FATIGUE STRENGTH OF 3/4 INCH STUDS IN LIGHTWEIGHT CONCRETE

(Push-out Tests)

by

H. G. Lehman

H. S. Lew

A. A. Toprac

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Fatigue Strength of Stud Shear Connectors in Lightweight Concrete (Push-Out Tests)

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PREFACE

This is the first and final report on an investigation of the fatigue life of 3/4 inch round headed studs in lightweight concrete. Fourteen push-out specimens were tested to obtain data on the effect of stress range and maximum stress in each range. Slips between the concrete slab and the steel section were measured and presented as typical curves.

The report discusses the preparation of specimens, the test procedure used and the measurement made. The results are presented and compared with previous investigations carried out at The University of Texas and elsewhere.

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I. INTRODUCTION

Composite structural members consisting of a steel beam and a concrete deck slab have been used during the last forty years. The concrete deck slab attached to the steel beam by mechanical connectors acts as a compression flange of a composite cross section. Such an arrangement provides an increase in lateral and flexural stiffness to resist lateral buckling of the compression flange and to limit vertical deflections, respectively.

In order for a steel beam and a concrete deck slab to act in unison and as an integral structural member, the connectors must have a double function ; first, they must transmit the horizontal shear between the slab and the steel beam; and second, they must tie the slab down to the beam. Channels, spirals, and round headed studs have been used successfully for this purpose. In recent years, with the development of automatic welding techniques, round headed studs have become popular due to the ease and economy with which they can be installed.

Since a major part of the forces carried in bridge structures are dead loads, composite construction can be furthered by the use of lightweight concrete. Thus, lightweight structural concrete, which weighs only about two thirds as much as regular weight concrete, results in savings in steel. However, due to a lack of test data, no design specification covers the use of light weight concrete in bridge construction or other structures subjected to fatigue loading.

In the summer of 1964, at the Structures Research Laboratory, a research program was initiated at The University of Texas to study the fatigue strength of 3/4 inch diameter Nelson studs in concrete made with coarse lightweight aggregate.

The purpose of this investigation was to determine (1) the effect of stud shear stress range, and (2) the effect of maximum stud connector stress in each stress range on the fatigue strength of 3/4 inch studs in lightweight concrete. The stress ranges considered in this investigation were 10, 14, and 18 ksi with minimum stresses in each stress range of 2 ksi, 6 ksi and 10 ksi respectively. The program called for the testing of fourteen specimens. For nine specimens the stress range was formalized as indicated above and the program called for the testing of an additional five specimens which were supposed to be duplicates of some of the previous nine. Later these additional specimens were tested with stress ranges of 12 and 16 ksi. The key for the identification of each specimen consisted of a number having three or four digits. The last two digits in this identification key denote the maximum shear stress (or upper stress), while the first digit (or digits) gives the minimum (or lower) shear stress to which the studs are subjected. The difference between the two sets of numbers gives the stress range.

II. DESCRIPTIONS OF TESTS

1. Test Specimens

In this investigation, fourteen specimens were tested. Each specimen consisted of an 8WF48 stub column connected to two lightweight concrete slabs by four round-headed studs imbedded in each slab. Fig. 1 shows the overall dimensions of each test specimen.

Steel Section. All steel sections were fabricated according to standard steel fabrication practices. On each face of the A36 steel stub column 3/4" Nelson studs were placed by an automatic welder. The studs were arranged in pairs, spaced six inches on center, while in each pair the studs were spaced at 4" apart.

One end of the column, the end projecting above the slabs, was milled to create a plane surface normal to the axis of loading for even distribution of applied load.

Concrete. The concrete for these specimens was made using lightweight coarse aggregate of 3/4" maximum size. The mix was designed by the Texas Highway Department for minimum cylinder strength of 3,000 psi with 3 inch slump. The main ingredients used for this mix were Featherlite aggregate, Type 1 cement, Colorado River sand, retarding and air entraining agents along with water. Table 1 lists the proportion of mix ingredients.

Concrete Reinforcement. Intermediate grade, deformed steel bars were used for concrete reinforcement. For a specimen in position to be tested, the vertical steel in each slab consisted of eight #4 bars arranged symmetrically in two rows about 2" from each face of the slab at a spacing of six inches on center. The horizontal steel consisted of six #5 bars arranged symmetrically in two rows 1 1/2" from each face of the slab at a spacing of seven inches on center. Figure 1 shows details of slab reinforcement.

2. Preparation of Test Specimens

Specimen forms were made using 3/4" plywood in such a way that the 8WF stub column was placed in horizontal position during concrete casting (Fig. 2). Once erected with the steel stub column in place, the forms were taped to prevent loss of water by direct seepage through cracks and nail holes. A thin coat of form oil was then applied to the interior surfaces of the forms to render them easily stripped. The flanges of the columns, but not the studs, were also oiled to eliminate bond between the steel and the concrete slabs and thus exclude this bond as a variable. Final preparation consisted of placing the concrete reinforcing steel in the forms. Movement of the reinforcement steel was prevented by securing the chairs against the sides of the forms with the wires.

Two test specimens were cast horizontally from each mix. Horizontal casting was chosen to minimize the collection of air bubbles under the studs in the direction of loading. As concrete was placed in the form, a 1/4 hp electric vibrator was employed to reduce honeycomb in the specimen.

During the casting, the air content of the mix was measured with an air meter and test cylinders for each specimen were prepared. Table 2 lists the individual and the average strength of the cylinders.

After completion of the pour, the exposed surfaces of the specimens were smoothed and covered with polyethylene sheets to prevent moisture evaporation. The form and cover were left in place until a pair of test cylinders indicated 3,000 psi. The specimen forms and those for the remaining cylinders were then stripped. The specimens and cylinders were stored together to ensure that each cured under the same conditions. The specimens were allowed to dry in air at least a week prior to testing.

Stud Inspection. The studs for all fourteen specimens were inspected by a field engineer from the Texas Highway Department. Upon visual inspection, any studs suspected of having deficient welds were bent approximately 30° off vertical. All other studs received several blows with a hammer. No deficient welds were discovered.

3. Test Set-Up

An overall view of the loading arrangement and the platform on which the specimen was placed are shown in Figures 3 and 4. The specimens were set on a 2 inch thick steel plate and levelled by means of threaded bolts in the same plate.

In order to achieve an even load distribution under the concrete slab, a 1/2 inch celotex board was inserted between the slab and the steel platform. At the top side of the steel stub column where the load was applied, a sandwich type of load block arrangement consisting of a 1 inch thick steel plate at the top, followed by a neoprene pad, and a thin steel plate, were used to transmit the applied load to the steel column evenly from the round headed sole plate of the testing cylinder.

To prevent lateral movements of slabs at the bottom, two channels as shown in Fig. 4 were installed with little or no clamping forces.

4. Instrumentation

Slip gages were used in all specimens to measure the relative displacement between the steel stub column and the concrete slab. Each slip gage assembly consisted of a slip gage and a bearing angle. The gages were clamped to each concrete slab as fixed position and the bearing angles were welded to each exposed face of the steel stub column. A dial gage of 0.001 inch graduation was attached to each slip gage so that when the bearing angle pushed the knife edged part of the slip gage downward, it was possible to read dial movements as an indication of slip between the steel and the slab.

Electrical resistance gages (SR-4) were used to measure local deformations of flanges in the immediate vicinity of stud locations as an indication of deterioration of studs during fatigue loading (Fig. 1). The gages were placed 3/8 inch above the center of each stud. This method of off-setting the gage location from the stud position was proved to be quite effective in composite beam tests.(1) (2)

5. Test Procedure

Prior to dynamic test, all specimens were subjected to the static load. Testing of a specimen was started by taking readings on all instruments at zero static load. This included slip gage and strain gage readings. Strain gage readings were limited to only a few specimens while slip gage readings were taken for all specimens.

