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Ultimate strength tests of curved composite plate girders, July 1977

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Fatigue of Curved Steel Bridge Elements

ULTIMATE STRENGTH TESTS OF CURVED COMPOSITE PLATE GIRDERS

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This work has been carried out as part of
an investigation sponsored by the
Federal Highway Administration.

Department of Civil Engineering

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INFORMATION RETRIEVAL ABSTRACT

ULTIMATE STRENGTH TESTS OF CURVED COMPOSITE PLATE GIRDERS

KEYWORDS: bridges (structures); composite construction; failure (structures); girder bridges (curved); load - deflection; stability; structural engineering; torsion; ultimate strength.

Highway bridge designers are making steadily increasing use of horizontally curved girder bridges. Many questions remain unanswered, however, with regard to the analysis, design, and behavior of curved girder bridges. As part of a continuing research effort on horizontally curved girder bridges, ultimate strength tests of two composite plate girder assemblies were undertaken.

Following a brief description of a preliminary theoretical analysis of the two composite assemblies under study, the ultimate strength tests are described in detail. The results of the tests with regard to the load - deflection behavior and governing failure modes are presented.

The report closes with a summary of significant conclusions and recommendations for further study.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (cont.)

ABSTRACT

Highway bridge designers are making steadily increasing use of horizontally curved girder bridges. Many questions remain unanswered, however, with regard to the analysis, design, and behavior of curved girder bridges. As part of a continuing research effort on horizontally curved girder bridges, ultimate strength tests of two curved composite plate girder assemblies were undertaken.

Following a brief description of a preliminary theoretical analysis of the two composite assemblies under study, the ultimate strength tests are described in detail. The results of the tests with regard to the load - deflection behavior and governing failure modes are presented.

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ULTIMATE STRENGTH TESTS

of

CURVED COMPOSITE PLATE GIRDERS

1. INTRODUCTION

Horizontally curved bridges are often used to simplify difficult highway alignment problems. The use of curved girders in such bridges can provide significant advantages over the use of straight girders as chords of the required curve. Curved girders are more aesthetically pleasing and can substantially reduce construction costs. Curved girders allow longer span lengths, thereby reducing the number of supports, bearings, and expansion details required. Curved girders also simplify formwork for the concrete deck (Thatcher, 1967).

As a result of the increased interest in curved girder bridges, a major research effort has been underway in the United States for the past ten years (CURT, 1975; Task Committee on Curved Girders, 1975; McManus, et al., 1969). The primary thrust of this work at Lehigh University is Fritz Laboratory Project 398, Fatigue of Curved Steel Bridge Elements, sponsored by the Federal Highway Administration.

Project 398 is a four-year, multi-phase investigation involving extensive analytical and experimental study of the fatigue of curved girder bridges. Included in the experimental study is the fatigue testing of five large-scale plate girder assemblies. Following the fatigue tests, a limited ultimate strength testing program was established in order to obtain as much information as possible from each large-scale plate girder assembly (Daniels, et al., 1976; Herbein and Daniels, 1977).

1.1 Objectives and Scope

The primary objective of this work is to obtain information on the ultimate strength behavior of horizontally curved, composite, plate girder assemblies.

Two composite plate girder assemblies, designated Assemblies 4 and 5, were tested to failure in Fritz Laboratory. Plan and section views of Assemblies 4 and 5 are shown in Figs. 1 through 4. The ultimate strength testing program is summarized in Table 1.

Following a brief discussion of the theoretical analysis of the assemblies under study, the ultimate strength tests of Assemblies 4 and 5 are described in detail. The load - deflection behavior and governing failure modes are presented for both assemblies. The paper closes with a summary of significant conclusions and recommendations for further study.

2. THEORETICAL ANALYSIS

2.1 Elastic Analysis

The elastic response of the composite assemblies was established by the finite element method using SAP IV (Bathe, et al., 1974). The model used in the analysis contained 166 nodes (876 degrees of freedom), 120 plate bending elements, 48 beam elements, and 20 truss elements. More complete information on the finite element analyses of composite Assemblies 4 and 5 is available (Tedesco and Batcheler, 1977). The results of the finite element analyses are summarized in Table 2.

