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16. Abstract

The research reported herein is part of a 5 year multiphase investigation involving extensive analytical and experimental studies of horizontally curved steel plate and box girders. The project, which began in 1973, is entitled "Fatigue of Curved Steel Bridge Elements". The work is sponsored by the FHWA and was carried out in Fritz Engineering Laboratory at Lehigh University.

This report presents the results of the ultimate strength tests of one curved non-composite plate girder assembly, two curved composite plate girder assemblies and two curved composite box girders.

The primary objectives of the research reported herein are: (1) to determine the load-deflection behavior of large size curved plate girder assemblies and curved box girders which are loaded to ultimate strength, and (2) to compare the experimental behavior with analytic predictions.

This study is of very limited scope and is intended only as a pilot study of the ultimate strength of curved plate and box girders. The study was conducted primarily because the test girders were available and could be retrofitted following the fatigue tests.

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ULTIMATE STRENGTH TESTS OF HORIZONTALLY CURVED PLATE AND BOX GIRDERS

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LIST OF NOMENCLATURE

f'_c	compressive strength of concrete
f_{sp}	tensile strength of concrete (split cylinder test)
F_y	yield strength of steel
P	the total concentrated load applied to the plate girder assemblies or the box girders by the testing machine
R	centerline radius of the plate girder assemblies or box girders
Δ_1	vertical deflection of Girder 1 on the plate girder assemblies or the inner web on the box girders due to the applied load P
Δ_2	vertical deflection of Girder 2 on the plate girder assemblies or the outer web on the box girders due to the applied load P

1. INTRODUCTION

1.1 Background

The research reported herein is part of a 5 year multiphase investigation involving extensive analytical and experimental studies of horizontally curved steel plate and box girders. The project, which began in 1973, is entitled "Fatigue of Curved Steel Bridge Elements". The work is sponsored by the FHWA and was carried out in Fritz Engineering Laboratory of Lehigh University. The project is divided into five tasks as described in Appendix A. Appendix B lists the project reports.

The primary objectives of the investigation are to study the fatigue behavior of curved steel plate and box girders as used in highway bridges and to recommend possible specification provisions for inclusion in AASHTO.

The experimental phase of the investigation consisted of the fatigue tests of five large size curved steel plate girder assemblies and three large size steel curved box girders. Reference 1 provides complete details on the analysis and design of the plate girder assemblies and box girders. References 2 and 3 provide the results of the fatigue tests of all eight test girders.

Early in the project it was thought that the test girders would be so extensively cracked following the fatigue tests that retrofitting for ultimate strength tests would not be feasible. Thus, Task 4, "Ultimate Load Tests of Curved Plate and Box Girder Assemblies" (Appendix A), was not part of the original project scope. However, the designs of the test girders prior to the fatigue tests took some account of the possibility of performing ultimate strength tests. For example, an attempt was made to size diaphragms and bearing stiffeners on the basis of some assumed ultimate loads.[1]

Techniques were developed during the fatigue tests for arresting the fatigue cracks thus limiting fatigue damage of the test girders.[2,3] Task 4 was then added to the project scope in 1976 when it was realized that the test girders could be retrofitted for a relatively modest increase in budget. Referring to Ref. 1, the girders selected for the ultimate strength tests were Plate Girder Assemblies 1, 4 and 5, and Box Girders 1 and 3. All except Plate Girder Assembly 1 were provided with composite reinforced concrete slabs prior to the ultimate strength tests.

1.2 Objectives and Scope

This report presents the results of the ultimate strength tests of one curved non-composite plate girder assembly (Plate Girder Assembly 1), two curved composite plate girder assemblies (Plate Girder Assemblies 4 and 5), and two curved composite box girders (Box Girders 1 and 3). The tests were conducted under Task 4 which is described in Appendix A.

The primary objectives of the research reported herein are: (1) to determine the load-deflection behavior of large size curved plate girder assemblies and curved box girders which are loaded to ultimate strength, and (2) to compare the experimental behavior with analytic predictions.

This study is of very limited scope and is intended only as a pilot study into the ultimate strength of curved plate and box girders. The study was conducted primarily because the test girders were available and could be retrofitted following the fatigue tests.

1.3 Research Approach

The five test girders selected for the ultimate strength tests were all previously tested to approximately 2,000,000 cycles in fatigue.[2,3] All experienced extensive fatigue cracking. Cracks which, due to size or location, could influence the ultimate strength results were repaired. Repairs consisted of welding or bolting small patch plates over the visible cracks where possible and welding cracks in areas where this was not possible. In a few instances the crack tip was removed by drilling or burning to eliminate the sharp notch condition.

Non-composite Plate Girder Assembly 1, which is described in Ref. 1, was tested to ultimate strength without modifications to the girder except for the addition of bearing stiffeners above the four roller support assemblies. (Refer to Fig. 21 for example.) A single concentrated load was placed at midspan. The assembly was not provided with a composite slab and is referred to in this report as Assembly 1.

Plate Girder Assemblies 4 and 5, which are described in Ref. 1, were each provided with identical composite reinforced concrete slabs and bearing stiffeners. In addition, the two bays of bottom lateral bracing in Assembly 4 were removed and placed in the outer two bays of Assembly 5. A single concentrated load was placed at midspan of each assembly. These two test girders are referred to as Assemblies 4 and 5 in this report.

Box Girders 1 and 3, which are described in Ref. 1, were each provided with composite reinforced concrete slabs. The stud shear connector arrangements and slab reinforcement differed in each girder. Box Girder 1 was loaded at midspan. Box Girder 3 was tested in a cantilever mode. These two test girders are referred to as Box Girders 1 and 3 in this report.

Each of the five test girders was loaded to its ultimate load capacity using the 5,000,000 pound Baldwin test machine located in Fritz Engineering Laboratory. Deflection measurements were taken at selected locations during each test. Some strain readings were recorded from strain gages that were left in place and still working after completion of the fatigue tests. This data was not sufficient to describe the stress field in the girders and no analysis of the stress field was performed. (References 1, 2 and 3 discuss the correlation between actual and predicted stresses in the elastic range for all eight test girders.)

The SAP IV finite element method of analysis was employed to predict the first-order, elastic, load-deflection behavior of each of the five test girders.[4] The ultimate strength of each test girder was estimated using a simple plastic analysis. Both analyses are described in Appendix C.

2. DESCRIPTION OF THE CURVED GIRDERS

2.1 Plate Girder Assemblies

Schematic plan and cross section views of Assemblies 1, 4 and 5 are shown in Figs. 1 through 6. Table 1 summarizes the cross-sectional dimensions and material properties for the three assemblies. The material properties are based on average values obtained from material tests and mill test reports.

The three curved plate girder assemblies were designed primarily for the fatigue testing phase of the investigation (Appendix A). Design details are presented in Ref. 1. Results of the fatigue tests are presented in Ref. 2. All three assemblies experienced extensive fatigue cracking. Cracks which, due to their size or location, could influence the ultimate strength results were repaired. Repairs consisted of welding small patch plates over the visible cracks or removing the crack tip.

Assembly 1 which is described in Refs. 1 and 2, was tested to ultimate strength without modification of the girder except for the addition of bearing stiffeners at the ends of Girders 1 and 2 above the roller bearing supports (see Fig. 21 for example).

Assemblies 4 and 5, which are described in Ref. 1, were modified for ultimate strength tests. The two interior bays of bottom lateral bracing in Assembly 4 were removed and placed in the two outer bays of Assembly 5. Assembly 4 therefore contained no bottom lateral bracing while Assembly 5 had continuous bottom lateral bracing, as shown in Figs. 3 and 5. In addition, each assembly was provided with identical composite slabs. Figures 4 and 6 show the composite slab and the reinforcing pattern. Figure 7 shows the arrangement of shear connectors on girders 1 and 2 of both assemblies. Figure 8 shows the formwork and reinforcing steel prior to pouring the concrete slab for Assemblies 4 and 5.

2.2 Box Girders

Schematic plan and cross section views of Box Girders 1 and 3 are shown in Figs. 9 through 14. Table 2 summarizes the cross-sectional dimensions and material properties of the two girders. The material properties are based on average values obtained from material tests and mill test reports.

The two curved box girders were designed primarily for the fatigue testing phase of the investigation (Appendix A). Design details are presented in Ref. 1. Results of fatigue tests are presented in Ref. 3. Both box girders experienced extensive fatigue cracking. Cracks which, due to their size or location, could influence the ultimate strength results were repaired. Repairs consisted of welding or bolting small patch or cover plates over the visible cracks or removing the crack tip.

Box Girders 1 and 3, which are described in Refs. 1 and 3, were modified for the ultimate strength tests. Both girders were provided with composite slabs which had identical cross section dimensions but different reinforcement and shear connector arrangements. Figure 9 shows the arrangement of shear connectors. Box Girder 1 had welded wire mesh reinforcement, as shown in Figs. 10 and 12. Box Girder 3 had heavier reinforcement, as shown in Figs. 10, 13 and 14. The formwork and reinforcement for both box girders is shown in Fig. 11 prior to pouring the composite slabs.

Prior to the ultimate strength test of Box Girder 3, the bottom flange stiffeners in the cantilever position of the girder were removed (compare Figs. 13 and 14). It was hoped that by removing the stiffeners the bottom flange would buckle prior to the ultimate load level. Unfortunately, following removal of the two stiffeners, the bottom flange had considerable out of plane distortions due to residual stresses resulting from the original welding and the flame cutting operation.

3. INSTRUMENTATION AND TESTING PROCEDURE

3.1 Instrumentation

The instrumentation for the curved plate girder assemblies and curved box girders was planned primarily for the fatigue testing program. For those tests electrical resistance strain gages were attached to the curved girders to determine the correlation between predicted and measured stresses, stress gradients and stress ranges in the vicinity of weldments. At the conclusion of the fatigue tests many of the strain gages were not working. Prior to each ultimate strength test a determination was made of which gages were still working. A selection of these strain gages was then made and strains were recorded during the ultimate strength tests. However, the data thus obtained was not sufficient to describe the stress field in the girders and no analysis of the stress field was made. The strain record has been retained since it may be useful if additional studies of curved girders are undertaken.

Vertical and horizontal deflection measurements were recorded at a number of points on the curved girders using Ames dial gages measuring to 0.001 in. The location of these gages is shown in Figs. 15 and 16.

3.2 Test Procedure

Each of the curved girders was tested in the 5,000,000 pound Baldwin Universal Testing Machine located at Fritz Engineering Laboratory, Lehigh University, Bethlehem, Pa.

Assembly 1 was supported at each end of Girders 1 and 2 (Fig. 1) by the roller support assemblies shown in Fig. 17. These roller supports were designed to simulate spherical supports and are described in detail in Ref. 2. The roller restraining bars shown in Fig. 17, which were used during the fatigue tests to restrain certain rollers (see Ref. 2), were altered so that all rollers had freedom of motion. The horizontal stability of the curved girders was maintained by the testing machine at the load point. The assembly was loaded at midspan by a concentrated load applied to a W14x730 loading beam bearing directly on the top flanges of each girder directly over the midspan diaphragm. The concentrated load was applied to the loading beam at a point 9 in. offset from the centerline of the assembly as shown in Fig. 1. It was necessary to offset the load for two reasons: (1) Since the spherical loading head of the testing machine could accept only limited rotation of the assembly cross section before jamming, the load was offset so that the cross section would deflect vertically with minimum rotation; (2) In order to place Assemblies 4 and 5 into the testing machine and provide clearance between the testing machine columns and the concrete slab, the load was offset 9 in. For comparative purposes the same offset dimension was used for Assembly 1.

Assemblies 4 and 5 are essentially identical except for bottom lateral bracing (Figs. 3 and 5). Each was supported at the ends of Girders 1 and 2 by roller supports (Fig. 17) and loaded at midspan through a W14x730 loading beam as described above.

Box Girder 1 was supported at the four corners of the bottom flange by roller supports (Fig. 17) and loaded at midspan through a W14x730 loading beam as described above. The concentrated load was offset 12 in. from the girder centerline as shown in Fig. 9 to minimize cross section rotation and possible jamming of the spherical loading head of the testing machine.

Box Girder 3 was tested in a cantilever mode as shown schematically in Figs. 9 and 18. The girder was loaded on the centerline through a W14x730 loading beam placed directly over an end diaphragm. Roller supports were placed under the quarter point diaphragm nearest the concentrated load. Figure 19 shows the concentrated load being applied through the loading beam to the cantilevered end of the curved girder. The far end was restrained from uplift by a hold-down frame, which is shown in Fig. 20. Roller supports were also placed at this end for support when the girder was not loaded.

The test procedure consisted of loading each curved girder with incremental loads until the girder reached its ultimate load capacity. The ultimate load capacity of a curved girder was considered to be the point at which additional deflection was accompanied by a drop in the applied load.

For the simply supported composite assemblages and box girders, gages were read at 50 kip load increments and the midspan deflections were plotted continuously throughout the tests. As the load-deflection curve departed from linearity, complete sets of readings were taken at approximately ½-in. increments of midspan deflection.

The test procedure was similar for Box Girder 3 except that after the load-deflection curve departed from linearity, the test continued by increasing the load in increments which produced approximately ½-in. deflections of the cantilevered end.

4. TEST RESULTS AND ANALYSIS

4.1 Load-Deflection Behavior

4.1.1 Non-Composite Plate Girder Assembly 1

Assembly 1 is shown in Fig. 21 at the start of the ultimate load test. The concentrated load at midspan is shown applied to the two curved plate girders by the W14x730 loading beam (girder 1 right; girder 2 left - see Fig. 1). The roller supports under the two girders and the bearing stiffeners which were added following the fatigue tests are shown in the foreground. A typical diaphragm is also shown. The diaphragms, in this assembly only, were oversized on purpose to maintain a high degree of stiffness during the fatigue tests. They were also proportioned to carry large forces without buckling during the ultimate strength tests. Although the diaphragms shown in Fig. 21 indicate that high strength bolted connections were used, the connections were also welded using only 3 or 4 inches of 1/8-in. weld per joint. The purpose of the welds was to maintain the highest joint stiffness during the fatigue tests, which subjected the welds to small forces. The bolts were installed partly for erection and alignment purposes prior to the fatigue tests and partly to maintain the diaphragm forces after the welds fractured during the ultimate strength tests.

The experimental load-deflection behavior of this assembly is compared with the predicted behavior in Fig. 22. The analyses used to obtain the predicted behavior are explained in Appendix C. The load P refers to the total applied concentrated load at midspan. The deflection Δ refers to the midspan vertical deflection of Girder 1 (Δ_1) or Girder 2 (Δ_2).

The ultimate strength test proceeded uneventfully until just prior to reaching a load of 300 kips. At this point a low rumbling sound was heard and it was observed that the web of Girder 2 in both end panels between the supports and the quarter point diaphragms (the west end panel is visible in Fig. 21) buckled noticeably due to tension fields developing in the panels. It appeared that elastic buckling had occurred so the load was reduced to see if the webs would resume their original shapes. As the load was reduced to 250 kips, the rumbling noise was again heard and it was observed that the end panels returned to their original shape. Upon returning to 300 kips the end panels of Girder 2 both buckled once more. In the buckled state the web was observed to be somewhat flatter in the lower half and deflected or bulged outward in the upper half.

At a load of about 350 kips yield lines and local buckling developed in the outer half of the top flange of Girder 2 near the quarter point and midspan diaphragms as shown in Fig. 23. This yielding was expected due to the combination of bending and warping compression stresses. Yielding also occurred in the web as shown in Fig. 23.

The assembly reached an ultimate load capacity of 372 kips. The lateral deflection of the compression flange and web panel near midspan of Girder 2 is shown in Fig. 24. The lateral torsional buckling of the compression flange of Girder 2 as viewed from between Girders 1 and 2 is more clearly shown in Fig. 25.

The predicted elastic behavior of Girders 1 and 2 agrees reasonably well with the experimental behavior, nearly to the ultimate load capacity. The analysis predicts a stiffer assembly mainly because the finite element analysis employed a rather coarse discretization (Appendix C). Because of instability of the compression flange and web, simple plastic analysis was not expected to accurately predict the ultimate load capacity.

4.1.2 Composite Plate Girder Assembly 4

Assembly 4 is shown in Fig. 26 at the start of the ultimate strength test. The experimental load-deflection behavior of this assembly is compared with the predicted behavior in Fig. 27. The analyses used to obtain the predicted behavior are explained in Appendix C. The load P refers to the total applied concentrated load at midspan. The deflection Δ refers to the midspan vertical deflection of Girder 1 (Δ_1) and Girder 2 (Δ_2).

No elastic buckling of the webs as occurred in Assembly 1 was observed. The first yield lines appeared in the flanges and webs, as shown in Fig. 28, at a load of about 500 kips. At approximately 600 kips the gage measuring the vertical deflection of Girder 1 became inoperable. As shown in Fig. 27, the behavior of both girders up to this load level was nearly identical. The curve in Fig. 27 above 600 kips is plotted for Girder 2 only.

At approximately 704 kips a loud noise was heard. The behavior of the girder at this point is estimated by the broken line in Fig. 27. Subsequent inspection showed that a previously undetected fatigue crack in a gusset plate detail had precipitated a brittle fracture of about one-third the width of the tension flange of Girder 2. The fracture was located on the inside half of the flange and about three feet from the midspan of Girder 2, near the right side of the photo shown in Fig. 28. After examining the fracture surface, the load was increased above 704 kips, and the fracture continued across the tension flange.

The fracture surface and initial fatigue crack are shown in Fig. 29, viewed from inside the girder. The fatigue crack was located at detail cc shown in Fig. 56 of Ref. 2 and grew from a porosity imbedded in the groove weld near the bottom of the gusset plate, and about 1½ inches from where the 6-in. radius transition becomes tangent to the flange. Figure 30 shows a schematic view of the fatigue crack and fracture surface after the fracture had severed the tension flange.

Further discussion of the results obtained from Assembly 4 is presented in Art. 4.1.3.

4.1.3 Composite Plate Girder Assembly 5

The load-deflection behavior of Assembly 5 is compared with the predicted behavior in Fig. 31. The analyses used to obtain the predicted behavior are explained in Appendix C. The load P refers to the total concentrated load at midspan. The deflection Δ refers to the midspan vertical deflection under the inner web (Δ_1) and outer web (Δ_2).

Yield lines first formed in the flanges and webs at a load of 500 kips. At a load of 678 kips the concrete slab on both sides of the loading beam began to spall. Local buckling of the webs of Girders 1 and 2 under the load points was also observed.

At an ultimate load of about 830 kips the compression diagonal in the midspan diaphragm buckled. This diagonal is shown in Fig. 32. Buckling of the diagonal was accompanied by considerable crushing of the concrete slab and yielding of the girders at midspan as shown in Figs. 33 to 35.

The behavior of Assembly 4 and Assembly 5, shown in 27 and 31 respectively, indicate more flexibility than predicted. This is mainly due to the rather coarse mesh used in the finite element analysis (Appendix C). Figure 36 compares the predicted and actual load-deflection behavior of both assemblies. The only difference between the two assemblies was the extent of bottom lateral bracing as shown in Figs. 3 and 5. It is evident that although Assembly 5 is stiffer than Assembly 4 the difference is rather small. Unfortunately, because of premature fracture of Assembly 4 it is not possible to compare the ultimate load capacities. The ultimate load capacity of Assembly 5, however, considerably exceeded the predicted capacity based on simple plastic theory.

4.1.4 Composite Box Girder 1

Box Girder 1 is shown in Fig. 37 at the start of the ultimate load test. The concentrated load was initially applied directly over the inner web at midspan through a W14x730 loading beam spanning across the slab. At about 150 kips the slab which overhangs the web under the load began to crack. The concentrated load was then repositioned 12 in. towards the inner web from the centerline of the box girder. The "window" in which to place the midspan load is rather narrow for the box girders. To prevent uplift at a roller support the load must be positioned between two imaginary straight lines. The first line runs between the roller supports under the outer web. The other runs between the roller supports under the inner web. Further the load should be placed between the webs at midspan unless measures are taken to prevent cracking of the overhanging slab and uplift of the loading beam. The resulting "window" or width in which the load can be placed is only about 19 inches. If the load is centered in this width the four reactions are equal. For Box Girder 1, the load was offset slightly toward the inner web.

The load-deflection behavior of Box Girder 1 is compared with the predicted behavior in Fig. 38. The analyses used to obtain the predicted behavior are explained in Appendix C. The load P refers to the total concentrated load at midspan. The deflection Δ refers to the midspan vertical deflection under the inner web (Δ_1) and outer web (Δ_2).

First yielding was observed in the inner web under the load point at about 375 kips. At a load of 388 kips the outer web buckled locally at midspan as shown in Fig. 39. The concrete slab began to crush under the loading beam at an ultimate load of 424 kips as shown in Fig. 40. At the same time a diagonal crack was observed in the slab as shown in Fig. 41. Figure 42 shows the extent of buckling of the inner web at the ultimate load.

Again, as for the composite plate girder assemblies, the actual load-deflection behavior showed more flexibility than predicted, and for the same reason explained earlier. The ultimate strength of Box Girder 1 was in rather good agreement with the prediction based on simple plastic theory.

4.1.5 Composite Box Girder 3

Box Girder 3 is shown in Figs. 19 and 20 at the start of the ultimate load test. The concentrated load was applied over the end diaphragm directly on the girder centerline and distributed by a W14x730 loading beam as shown in Fig. 19.

The load-deflection behavior of Box Girder 3 is compared with the predicted behavior in Fig. 43. In the figure, P refers to the total concentrated load applied to the end of the girder. The deflection Δ refers to the vertical deflection of the inner (Δ_1) and outer (Δ_2) webs. The analyses used to obtain the predicted behavior are explained in Appendix C.

Initial cracking of the concrete slab in tension was observed at a load of 38 kips. At a load of about 125 kips the bottom flange adjacent to the interior support, between the interior and end supports (lower moment gradient region), started to buckle locally. It was difficult to obtain a better estimate of the buckling load because of the distortions of the flange as explained in Art. 2.2. As the load was increased, the buckled region deflected upwards significantly while the bottom flange adjacent to the interior support but on the opposite or load side deflected downward.

At the ultimate load of 266 kips the bottom flange adjacent to the interior support which was buckling upwards had undergone very large deflections as shown in Fig. 44. In the region of upward deflection of the bottom flange the adjacent webs buckled outward significantly as shown in Fig. 45.

The extent of slab cracking over the interior support at the ultimate load is shown in Fig. 46.

It is interesting to note in Fig. 43 that although the actual load-deflection behavior was considerably more flexible than predicted, the ultimate strength predicted by simple plastic theory coincided almost exactly with the actual ultimate load. In effect, the local buckling of the flange and web at the interior support had the same result on the ultimate strength as the plastic hinge assumed in the analysis.

5. SUMMARY AND CONCLUSIONS

The results of the ultimate strength tests of one non-composite and two composite plate girder assemblies and two composite box girders are presented. A summary of the results of this investigation are as follows:

(1) Assembly 1, tested without a composite concrete slab, attained the ultimate strength by lateral torsional buckling of the compression flange and local buckling of the web at midspan of Girder 2.

(2) The mode of failure for Assembly 4 was brittle fracture of the tension flange of Girder 2. The brittle fracture of the flange resulted from a previously undetected fatigue crack. This underscores the importance of fatigue crack detection on the ultimate strength capacity of bridge girders.

(3) The mode of failure for Assembly 5 was crushing of the concrete deck and local buckling of the webs under the concentrated load at midspan.

(4) The mode of failure for Box Girder 1 was local buckling of Girder 1 near the bottom flange and crushing of the concrete deck under the concentrated load at midspan.

(5) The mode of failure for Box Girder 3 was local buckling of the bottom flanges and webs at the interior support.

The conclusions resulting from this investigation are:

(1) The finite element analysis employing SAP IV satisfactorily predicts the elastic load-deflection behavior of the test girders. It is believed that a much better correlation would be obtained using a finer discretization. SAP IV was also used to predict the elastic load-deflection behavior, stress range gradient and local stress range for the three box girders tested in fatigue, with good results, as reported in Refs. 1 and 3.

(2) The use of simple plastic theory to predict the ultimate strength of curved girders is a crude approach and cannot be applied in many cases. Because of the compactness of the composite assemblages and box girders reasonable agreement was obtained. It should not be applied to non-composite girders or to girders where web behavior dominates the ultimate

strength. Research into methods of predicting the ultimate strength of curved girders is needed.