Load was then applied gradually up to a predetermined level, at which measurements were again made. This procedure was continued until the specified maximum load for the particular specimen was reached. After the load reached its maximum (upper) limit, it was reduced step by step to zero. Measurements similar to those described above were also made during unloading and at zero load residual slips were recorded.

Dynamic testing followed immediately after the termination of static loading. Fluctuating load was applied ranging from a positive minimum to a positive maximum according to the predetermined stress range and the maximum stress level in studs. The loads were applied with a frequency of 300-350 cycles per minute.

At the beginning of fatigue testing slip gages were read frequently, i. e., every 1000-2000 cycles until the rate of increase in slip became negligible. The interval between slip gage reading was then increased until near failure when the rate of slip began to increase. Near failure, slip gage readings were again taken whenever possible, as often as deemed necessary to define the slip vs. cycle curve. To read strain gages at preselected cycle intervals, fatigue loading was stopped to permit static strain gage readings. The zero load reading was taken at each measurement, and the static test was completed in about an hour in each case, and fatigue testing was resumed.

After failure, each specimen was removed from the testing platform for inspection. The concrete was carefully broken away from the studs with a hammer and the studs were inspected. Modes of failure and remaining effective shear areas of studs were then recorded for each individual stud.

III. TEST RESULTS

The results of fourteen specimens tested are presented as a group corresponding to each stress range of 10, 12, 14, 16 and 18 ksi. For stress ranges of 12 and 16 ksi five duplicate specimens were used. It was observed that the specimens within each stress range behaved similarly, hence only the typical behavior of each group will be described. The results for individual test specimens are listed in Table 3.

1. General Behavior

The general behavior of a specimen can be depicted by a load-slip-cycle curve. For three of the stress ranges (10, 14 and 18 ksi) a typical load-slip-cycle curve is plotted for the side that had larger slip (Figures 5, 6 and 7). In these figures the curves on the load-slip axes plane and on the slip-cycle axes plane represent the slip measurements of a specimen under static and dynamic loads, respectively. With this load-slip-cycle curve available the complete testing history can be traced.

These figures show that all specimens exhibited three separate stages of slip characteristic under fatigue load: first, a gradual increase of slip characteristic under fatigue load; second, a "plateau level" of slip curve with little increase in slip until failure* became imminent; and third, a sharp increase in the rate of slip as specimens reached failure. Having observed this type of slip characteristic of the first few specimens, it was possible to predict impending failure of other specimens.

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*The term "failure" is used to describe the condition at which the concrete slab separates completely from the steel section and the loss of composite action.

2. Stud Failure

The effectiveness of the individual stud during the test and its progressive deterioration can be depicted by plotting strain readings for the individual stud versus cycles. In Fig. 8 strains measured using SR-4 electrical gages are shown for specimen 616 as a typical example. The strain readings can be considered as an index to the magnitude of load transfered from the concrete to the stud. In this figure, if 100 percent effectiveness of the stud is assigned to the peak values of the strain readings, its subsequent deterioration, and hence the loss of interaction, can be estimated qualitatively as cycles increased.

In most casts fractures took place in the heat affected base metal (flange of stub column). Only in a few cases with higher stress range did studs fracture in the stem of the stud near the bottom. Both of these cases are shown in Figures 9 and 10. As a typical example a schematic mapping of these figures showing fractured and unfractured areas of studs are presented in Figure 11 with the percent of remaining area indicated. This is a typical figure with values for uncracked areas of studs of all other individual specimens listed in Table 4.

10 ksi Range (Specimens 212, 616 and 1020). Among three specimens tested, two (212 and 616) were stopped at 6.73 and 5.81 million cycles respectively, before any excessive indication of an increase in slip. Since Specimen 1020 carried 6.71 million cycles, the fatigue life span of composite action with push-out specimens at 10 ksi stress range can be assumed to fall in the neighborhood of 6.5 million cycles. The visual inspection of studs revealed that all fractures occurred in the base metal. The remaining effective areas ranged from 25% to 40%.

12 ksi Range (Specimens 214 and 618). Both specimens had one side sheared off completely at failure which occurred at 2,230,000 and 2,960,000 cycles for Specimens 618 and 214 respectively. All fractures occurred in the base metal except for one stud (214) which had its fracture in the stem. With one side of 214 completely separated from the steel section, the studs on the other side had an unfractured area of about 5 percent.

14 ksi Range (Specimens 216, 620, and 1024). The behavior of all three specimens was similar to that of the 12 ksi range specimens. However, because of the higher stress range, the fatigue life span was reduced and varied from 305,000 to 726,000 cycles. All fractures occurred in the base material, except that two studs of 620 fractured in the stem.

16 ksi Range (Specimens 218 and 622). Specimen 218 had complete fractures in all eight studs in the heat affected base metal at 292,000 cycles, and both sides completely sheared off. In Specimen 622, four studs fractured in the base metal and the other four in the stem at 435,720 cycles, and one side separated from the concrete slab.

18 ksi Range (Specimens 220, 624, and 1028). As anticipated this group had the shortest fatigue life because of the higher stress range spanning from 100,000 to 340,310 cycles. The average remaining effective stud area was less than 25% in all specimens with fractures occurring in the base metal except for one stud in Specimen 220 and two in Specimen 1028 which fractured in the stem.

IV. DISCUSSION OF TEST RESULTS

The fourteen pushout specimens tested in this program yielded data on the fatigue strength of 3/4" round headed studs in the lightweight concrete. The parameters considered were stress range (applied maximum shear stress minus minimum shear stress) and the minimum (or maximum) stress applied in each stress range.

In studying above two parameters, attention was primarily given to a specimen as a whole unit rather than to individual studs. Discussions herein presented, therefore, will describe the behavior of the specimens.

1. Mode of Failure

All specimens failed* by shearing off of studs. In most cases the studs in one slab sheared off and the studs in the other slab showed considerable deterioration and fracture but were not completely sheared off. Inspection made after the fatigue test showed that the majority of the studs fractured in the heat affected base metal with the exception of a few cases in which the studs fractured in their stems.

2. Deterioration of Individual Stud

Performance of individual stud during the fatigue testing can be described with the aid of Fig. 8. Assuming that the peak values of strain reading correspond to no fracture in the stud, the figure reveals that the first pair of studs in the direction of loading, 2B and 3B, failed first. Subsequent propagation of the crack, after the initial fracture, is gradual rather than sudden. This phenomenon is analogous to the behavior of studs in composite beams in which

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*See footnote on page 8.

fracture is initiated in a pair of end studs. Both for the above delineated cases are depicted in Figures 12a and 12b.

Although the strain readings plotted in Figure 8 indicate that both studs 2B and 3B exhausted their effective load carrying capacity when fatigue testing was stopped at 5.8 million cycles, a qualitative comparison between the strain readings and the uncracked area listed in Table IV agrees well.

3. Slip Measurements

The maximum slip for individual specimens between concrete slabs and the steel section when the fatigue testing was terminated is listed in Table 3. As can be seen in the table, the relationship between the maximum slip and cycle under a particular stress range is erratic, and for this series of tests no conclusive correlation can be made between them. This inconsistency might be due partly to changes made to slip measurement set-up and to the bearing platform arrangements during the test program.

However, when the slip data are plotted against the cycle, (Figures 5, 6, and 7), all specimens exhibited a definite slip characteristic under dynamic loading as described in Section II. 4. A similar characteristic was also observed in composite beam tests.(1) Thus in both beam and pushout tests, sudden increase in slip can be used as a failure criterion.

4. Stress Range-Cycle Curve

Results from the fourteen tests were used to plot an S-N curve (stress range versus cycles). After many trials of curve fitting by the least square method, a first order fit proved to be the best and it is shown in Fig. 13. The curve ranged from approximately 10 ksi to 19 ksi between 100,000 and about 10 million cycles.

