MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Department of Civil and Sanitary Engineering
Structural Division

BEHAVIOR OF BOND UNDER DYNAMIC LOADING

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PREFACE

This research program was conducted by Massachusetts Institute of Technology, Department of Civil and Sanitary Engineering under Contract AT(29-2)-616 with the United States Atomic Energy Commission. Technical supervision of the contract for the United States Atomic Energy Commission was performed by Holmes and Narver, Inc.. Mr. Sherwood B. Smith of Holmes and Narver, Inc., was project officer.

The research program was completed at M.I.T. in the Structural Division of the Department of Civil and Sanitary Engineering, using the large capacity dynamic loading machine designed and constructed by M.I.T. for the Office of the Chief of Engineers, under Contract DA 49-129-Eng-325. The Office of the Chief of Engineers is acknowledged for the permission to use the loading machine for this research program.

The research program was carried out by Joseph Antebi assisted by Messrs. Jayantilal M. Shah and Atis A. Liepins, Arthur Casey, Ernest Brinkerhoff and Robert Cronin, under the general supervision of Professor Robert J. Hansen. The report for this research program was prepared by Atis A. Liepins.

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1. SUMMARY

1.1 OBJECTIVES

The objectives of this research program are to determine bond strength under dynamic loading, to compare bond strengths under static and dynamic loading, and to test the adequacy of ACI Building Code bond requirements for structural elements subjected to blast loads.

1.2 RESEARCH PROGRAM

The research program consisted of static and dynamic tests on:

1) Specimens with #6 bars embedded according to ACI Building Code, Type VIII.
2) Specimens with #6 bars embedded 5", Type V.
3) Specimens with #4 bars embedded 2", 3" and 4", Type VI
4) Specimens with #6 bars with standard hooks, Type VII

In dynamic tests blast loading was simulated by a triangular load pulse with a rise time of 10 to 25 milliseconds and a decay time of 0.5 to 2 seconds.

1.3 CONCLUSIONS

These tests have shown that local static bond strengths may be as high as 0.75 f_c' and that under dynamic loading this strength increases to f_c'. For all practical lengths of embedment of bars, steel failure is to be expected both under static and dynamic loading. Such bars loaded dynamically will carry a larger load than bars loaded statically, this increase in load carrying capacity of bars being solely due to the increase of steel strength under dynamic loading. Ultimate bond stresses observed in these tests are presented in Table 1.1.

TABLE 1.1 BOND STRESS AT FAILURE

TYPE	TYPE OF FAILURE	STATIC	DYNAMIC	PERCENT INCREASE
#6 Bars Embedded According to ACI Code (11") Type VIII	Steel Fracture	1370 psi	1530 psi	12%
#6 Bars Embedded 5" Type V	Split-Out	1620 psi	1620 psi	0
#4 Bars Embedded 4" Type VI	Steel Fracture	2310 psi	2550 psi	10%
#4 Bars Embedded 3" Type VI	Pull-out Without Splitting	0.56 f_c'	-	-
#4 Bars Embedded 2" Type VI	Pull-out Without Splitting	0.75 f_c'	0.98 f_c'	30%
#6 Standard Hooks Type VII	Steel Fracture	30.5 kips per hook	34.0 kips per hook	11%

2. INTRODUCTION

2.1 PREVIOUS WORK

Bond is the phenomenon in reinforced concrete which is responsible for the transfer of loads between concrete and reinforcement. The word bond is probably most commonly associated with adhesion of some sort, although even for plain steel bars, which were the most common reinforcement in the earlier days, bond was shown to be more a friction than adhesion phenomenon.(2)* In a deformed bar, which is a common reinforcing today, the bearing of deformations on the surrounding concrete takes most the responsibility for load transfer, and friction and adhesion have lost their significance as factors in bond strength.

There is extensive literature on bond tests between concrete and steel. Bond tests have been performed on pullout specimens and beams and it has been found that pullout specimens represent bond conditions in beams with reasonable accuracy. For this reason pullout tests for bond are comparable to cylinder compression tests for concrete strength.

Tests (1,4) have shown that bond strength 1) is greater for deformed bars than plain bars; 2) increases with average height and bearing area of deformations; 3) decreases with the increasing ratio of shearing to bearing area of deformations; and 4) is unaffected by the pattern of the deformations.

Bond of plain bars increases with concrete strengths below 2000 psi. Above 2000 psi the increase in bond strength with increasing concrete compressive strength is very small, so that for most practical cases, bond for plain bars is independent of concrete compressive strength.(2) A. P. Clark(7) has shown that for deformed bars at the same amount of slip, bond stress increases with increasing concrete compressive strength.

The orientation of bars at the time of the casting of concrete is an important factor.(2,3) Bars oriented horizontally will draw up water beneath them and a stiff concrete mix, as it settles, will draw away from the bar, resulting in poor bond. The above factors are eliminated if the bars at the time of casting are oriented vertically. Vibration of concrete, and bars especially, increases the quality of bond in both horizontal and

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[*] Superscript numbers in parenthesis are references presented in the Bibliography.

vertical casting.

The distribution of bond stress along the bar is such that it reaches its maximum almost immediately inside the effective bond length at the loaded end and drops off toward the unloaded end of the bar. At a length of 24 diameters from the loaded end of the bar, bond stresses are practically zero. Therefore, increasing the bond length does not necessarily increase the resistance to pullout of a bar. As the load on the bar is increased bond will be broken near the loaded end and the peak of the curve of bond stress vs. length of bar will travel towards the end of the bar. Average bond stresses have been observed as high as 1600 psi, but investigators have pointed out that in most of their tests the bar fractured and that bond strengths were probably in excess of those observed.(5,8)

There are no reports of bond tests where the test specimens were loaded otherwise than statically. There is a complete lack of information on bond behavior under rapid loading conditions.

2.2 RESEARCH PROGRAM

Due to the complete lack of information about bond stresses under dynamic loading, a research program was conceived by Holmes & Narver, Inc. This research program was designed to give information about bond stress under dynamic loads similar to those experienced by structures under nuclear blast loading. This information is necessary in the design of splices in reinforcement, anchorage of reinforcement for hinges, anchorage of tension reinforcement in beams, and anchorage of reinforcement through construction joints.

The above information was to be obtained from laboratory testing of 24 specimens of 4 general types:

Type V. Specimens of this type were designed to pull out, so that the effectiveness of bond to resisting pullout could be studied.

Type VI. These specimens were similar to Type V, except that bars of smaller diameter were to be used to determine the influence of bar size on average bond stress at pullout.

Type VII. Specimens were designed with hooked bars so that the load capacity of hooks could be determined.

Type VIII. Bars for these specimens were to be embedded according to the latest ACI building code in order to test the adequacy of the code requirements regarding bond for structural elements experiencing blast loads.

It was intended to test 2 specimens statically and 4 specimens dynamically of each type. As testing progressed, certain modifications in the above test program were thought desirable. Since tests on specimens #1 through #6 had shown that steel strength and not bond strength was the limiting factor of the failure load, it was predicted that steel strength would also limit the failure load of specimens with hooks. It was decided that more useful information about bond behavior would be obtained from additional tests on specimens of Type V and Type VI. The actual number of specimens tested of each type was as follows: Type V - 9 specimens; Type VI - 7 specimens; Type VII - 2 specimens; Type VIII - 6 specimens.

2.3 SCOPE OF RESEARCH PROGRAM

The type of loading was the same for all specimens tested dynamically. The load in bars was measured at the loaded end and for some specimens near the unloaded end, so that an indication of the distribution of bond stress along the bar could be obtained. The deflection of the specimen relative to the supporting frame was measured. Emphasis was placed on the comparison of ultimate load capacity and average bond stress of specimens tested statically and dynamically as the two basic parameters, effective bond length and bar diameter, were varied. Bond stress distribution and load deflection characteristics of specimen was a secondary interest. Recommendations are given for future tests so that conclusive information can be obtained to form a basis for rational design where dynamic behavior of bond is involved.

3. TEST SPECIMENS

3.1 DESCRIPTION OF SPECIMENS

A specimen consisted of a reinforced concrete block shown in Figures 3.1 and 3.2 into which bond bars were embedded. There was a total of 24 specimens of 4 general types:

Type V. 9 specimens with 4 #6 deformed bars each having an approximate bond length of 5".

Type VI. 7 specimens with 8 #4 deformed bars. In three specimens each bar had a bond length of 4". Two specimens were with bond lengths of 3" and two with 2".

Type VII. 2 specimens with 4 #6 hooked bars. Only the hooked part of the bar was allowed to bond, while that part of the bar in front of the hook was prevented from bonding by an aluminum sheet sleeve.

Type VIII. 6 specimens with 4 #6 deformed bars embedded according to A.C.I. Building Code (ACI 318-56).

Details of bond bars are shown in Figure 3.3 and individual specimen information is presented in Table 3.1. The general appearance of all specimens was as shown in Figure 3.1, except that #14 and #15 were with hooked bars with hooks turned diagonally inward and specimens #18-24 were with 8 #4 bars placed 2" on centers.

Sleeves, made of a thin aluminum sheet, were employed on specimens #14, #15, and #18-24 to prevent concrete from bonding to steel bars. This permitted the placing of the effective bond length of bars far inside the specimen where there was adequate reinforcing to prevent splitting and cracking.

Most specimens had 2 gages on each bond bar as shown in Figure 3.3. Specimen #1 had 3 gages on each bond bar. This arrangement broke up the effective bond length in short lengths and was abandoned. Speciments #12 and #16 were prepared without gages, and #17 was prepared with only one gage on each bond bar, with the intention to determine if the gages had any appreciable effect on bond stress. Specimens #18-24 were prepared with only one gage because another gage would break up the already short bond length into even shorter pieces.

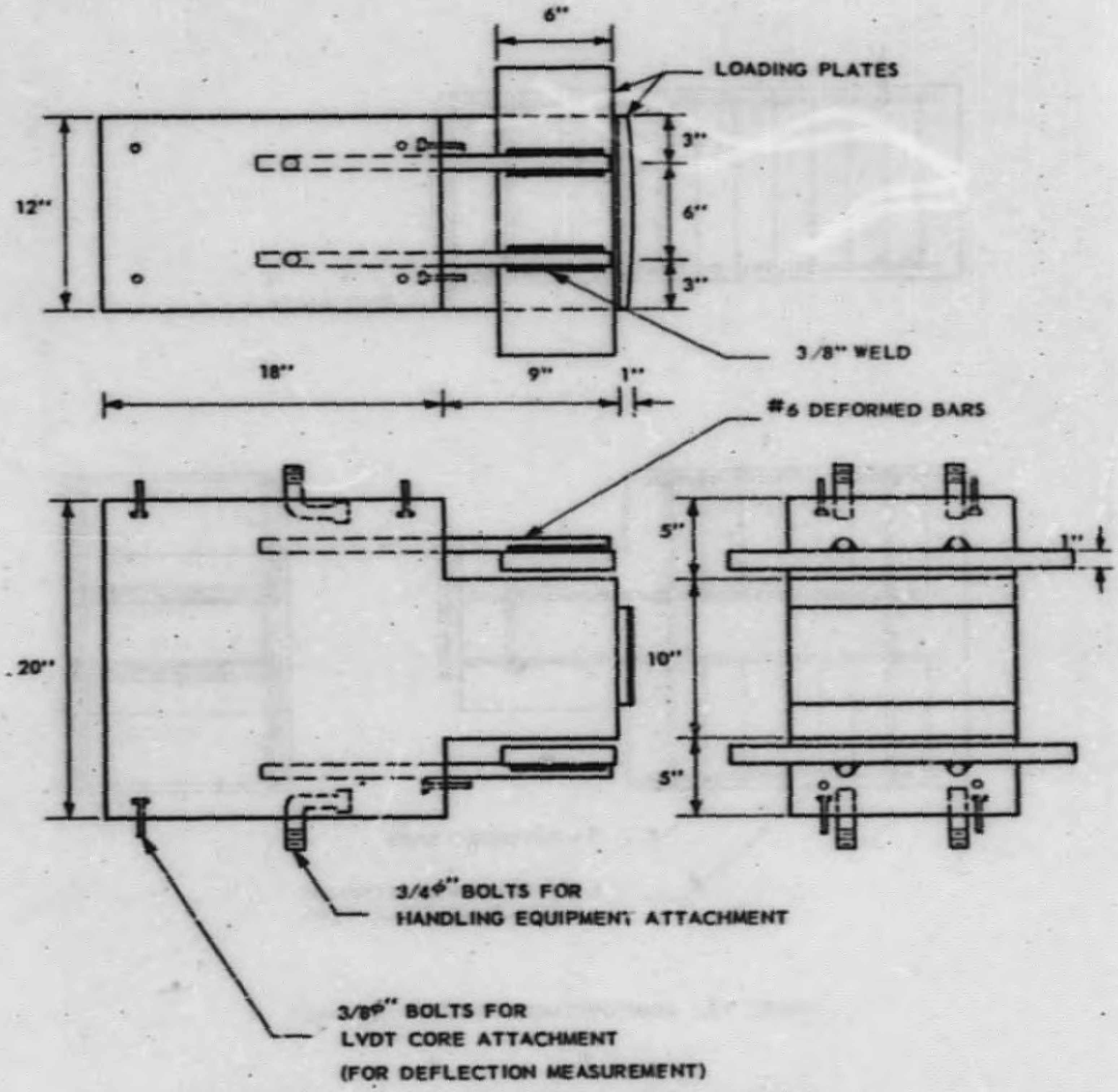

FIGURE 3.1 EXTERNAL APPEARANCE OF TEST SPECIMEN

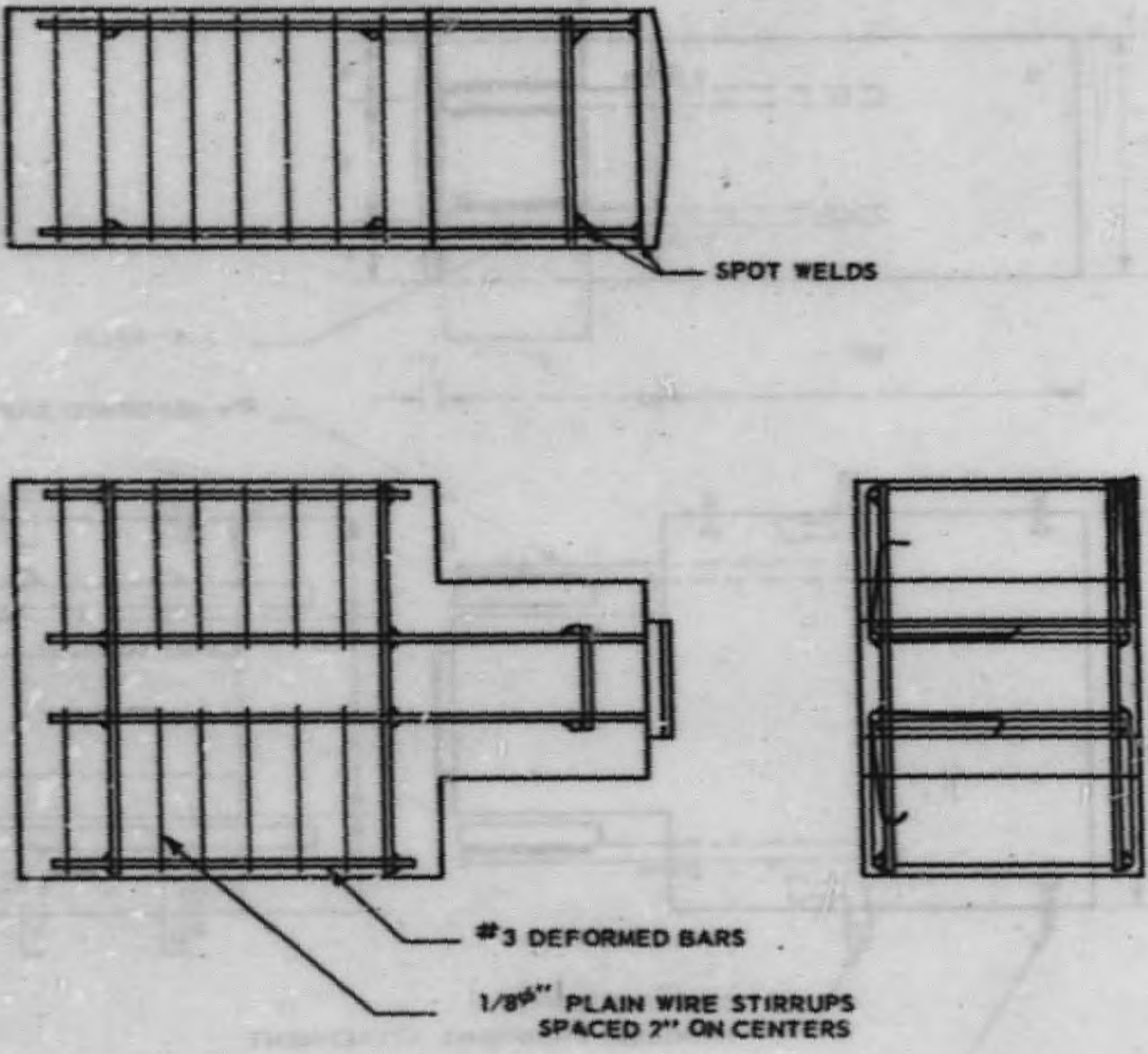

FIGURE 3.2. REINFORCEMENT OF TEST SPECIMEN

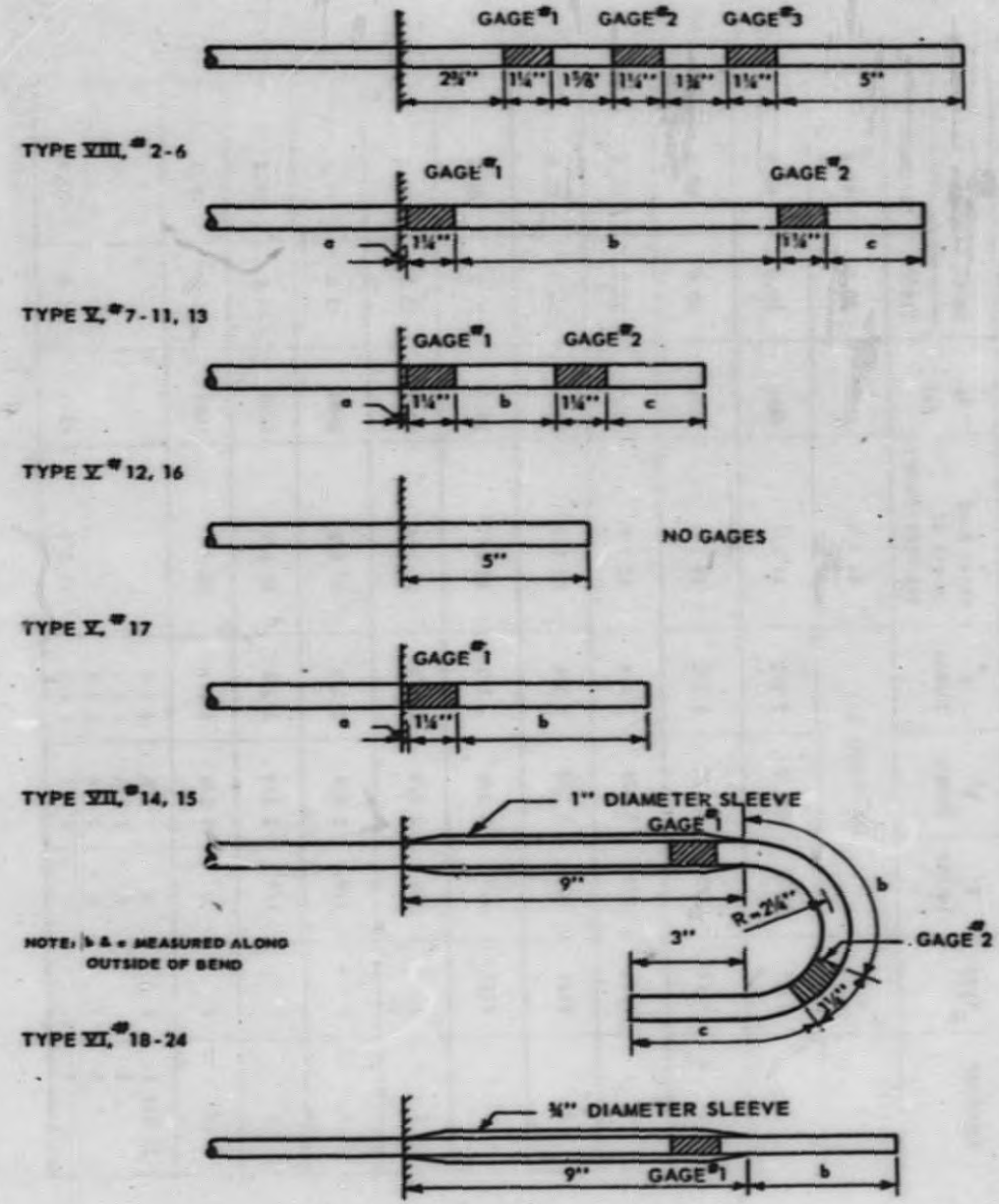

FIGURE 3.3. DETAILS OF BOND BARS

TABLE 3.1 GENERAL DATA OF SPECIMENS

Specimen	Type	a* Inches	b* Inches	c* Inches	Total Bond Length of all Bars, Inches	f'_c, psi	Steel Strength, ksi	
							Yield	Ultimate
1	VIII	SEE FIGURE 3			44 3/8	4120	50.0	80.6
2	VIII	3/8	8 1/2	2 1/2	44 1/4	4860	50.0	80.6
3	VIII	1/8	8 1/2	2 3/8	43 1/2	3880	50.0	80.6
4	VIII	1/4	8 3/8	2 3/8	42 7/8	4360	50.0	80.6
5	VIII	0	8 3/8	2 3/8	43 1/8	4100	50.0	80.6
6	VIII	1/4	8 3/8	2 1/2	43 1/4	3850	50.0	80.6
7	V	1/4	2 7/8	2 1/2	21 1/4	4200	45.5	79.3
8	V	1/8	2 5/8	2 1/2	20 5/8	2960	45.5	79.3
9	V	1/4	2 3/4	2 3/8	20 1/2	3520	45.5	79.3
10	V	0	2 3/4	2 1/4	20	3440	45.5	79.3
11 Bar 1	V	0	3/8	4 1/4	19 5/8	4240	45.5	79.3
2		0	1 7/8	3 1/4				
3		0	2 5/8	2 3/8				
4		0	3 3/4	1 1/2				

TABLE 3.1 GENERAL DATA OF SPECIMENS (Cont'd.)

Specimen No.	Type	a* Inches	b* Inches	c* Inches	Total Bond Length of all Bars, Inches	f'_c, psi	Steel Strength, ksi	
							Yield	Ultimate
12**	V		5	-	20	3990	45.5	79.3
13 Bar 1 2 3 4	V	1/4 1/8 1/8 1/8	1 1 7/8 2 3/4 4	4 3 1/8 2 1 1/8	20 1/2	3780	45.5	79.3
14 Bars 2,3 1,4	VII	- -	8 1/4 4 5/8	2 5 1/2	39 1/2	5290	39.6	69.3
15 Bars 1,3 2,4	VII	- -	9 1/8 6	2 5 3/8	44 3/4	4860	39.6	69.3
16**	V	-	5	-	20	5040	45.5	79.3
17	V	0	5 1/8	-	20 3/8	4490	45.5	79.3
18**	VI	-	4	-	32	4310	44.7	77.0
19	VI	-	4		32	4400	44.7	77.0
20	VI	-	4	-	32	4460	44.7	77.0
21	VI	-	3	-	24	4760	42.4	74.5
22	VI	-	3	-	24	5400	46.4	73.4
23	VI		2	-	16	4570	48.3	77.6
24	VI		2	-	16	4000	40.2	71.3

* a,b,c, see Figure 3.3, are average values of all bars.

** Specimens without gages

3.2 PROPERTIES OF MATERIALS

The concrete mix was designed for 3500 psi at 7 days and consisted of:

1 part by weight high early strength Portland cement,
2.72 parts by weight of fine aggregate,
3.00 parts by weight of coarse aggregate,
6.4 gallons of water per sack of cement.

The fine aggregate had a fineness modulus between 2.7 and 3.0 and the coarse aggregate size ranged between 1/2" and 3/4".

Because specimens could not always be tested after 7 days, the concrete strengths given in Table 3.1 are somewhat in variance with the design value.