6. TABLES AND FIGURES

TABLE 1 - Cross-Section Dimensions and Material Properties for the Plate Girder Assemblies

		Non-Composite Plate Girder Assembly 1	Composite Plate Girder Assembly 4	Composite Plate Girder Assembly 5
Centerline span length	ft	40	40	40
Centerline radius	ft	120	120	120
Cross section properties:				
Girder 1:				
radius	ft	117.5	117.5	117.5
web depth	in	52	52	52
web thickness	in	3/8	3/8	3/8
flange width	in	12	8	8
flange thickness	in	1	1/2	1/2
Girder 2:				
radius	ft	122.5	122.5	122.5
web depth	in	52	52	52
web thickness	in	9/32	3/8	3/8
flange width	in	12	12	12
flange thickness	in	1	1	1
Composite slab:				
width	in	-	96	96
thickness	in	-	7	7
Bottom lateral bracing		none	none	L3x3x3/8
Material Properties:				
flanges - F_y	ksi	36	41	40
webs - F_y	ksi	45	44	48
slab - f'_c	psi		4,500	4,500
- f'_{sp}	psi		500	500
reinforcement - F_y	ksi		60	60

TABLE 2 - Cross-Section Dimensions and Material Properties for the Box Girders

		Composite Box Girder 1	Composite Box Girder 3
Centerline span length	ft	37	37
Centerline radius	ft	120	120
Cross-section properties:			
web depth	in	34-1/8	34-1/8
web thickness	in	3/8	3/8
flange width	in	38	38
flange thickness	in	3/8	3/8
Composite slab:			
width	in	54	54
thickness	in	6	6
Material properties:			
steel - F_y	ksi	44	44
slab - f'_c	psi	4,600	4,800
- f'_{sp}	psi	500	500
reinforcement - F_y	ksi	60	60

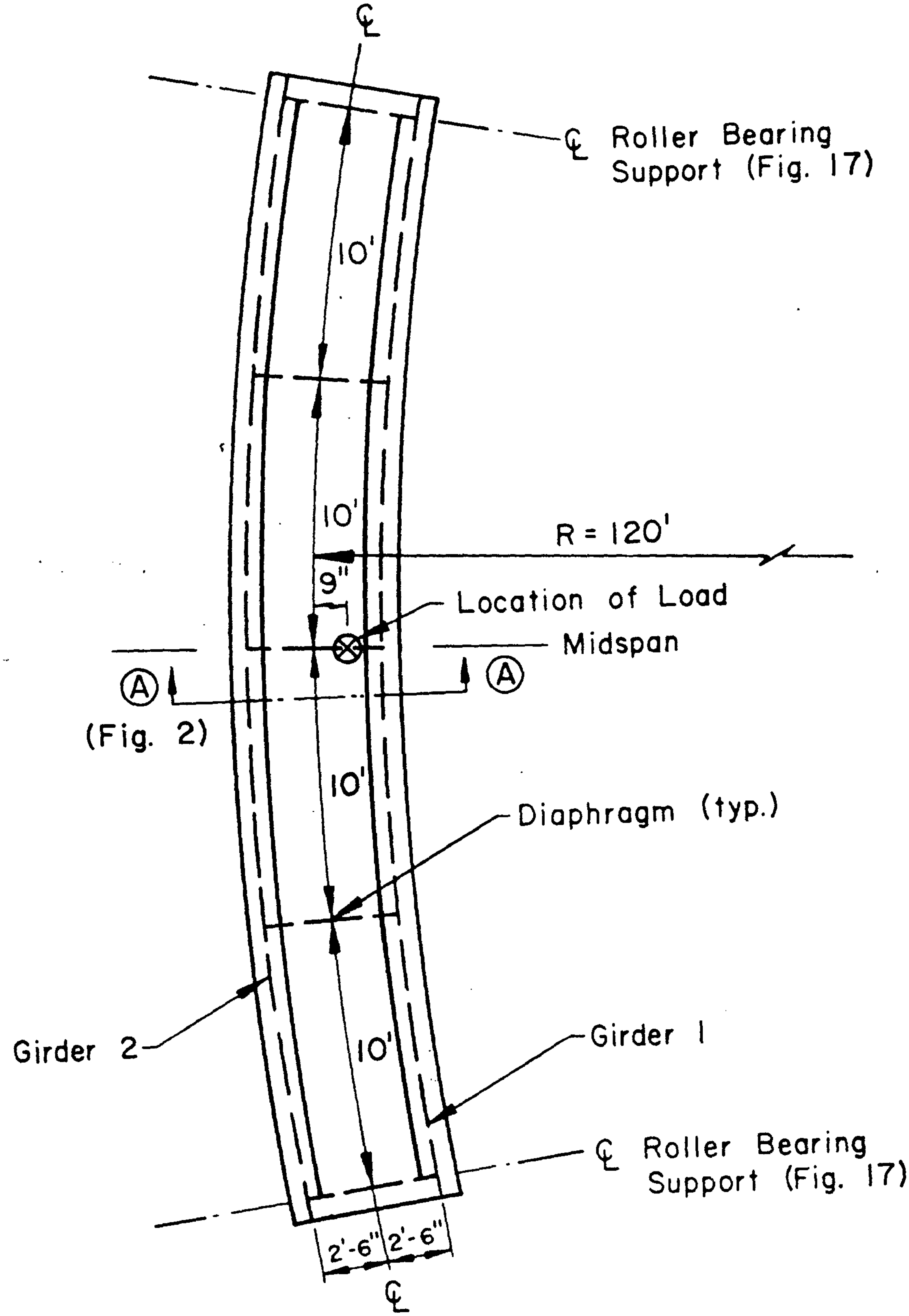


Fig. 1 Plate Girder Assembly 1 - Schematic Plan View

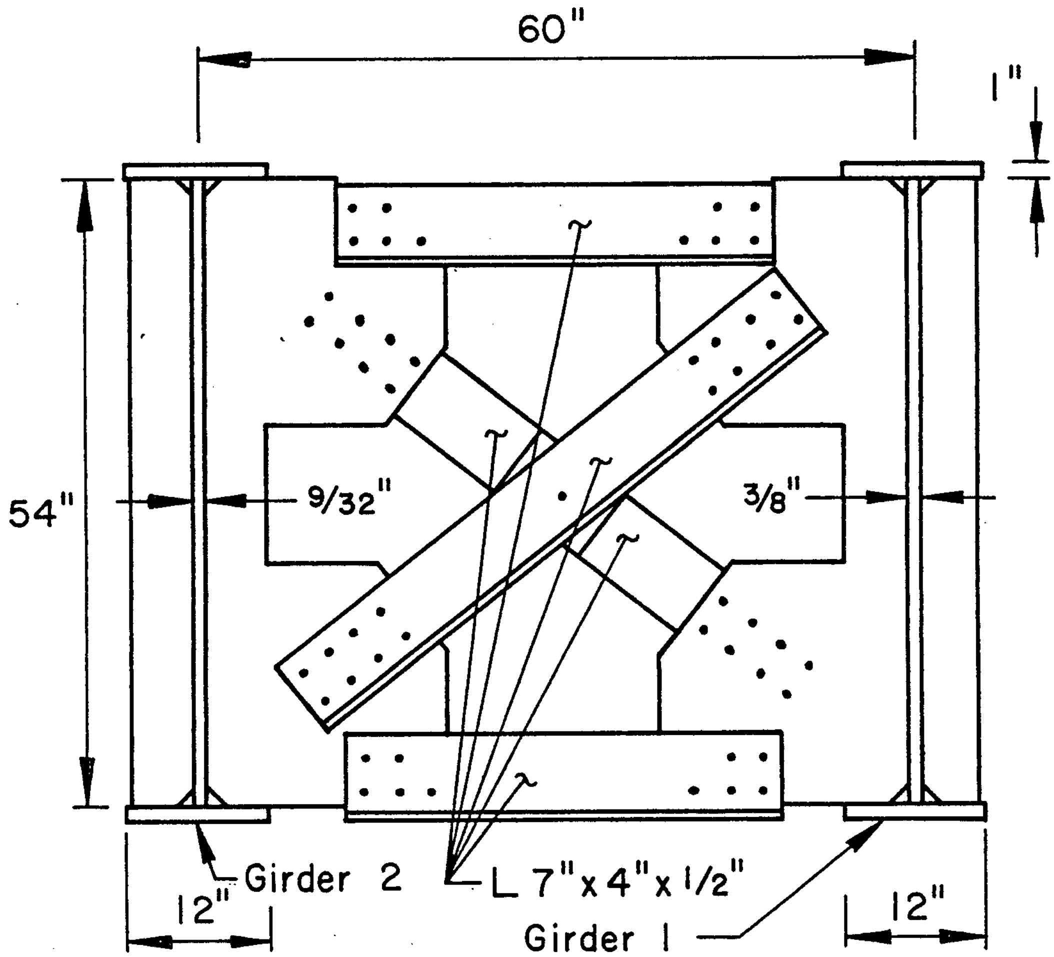


Fig. 2 Plate Girder Assembly 1 - Section A, (Fig. 1)

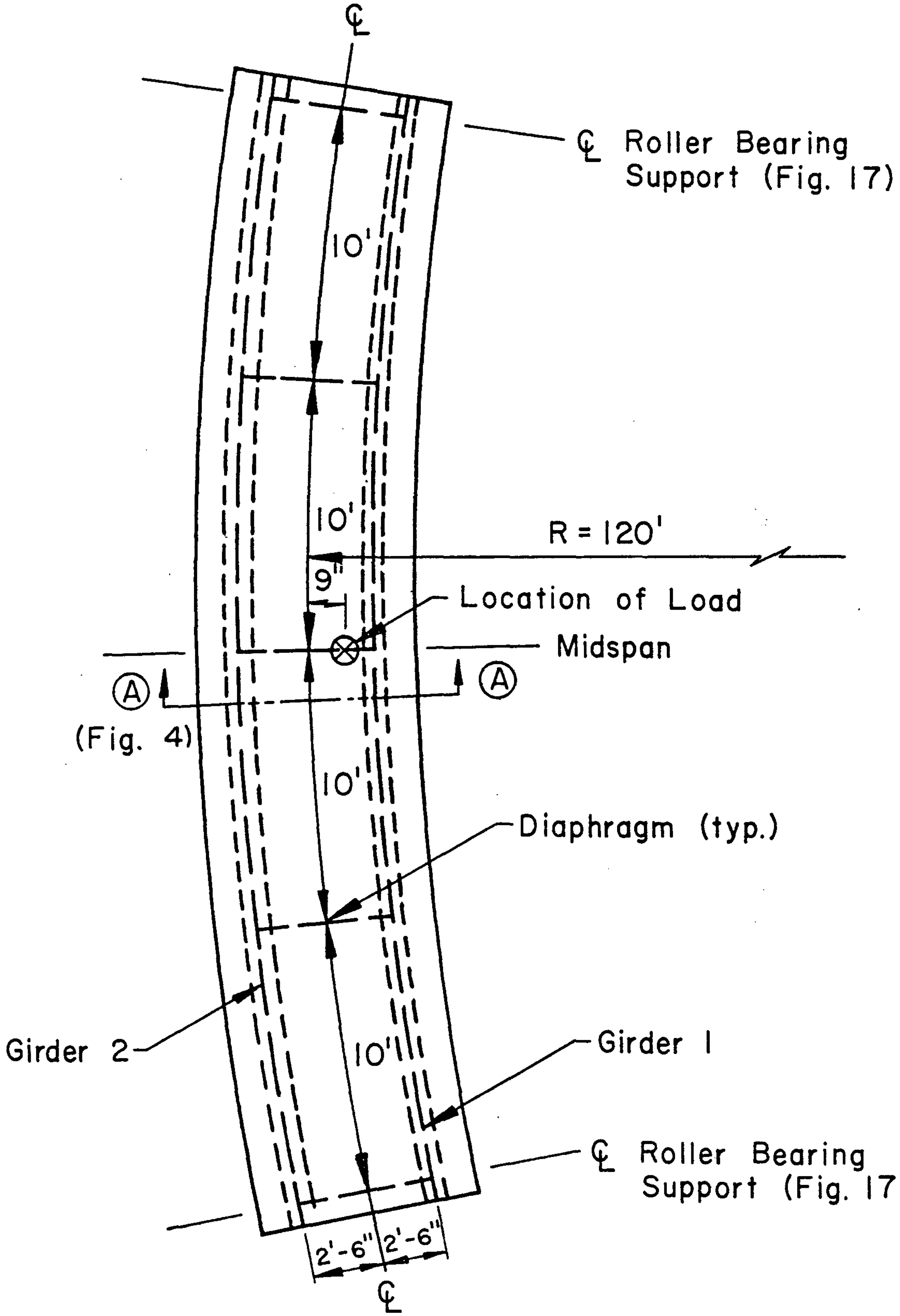


Fig. 3 Composite Plate Girder Assembly 4 - Schematic Plan View

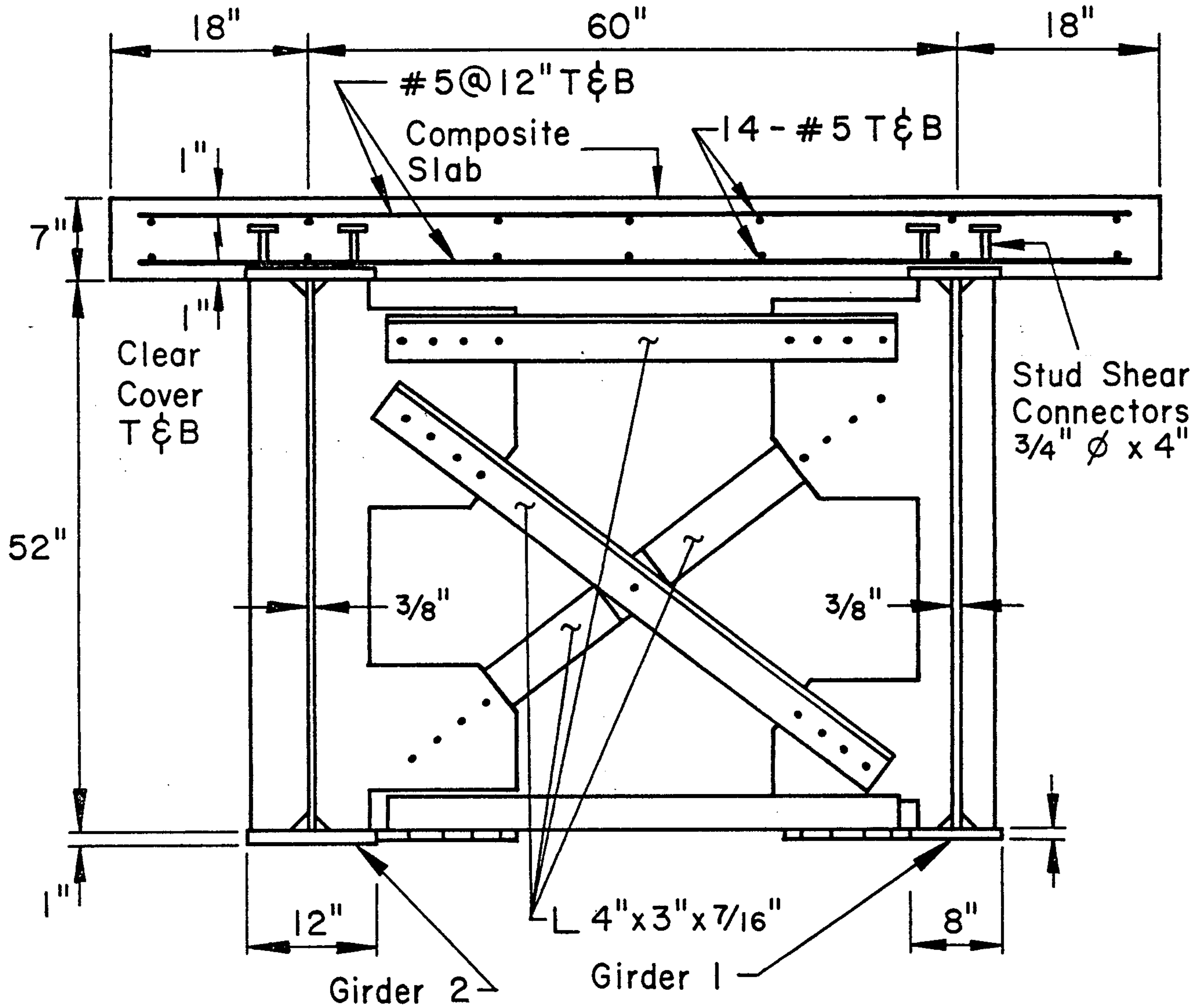


Fig. 4 Composite Plate Girder Assembly 4 - Section A, (Fig. 2)

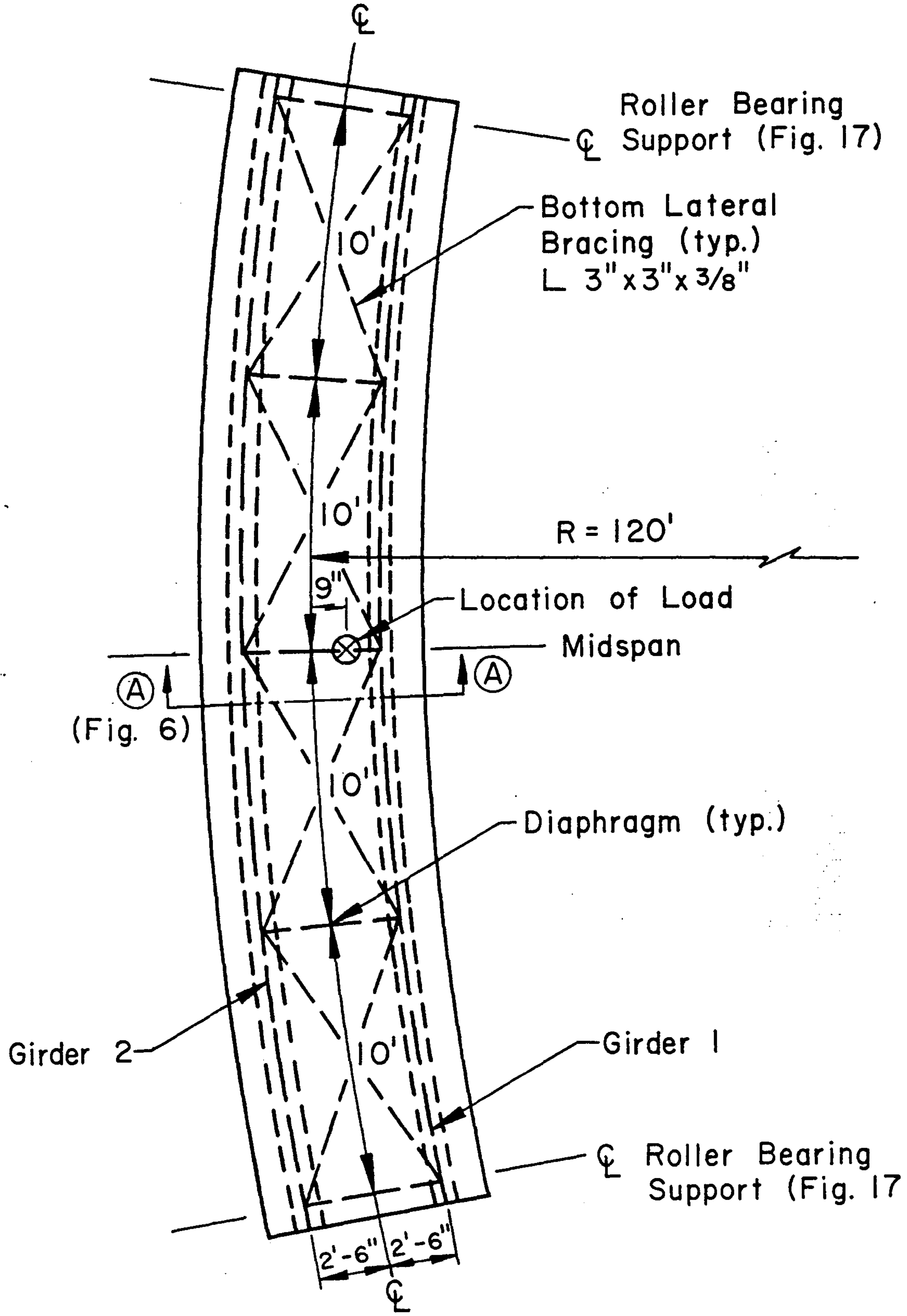


Fig. 5 Composite Plate Girder Assembly 5 - Schematic Plan View

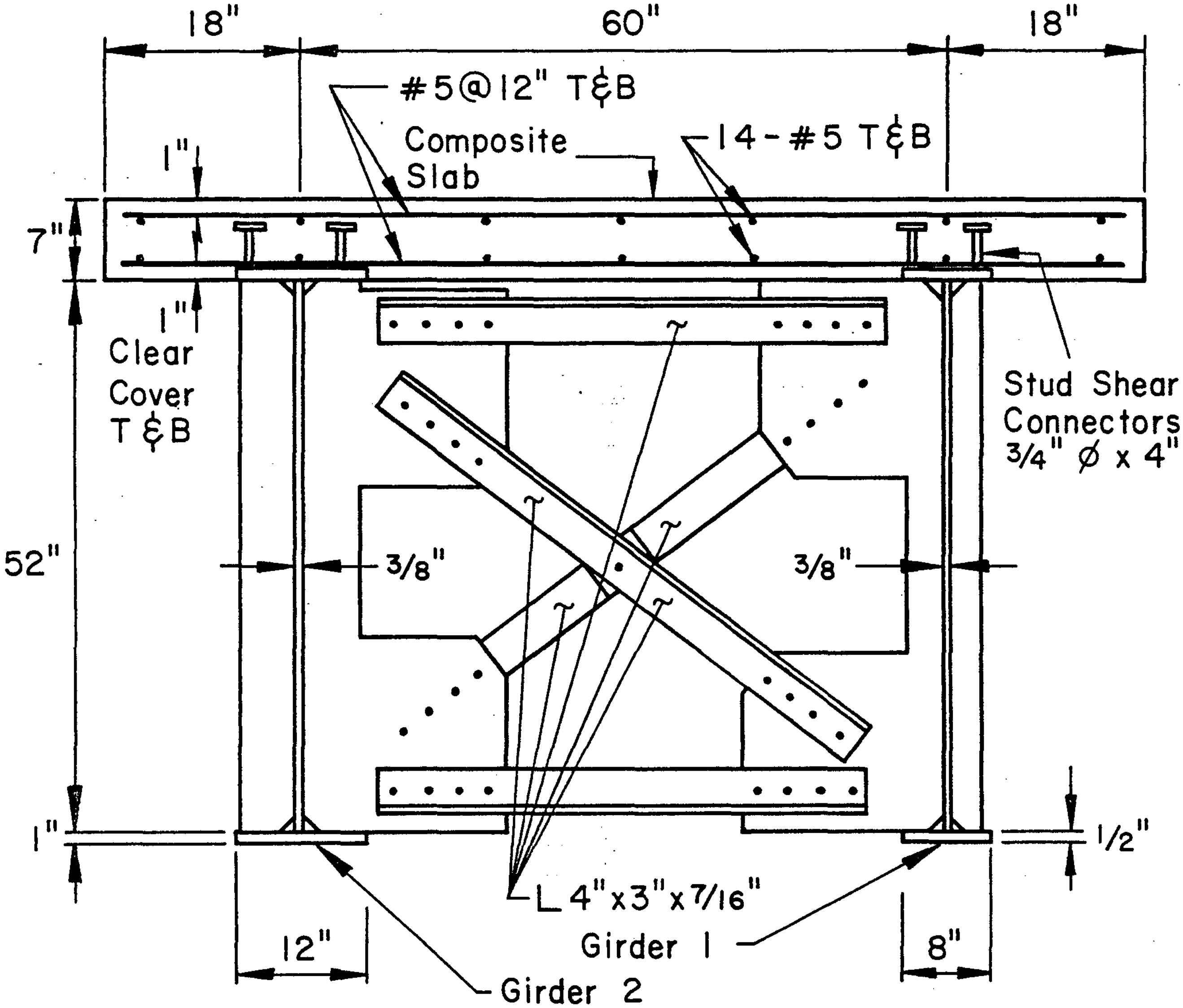
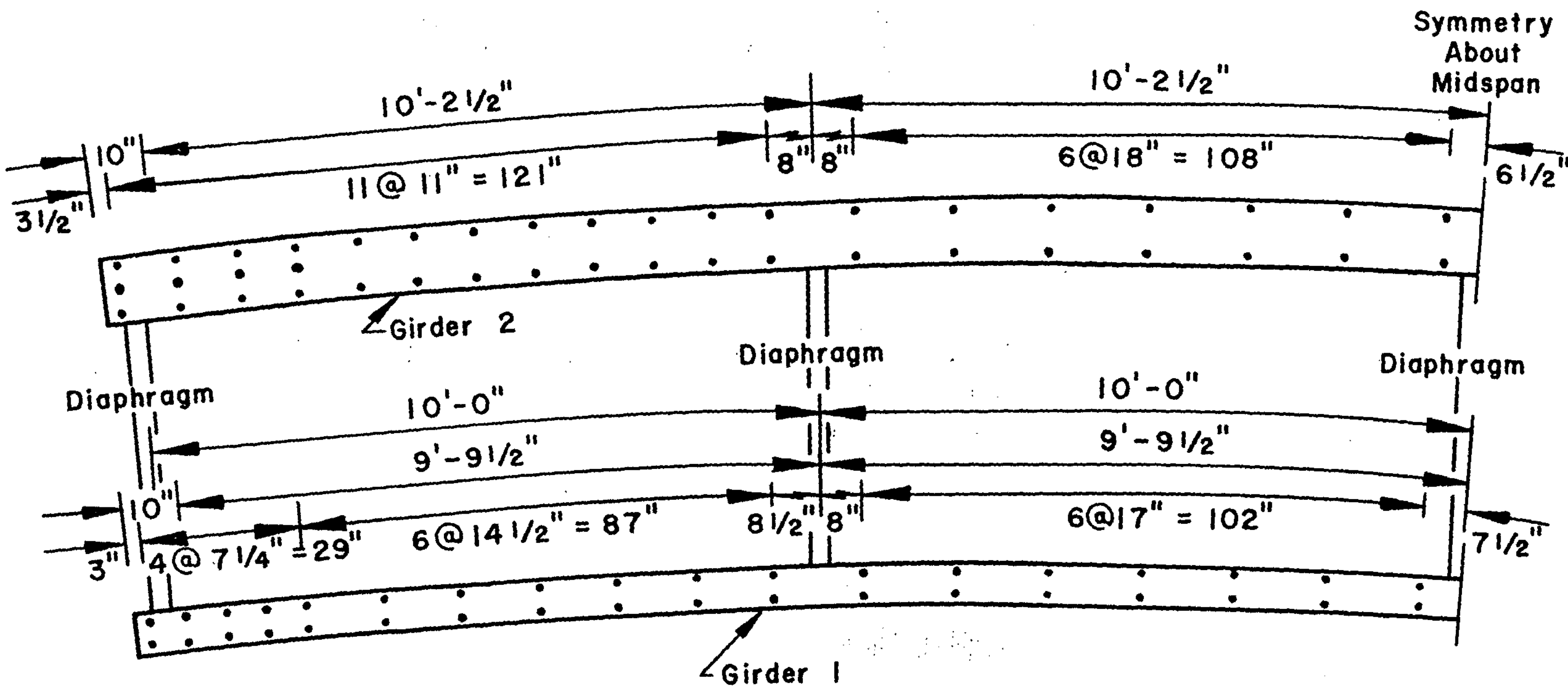