To make a comparison with other fatigue tests, results obtained from the current investigation are redrawn in Fig. 14 together with other S-N curves obtained from composite beams and pushout tests carried out at The University of Texas and Lehigh University.

A close examination of this figure reveals that the S-N curves of beam and pushout tests with 3/4" dia. studs have steeper slopes than those of 1/2" dia. studs. The difference in stress range of the S-N curves between 100,000 and 10 million cycles are about 3.8 ksi and 9.0 ksi for 3/4" dia. stud beam and pushout tests and 2.5 ksi and 5.0 ksi for 1/2" dia. beam and pushout tests, respectively. There is also a marked difference in stress ranges of the S-N curve of beam and pushout tests.

It has been shown by previous investigation(2) that an S-N curve obtained based on results of pushout specimens is always lower than that of beam tests, thus establishing a possible lower bound.

If the same postulation is applied to the S-N curve of the currently investigated pushout specimens, the S-N curve of beam tests would lie a few ksi above this curve. Therefore, at two million cycles, the composite beam with lightweight concrete slab might have the same stress range as the one with regular concrete slab.

Such a postulation cannot be accepted readily as a design guide, but it does show that lightweight concrete of the kind used in this project, can be substituted for regular concrete in structural bridge members with the same factor of safety.

The authors believe that tests should be carried out on composite beams with lightweight concrete to substantiate the results obtained with pushout specimens. A broader range of types of lightweight concrete and of varying strengths should be tested to ascertain the factor of safety applicable.

V. SUMMARY AND CONCLUSIONS

A study was made to ascertain the fatigue life of a composite section of steel and lightweight concrete connected by 3/4" diameter round headed studs. The investigation can be summarized as follows:

In this constant cycle fatigue testing program fourteen pushout specimens were used to obtain data on the effect of (a) stress range and (b) maximum stress in each stress range on the fatigue life of such sections. The least square curve fit method was used in presenting the test results as an S-N curve.

As a result of this investigation, the following conclusions can be drawn:

1. The fatigue strength of 3/4" diameter round headed studs in lightweight concrete made with Featherlite coarse aggregate is independent of the maximum applied stress for any given stress ranges.
2. Stress range has a significant effect on the fatigue life of shear studs and is the main parameter. For each stress range, it seems that there exist a definite upper and lower bound of fatigue life.

3. Slip results do not show any immediate relations to the fatigue life, but they do exhibit a definite characteristic under fatigue loading.
4. In most specimens, fractures occurred in the heat affected base metal except in specimens subjected to higher stress range. In these, studs fractured in their stems.
5. The S-N curve obtained from the results of this investigation indicates only a small difference from that of regular concrete. Results show better fatigue strength can be expected below one million cycles.
6. Because of the small difference in fatigue strength behavior, it may be possible to use the same factor of safety for the type of lightweight concrete used in this investigation and regular concrete composite sections.

REFERENCES

1. Toprac, A. A., "Fatigue Strength of 3/4 inch Stud Shear Connectors," Presented during the Highway Research Board Meeting, Washington, D. C., January, 1965.

2. King, D. C., Slutter, R. G., Driscoll, Jr., G. C., "Fatigue Strength of 1/2 inch Diameter Stud Shear Connectors," Fritz Engineering Lab. Report No. 285.6, March, 1964.

TABLE 1.
CONCRETE MIX PROPORTIONS

Featherlite Coarse Aggregate	Colorado River Sand	Type I Cement	Total Water	Sika Air	Pozzilith
283 lbs.	518 lbs.	211 lbs.	148 lbs.	36cc.	255 gm.

TABLE 2.
CONCRETE CYLINDER STRENGTHS

Specimen No.	Cylinder Strengths psi		Age At Test	Average Cylinder Strengths psi
212	4380	4630	47	4505
616	----	----	47	unknown
1020	----	4980	36	4980
214	4700	5130	17	4915
618	5040	5550	46	5295
216	----	----	60	unknown
620B	5250	4770	57	5005
1024	4410	4080	33	4245
218	5750	5400	30	5575
622	5000	5250	36	5125
220	4200	5070	34	4635
624	4750	5320	41	5035
1028	----	5000	28	5000
620	5090	5800	48	5445

TABLE 3.

TEST PROGRAM AND SUMMARY OF FATIGUE TEST RESULTS

	Specimen Number	Stress Range*	Stresses* Min.	Stresses* Max.	Maximum Slip (inch)	Total Number of Cycles
1	212	10	2	12	0.0169	6,730,000**
2	616	10	6	16	0.0624	5,810,000**
3	1020	10	10	20	0.2371	6,711,000
4	214	12	2	14	0.1166	2,960,000
5	618	12	6	18	0.3000	2,223,000
6	216	14	2	16	0.0090	305,000
7	620B	14	6	20	0.5366	726,000
8	1024	14	10	24	0.0605	390,000
9	218	16	2	18	0.5438	292,000
10	622	16	6	22	0.0070	435,700
11	220	18	2	20	0.3154	100,000
12	624	18	6	24	0.3792	142,680
13	1028	18	10	28	0.0403	340,300
14	620	14	6	20	0.1971	1,345,000

*shear stress on the studs

**test stopped before failure

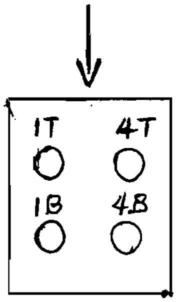
TABLE 4.

UNFRACTURED STUD AREA AT THE END OF TEST IN PERCENT

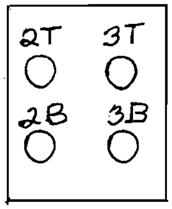
	Spec. No.	Flange A				Flange B			
		1T	1B	4T	4B	2T	2B	3T	3B
1	212	15	10	25	10	10	10	10	10
2	616	50	30	20	10	20	5	25	5
3	1020	0	0	0	0	45	25	30	40
4	214	5	5	0^b	5	0	0	0	0
5	618	0	0	0	0	10	10	10	10
6	216	55	100	100	50	0	0	0	0
7	620B	0	0	0	0	2	5	2	5
8	1024	85	0	100	15	5	2	5	2
9	218	0	0	0	0	0	0	0	0
10	622	15^a	5	10	0^b	0^b	0	0^b	25^a
11	220	10	10^a	20^a	0	0^a	0^a	20^a	0^a
12	624	0	0	0	0	40	30	10	20
14	620	0	0^b	0^b	0	5	5	5	5

