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J. Hartley Daniels

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ULTIMATE STRENGTH TEST OF A
HORIZONTALLY CURVED
COMPOSITE BOX GIRDER

by

J. Hartley Daniels

This work has been carried out as part of an investigation
sponsored by the American Iron and Steel Institute

Department of Civil Engineering
Fritz Engineering Laboratory, #13
Lehigh University
Bethlehem, Pennsylvania 18015

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The author wishes to thank the Committee of Structural Steel Producers and the Committee of Steel Plate Producers of the American Iron and Steel Institute for their support. The assistance of Dr. B. T. Yen in carrying out the box girder tests is acknowledged.

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ABSTRACT

Ultimate strength test results are presented for a horizontally curved closed composite steel-concrete box girder. Prior to casting the concrete slab the non-composite steel box girder was also tested under low load elastic conditions with and without the steel Bridgform in place. All tests were performed with a concentrated load placed at mid-span directly above the outside web (web having the largest radius). The tests were conducted in the 5,000,000 lb. Baldwin testing machine located in Fritz Engineering Laboratory, Lehigh University. Test results presented herein consist of load-deflection behavior and stresses at selected locations. Premature failure of the concrete slab and shear connection near the two ends of the girder did not permit attainment of a higher ultimate strength of the girder which would involve yielding of the steel girder near mid-span.

1. INTRODUCTION

1.1 Background

The research reported herein is part of an investigation into the ultimate strength of horizontally curved steel plate and box girder members for bridges. Reference 1* is the first of two proposed reports on the results of the plate girder investigation. Fritz Laboratory Report No. 454.2 containing design recommendations which are applicable to the design of compression flanges for curved steel plate girders over interior supports is in preparation by B. T. Yen, Professor of Civil Engineering, Lehigh University.

This report presents the results of an ultimate strength test of one horizontally curved single cell closed composite steel/concrete box girder. Also presented are the results of tests conducted on the non-composite steel box girder with and without the steel Bridgform in place. The steel portion of this box girder was part of a horizontally curved steel box girder assembly which was fabricated and tested in 1974-76 to over 2,000,000 cycles of loading during a previous investigation into the fatigue behavior of curved steel bridge elements (2)*. That study consisting of fatigue tests of 8 full sized curved plate and box girder test assemblies was sponsored by the Federal Highway Administration (FHWA) of the U. S. Department of Transportation (US DOT). Reference 2 describes the steel plate and box girder test assemblies which were tested in fatigue during the FHWA sponsored study. Box Girder Test Assembly 2, described in Ref. 2, was made available after the fatigue tests were completed, and modified for use in the investigation reported herein.

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* References are presented in Chapter 7 at the end of this report.

The modifications consisted of making welded or bolted splice repairs to fatigue damaged areas of the girder, removing the horizontal web stiffeners over the central half of the girder and adding four transverse web stiffeners to the 9 foot bays on either side of mid-span, as shown in Fig. 1.

1.2 Objective and Scope

The objectives of the investigation reported herein are as follows:

1. To experimentally determine the low-load elastic behavior of the non-composite curved steel box girder under the following load conditions and test configurations:

   (a) Concentrated load at mid-span of the outside web (Fig. 1) of an open steel cross-section. (Referring to Fig. 2 the concrete slab and steel Bridgform are not present in the open cross-section).

   (b) Concentrated load at mid-span of the outside web with the Bridgform in place using the recommended pattern of connecting screws. (Art. 3.2.2)

   (c) Concentrated load at mid-span of the outside web with the Bridgform in place using a closer screw spacing along each web than the recommended spacing. (Art. 3.2.2)

2. To experimentally determine the ultimate strength behavior of the closed composite steel-concrete curved box girder under a concentrated load at mid-span above the outside web.

The scope of the investigation is as follows:

1. To report the experimental elastic and ultimate strength load-deflection test results for curved girders at selected girder locations.

2. To report selected stress levels in the curved girders for the several test configurations.
3. To report other experimentally obtained results of interest.

The scope of the investigation does not include theoretical analyses of the test results or the computation of analytical predictions with which the test results can be compared. Although it was originally planned to compare the ultimate strength load-deflection behavior with a predicted behavior, assuming complete interaction, the premature failure of the composite slab and shear connection near the ends of the girder does not enable such a comparison to be made.

2. DESCRIPTION OF CURVED BOX GIRDER

Schematic plan and cross section views of the box girder are shown in Fig's. 1 and 2. North is to the right in Fig. 1. Table 1 summarizes the cross-sectional dimensions and material properties of the composite box girder. The material properties are based on average values obtained from material tests and mill test reports.

The box girder used in this study was originally designed for the fatigue investigation reported in Ref. 2. Box Girder Test Assembly 2, which is described in Ref. 2, was modified for use in the investigation reported herein. At the conclusion of the fatigue study the box girder had experienced some fatigue cracking, Cracks which, due to their size and location, could influence the ultimate strength test results were repaired. Repairs consisted of welding or bolting small patch or cover plates over the visible cracks or removing the crack tip by means of drilling a small hole.

As shown in Fig. 2 and referring to Ref. 2, only the portion of Box Girder Test Assembly 2 below the tops of the webs, was retained (including the 5" x 1" plates) for the ultimate strength tests. A composite concrete slab was attached to the webs using 3/4 in. diameter shear studs as shown in Fig's. 1 and 2. The slab was constructed using steel BRIDGFORM spanning between the webs. Figures 3 and 4 show the box girder with Bridgform in place prior to and after pouring the composite concrete slab.

Prior to performing the tests reported herein the longitudinal 3" x 1/4" web stiffeners which existed on Test Assembly No. 2 (Ref. 2) were removed from the central 18 ft. length of both webs of the girder, retaining them only in the outer two 9 ft. bays. The longitudinal stiffeners are located 9 in. above the bottom flange. After removal of the longitudinal stiffeners, 3½" x 1/2" transverse web stiffeners were welded to the inside of each web midway between the center and quarter point diaphragms, both sides of the mid-span, for a total of 4 stiffeners as shown in Fig. 1. The original longitudinal stiffener on the bottom flange, which were needed in the fatigue tests (Ref. 2), were left in place, as shown in Fig. 2. The left most stiffener in Fig. 2 was not continuous through the mid-span.

3. INSTRUMENTATION AND TESTING PROCEDURE

3.1 Instrumentation

The strain gages and girder displacement gages used for the box girder tests are shown in Fig's. 5 and 6.

Figure 5 shows the locations of the electrical resistance strain gages used in conjunction with a 120-channel B&F data acquisition system. The strain gages are located on the two webs and bottom flange at three cross-sections adjacent to mid-span as shown in the figure. Two types of strain gages are used; single gages and rosette gages. All single gages are mounted to measure strain parallel to the longitudinal axis of the box girder. The rosette gages on the webs consist of three strain gages. These gages are mounted so that the two legs of the rosette at 90° to each other measure strains parallel to and perpendicular to the longitudinal axis of the girder. The third leg of the rosette measures strains at 45° to the parallel and perpendicular gages and are oriented up and away from mid-span as shown in the figure. Strain data was not always recorded for all gages at all load levels. Only selected data of interest was recorded.

Figure 6 shows the locations of the Ames dial gages to measure vertical and horizontal displacements of the box girder and out-of-plane displacements of the outside web. The letters H and V refer to the horizontal and vertical box girder displacements, respectively. The letters A through G and I through K refer to locations of potential web displacement measurements. Web displacements were not always measured at all locations. When web displacement data was taken, measurements were made at locations 1 through 5 as shown on the typical cross-section X-X.

Ames dials reading to 0.001 in. were used for the box girder displacements. Ames dials reading to 0.0001 in. were used for the web displacements. All Ames dials had a stroke of 1 in. except for those measuring vertical displacements within the middle half of the box girder. Those had strokes of 6 in.

Figure 7 shows a view of some of the strain gages on the outside web as well as some Ames dial deflection gages. Vertical and horizontal displacements were measured at the intersection of the web plates and bottom flange plate. Horizontal displacements were measured at the top of the web in Tests 1, 2A and 2B and at mid-depth of the concrete slab in Test 3. (See Chapter 3).

Figure 8 shows the device used to take the web out-of-plane displacements. Ames dials 1 through 5 (Fig. 6) were bolted to a bar which could be moved to locations A through G and I through K. The bar was fitted with magnets to hold the bar against the web while dial readings were being taken. Web displacements are therefore out-of-plane displacements measured relative to the top and bottom edges of the outside web.

3.2 Test Procedure

Four tests of the box girder were carried out culminating with the ultimate strength test of the composite box girder. The four tests are described in Art's. 3.2.1 through 3.2.3 below.

3.2.1 Test 1 - Without Bridgform

The purpose of this test was to establish the load-deflection behavior, under low load, of the open steel box girder without the Bridgform and composite concrete slab in place.

Figure 9 shows the non-composite box girder prior to testing. The east end of the girder is in the foreground. The girder was positioned under the 5,000,000 lb. Baldwin universal testing machine located in Fritz Engineering Laboratory. Vertical concentrated load was applied to the girder at mid-span of the outside web. The small plates shown in the figure were used to transmit load to the outside web.

The girder was supported at each of the four corners with the roller assemblies shown in Fig. 9 and again in Fig. 10. The roller assembly in Fig. 10 is at the SE corner of the girder. These roller assemblies were used throughout all the fatigue tests reported in Ref. 2 and functioned very well. Two 8 in. diameter steel rollers at right angles to each other are stacked together with three 2 in. thick steel plates between rollers as shown in Fig. 10. Steel pintels maintain alignment of each roller with the steel plates. At each of the four supports the roller assemblies permit horizontal displacement in any horizontal direction, as well as rotation, about any horizontal axis. Rigid body horizontal displacement of the girder is restrained at the point of loading by the test machine itself. Rigid body rotation of the girder about a vertical axis through the point of loading is restrained by a suitably placed strut at one end of the girder.

Uplift of the supports at each end of the inside web was prevented, using two 1 in. diameter tension rods, as shown in Fig. 11, which shows the NE corner of the box girder. A small compression load cell was placed on top of the inside web, as shown in the figure, to measure the uplift force.

3.2.2 - Tests 2A and 2B - With Bridgform

Two tests were made to establish the load-deflection behavior, under low load, of the box girder with only the steel Bridgform in place. The two tests differed only in the configuration of the Super Tek/3 screws used to attach the sheets to the girder. Figure 12 shows a view of the box girder with Bridgform in place prior to testing. The girder was positioned under the 5,000,000 lb. testing machine, loaded and supported in the same manner as that for Test 1, described in Art. 3.2.1. The steel plates shown in the figure and located at mid-span over the outside web shows the lcoation of the test load.

In each test the steel Bridgform was attached to steel angles which were welded to the steel box girder, as shown in Fig. 2. The two different screw configurations used to attach the Bridgform to the angles for each of the two tests are described below:

Test 2A - In the first test the Bridgform was connected to the girder using the screw configuration shown in Fig. 13. The outside web is in the foreground. The screws connect the Bridgform to the angles at sheet laps and at mid-sheet. Screws also connect sheets at mid-span of each sheet. This was the screw configuration recommended by the Bridgform supplier.

Test 2B - In the second test the Bridgform was connected to the angles using the configuration shown in Fig. 14. The screws connect the Bridgform to the angles at sheet laps at seven points along each sheet as shown in the figure. The screws were located at the center of each trough and midway between troughs as shown. Sheets were also connected together at mid-span of each sheet as described for Test 2A.

3.2.3 - Test 3 - With Composite Concrete Slab

The purpose of this test was to establish the load-deflection behavior of the composite box girder up to the ultimate load.

Figure 15 shows the composite box girder prior to the ultimate strength test. The west end of the girder is to the left. The composite box girder was positioned under the 5,000,000 lb. Baldwin Universal testing machine located in Fritz Laboratory. Vertical load was applied to the top of the concrete slab at mid-span directly over the outside web as shown in Fig. 16. The composite box girder was supported at each of the four corners using the roller assemblies described in Art. 3.1. Uplift of the supports at each end of the inside web was prevented using two 1 in. tension rods and the large capacity compression load cell as shown in Fig. 17. The east end of the girder is shown in the figure. Due to the larger loads involved in the ultimate strength tests, rigid body horizontal displacement was not permitted to be restrained by the test machine itself at the point of load as was done in Tests 1, 2A and 2B. Instead, both ends of the girder were restrained so that although horizontal displacements in any direction at each of the four supports was permitted, overall rigid body horizontal displacements of the girder was prevented. Figure 18 shows the two orthogonal rigid body restraints used to prevent lateral and longitudinal rigid body horizontal displacements at the east end of the girder. These restraints are provided by the two rods shown in the figure which connect the girder to the two rings on the steel floor plate. A similar rod was used at the west end as shown in Fig. 8.

4. TEST RESULTS AND DISCUSSION

4.1 Load-Deflection Behavior

Figure 19 shows the load-deflection behavior obtained for Tests 1, 2A and 2B. The load P is a concentrated load at mid-span of the outside web (Art. 3.2). The deflection Δ_1 is the mid-span deflection directly below the outside web. The deflection Δ_2 is the mid-span deflection directly below the inside web. The load was limited to 50 kips in each test so that elastic behavior would result. Loading and unloading behavior was nearly the same in each test.

Test 1 was performed on the open steel box girder without the steel Bridgform in place. At the load of 50 kips no distress was observed in the open section. The resulting load-deflection curve is the base line behavior which can be used to compare the stiffening effect of the Bridgform in Tests 2A and 2B.

Test 2A was performed with the Bridgform in place and with the recommended screw configuration shown in Fig. 13 (Art. 3.2.2). At a load of 20 kips the Bridgform began to lift slightly between the fasteners at several locations along the outside web. Figure 20 shows one of these locations near mid-span. At a load of 50 kips the Bridgform at the same location lifted about 1 inch as shown in Fig. 21. At most other locations along the outside web the upward lifting of the Bridgform at 50 kips was about the same as shown in Fig. 20. Little or no uplifting of the Bridgform was observed along the inside web.

As a result of the behavior shown in Figs. 20 and 21, it was decided to repeat the test but with a closer spacing of the screws over both webs, as shown in Fig. 14 (Art. 3.2.2). At a load of 20 kips in Test 2B, no significant lifting was observed along either web. Figure 14 shows the Bridgform at a load of 20 kips. When the load reached 50 kips some slight lifting of the Bridgform occurred near mid-span over the outside web as shown in Fig. 22. Elsewhere along both webs little or no lifting occurred at a load of 50 kips.

A study of Fig. 19 indicates that in Test 2A, although the Bridgform reduced the mid-span deflection, Δ_1 under the load the deflection, $\Delta 2$, under the inside web opposite the load was essentially unaffected. However, in Test 2B, with the decrease in screw spacing the mid-span deflections on both sides of the girder were affected. The Bridgform in Test 2B therefore, was more effective in closing the box girder and reducing vertical and torsional displacements.

No analyses were performed to predict the load-deflection behavior of the box girder in the Test 1, 2A or 2B configurations.

Figure 23 shows the load-deflection behavior obtained for Test 3. For comparison the P versus Δ, curves for Tests 1, 2A and 2B are also shown in the figure. The load P is a concentrated load applied at mid-span to the top of the concrete slab directly over the outside web (Fig. 16). The deflections Δ_1 and Δ_2 are as previously defined.

The solid line shows the loading and unloading behavior of the composite box girder at mid-span of the outside web. The loading and unloading behavior at mid-span of the inside web was essentially the same and is shown by the dashed line.

With reference to the lettered points along the solid line in Fig. 23 the following observations were made during the test.

A - At a load of 100 kips and a deflection of 0.55 in. cracking of the concrete slab was observed around the compression load cells over the inside web at the two ends of the girder. A single crack occurred about 3 inches from each load cell on the side away from the corner of the slab and extended around the load cell, intersecting both edges of the slab at approximately right angles.