Fig. 6 Composite Plate Girder Assembly 5 - Section A, (Fig. 3)



Note: All longitudinal distances are measured along ℄

Fig. 7 Composite Plate Girder Assemblies 4 and 5 - Arrangement of Shear Connectors on Girders 1 and 2

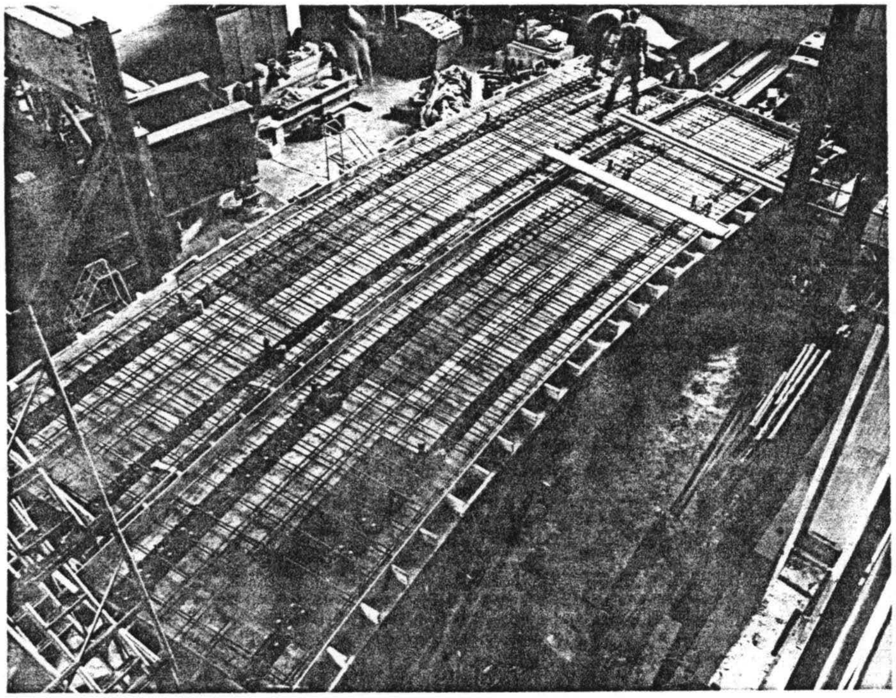


Fig. 8 Composite Slab Formwork and Reinforcing Steel for Plate Girder Assembly 4 (left) and Plate Girder Assembly 5 (right)

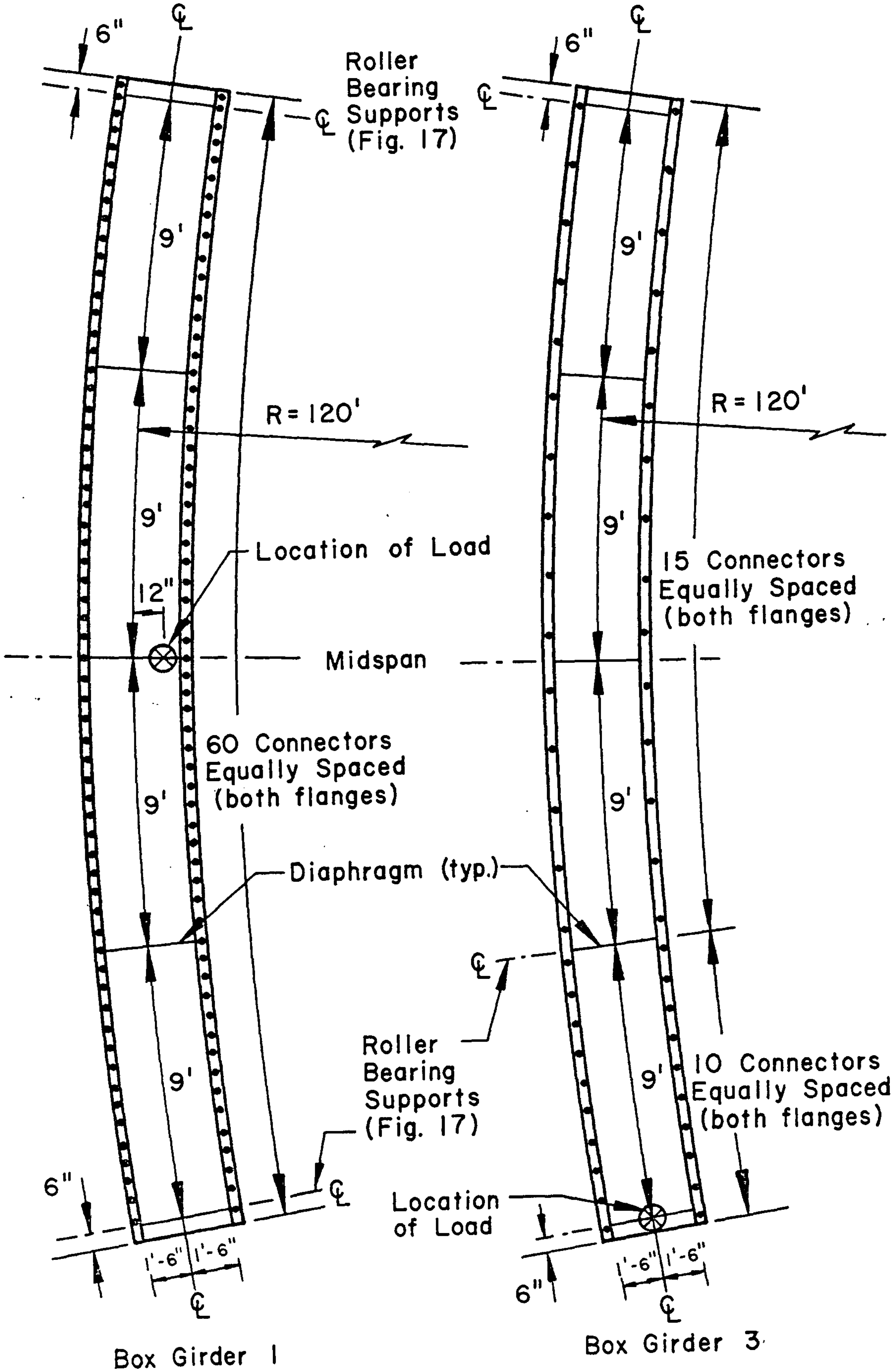


Fig. 9 Box Girders 1 and 3 - Schematic Plan View Showing Shear Connector Arrangement

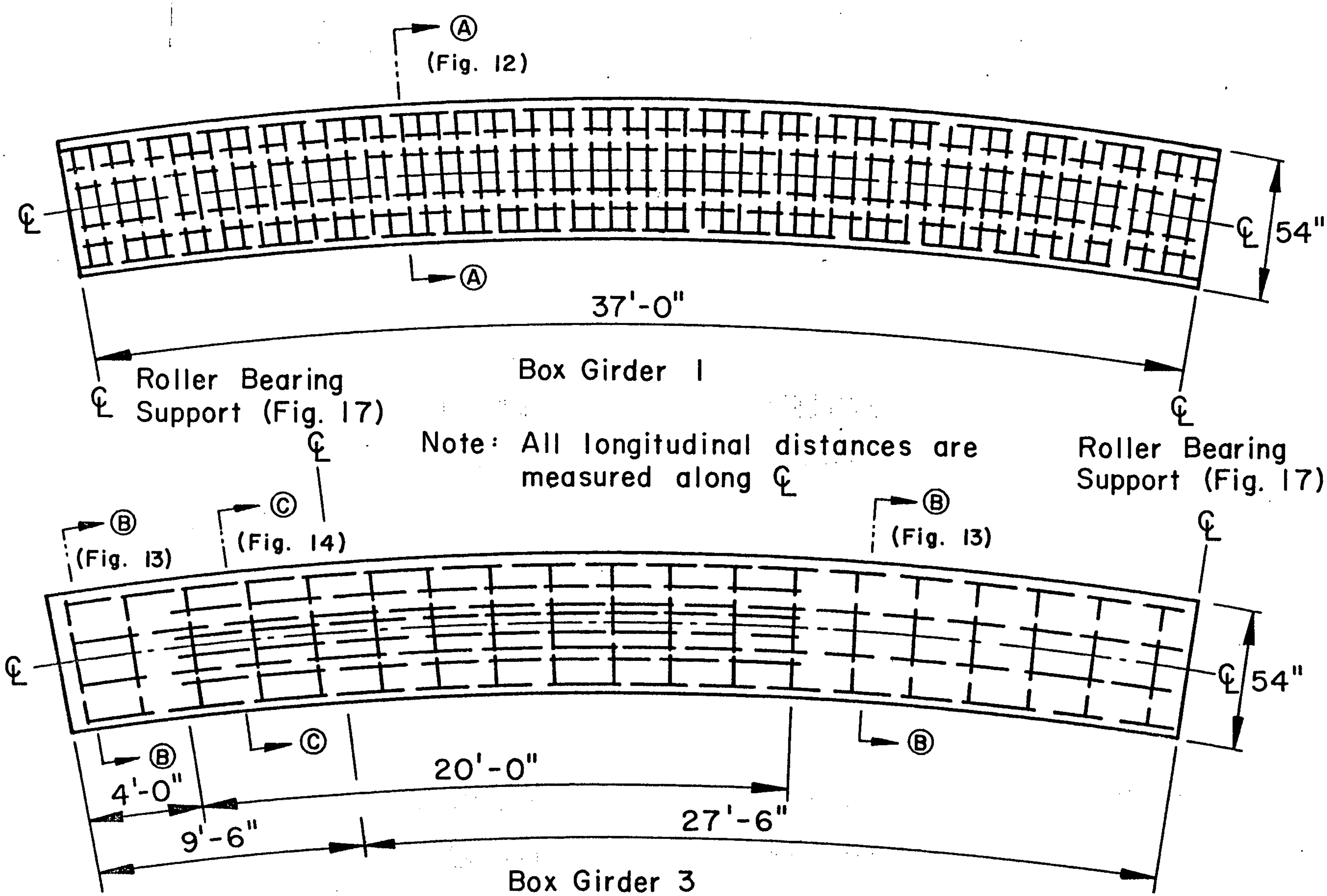


Fig. 10 Composite Box Girders 1 and 3 - Deck Reinforcing

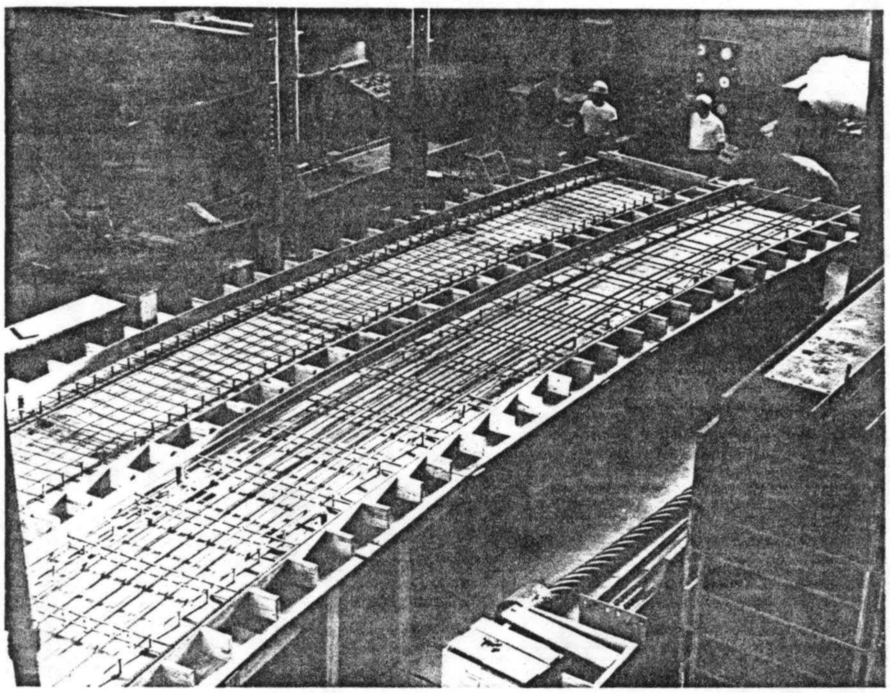
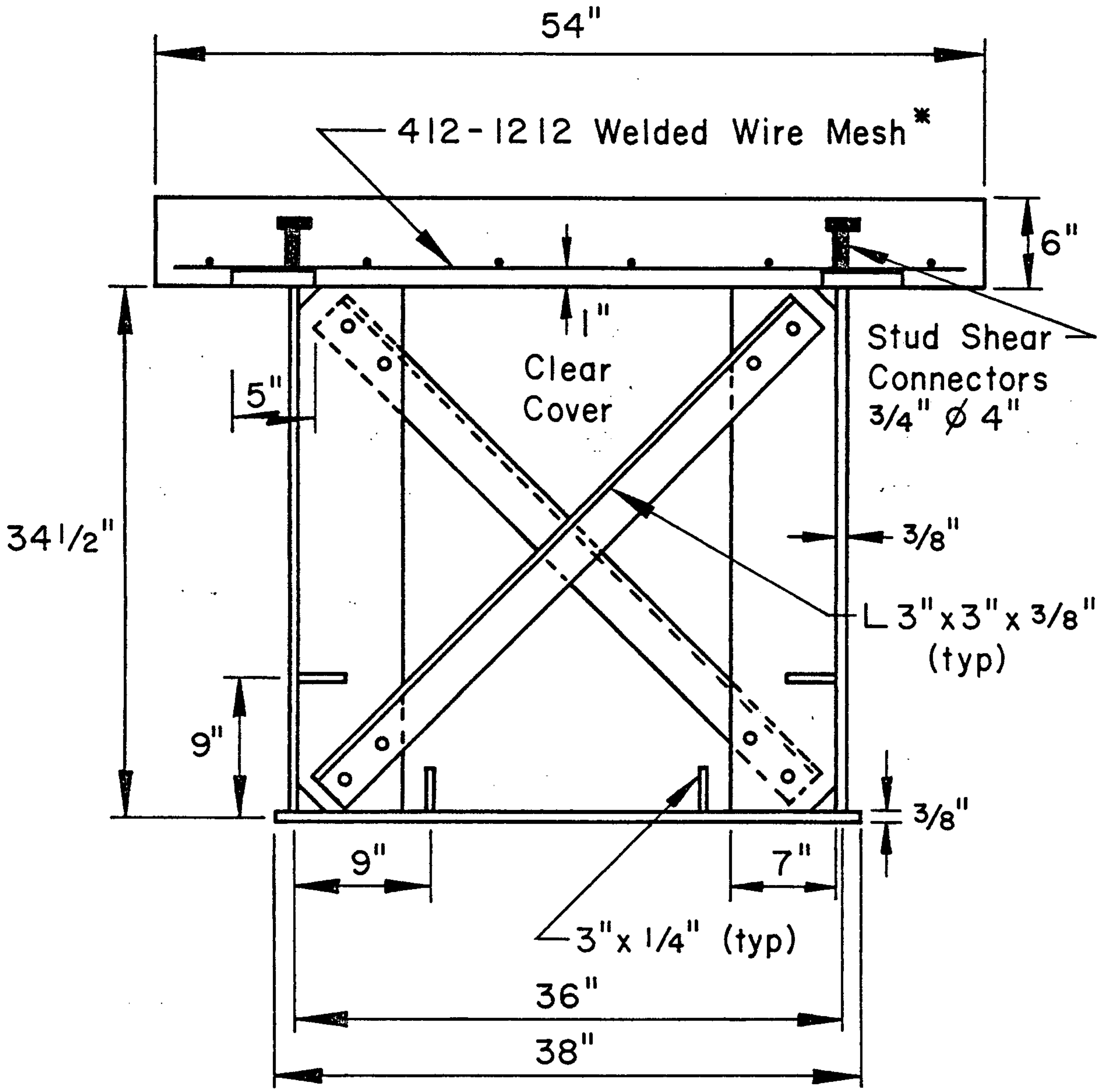


Fig. 11 Composite Slab Formwork and Reinforcing Steel for Box Girder 1 (left) and Box Girder 3 (right)



* Note: Gage No. 4 bars @ 12" run transverse to girder; Gage No. 12 bars @ 12" run longitudinally along girder.

Fig. 12 Composite Box Girder 1 - Cross Section A (Fig. 10)

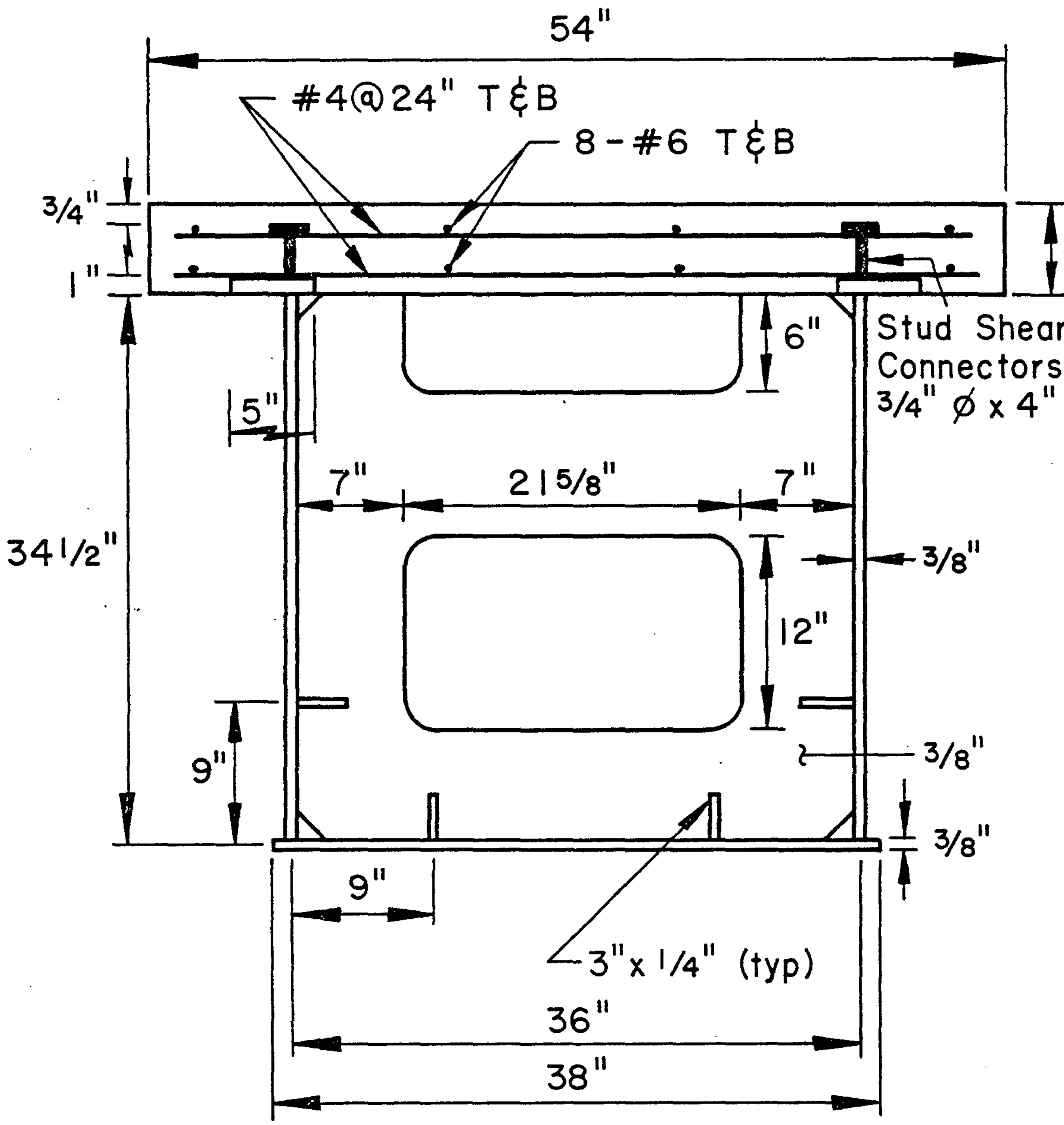


Fig. 13 Composite Box Girder 3 - Cross Section B (Fig. 10)

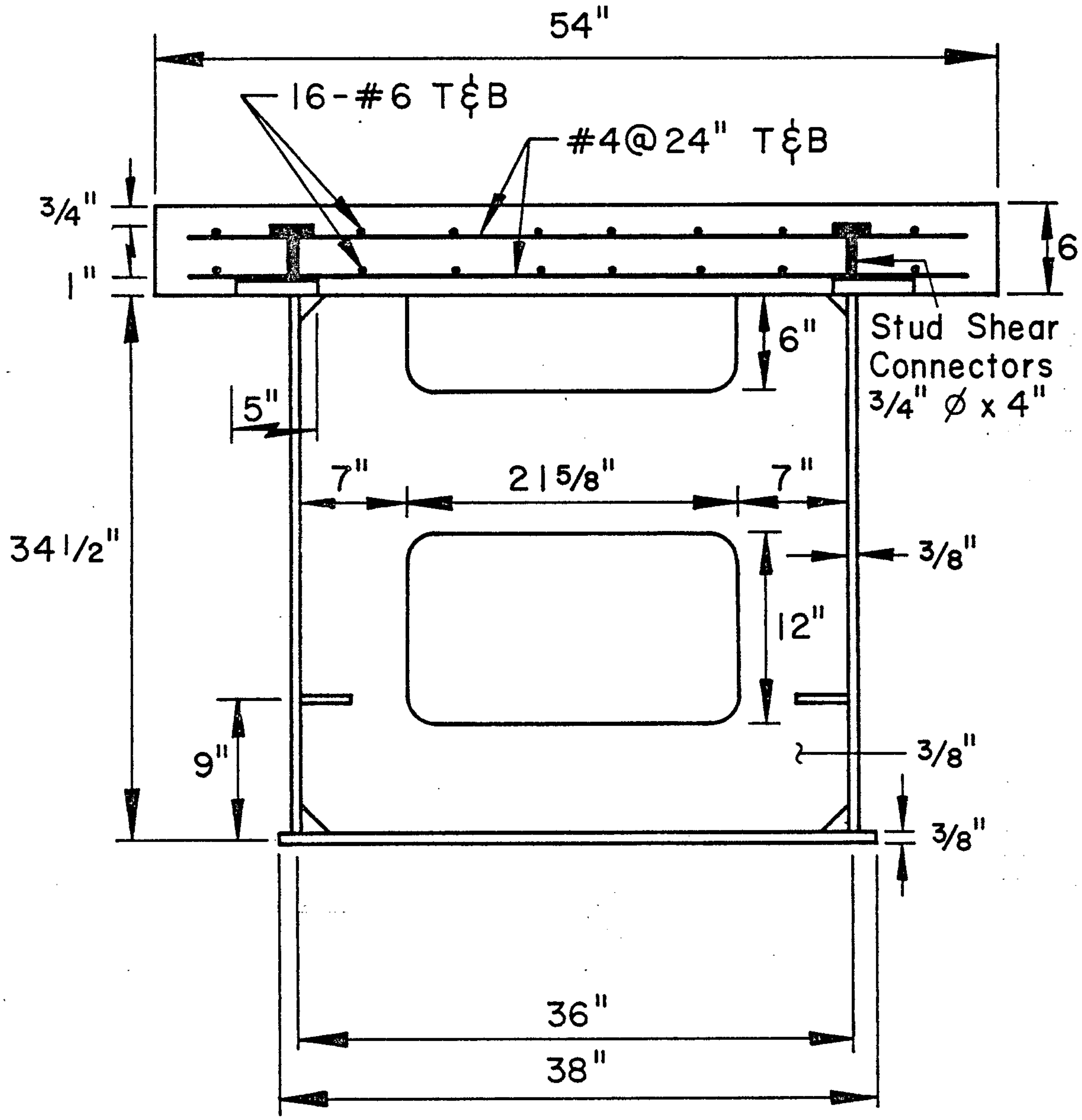


Fig. 14 Composite Box Girder 3 - Cross Section C (Fig. 10)