2.2 Plastic Analysis

Models for the determination of the governing failure modes of curved composite plate girder assemblies are presently in a rather embryonic stage of development (Mozer, et al., 1972). In order to obtain an approximate value for the ultimate load the assemblies will carry, a simplified approach was adopted based on simple plastic theory (Beedle, 1958).

Assuming the steel reaches its yield stress, the concrete develops 85% of its specified compressive strength, and neglecting the small contribution of the bottom lateral bracing system in Assembly 5, the plastic moment capacity of Assemblies 4 and 5 is 72 000 kip-in.

The plastic limit load was estimated by assuming the assemblies are straight, with a span length equal to the centerline span length of the assemblies. The plastic limit load is thereby estimated by statics to be 600 kips.

A more rigorous analysis of the failure modes and ultimate strength of the curved composite assemblies is planned for early next fall.

3. EXPERIMENTAL PROGRAM

3.1 Modification of Assemblies 4 and 5

Following fatigue tests of Assemblies 4 and 5, all detected fatigue cracks were repaired. Preparation of the assemblies proceeded with the addition of the composite decks indicated in Figs. 2 and 4. Figures 5 through 8 show the modifications underway in Fritz Laboratory.

3.2 Test Procedure

After the assemblies had cured a minimum of 28 days, each was tested in the Baldwin universal testing machine as shown in Fig. 9. The assemblies were loaded by a concentrated load applied to an essentially rigid (W14 x 730) loading beam. The concentrated load was applied to the loading beam at a point 9 inches toward Girder 1 from the centerline of the assemblies. This eccentricity was provided because the loading head of the Baldwin machine has limited rotational capabilities.

The assemblies were supported at both ends of Girders 1 and 2 by roller bearing assemblies shown in Fig. 10. The bearing assemblies simulate spherical bearings which only provide resistance to vertical displacements and rotations about a vertical axis. The loading head of the Baldwin machine provided stability in the horizontal plane.

Instrumentation included 22 dial gages which indicated horizontal or vertical deflections, and approximately 120 strain gages which were monitored by a B&F Data Acquisition system. The dial gages and strain gages were read at 50 kip load increments and the midspan deflections for both Girders 1 and 2 were plotted continuously throughout the test. As the load - deflection curve departed from linearity, complete sets of dial gage and strain gage readings were taken at approximately 1/2 inch increments of midspan deflection.

The tests were continued to failure of the assemblies which was considered to be the point at which additional deflection was accompanied by a drop in the applied load.

4. TEST RESULTS AND DISCUSSION

4.1 Assembly 4

The experimental and theoretical load - deflection behavior of Assembly 4 is shown in Fig. 11. The midspan deflections, Δ, for Girder 1 (the inner girder) and Girder 2 (the outer girder) are shown as a function of the applied load, P.

The ultimate strength test of Assembly 4 proceeded uneventfully to an applied load of approximately 500 kips. As the applied load passed 500 kips, yield lines began to develop on the webs and flanges in the manner shown in Fig. 12. At approximately 600 kips the gage measuring the vertical deflection of Girder 1 ran out of stroke. Therefore, no subsequent readings could be taken. At approximately 704 kips an extremely loud report was heard. Subsequent inspection showed that a previously undetected fatigue crack at a gusset plate detail had precipitated a brittle fracture of the tension flange of Girder 2. The gusset plate detail was located about 3 ft west of midspan on Girder 2 (Fig. 12). The fracture surface and fatigue crack are shown in Fig. 13. Figure 14 shows a schematic view of the fracture surface, establishing the size of the fatigue crack and the point at which the "running" crack arrested. The crack arrested only because the flexibility of the assembly increased due to the fracture, thereby causing the load to drop off. If the load had been applied by a dead weight testing machine (instead of a displacement-controlled machine like the Baldwin) it is unlikely the crack would have arrested.