B - At a load of 200 kips and a deflection of 1.04 in. the concrete slab and Bridgform separated from the top of the web at the west end of the outside web, as shown in Fig. 24. The figure shows the west end of the outside web. The concentrated load is at mid-span over this outside web. The top of the outside web appears to have moved horizontally to the left relative to the concrete slab. Actually the entire slab has moved horizontally to the right as the box girder rotates clockwise at mid-span under the load. The displacement shown in the figure was accompanied by a large noise as the shear connectors and Bridgform near the ends of the outside web failed in shear.

C - Between 200 kips and 260 kips the concrete cracks described in A above widened considerably. Additional cracks in the concrete slab were evident further from the load cells.

D - Point D corresponds to the attainment of the ultimate load of 263 kips and a deflection of 2.42 in. Figures 25 through 28 show the girder at the ultimate load. Figure 25 is a view of the west end of the girder. The concrete under the load cell has separated from the remainder of the slab. The 1½ in. crack in the end of the slab is a result of the shear displacement occurring over the outside girder on the right which is shown at the 200 kip load level in Fig. 24. Figure 26 shows a view of the east end of the girder with the outside web on the left. The slab did not displace horizontally relative to the two webs at this end of the girder. The cracks are therefore much smaller than those at the west end. Figures 27 and 28 show views of the west and east halves of the girder, respectively, at the ultimate load. The large crack shown in Fig. 25 can be seen in Fig. 27 to extend directly over the inside web to the quarter point. The shear connectors were exposed by this crack. At the quarter point the crack branches. One branch continues along the inside web exposing more shear connectors. The other crosses the slab, reaching almost to the outside web. Figure 28 shows that on the east half the slab cracking is confined to a fairly large region around the load cell.

E - Unloading of the girder was initiated at a load of 240 kips and a corresponding vertical deflection of 3.95 in. It was obvious at this point that the large crack in the west half of the slab was getting larger and no further increase in the load could be expected.

With increased cracking over the inside web and exposing of the shear connectors, the box girder is reverting basically to an open section.

F - At zero load the permanent deflection is 1.62 in.

No analyses were performed to predict the ultimate strength behavior of the composite box girder.

The premature failure of the concrete slab is attributed to the manner in which uplift of the inside web was resisted. With the configuration of rollers used to support the four corners it was more practical to resist uplift and measure the uplift forces using the compression load cells mounted on the surface of the slab. Although the shear connection and slab reinforcement was calculated to be sufficient to achieve the primary ultimate load capacity of the girder these calculations did not consider the additional slab reinforcement which would be needed to resist the slab forces introduced by the load cells.

A nearly identical composite box girder was tested to ultimate strength as part of the previous FHWA project reported in Ref. 2. That girder was designated Box Girder Assemblage 1. It was also modified for the ultimate strength test following fatigue testing. The results of the ultimate strength test are reported in Ref. 3 and the girder is designated Composite Box Girder 1 in that reference. Except for a slight difference in configuration of the interior diaphragms Composite Box Girder 1 and the composite girder reported herein have the same steel cross-sections.

However, Composite Box Girder 1 had a 54" by 6" concrete slab without Bridgform, which is to be compared with the 60" by 8" concrete slab with Bridgform for the box girder reported herein. Composite Box Girder 1 had a mid-span concentrated load offset 12 in. towards the inside web, which is to be compared with the mid-span concentrated load offset 18 in. and over the outside web of the girder reported herein. The ultimate strength of Composite Box Girder 1 was 424 kips as reported in Ref. 3. The mode of failure was crushing of the slab together with yielding and buckling of the inside web under the load.

4.2 - Web Out-of-Plane Displacements

Figure 29 shows the measured out-of-plane displacements of the outside web. In the figure, locations A through G and I through K correspond to the same locations shown in Fig. 6. The locations 1 through 5 also correspond to the same locations shown on the typical cross-section X-X in Fig. 6. The out-of-plane web displacements were measured using the device shown in Fig. 8.

In Fig. 29 the dashed curves indicate the initial out-of-plane web displacements before beginning the ultimate strength tests. The initial web displacement corresponds to the initial fabricated condition of the web which was subsequently modified an unknown amount due to the previous fatigue testing as well as Tests 1, 2A and 2B of this investigation. Since all of these tests were conducted in the elastic range the modification should be relatively small. The solid curves indicate the out-of-plane web displacements at the ultimate load of 263 kips reached in Test 3.

All of the out-of-plane displacements shown in Fig. 29 are relative to the top and bottom edges of the web as explained in Art. 3.1. It is apparent that at locations containing the longitudinal stiffener, the stiffener was quite effective in preventing out-of-plane web displacement except at location A. The longitudinal stiffener was needed near the bottom flange of the box girder in the previous fatigue investigation and is not in the optimal location for the ultimate strength test. Calculations indicated that longitudinal or transverse stiffeners between diaphragms were not needed in the ultimate strength test. However, the longitudinal stiffeners in the middle two 9 ft. bays were removed and transverse stiffeners added as mentioned in Chapter 2, in order to minimize out-of-plane web displacements of the webs in the vicinity of the strain gages. Figure 29 shows that at location E, which is at section 2 of Fig. 5, the web displacements under load are relatively small.

4.3 - Girder Rotations

Figure 30 shows the measured girder displacements from which girder rotations can be determined at the west quarter-point and mid-span diaphragms at the ultimate load of 263 kips. The displacements shown in the figure were measured using Ames dials placed as shown in Fig. 6.

In Fig. 30 the solid lines represent schematically the mid-planes of the steel webs, bottom flange and concrete slab as well as the diaphragm member axes. The displacements are shown to an exaggerated scale for clarity.

4.4 - Flexural Stresses

Flexural stresses (stress in the direction of the girder) in ksi are shown in Fig's. 31 through 36 for several cross-section configurations and locations and for several load levels.

Fig's. 31 and 32 show flexural stresses at cross-section 1 of Fig. 5. Values of stress without parentheses are computed from the experimental strains recorded at each of the horizontal strain gages shown in Fig. 5. Where a value is missing (indicated by dashes) either the strain gage did not function or it was indicating an obviously erroneous value of strain. Corresponding stresses on adjacent sides of the web are expected to differ because of membrane stresses generated by out-of-plane web displacements. An average of the two adjacent stresses provides an indication of the in-plane flexural stress.

Values of stress in parentheses in Fig's. 31 and 32 are computed from the calculated elastic cross-section properties of the girder in the Test 1 and Test 3 configurations. These stresses were computed assuming a straight girder of 36'-0" span with a mid-span concentrated load placed midway between girder webs. In the Test 1 configuration the calculated moment of inertia about a horizontal axis is 9,871 in.^{4}. The section modulus for stress in the extreme bottom fiber of the bottom flange is 609 in.^{3}. The corresponding values in the Test 3 configuration are 21,225 in.^{4} and 802 in.^{3}. The stresses computed from these elastic properties are shown only for comparative purposes. Elastic analyses of the curved girder in the test configurations were not performed. No attempt was made to compute the cross-section properties of the girder in the Test 2A and Test 2B configurations.

A maximum experimental stress of 31.1 ksi was reached in the Test 3 configuration at the ultimate load of 263 kips. This stress is somewhat below the average yield stress of 44 ksi for the steel plates which is shown in Table 1, confirming the premature failure of the concrete slab.

Figures 33 and 34 show flexural stresses at cross-section 2 of Fig. 5. Although in-plane flexural stress may be expected to be lower at this cross-section compared to cross-section 1, out-of-plane displacements result in some higher surface stresses. Cross-section 2 is midway between the mid-span diaphragm and the first transverse web stiffener, and coincides with location E, Fig. 6 where relative out-of-plane displacements of the outside web were measured and shown in Fig. 29. The displacement pattern at location E in Fig. 29 is compatible with the increased stress of 46 ksi shown in Fig. 34 on the inner surface near the bottom of the outside web at the ultimate load of 263 kips. Since the average yield stress of the plate material is 44 ksi, as shown in Table 1, onset of yielding probably occurred at this point at the ultimate load.

Figures 35 and 36 show flexural stresses at cross-section 3 of Fig. 5. Out-of-plane displacements and resulting stresses are somewhat less since this cross-section is close to the transverse web stiffener.

4.5 - Yield Patterns

The outside surfaces of the steel webs and bottom flange were painted white for the purpose of observing yield patterns during the ultimate strength test. Figure 37 shows the only yield pattern that was observed. Yielding occurred in the outside web near the west support and was associated with the separation of the concrete slab and Bridgform from the top of the outside girder, as shown in Fig. 24. Figure 24 also shows the steel bars that were welded to the west end of the outside girder to reinforce this area during the ultimate strength test. Following the test, these bars were cut away as shown in Fig. 38. This figure shows the tearing of the upper part of the west end diaphragm from the outside web which occurred at a load of 200 kips (Point B, Fig. 23).

5. CONCLUSIONS

Results of an ultimate strength test of a horizonally curved steel-concrete box girder are presented. The test was performed at Fritz Engineering Laboratory, Lehigh University. Results are also presented of low-load elastic tests of the non-composite steel box girder prior to and after installation of the Bridgform which was used to support the concrete slab during construction of the composite box girder. The tests with the Bridgform in place were conducted with two different patterns of screws used to attach the Bridgform to the steel box girder. The first pattern used the screw spacing recommended by the Bridgform supplier. A closer screw spacing was used for the second pattern.

The test results of the non-composite steel box girder indicate that the steel Bridgform significantly reduced the vertical deflection of the outside web, especially when the second pattern of screws was used. With this pattern the deflection of the outside web at mid-span is about half of that attained without the Bridgform and about three-quarters of that attained when the Bridgform is attached with the recommended screw pattern. The deflection of the inside web was not significantly altered when the recommended screw pattern was used but increased somewhat with the second screw pattern. Thus, installation of the steel Bridgform with a closer screw pattern, resulted in about half the rotation of the box girder compared to the open section without the Bridgform. Analytical predictions of the box girder behavior with and without the Bridgform were not performed.

The test results of the composite box girder were inconclusive with respect to attainment of the expected ultimate strength. The manner in which the ends of the inside web were supported to prevent uplift due to the large applied torque is believed to have resulted in premature splitting and failure of the concrete slab. Crushing of the slab, buckling of the steel webs and yielding of the steel bottom flange of the composite box girder did not occur.

6. TABLES AND FIGURES

TABLE 1 - CROSS-SECTIONAL DIMENSIONS AND MATERIAL PROPERTIES*

Centerline total length	ft.	37
Centerline span length	ft.	36
Centerline radius	ft.	120
Cross-section properties:		
web depth	in.	34½
web thickness	in.	3/8
bottom flange width	in.	38
bottom flange thickness	in.	3/8
composite slab width	in.	60
composite slab thickness	in.	8
Material properties:		
Steel - F_y (average for plates)	ksi	44
Concrete - f'_c	psi	4,300
- f'_{sp}	psi	500
Reinforcement - F_y	ksi	60

* Refer to Ref. 2 for further information.

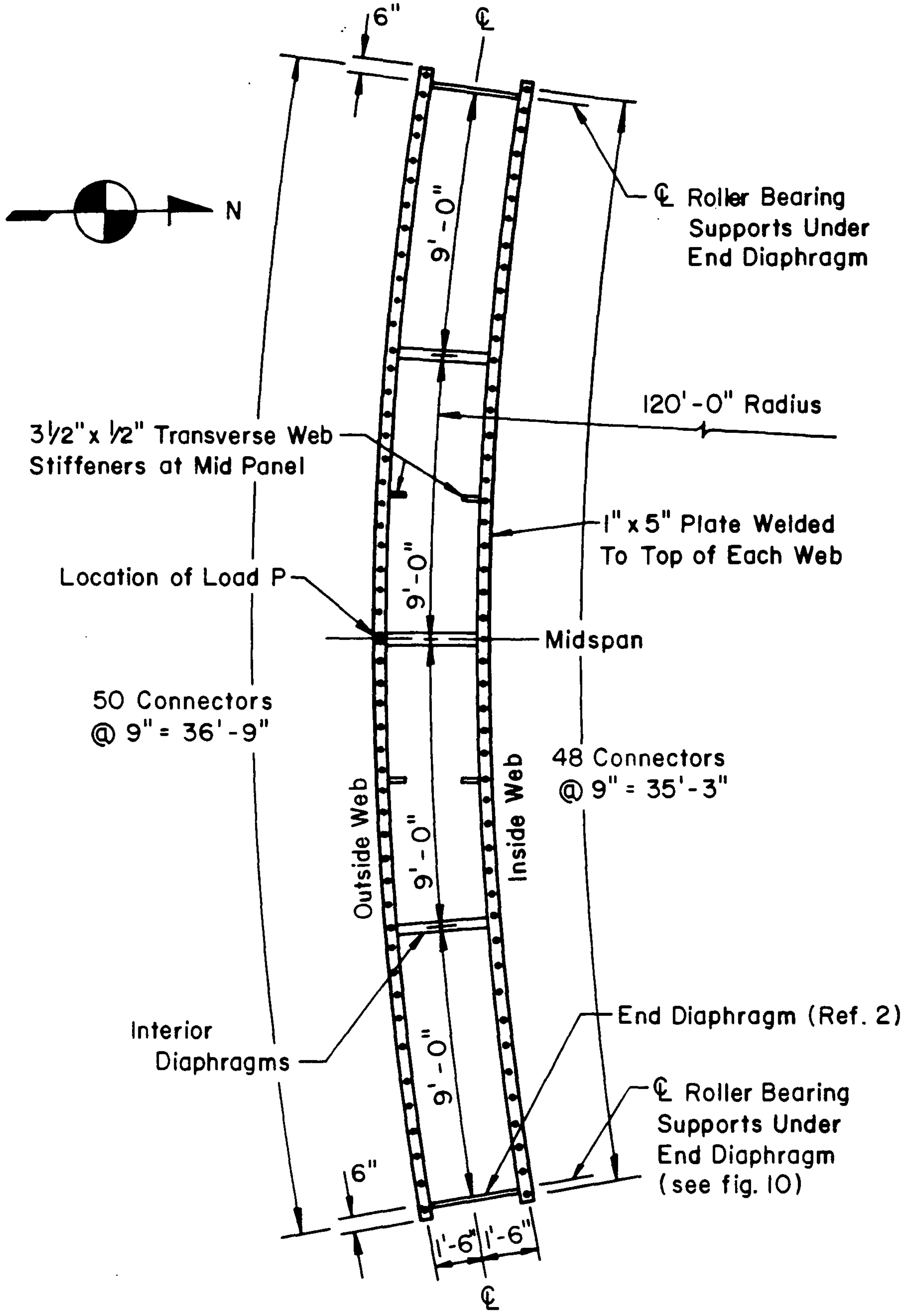
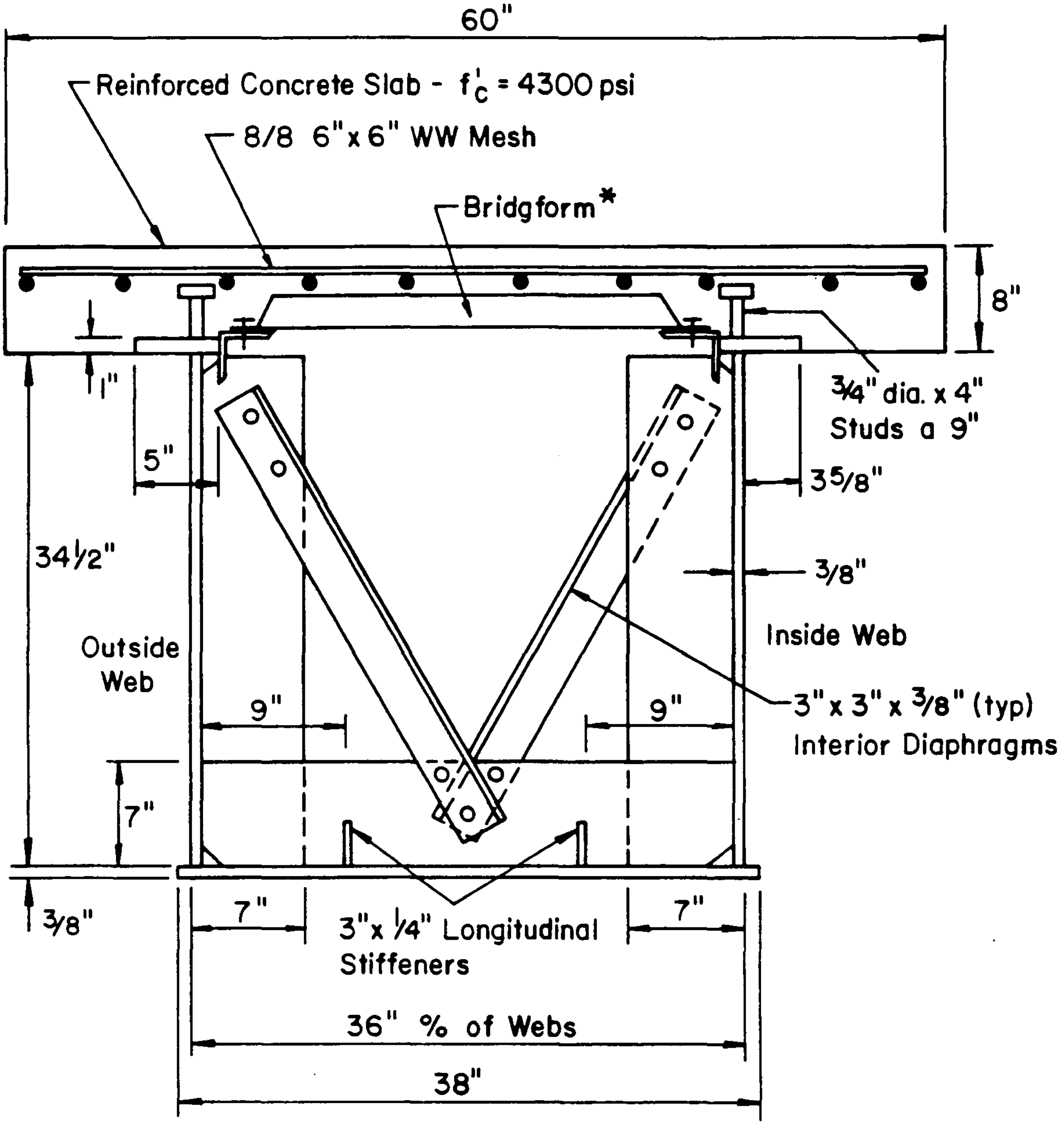