a: Fractures in Stud

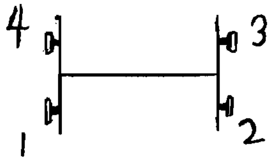
b: Fractures in Stud and Flange



Flange A



Flange B



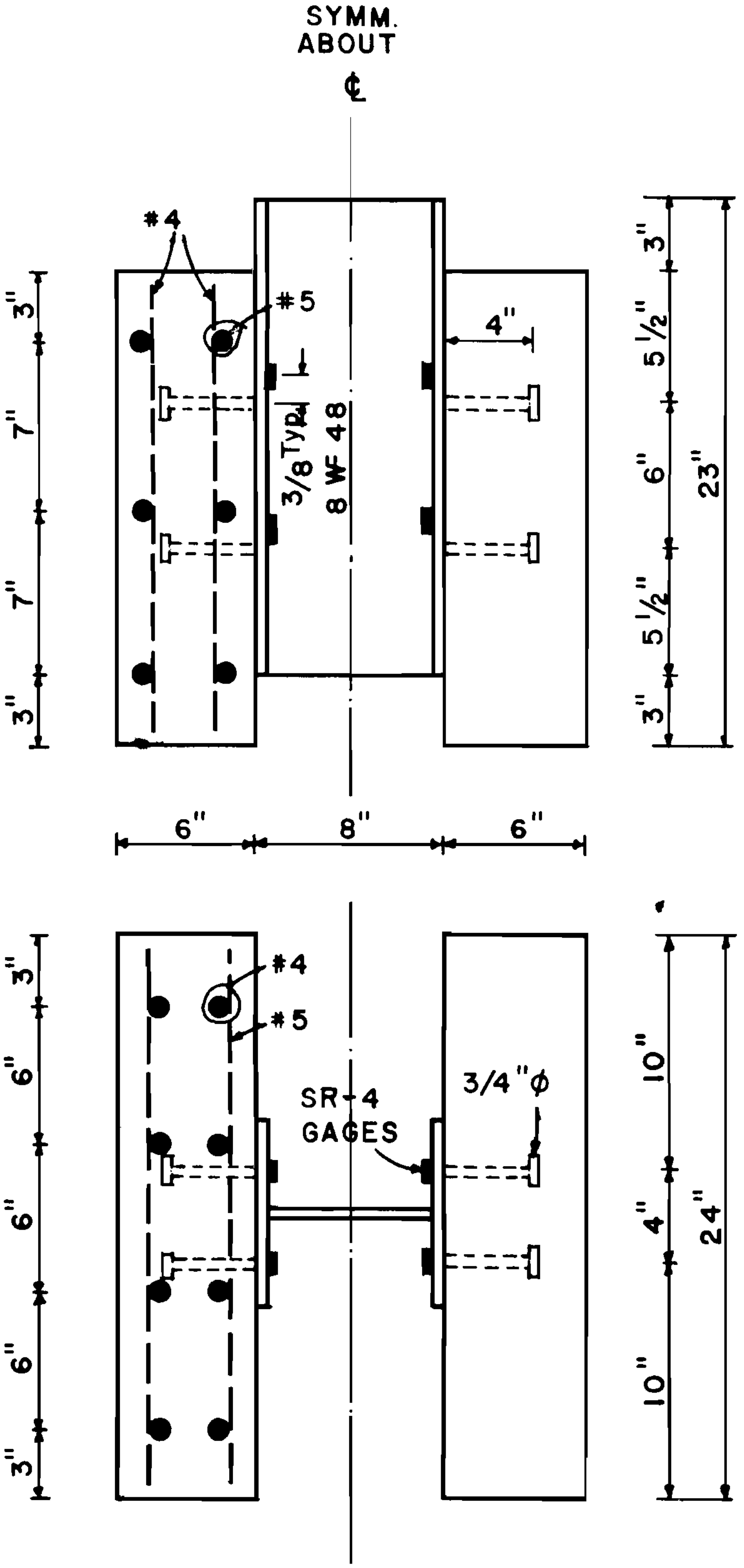


FIG. I. DIMENSIONS OF SPECIMEN

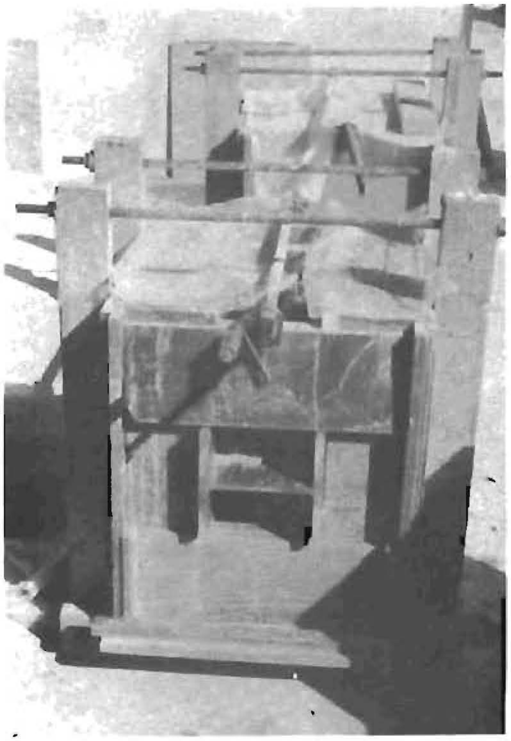


FIGURE 2
FORM WORK DETAILS

FIGURE 3
OVERALL VIEW OF TEST SET-UP