All bond bars were of the diamond deformation type manufactured by Jones & Laughlin Steel Corp. The yield stress of steel varied between 39.6 ksi and 50.0 ksi. Steel strengths for each specimen are given in Table 3.1, and a typical stress strain diagram is shown in Figure 3.4. The stress strain properties of bond bars were somewhat affected by welding as shown in Figure 3.4.

It is well known that metals with a sharply defined yield point exhibit a delayed yield effect when subjected to a fast rate of strain.(9) The yield strength of steel under rapid loading can be estimated by the formula:(10)

$$f_{dy} = f_y - 3.8 \log_{10} t$$

where: f_{dy} = yield strength under rapid loading, ksi
f_y = yield strength under standard rate of loading, ksi
t = time to reach yield point in seconds

3.3 PREPARATION OF SPECIMENS

Preparation of bond bars was started by cutting the bars to 2' lengths and cleaning them with a wire brush. The deformations of the bond bars were removed at two places diametrically opposite from each other by grinding and filing. Each of these surfaces was sandpapered and cleaned with acetone to receive one SR-4 strain gage. Gages were mounted in line with the axis of the bar with fast drying strain gage cement, and were allowed to dry for 24 hours. When dry, the gages were connected in series and lead wires were attached. Waterproofing consisted

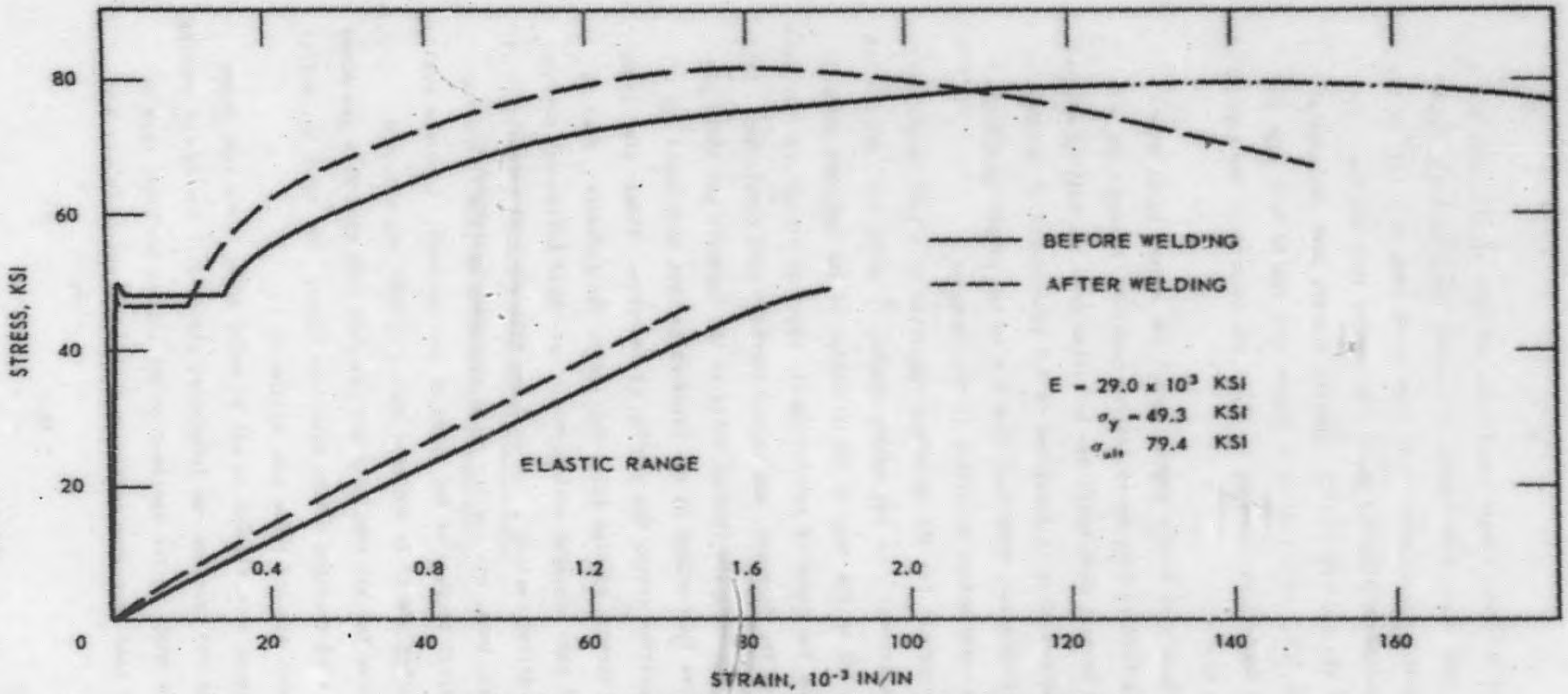

FIGURE 3.4 TYPICAL STRESS-STRAIN CURVE OF A BOND BAR

of two coats of neoprene rubber cement covered with plastic tape and a coat of wax. Lead wires were draped in plastic tubes to avoid injury during the placing of concrete. Each gage point took up 1 1/4" of bar length and appeared in diameter about 1/4" larger than the bar. For specimens #14, #15 and #18-24 thin aluminum sleeves were employed as shown in Figure 3.3. Both ends of a sleeve were sealed with tape and wax to prevent bonding of concrete to steel and to protect the gage which was inside the sleeve.

All bars with strain gages, except the hooked bars, were calibrated in a Baldwin-Tate-Emery testing machine. Hooked bars were not calibrated because they could not be fitted into the testing machine. The calibration procedure is described in 4.3 Measurement of Stresses in Bars. After calibration, bond bars were cut to the proper length and cleaned with acetone before insertion in the formwork.

The formwork for all specimens consisted of a 1/8" thick steel plate placed horizontally on two wooden blocks, to which 1/8" thick steel plates were bolted in the form of the elevation of the specimen shown in Figure 3.1. The two cages of reinforcement, shown in Figure 3.2 were prepared, placed in the formwork, and welded together with steel bars. Next the bond bars were inserted through holes in the formwork and their protruding ends were tack-welded to the formwork so that they would not change their position during the placing of concrete. Strain gage leads were taken out through special holes drilled in the formwork. When in place, the bond bars appeared horizontally, and their horizontal position was maintained during casting . It is known that vertical orientation of bars gives better bond, but casting these specimens vertically was considered impractical because of the shape of the specimen. Concrete was vibrated thoroughly and it is believed that good bond was obtained.

Concrete for all specimens and standard test cylinders was mixed in a 1/3 cubic yard rotating tilted drum type mixer. One batch was sufficient for one specimen and three test cylinders.

Specimens were allowed to set 24 hours after which time forms were removed and the specimen was laboratory cured until the day of testing.

Before mounting the specimen in the loading machine, each of the two rows of bond bars were welded to a plate, shown in Figure 3.1, which transferred the bond bar loads to the supporting frame. When the specimen was in place in the machine, the LVDT's were attached and connected to recording equipment and strain gages connected to recording equipment.

4. EQUIPMENT AND INSTRUMENTATION

4.1 LOADING MACHINE

Loading of the specimens was provided by the large capacity dynamic loading machine designed and constructed under Contract DA 49-129-Eng-325 with the Department of the Army. The machine was designed to supply a maximum load of 300,000# in 10 milliseconds. It is capable of producing a variety of different pulses with rise times not less than 10 milliseconds. The machine can also be used for static tests. For a more thorough discussion of the loading machine see reference No. 11.

To receive the test specimen the support arrangement of the machine as used to test shear walls was slightly modified. The new support arrangement is shown in Figure 4.1. Essentially it consists of a supporting frame which holds the specimen (see Figure 4.2) and which in turn is supported by an A-frame. The load is transferred from the specimen to the supporting frame which transfers the load to the truss of the machine via a strut.

4.2 MEASUREMENT OF LOAD

The applied load was sensed by a strain gage bridge located on the ram of the machine. For details of this load cell see reference No. 11.

The output of the ram load cell in a dynamic test was displayed on two oscilloscopes. One oscilloscope displayed the total pulse and at the same time the other oscilloscope displayed on an expanded scale the rising part of the pulse. This expanded display of the load pulse was necessary for an accurate determination of the rise time of the pulse. The oscilloscopes were Dumont - Dual Beam Type 322, 322A and 333. The trace on each of the oscilloscopes was recorded on polaroid film by Dumont Oscillograph Recording Cameras, Type 297.

In a static test the load was increased slowly in suitable increments. The output of the ram load cell was displayed on one oscilloscope and the deflection of the trace was recorded directly after each increment.

The ram load cell was calibrated at the beginning of this series of tests and again when the tests were completed. Both calibrations agreed within less than 3%, and an average value of the calibration was used to calculate the load of all pulses.

The load as determined by this method could be in error by not more than 5 kips, which for the majority of pulses corresponds to less than 5%.

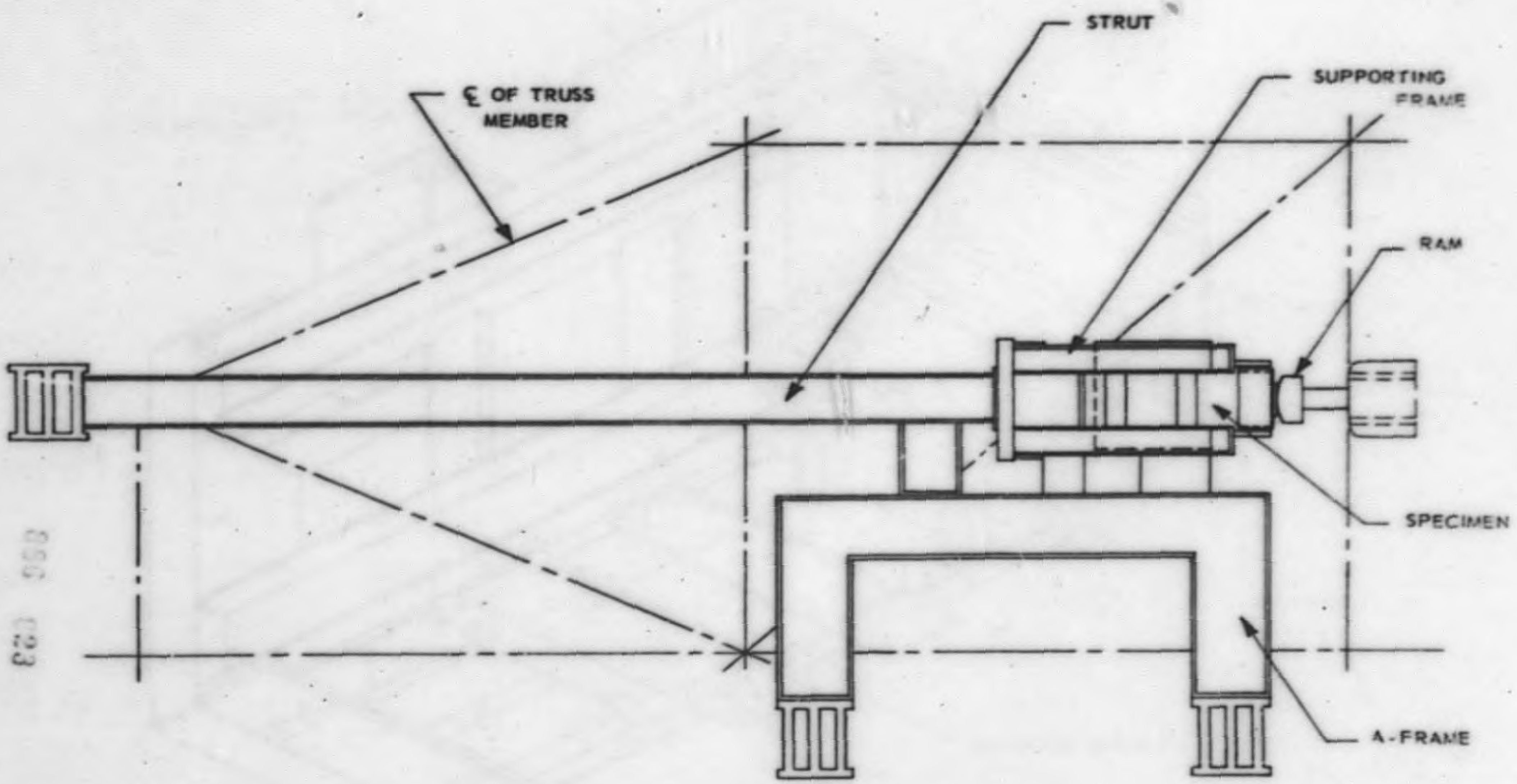

FIGURE 4.1 SUPPORT ARRANGEMENT FOR TEST SPECIMEN

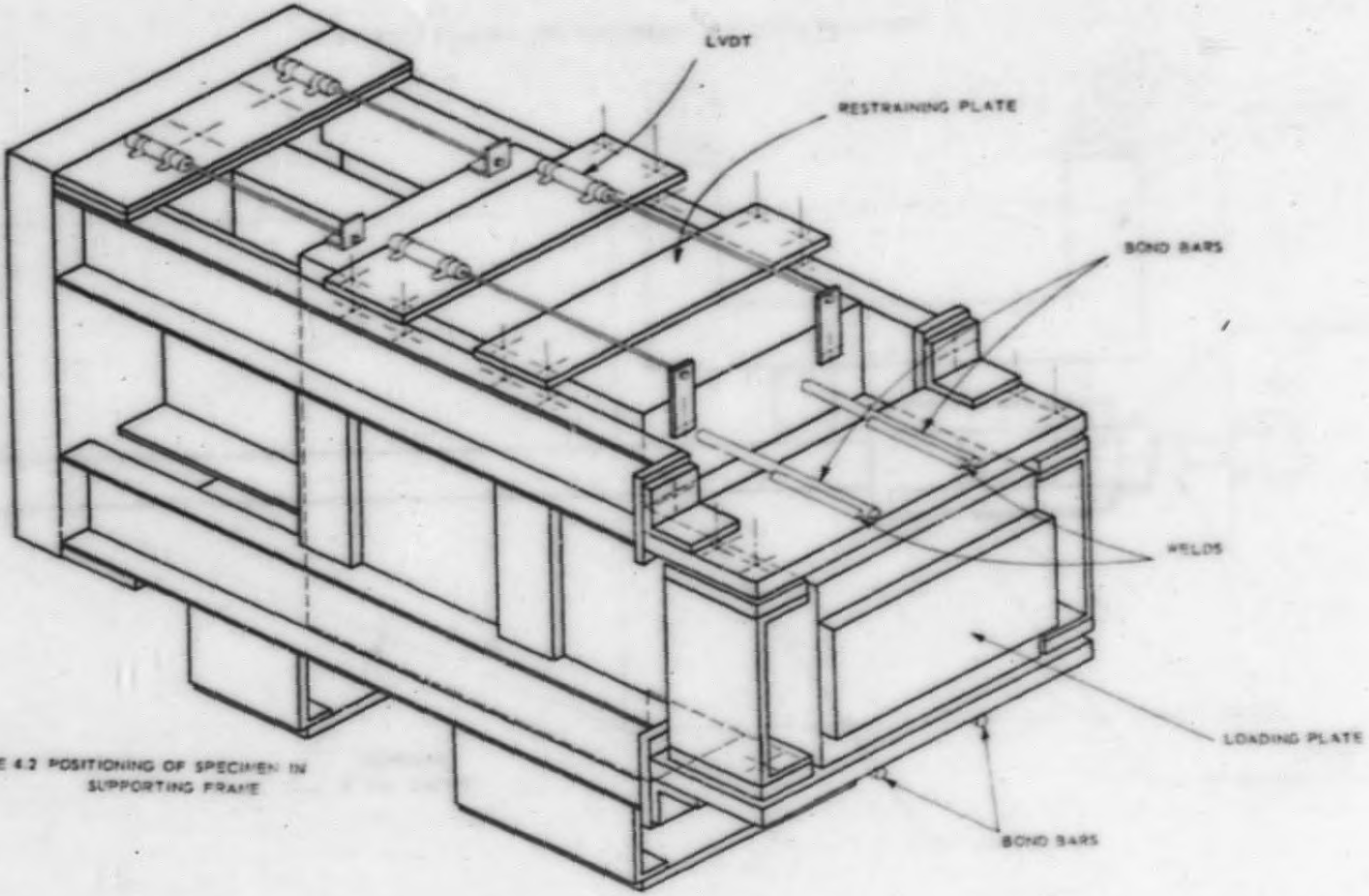

FIGURE 4.2 POSITIONING OF SPECIMEN IN SUPPORTING FRAME

4.3 MEASUREMENT OF STRESSES IN THE BARS

Generally, stresses in bond bars were measured at two places: immediately before the start of bond and at a place near the unloaded end of the bar (see Figure 3.3 for gage locations). The main purpose of the front gage was to measure the load in the bond bar. The gage near the unloaded end of the bond bar was to give some indication of the bond stress distribution. In two specimens the location of the second gage was different for each of the four bond bars so that a more accurate distribution of bond stress could be obtained.

The strain gages used were the SR-4 Type A-19 and A-7 manufactured by the Baldwin-Lima-Hamilton Corp. It was necessary to switch from A-19 to A-7 in the middle of the test series because A-19 was not readily available. The only difference, as far as these tests are concerned, between the 2 gages is that the A-19 has a resistance of 60 ohms, but the A-7 120 ohms. The results are not affected in any way by this change. Each gage made up a leg in a strain gage bridge, whose balance was upset when the bar was stressed. The signal due to this unbalance was sensed and amplified by Amplifier System D, Type 1-113B manufactured by the Consolidated Electrodynamics Corp. (C.E.C.). The signal from the amplifier was received by galvanometers of 2 Hathaway Type S-14-H oscillographs. The deflection of these galvanometers was recorded as a continuous trace.

All bond bars except hooks were calibrated by stressing them in a Baldwin-Tate-Emery Testing Machine (60-TE-1371) to 75% of their yield stress, and recording the output of the strain gage at this level of stress by a 2 channel Sanborn recorder. Since in tests strain gage outputs were recorded by the C.E.C. the output of the Sanborn recorder has to be correlated with the output of C.E.C. This was done by shunting a resistor across one of the arms of a strain gage bridge. The output of this unbalanced bridge was recorded by a Sanborn recorder at the time of calibration and again on all channels of the C.E.C. just before testing.

The output of gage #1 of specimens #1 - 11, #13 and #17 is not believed to represent the actual loads carried by bond bars in these specimens. The reason for this belief is that the welding of bearing plates to bond bars after calibration of gages affected the properties of steel and the output of the gages. All other gages which were not in the immediate vicinity of welds are believed to give accurate loads.

4.4 MEASUREMENT OF THE MOVEMENT OF SPECIMEN

Horizontal movement of specimens relative to the supporting frame was sensed by 8 linear variable differential transformers - LVDT's, at the 8 points shown in Figure 4.3. The LVDT's were of the moving core type, Type 1000 S-L with a linear range of ± 1.0" and an accuracy of 0.5% of linear range, manufactured by Schaevitz Engineering Company.

Small angles were attached to bolts (see Figure 3.1) located at the above-mentioned 8 points and a flexible aluminum rod was employed to connect the angle and the movable core of the LVDT. To protect the LVDT from damage, the rod was passed through a bushing located between the LVDT and the angle which prevented the rod from moving out of line as the specimen moved. The flexible rods were equipped with long nuts, so that the core could be moved without moving the specimen. This was necessary to facilitate balancing of LVDT's which was essentially the location of the core at the LVDT's null point.

The moving of the LVDT core with the specimen upset the balance of the LVDT. Both C.E.C. and two Sanborn recorders were used to record the signal from the unbalance of the LVDT's. Horizontal movement of points 1, 1', 3, and 3' was recorded by the C.E.C., and that of points 2, 2', 4 and 4' was recorded by the two Sanborn recorders.

The LVDT's were calibrated 6 times during the duration of this test series. Calibrations dated nearest to the testing date were used to interpret the recordings of a test. Calibration consisted in moving the core a certain distance which was measured by an Ames dial, and recording the output of the LVDT at the end of each movement by the C.E.C. or Sanborn recorder depending on which was used to measure the output of a particular LVDT in a test.

The error in the measurement of deflections induced by the non-linearity of the LVDT output with the movement of the core, the calibration and interpretation of the C.E.C. traces has been estimated at ± 0.005 inches.

In static tests Ames dial gages were employed to provide a cross-check for the movements recorded by the C.E.C. and Sanborn recorders. Points of attachment of Ames dial gages were the same as those for LVDT's shown in Figure 4.3.

The LVDT attachment was such that it measured the elongation of steel between load plate and front face of specimen. Since the front strain

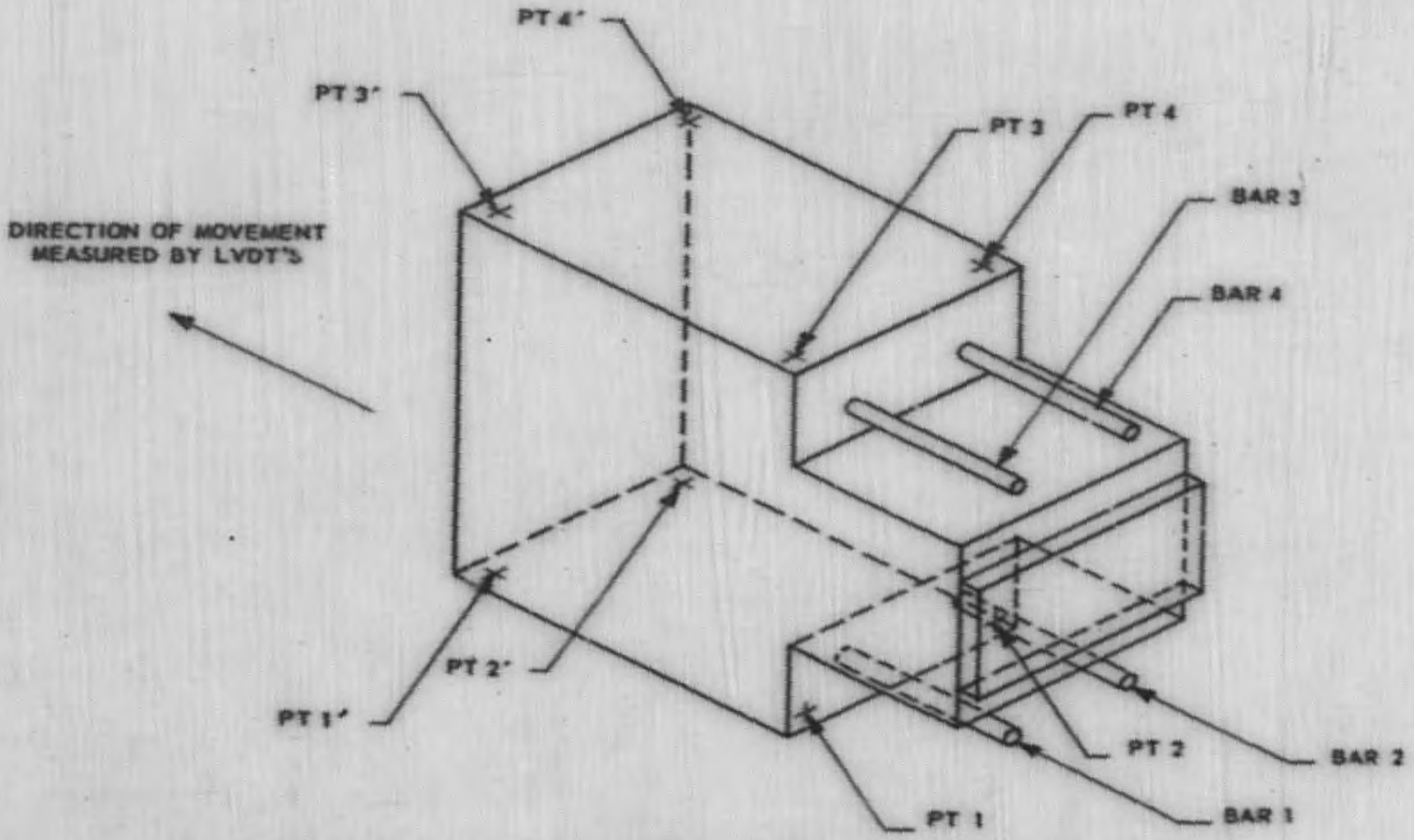

FIGURE 4.3 POINTS OF ATTACHMENT OF LVDT'S, AND NUMBERING OF BARS

gages are believed to give unreliable outputs it is not possible to determine the amount of deflection due to elongation of steel, which in turn makes it impossible to determine the amount of slip of bond bars. The same is true for the Ames dial deflections.