Fig. 1 Plan View of Box Girder At Top of Steel (See Fig. 2)



* 18 Sheets Bridgform, 22 gage, 6 1/2" Pitch, ASTM A-446 Grade E, 2 1/2" Nom. Depth, Connected to 2 1/4" x 3 1/2" Type 24 Angles With SUPER TEK/3 Screws Described in Art. 3.2.2

Fig. 2 - Cross Section of Box Girder at the Midspan Diaphragm (See Fig. 1)

Fig. 3 Box Girder Prior to Pouring Slab

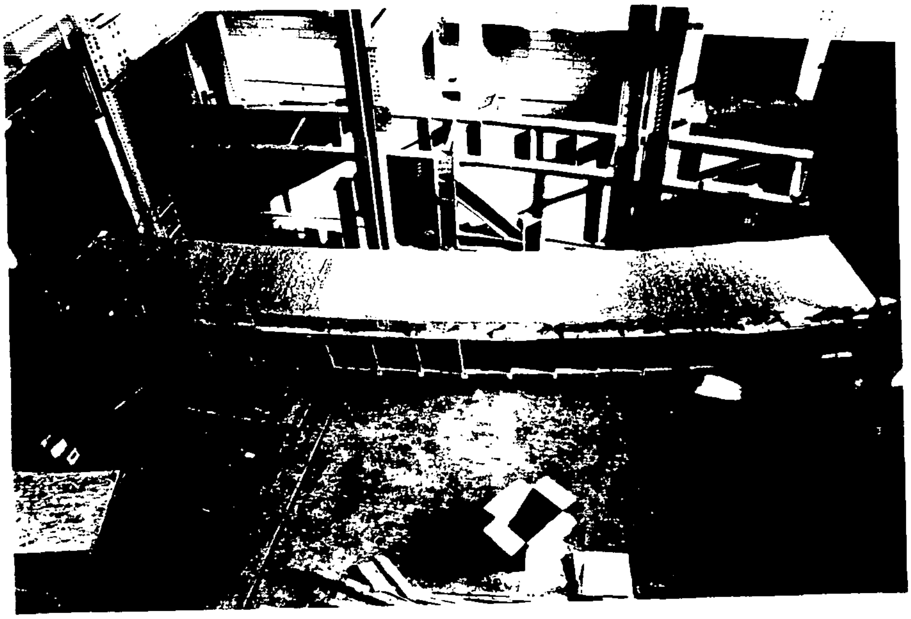


Fig. 4 Box Girder After Pouring Slab

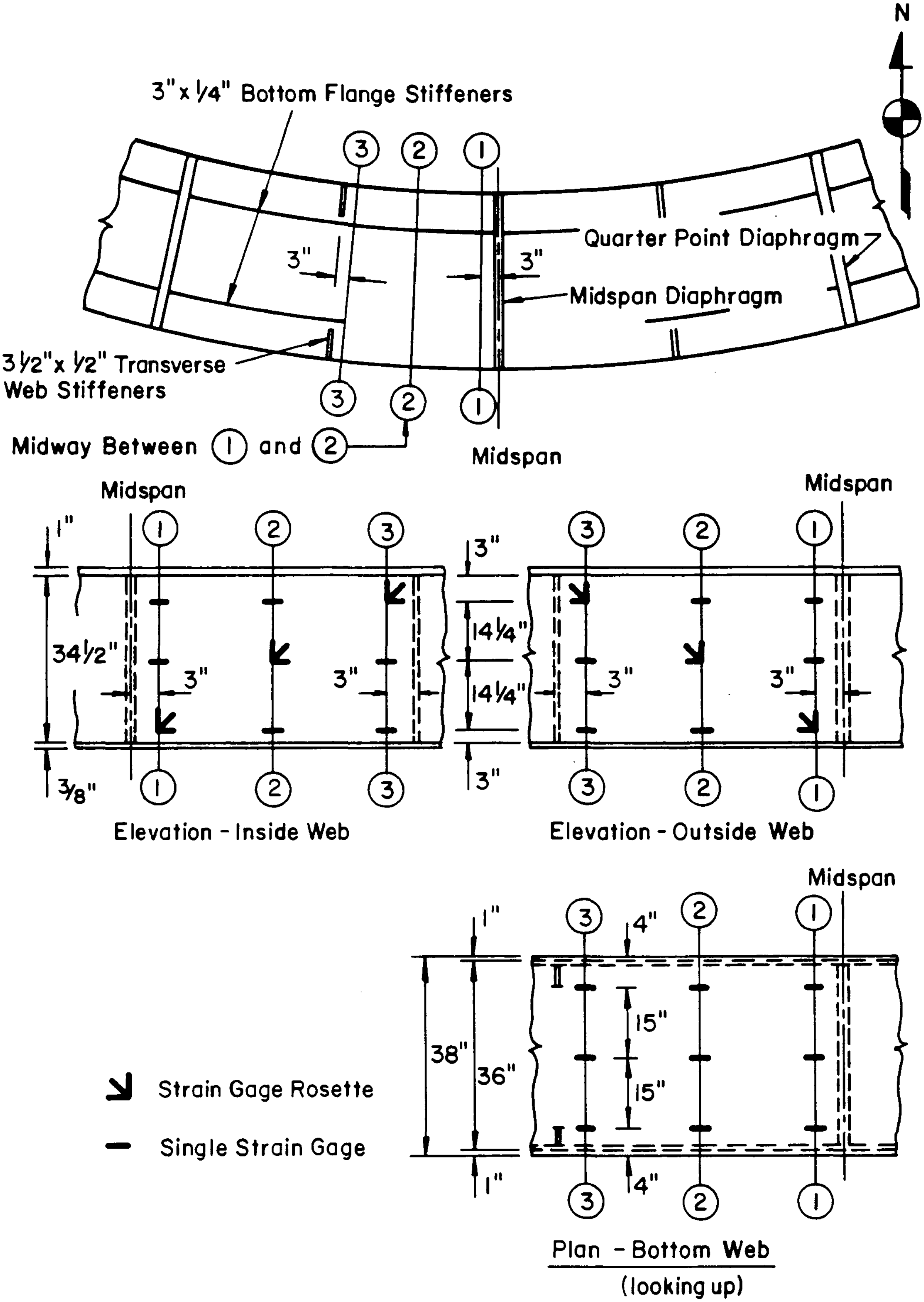
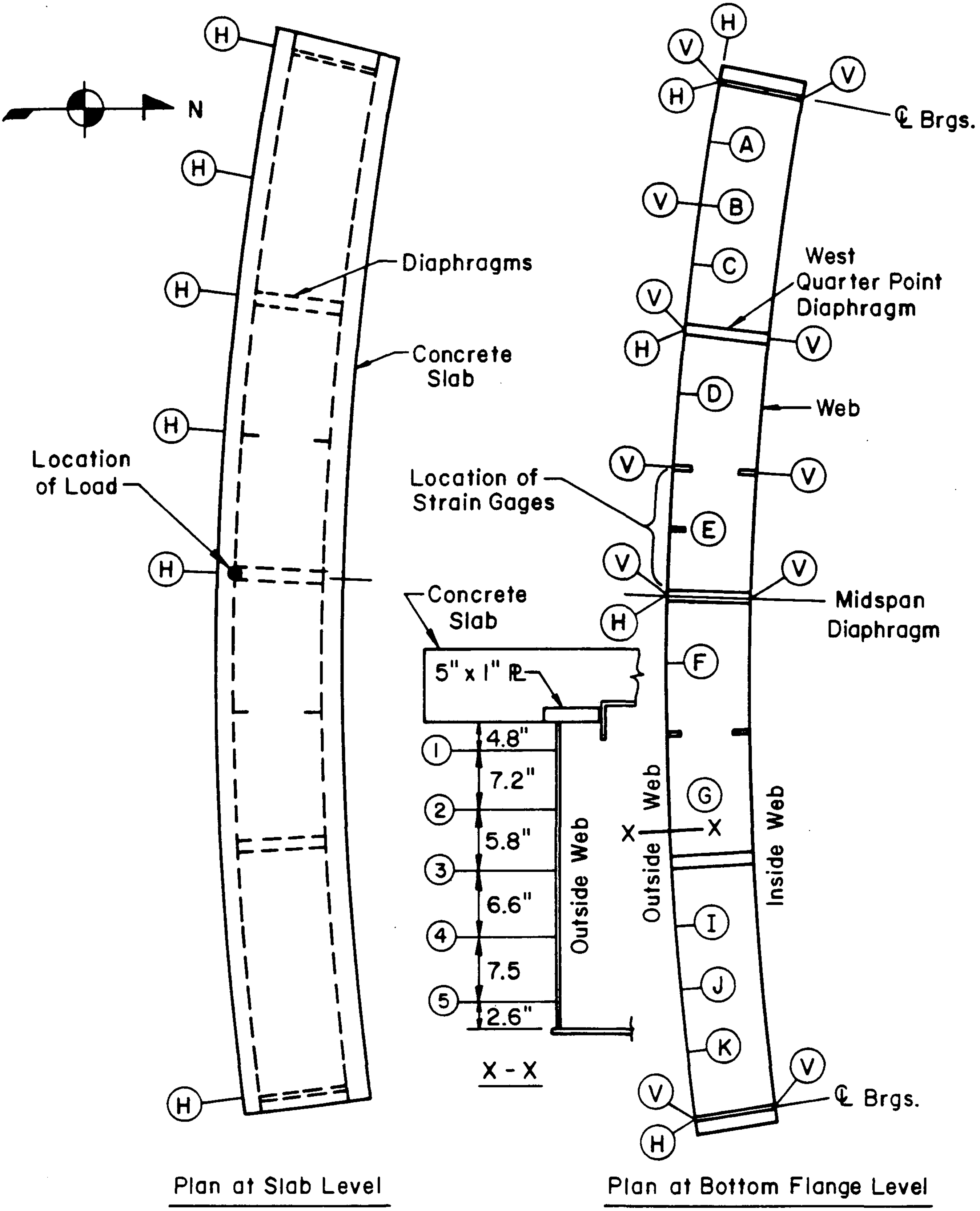