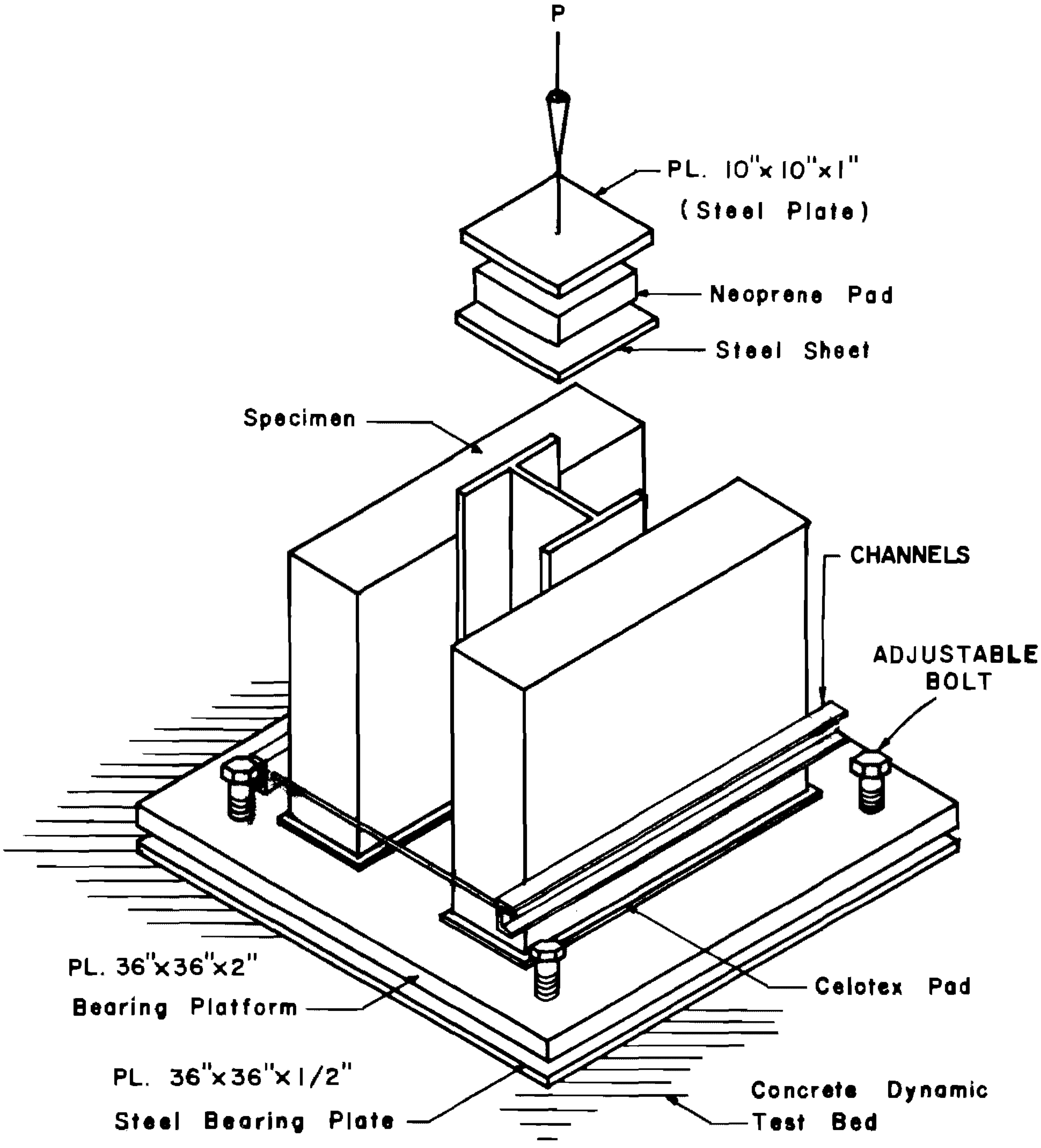


FIG. 4. LOADING ARRANGEMENTS

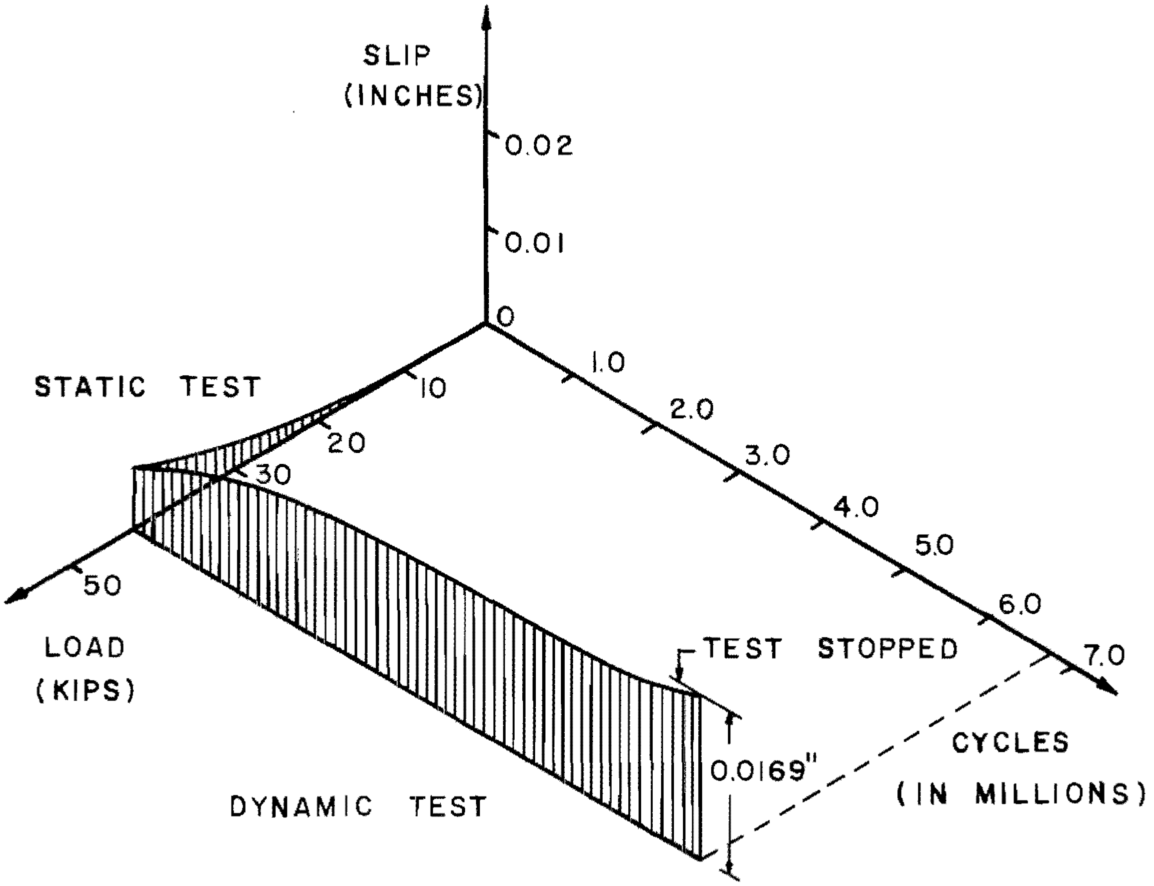


FIG. 5. LOAD - SLIP - CYCLES (SPECIMEN 212)
FOR STRESS RANGE OF 10 k.s.i.

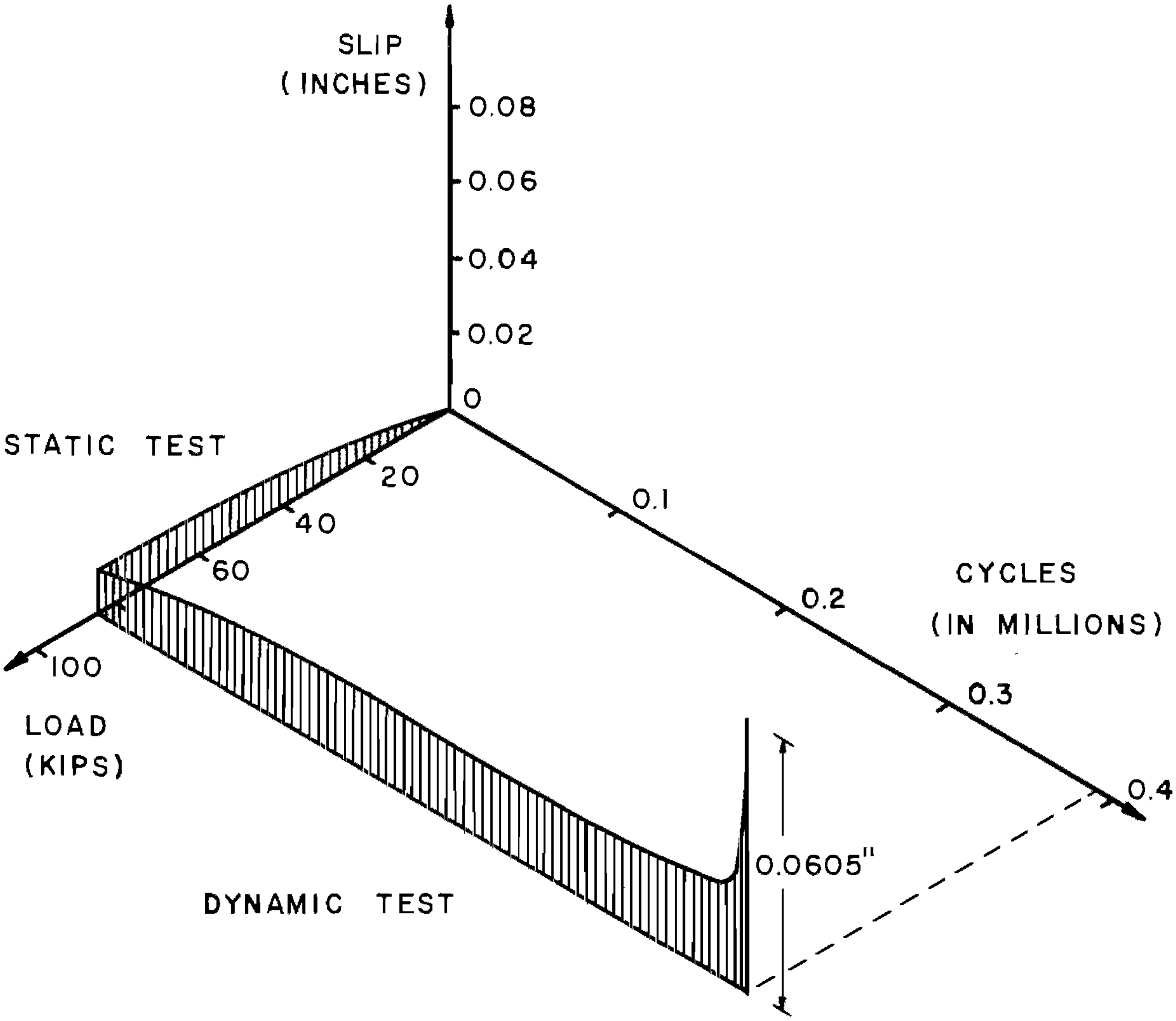


FIG. 6. LOAD - SLIP - CYCLES (SPECIMEN 1024)
FOR STRESS RANGE OF 14 k.s.i.