5. TESTS

5.1 GENERAL

In static tests the load on the specimen was increased in suitable increments and the deflections, bar stresses and load recorded after each increment. As the ultimate load was approached continuous traces of deflections and bar stresses were taken, so that their values at the instant of failure of the specimen could be obtained. Before a test was started a small static load was applied and removed to check all equipment and to push the bearing plates solidly against the supporting frame.

In dynamic tests the shape of the applied load pulse was approximately triangular with a rise time between 10 and 25 milliseconds and a total duration between 500 and 2000 milliseconds. A typical load pulse is shown in Figure 5.1. To check all equipment a load pulse of about 40 kips was applied before the start of testing. A 40 kip pulse was the smallest load that could be applied satisfactorily with the machine.

The natural period of vibration of a test specimen was estimated at 0.5 milliseconds. Since the rise time of a load pulse was never less than 9 milliseconds, the response of the specimen to the load pulse was expected and observed to be essentially static with rapid loading effects on steel and concrete.

5.2 TESTS OF TYPE VIII

5.2.1 Static Tests. Results of static tests performed on specimens #1 and #6 are presented in Appendix 1.

Specimen #1 failed at a load of 119 kips and #6 at 138 kips which is 14% higher than #1. Both specimens were considered as failed when one of the bars fractured. Specimen #1 failed at a lower load than #6 probably because of a slight eccentricity of the applied load which loaded one of the bars of #1 more severely than the others, while the bars of #6 were more evenly stressed. The total ultimate tensile strength of 4 bars of both specimens was estimated at 142 kips, which was very nearly reached in the test on #6. Strain gages 5" from the unloaded ends of bars in specimen #1 showed loads at yield or very near the yield load of bars. Gages 2 1/2" from the unloaded ends of bars in specimen #6 showed loads considerably lower than those of #1.

Both specimens were split extensively at front near the bars and

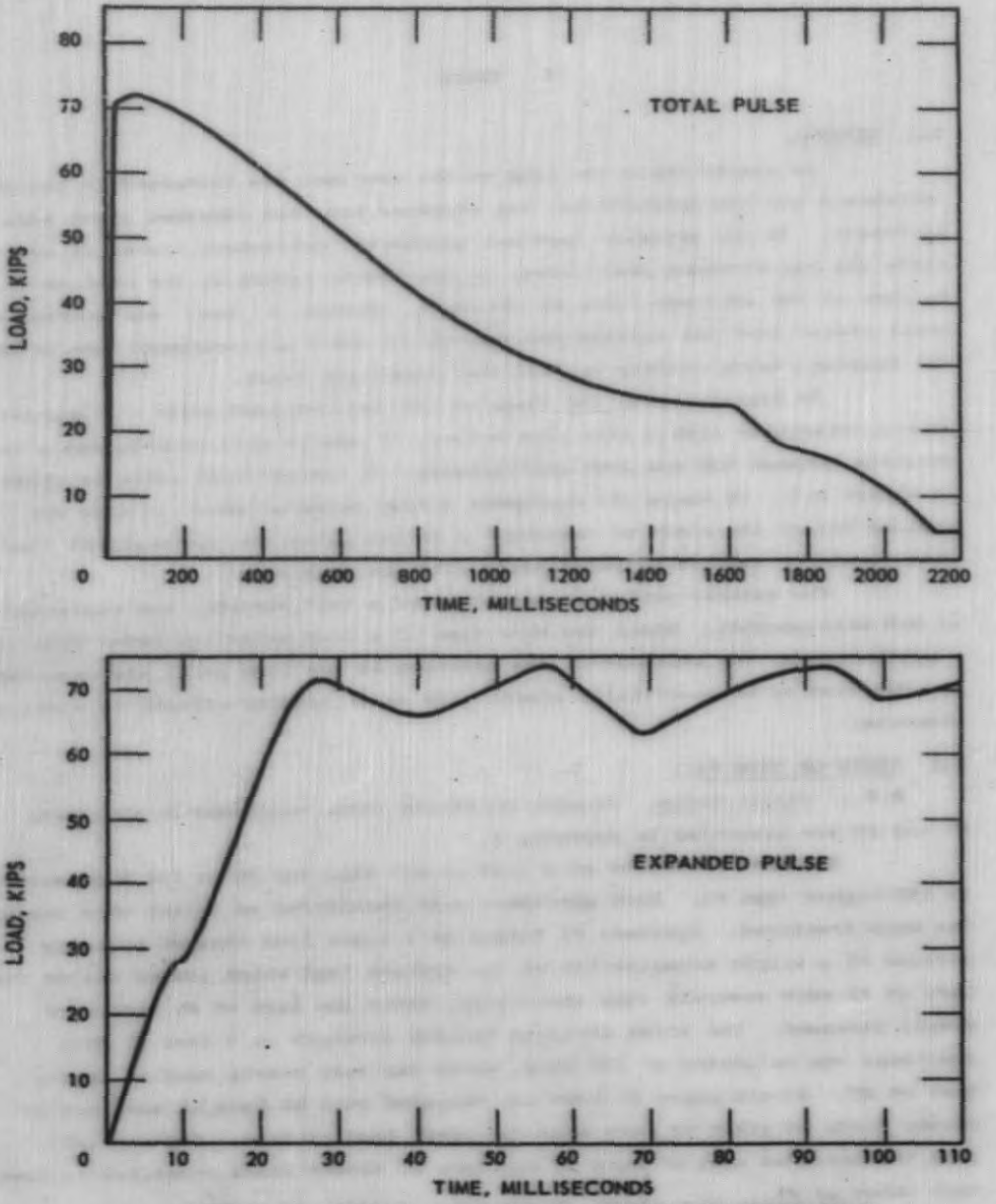

FIGURE 5.1 TYPICAL LOAD PULSE (PULSE 3 ON SPECIMEN 3)

#1 also showed extensive cracking at the top of specimen.

Concrete strength of #6 was 3850 psi, or 7% less than #1.

5.2.2 Dynamic Tests. Results of dynamic tests performed on specimens #2, 3, 4, 5 are presented in Appendix 2 and Appendix 3.

Failure loads of these specimens were 155, 161, 156 and 156 kips respectively. No bars were fractured in any of these specimens. A specimen was considered failed when the deflections had reached the order of magnitude of 1". Further deflection could not be allowed without endangering the safety of measuring instruments.

Eleven pulses were applied to specimen #2 and nine pulses to specimen #3. It was necessary to apply so many pulses because of the difficulties with recording equipment and because of the high failure loads of specimens. As a result of this, both specimens were subjected to large repeated loads. Gage #2 registered increasing loads with repeated application of a large load which indicates that large repeated loads induce progressive bond failure. Only two pulses, a small pulse and the failure pulse, were applied to specimen #4. This specimen probably would have resisted another pulse of a magnitude comparable to the failure pulse of 156 kips. However, since the effect of this pulse would be to increase the deflections and induce progressive bond failure as shown by specimens #2 and #3, the specimen was considered failed. Four pulses were applied to specimen #5.

All four specimens were badly cracked in the same manner as in static tests.

Concrete strengths of these specimens varied from 3880 to 4860 psi. Since all specimens failed at practically the same load there is no correlation between ultimate load and concrete strength.

5.2.3 Discussion. A summary of type VIII tests is presented in Table 5.1. Because one of the bars fractured in both static tests, even though the total loads were different, both specimens can be considered as failed at the same average bond stress of at least 1370 psi. Large failure loads, which imply large steel strains, and high stresses near the unloaded ends of bars are a good indication that bond was broken near the loaded end. From the loads measured by the second gage it is estimated that not more than 1/2 of the original bond length of 11" was effective in resisting pullout at failure. Therefore, average bond stress at failure in static tests is estimated at 2500 psi or more.

TABLE 5.1 SUMMARY OF TYPE VIII TESTS

Type of Test	Specimen	f'_c, psi	Steel Strength, Kips		Number of Pulses Applied	Failure Load, Kips	Rise Time of Failure Load, Milliseconds	Average Bond Stress, u, at Failure, psi	u/f'_c
			Yield	Ultimate Static					
Static	1	4120	88	142	-	119	-	1370	0.33
	6	3850	88	142	-	138	-	1370	0.36
Dynamic	2	4860	99	142	11	155	23	1480	0.31
	3	3880	101	142	9	161	15	1570	0.40
	4	4360	100	142	2	156	16	1540	0.35
	5	4100	101	142	4	156	15	1530	0.37

The average bond stress at failure in dynamic tests averaged to at least 1530 psi. This is a 11% increase over static tests, which is due to the increase in the ultimate strength of steel under rapid loading conditions. The increase in ultimate steel strength of 11% is rather high as the ultimate strength is generally supposed to be time insensitive.

The loads measured by gage #2 vary considerably and are not capable of comparison to values of static tests. Progressive bond failure due to the large number of pulses applied to specimen #2 and #3 is partially responsible for this variation.

An estimate of the effective bond length at failure is not possible from the scattered loads recorded by gage #2. However, it is believed that as in static tests not more than 1/2 of the original bond length was effective. Therefore, average bond stresses at failure are estimated at 3000 psi or more.

Since in both static and dynamic tests steel strength was the limiting factor, these tests do not give any conclusive information regarding ultimate bond strength in either case. The tests show, however, that the pullout capacity of bars embedded according to ACI Building Code (ACI 318-56) is increased only as much as the ultimate steel strength increases under dynamic loading. There are indications that under repeated loads near the ultimate tensile capacity of bars, progressive failure of bond occurs.

5.3 TESTS OF TYPE V.

5.3.1 Static Tests.

Results of static tests performed on specimens #7, 11 and 17 are presented in Appendix 1.

Failure loads of these specimens were 66, 84 and 84 kips respectively. No. 11 and #17 failed at a load 32% higher than #7. All three specimens failed by complete pullout with very heavy splitting at the front near the bars. Bars of specimen #7 were removed and the failure surfaces were inspected. This inspection revealed that on two of the bars there was fine material, ground up by the sliding of the bar, over the entire length of the bar. The other two bars showed fine material only over the length between gage #2 and the end of the bar. Between gage #1 and gage #2 the impressions from the deformations in the surrounding concrete were clearly visible. This indicates that a crack had reduced the effective bond length of two bars from $5\frac{1}{4}$" to $2\frac{1}{2}$". This is probably the main reason why #7 failed at a much lower load than #11 and #17. Failure surfaces of #11 and #17 were not inspected. Generally, failure surface inspection was made only occasionally because of the difficulties in removing bars.

Gage #2 which was located at the midpoint of bond length, showed an average of 10 kips at failure, which is 1/2 of the yield load of 20 kips of each bar.

Movement of specimen #7 was of the order of 0.1", that of #11 and #17 of the order of 0.2".

Concrete strengths of these three specimens were 4200, 4240 and 4490 psi respectively. No correlation of concrete strength and failure load is possible because of the large influence of cracking and splitting on failure load.

5.3.2 Dynamic Tests. Results of dynamic tests performed on specimens #8, 9, 10, 12, 13 and 16 are presented in Appendix 2 and Appendix 3.

Failure loads for these specimens were 73, 98, 71, 71 and 75 kips. No record of the failure load was obtained for specimen #10 because of difficulties with recording equipment. All specimens failed by pullout with heavy cracking and splitting. Failure load of #9 is 34% higher than failure loads of other specimens in this group. This difference is probably due to cracking, or rather the absence of cracking in #9 and presence of it in all other specimens of this group.

There is a considerable scatter in the loads measured by gage #2 at failure. However, they tend to be higher than the 10 kips measured in static tests.

Movement just before failure of all specimens was of the order of 0.2".

Concrete strengths of these specimens ranged from 2960 to 5040 psi. There is no apparent connection between failure load and concrete strength as exemplified by specimen #9 which had a concrete strength of 3520 psi and failed at 98 kips and specimen #16 which had a concrete strength of 5040 psi, but failed at 75 kips.

5.3.3 Discussion. A summary of Type V tests is presented in Table 5.2. Since all specimens of Type V failed by pullout, the average bond stress at failure bears some relation to average ultimate bond strength. Ignoring cracking and assuming that at failure the total original bond length was effective in resisting pullout, the average bond stress at failure, and therefore, average ultimate bond strength for all specimens

TABLE 5.2 SUMMARY OF TYPE V TESTS

Type of Test	Specimen	f'_c, psi	Steel Strength, Kips		Number of Pulses Applied	Failure Load, Kips	Rise Time of Failure Load, Milliseconds	Average Bond Stress, u, at Failure, psi	$^u/f'_c$
			Yield	Ultimate Static					
Static	7	4200	80	140	-	66	-	1320	0.31
	11	4240	80	140	-	84	-	1820	0.43
	17	4490	80	140	-	84	-	1750	0.39
Dynamic	8	2960	92	140	4	73	13	1500	0.51
	9	3520	93	140	4	98	16	2030	0.58
	12	3990	93	140	2	71	12	1510	0.38
	13	3780	92	140	2	71	15	1470	0.39
	16	5040	92	140	3	75	15	1590	0.32

tested both statically and dynamically was computed to be 1620 psi. Considering the reduction in effective bond length caused by cracking, and recognizing the fact that in some bars this reduction was 50%, a speculative estimate of average ultimate bond strength would be 3200 psi. This is supported by the fact that in dynamic tests loads up to 20 kips were recorded by gage #2, located 2½" from the unloaded end of the bar. This means that 20 kips was resisted by a bond length of 2½" giving an average bond stress of 3400 psi.

The above estimates of ultimate bond strength depend on the definition of failure of bond. If cracking and splitting are considered as an essential part of the failure process, then the value of 1620 psi is a good estimate of average ultimate bond strength both under static and dynamic loading. If, however, cracking and splitting are considered as side effects of bond failure and measures are taken to prevent them, then the 3400 psi estimate for dynamic average ultimate bond strength would be more correct. In this and following considerations splitting and cracking will not be considered as essential parts of bond failure, but their effects on the resistance to pullout of bars are recognized. Therefore, specimens of Type V can be considered as failed prematurely due to splitting and an average ultimate bond strength of 3400 psi or more could be expected if splitting was prevented.

Comparing the average ultimate load of 3 static tests to the average ultimate load of 6 dynamic tests it is found that the two values are the same. This is probably due to splitting which involves tension strength of concrete which is believed to be insensitive to rate of strain.

Because of extensive cracking at failure, which has a considerable influence on the size of the failure load and which is not considered here as an essential part of bond failure, these tests do not give any conclusive information regarding either static or dynamic average ultimate strength of bond, even though all specimens failed by pullout.

In specimens #11 and #13 the location of gage #2 was varied to obtain a bond stress distribution along the bar. Curves of percent of total load in bar vs. bond length of bar and bond stress vs. bond length for static test on specimen #11 are presented in Figure 5.2, and Figure 5.3, respectively. Curves of Figure 5.2 were obtained directly from test

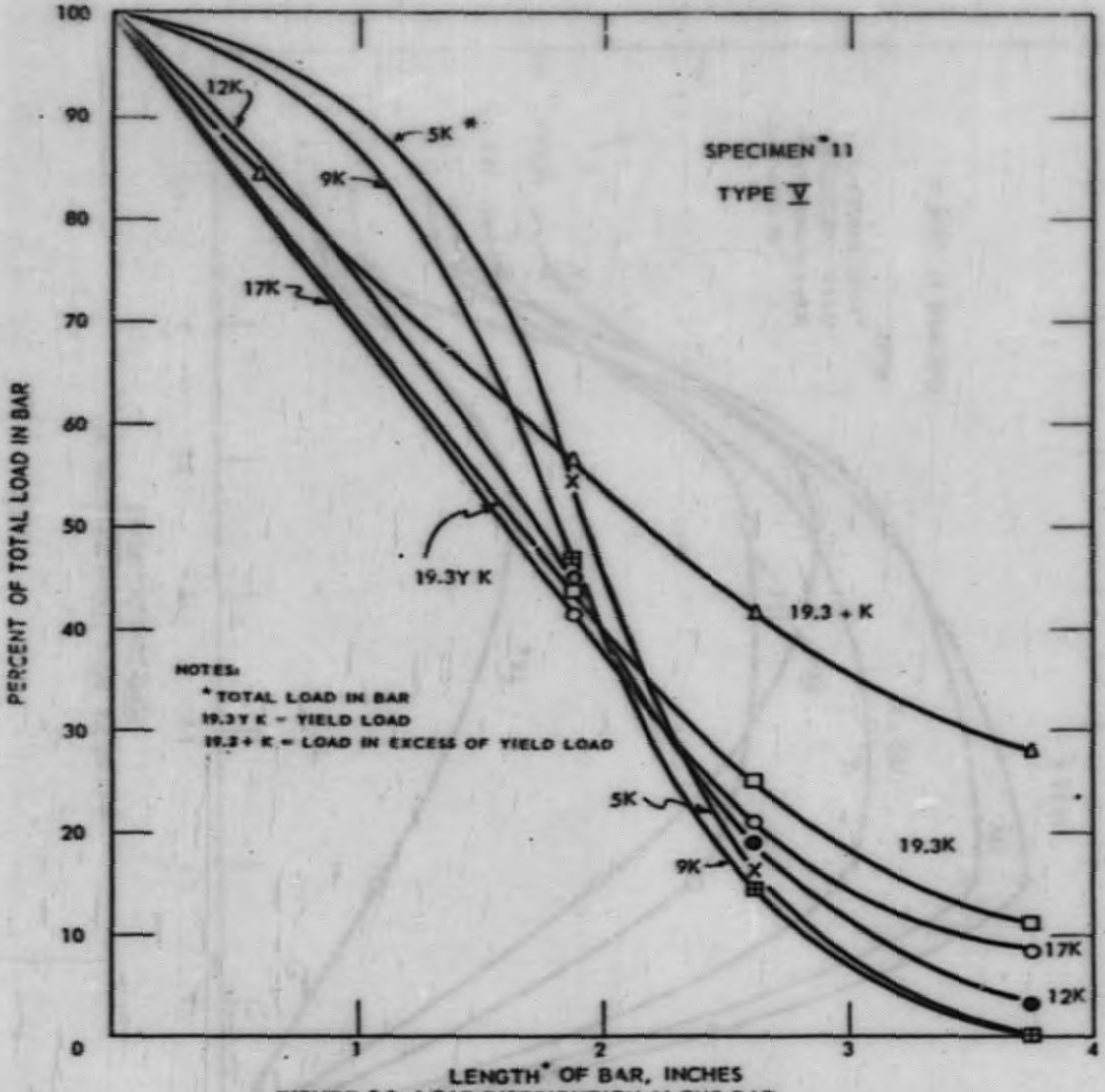

FIGURE 5.2 LOAD DISTRIBUTION ALONG BAR

*EXCLUDES LENGTH OF BAR OCCUPIED BY GAGES

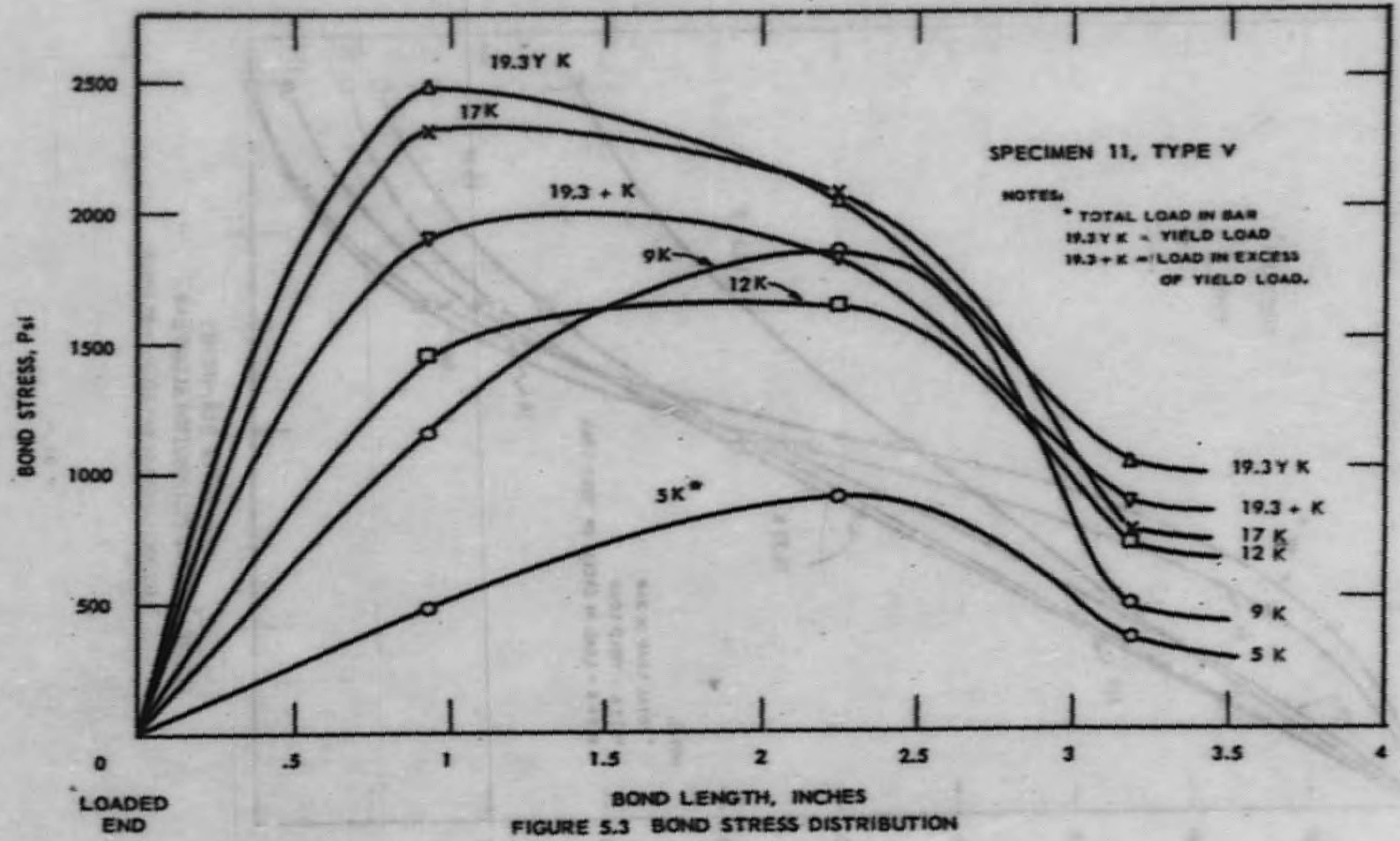

FIGURE 5.3 BOND STRESS DISTRIBUTION

results of specimen #11 presented in Appendix 1. Bond stresses in Figure 5.3 were obtained by taking the difference of loads measured by adjacent gages, which were used in Figure 5.2, and dividing this difference by the bond area between adjacent gages. Curves in both figures are rough approximations since the load on which percentages of Figure 5.2 were based, varied as much as 20% from bar to bar. The curves of Figure 5.3 even though approximate, point out the wave-like distribution of bond stress along the bar observed by earlier investigators. Curves for specimen #13 which was tested dynamically could not be obtained because of scarcity of data.

5.4 TESTS OF TYPE VII

Only two specimens of this type were tested. Specimen #14 was tested statically and specimen #15 dynamically. Test results of these two specimens are presented in Appendix 1 and Appendix 2 respectively. The state of both specimens at failure is summarized in Table 5.3.

Specimen #14 was considered as failed when one of the bars fractured near the location where bond bars were attached to the bearing plate by welds. The failure load was 113 kips which is close to the ultimate tensile capacity of 122 kips of 4 bond bars. The deflection of the specimen just before failure was of the order of 1.5". Specimen #15 failed at a load of 136 kips. Specimen was considered as failed when it had reached the end of its allowed length of travel of 1.5".

There was no splitting or cracking anywhere on the specimen, because the hooked part of each bar, which was the only part of the bar that was allowed to bond to concrete, was located in the heavily reinforced part of the specimen.

One of the gages located 4½" from the beginning of effective bond length, measured around the bend of the hook, indicated a load of only 6 kips at failure. Other gages at the same location of both #14 and #15 showed even smaller loads. This indicates that the transfer of load from steel to concrete takes place more intensively near the beginning of bond length on hooks than on straight bars, which is to be expected because of the additional bearing of hook as a whole against concrete.

It is apparent from these two tests that steel strength is the limiting factor of load capacity of hooks loaded either statically or

TABLE 5.3 SUMMARY OF TYPE VII TESTS

Type of Test	Specimen	f'_c, psi	Steel Strength, Kips		Number of Pulses Applied	Failure Load, Kips	Rise Time of Failure Load, Milliseconds
			Yield	Ultimate Static			
Static	14	5290	70	122	-	113	-
Dynamic	15	4860	81	122	5	136	19

dynamically. This must be qualified by requiring that cracking and splitting be prevented. If the hook had been placed immediately inside the specimen, it would have split out as exemplified by the heavy splitting of Types V and VIII. The increase in load capacity of #15 over #14 is again as in Type VIII solely due to the increase of ultimate tensile strength of steel under rapid loading conditions.