Fig. 5 - Locations of Electrical Resistance Strain Gages



Plan at Slab Level

Plan at Bottom Flange Level

Fig. 6 - Locations of Ames Dial Gages

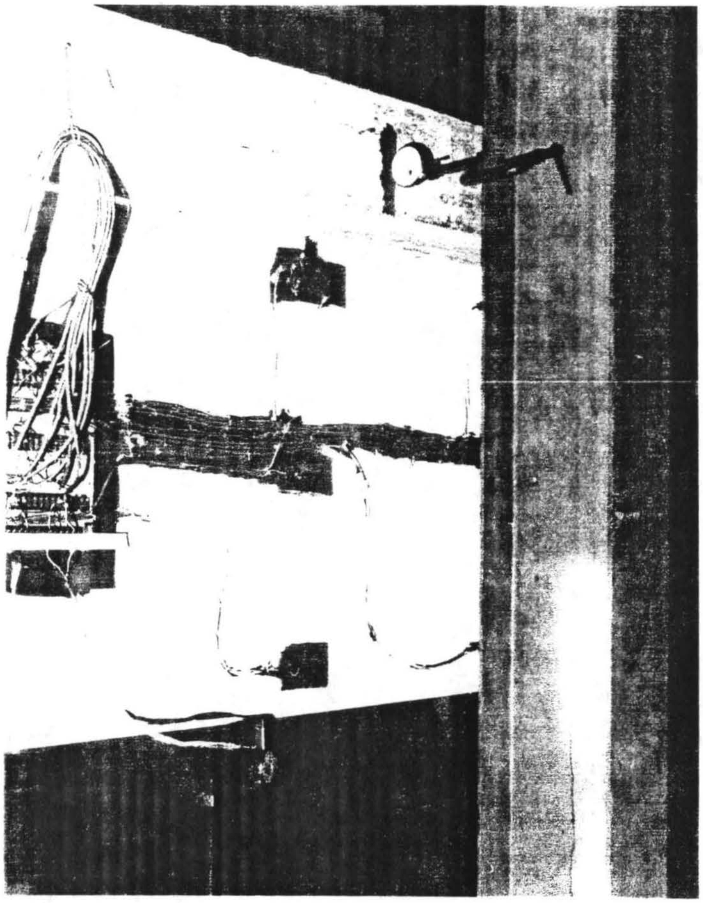


Fig. 7 View of Some of the Strain Gages and Ames Dial Deflection Gages

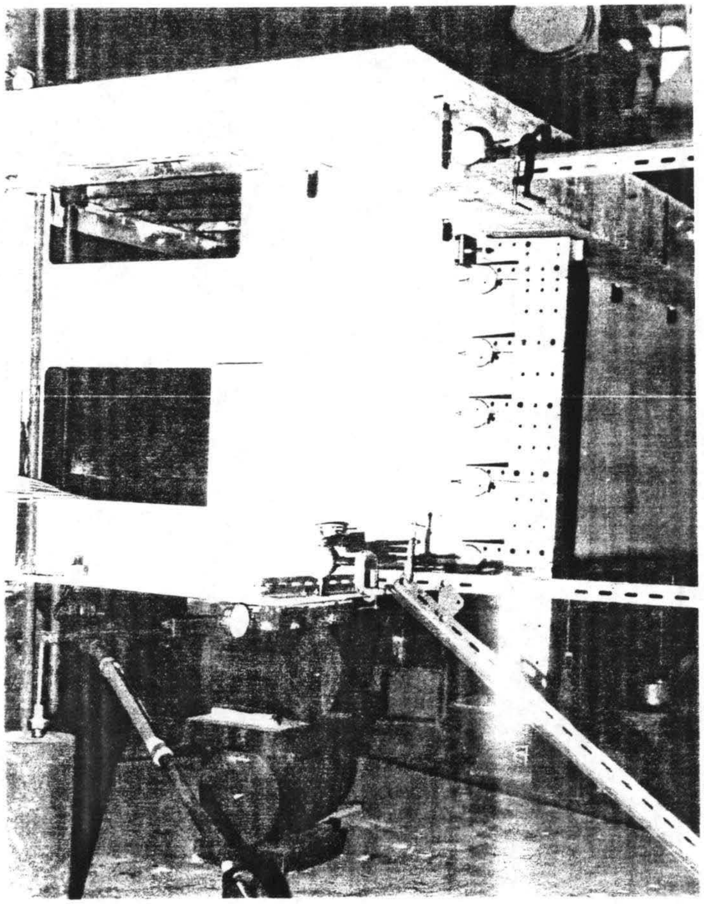


Fig. 8 View of Device Used to Measure
Web Out-Of-Plane Displacements

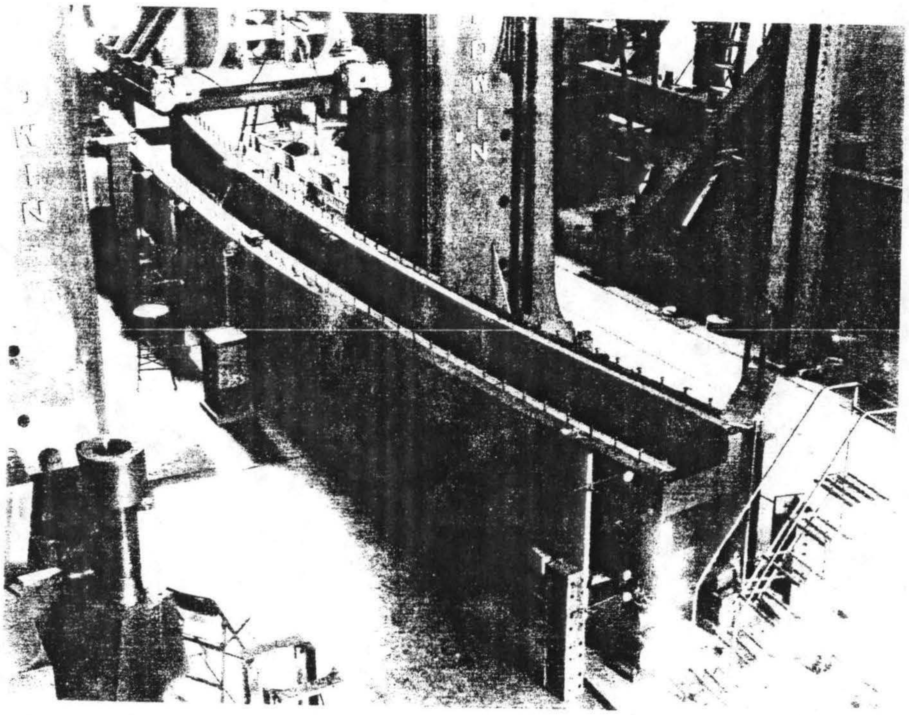


Fig. 9 View of Non-Composite Box Girder Prior to Testing

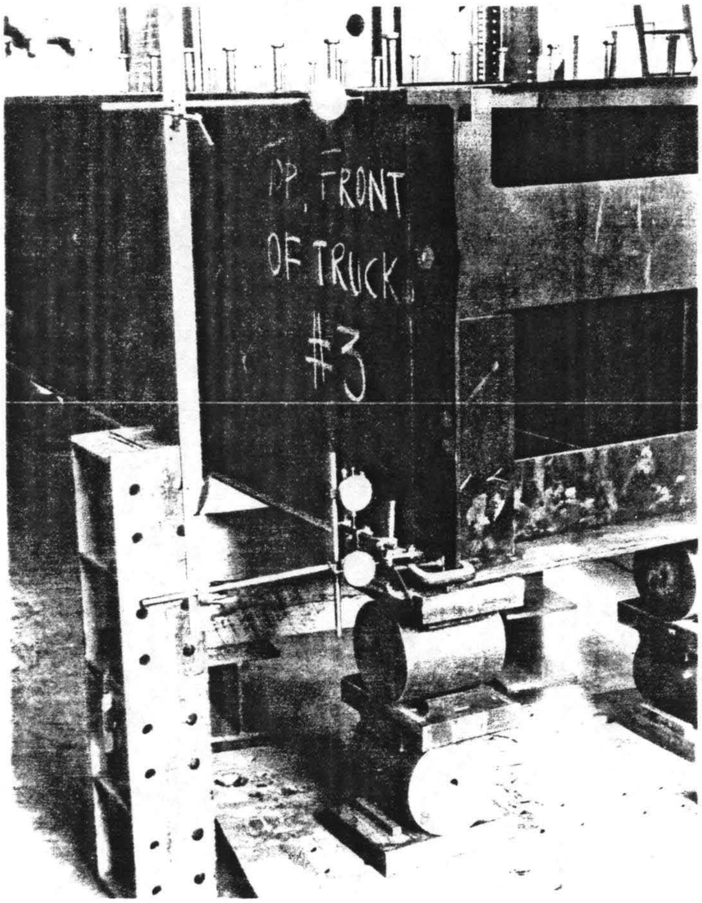


Fig. 10 View of Roller Assemblies Used at Each of the Four Supports

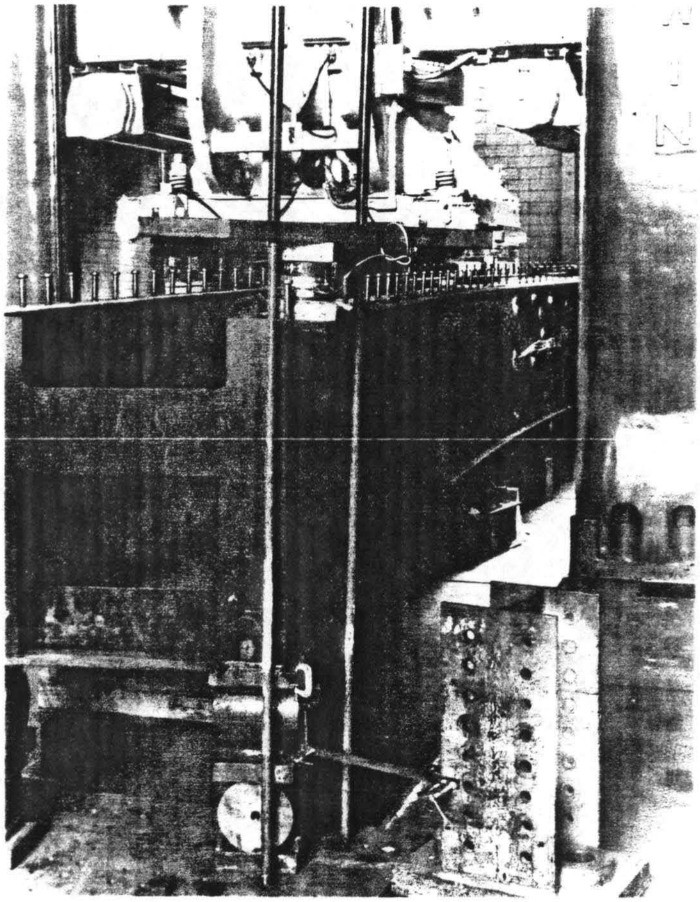


Fig. 11 View of Tension Rods and Load Cells Used to Prevent Uplift at each end of the Inside Web

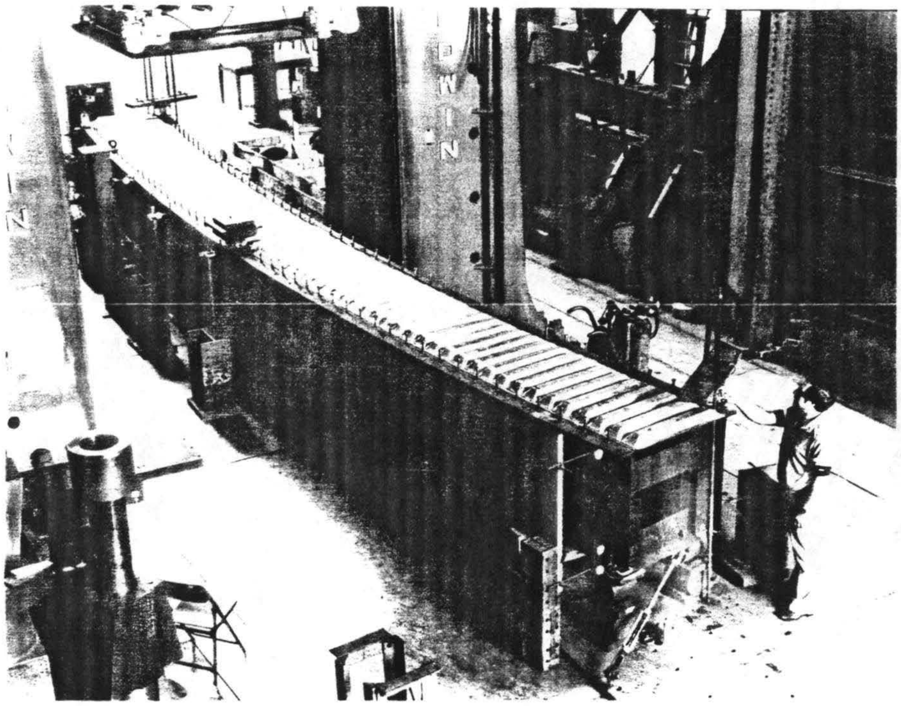


Fig. 12 View of Box Girder with Bridge form in place prior to Testing

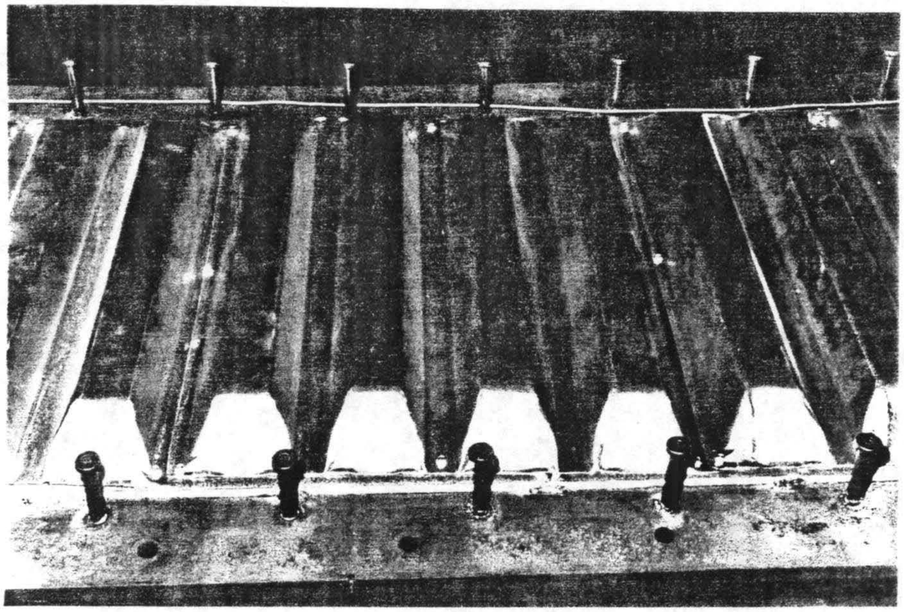


Fig. 13 - Screw Configuration Used in Test 2A and Described in Art. 3.2.2.

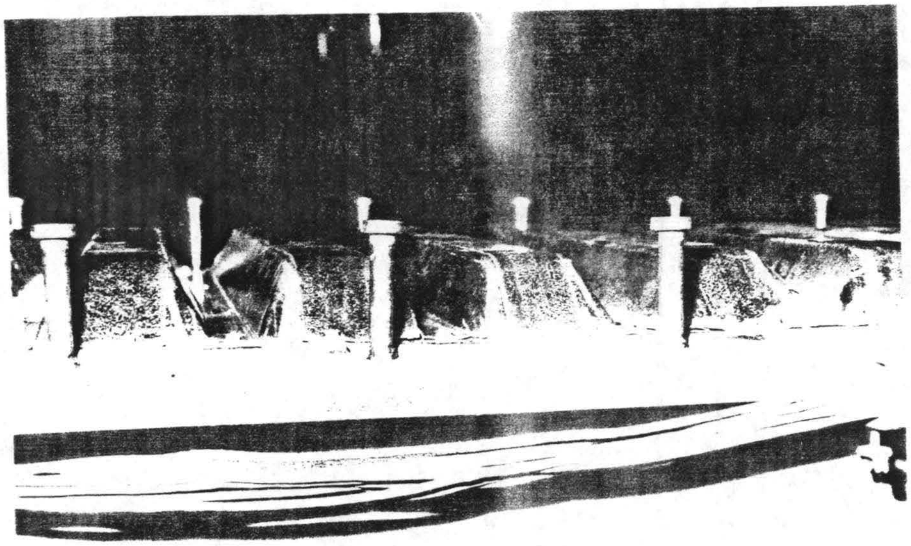


Fig. 14 Screw Configuration Used in Test 2B and Described in Art. 3.2.2.