Testing was suspended after the fracture of Girder 2.

4.2 Assembly 5

The experimental and theoretical load - deflection behavior of Assembly 5 is shown in Fig. 15. The midspan deflections, Δ, for Girder 1 and Girder 2 are shown as a function of the applied load, P.

At an applied load of 500 kips yield lines began to develop in the webs and flanges. At 678 kips small cracks in the concrete deck and local yielding of the webs under the loading beam were noted. At approximately 830 kips a loud noise accompanied the buckling of several diaphragm members. The maximum load sustained by Assembly 5 was 858 kips at which point extensive crushing of the concrete deck and local buckling of the web caused failure. Figures 16 through 19 show the various elements contributing to the failure of the assembly.

5. SUMMARY AND CONCLUSIONS

The results of a theoretical and experimental investigation of the ultimate strength of curved composite plate girders are presented. The significant conclusions of this investigation are as follows:

(1) The theoretical and experimental load - deflection behavior of Assemblies 4 and 5 is shown in Figs. 11 and 15, respectively. Relatively poor agreement between the theoretical and experimental results was observed. The discrepancies are attributed primarily to the relatively coarse discretization used for the elastic theoretical analysis and the gross simplifications introduced in the plastic theoretical analysis.

(2) The governing failure mode for Assembly 4 was brittle fracture of the tension flange of the outer girder. Although the crack arrested in the test of Assembly 4, only the inherent redundancy of most highway bridge structures would prevent a potentially catastrophic collapse under extreme service conditions.

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

Recommendations for further study include:

(1) A refined theoretical analysis of the elastic and

ultimate strength behavior of the composite assemblies should be undertaken.

(2) Reduction of the recorded strain data should be performed to permit comparison of the measured and theoretical stresses in the various structural elements.

(3) Determination of the theoretical value of the stress intensity at the instant of fracture of Girder 2 in Assembly 4 should be carried out. Comparison of the results to the fracture toughness of the material (to be determined by compact tension testing) would be enlightening.

6. ACKNOWLEDGEMENTS

This study was conducted at the Fritz Engineering Laboratory, Department of Civil Engineering, at Lehigh University. Dr. L. S. Beedle is Director of Fritz Engineering Laboratory, and Dr. D. A. VanHorn is Chairman of the Department of Civil Engineering.

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The contributions of the Lehigh Project Advisory Panel are gratefully acknowledged. The Advisory Panel members are Messrs: A. P. Cole, C. G. Culver, R. S. Fountain, G. F. Fox, A. Lally, and I. M. Viest.

The following members of the faculty and staff of Lehigh University made major contributions to the conduct of this work: Dr. J. W. Fisher, Dr. B. T. Yen, Dr. R. G. Slutter, W. C. Herbein, D. Abraham, R. Dales, and R. Longenbach.

7. TABLES AND FIGURES

TABLE 1 SUMMARY OF ULTIMATE STRENGTH TESTING PROGRAM

	Assembly 4	Assembly 5
Centerline span length	40 ft	40 ft
Centerline radius	120 ft	120 ft
Cross-section properties		
Girder 1:		
web depth	52 in.	52 in.
web thickness	3/8 in.	3/8 in.
flange width	8 in.	8 in.
flange thickness	1/2 in.	1/2 in.
Girder 2:		
web depth	52 in.	52 in.
web thickness	3/8 in.	3/8 in.
flange width	12 in.	12 in.
flange thickness	1 in.	1 in.
Composite deck:		
width	96 in.	96 in.
thickness	7 in.	7 in.
Material properties		
Steel:		
Specified tensile strength	36 ksi	36 ksi
Concrete:		
Specified compressive strength	3000 psi	3000 psi
Bottom lateral bracing	none	L 3x3x3/8

Both assemblies were loaded at midspan by a concentrated load applied at a point 9 inches from the centerline toward Girder 1 (the inner girder).