Any discussion of bond stress is irrelevant since hooks transfer load in a somewhat different manner than straight bars.

5.5 TESTS OF TYPE VI

5.5.1 Static Tests. Test results of static tests performed on specimen #19 and #22 are presented in Appendix 1.

Specimen #19 was considered as failed when one of the bars fractured at a total load of 116 kips on the specimen, which is very near to the total ultimate tension load capacity of 8 bars of 123 kips. Specimen #22 failed by pullout at a total load on the specimen of 114 kips which is also very near to the total ultimate tension load capacity of the steel of 117 kips. Deflection of specimen #22 was of the order 1.2" or 50% greater than that of specimen #19.

The reason for the two different modes of failure is mainly the difference in effective bond lengths of the two specimens. Each bar of #19 had an effective bond length of 4" as compared to only 3" on each bar of #22.

There was no splitting or cracking anywhere on either specimen. Concrete strength of these two specimens were 4400 and 5400 psi respectively.

5.5.2 Dynamic Tests. Test results of dynamic tests performed on specimens #18, 20, 21, 23 and 24 are presented in Appendix 2 and Appendix 3. These specimens can be arranged in three groups according to the bond length on each bond bar.

Specimens #18 and #20 with 4" bond length on each bar comprise one group. In both specimens steel failure was observed, though #18 failed at 137 kips, but #20 only at 119 kips total load on the specimen. This difference is probably due to an eccentricity of the applied load.

Specimen #21 was the only one with 3" bond length on each bar, which was tested dynamically. No record of the failure load was obtained due to difficulties with the recording equipment. The specimen failed by pullout.

Specimens #23 and #24 had 2" bond lengths on each bar. Both specimens failed by complete pullout. Specimen #23 failed at 113 kips but #24 at 97 kips. It is to be noted that both steel and concrete were stronger in #23 than in #24, and that steel yielded in both even though each bar had a bond length of only 2".

5.5.3 Discussion. The state of all specimens of this type at failure is summarized in Table 5.4.

The average static bond stresses at failure of specimens #19 and #22 were computed to be at least 2310 and 3030 psi respectively. Since steel failure was observed in #19, and the load on #22 was quite near the ultimate tension load capacity of steel, implying large strains, it is believed that the original bond lengths of 4" and 3" respectively were reduced at failure. This indicates that local ultimate bond strength is quite near to the compressive strength of concrete.

The dynamic test on specimen #18 shows an increase in load capacity over specimen #19, its static counterpart. This increase is again about 11% and is due to the increase in ultimate tension strength of steel under rapid loading conditions. Specimen #20 was considered as failed at 119 kips although it is believed that it could have resisted another pulse of about 130 kips which would support the discussion of #18.

The average bond stress at failure of specimens #23 and #24 was computed to be 4500 and 3860 psi, which is 98% and 97% of concrete strengths of 4570 and 4000 psi respectively. Since both specimens failed by pullout the above bond stresses are representative of dynamic ultimate average bond strength.

5.6 SUPPLEMENTARY TESTS

Because a comparison of static and dynamic bond strengths could not be obtained from tests on the 24 specimens of this research program, additional static tests were performed. This supplementary program consisted of two parts:

1) Static tests on three specimens (#25, 26, 27) with one #4 deformed bar embedded 2" and splitting prevented, to determine static ultimate average bond strength and to

TABLE 5.4 SUMMARY OF TYPE VI TESTS

Type of Test	Specimen	Total Bond Length, Inches	f'_c, psi	Steel Strength, Kips		Number of Pulses Applied	Failure Load, Kips	Rise time of Failure Load, Milliseconds	Average Bond Stress u, at Failure, psi	$^u/f'_c$
				Yield	Ultimate Static					
Static	19	32	4400	72	123	-	116	-	2310	0.56
Dynamic	18	32	4310	82	123	6	137	20	2730	0.63
Dynamic	20	32	4460	82	123	4	119	21	2370	0.53
Static	22	24	5400	74	117	-	114	-	3020	0.56
Dynamic	23	16	4570	87	124	5	113	22	4500	0.98
Dynamic	24	16	4000	74	114	3	97	22	3860	0.97

facilitate a comparison between static and dynamic ultimate average bond strengths.

2) Static tests on three specimens (#28,29,30) with one #4 plain bar embedded 2" with splitting prevented, to determine the bond strength or the frictional and adhesive forces and displacements of plain bars so that a better understanding of the mechanism of load transfer between deformed bars and concrete could be gained.

The appearance of a test specimen of this supplementary program is shown in Figure 5.4.

Concrete mix for 6 specimens and 3 cylinders was the same and prepared under the same conditions as in the main program of this research. Forms for specimens were those used to cast cylinders. Spiral reinforcement extending the whole length of specimen was prepared from 1/8" diameter steel wire. Bond bars were oriented vertically at casting and the mix was vibrated thoroughly. Specimens were laboratory cured for 7 days at which time the strength of concrete was 4000 psi.

Steel strengths of deformed bars were 44.9 ksi yield and 73.8 ksi ultimate. Those of plain bars were 42.5 ksi yield and 64.5 ksi ultimate.

A specimen was supported on the top cross-bar of a Baldwin-Tate-Emery Testing Machine (60-TE-1371) and load was applied by the lower cross-bar of the machine. Load was increased continuously at a rate of 1000# per minute on specimens with deformed bars and at a rate of 250# per minute on specimens with plain bars. Slip of the unloaded end of bar was measured with an Ames dial to 0.001".

Specimens #25, #26 and #27 with deformed bars failed at 9.00, 9.57 and 9.50 kips respectively. At these loads bars slipped in jumps with load decreasing at each slip. Specimens did not fail suddenly by pullout because the load was not allowed to follow the deformation, as the testing machine is a constant strain not constant load machine. At a total slip of 0.5" specimen #25 still carried 2 kips. Load deflection curves of specimens #25, #26, #27 are presented in Figure 5.5. No deflections were recorded up to 3 kips for specimens #25 and #27 and large

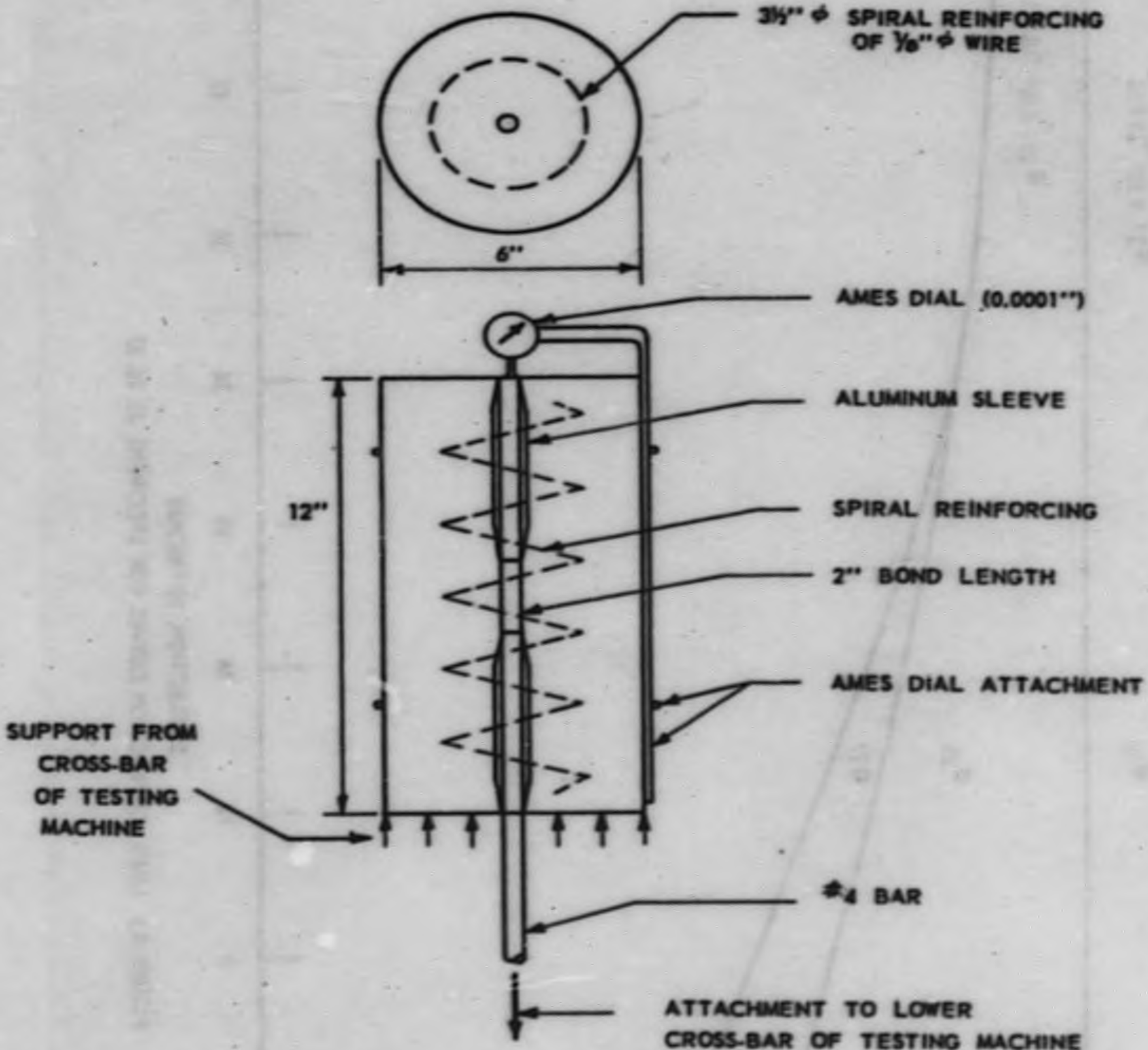

FIGURE 5.4 TEST SPECIMEN OF SUPPLEMENTARY TEST PROGRAM

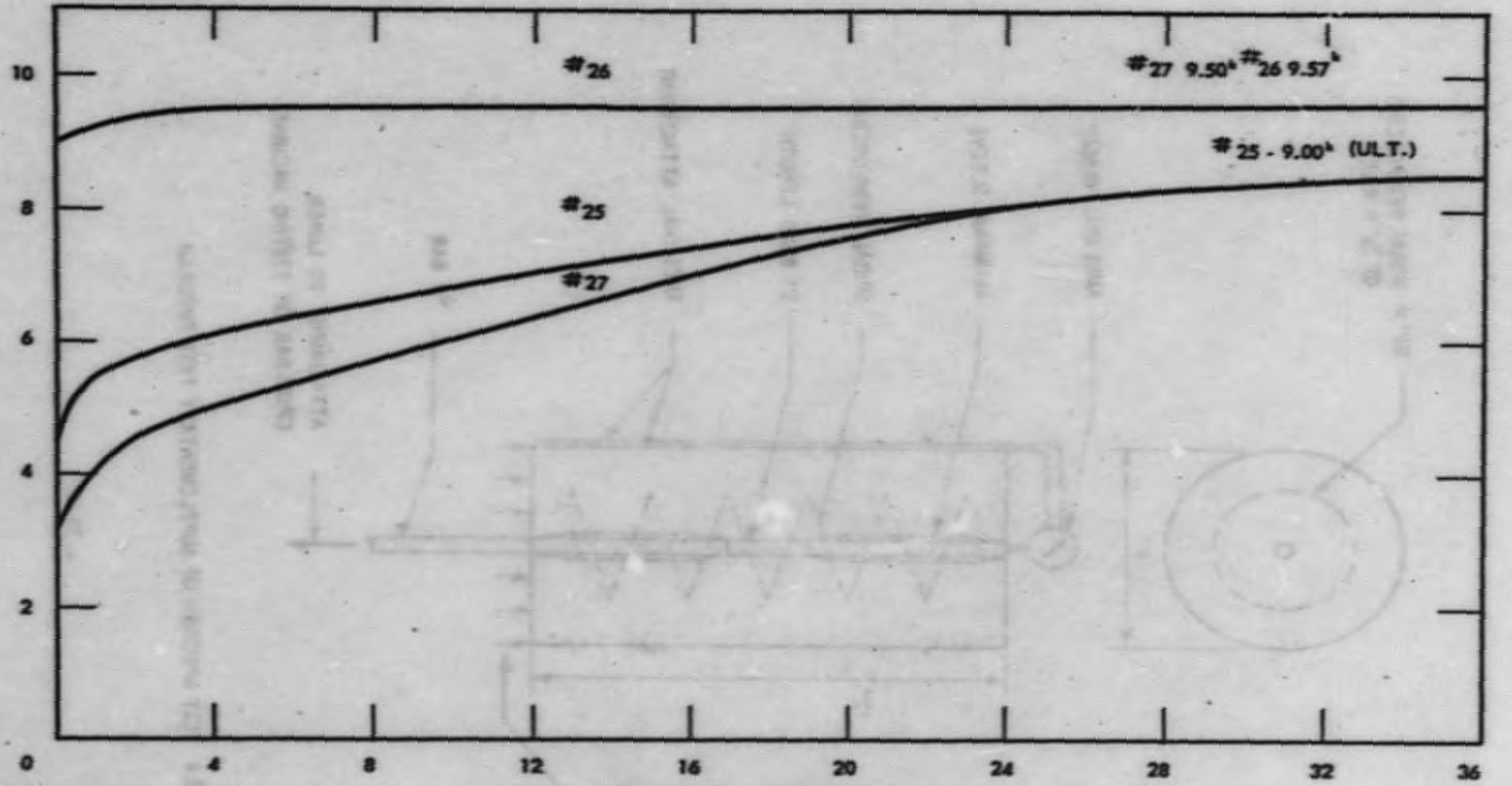

FIGURE 5.5 LOAD - DEFLECTION CURVES FOR SPECIMENS 25, 26, 27

deflections started at 9 kips. The failure of specimen #28 was much more brittle with large deflections starting almost suddenly at 9.5 kips.

Specimens #28, #29 and #30 with plain bars failed at loads 1.83, 2.22 and 1.64 kips respectively with almost no deflection at all before failure. After failure specimens continued to carry decreasing load at increasing deflections.

From these tests the static ultimate average bond strength of deformed bars was established at 2980 psi or 0.75 f_c'. A bonding stress of 600 psi was obtained for plain bars.

6. GENERAL DISCUSSION

All tests can be grouped into six categories according to the length of embeddment of each bar of a specimen. For each of these groups, except hooks, the average bond stress at failure, u, and the ratio of average bond stress to cylinder compressive strength, $^{u}/f_c'$, is presented in Table 6.1. This table shows that there are three modes of failure: failure by fracture of steel, failure by splitout, and failure by pullout without splitting.

The failure of a bond bar by fracture of steel requires a certain bond stress which is a function of steel strength and length of embedment, but not a function of concrete compressive strength. Therefore, for this mode of failure the ratio $^{u}/f_c'$ is meaningless, and only static and dynamic bond stresses should be compared. Any increase of dynamic bond stress over static bond stress at failure is solely due to the strain rate sensitiveness of steel strength and was observed to be 10 - 12%.

In splitout tests the load capacity of a bond bar depends on concrete tension strength and on the shape of the failure surface. Since both of these factors are hard to evaluate quantitatively, it is more reasonable to express bond stress at splitout in psi rather than involve another parameter, namely f_c'. Because it is believed that concrete tension strength is not sensitive to strain rate, it is not surprising that the load capacity of bond bars did not increase under dynamic loading.

Dynamically tested pullout specimen #24 and statically tested pullout specimens #25, #26, and #27 had the same cylinder compressive strength of 4000 psi, which made the comparison of static and dynamic ultimate average bond strengths possible without involving cylinder compressive strength. For the dynamically tested pullout specimen #23, cylinder compressive strength was 4570 psi or 14% higher than that of specimen #24. The dynamic ultimate average bond strength increased 17% but the ratio $^{u}/f_c'$ for both #23 and #24 remained essentially the same. This has led the author to believe that comparisons of static and dynamic ultimate average bond strengths of pullout tests should be based on the ratio $^{u}/f_c'$ rather than on bond stress. This is by no means a conclusive observation because of the limited data on which it is based.

TABLE 6.1 BOND STRESS AND RATIO OF BOND STRESS TO COMPRESSION STRENGTH AT FAILURE

Type	Type of Failure	Static		Dynamic		Percent Increase	
		u, psi	u/f'_c	u, psi	u/f'_c	u	u/f'_c
#6 Bars Embedded According to ACI Code (11")	Steel Fracture	1370	0.35	1530	0.36	12%	3%
#6 Bars Embedded 5"	Split-Out	1620	0.38	1620	0.44	0	16%
#4 Bars Embedded 4"	Steel Fracture	2310	0.52	2550	0.58	10%	12%
#4 Bars Embedded 3"	Pull-out Without Splitting	3020	0.56	-	-	-	-
#4 Bars Embedded 2"	Pull-out Without Splitting	2980	0.75	4180	0.98	40%	30%
#6 Standard Hooks	Steel Fracture	30.5 kips per hook		34.0 kips per hook		11%	

TABLE 6.2 BOND STRESS AT FAILURE

Type	Type of Failure	Static	Dynamic	Percent Increase
#6 Bars Embedded According to ACI Code (11")	Steel Fracture	1370 psi	1530 psi	12%
#6 Bars Embedded 5"	Split-Out	1620 psi	1620 psi	0
#4 Bars Embedded 4"	Steel Fracture	2310 psi	2550 psi	10%
#4 Bars Embedded 3"	Pull-Out without Splitting	0.56 f'_c	-	-
#4 Bars Embedded 2"	Pull-Out without Splitting	0.75 f'_c	0.98 f'_c	30%
#6 Standard Hooks	Steel Fracture	30.5 kips Per Hook	34.0 kips Per Hook	11%

The difference in static ultimate average bond strengths of 3" pullout bars and 2" pullout bars is due to bond stress distribution along bar. Previous investigators have observed that bond stresses are essentially zero at 24 diameters from the loaded end. Since 3" and 2" represent 6 and 4 diameters respectively it follows, and tests indicate this, that at the end of the bar there are substantial bond stresses. However, in the 2" bar these stresses are higher than in the 3"bar, resulting in average bond strengths as presented in Table 6.1. For the above reasons the ultimate average bond strengths given for the 2" bars should be very near to the ultimate local bond strengths.

For the reasons discussed above it is believed that Table 6.2 is more representative of the behavior of bond under static and dynamic loading than Table 6.1.

Bond stress-slip curves could not be obtained for reasons given in 4.4 Measurement of the Movement of Specimen, for any specimens, except #25, #26 and #27 which are presented in Figure 5.5. The deflections presented in Figure 5.5 indicate that most of the deflection in specimens #1 - 24 was due to the elongation of steel between loading plate and the front face of specimen.

It is of interest to look into the mechanism of bond of deformed bars which is capable of transferring stresses of the order of f_c' from concrete to steel. At failure a bar of specimen #23 carried at least 14.1 kips, which is the total load applied by the ram divided equally among 8 bars. Because of a slight eccentricity of the applied load which is unavoidable, some bars carried slightly more than 14.1 kips and others less, so that the 14.1 kips is a lower limit on the maximum load carried by a bar at failure. The surface area of a 2" long #4 bar is 3.14 in.^{2} The ratio of bearing area of deformations to shearing area of #4 bars with diamond deformations is 11.6. Assuming the area of deformations is small, the shearing area can be taken as 3.14 in.^{2} and the bearing area as 0.29 in.^{2} Concrete with a strength of 4.57 ksi, with its strength corrected in accordance with the rate of strain, could provide a pullout load of only slightly larger than 1.6 kips, if the pullout capacity of a bar was derived only from the bearing of deformations on concrete. This means that 12.5 kips would have to be transferred by friction and adhesion at 4000 psi.

This is not possible because previous investigators have reported plain bar bond stresses of only 300 psi, and because tests on specimens #28, #29, #30, which were with plain bars, indicated plain bar bond strength of 600 psi. Furthermore, failure of plain bar bond takes place at very small deformations so that the adhesion and friction on a deformed bar could never follow the yield strain of a steel bar. It is clear from this that all load at or near failure is transferred by the deformations in bearing, with bearing stresses of the order of 50 ksi, which implies concrete compression strength of the same order of magnitude. However, since cylinder strength was given as 4.57 ksi there is a discrepancy. This discrepancy can be explained by the high degree of confinement of concrete undergoing compression in the vicinity of bond bar deformations. Tests performed by Bridgman(13) on metals and other materials including quartz and marble under high hydrostatic pressures show that compressive strength of these materials increases with increasing hydrostatic pressures. These tests did not include concrete as one of the materials, but since the tests included a variety of materials, it is reasonable to extrapolate an increase in compression strength of concrete under lateral confinement. Since this confinement is of a high degree, a concrete compression strength of 50 ksi is not perhaps so unreasonable as it appears. The fact remains that the deformations are capable of transferring 14.1 kips of load to surrounding concrete.

After the load has been transferred to the concrete occupying the spaces between deformations, pure shear strength of concrete on a cylindrical surface parallel to the axis of the bond bar just outside the deformations becomes critical resulting in "bond" failure. Bond bars removed from specimen #22 which failed by pullout had concrete sticking to the bar between deformations, which supports the shear type of failure involved in bond failure. Assuming that the shear stress distribution is uniform along the bar, the dynamic average ultimate shear strength is established at 4500 psi or 0.98 f_c' . This strength is much in excess of the 0.50 f_c' reported by Nawy and Shah(12). However, these authors pointed out that shear strengths under dynamic loading could be higher than those reported depending on the type of aggregate used and the amount of transverse compression applied. It is believed that the transverse compression on the failure plane around bond bars is much higher than that in the shear key specimens, due to shrinkage and confinement. Considering the above, the observed shear strengths in these tests are not unreasonable.

Shear key failure differs from bond failure in that in shear keys the failure plane may have to pass through pieces of gravel, while in bond failure the failure plane passes entirely through the fine material of the concrete mix consisting of fine sand and gel drawn to the bond bar by vibration. It is beyond the scope of this report to estimate the influence of aggregate on the shear strength in bond failure.

It is clear from the above discussion that bond failure involves shear strength which for static loading is of the order of 0.75 f_c' and for dynamic loading of the order of f_c'. Concrete compression strength and the degree of confinement under which concrete is compressed are important in bond, but shear strength is the critical factor. Bond strength is also influenced by the type of concrete mix.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

From the discussions of the two previous sections it is concluded that:

1) Bond is a complex phenomenon involving concrete compression strength, pure shear strength, and the degree of confinement under which these strengths are developed. Pure shear strength which is of the order of 0.75 f_c' under static loading and of the order of f_c' under dynamic loading, is the critical factor in bond failure.
2) Splitting and cracking are very important factors influencing the pullout resistance of bonded bars. If these factors are effective no increase in load capacity of bond bars under dynamic loading over static loading should be expected.
3) The ultimate load capacity of hooks prevented from splitting out increases with the rate of strain. This increase is solely due to the increase of steel strength under dynamic loading.
4) Bond strengths under both static and dynamic loading is high and in all but impractically short bond lengths steel failure is to be expected. For all practical lengths of embeddment of bond bars the increase in load capacity of a bond bar under dynamic loading over static loading is due only to the increase of steel strength under dynamic loading.
5) Bond requirements of ACI Building Code (ACI 318-56) are adequate for structural elements experiencing blast loads, but progressive bond failure and large slip should be expected from large repeated dynamic loads.

7.2 RECOMMENDATIONS

In order to gain a better understanding of the behavior of bond under static and dynamic loading, and to establish the observations of these tests conclusively, it is recommended that the present research program be extended to include the following investigations:

1) Static and dynamic tests on bond bars preferably 2" long with different diameters to determine the influence of bar diameter

on pullout resistance of bond bars.

2) Static and dynamic tests on bond bars with same length and diameter embedded in concretes of different strength, to determine the influence of f'_c on bond strength.
3) Tests involving progressive failure of bond.
4) Tests on bond bars embedded according to ACI Building Code with means of investigating the bond stress-slip characteristics of bond bars under dynamic loading.

In carrying out the above investigations it is recommended that slip of loaded and unloaded end of bar be measured to 0.0001" so that accurate bond stress-slip curves can be determined in all tests. Preferably, specimens should consist of one bond bar to make the deflection sensing easier and more accurate. Welding or any other process which alters the state of steel from its normal state, should be avoided.