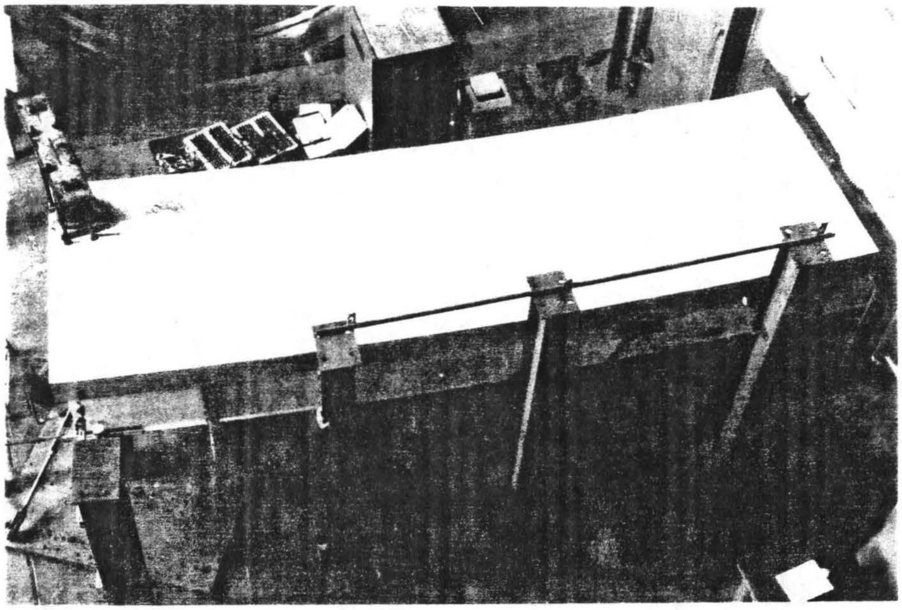


Fig. 15 View of Composite Box Girder Prior to the Ultimate Strength Test

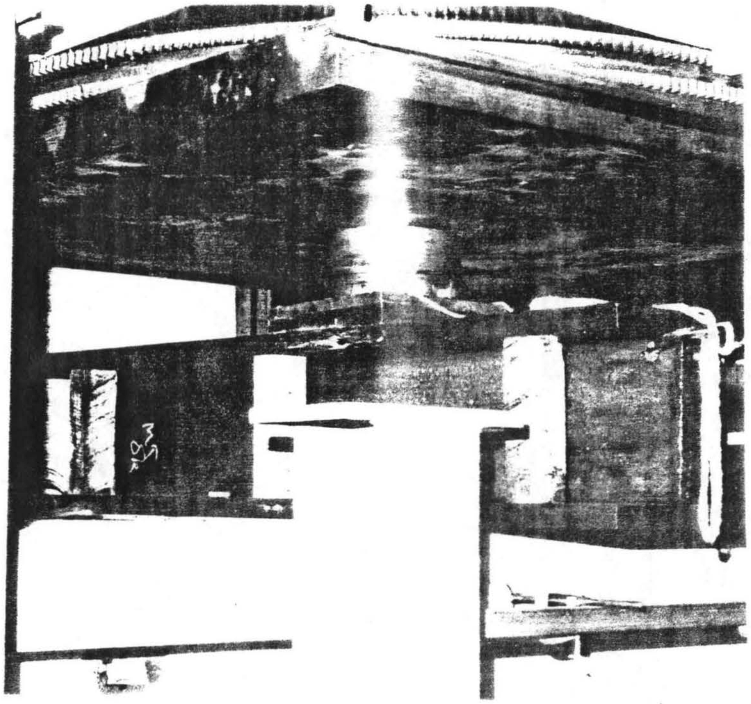


Fig. 16 View of Point of Load Application

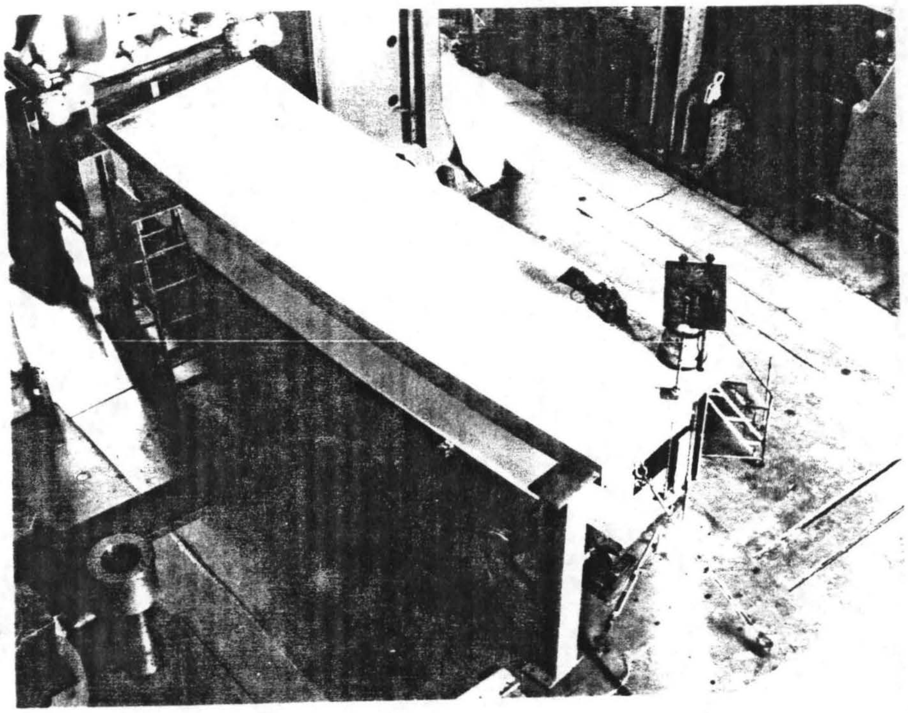


Fig. 17 View of Girder showing Compression Load Cell at ends of the Web

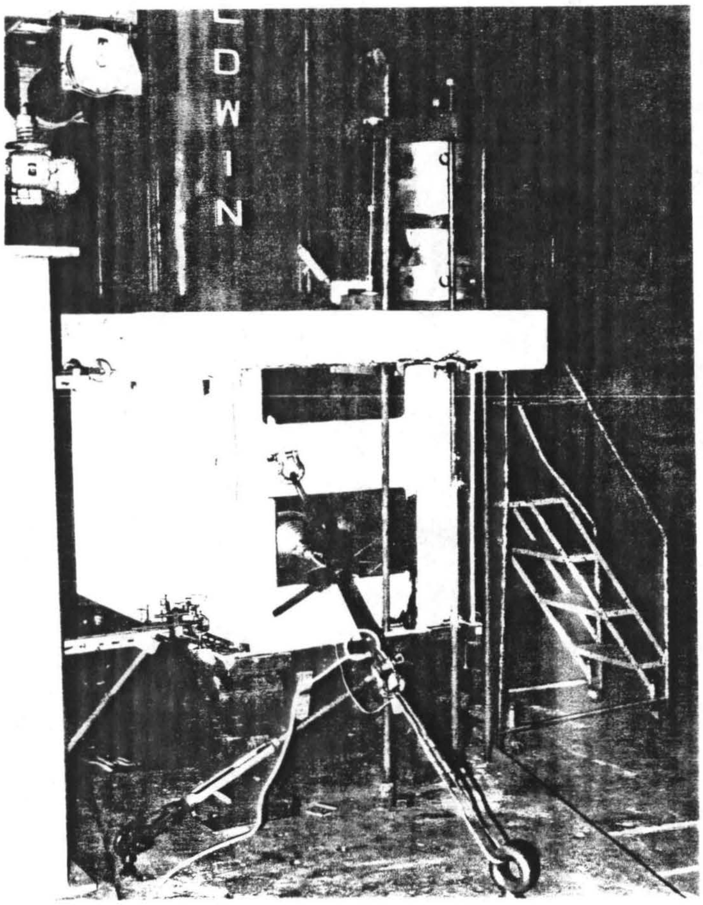


Fig. 18 View of East End of Girder Showing Compression Load Cell and Two Orthogonal Rigid Body Restraints

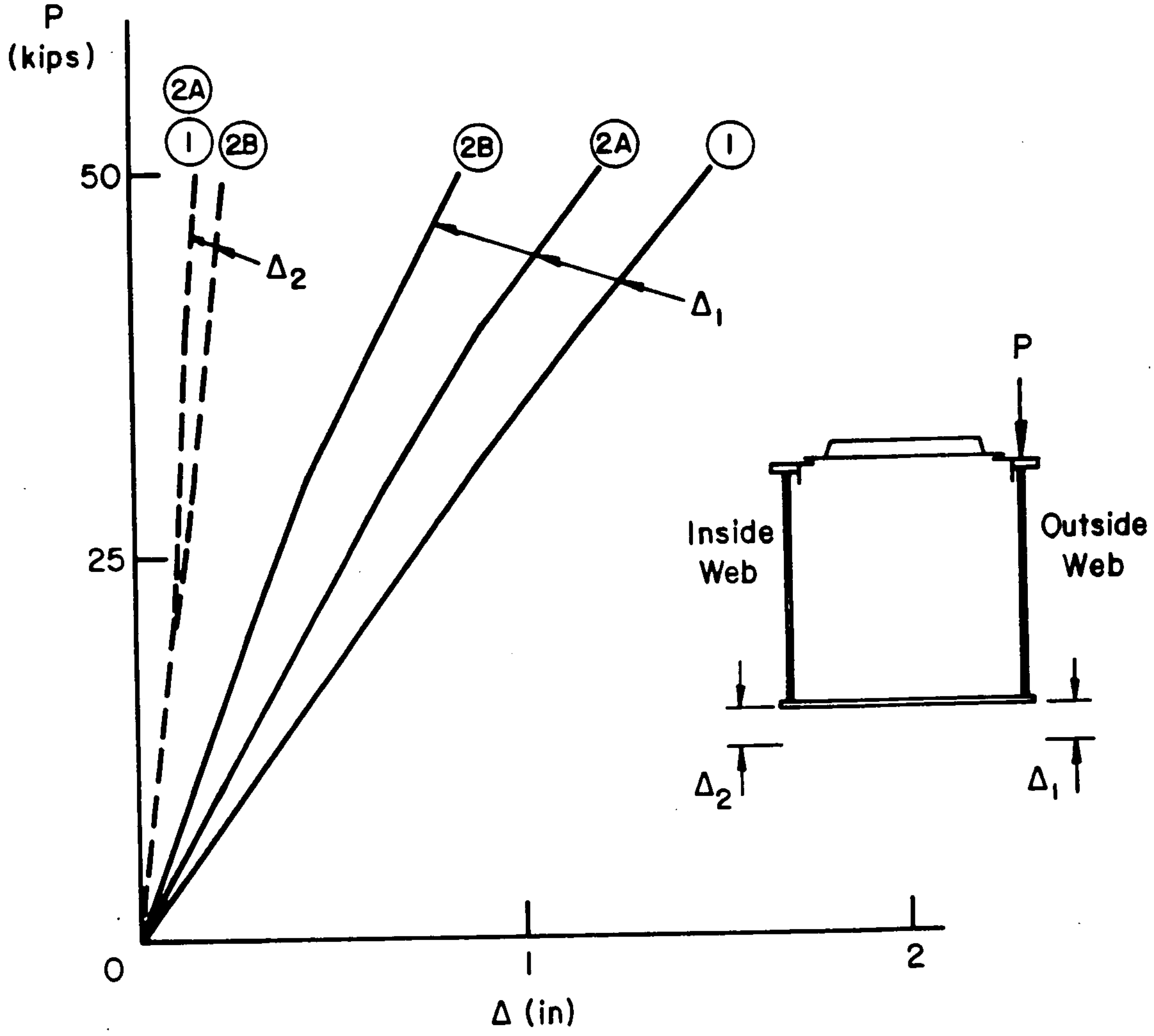


Fig. 19 - Midspan Load-Deflection Behavior
Tests 1, 2A and 2B

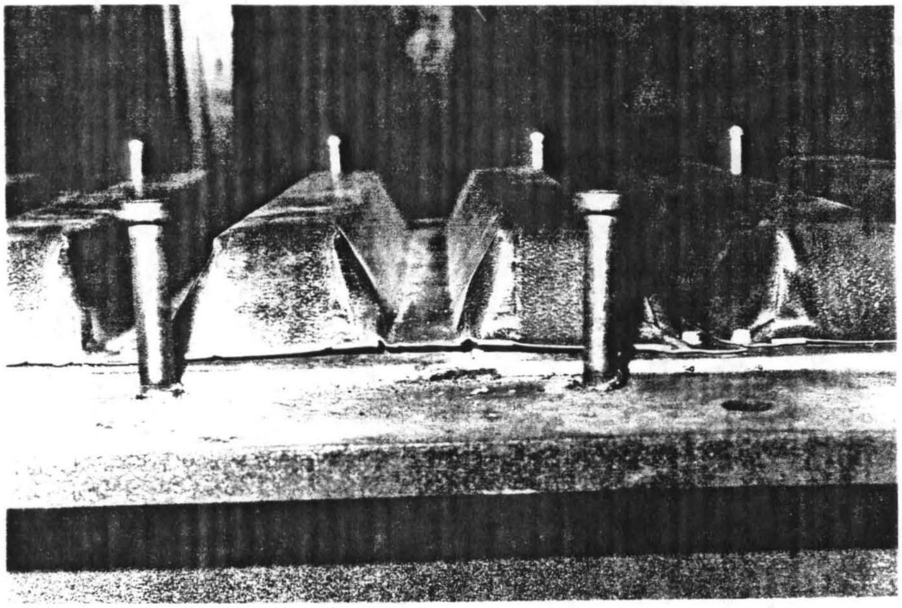


Fig. 20 Upward Lifting of Bridgform Between Fasteners Over the Outside Web at a Load of 20 Kips

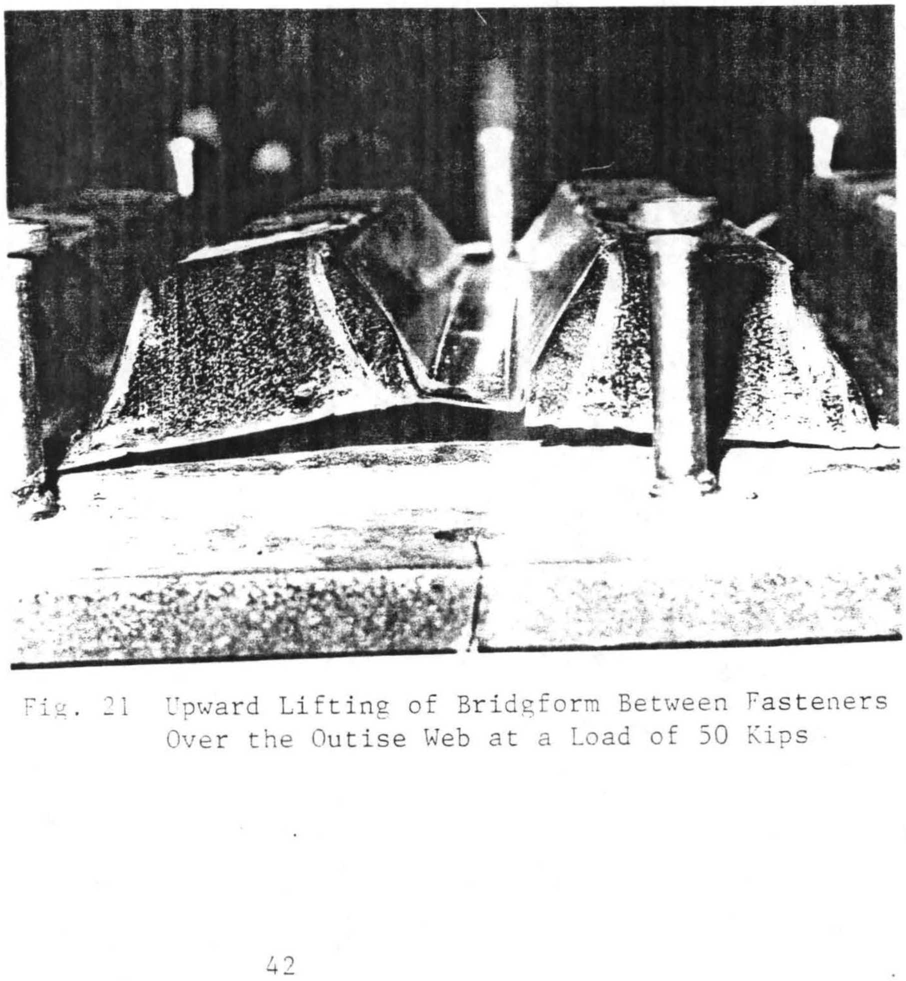


Fig. 21 Upward Lifting of Bridgform Between Fasteners Over the Outise Web at a Load of 50 Kips