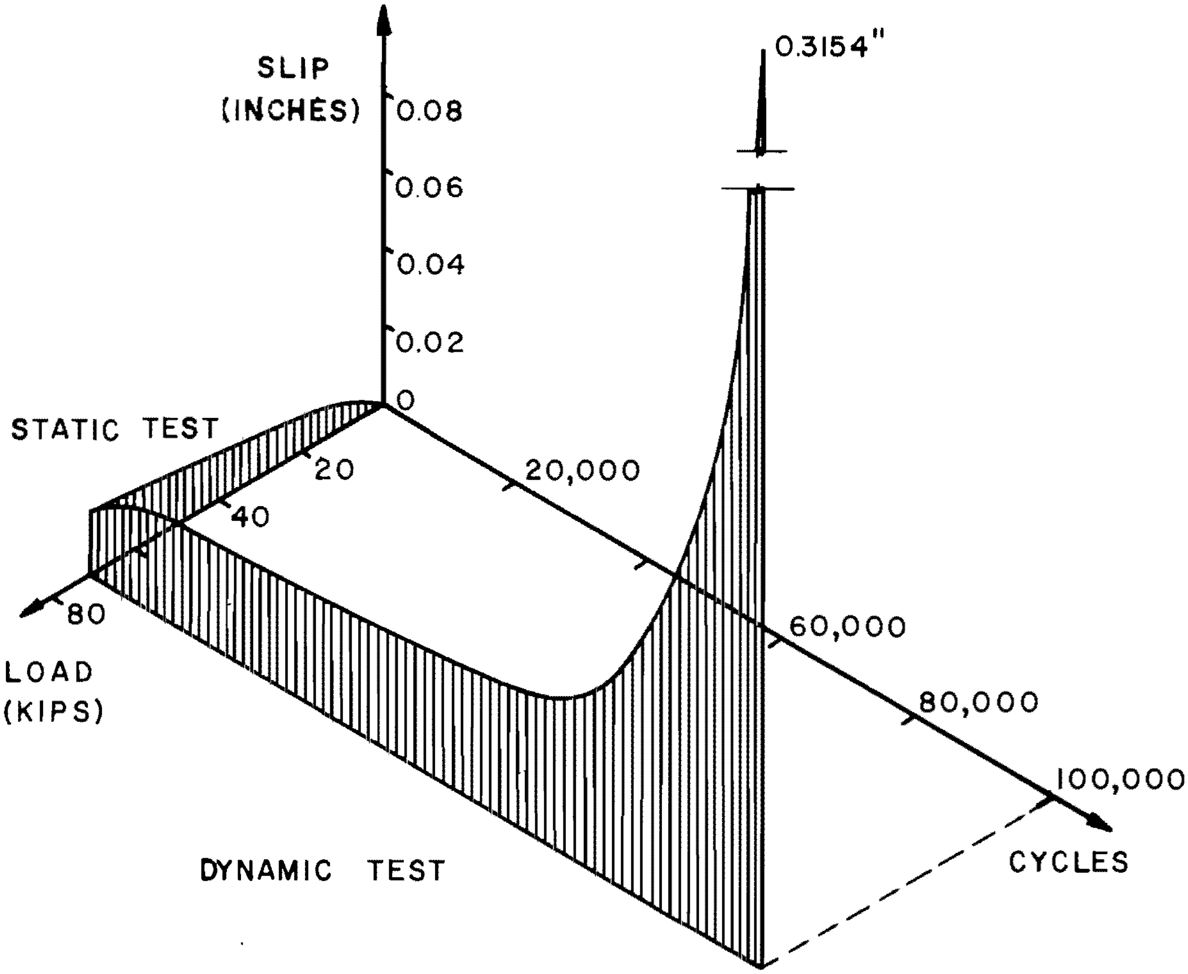


FIG. 7. LOAD-SLIP-CYCLES (SPECIMEN 220)
FOR STRESS RANGE OF 18 k.s.i.