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APPENDIX 1.

TABLES OF STATIC TEST RESULTS

BAR LOADS

NOTE: ALL LOADS IN KIPS

SPECIMEN #1

Load Kips	BAR 1			BAR 2			BAR 3			BAR 4		
	Gage 1	Gage 2	Gage 3	Gage 1	Gage 2	Gage 3	Gage 1	Gage 2	Gage 3	Gage 1	Gage 2	Gage 3
0	0	0	0	0	0	0	0	0	0	0	0	0
13	3.1	1.1	0.1	0.3	0.2	0	3.9	1.6	0.9	2.4	1.4	0.8
30	7.6	2.6	0.5	1.7	0.8	0.4	8.6	3.4	1.5	6.5	3.0	1.5
57	13.1	6.2	2.0	5.1	3.4	2.0	18.3	9.6	4.3	13.5	7.8	4.6
78	19.5	11.0	4.2	9.7	7.1	5.2	22.0	18.3	9.0	22.0	15.0	9.1
96	22.0	15.5	6.5	20.8	16.2	12.1	22.0	22.0	14.8	22.0	22.0	15.8
103	22.0	16.7	7.4	22.0	19.6	14.4	22.5	22.0	16.5	24.5	22.0	18.5
111	22.0	18.6	8.4	22.0	22.0	17.1	-	22.0	18.2	-	22.0	20.8
119	22.0	21.3	9.9	22.0	22.0	19.0	35.5	22.0	19.3	-	23.5	22.0

YIELD LOAD 22.0 KIPS

SPECIMEN #6

Load Kips	BAR 1		BAR 2		BAR 3		BAR 4	
	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2
0	0	0	0	0	0	0	0	0
18	11.5	0.2	1.9	0	4.4	0.2	10.0	0.2
36	17.9	0.3	7.4	0.2	11.3	0	15.3	0.5
54	22.0	0.6	16.8	0.5	20.0	0.2	20.6	1.7
67	25.3	0.6	22.0	1.9	22.0	0	22.0	2.5
76	-	0.6	22.0	4.1	22.0	5.3	22.0	3.0
85	-	0.6	22.0	6.5	22.0	6.4	22.0	3.5
89	-	0.6	22.0	7.9	25.0	6.4	22.0	5.3
98	-	0.8	-	9.5		10.6	27.2	6.0
103	-	1.1	-	9.7		-1.3		7.0
106	-	1.5	-	10.6		-3.0		7.8
110	-	2.0	-	11.2		-2.2		8.3
116	-	2.2	-	11.5		-1.8		8.8
119	-	2.3	-	12.0		-1.6		9.3
121	-	2.5	-	12.3		-1.4		9.6
125	-	3.7	-	14.4		0		10.6
129	-	3.8	-	15.5		0.2		10.9
134	-	4.6	-	17.4		1.0		11.6
138	35.5	9.5	-	17.2		-1.6		6.6

YIELD LOAD 20.0 KIPS

SPECIMEN #7

Load Kips	BAR 1		BAR 2		BAR 3		BAR 4	
	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2
0	0	0	0	0	0	0	0	0
13	9.0	2.5	-3.1	-0.4	2.4	0.4	7.7	1.9
23	12.9	4.4	-3.1	-0.2	5.9	0.9	11.6	2.6
31	15.8	7.6	-2.1	-0.2	13.9	1.5	15.5	4.4
36	16.8	8.6	+1.6	0	12.2	3.1	17.0	5.0
39	18.8	8.8	2.9	-0.9	14.6	4.2	17.8	5.6
41	20.0	9.2	7.2	+0.9	16.5	5.5	18.6	6.3
44	20.0	9.2	10.5	4.4	18.9	6.6	19.7	5.5
48	20.0	9.2	13.2	5.9	20.0	7.7	20.0	6.9
52	20.0	9.6	17.3	7.9	20.0	9.4	20.0	8.4
55	20.0	9.9	19.6	9.0	20.0	10.7	20.0	8.6
59	20.0	9.9	20.0	9.4	20.0	12.3	20.0	8.8
63	20.0	10.1	20.0	11.1	20.0	19.3	16.7	8.6
66	-	-	-	-	-	-	-	-

YIELD LOAD 20.0 KIPS

SPECIMEN #11

Load Kips	BAR 1		BAR 2		BAR 3		BAR 4	
	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2
0	0	-	0	0	0	0	0	0
14	2.9	-	0.9	0.4	5.6	0.9	0.5	-0.3
22	5.3	-	1.7	0.8	8.5	1.2	1.9	-0.1
29	9.5	-	2.9	1.4	12.2	2.3	4.4	-0.1
37	19.1	-	4.6	2.5	16.7	3.6	6.7	0
44	20.0	-	5.9	3.0	20.0	4.8	7.6	0
52	20.0	-	8.0	4.0	20.0	6.0	9.2	0
55	20.0	-	9.6	4.5	20.0	6.8	10.0	0
59	-	-	11.6	5.2	20.0	7.7	11.1	0.1
63	-	-	13.5	5.9	-	8.0	12.4	0.4
66	-	-	17.4	7.2	-	8.5	15.6	0.9
70	-	-	20.0	8.4	-	8.6	17.9	1.5
74	-	-	20.0	9.7	-	8.7	20.0	2.1
77	-	-	20.0	10.1	-	8.7	20.0	2.0
81	-	-	20.0	10.9	-	9.0	20.0	2.8
84	-	-	-	11.6	-	9.2	20.0	3.4

YIELD LOAD 20.0 KIPS

SPECIMEN #14

Load Kips	BAR 1		BAR 2		BAR 3		BAR 4	
	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2
0	0	0	0	0	0	0	0	0
13	5.5	0.1	-1.4	0.4	6.1	-0.2	0.5	0
30	8.8	0.1	+4.2	1.0	12.5	-0.2	3.0	0.1
48	17.4	0.5	10.4	1.4	16.6	-0.2	7.3	1.3
54	17.5	0.8	12.2	1.6	17.4	0	8.4	1.6
60	-	1.7	15.0	1.6	17.4	0	11.1	2.2
66	-	2.7	17.4	1.6	-	0	-	1.7
74	-	2.9	-	1.9	-	1.1	-	1.7
77	-	3.1	-	2.3	-	1.1	-	-
86	-	3.4	-	2.5	-	1.2	-	-
89	-	3.7	-	3.0	-	1.4	-	-
92	-	3.0	-	3.6	-	1.7	-	-
95	-	3.8	-	3.7	-	1.7	-	-
101	-	3.8	-	3.7	-	1.8	-	-
102	-	3.5	-	3.8	-	1.8	-	-
107	-	3.9	-	4.4	-	2.0	-	-
111	-	4.1	-	4.7	-	2.1	-	-
113		4.2	-	6.0	-	2.1	-	-

YIELD LOAD 17.4 KIPS

SPECIMEN #17

Load Kips	BAR 1	BAR 2	BAR 3	BAR 4
0	0	0	0	0
11	4.1	2.8	7.1	-1.4
21	6.4	3.0	9.9	-0.1
27	9.0	3.3	12.0	+1.0
36	13.0	3.6	14.6	2.5
45	19.6	4.4	17.7	4.1
49	20.0	5.4	19.1	4.9
54	20.0	6.8	20.0	5.4
59	20.0	8.7	20.0	6.3
62	-	10.7	20.0	7.9
64	-	12.3	20.0	8.7
71	-	16.2	20.0	10.2
76	-	20.0	20.6	12.6
80	-	20.0	20.8	14.1
82	-	20.0	20.8	16.6
84	-	20.5	21.0	18.0

YIELD LOAD 20.0 KIPS

SPECIMEN #19

Load Kips	BAR 1	BAR 3	BAR 5	BAR 7	BAR 8
0	0	0	0	0	0
12	2.00	0.97	2.37	0.50	0
21	3.10	1.55	3.96	1.05	0.19
27	3.95	2.14	5.36	1.79	0.58
40	5.66	3.10	7.43	2.71	1.34
45	6.52	6.35	8.52	3.21	1.82
54	7.57	7.71	8.95	4.13	2.40
62	8.10	8.95	8.95	5.87	2.92
67	8.38	8.95		6.70	3.40
72	8.62	-	-	8.26	4.36
74	8.95	-	-	8.95	5.41
79	-	-	-	8.95	7.29
81	-	-	-	-	8.95
85	-	-	-	-	8.95
89		-	-		-
94	-	-	-	-	-
98	-	-	-	-	-
103	-	-	-	-	-
107	-	-	-	-	-
112	-	-	-	-	-
116	-	-	-	-	-

YIELD LOAD 8.95 KIPS

NO RECORD FOR BARS 2,4,6

SPECIMEN #22

Load Kips	BAR 4	BAR 5	BAR 6	BAR 7	BAR 8
0	0	0	0	0	0
15	0.24	1.67	1.02	0.91	0.93
22	0.39	2.59	2.04	1.39	1.30
30	0.73	3.82	3.31	2.11	1.93
37	1.17	5.12	3.83	3.07	2.67
44	1.46	6.29	3.31	3.98	3.36
52	1.90	7.46	3.93	4.89	3.91
59	2.58	8.88	3.93	5.75	4.41
63	3.01	9.13	6.81	6.42	4.47
66	3.79	9.28	7.04	7.33	4.91
70	5.10	9.28	8.11	8.15	5.53
74	6.08	9.28	7.40	9.28	6.52
77	7.15	9.28	6.60	9.28	7.58
81	9.00	9.28	6.60	9.28	9.28
84	9.28	9.28	9.28	9.28	9.28
88	9.29	-	9.28	-	9.28
92		-	9.28	-	9.28
96	-	-	9.28	-	-
99	-	-	9.28	-	-
103	-	-	-	-	-
107	-	-	-	-	-
110	-	-	-	-	-
114	-	-	-	-	-

YIELD LOAD 9.28 KIPS

NO RECORD FOR BARS 1,2,3

DEFLECTIONS

NOTE: ALL DEFLECTIONS IN 10^{-3} INCHES

SPECIMEN #1

Load Kips	Pt.1	Pt.2	Pt.3	Pt.4	Pt.1'	Pt.2'	Pt.3'	Pt.4'
0	0	0	0	0	0	0	0	0
13	13	8	50	70	23	18	46	4
30	32	20	61	75	44	28	69	12
57	38	28	89	92	54	35	89	26
78	51	34	106	130	67	46	126	53
96	129	45	125	268	72	44	152	125
103	185	55	166	356	88	44	307	154
111	76	-	263	456	96	43	369	-
119	116	-	325	555	120	92	436	-

SPECIMEN #6

0	0	0	0	0	0	0	0	0
18	0	0	59	33	8	0	52	43
36	10	0	70	37	16	0	64	52
54	30	1	86	48	37	7	78	64
67	42	8	98	56	62	14	91	72
76	62	16	111	62	81	21	99	78
85	100	20	95	63	109	29	115	83
89	130	39	134	88	146	43	148	104
98	177	69	175	128	186	69	181	150
103	232	118	225	170	237	93	225	197
106	282	-	264	-	282	-	262	-
110	342	163	314	210	328	116	306	236
116	362	208	336	257	353	137	324	270
119	395	230	366	274	382	145	351	282
121	440	254	407	297	424	158	384	298
125	517	396	470	337	498	176	444	307
129	585	346	525	381	558	200	495	-
134	657	392	586	430	630	217	545	-
138	793	434	573	473	1000	244	566	-

SPECIMEN #7

0	0	0	0	0	0	0	0	0
13	2	12	25	78	9	3	37	-14
23	15	0	27	86	24	12	42	-11
31	32	35	30	107	40	26	47	-6
36	42	50	32	130	48	30	56	+1
39	49	49	34	134	51	30	58	1
41	52	57	39	145	57	34	61	3
44	62	77	42	149	66	39	63	5
48	72	87	44	161	70	41	70	9
52	77	95	47	174	75	48	75	12
55	77	104	52	187	82	49	82	15
59	83	128	54	202	86	53	84	23
63	82	141	66	266	86	57	98	46
66	573	-	801	-	909	-	-	-

SPECIMEN #11

Load Kips	Pt.1	Pt.2	Pt.3	Pt.4	Pt.1'	Pt.2'	Pt.3'	Pt.4'
0	0	0	0	0	0	0	0	0
14	2	2	14	13	5	1	22	16
22	8	2	20	14	11	1	36	18
29	15	0	30	14	25	1	43	20
37	25	5	36	20	36	4	54	25
44	38	5	41	26	52	6	63	26
52	50	5	50	27	67	9	72	28
55	62	12	54	27	78	13	81	30
59	78	15	61	27	94	13	90	29
63	90	16	71	29	116	17	103	27
66	115	17	82	30	136	21	118	28
70	135	22	91	31	160	28	130	29
74	162	28	102	41	180	32	152	33
77	170	31	107	41	190	38	154	37
81	185	42	116	43	211	51	161	39
84	212	66	122	47	237	71	172	44

SPECIMEN #14

0	0	0	0	0	0	0	0	0
13	30	104	25	46	51	51	29	27
30	55	161	50	-	107	75	74	43
48	110	200	109	119	193	102	157	62
54	130	214	116	131	209	111	172	66
60	172	-	141	148	261	129	206	75
66	232	-	168	-	338	183	249	93
74	365	336	252	-	480	281	386	178
77	-	398	346	234	570	283	493	267
86	-	428	431	309	695	-	610	315
89	-	434	545	398	828	-	762	-
92	-	441	593	445	920	-	875	-
95		428	648	445	946	-	913	-
101	-	441	725	465	1006	-	1020	-
102	-	445	823	555	1138	-	1169	-
107	-	-	1068	790	736	-	1510	-
111	-	-	1200	925	468	-	1690	-
113	-	-	1370	1090	159	-	1872	-

SPECIMEN #17

Load Kips	Pt.1	Pt.2	Pt.3	Pt.4	Pt.1'	Pt.2'	Pt.3'	Pt.4'
0	0	0	0	0	0	0	0	0
11	0	0	33	32	0	-4	45	26
21	0	0	48	39	4	-4	62	33
27	4	0	52	44	41	-4	71	36
36	15	0	65	50	18	-4	88	41
45	30	0	76	56	32	-4	107	44
49	35	0	83	58	37	-4	112	45
54	43	0	87	60	50	-1	122	47
59	56	2	91	63	61	+1	131	48
62	61	4	98	64	69	4	137	49
64	73	7	104	66	79	6	143	49
71	81	11	109	69	94	10	157	50
76	101	17	122	72	112	14	174	51
80	115	21	128	75	128	18	193	52
82	126	26	135	79	141	22	197	54
84	144	36	142	81	153	30	214	69

SPECIMEN #19

0	0	0	0	0	0	0	0	0
12	-11	0	25	13	8	-2	36	12
21	+4	0	43	20	20	-2	54	19
27	14	2	59	29	31	-2	69	28
40	32	2	75	40	40	+1	90	38
45	38	4	89	49	50	3	107	45
54	43	6	107	59	57	5	126	58
62	58	7	132	74	79	6	165	70
67	65	9	152	82	88	6	184	76
72	84	12	175	94	101	5	212	87
74	93	15	188	104	112	7	232	95
79	110	28	213	119	137	17	257	107
81	135	56	236	133	161	36	283	120
85	222	117	295	145	240	107	347	188
89	291	210	364	208	306	188	433	227
94	327	248	407	274	349	226	471	258
98	376	298	468	324	400	273	538	-
103	418	346	505	360	425	305	579	-
107	476	401	559	404	476	-	643	-
112	534	443	614	452	531	-	707	-
116	648	482	732	531	640	-	836	-

SPECIMEN #22

Load Kips	Pt.1	Pt .2	Pt.3	Pt.4	Pt.1'	Pt.2'	Pt.3'	Pt.4'
0	0	0	0	0	0	0	0	0
15	0	-1	22	5	11	0	21	6
22	0	0	34	9	25	2	34	9
30	14	3	46	14	37	5	49	12
37	35	6	64	19	50	8	71	16
44	56	9	80	26	66	11	94	21
52	72	12	93	31	81	15	105	25
59	92	17	116	35	108	18	130	26
63	110	20	134	36	123	18	145	26
66	132	26	152	39	147	19	171	22
70	152	31	166	42	169	22	138	22
74	161	37	181	49	183	26	205	27
77	179	44	202	57	199	30	227	32
81	204	57	241	73	229	33	268	42
84	264	111	280	113	284	100	332	82
88	488		505	-	490	-	557	-
92	566	-	591	-	567	-	650	269
96	649	417	666	381	635	-	729	-
99	727	460	748	438	710	-	816	
103	818	484	841	501	795	-	921	
107	894	494	919	543	861	-	1008	
110	997	500	1025	-	1016	-	1130	
114	1175	-	1202	-	1250	-	1350	

APPENDIX 2

TABLES OF DYNAMIC TEST RESULTS

BAR LOADS

NOTE: 1) All loads are in kips at the end of rise time

2) The second set of loads for each pulse are the residual deflections from that particular pulse.

SPECIMEN #2

Pulse No.	Load, Kips	Rise Time, Millisec.	BAR 1		BAR 2		BAR 3		BAR 4	
			Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1˙	Gage 2
1	62	27	4.9 * 0	0 0	8.8 0	0.9 0	4.6 0	0 0	–	0
2	72	31	24.7 1.3	0.7 0	24.7	1.6 0	24.7 1.2	1.1 0	–	1.2 0
3	92	28	24.7 17.0	1.3 0	– –	1.9 0	24.7 10.5	2.2 0	–	3.1 0
5	104	27	24.7 –	1.8 0	-24.7 -24.7	2.1 0	24.7 17.6	2.9 0	–	4.4 –
6	121	36	24.7 –	1.4 0	-17.8 -13.2	3.5 0	24.7 24.7	2.9 0	–	5.0 0
7	121	23	–	2.0 –	-12.9 -7.2	3.7 0	24.7 24.7	3.0 0	–	5.6 0
8	132	27	–	3.1 1.1	24.7 9.7	4.7 0	24.7 –	4.3 0	–	6.6 0
9	144	24	–	4.9 0.9	24.7 19.2	7.6 0	24.7 –	6.8 0	–	9.5 0
10	152	25	–	5.4 0.7	24.7 24.7	10.0 0.7	–	7.5 1.6		12.4 1.2
11	155	23	–	6.8 3.1	–	13.7 2.1	–	13.6 2.5	–	12.4 0.8

YIELD LOAD 24.7 KIPS

SPECIMEN #3

Pulse No.	Load, Kips	Rise Time, Millisec.	BAR 1		BAR 2		BAR 3		BAR 4	
			Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2
1	30	24	25.2 -3.0	1.2 0	25.2 8.5	1.4 0	25.2 21.8	1.2 0.5	25.2 25.2	2.2 0.7
4	36	12	16.2 0	0.7 0	22.0 0	1.6 0	25.2 22.9	1.2 0	25.2 0.5	4.6 0.4
5	64	12	14.2 0	0.7 0	22.4 0	1.6 0	25.2 7.1	1.0 0	25.2 -	3.9 0
6	112	9	25.2 -	1.3 0	25.2 -	2.9 0	25.2 -	1.8 0	25.2 -	4.8 0
7	112	17	25.2+ -	1.8 0.8	25.2+ -	4.9 1.3	25.2 25.2	2.8 1.4	25.2 25.2	6.8 1.1
8	160	15	-	5.2 2.2	-	10.7 3.3	-	7.0 3.3	-	13.7 2.8
9	161	15	-	11.0 -	-	17.7 -	-	10.6 4.5	-	22.2 3.9

YIELD LOAD 25.2 KIPS

SPECIMEN #4

1	56	19	25.0 25.0	1.1 0.5	-	1.3 0.9	25.0 25.0	1.0 0.7	18.9 1.6	0.7 0.6
2	156	16	25.0+ -	4.2 5.6	-	5.4 2.5	25.0+ -	7.7 5.8	25.0+ -	11.5 3.5

YIELD LOAD 25.0 KIPS

SPECIMEN #5

Pulse No.	Load, Kips	Rise Time, Millisec.	BAR 1		BAR 2		BAR 3		BAR 4	
			Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2
1	45	12	25.2 1.7	0.4 0	23.4 2.9	1.3 0	25.3 25.3	0 0	25.3 16.4	3.0 1.6
2	52	10	24.8 0	0.4 0	21.5 0	1.4 0	16.1 1.4	0 0	25.3 3.2	1.7 0
3	149	9	25.3+ -	4.5 2.6	25.3+ -	8.1 3.2	25.3+ -	4.1 3.4	25.3+ -	7.8 0
4	156	15	-	4.5 6.9	-	25.3+ -	-	25.3+ -	-	25.3+ -

YIELD LOAD 25.3 KIPS

SPECIMEN #8

1	41	13	-	18.6 3.6	9.8 5.6	4.8 3.3	23.1 11.7	7.5 2.4	13.6 -3.7	4.0 0
2	48	13	-	15.2 0	5.4 0	1.3 1.2	23.1 9.2	8.8 0	16.6 0	4.6 0
3	58	18	-	17.9 -3.6	21.8 1.8	6.6 0.8	23.1 23.1	13.5 0.9	23.1 0	7.2 0
4	73	13	-	-	-	-	-	-	23.1	-

YIELD LOAD 23.1 KIPS

SPECIMEN #9

Pulse No.	Load, Kips	Rise Time, Millisec.	BAR 1		BAR 2		BAR 3		BAR 4	
			Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2
1	45	14	-	9.0 3.8	9.4 0	3.7 0	20.6 2.2	6.8 1.7	23.2 6.5	6.6 0
2	70	14	-	10.7 0	18.8 -1.8	5.9 0	23.3 8.6	9.8 0	23.2 8.3	10.7 0
3	98	18	-	15.4 1.1	23.2	20.8 2.0	23.2+ -	18.5 0.8	23.2+ -	21.6 3.5
4	98	16	-	23.2	-	23.2	-	-	23.2+	23.2

YIELD LOAD 23.2 KIPS

SPECIMEN #10

1	32	13	23.2	8.0	6.4	5.7	23.2	5.1	15.2	6.3
2	.-	-	23.2	17.2	23.2	-	22.0	19.4	23.2	10.6

YIELD LOAD 23. 2 KIPS

SPECIMEN #13

1	20	12	10.0 -1.0	7.7 0	1.6 0.9	1.0 0.4	9.2 1.2	3.0 0.8	3.3 -0.7	0.8 0
2	71	15	20.2 -	-	7.0 -	-	15.6 -	-	-	7.5 -

YIELD LOAD 23.1 KIPS

SPECIMEN #15

Pulse No.	Load, Kips	Rise Time, Millisec.	BAR 1		BAR 2		BAR 3		BAR 4	
			Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2	Gage 1	Gage 2
1	25	22	6.4 0.7	-0.2 0	4.5 0.5	0.6 0.5	-	-	2.5 0.8	0 0
2	72	16	20.3 2.0	0 0	10.2 -	2.4 1.5	-	-	13.2 2.0	0.7 0.6
3	110	20	20.3+ -	0 0	20.3+ -	3.0 0	-	-	20.3+ -	2.0 0
4	119	18	-	0 0	-	3.8 0	-	-	-	1.8 0
5	136	-	-	0.5	-	0				0

YIELD LOAD 20.3 KIPS

SPECIMEN #20

Pulse No.	Load, Kips	Rise Time, Millisec.	BAR 1	BAR 2	BAR 3	BAR 4	BAR 5	BAR 6	BAR 7	BAR 8
1	-	-	5.9 1.0	3.4 0.8	1.4 0	-1.6 -1.0	5.7 0.5	3.4 0	2.0 -0.2	0.8 0
2	55	15	9.0 -1.7	6.2 1.1	3.4 0.7	1.0 0	9.5 1.0	6.1 0	3.9 -0.9	2.1 -0.6
3	103	18	10.3+	10.3+	10.3+	10.3+	10.3+	10.3+	10.3+	10.3+
4	119	21	-	-	-	-	-	-	-	-

YIELD LOAD 10.3 KIPS

SPECIMEN #21

1	40	16	7.6 0.4	5.0 0	4.3 0	-	-	-	3.8 0.1	-
2	68	24	9.8 9.8	8.1 9.8	7.7 2.0	-	-	-	5.9 -0.2	-

YIELD LOAD 9.8 KIPS

SPECIMEN #23

Pulse No.	Load, Kips	Rise Time, Millisec.	BAR 1	BAR 2	BAR 3	BAR 4	BAR 5	BAR 6	BAR 7	BAR 8
1	30	-	6.8 0	-	-	-	5.2 0	3.5 0	2.7 0	1.9 0
2	35	19	8.1	-	-	-0.8 0	5.3 0	3.8 0	3.1 0	1.9 0
3	73	23	10.9 -2.4	10.9 10.9	-	2.0 0	10.9 0	9.8 1.0	7.5 0.5	4.1 -1.4
4	104	22	10.9+	10.9+	-	10.9+	10.9+	10.9+	10.9+	10.9+ 10.9
5	113	22	-	-	-	-	-	-	-	-

YIELD LOAD 10.9 KIPS

SPECIMEN #24

1	-	-	5.8 0	4.0 0	2.1 0.2	0.7 0	6.5 0.4	3.7 0.2	2.3 0	0.5 0
2	30	19	5.9 0	4.0 0	2.1 0.1	0.8 0	3.8 0	3.7 0	2.2 0	0.5 0
3	97	22	9.3+	9.3+	9.3+	9.3+	9.3+	9.3+	9.3+	9.3+

YIELD LOAD 9.3 KIPS

DEFLECTIONS

NOTE: 1) All Deflections are in 10^{-3} inches at the end of rise time.