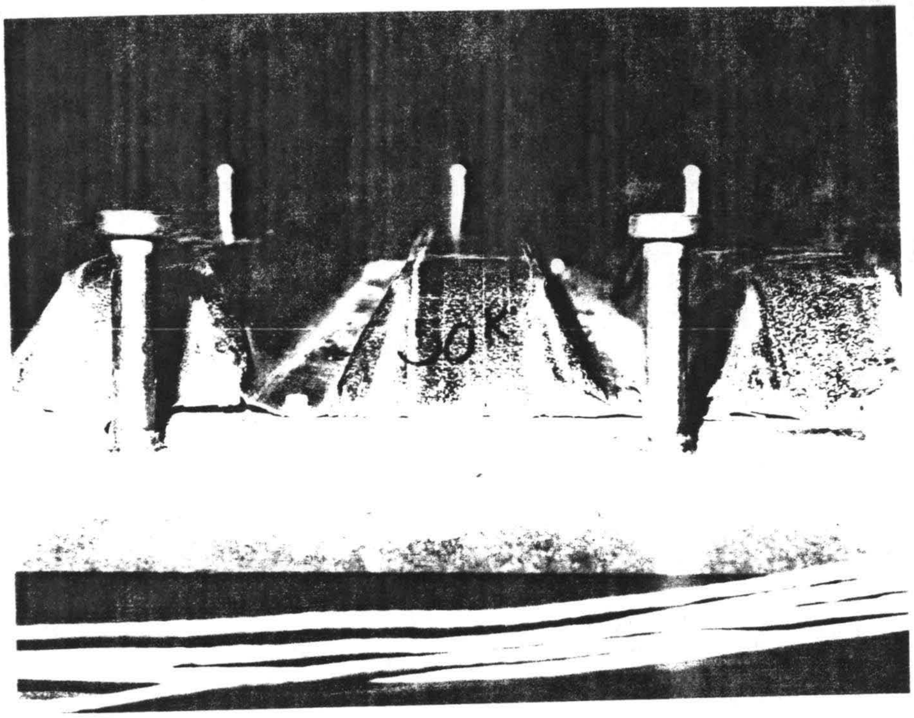


Fig. 22 Behavior of Bridgform Over the Exterior Web at a Load of 50 Kips

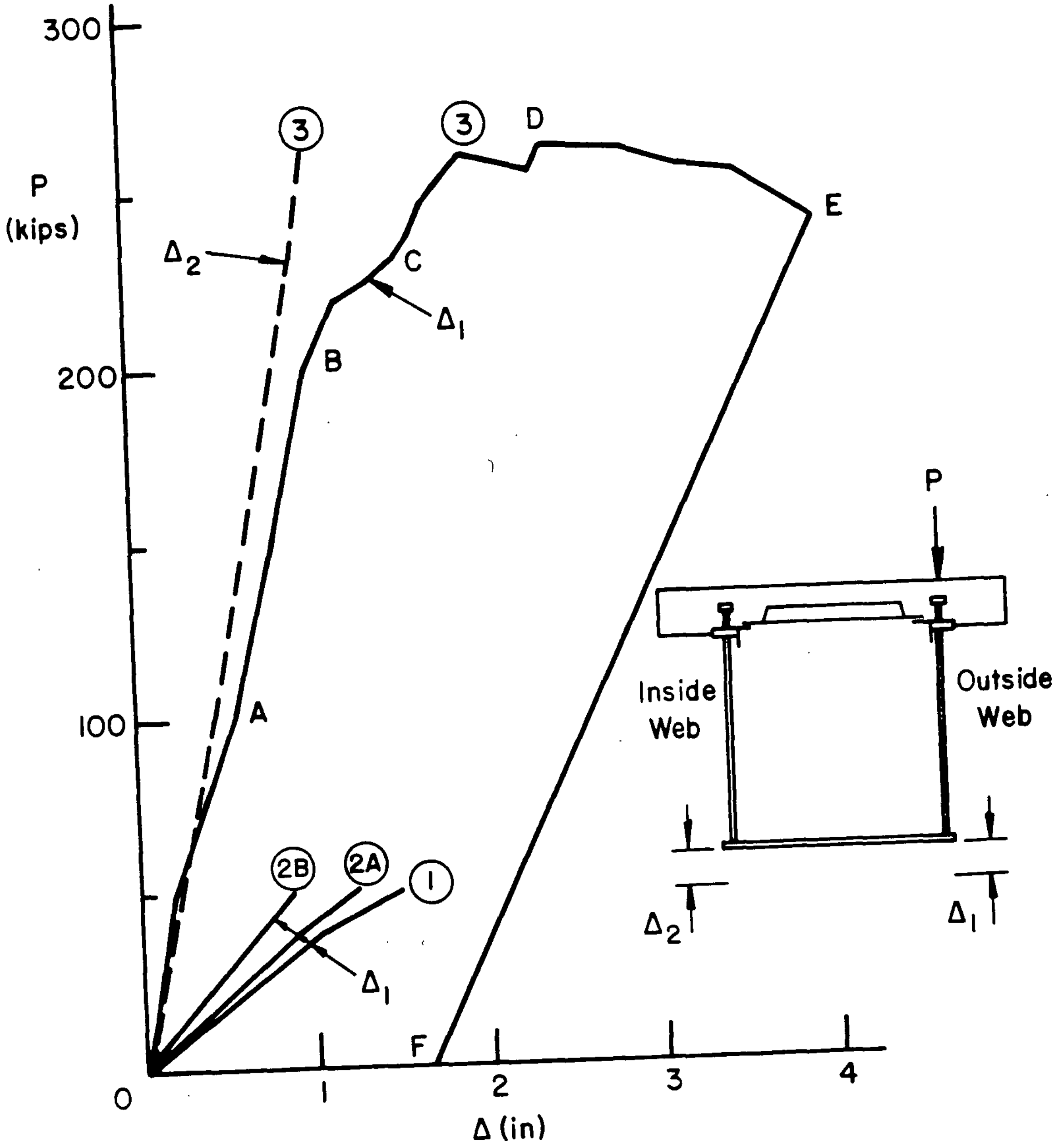


Fig. 23 - Midspan Load-Deflection Behavior
Tests 1, 2A, 2B and 3

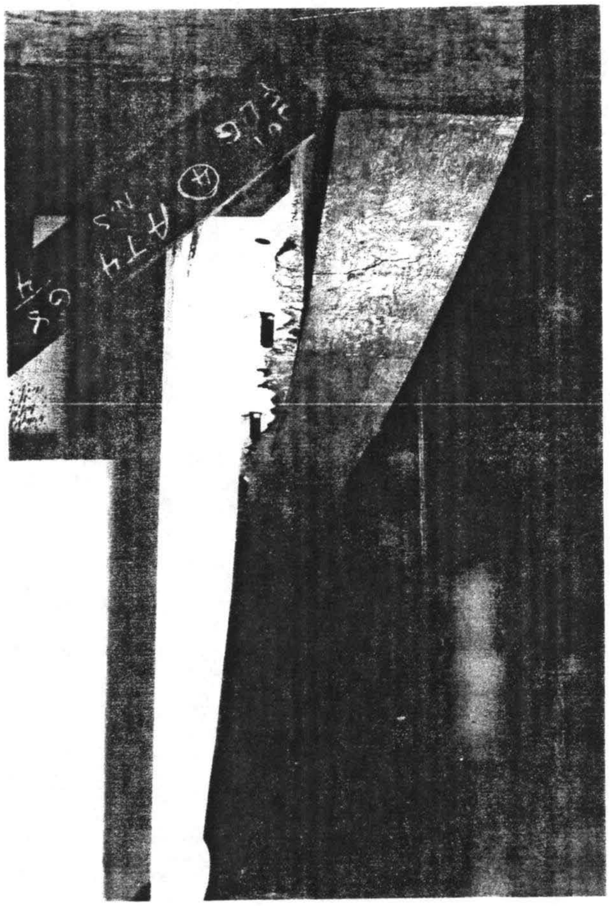


Fig. 24 Separation of Concrete Slab and Bridgform from the Top of the Outside Girder - West End