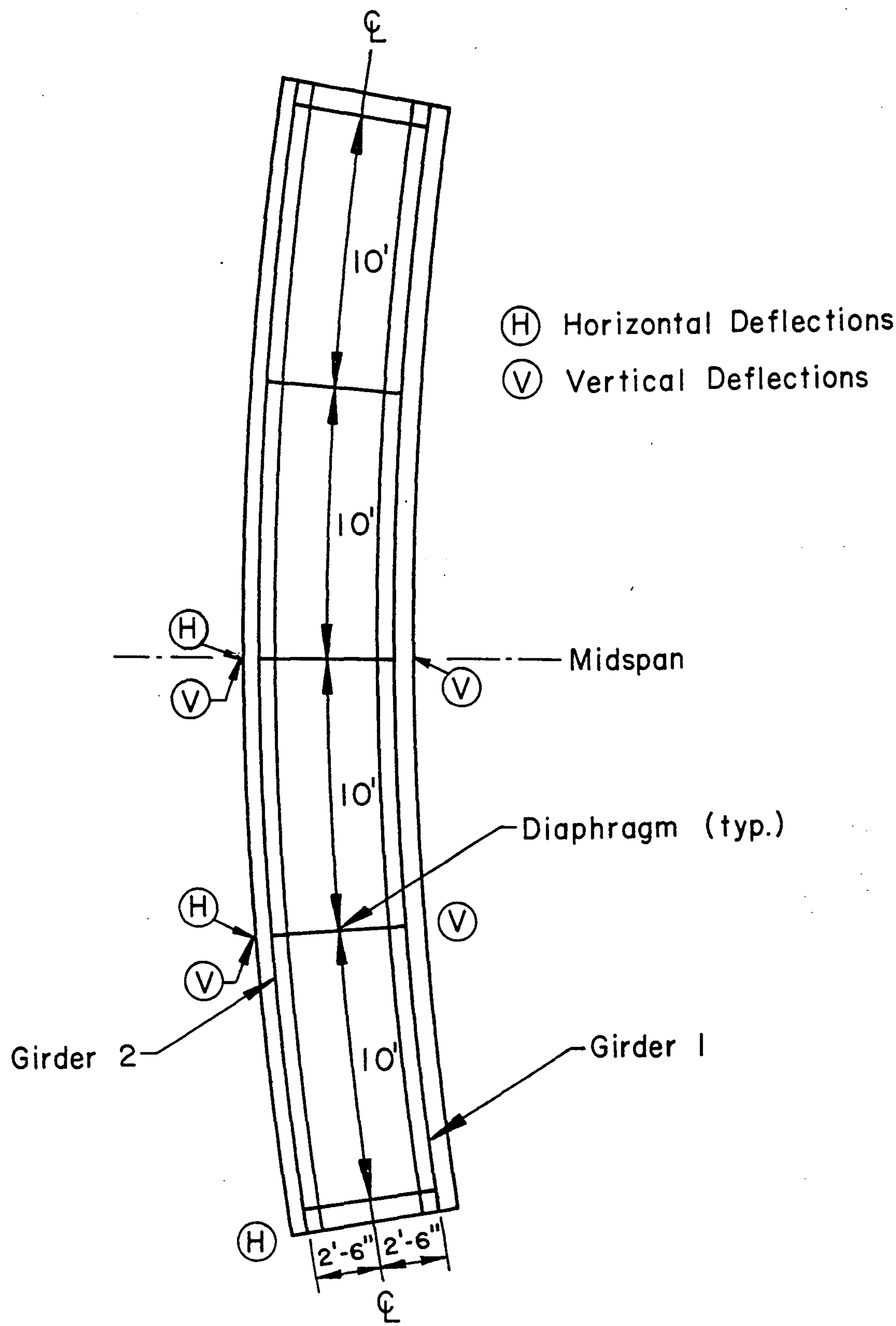


Fig. 15 Plate Girder Assemblies 1, 4, and 5 - Dial Gage Locations on Bottom Flanges

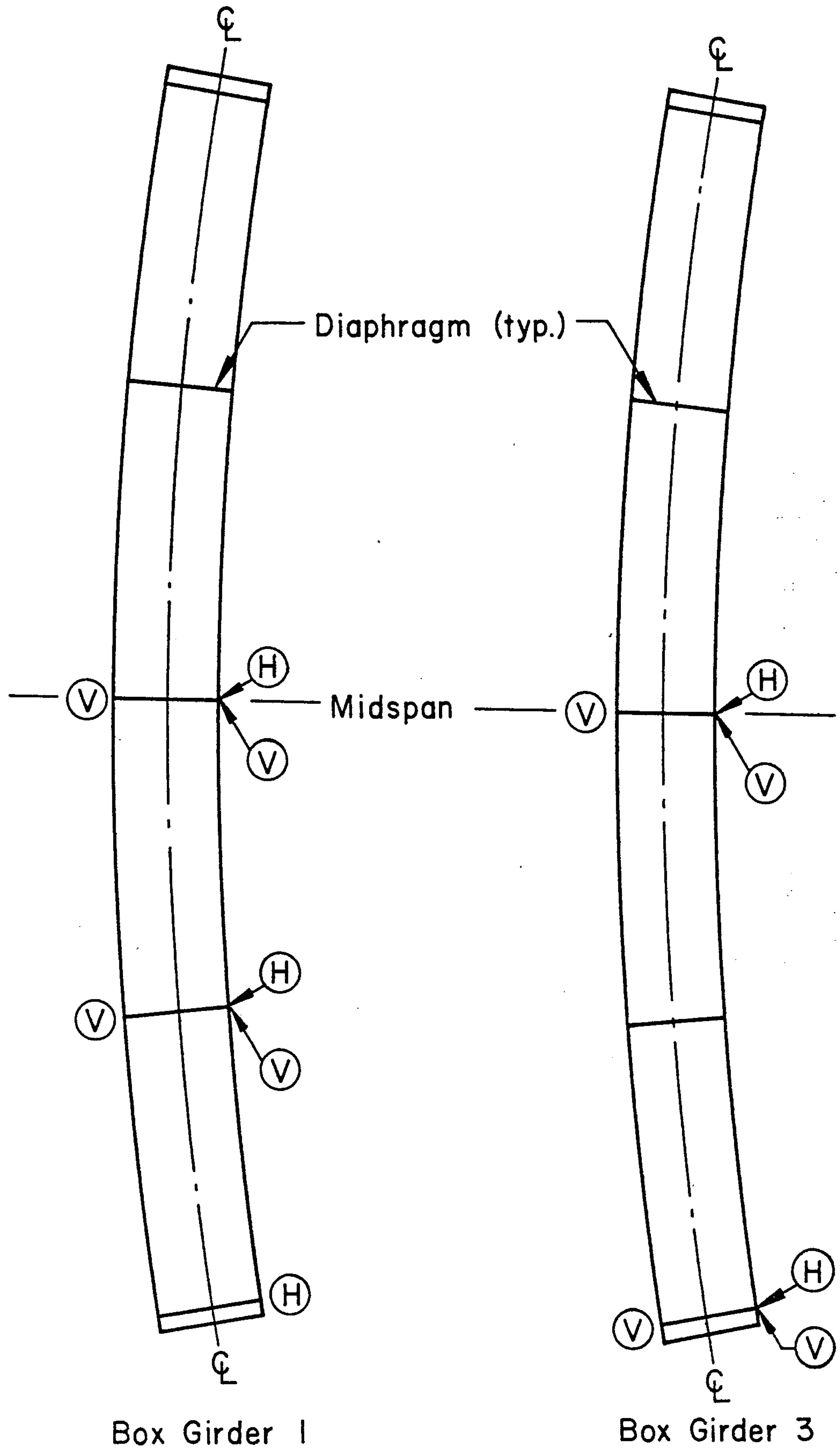


Fig. 16 Composite Box Girders 1 and 3 - Dial Gage Locations on Bottom Flanges

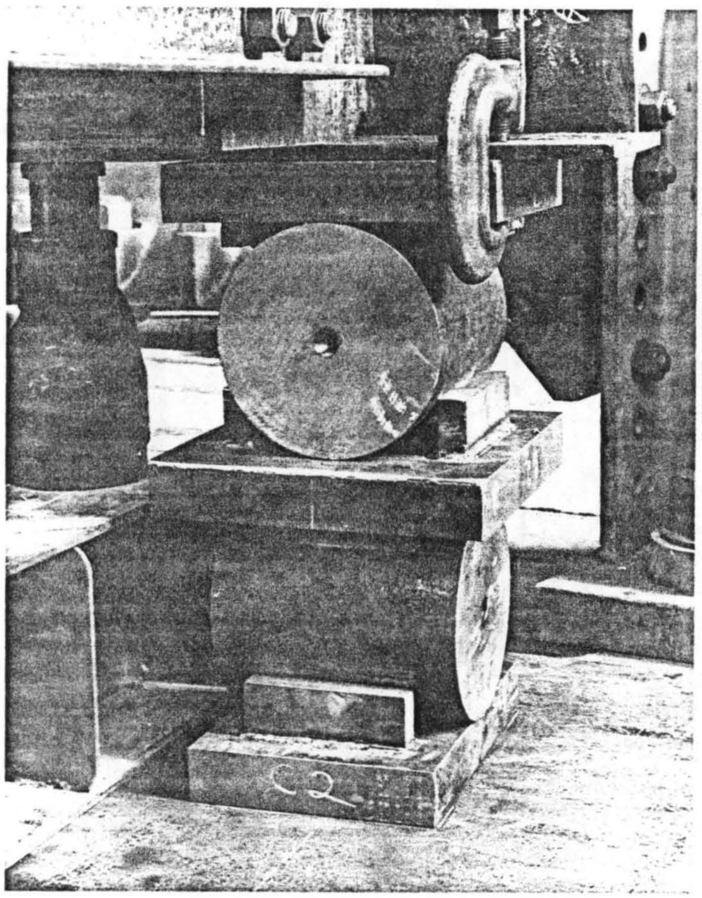


Fig. 17 Roller Support Assembly

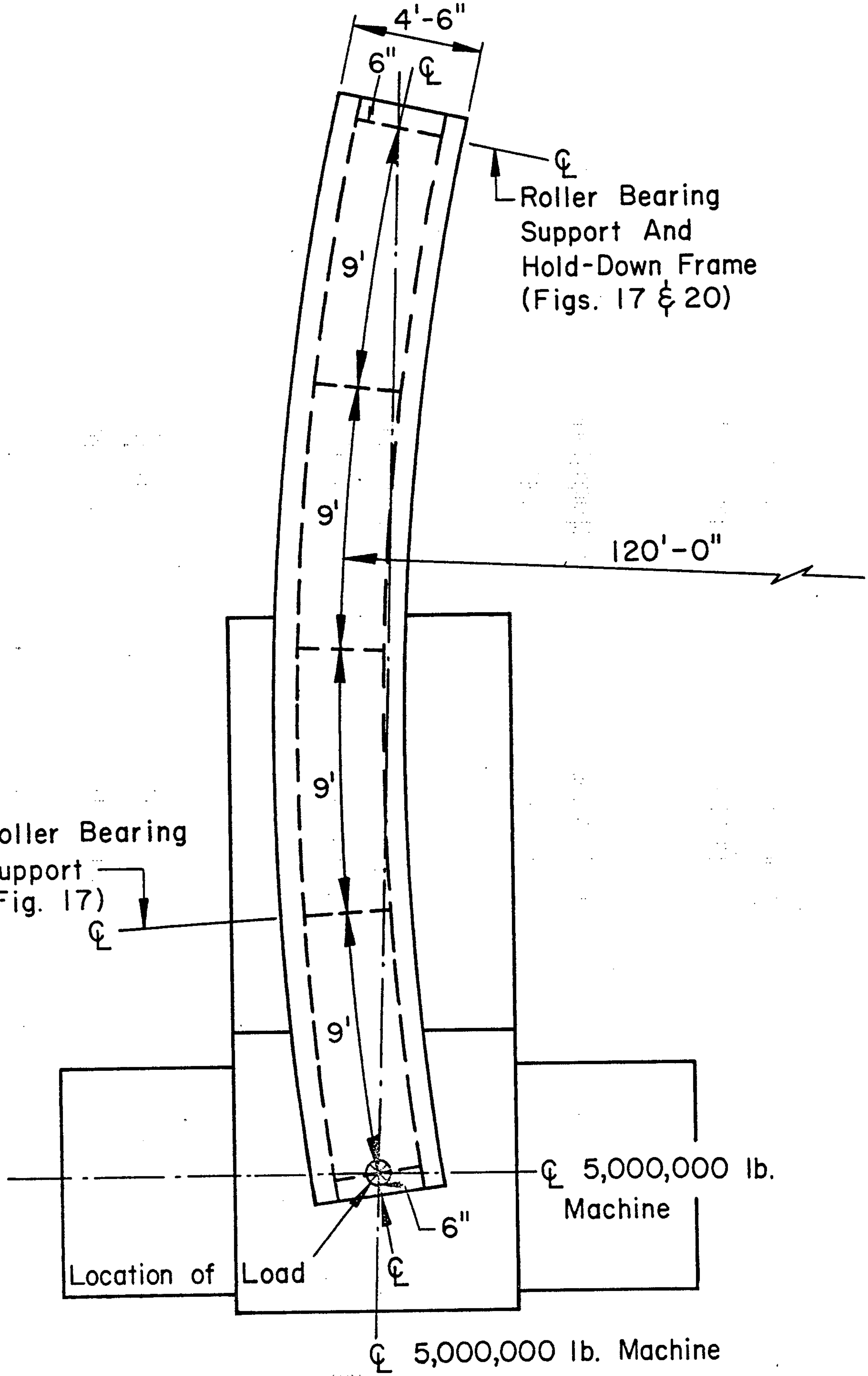


Fig. 18 Composite Box Girder 3 - Schematic Plan View of Test Setup

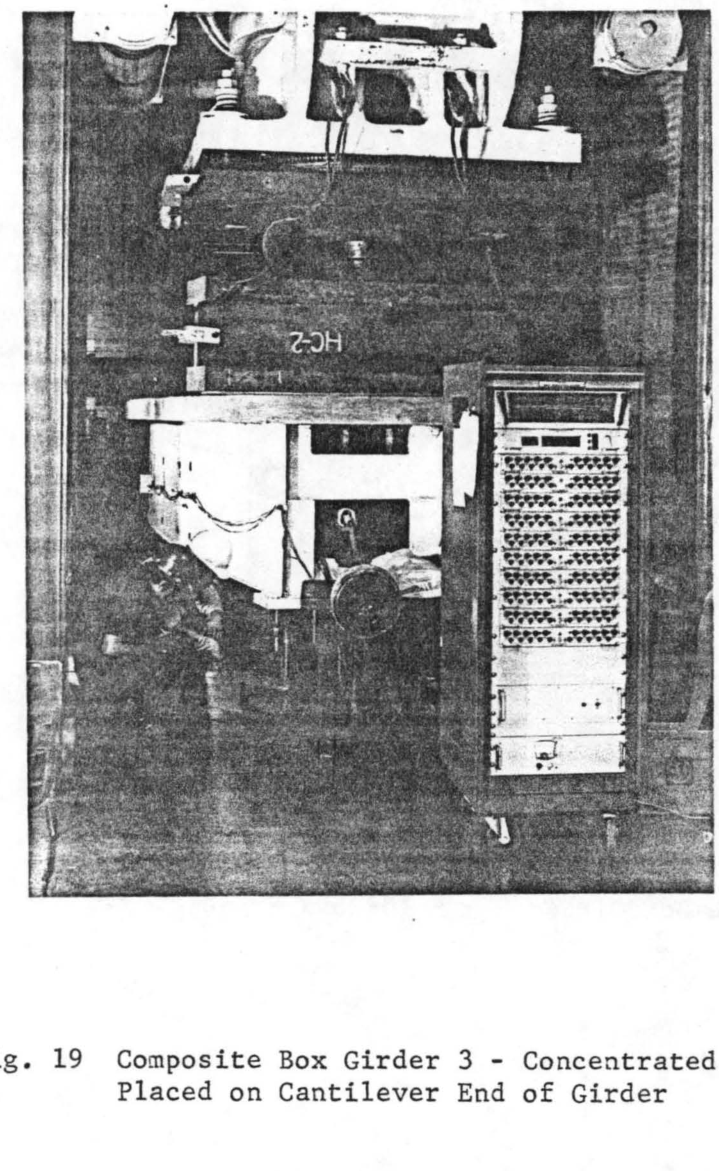


Fig. 19 Composite Box Girder 3 - Concentrated Load Placed on Cantilever End of Girder

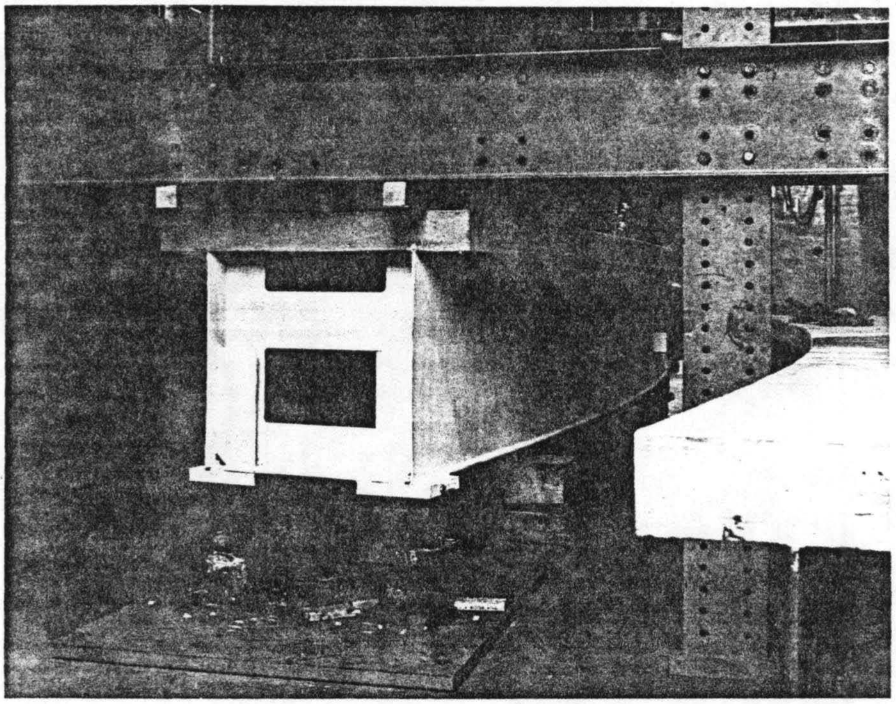


Fig. 20 Composite Box Girder 3 - Hold-Down Frame at Far End of Girder

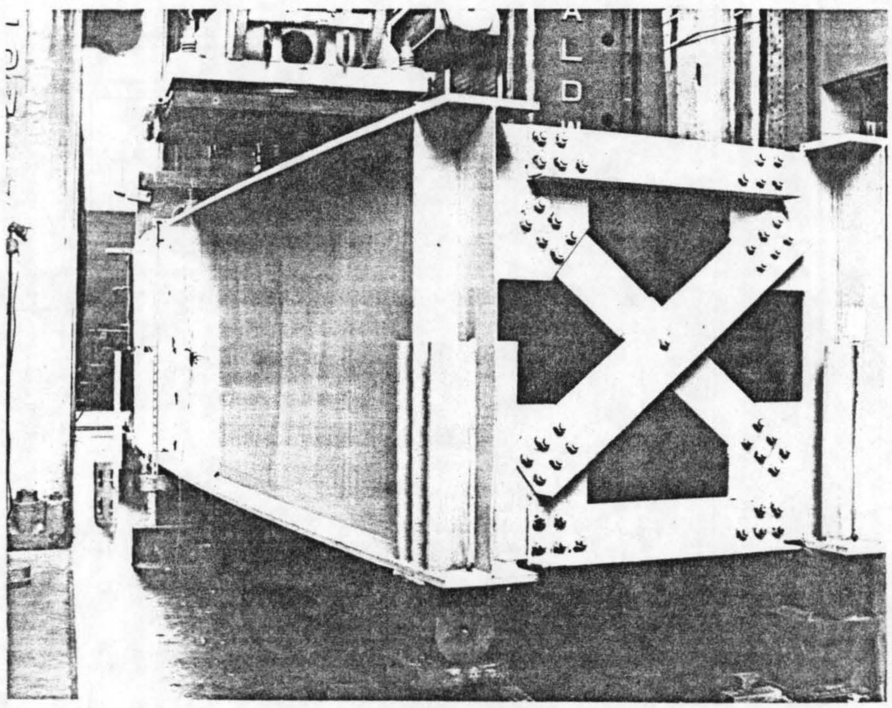


Fig. 21 Non-Composite Plate Girder Assembly 1 - Setup in 5,000,000 Pound Baldwin Universal Testing Machine. Load at Midspan. Roller Supports under the Ends of Girders 1 (right) and 2 (left) (see Fig. 1)

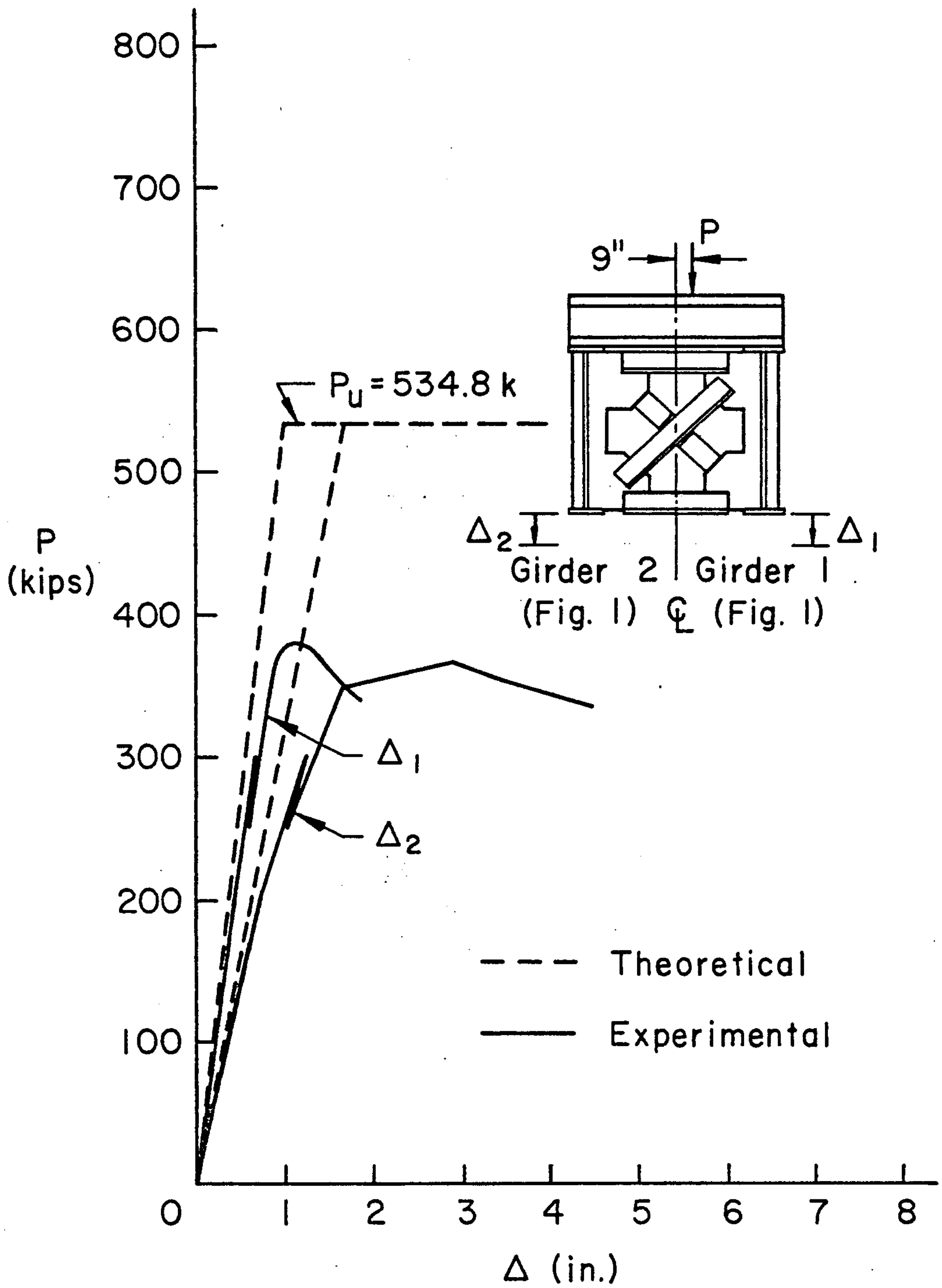


Fig. 22 Non-Composite Plate Girder Assembly 1 - Load-Deflection Behavior

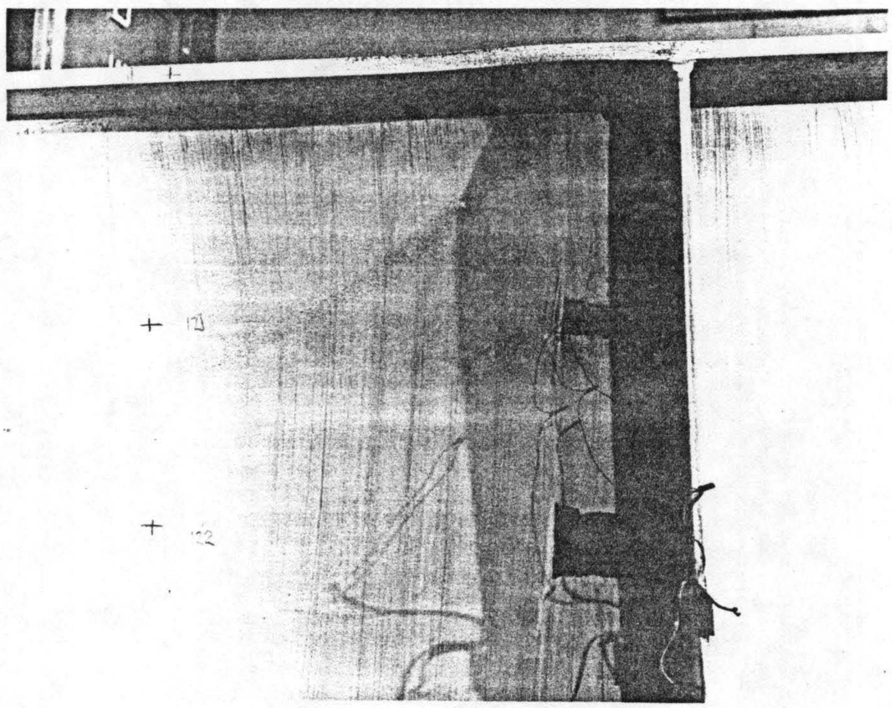


Fig. 23 Non-Composite Plate Girder Assembly 1 - Yield Lines and Local Buckling of the Compression Flange Near the Quarter Point of Girder 2