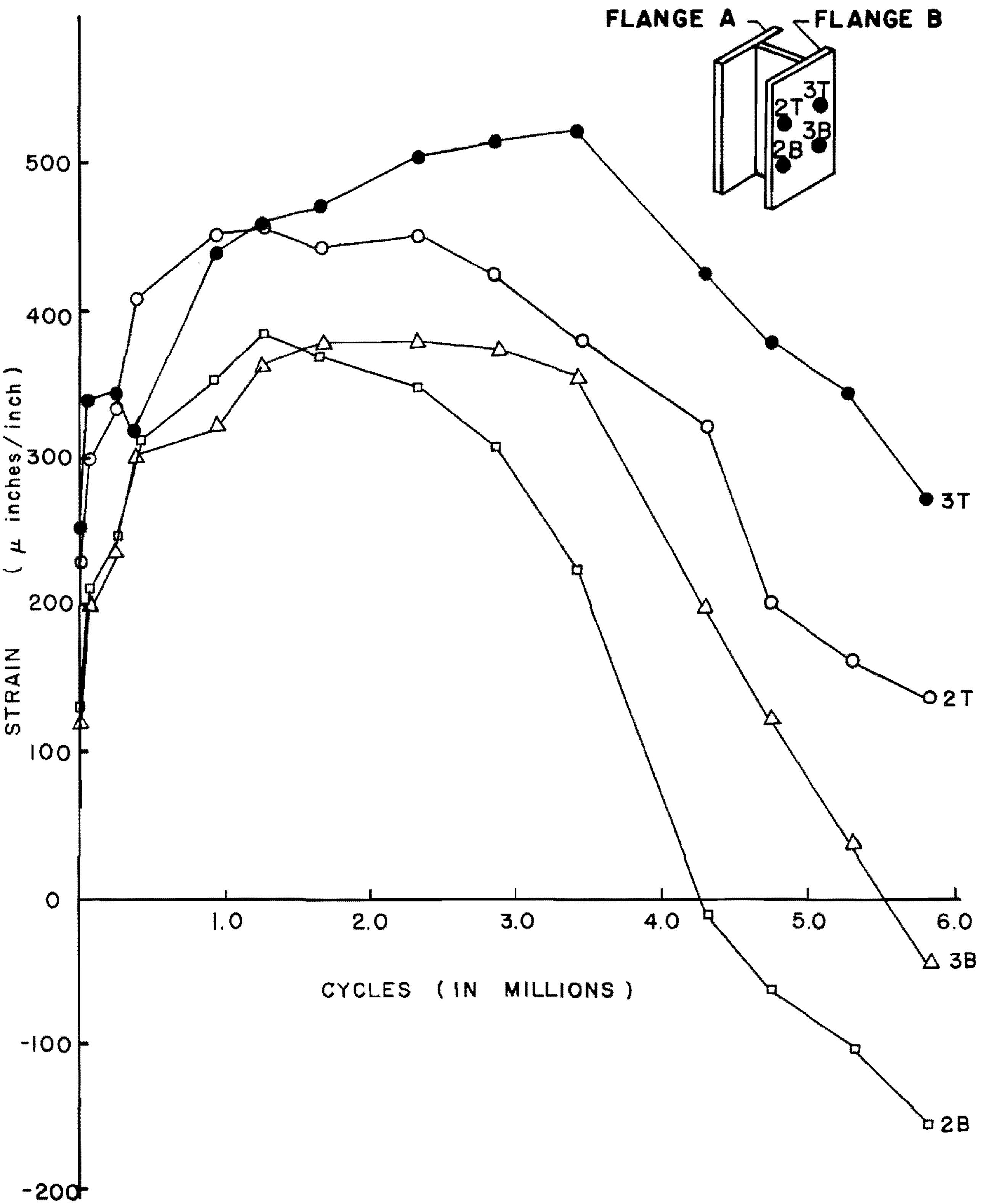


FIG.8. STRAIN READINGS OF SR-4 FLANGE DEFORMATION GAGES VERSUS CYCLES FOR INDIVIDUAL STUD - SPECIMEN 616

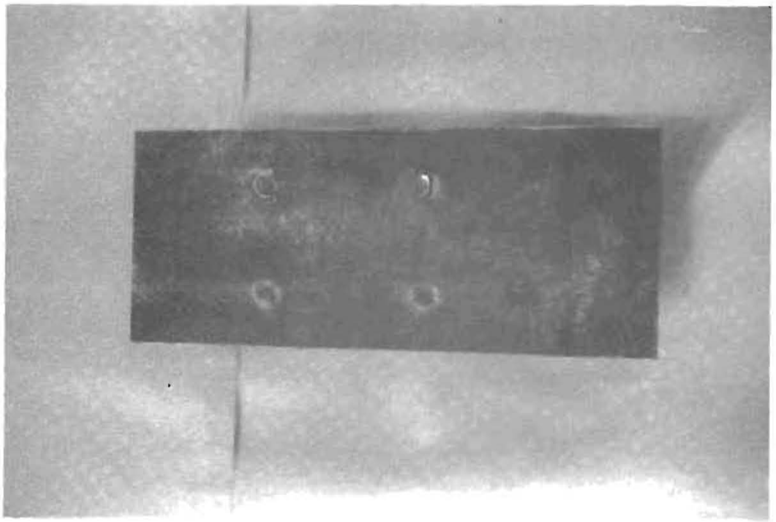
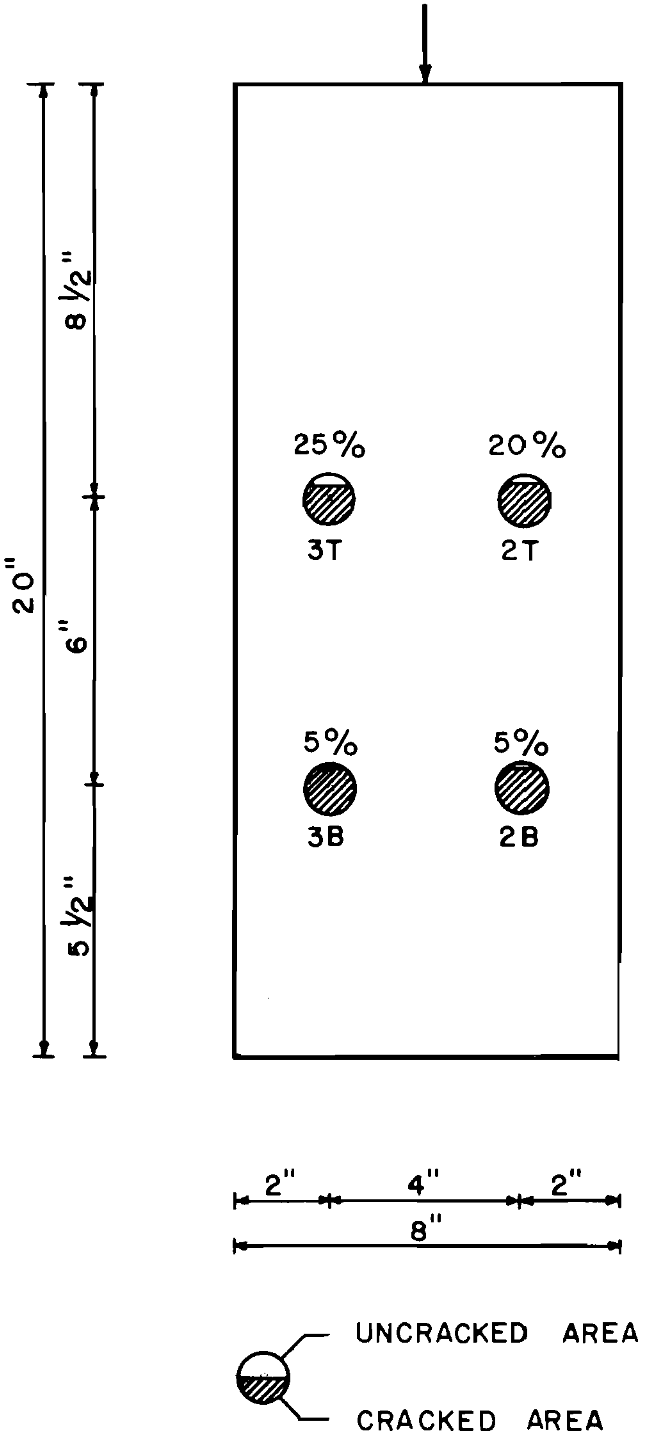


FIGURE 9.

TYPICAL STUD FATIGUE FAILURES IN THE HEAT AFFECTED ZONE OF THE BASE METAL

FIGURE 10.

TYPICAL STUD FATIGUE FAILURES IN STEM OF STUD



NOTE:
PERCENTAGE FIGURES SHOW UNCRACKED AREA.