2) The second set of deflections for each pulse are the residual deflections from that particular pulse.

SPECIMEN #2

Pulse No.	Load, Kips	Rise Time, Millisec.	Pt.1	Pt.2	Pt.3	Pt.4	Pt.1'	Pt..2'	Pt..3'	Pt..4'
1	62	27	0	12	23	37	12	15	21	73
			0	0	0	0	0	0	0	12
2	72	31	6	12	57	34	84	39	67	55
			0	0	11	0	0	0	8	0
3	92	28	8	46	65	57	127	60	77	98
			0	23	0	24	.0	45	0	42
5	104	27	18	56	76	58	231	84	92	87
			17	37	0	11	90	48	0	29
6	121	36	26	81	72	63	245	91	88	92
			14	48	0	23	87	52	0	16
7	121	23	32	81	76	67	234	82	94	104
			18	50	0	32	52	49	0	26
8	132	27	92	210	130	120	537	179	151	170
			88	168	57	66	384	142	65	86
9	144	24	121	271	173	153	872	196	213	189
			92	250	84	90	685	170	132	106
10	152	25	92	235	206	191	974	113	251	159
			86	229	139	129	855	116	153	133

SPECIMEN #3

Pulse No.	Load, Kips	Rise Time, Millisec.	Pt.1	Pt.2	Pt.3	Pt.4	Pt..1'	Pt.2'	Pt.3'	Pt.4'
1	30	24	-42 -26	15 0	48 -13	14 5	84 58	18 -15	72 -24	59 59
4	36	12	- -	21 0	-	8 0	49 0	12 0	58 0	52 0
5	64	12	28 0	42 23	42 0	26 17	49 0	15 0	54 0	52 0
6	112	9	60 0	-	63 0	-	131 0	25 3	90 0	80 8
7	112	17	110 68	-	158 86	-	241 136	37 7	211 111	146 80
8	160	15	375 357	212 187	400 304	20 -	1247 1120	315 281	538 405	262 222
9	161	15	168 240	121 135	232 84	-	582 -	151 282	323 135	51 -
SPECIMEN #4										
1	56	19	0 0	0 0	88 29	49 5	-	8 -1	88 31	65 7
2	156	16	668 739	229 244	585 587	404 301	-	-	485 545	-
SPECIMEN #5										
1	45	12	35 0	0 0	62 69	0 0	38 4	-14 - 9	58 70	98 73
2	52	10	28 0	11 3	59 0	86 9	38 0	0 7	56 14	82 7
3	149	9	439 425	493 480	206 162	344 263	438 430	-	202 148	-
4	156	15	566 -	382 -	1320 -	579 -	725 -	178 -	956 -	-

SPECIMEN #8

Pulse No.	Load, Kips	Rise Time, Millisec.	Pt.1	Pt.2	Pt.3	Pt.4	Pt.1'	Pt.2'	Pt.3'	Pt.4'
1	41	13	105 40	43 10	32 13	16 0	96 38	68 18	42 18	24 0
2	48	13	78 13	35 5	24 0	10 0	80 9	48 5	40 0	16 - 3
3	56	18	100 38	57 15	48 0	27 4	112 40	69 12	54 17	24 -14
4	73	13	-	-	110	609	58	-	358	-
			SPECIMEN #9							
1	45	14	30 0	7 0	53 0	26 9	32 0	0 0	72 13	0 0
2	70	14	92 0	15 2	74 0	54 9	63 9	9 0	107 17	8 0
3	98	18	124 52	52 25	137 98	182 94	121 50	4 0	184 121	5 0
4	98	16	1387	-	1453	481	-	-	1562	-
			SPECIMEN #10							
1	32	13	204	167	11	11	137	-	0	-
2	-	-	55	130	46	27	150	112	99	21
			SPECIMEN #12							
2	71	12	1880	268	1730	-	286	288	1410	-
			SPECIMEN #13							
1	20	12	-	5 -	43 18	70 13	-	-3 0	49 20	35 7
2	71	15	-	540 -	296 -	575 -	-	330 -	444 -	323 -

SPECIMEN #15

Pulse No.	Load, Kips	Rise Time, Millisec.	Pt.1	Pt.2	Pt.3	Pt.4	Pt.1'	Pt.2'	Pt.3'	Pt.4'
1	25	22	35 0	5 1	50 11	2 0	29 0	3 0	72 18	2 0
2	72	16	150 85	7 5	75 64	45 11	128 89	13 0	128 103	42 11
3	110	20	433 583	52 17	150 323	50 2	380 553	46 14	241 480	52 2
4	119	18	328 345	-	264 222	-	292 296	-	259 315	-
5	136	-	260 378	-	150 261	-	150 155	-	243 396	-
SPECIMEN #16										
1	40	15	27 0	2 4	30 0	16 2	27 0	6 3	45 0	19 3
2	71	15	37 0	1 4	43 0	25 3	40 0	9 1	63 0	31 4
3	75	15	90	98	70	63	98	90	112	47
SPECIMEN #18										
4	113	20	342 306	-	370 318	-	320 301	-	418 345	-
5	120	20	172 106	-	182 96	-	153 111	-	214 107	-
6	137	20	-	-	-	-	-	-	-	-
SPECIMEN #20										
1	-	-	51 11	5 -2	41 23	18 6	31 8	6 -1	45 19	14 4
2	55	15	61 0	18 2	64 0	18 1	34 13	10 0	45 13	13 -1
3	103	18	250 530	-	295 520	-	217 345	-	336 559	-
4	119	21	165 83	-	136 73	-	121 65	-	171 88	-

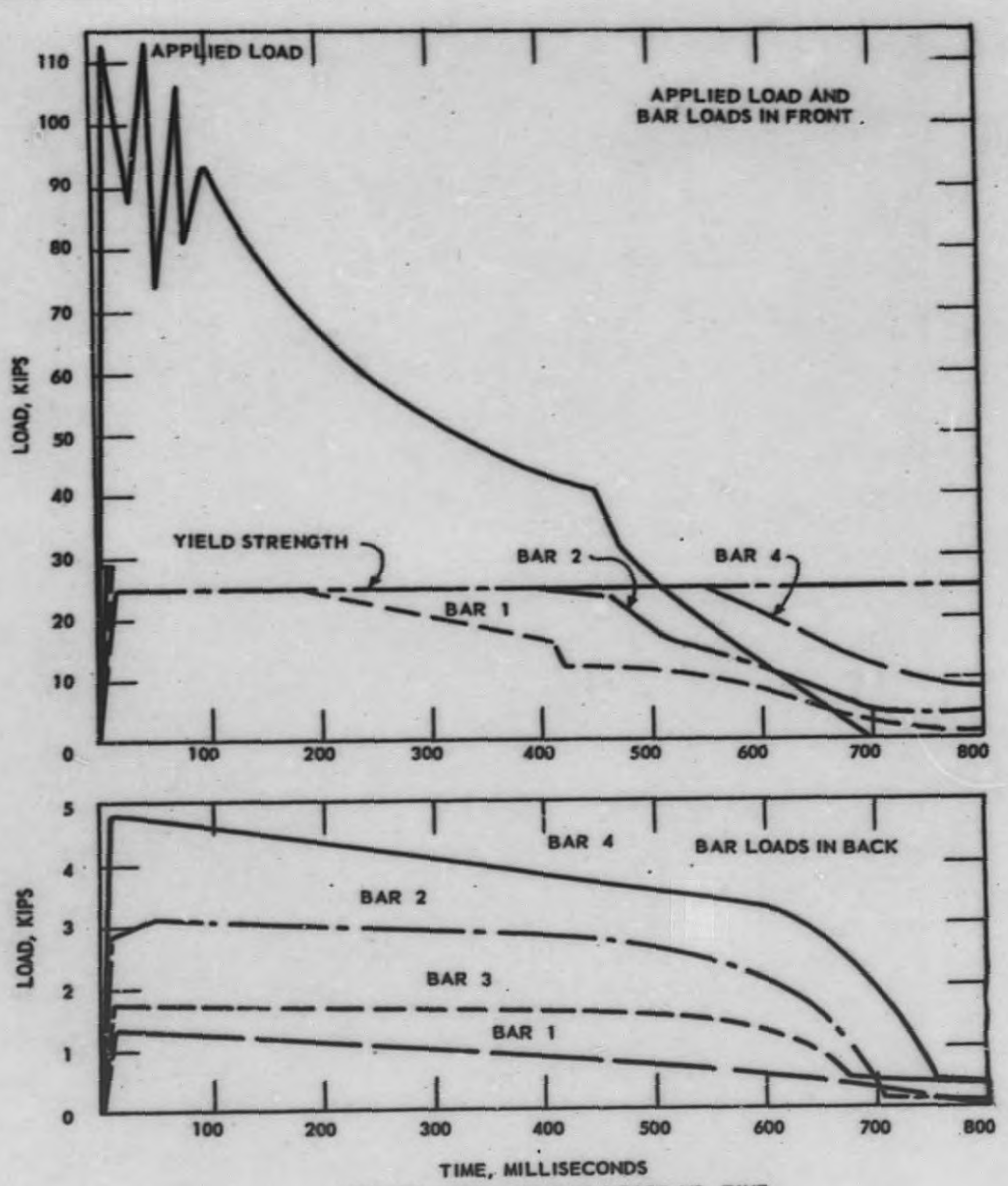
SPECIMEN #21

Pulse No.	Load, Kips	Rise Time, Millisec.	Pt.1	Pt.2	Pt.3	Pt.4	Pt.1'	Pt.2'	Pt.3'	Pt.4'
1	40	16	51	7	64	28	50	10	84	32
			0	7	16	9	12	-1	21	4
2	68	24	63	16	68	52	69	29	84	53
			48	-3	34	6	48	-2	43	-1
			SPECIMEN #23							
1	30	-	99	54	45	8	98	50	58	6
			32	31	0	2	32	20	0	-1
2	35	19	99	32	45	8	95	40	49	8
			0	5	0	-1	12	7	0	-1
3	73	28	181	70	118	19	189	62	135	10
			81	24	25	-7	78	15	36	-10
4	104	22	240	-	215	68	445	-	621	55
			190		136	12	345		292	-3
5	112	22	-	-	-	-	-	-	-	-
			SPECIMEN #24							
1	-	-	30	5	-30	6	50	2	60	6
			18	1	0	3	15	-1	19	2
2	30	19	18	4	-38	4	48	0	24	0
			0	0	0	0	0	0	0	0
3	97	22	-	-	-	-	-	-	-	-

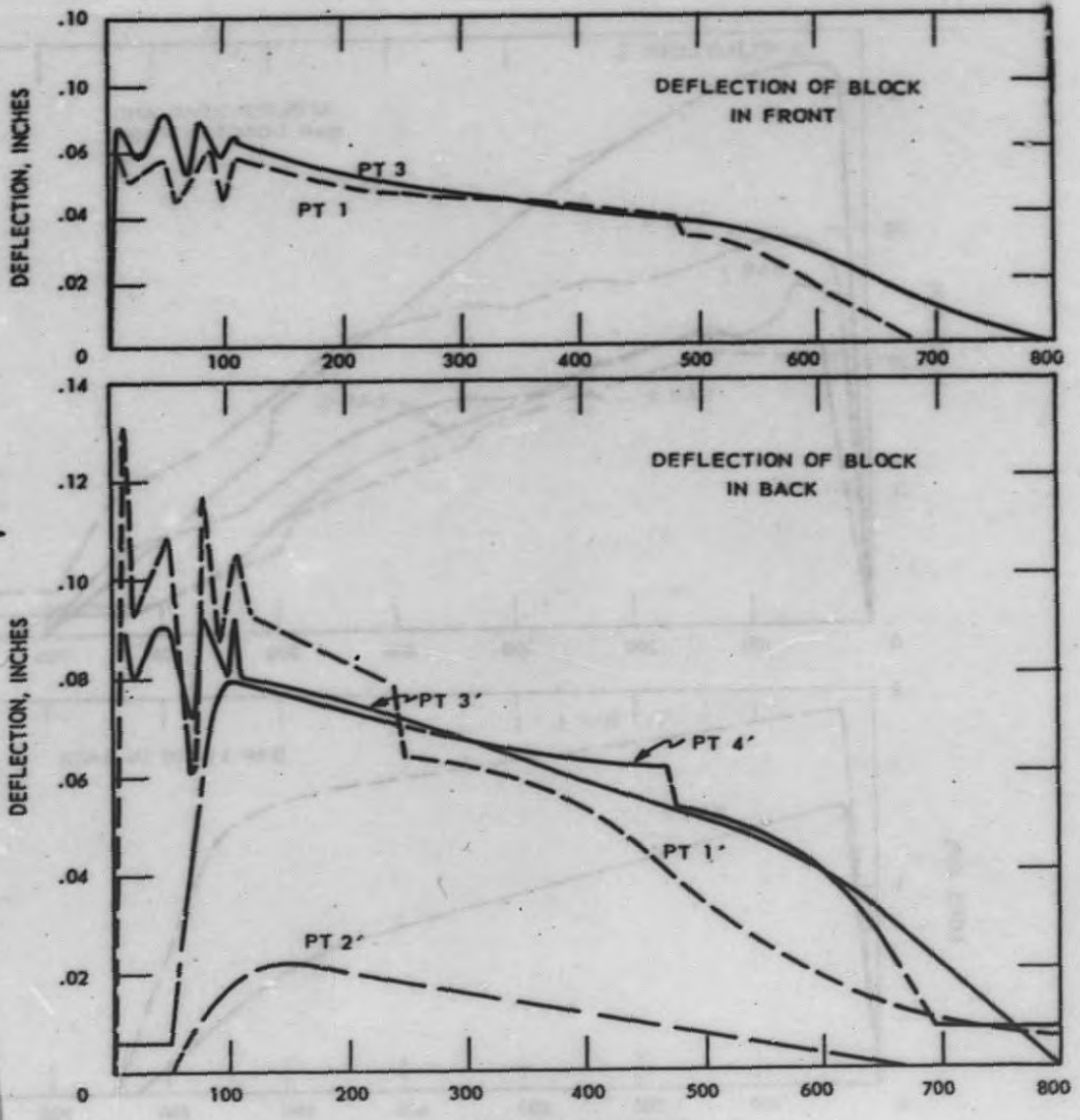
APPENDIX 3

GRAPHS OF LOAD PULSE, BAR LOADS, AND DEFLECTIONS

SPECIMENS #3,5,8,9,15,20,23,24



APPLIED LOAD AND BAR LOADS VS. TIME
SPECIMEN 3, TEST 6

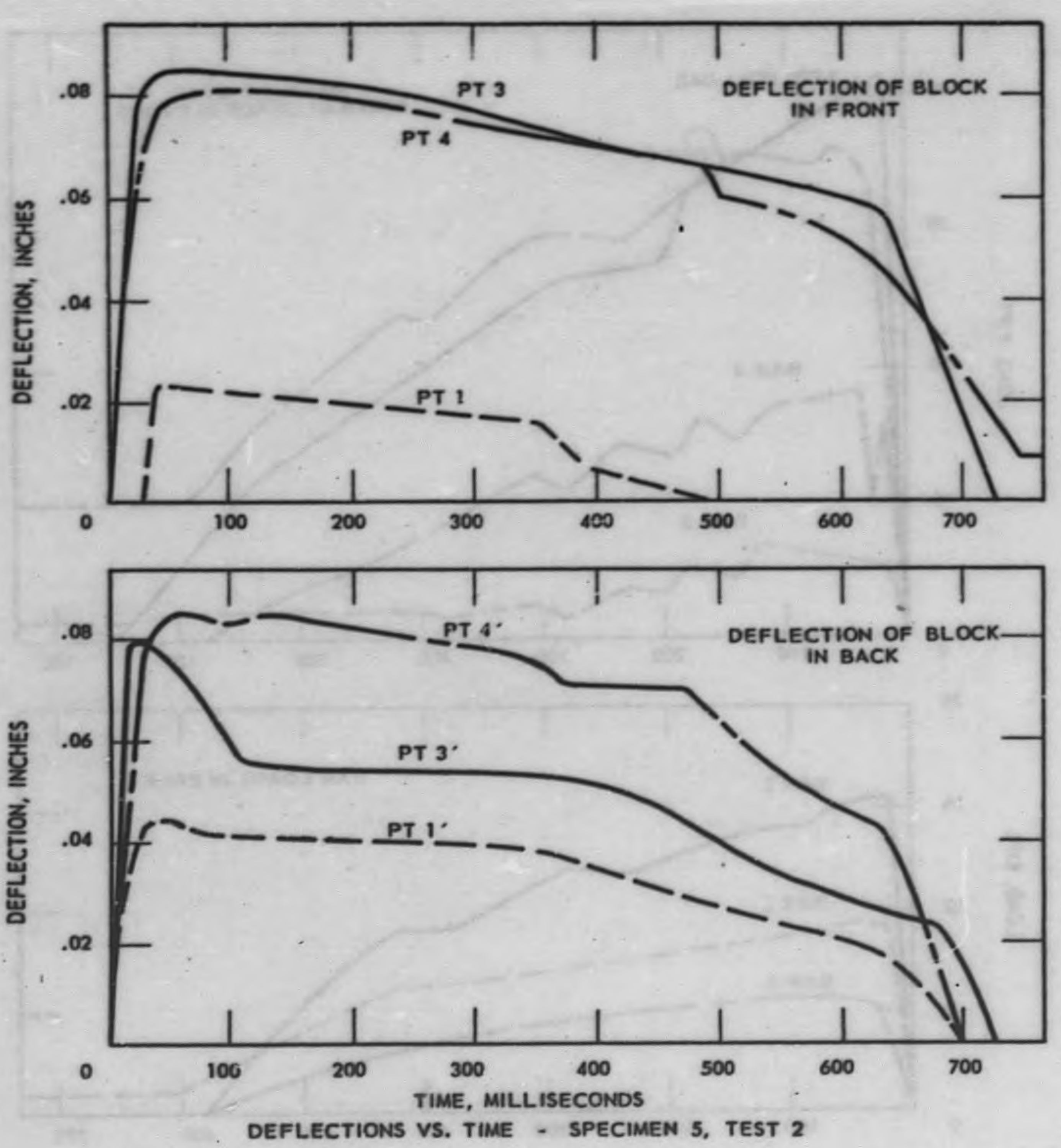


TIME, MILLISECONDS

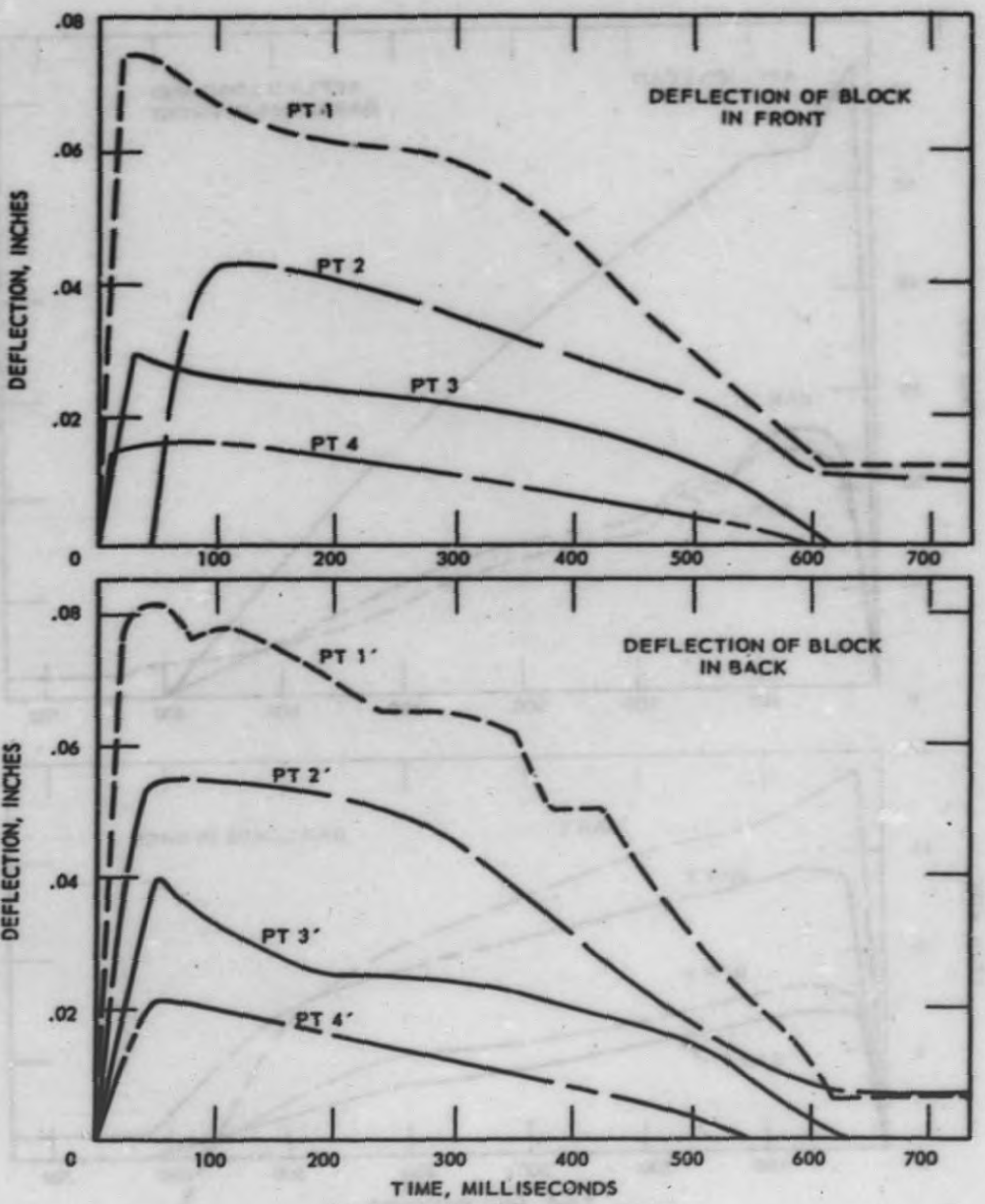
BLOCK DEFLECTIONS VS. TIME
SPECIMEN 3, TEST 6