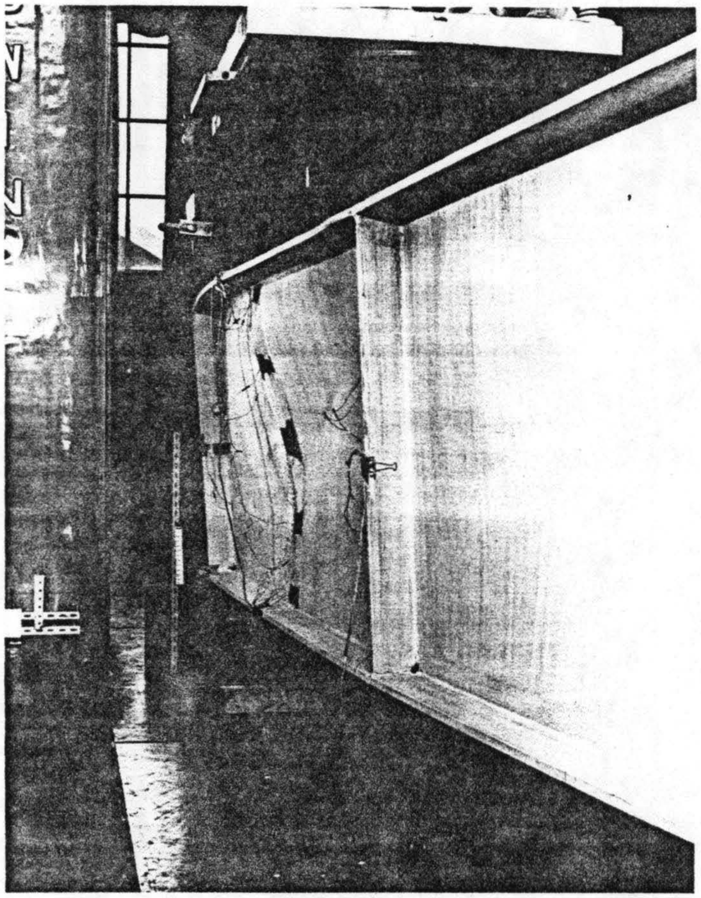


Fig. 24 Non-Composite Plate Girder Assembly 1 - Lateral Deflection of Compression Flange and Web Panel near Midspan of Girder 2

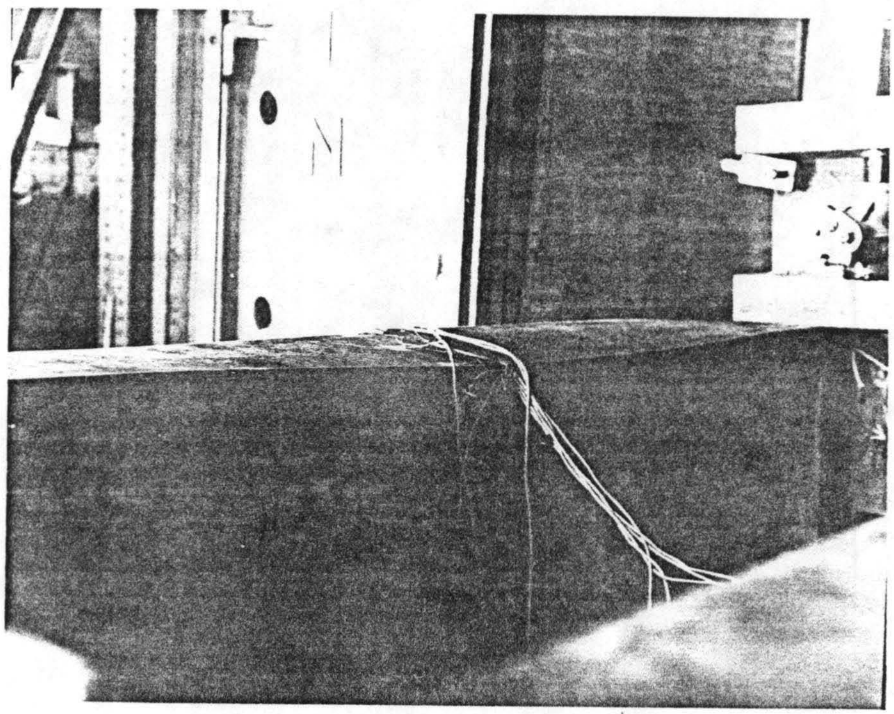


Fig. 25 Non-Composite Plate Girder Assembly 1 - Lateral Torsional Buckling of Compression Flange

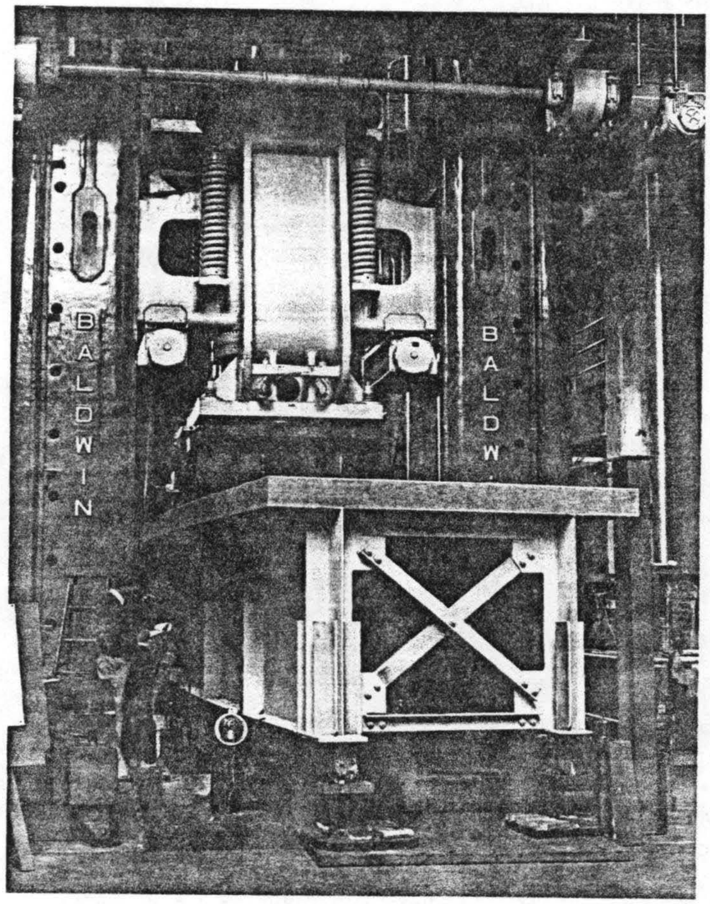


Fig. 26 Plate Girder Assembly 4 at Start of Test

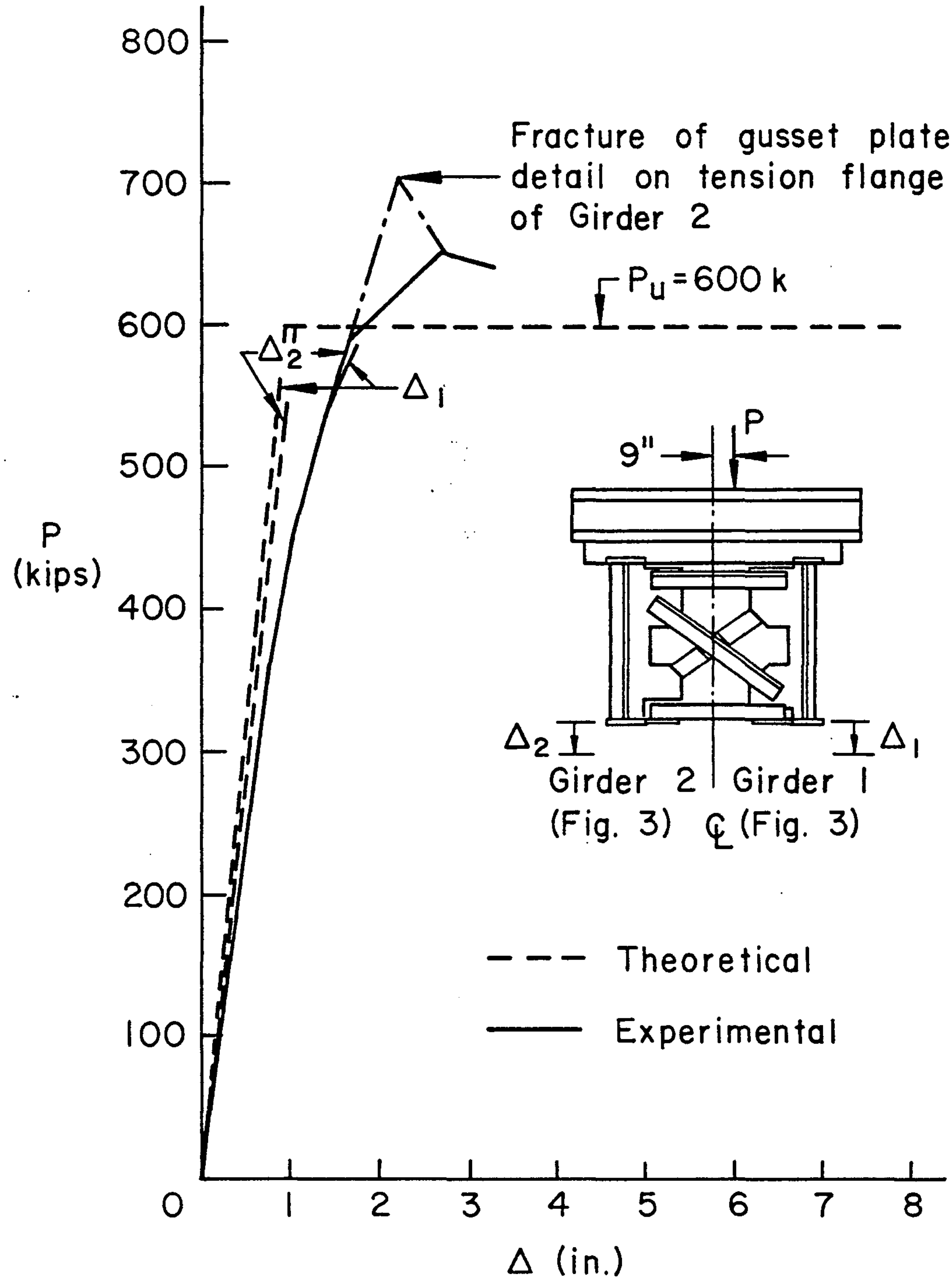


Fig. 27 Composite Plate Girder Assembly 4 - Load-Deflection Behavior

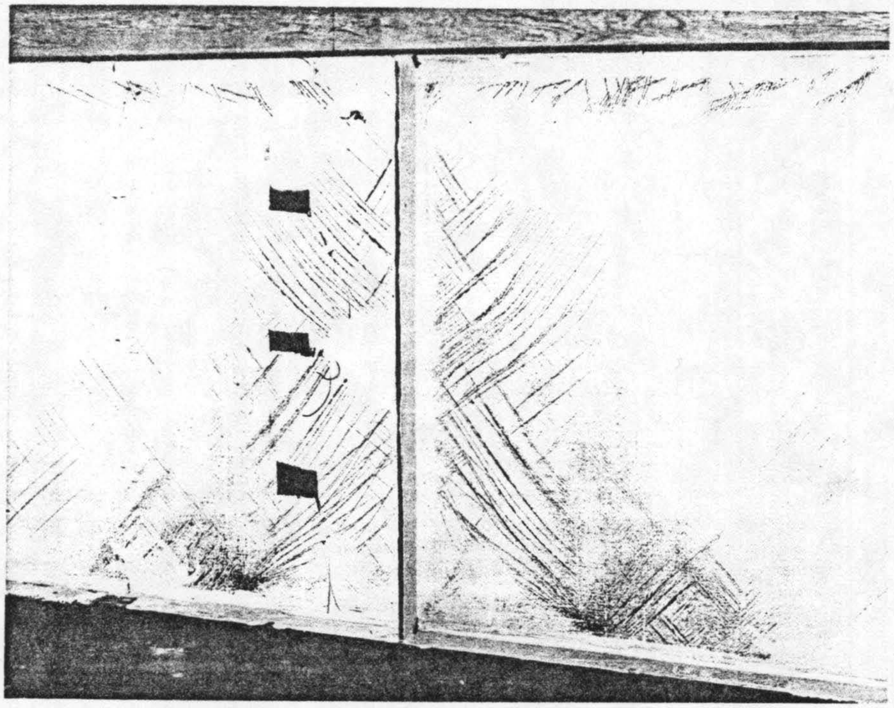


Fig. 28 Composite Plate Girder Assembly 4 - Flange and Web Yielding at Midspan of Girder 2

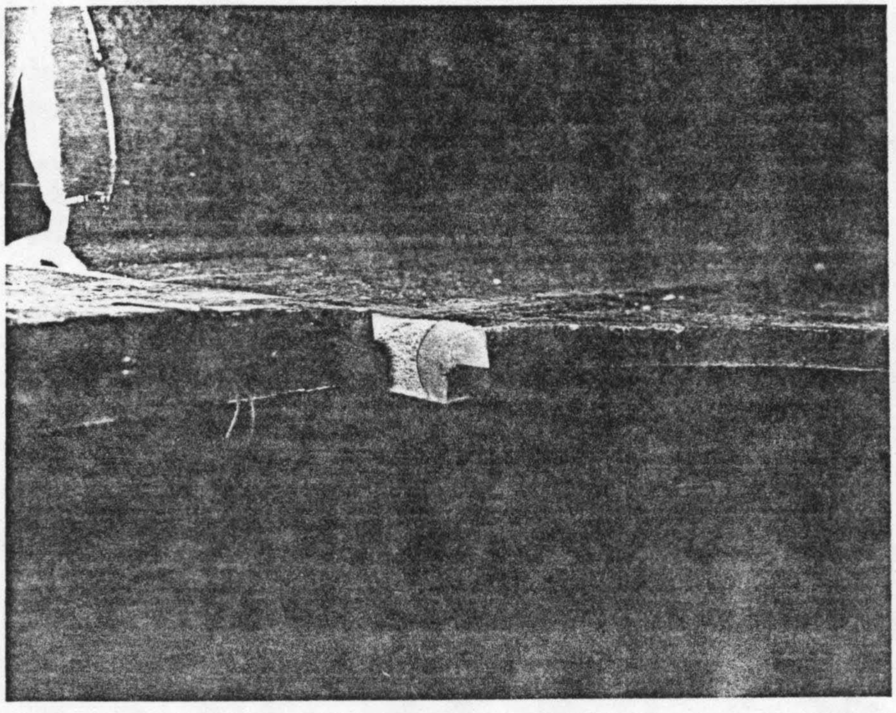


Fig. 29 Composite Plate Girder Assembly 4 - Fracture Surface and Fatigue Crack at Gusset Plate Detail

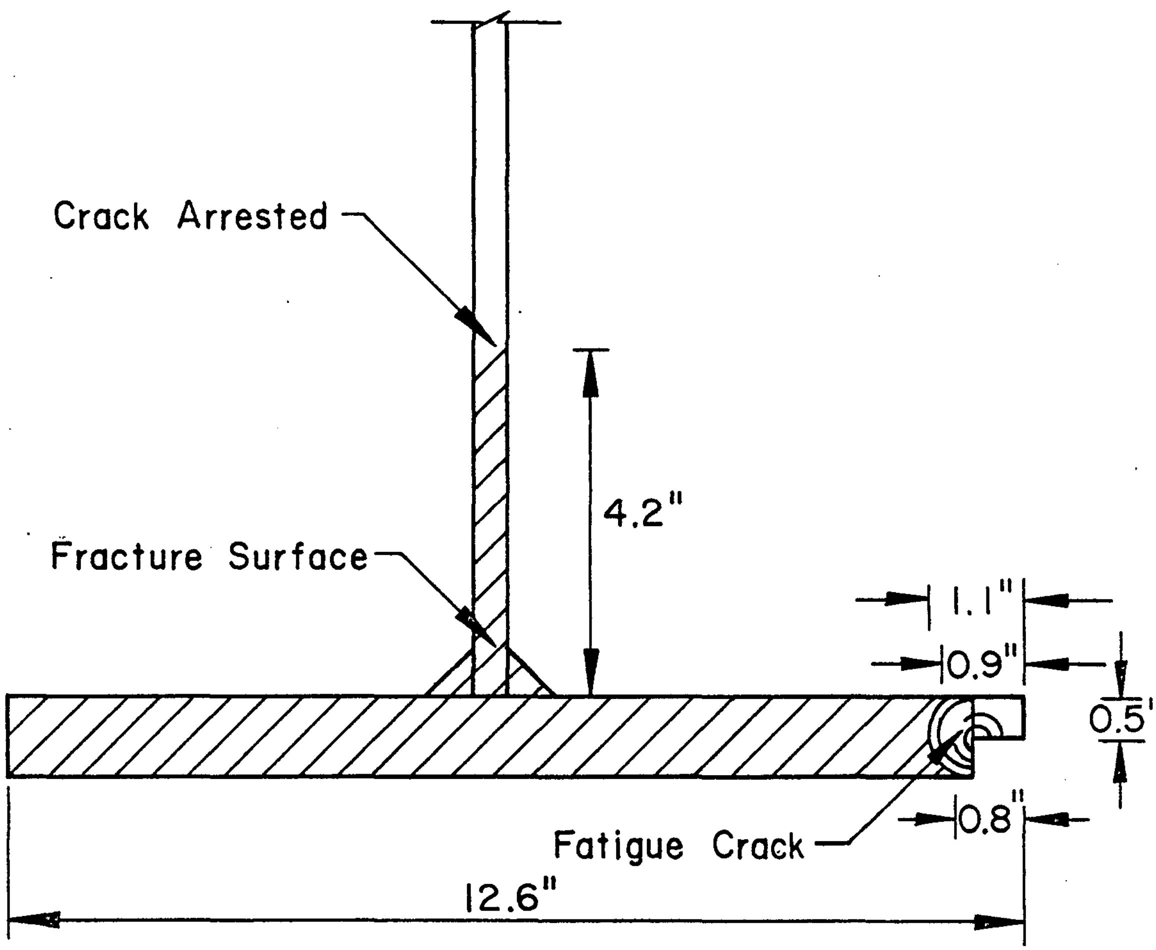


Fig. 30 Composite Plate Girder Assembly 4 - Schematic View of Fatigue Crack and Fracture Surface

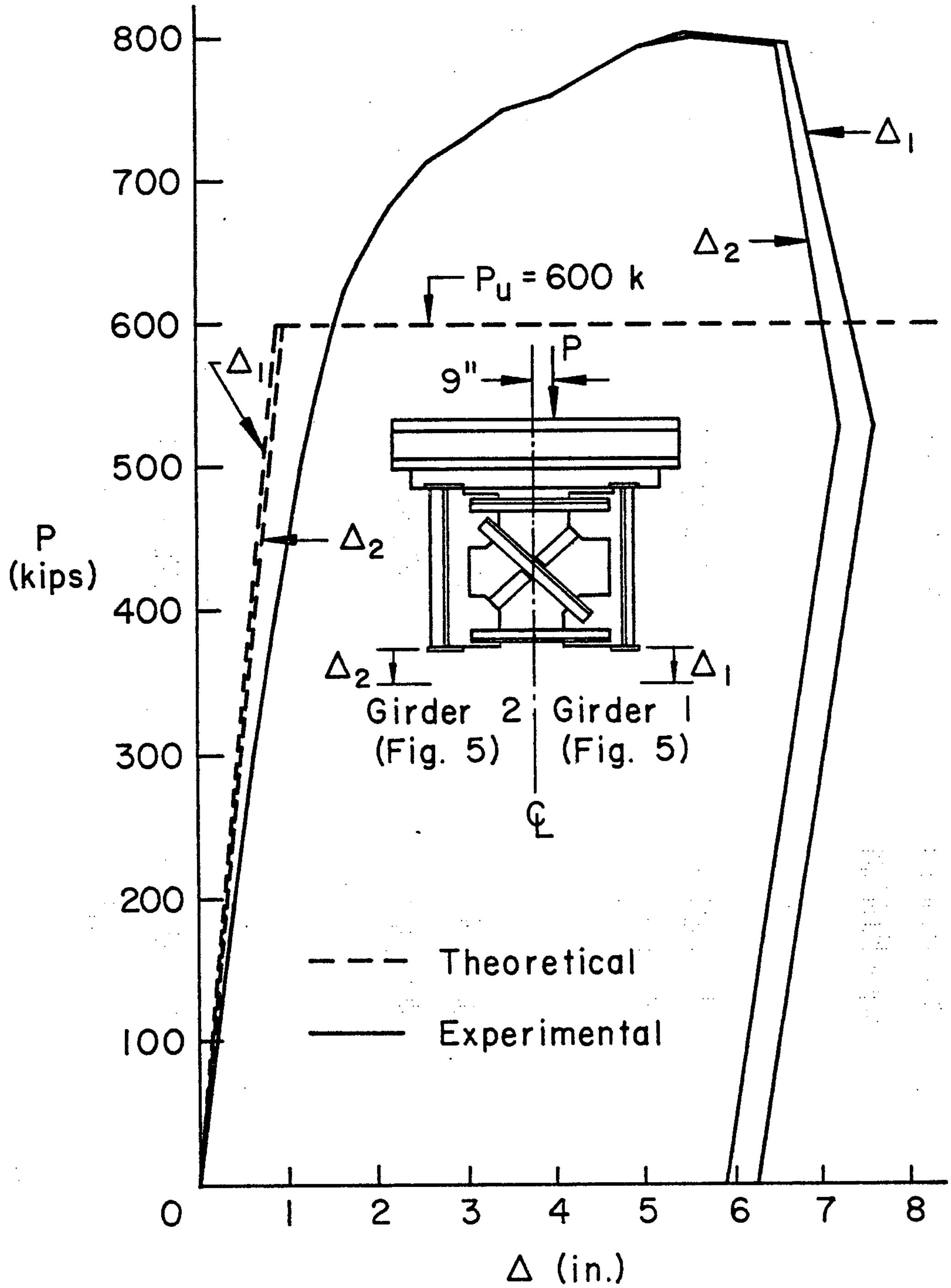


Fig. 31 Composite Plate Girder Assembly 5 - Load-Deflection Behavior

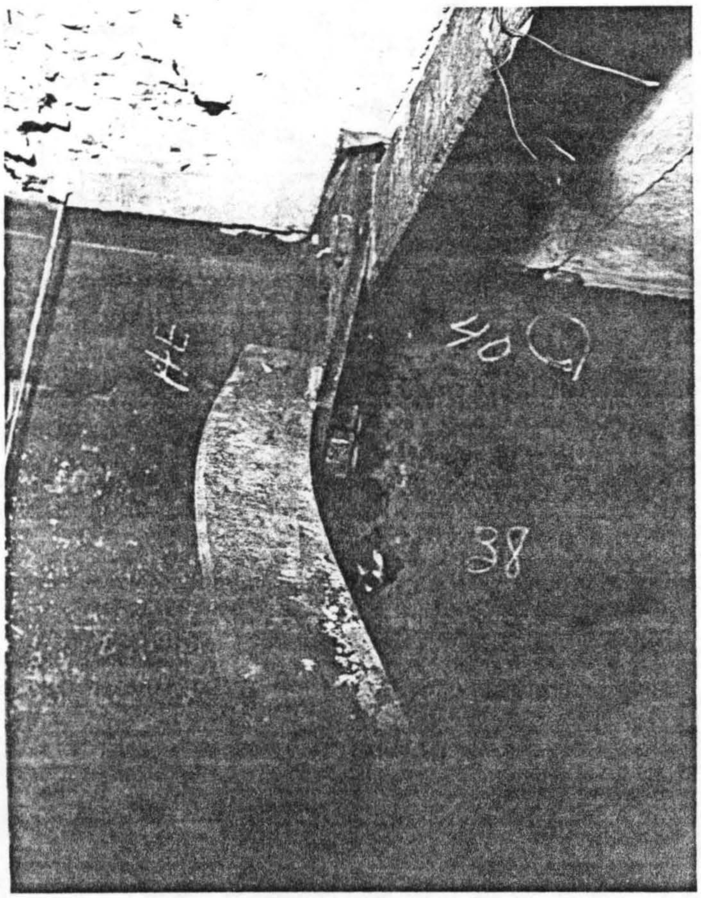


Fig. 32 Composite Plate Girder Assembly 5 - Buckled Compression Diagonal in Midspan Diaphragm (looking towards the top flange of Girder 1 from inside the assembly)