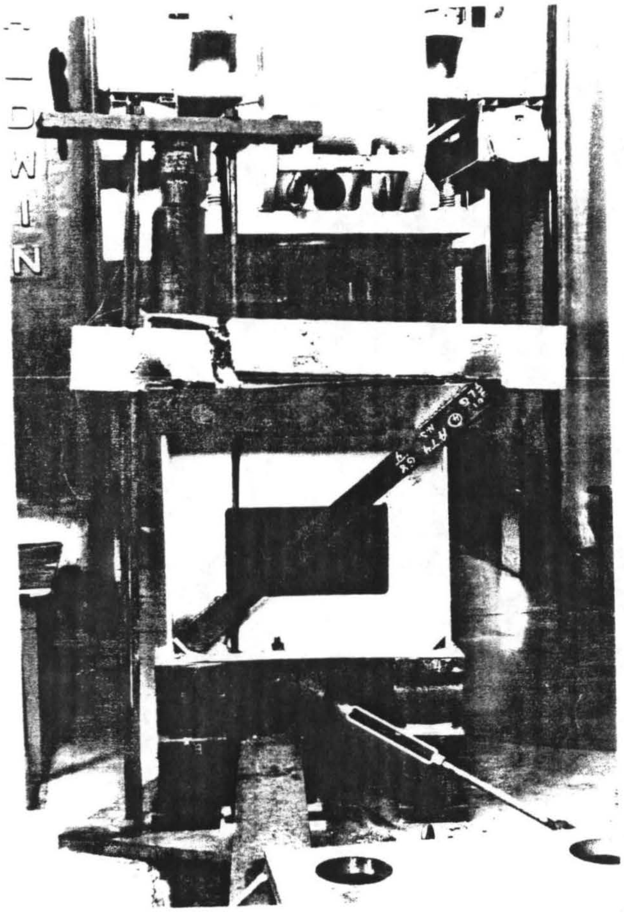


Fig. 25 West End of Girder with Outside Web on the Right

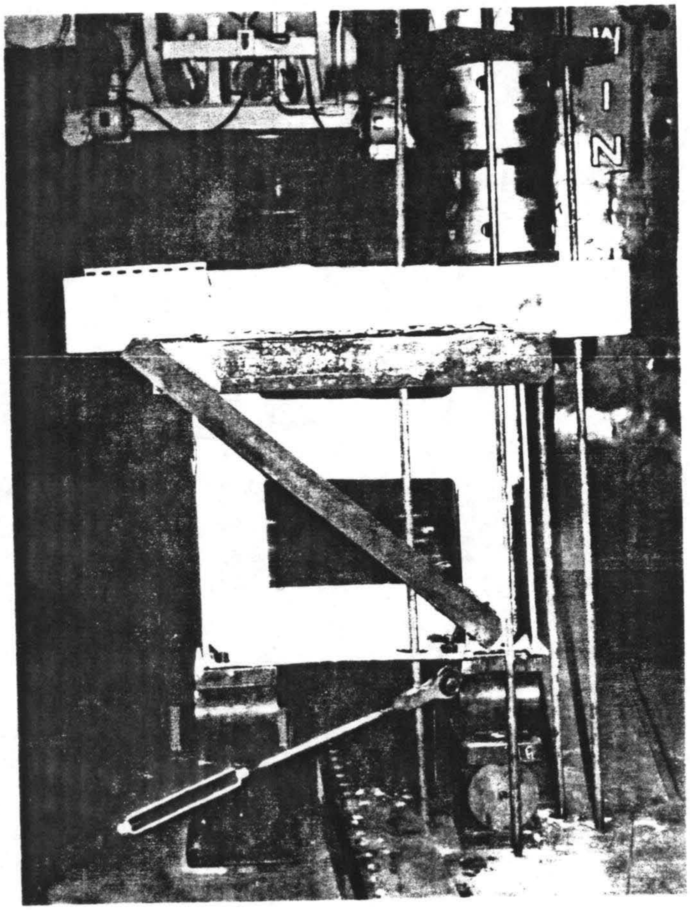


Fig. 26 East End of Girder With Outside Web on the Left

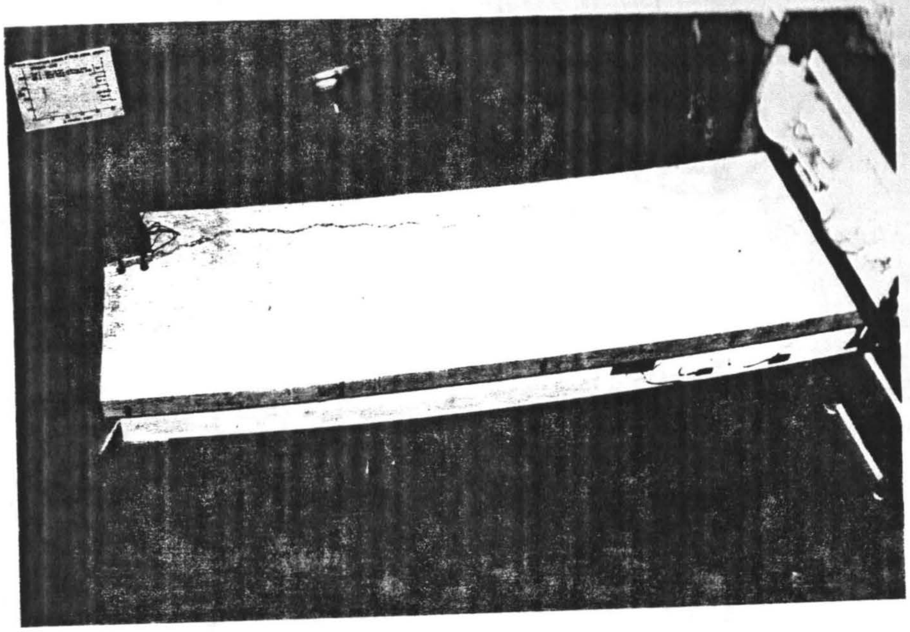


Fig. 27 West Half of Girder at the Ultimate Load

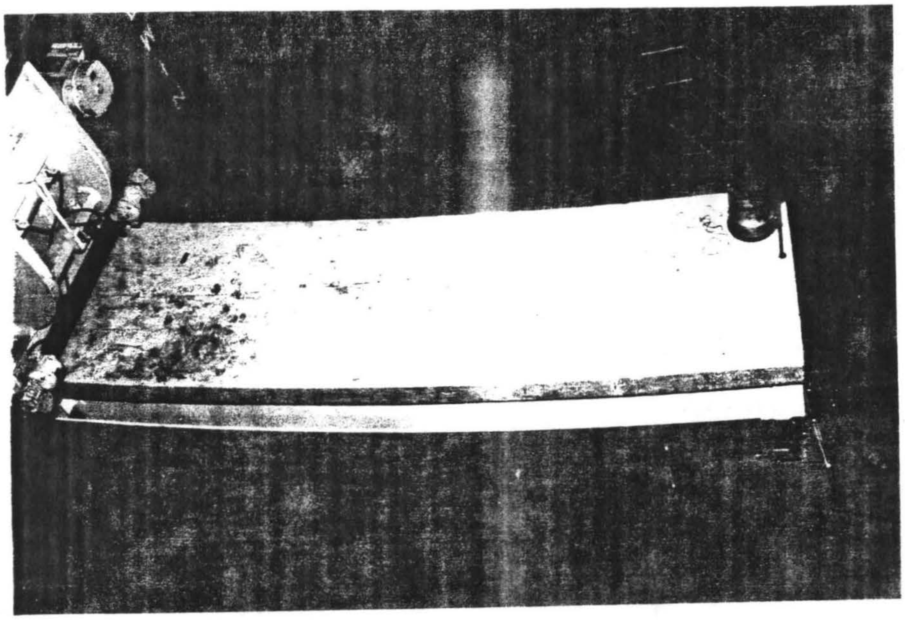


Fig. 28 East Half of Girder at the Ultimate Load

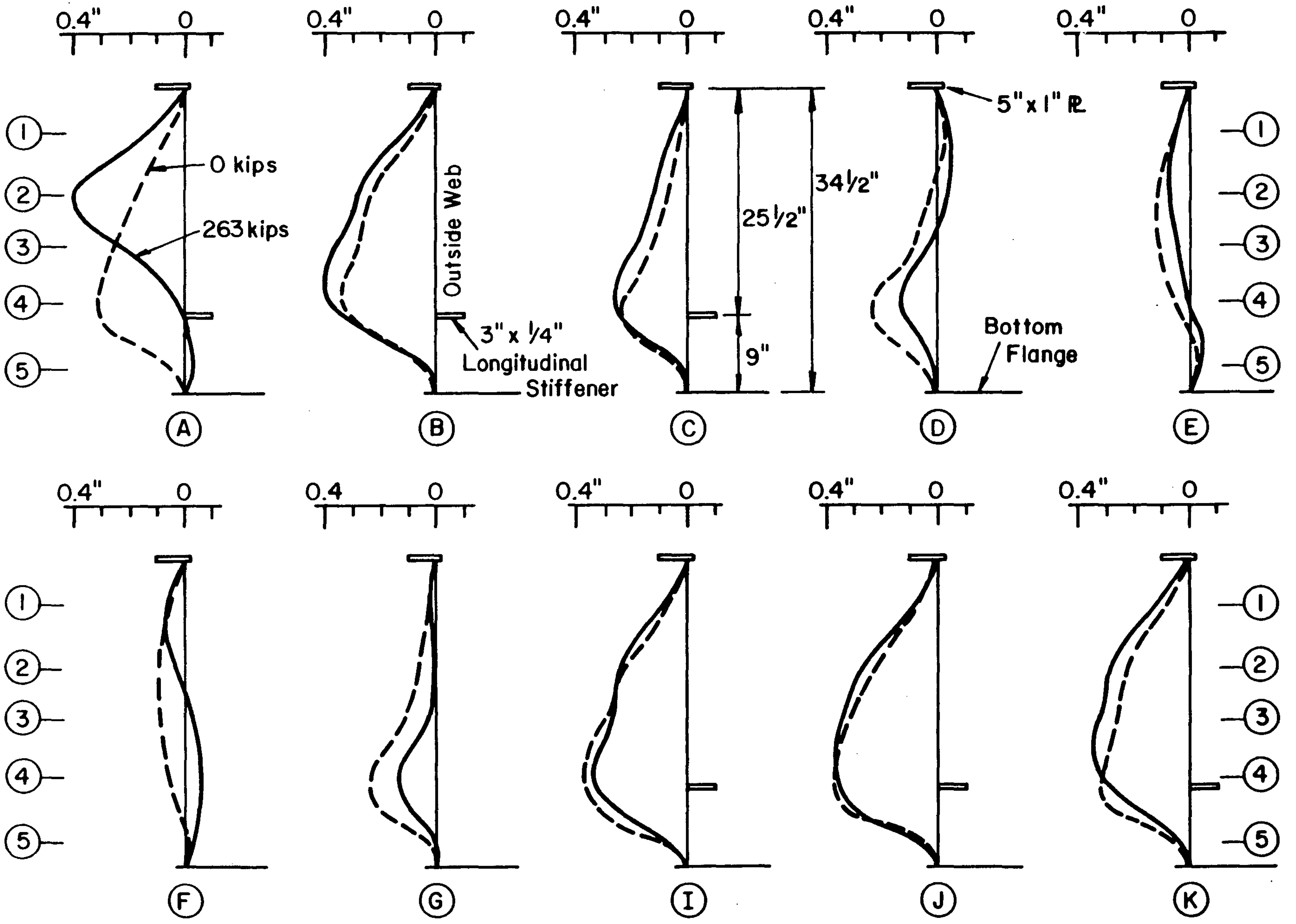
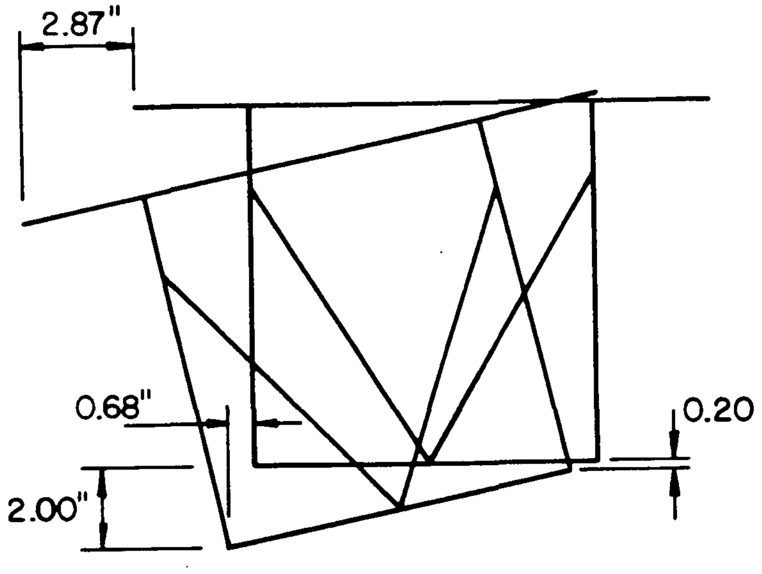
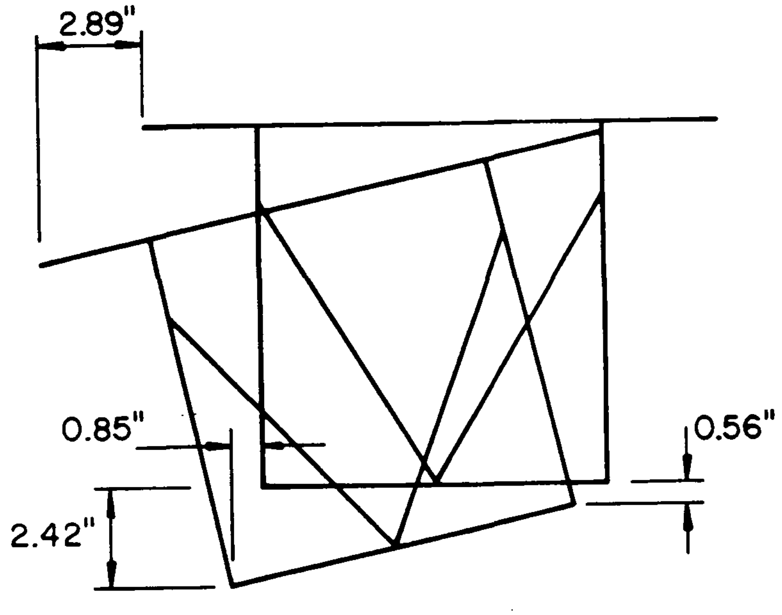


