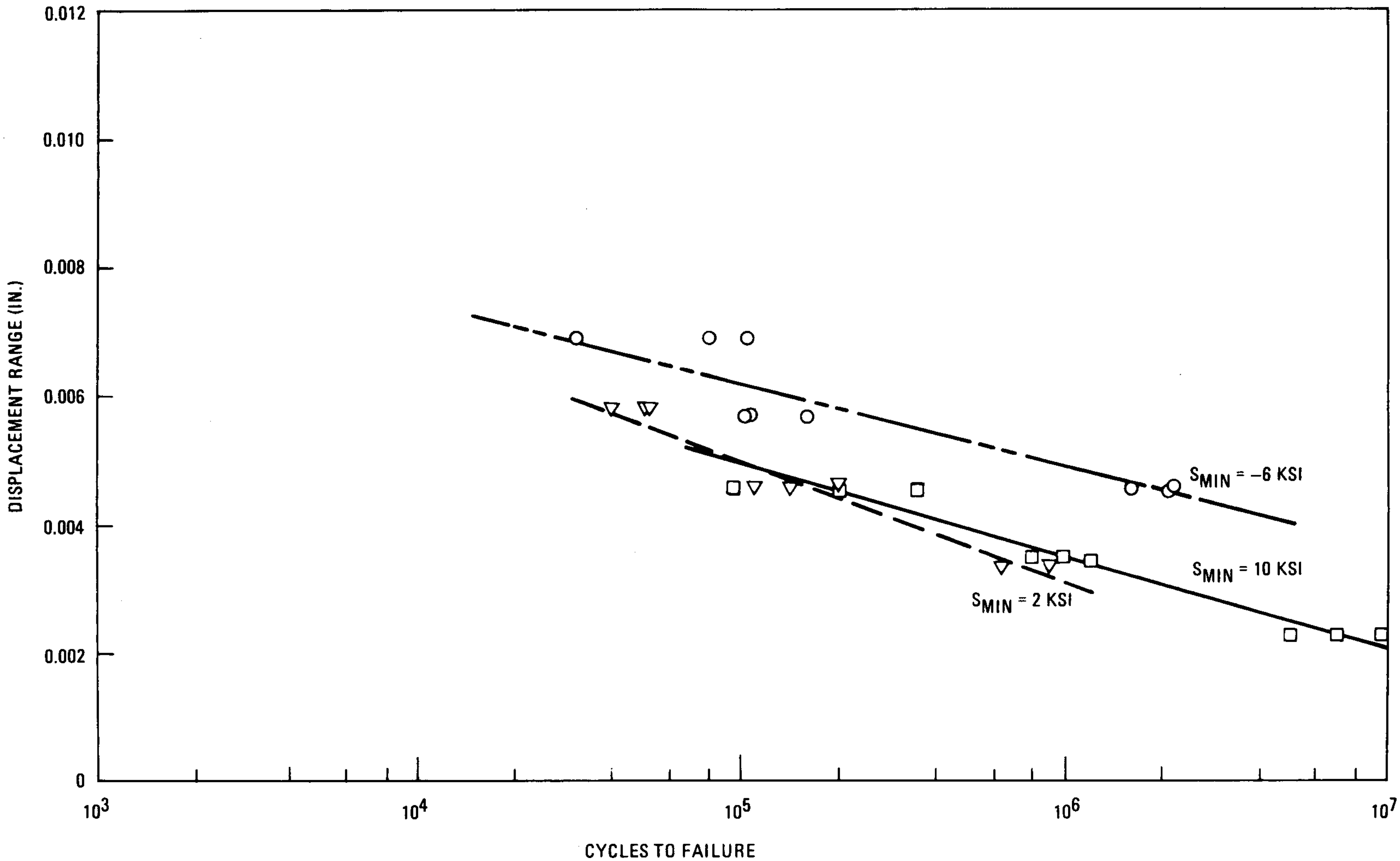


Fig. E-3. Shear fatigue test results of Ref. 6