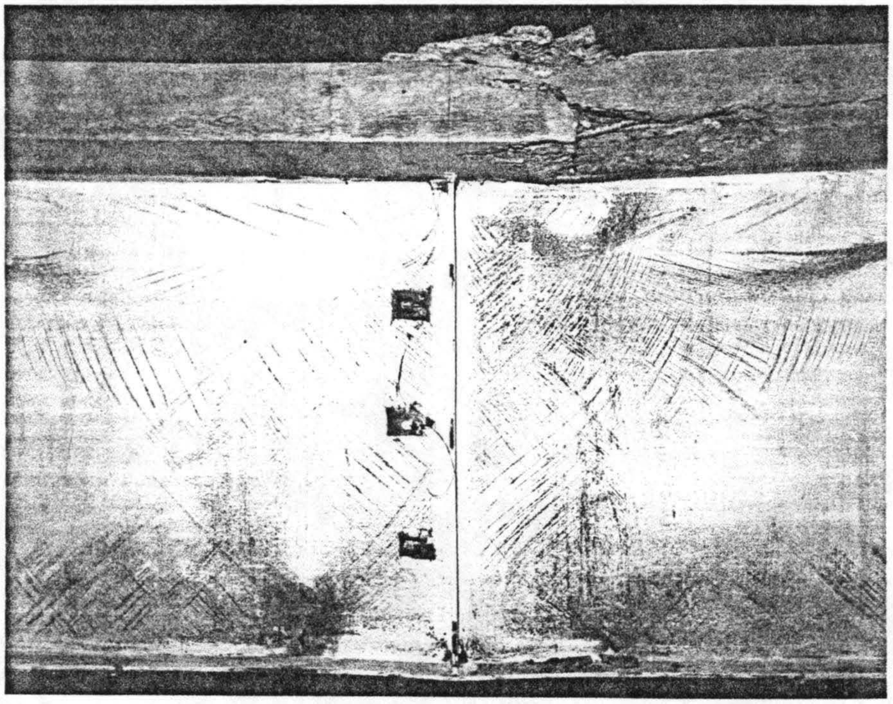


Fig. 33 Composite Plate Girder Assembly 5 (midspan of Girder 1) - Concrete Slab Crushing and Web Buckling at Midspan under the Concentrated Load

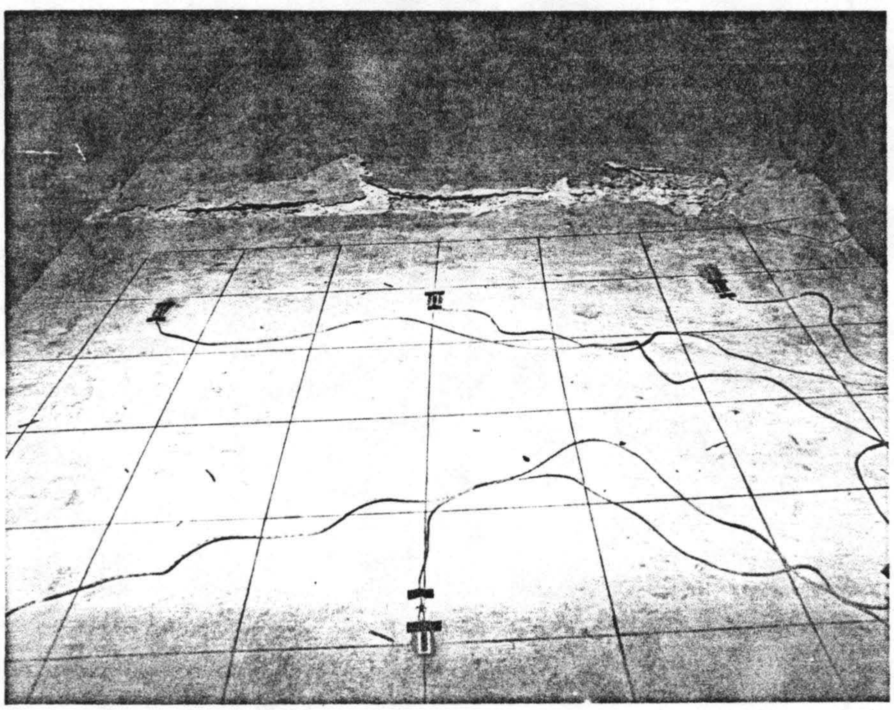


Fig. 34 Composite Plate Girder Assembly 5 - Concrete Slab at Midspan Viewed from Above

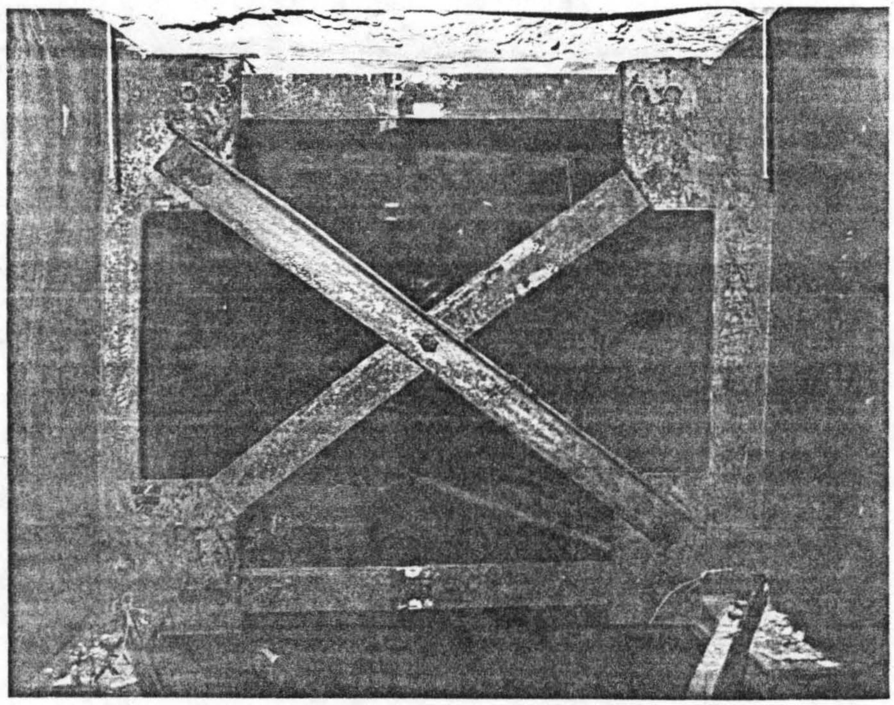


Fig. 35 Composite Plate Girder Assembly 5 - Midspan Diaphragm and Concrete Slab Viewed from inside the Assembly (the buckled diagonal runs from lower right (Girder 2) to upper left (Girder 1))

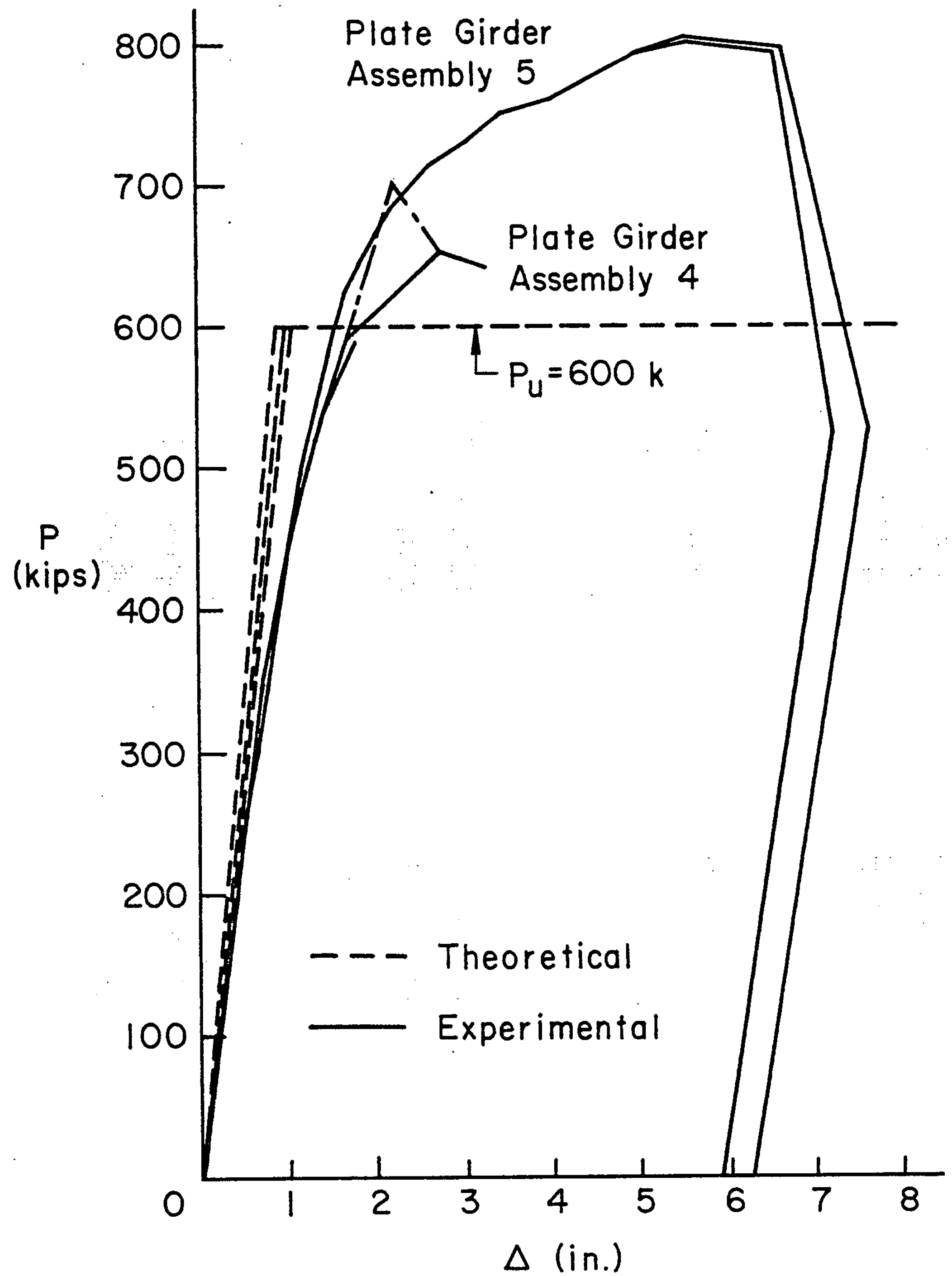


Fig. 36 Comparison of Experimental and Predicted Load-Deflection Behavior of Plate Girder Assemblies 4 and 5

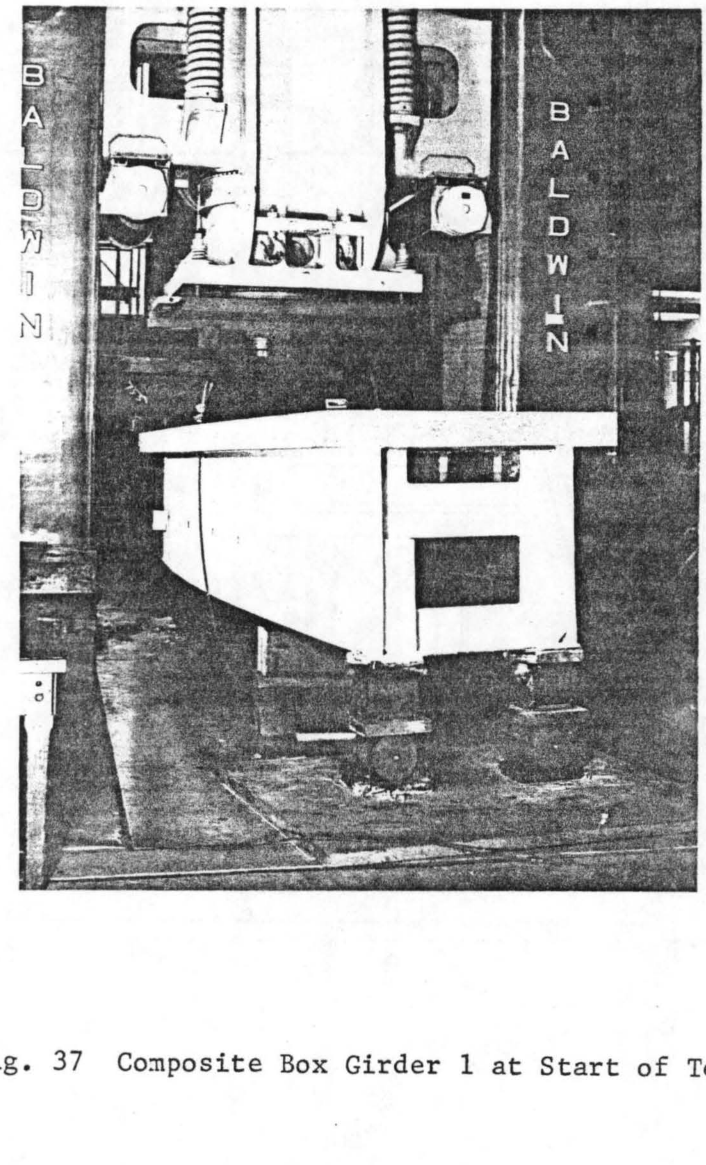


Fig. 37 Composite Box Girder 1 at Start of Test

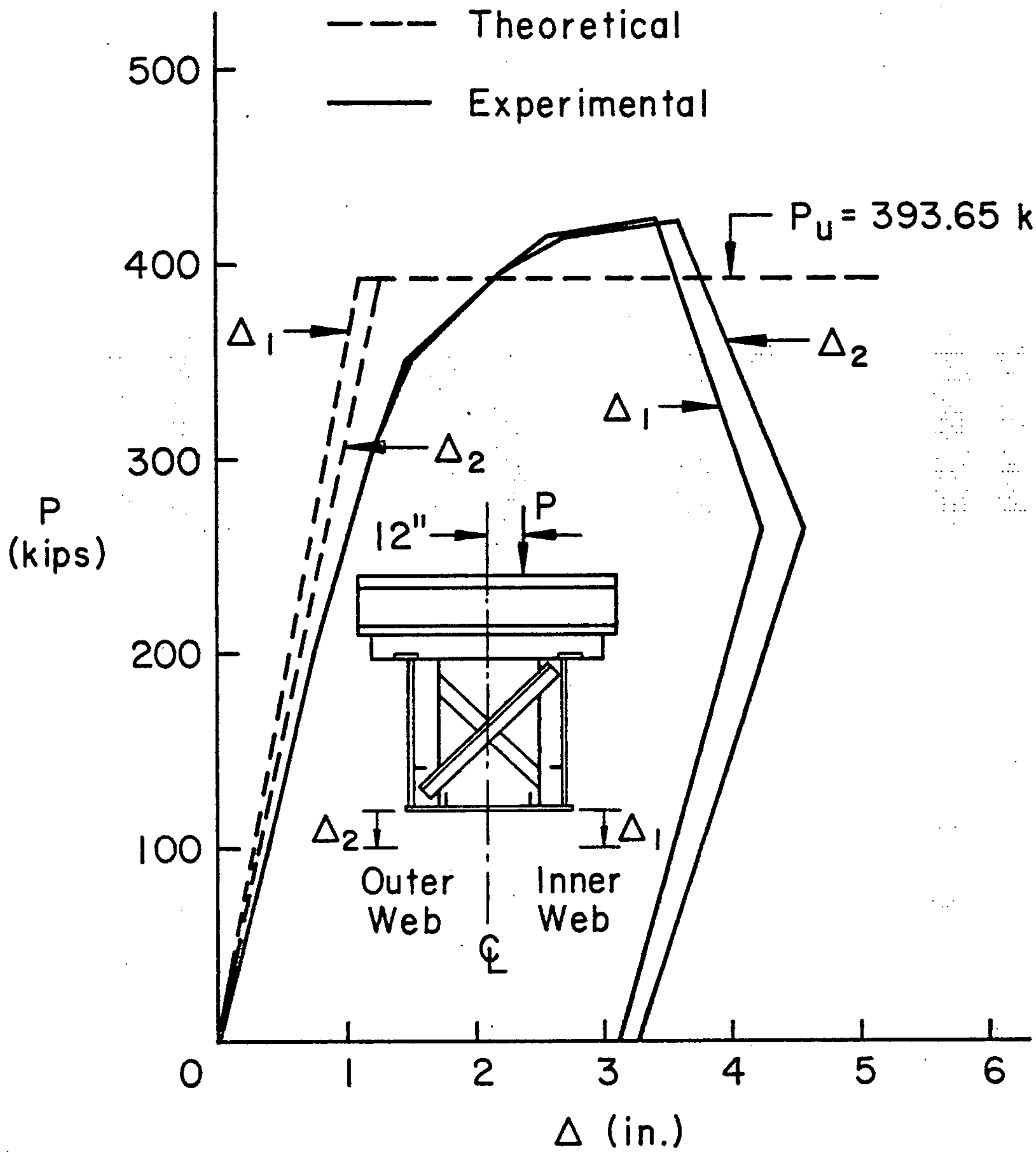


Fig. 38 Composite Box Girder 1 - Load-Deflection Behavior

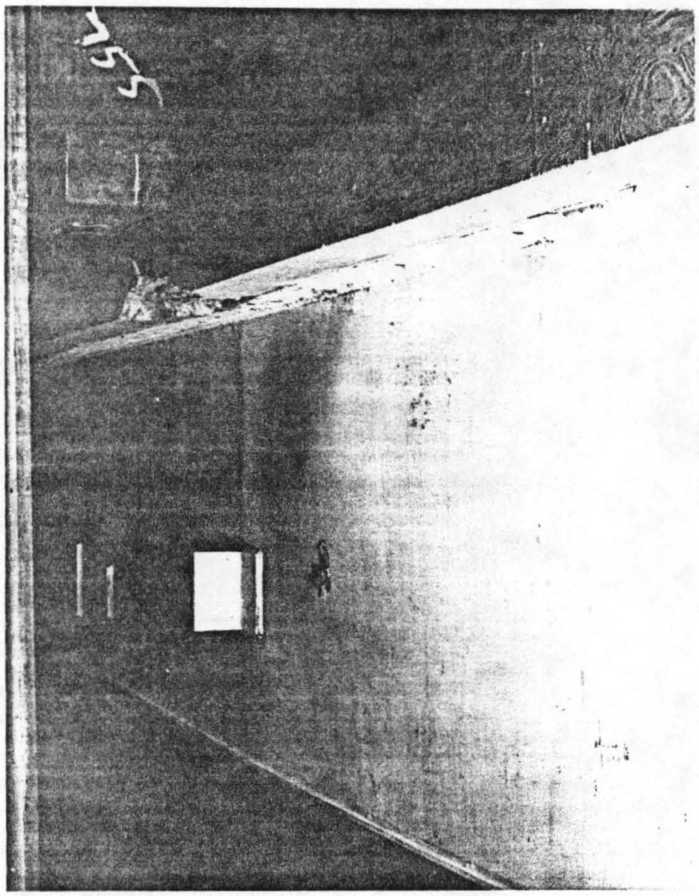


Fig. 39 Composite Box Girder 1 - Local Buckling of the Inner Web under the Load Point