896

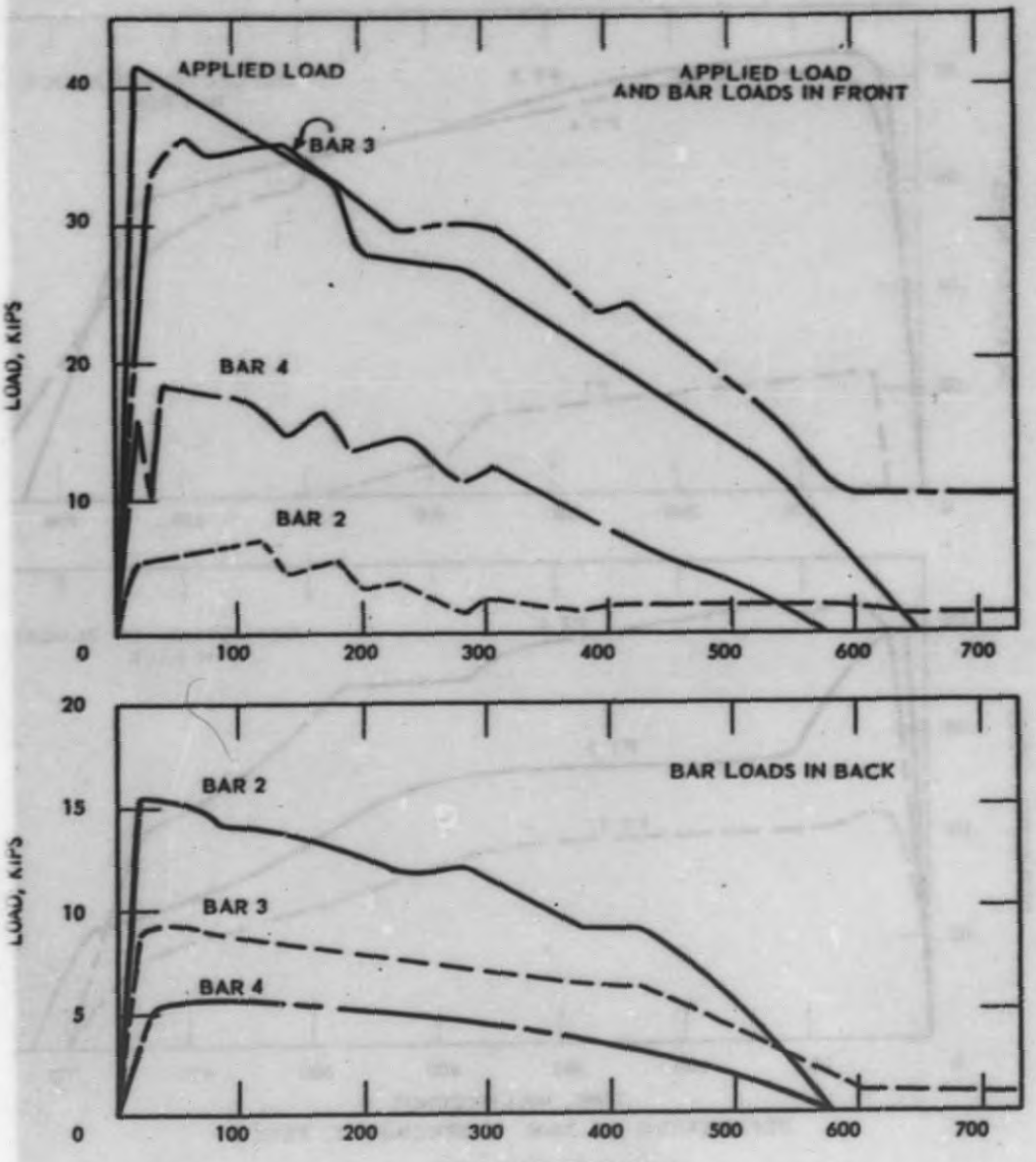
085



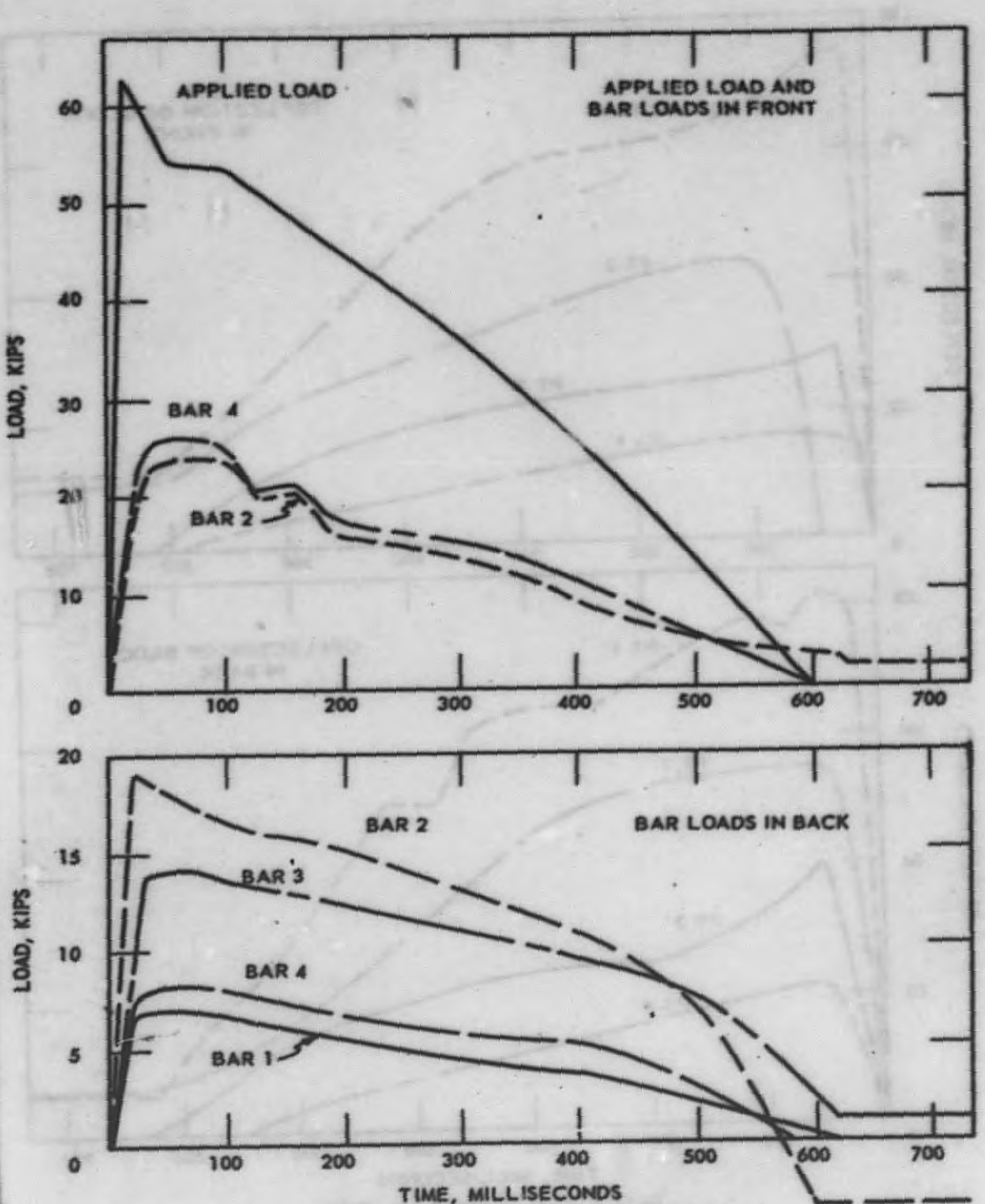
DEFLECTIONS VS. TIME - SPECIMEN 5, TEST 2



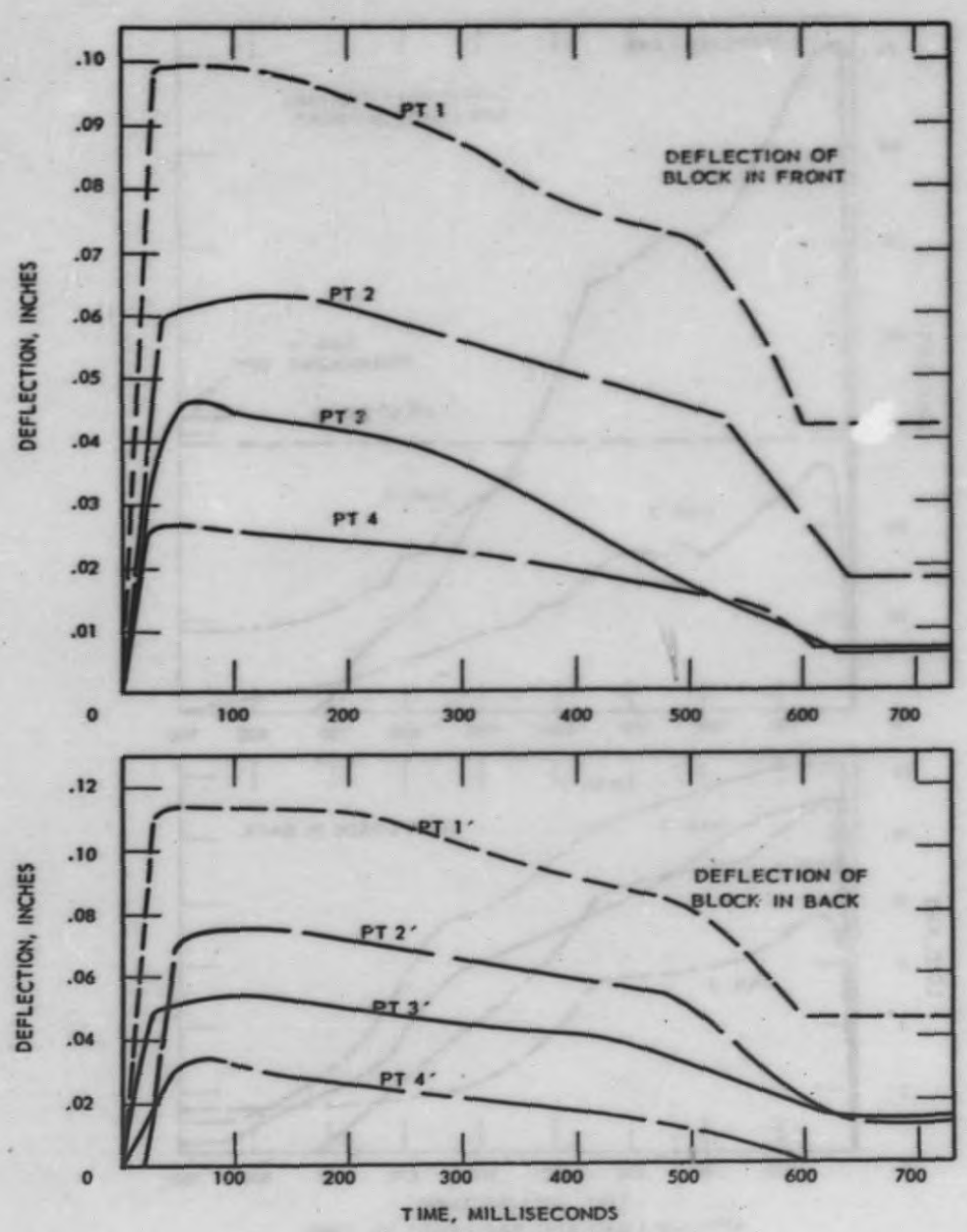
BLOCK DEFLECTIONS VS. TIME
SPECIMEN 8, TEST 2