FIG. 11. MAPPING OF STUD FAILURES FOR SPECIMEN 616

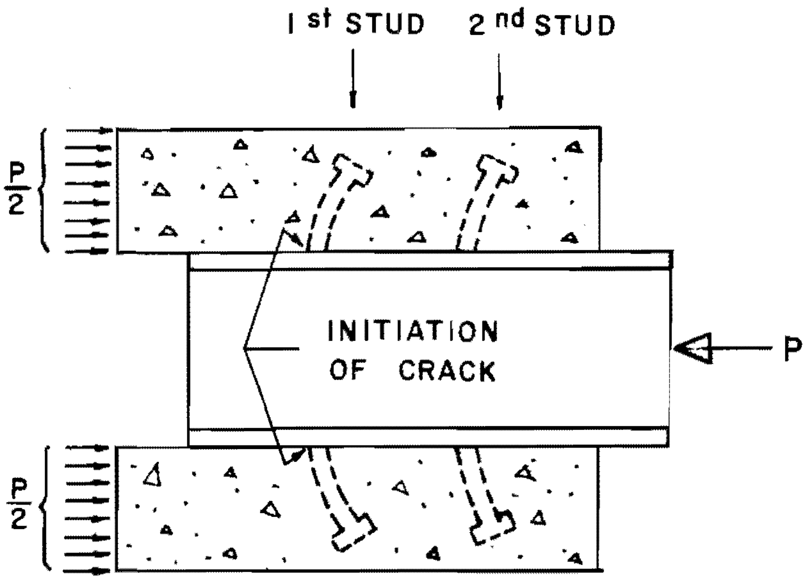


FIG. 12 a. DEFORMATION OF STUDS IN PUSHOUT TEST

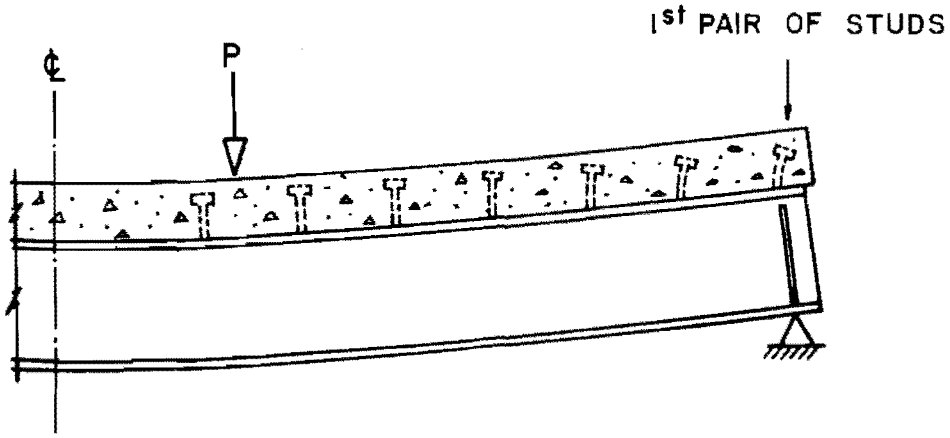


FIG. 12 b. DEFORMATION OF STUDS IN BEAM TEST

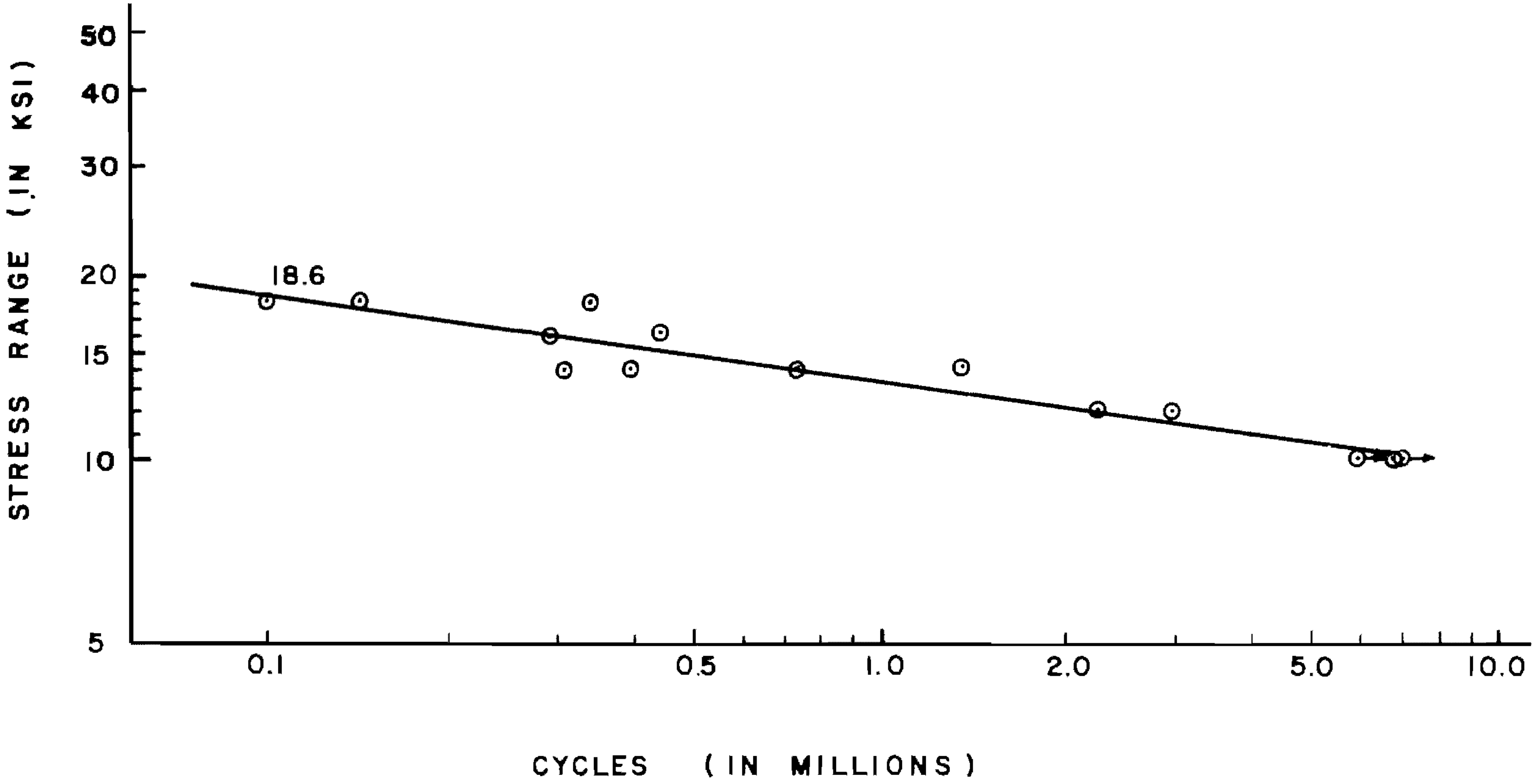


FIG. 13 STRESS RANGE - CYCLE CURVE

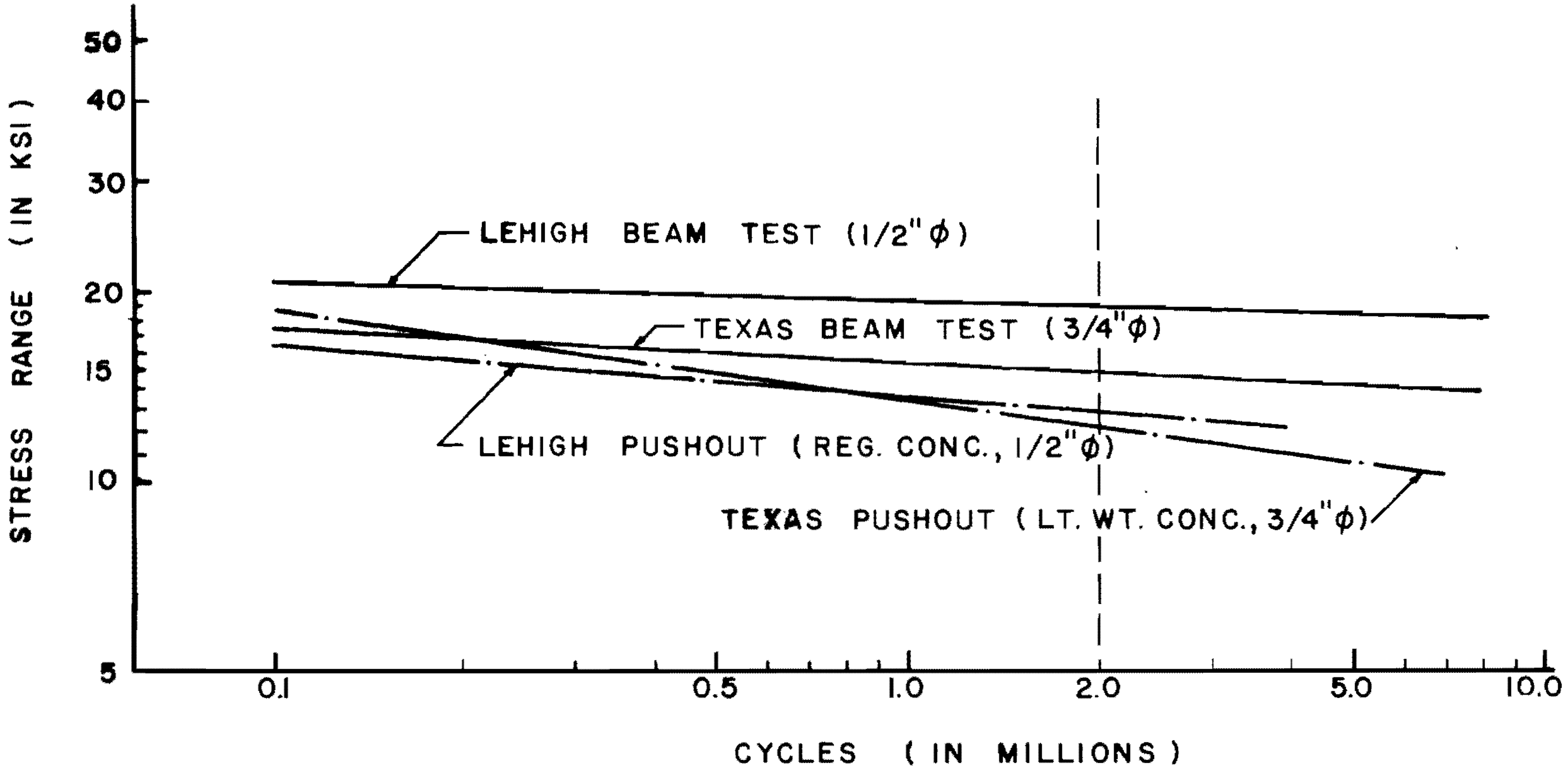


FIG. 14. S-N CURVE FOR BEAM AND PUSHOUT TEST