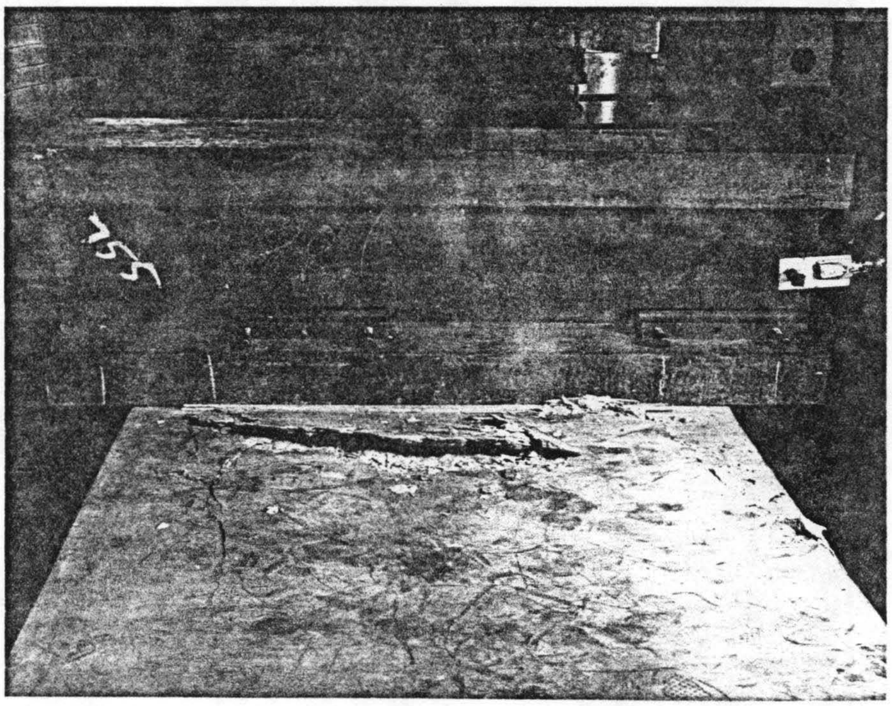


Fig. 40 Composite Box Girder 1 - Crushing of the Concrete Slab

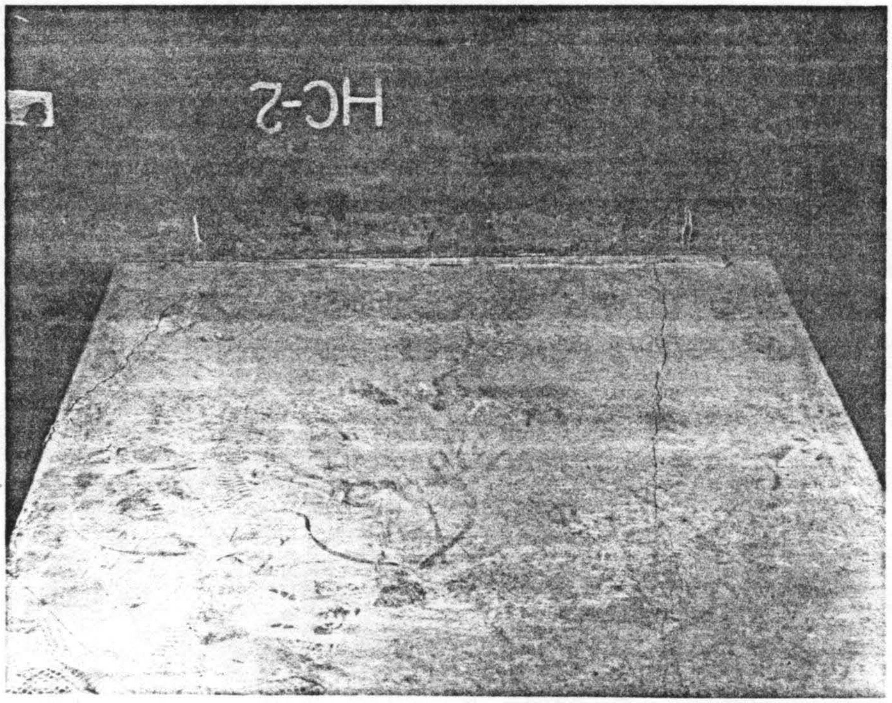


Fig. 41 Composite Box Girder 1 - Diagonal Crack in the Slab

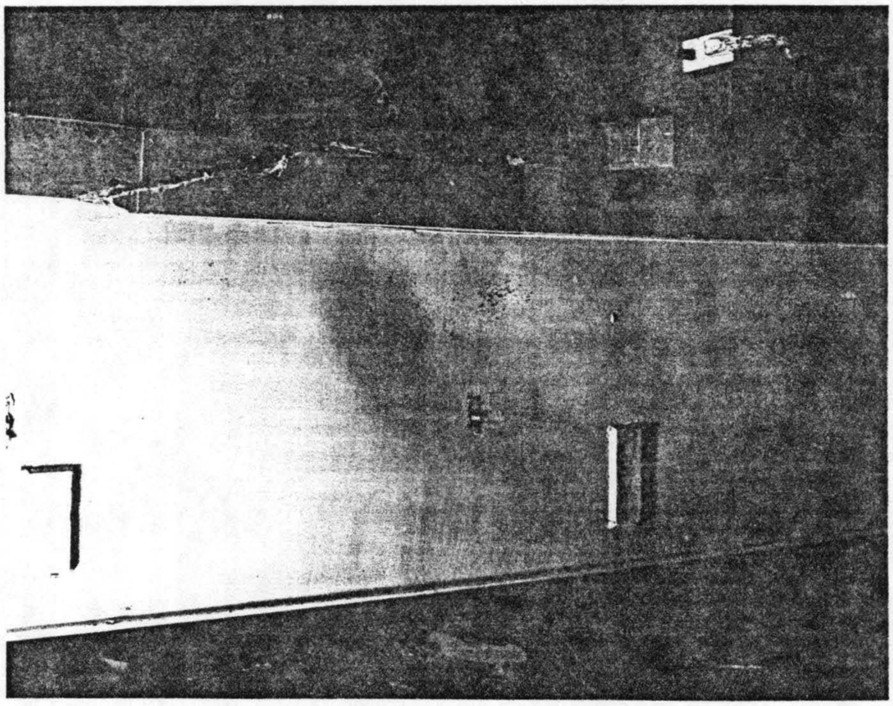


Fig. 42 Composite Box Girder 1 - Web Buckling of the Inner Web at Midspan

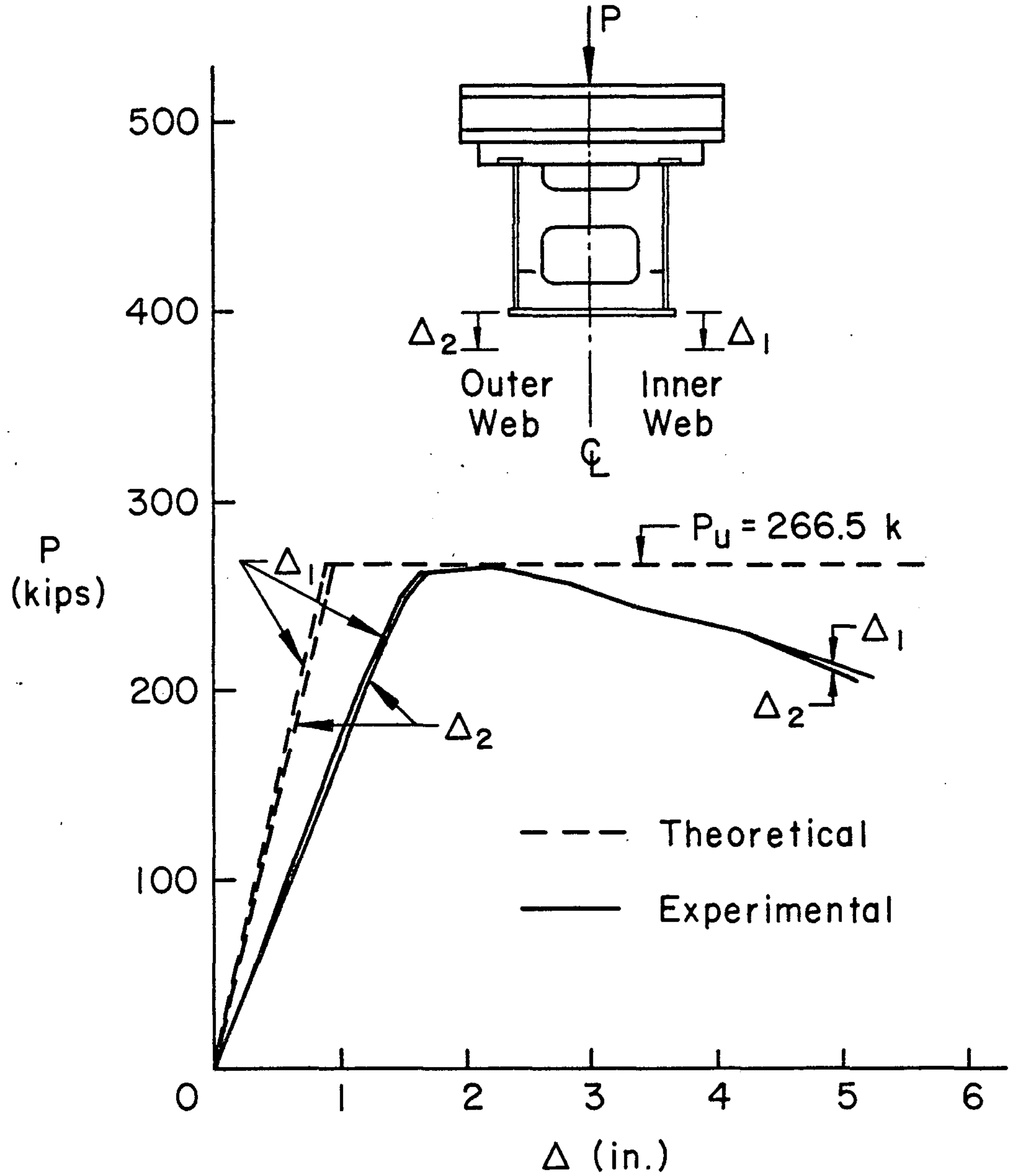


Fig. 43 Composite Box Girder 3 - Load-Deflection Behavior

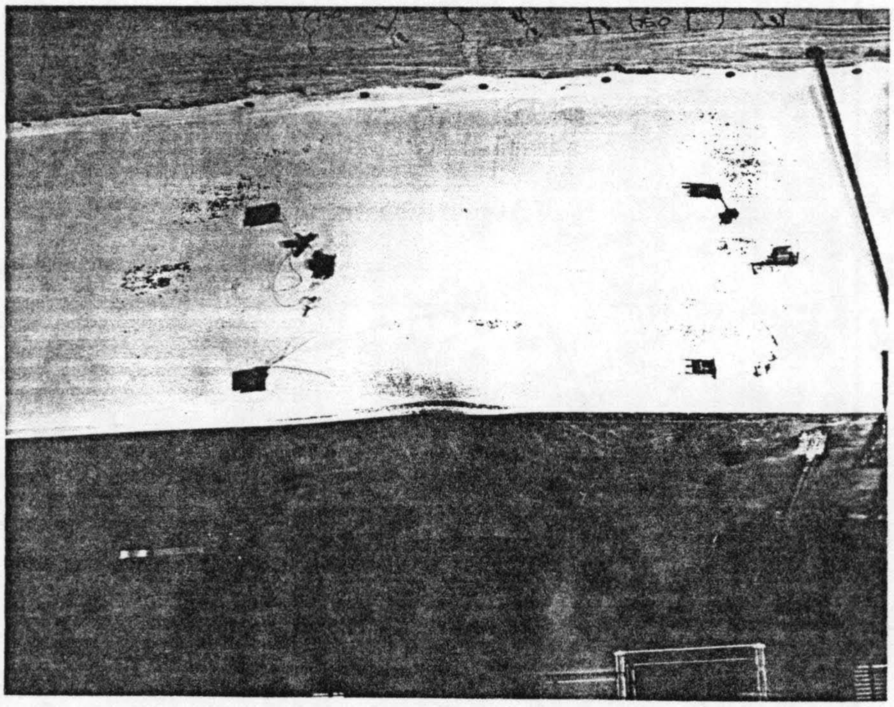


Fig. 44 Compoiste Box Girder 3 - Upward Bottom Flange Buckling at the Ultimate Load (the interior support was to the right of the large buckle and directly under the weldment across the flange)

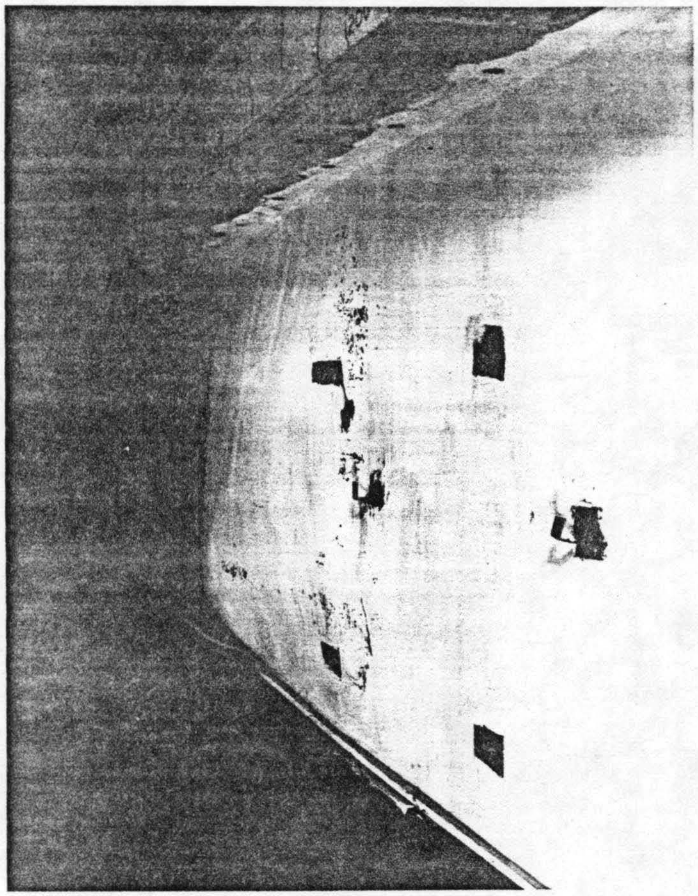


Fig. 45 Composite Box Girder 3 - Outward Web Buckling at the Ultimate Load

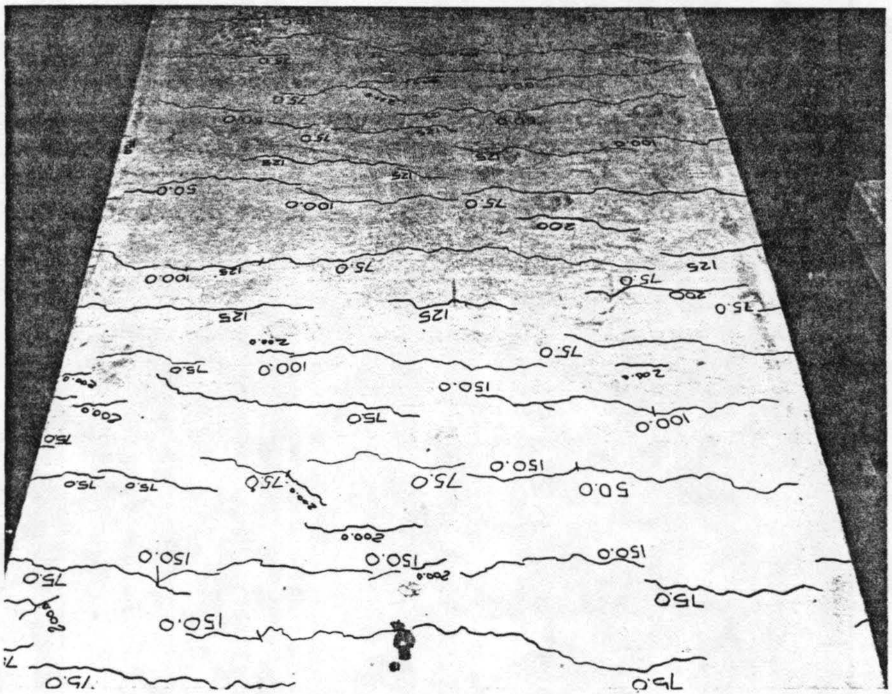


Fig. 46 Composite Box Girder 3 - Cracking of the Composite Slab over the Interior Support

7. APPENDICES

APPENDIX A: STATEMENT OF WORK

"Fatigue of Curved Steel Bridge Elements"

OBJECTIVE

The objectives of this investigation are: (1) to establish the fatigue behavior of horizontally curved steel plate and box girder highway bridges, (2) to develop fatigue design guides in the form of simplified equations or charts suitable for inclusion in the AASHTO Bridge Specifications, and (3) to establish the ultimate strength behavior of curved steel plate and box girder highway bridges.

DELINEATION OF TASKS

Task 1 - Analysis and Design of Large Scale Plate Girder and Box Girder Test Assemblies

Horizontally curved steel plate and box girder bridge designs will be classified on the basis of geometry (radius of curvature, span length, number of spans, girders per span, diaphragm spacing, types of stiffener details, type of diaphragm, web slenderness ratios and loading conditions). This will be accomplished through available information from existing literature and other sources, as required.

Current research on the fatigue strength of straight girders has identified and classified those welded details susceptible to fatigue crack growth. This classification shall be extended to include critical welded details peculiar to curved open and closed girder bridges. These welded details shall be examined with respect to their susceptibility to fatigue crack growth and analyses shall be made to estimate the conditions for fatigue crack growth.

Based on the analyses described above, a selected number of representative open and closed section curved bridge girders shall be defined for the purposes of performing in-depth analyses, design, and laboratory fatigue tests of large scale test assemblies. These girders shall be typical and will characterize commonly used girders, to include the use of welded details. The assemblies shall be analyzed and designed using currently available design guides, methods, and/or computer programs. Each test assembly shall be designed to incorporate the maximum number of welded details susceptible to fatigue crack growth. Stresses in all components of the cross section shall be examined so that the significance of each stress condition can be evaluated. An assessment of the significance of flexural stress, principal stress, stress range and stress range gradient shall be determined at each welded detail. The significance of curved boundaries on the stresses shall be examined. Stress states in welded details equivalent to those used in straight girders shall be examined.

Curved plate and box girder test assemblies shall be designed so that ultimate strength tests can be carried out following the planned fatigue tests, with a minimum of modification.

Task 2 - Special Studies

In addition to but independent of the analyses and designs described in Task 1, certain other special studies shall be performed. These special studies are specifically directed towards those problems peculiar to curved girder bridges, as follows: (1) the significance of a fatigue crack growing across the width of a flange in the presence of a stress range gradient shall be studied, (2) the effect of heat curving on the residual stresses and fatigue strength of welded details shall be examined, (3) newly suggested web slenderness ratios for curved girder webs reduce present slenderness ratios of unstiffened webs. These slenderness ratios shall be examined in terms of fatigue performance of curved webs, and (4) the effect of internal diaphragms in box beam structures will be examined with regard to fatigue behavior.

Task 3 - Fatigue Tests of Curved Plate Girder and Box Girder Test Assemblies

The plate and box girder test assemblies designed in Task 1 shall be tested in fatigue. Emphasis shall be placed on simulating full-scale test conditions. The test results shall be correlated with the analyses made in Task 1 and the results of the special studies performed in Task 2.

Task 4 - Ultimate Load Tests of Curved Plate and Box Girder Assemblies

Following the fatigue tests of Task 3, each plate and box girder test assembly shall be tested statically to determine its ultimate strength and mode of behavior. Fatigue cracks shall be repaired, where necessary, prior to the static tests. Consideration shall be given to providing a composite reinforced concrete slab on each test girder prior to the static tests.

Task 5 - Design Recommendations

Design recommendations for fatigue based on the analytical and experimental work shall be formulated in a manner consistent with that for straight girders. Specification provisions shall be formulated for presentation to the AASHTO Bridge Committee.

APPENDIX B: LIST OF REPORTS PRODUCED UNDER DOT-FH-11.8198

"Fatigue of Curved Steel Bridge Elements"

Daniels, J. H., Zettlemoyer, N., Abraham, D. and Batcheler, R. P.
ANALYSIS AND DESIGN OF PLATE GIRDER AND BOX GIRDER TEST ASSEMBLIES, DOT-FH-11.8198.1, September 1976.

Zettlemoyer, N. and Fisher, J. W.
STRESS CONCENTRATION, STRESS RANGE GRADIENT AND PRINCIPAL STRESS EFFECTS ON FATIGUE LIFE, DOT-FH-11.8198.2, June 1977

Daniels, J. H. and Herbein, W. D.
FATIGUE TESTS OF CURVED PLATE GIRDER ASSEMBLIES, DOT-FH-11.8198.3, May 1977.

Batcheler, R. P. and Daniels, J. H.
FATIGUE TESTS OF CURVED BOX GIRDERS, DOT-FH-11.8198.4, January 1978.

Daniels, J. H. and Batcheler, R. P.
EFFECT OF HEAT CURVING ON THE FATIGUE STRENGTH OF PLATE GIRDERS, DOT-FH-11.8198.5, August 1977.

Abraham, D., Yen, B. T. and Daniels, J. H.
EFFECT OF INTERNAL DIAPHRAGMS ON FATIGUE STRENGTH OF CURVED BOX GIRDERS, DOT-FH-11.8198.6, February 1978.

Daniels, J. H., Fisher, T. A., Batcheler, R. P., and Maurer, J. K.,
ULTIMATE STRENGTH TESTS OF HORIZONTALLY CURVED PLATE AND BOX GIRDERS, DOT-FH-11.8198.7, June 1978.

Daniels, J. H., Fisher, J. W., and Yen, B. T.
DESIGN RECOMMENDATIONS FOR FATIGUE OF CURVED PLATE GIRDER AND BOX GIRDER BRIDGES, DOT-FH-11.8198.8, June 1978.

APPENDIX C: THEORETICAL ANALYSIS

Elastic Analysis

The elastic response of the plate girder assemblies and box girders was established by the finite element method using SAP IV (Bathe et al., 1974).[4] Table C1 lists the number of nodes, degrees of freedom, and element types used in the models for the various assemblies. A plan view of each assembly is shown in Figs. C1 through C5. Figures C6 through C8 reveal the typical cross section discretizations for the plate girder assemblies and box girders. Results of the finite element analyses for an assumed 100^k load are summarized in Table C2.

Plastic Analysis

Models for the determination of the failure modes of curved composite plate girder assemblies and box girders are presently in an embryonic stage of development (Mozer et al., 1972).[5] In order to obtain an approximate value for the ultimate capacities, a simplified approach was adopted, based on simple plastic theory (Beedle, 1958).[6] The results of the plastic analyses are presented in Table C3. The steel was assumed to reach its yield stress level (F_y). Concrete was assumed to crush at 0.85 times its measured compressive strength (f'_c).

TABLE C1 - Description of Finite Element Models

TYPE OF ASSEMBLY	NO. OF NODES	DEGREES OF FREEDOM	ELEMENT TYPE
Plate Girder Ass. #1 (Deck Slab Excluded)	205	1186	66 Beam Elements 160 Pl.Bending Elements 66 Boundary Elements
Plate Girder Ass.#4 (Composite Deck Slab	303	1455	15 Beam Elements 286 Pl Bend. Elements 66 Boundary Elements
Plate Girder Ass.#5 (Composite Deck Slab)	303	1581	42 Beam Elements 286 Pl Bend. Elements 66 Boundary Elements
Box Girder #1 (Composite Deck Slab)	281	1461	4 Beam Elements 248 Pl Bending Elements 66 Boundary Elements
Box Girder #3 (Composite Deck Slab)	525	2854	500 Pl Bend. Elements 126 Boundary Elements

TABLE C2 - Summary of Results of Elastic Analyses

PLATE GIRDER ASSEMBLIES

	Assembly #1	Assembly #4	Assembly #5
Load	100 Kips	100 Kips	100 Kips
Midspan Deflection			
Girder 1	0.177 in.	0.167 in.	0.151 in.
Girder 2	0.307 in.	0.172 in.	0.159 in.
Max. Longitudinal Stress			
Girder 1	5.35 KSI	10.95 KSI	10.24 KSI
Girder 2	8.41 KSI	8.189 KSI	7.416 KSI
Composite Slab		0.226 KSI	0.231 KSI

BOX GIRDERS

	NO. 1	NO. 3
Load	100 Kips	100 Kips
Midspan Deflection		
Inner Web	0.286 in.	
Outer Web	0.328 in.	
End Deflection		
Inner Web		0.356 in.
Outer Web		0.349 in.
Maximum Longitudinal Stress		
Inner Web	10.54 KSI	13.54 KSI
Outer Web	10.34 KSI	11.87 KSI
Bottom Flange	12.24 KSI	13.42 KSI
Composite Slab	0.60 KSI	0.571 KSI

TABLE C3 - Summary of Results of Plastic Analyses

TYPE OF ASSEMBLY	PLASTIC MOMENT CAPACITY (K-FT)	ULTIMATE LOAD (KIPS)
Plate Girder Assembly No. 1	4813.2	534.8
Plate Girder Assemblies No. 4 and No. 5	5976.5	600
Box Girder No. 1	3665.8	393.65
Box Girder No. 3	2459.3	266.5