Fig. 29 - Measured Out-of-Plane Displacements of the Outside Web



(a) At West Quarter - Point Diaphragm



(b) At Midspan Diaphragm

Fig. 30 - Measured Girder Displacements at the Ultimate Load of 263 Kips

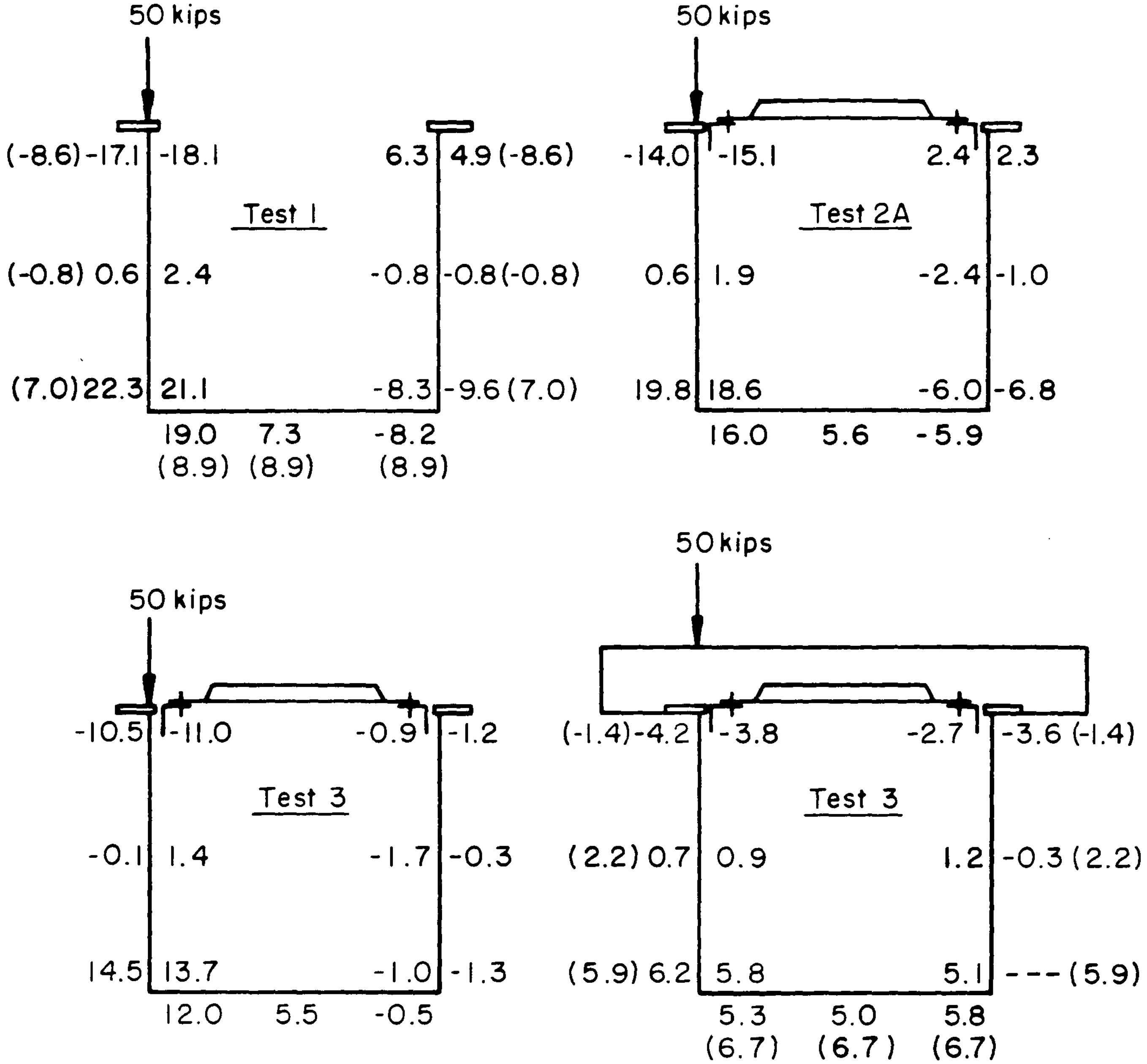


Fig. 31 - Flexural Stresses (Ksi) at
Cross-Section 1 of Fig. 5

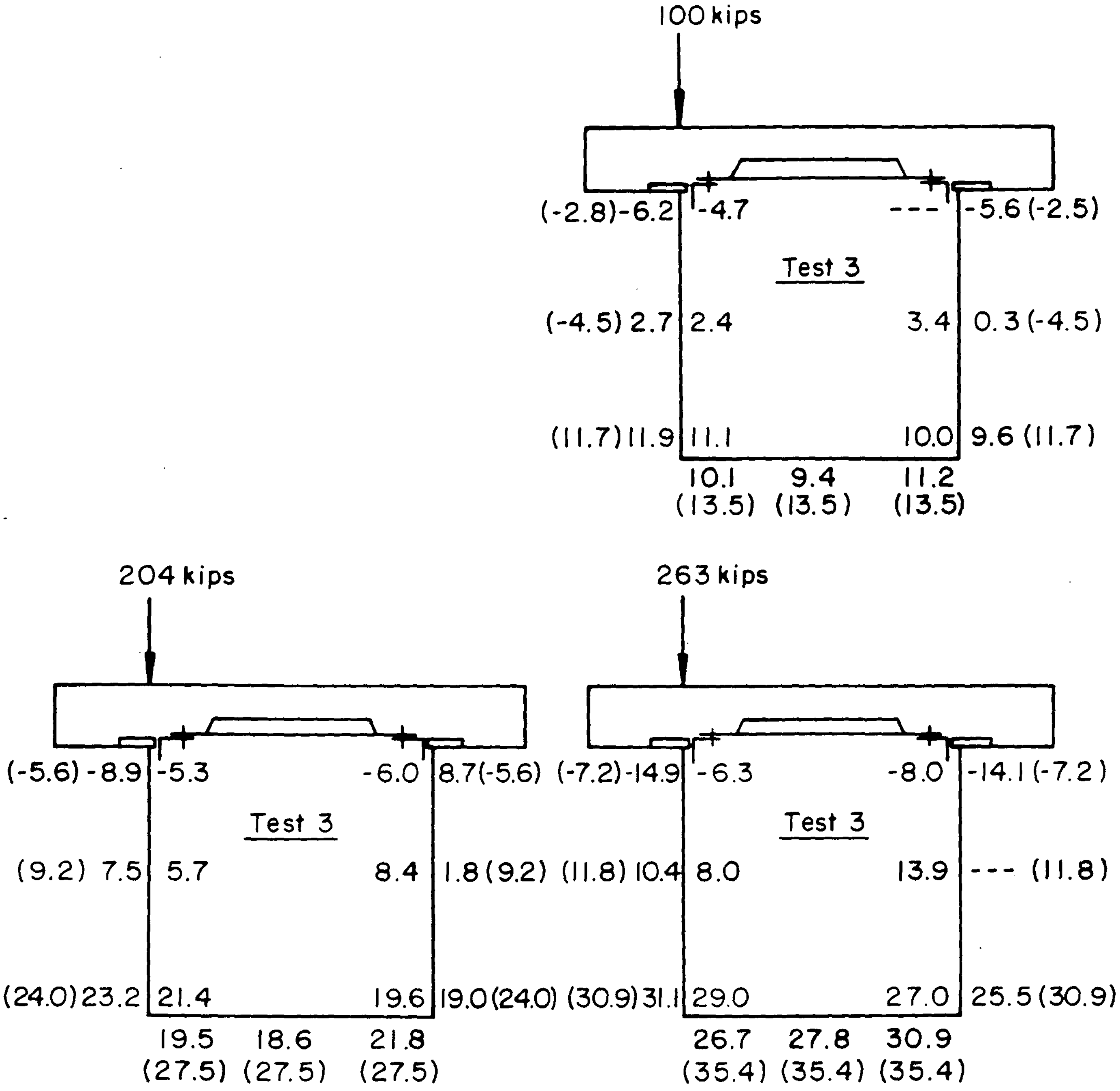


Fig. 32 - Flexural Stresses (Ksi) at Cross-Section 1 of Fig. 5

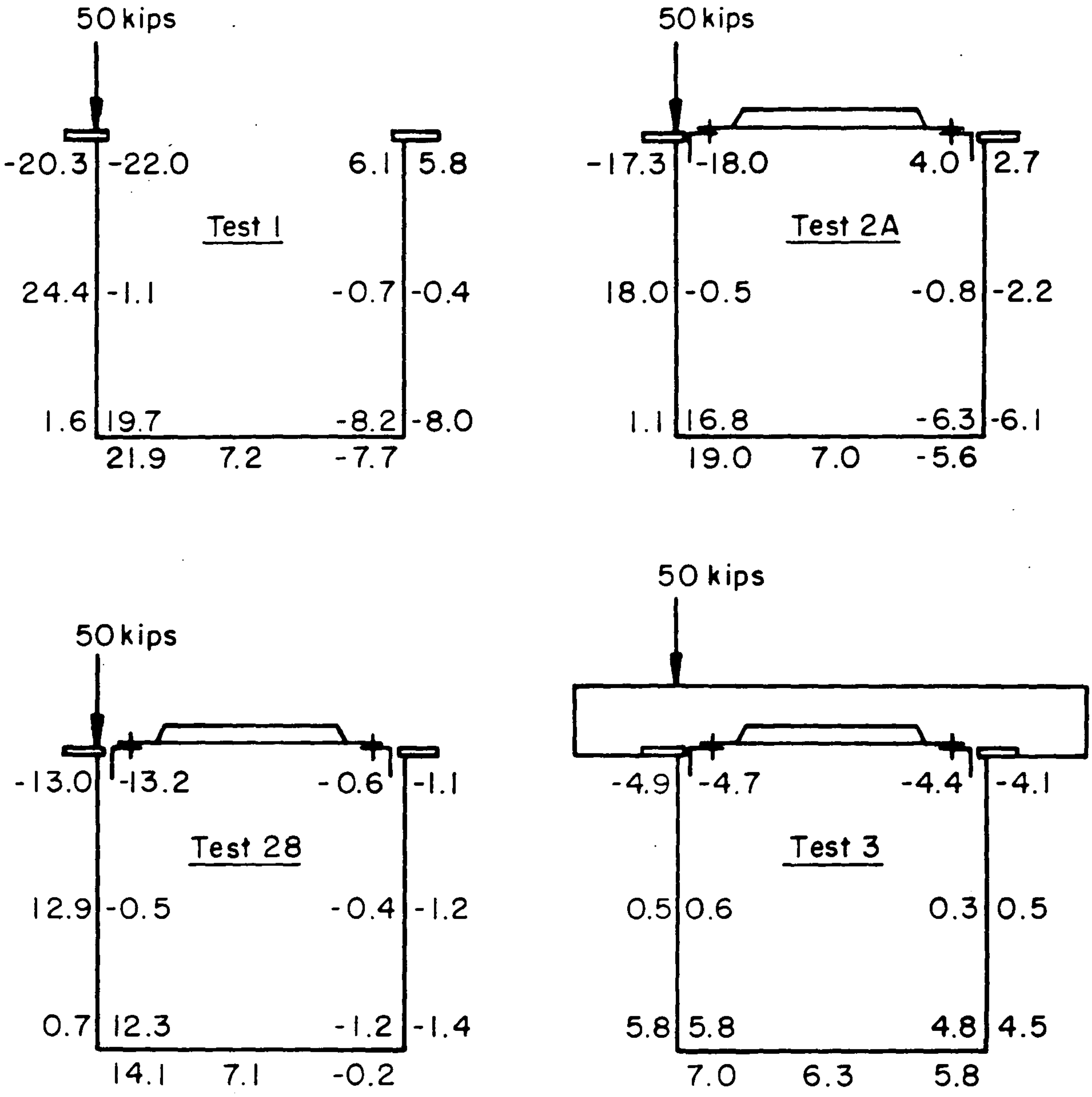


Fig. 33 - Flexural Stresses (Ksi) at Cross-Section 2 of Fig. 5

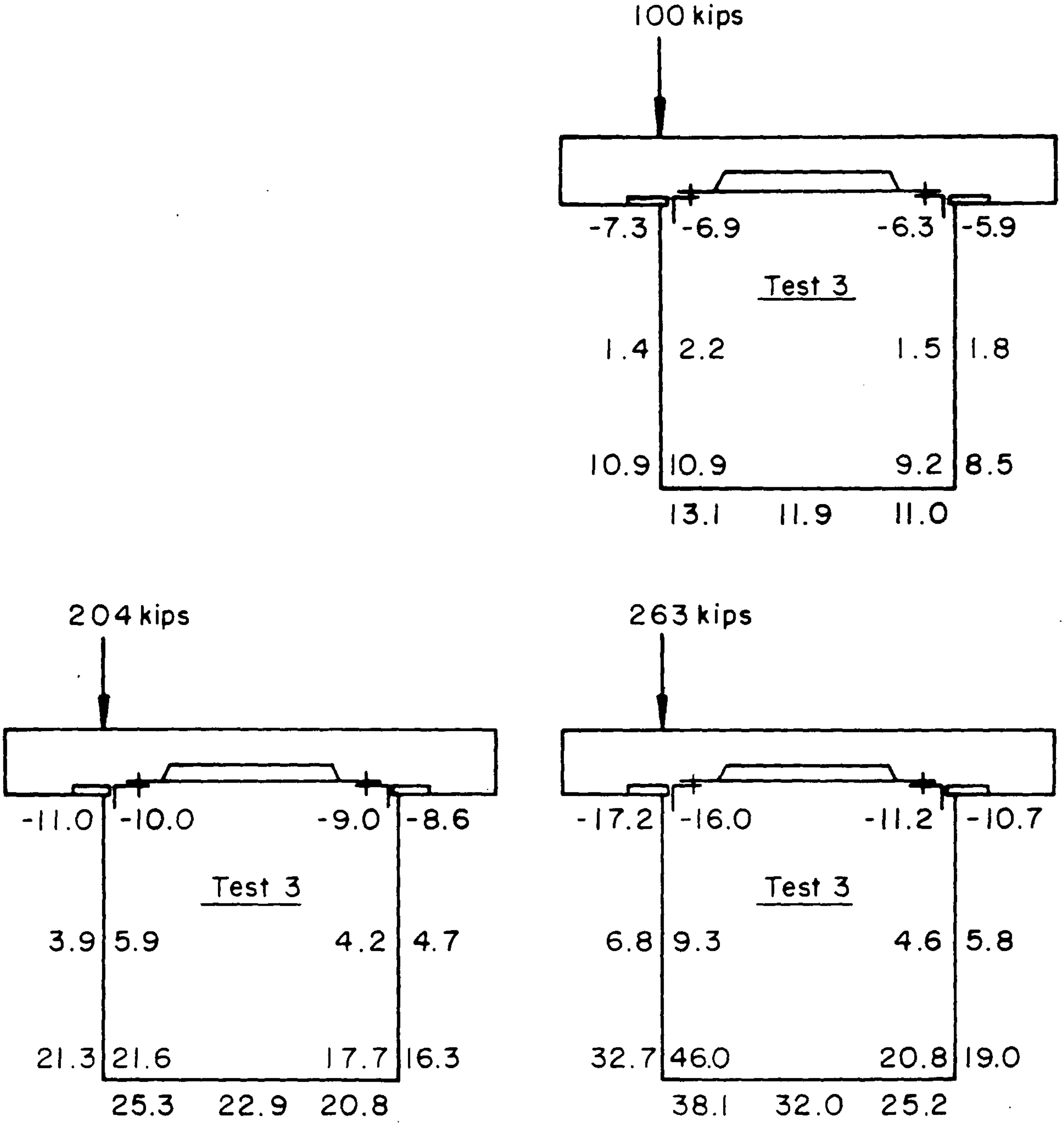


Fig. 34 - Flexural Stresses (Ksi) at Cross-Section 2 of Fig. 5

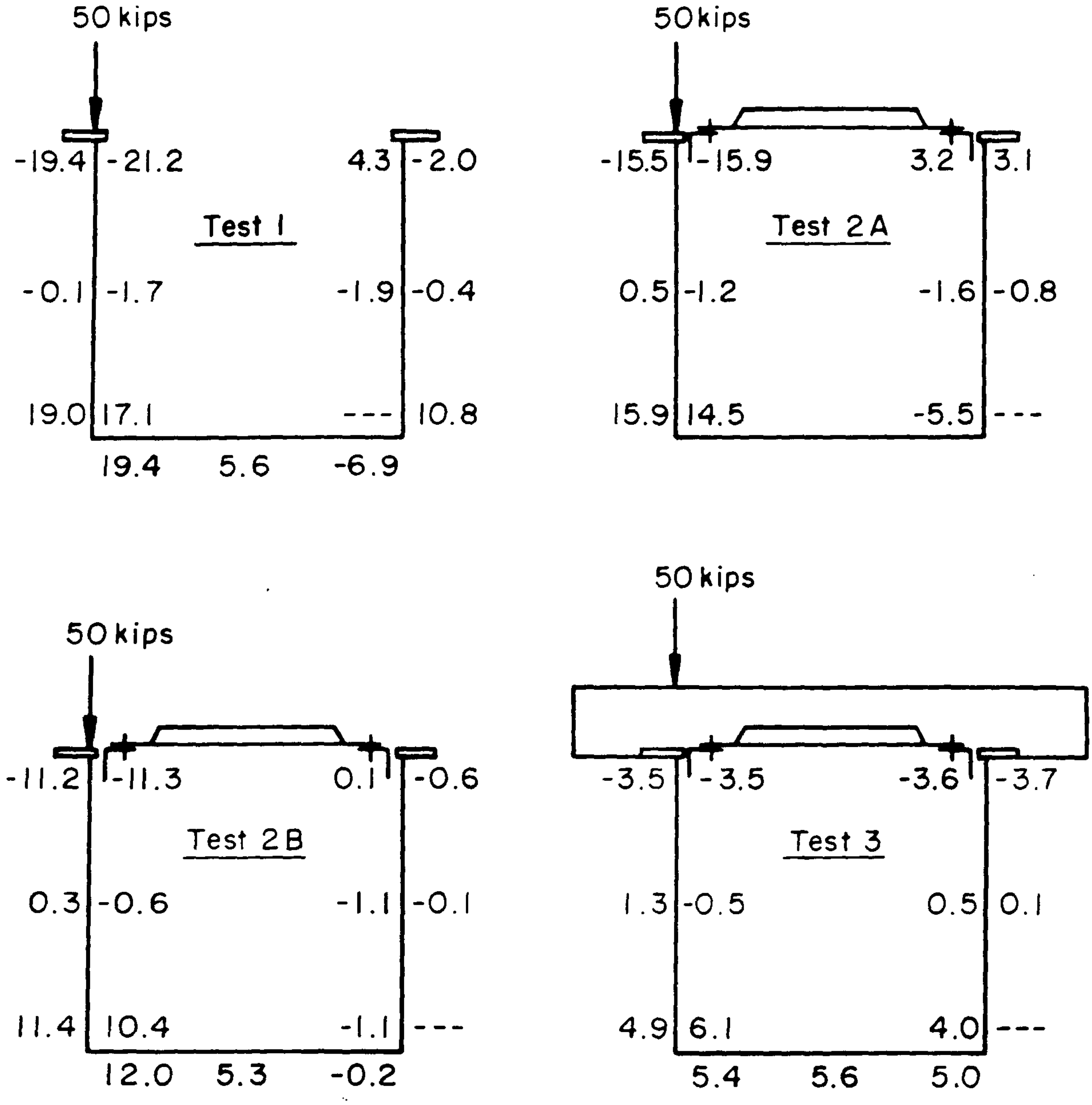


Fig. 35 - Flexural Stresses (ksi) at
Cross-Section 3 of Fig. 5

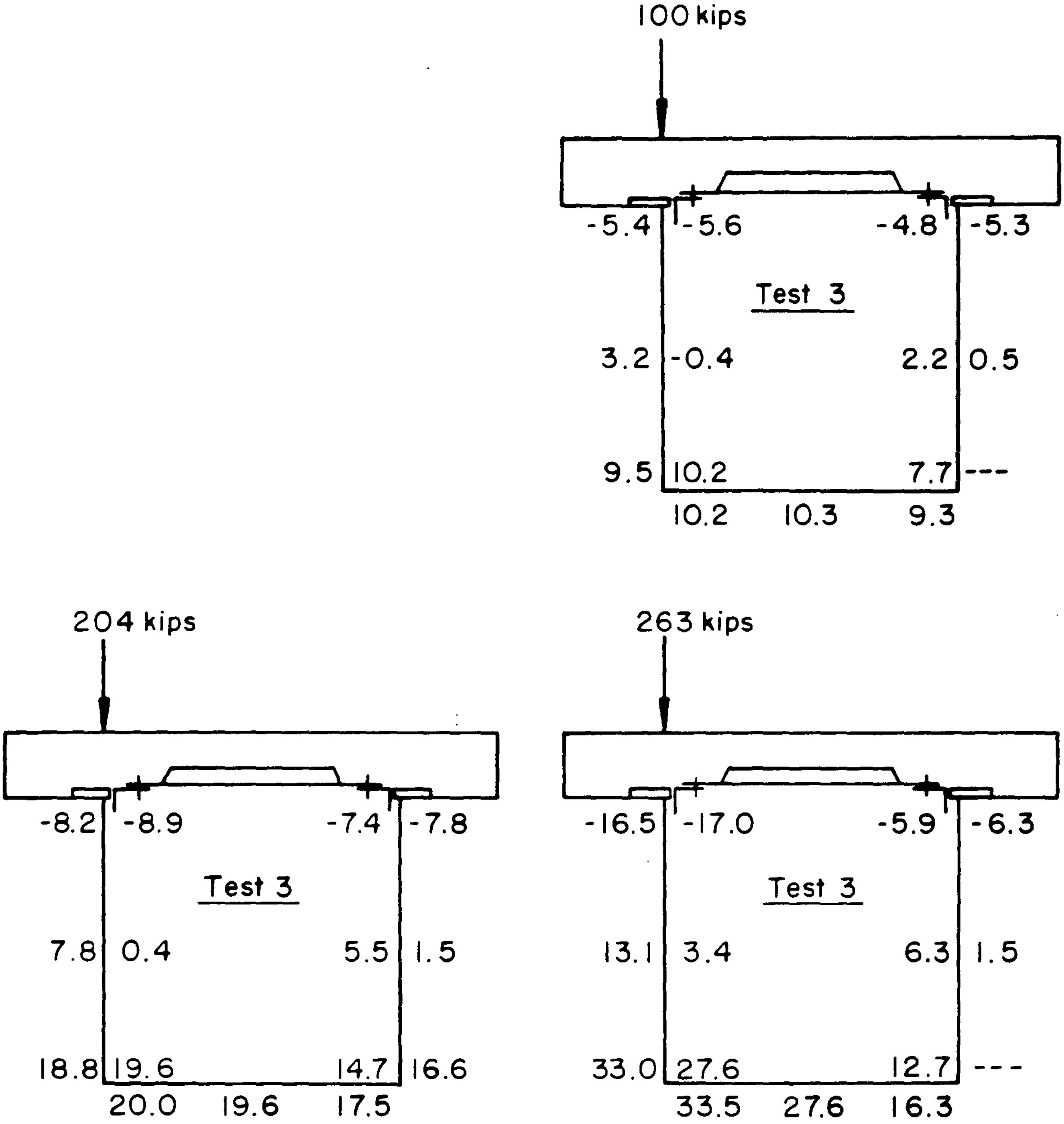


Fig. 36 - Flexural Stresses (Ksi) at
Cross-Section 3 of Fig. 5

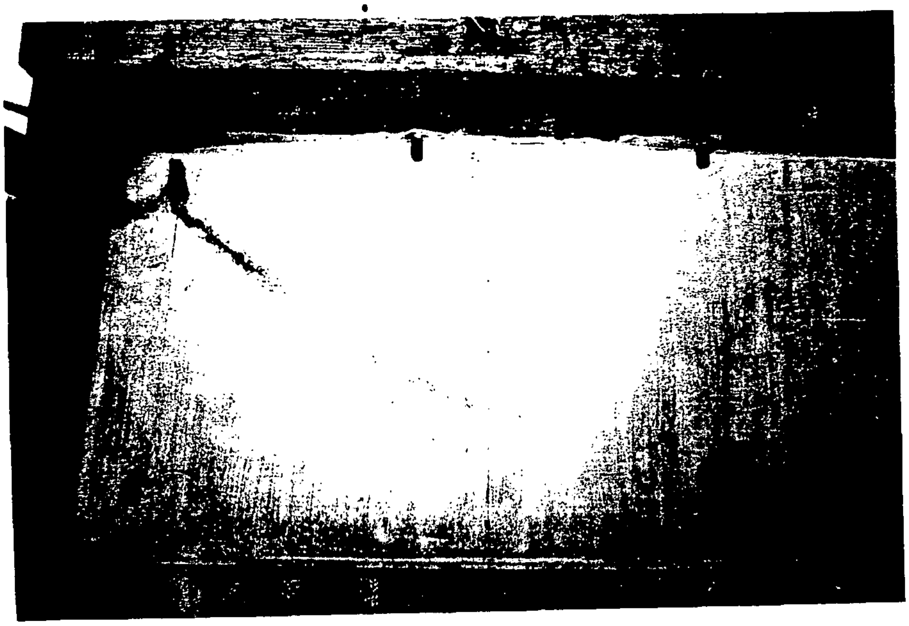


Fig. 37 Yielding of Outside Web Near the West Support

Fig. 38 Tearing of the Upper Part of the West End Diaphragm from the Outside Web

7. REFERENCES

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STRENGTH OF HORIZONTALLY CURVED STEEL PLATE GIRDERS,
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