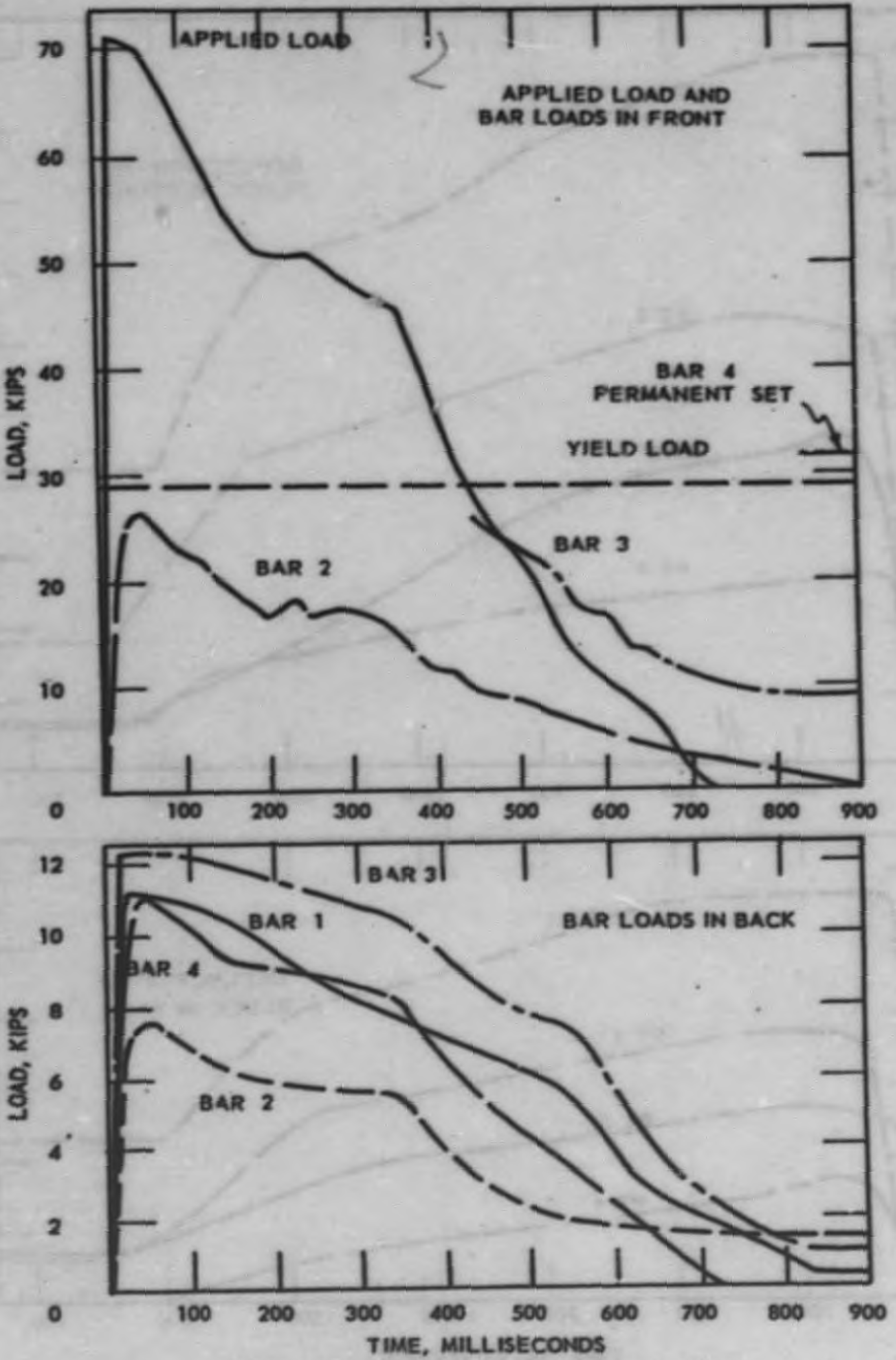
APPLIED LOAD AND BAR LOADS VS. TIME
SPECIMEN 8, TEST 2



APPLIED LOAD AND BAR LOADS VS. TIME
SPECIMEN 8 TEST 3

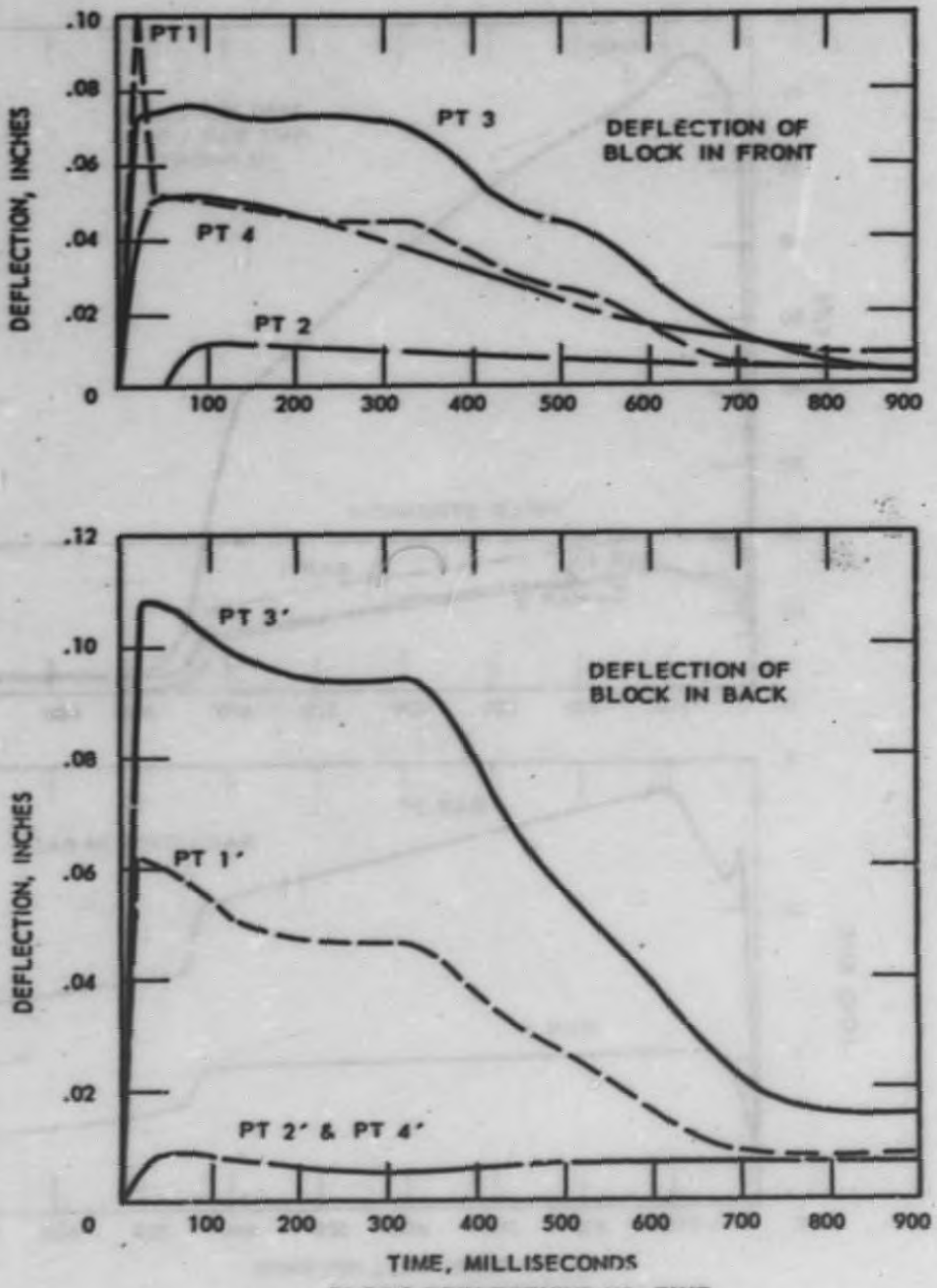


DEFLECTIONS VS. TIME
SPECIMEN 8, TEST 3

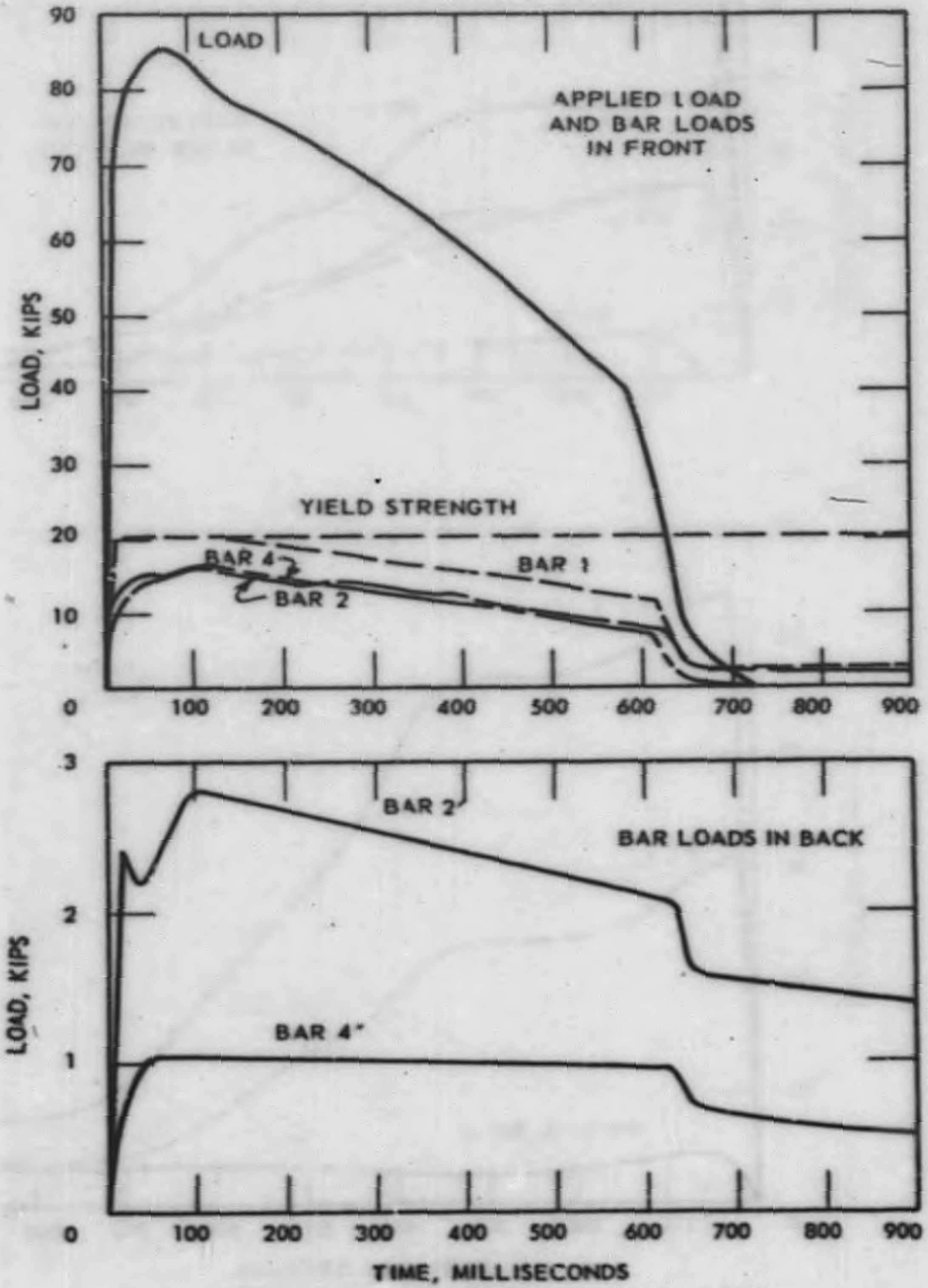


APPLIED LOAD AND BAR LOADS VS. TIME

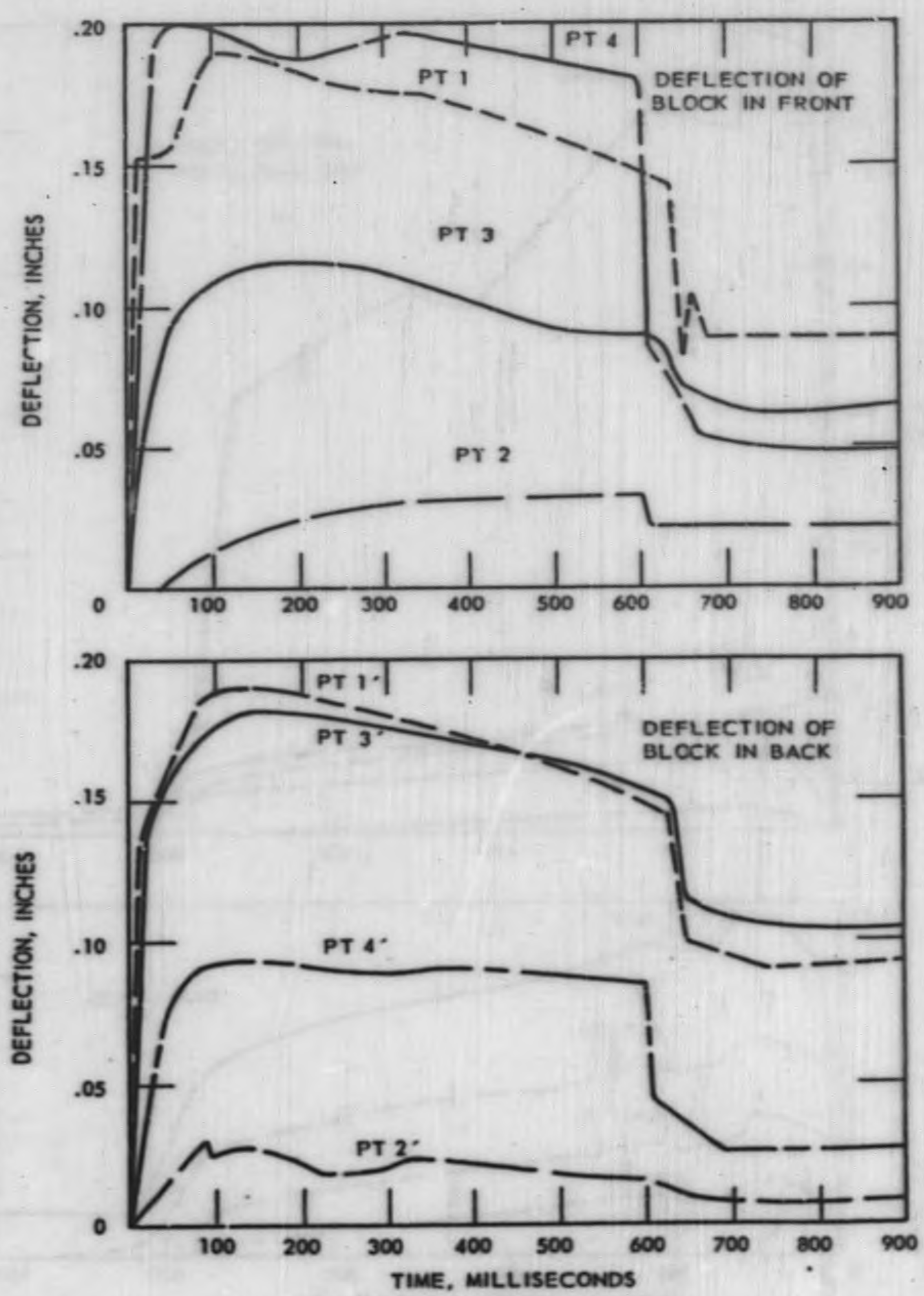
SPECIMEN 9, TEST 2



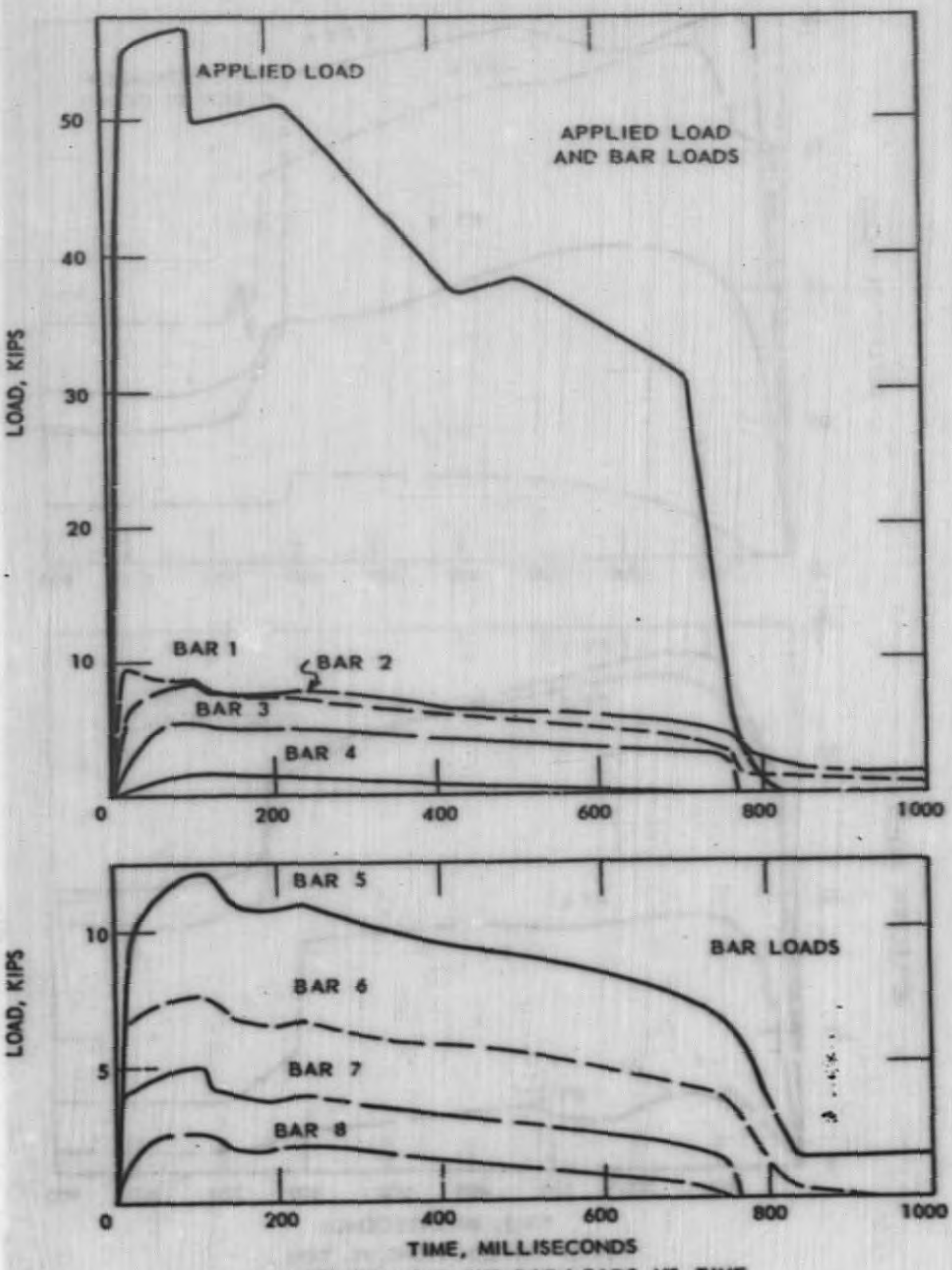
BLOCK DEFLECTIONS VS. TIME
SPECIMEN 9, TEST 2



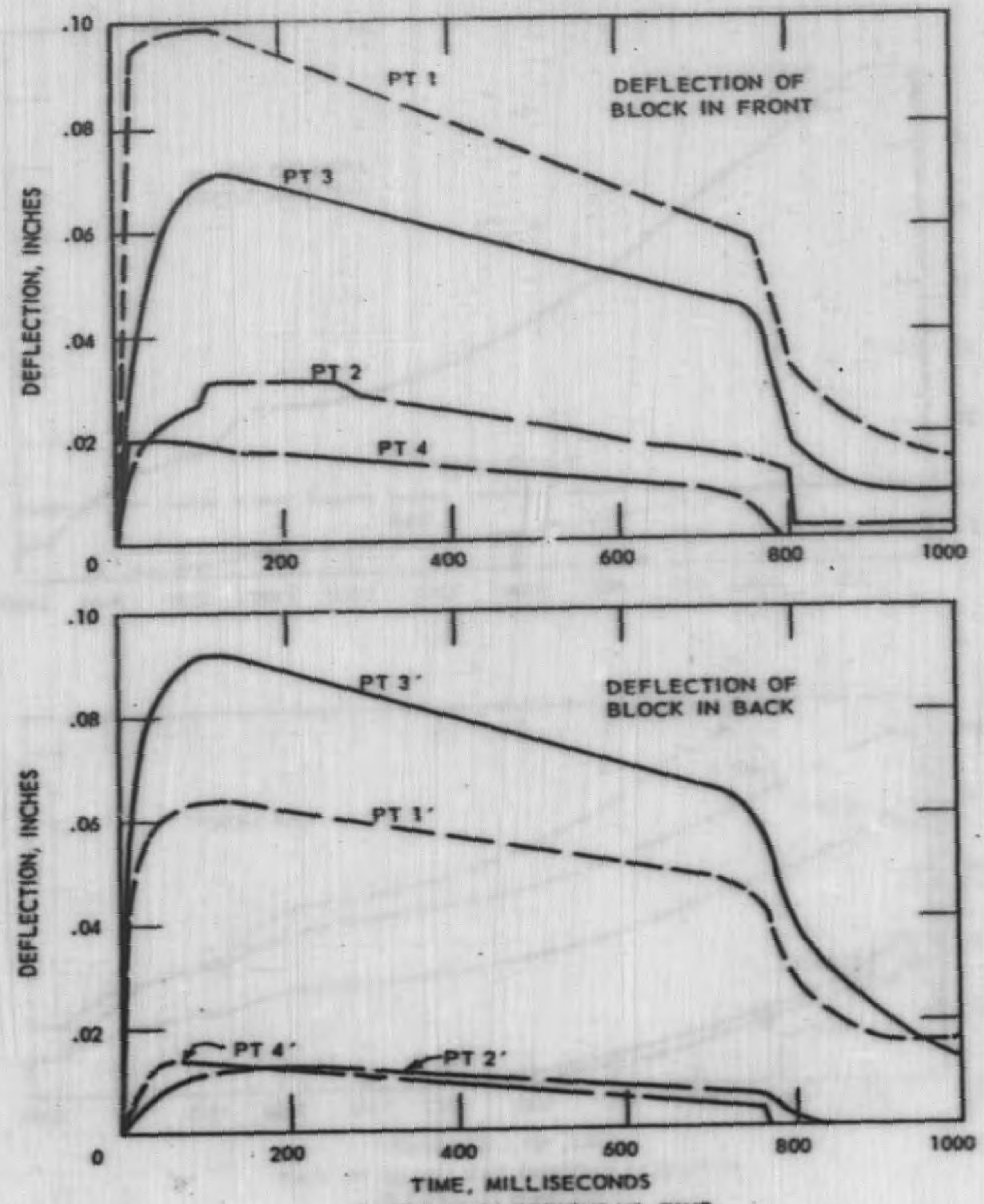
APPLIED LOAD AND BAR LOADS VS. TIME
SPECIMEN 15, TEST 2



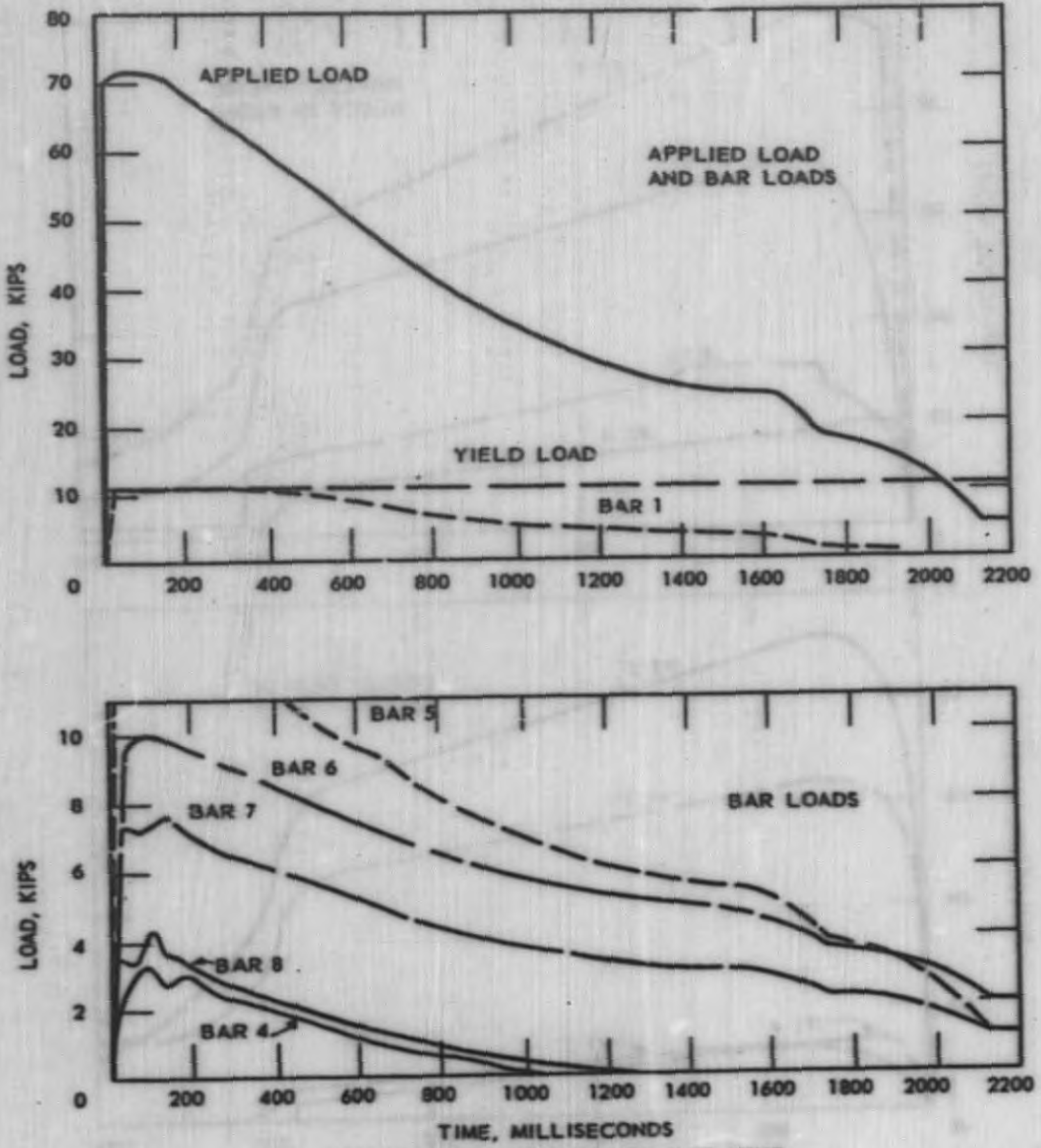
BLOCK DEFLECTIONS VS. TIME
SPECIMEN 15, TEST 2



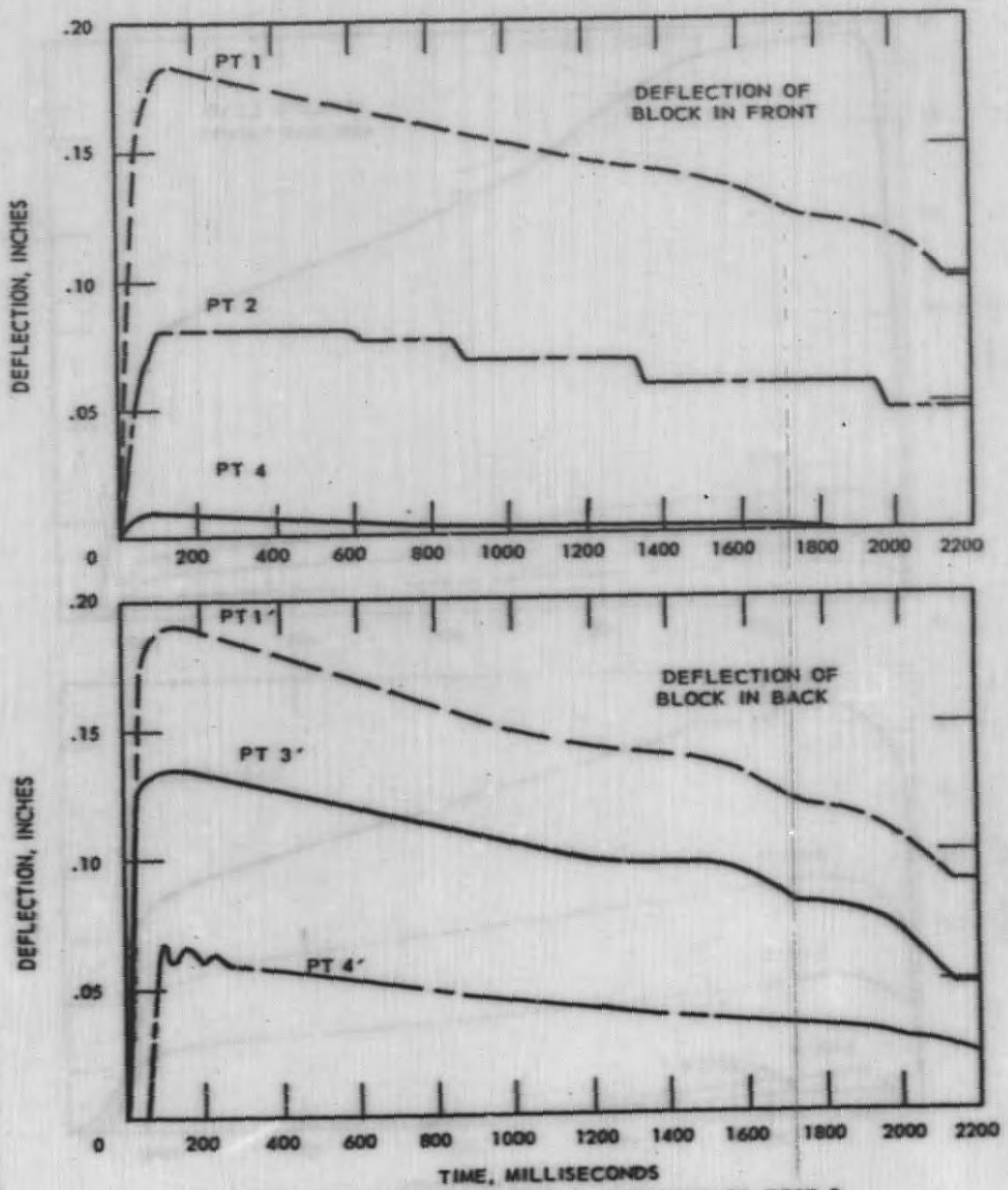
APPLIED LOAD AND BAR LOADS VS. TIME
SPECIMEN 20, TEST 2



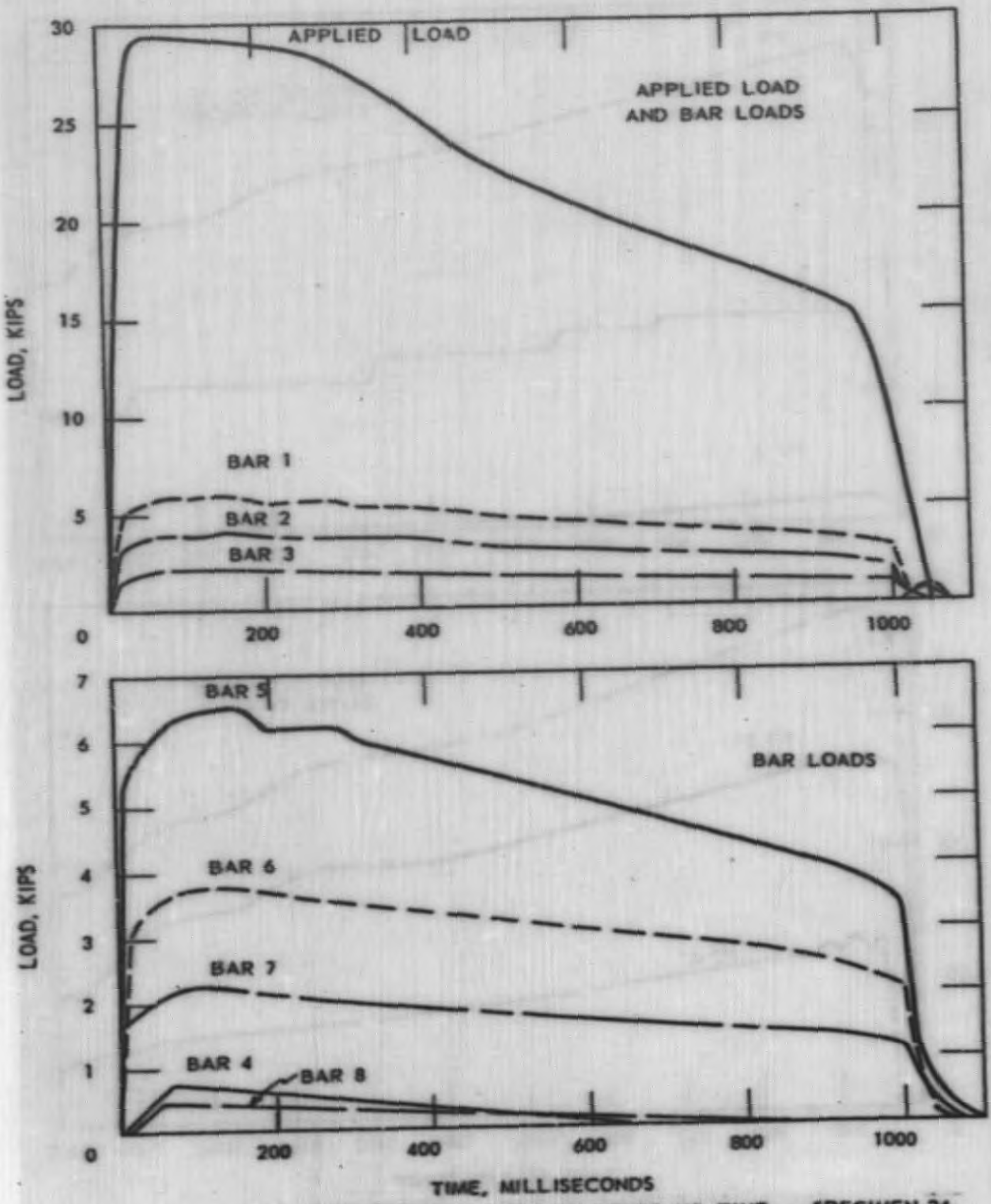
BLOCK DEFLECTIONS VS. TIME
SPECIMEN 20, TEST 2



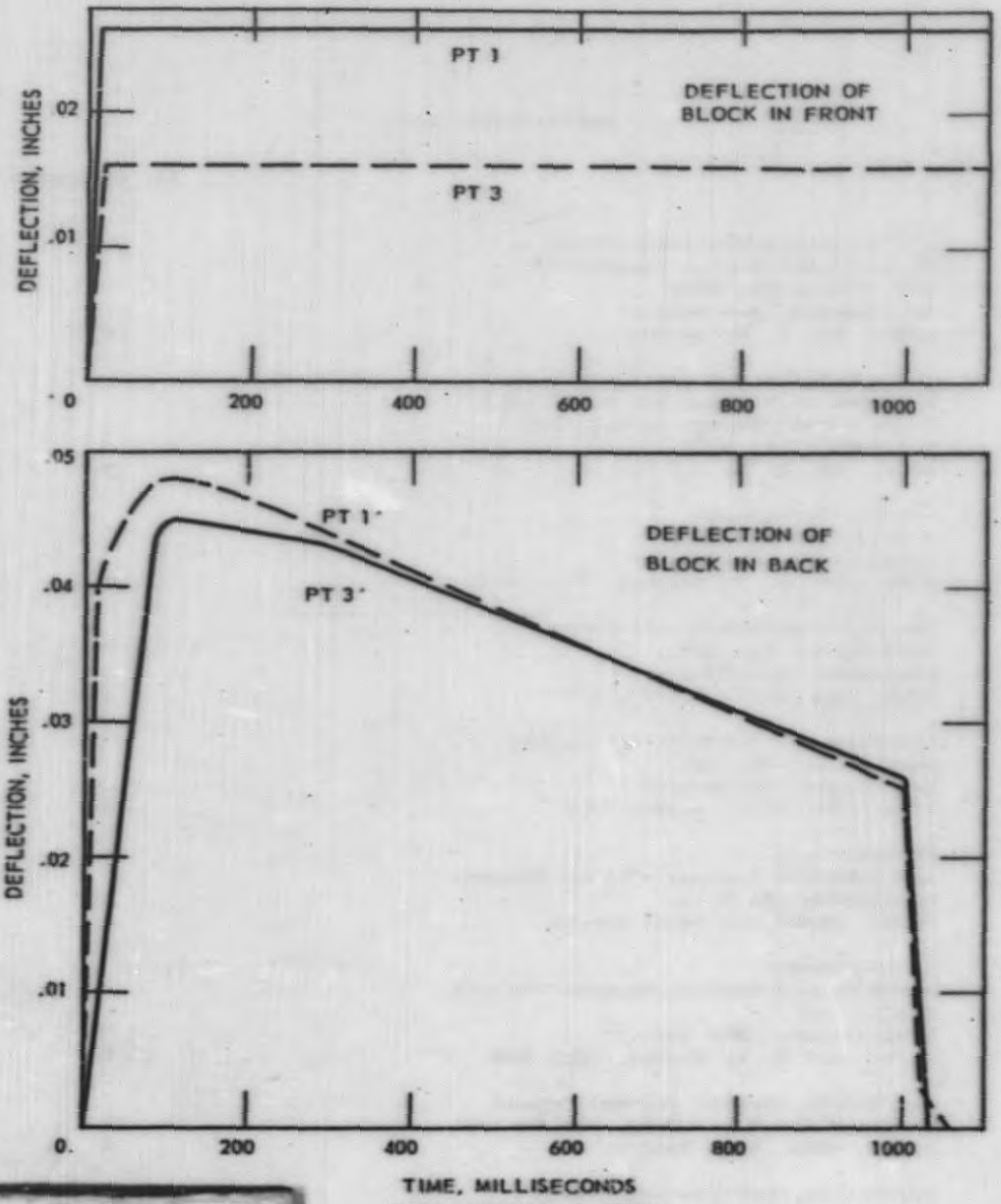
APPLIED LOAD AND BAR LOADS VS. TIME
SPECIMEN 23, TEST 3



BLOCK DEFLECTIONS VS. TIME - SPECIMEN 23, TEST 3



APPLIED LOAD AND BAR LOADS VS. TIME - SPECIMEN 24, TEST 2



DEFLECTIONS VS. TIME
SPECIMEN 24, TEST 2