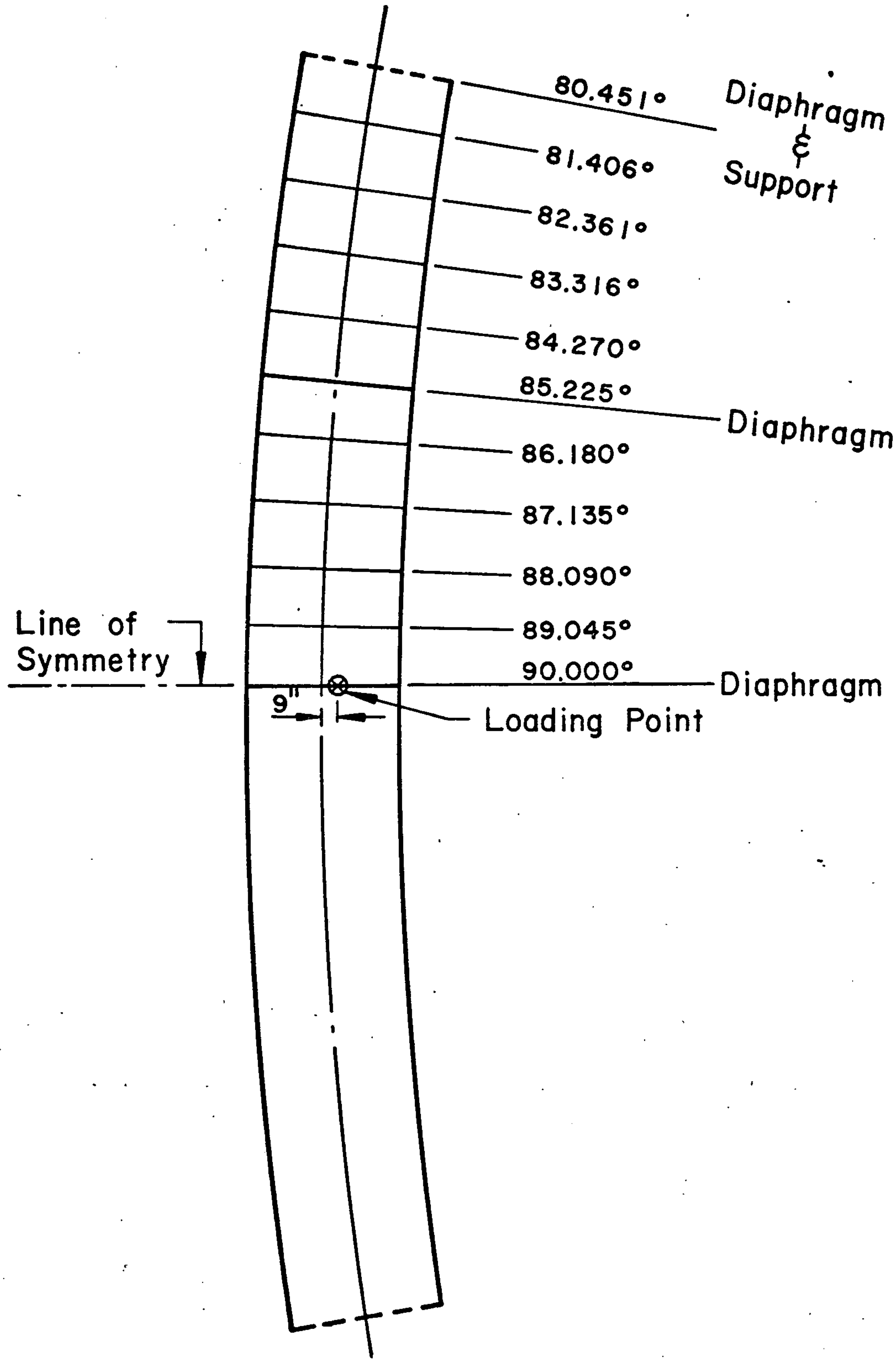


Fig. C1 Plate Girder Assembly 1 - Plan of Finite Element Model

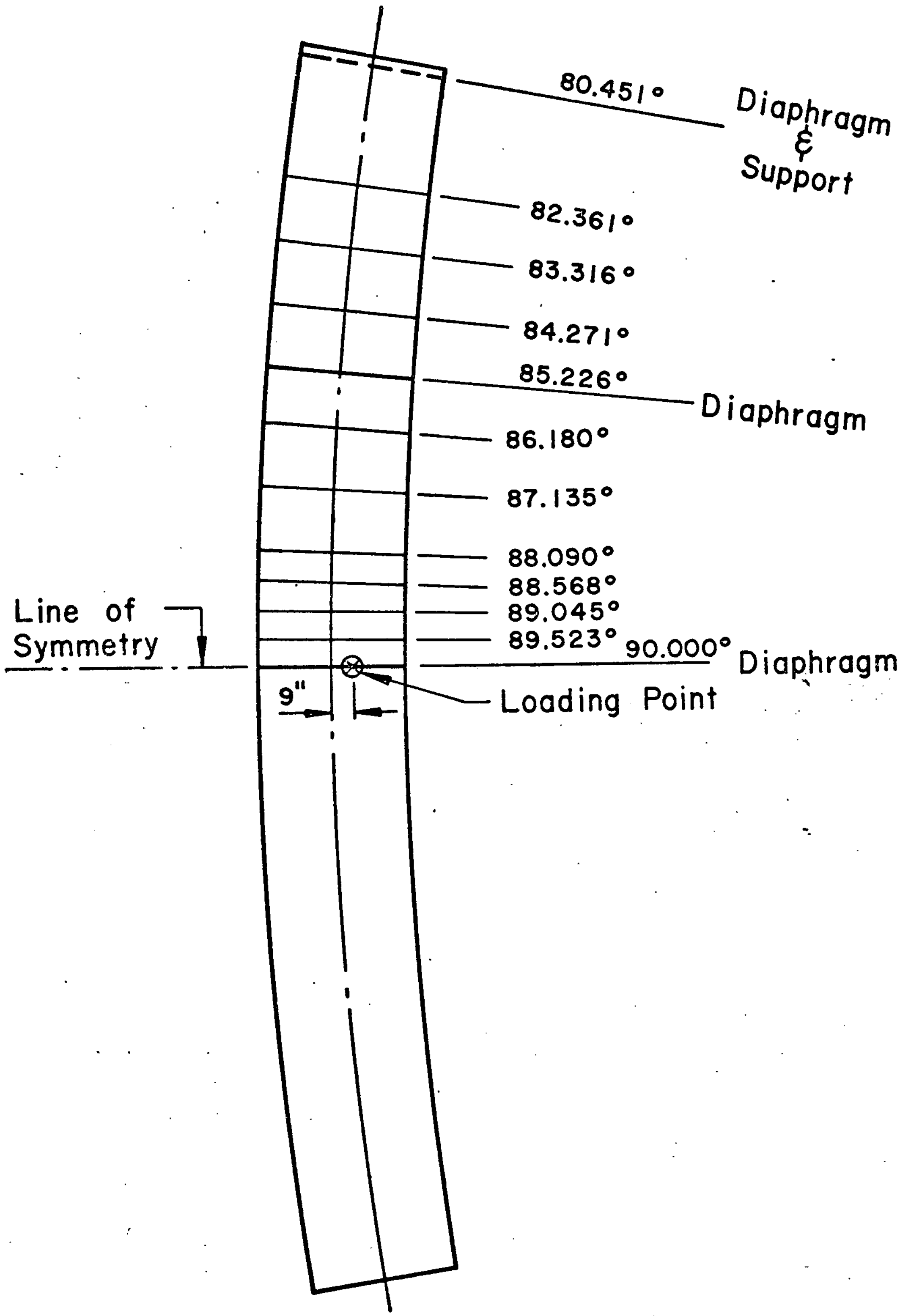


Fig. C2 Composite Plate Girder Assembly 4 - Plan of Finite Element Model

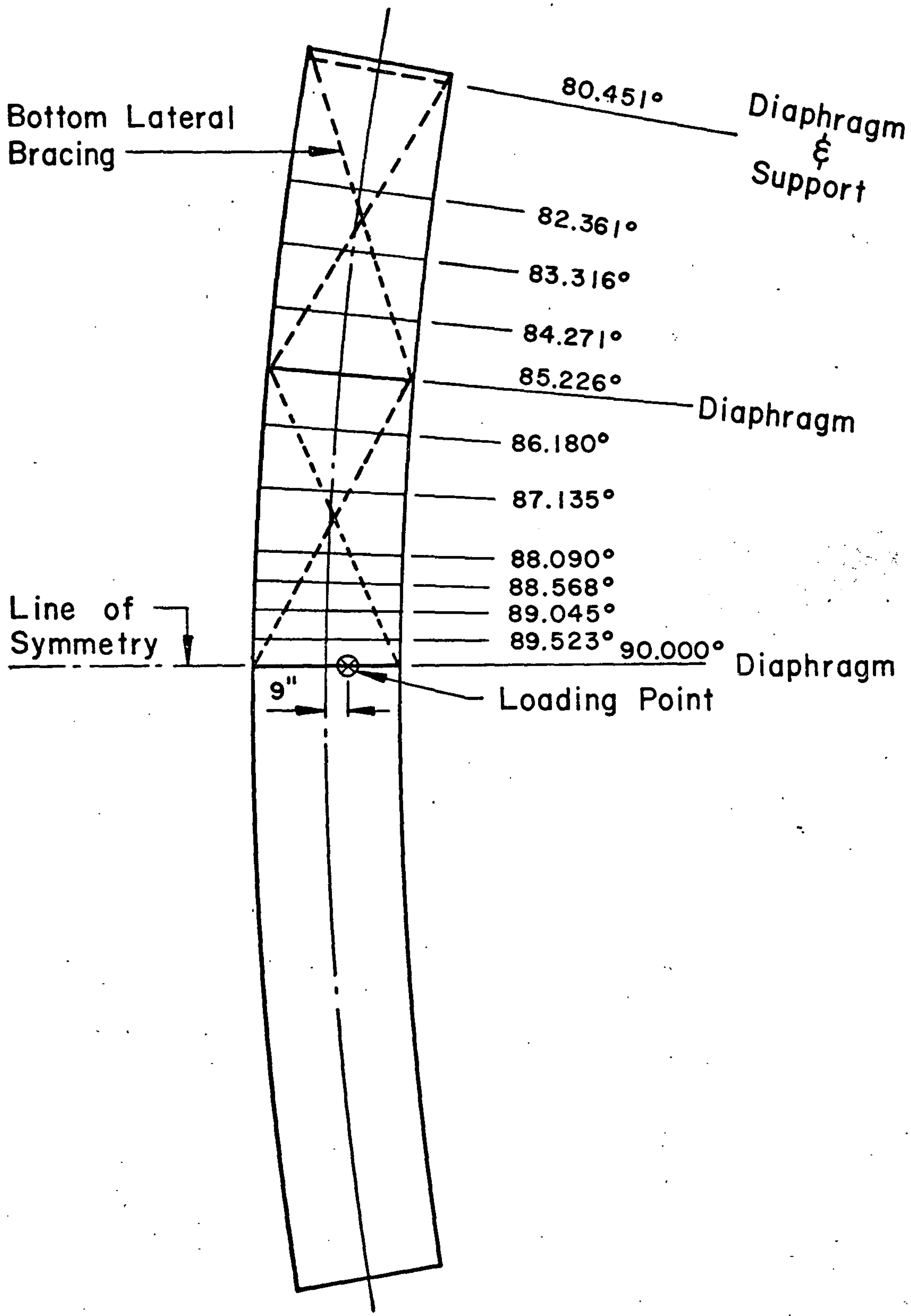


Fig. C3 Composite Plate Girder Assembly 5 - Plan of Finite Element Model

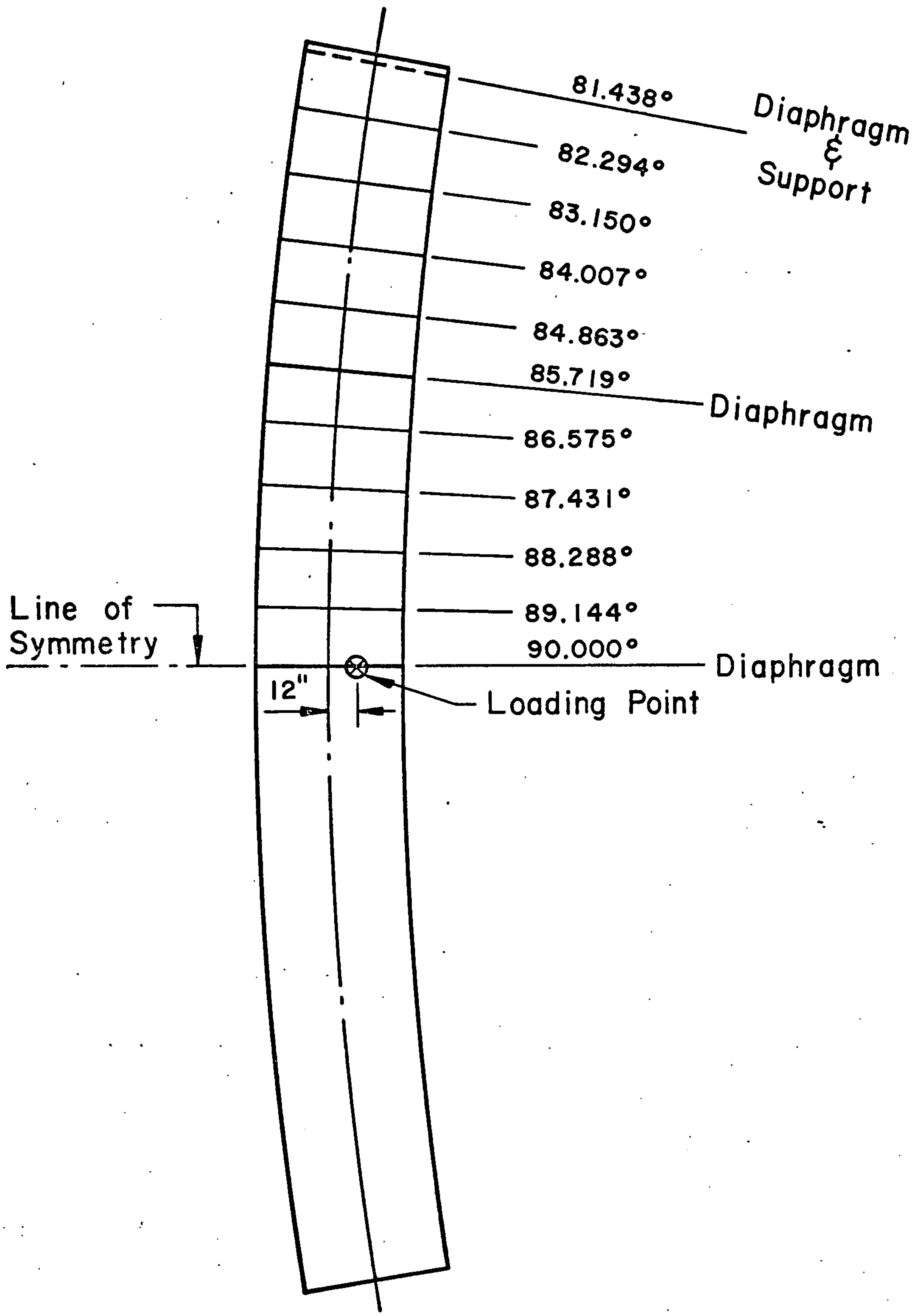


Fig. C4 Composite Box Girder 1 - Plan of Finite Element Model

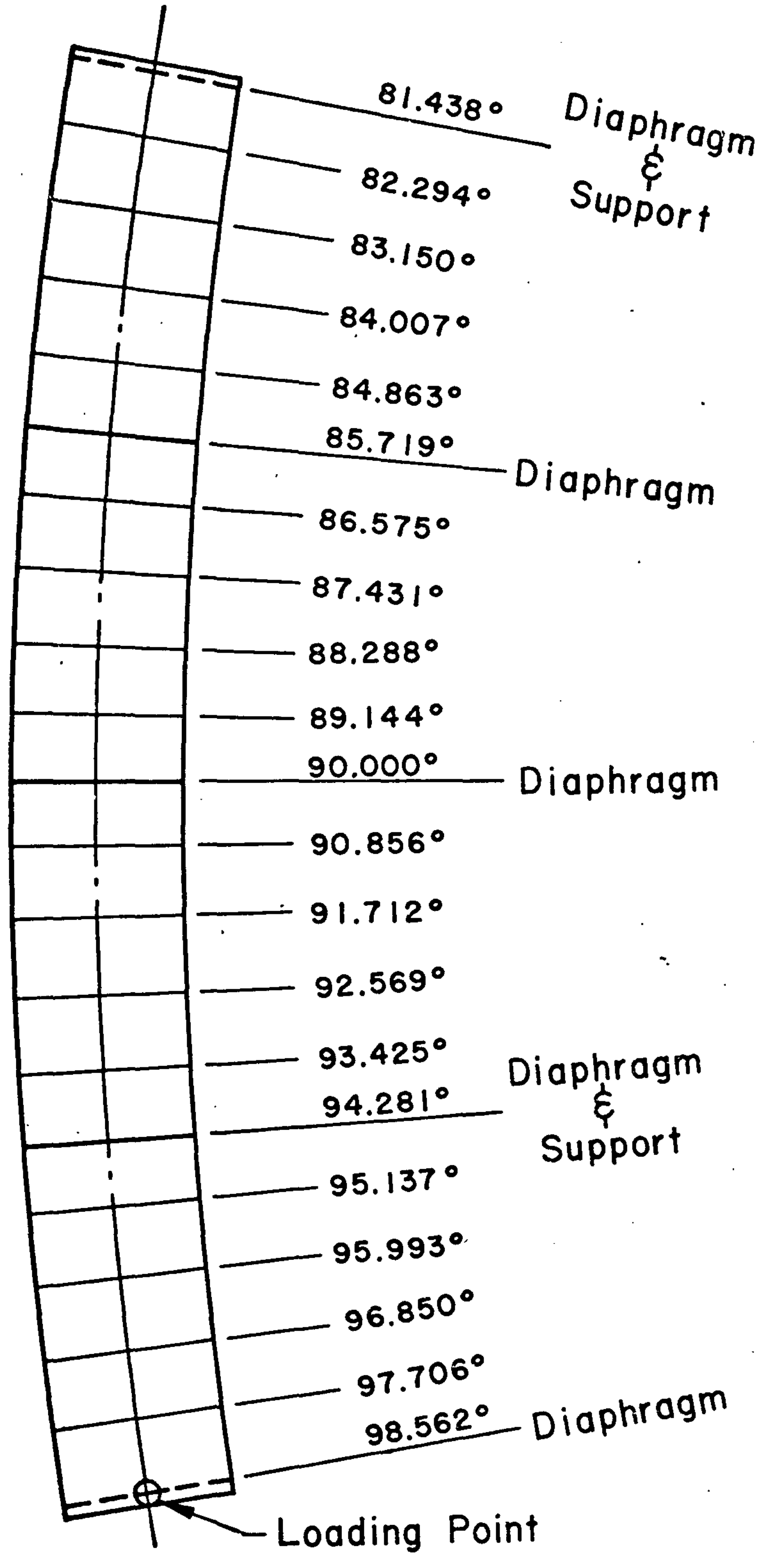


Fig. C5 Composite Box Girder 3 - Plan of Finite Element Model

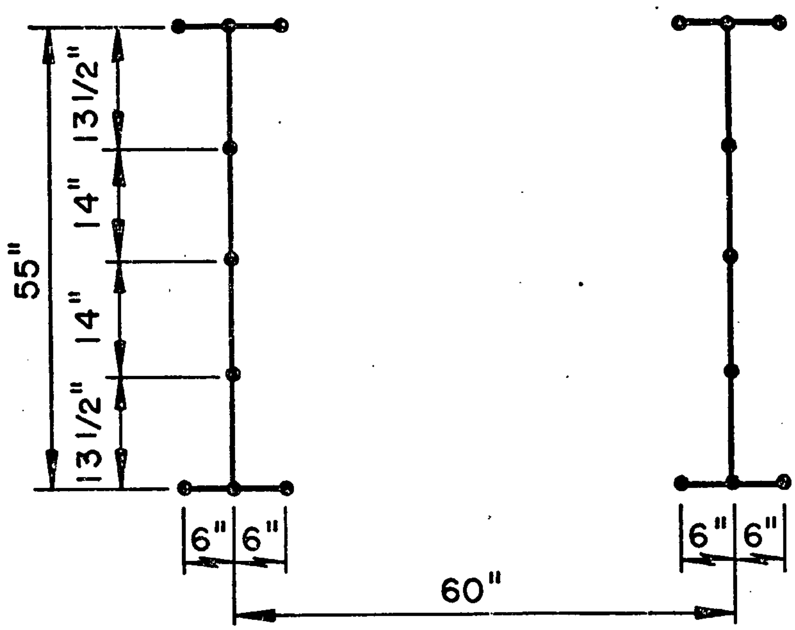


Fig. C6 Plate Girder Assembly 1 - Typical Cross Section Discretization

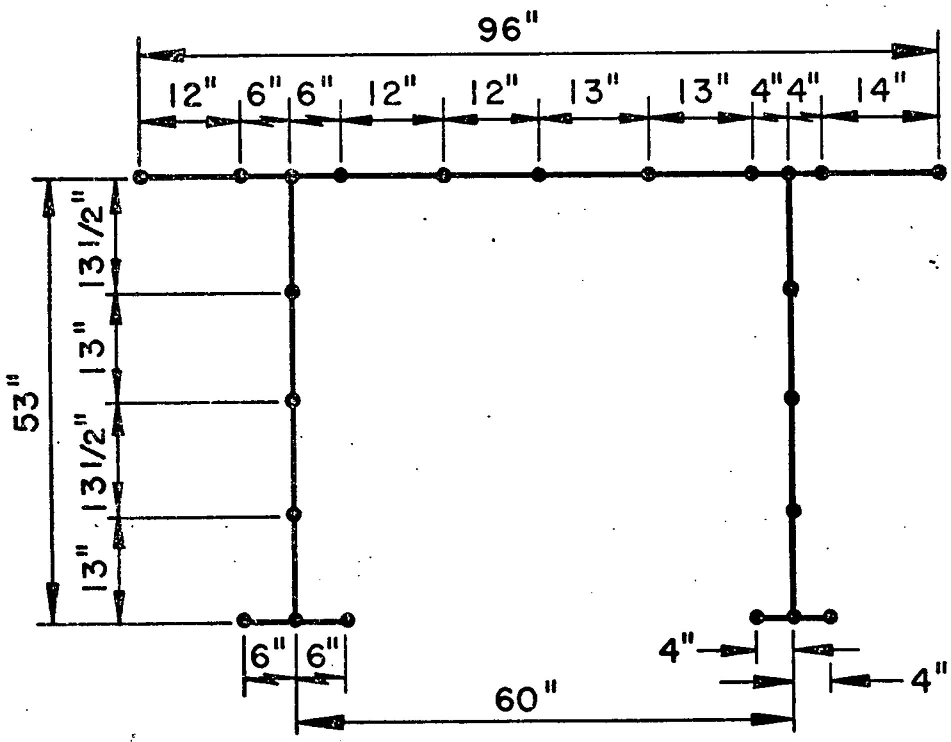
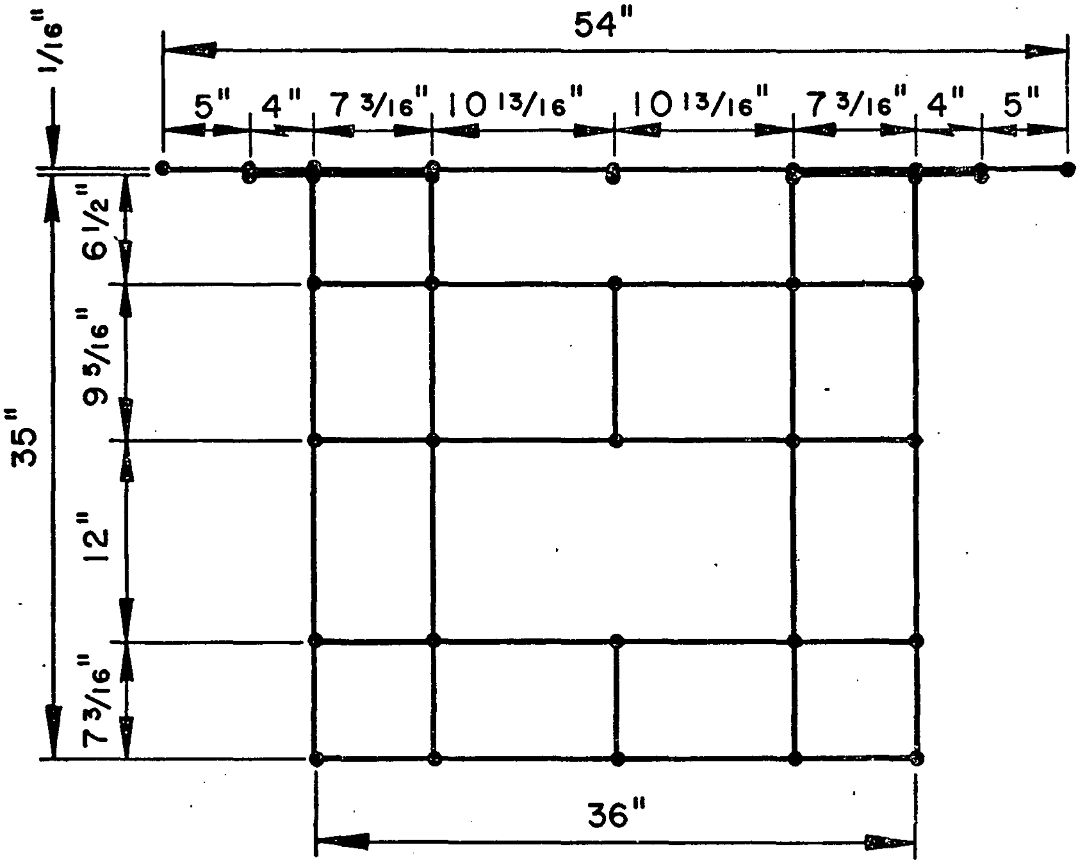


Fig. C7 Composite Plate Girder Assemblies 4 and 5 - Typical Cross Section Discretization



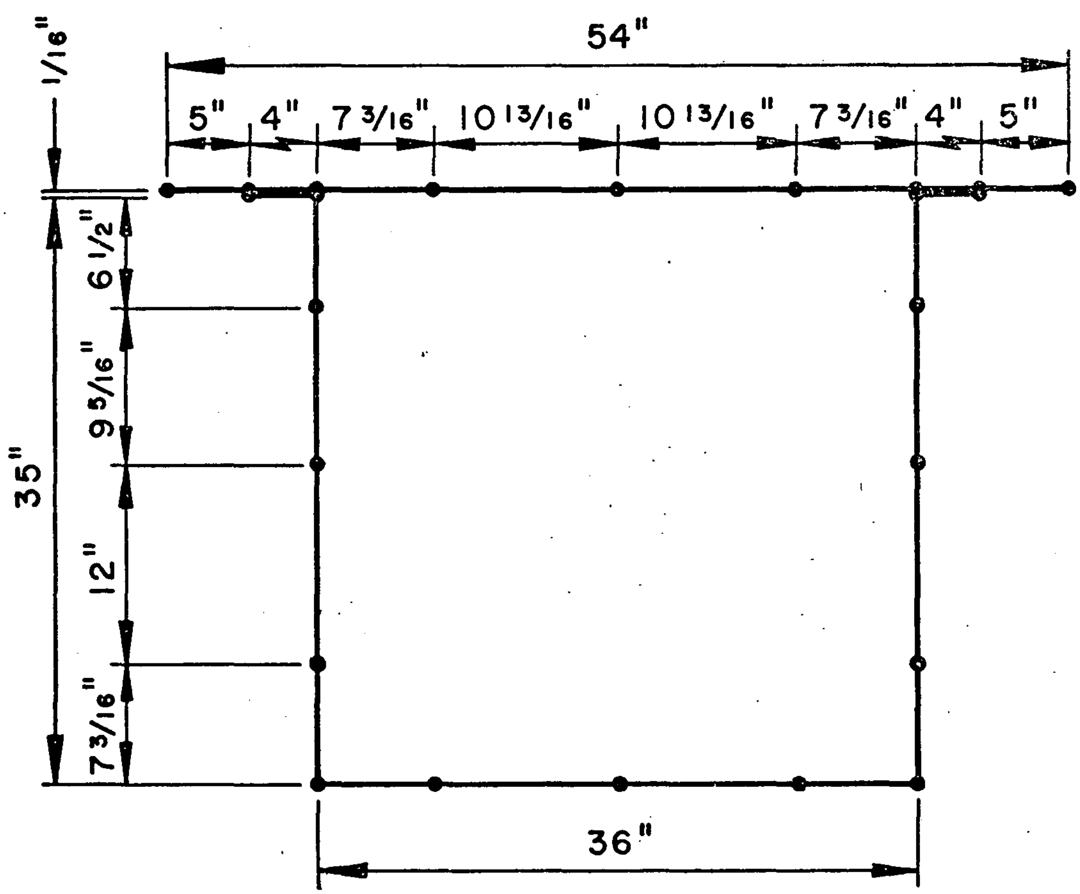


Fig. C8 Composite Box Girders 1 and 3 - Typical Cross Section Discretization

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. Daniels, J. H., Zettlemoyer, N., Abraham, D., and Batcheler, R. P. ANALYSIS AND DESIGN OF PLATE GIRDER AND BOX GIRDER TEST ASSEMBLIES, Fritz Engineering Laboratory Report No. 398.1, Lehigh University, Bethlehem, Pa., October 1976.

2. Daniels, J. H., and Herbein, W. C. FATIGUE TESTS OF CURVED PLATE GIRDER ASSEMBLIES, Fritz Engineering Laboratory Report No. 398.3, Lehigh University, Bethlehem, Pa., May 1977.

3. Batcheler, R. P. and Daniels, J. H., FATIGUE TESTS OF CURVED BOX GIRDERS, Fritz Engineering Laboratory Report No. 398.4, Lehigh University, Bethlehem, Pa. January 1978.

4. Bathe, K. J., Wilson, E. L. and Peterson, F. E. SAP IV, A STRUCTURAL ANALYSIS PROGRAM FOR STATIC AND DYNAMIC RESPONSE OF LINEAR SYSTEMS, Earthquake Engineering Research Center Report No. EERC 73-11, University of California, Berkeley, Ca., June 1973, revised April 1974.

5. Mozer, J., Cook, J. and Culver, C. G. HORIZONTALLY CURVED HIGHWAY BRIDGES - STABILITY OF CURVED PLATE GIRDERS, Carnegie-Mellon University, Report P3, Pittsburgh, Pennsylvania, November 1972.

6. Beedle, L. S. PLASTIC DESIGN OF STEEL FRAMES, Wiley, New York, 1958.