TABLE 2 SUMMARY OF RESULTS OF ELASTIC ANALYSIS

	Assembly 4	Assembly 5
Midspan deflection[1]		
Girder 1	0.156 in.	0.147 in.
Girder 2	0.166 in.	0.153 in.
Maximum longitudinal stress[2]		
Girder 1	9.48 ksi	8.86 ksi
Girder 2	7.21 ksi	6.56 ksi
Composite deck	- 1.45 ksi	- 1.02 ksi

[1] Deflections tabulated are for 100 kip load at midspan, positioned 9 inches toward Girder 1 from the centerline of the assembly.

[2] Stresses tabulated are for 100 kip load at midspan, positioned 9 inches toward Girder 1 from the centerline of the assembly. Stresses tabulated are the absolute maximums for each structural element; + = tension, - = compression.

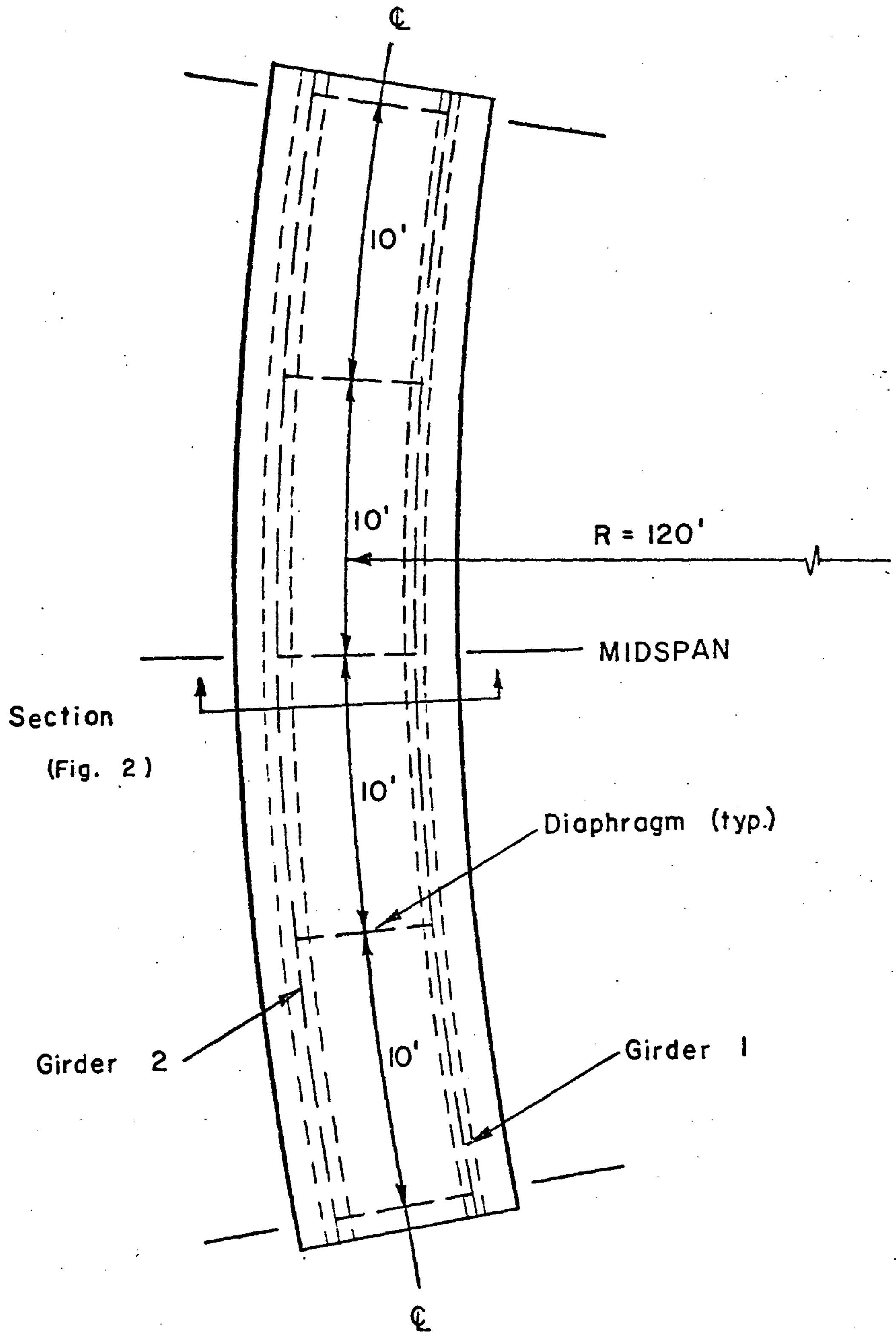


Fig. 1 Plan View of Composite Assembly 4

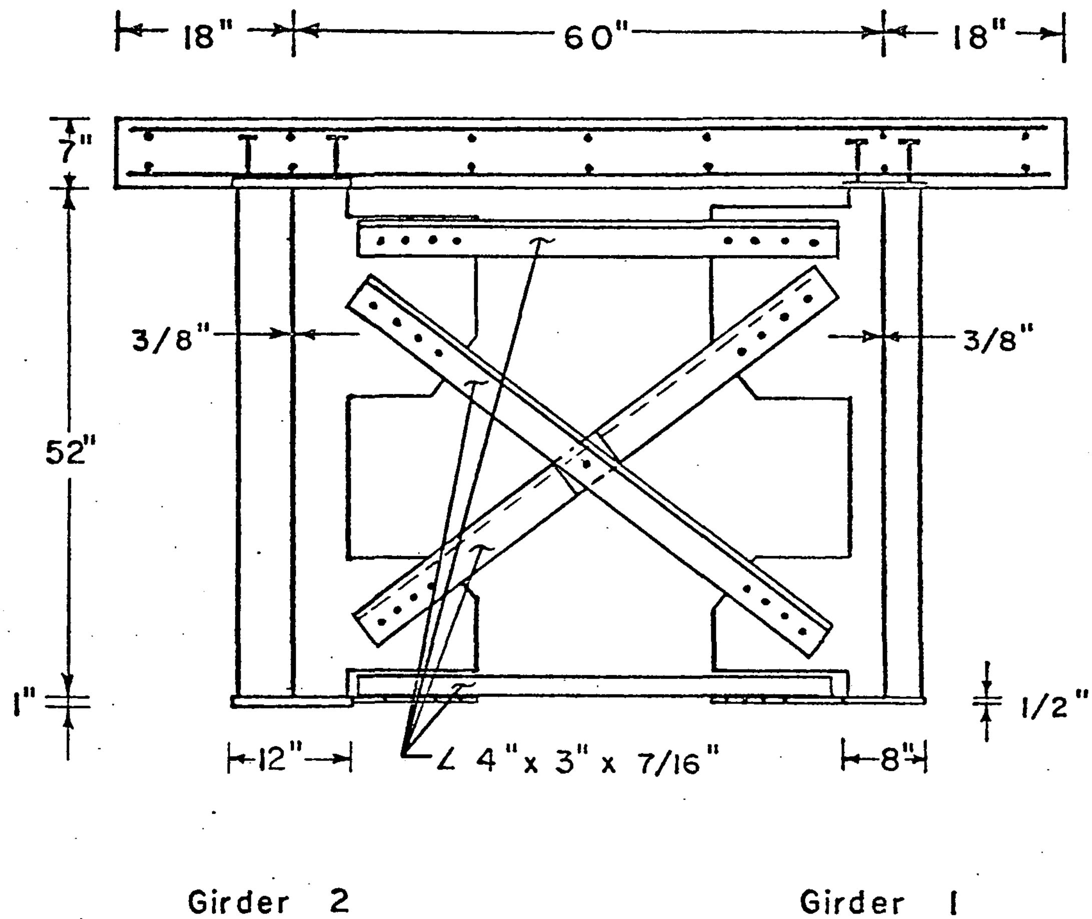


Fig. 2 Typical Diaphragm Section of Composite Assembly 4

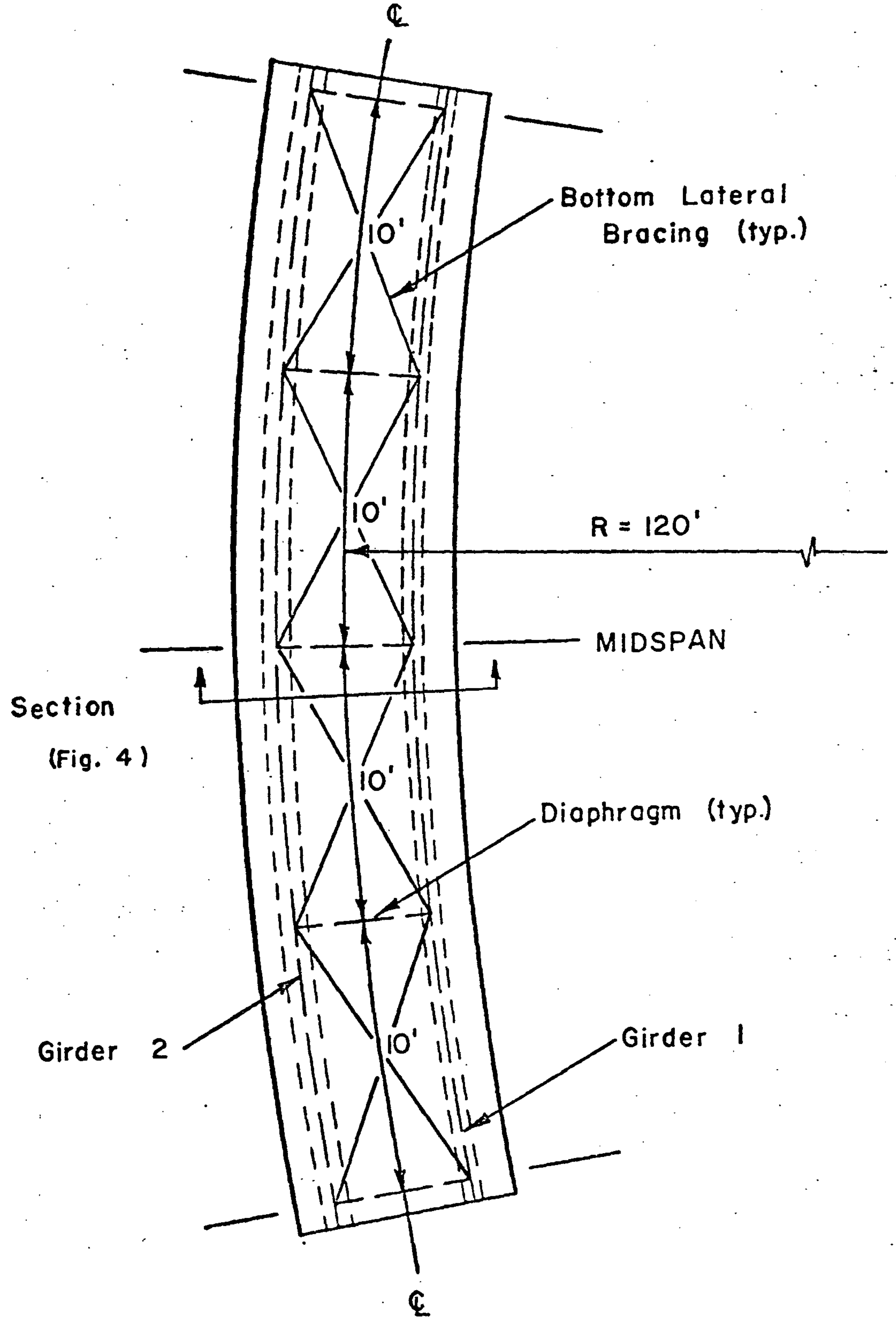


Fig. 3 Plan View of Composite Assembly 5

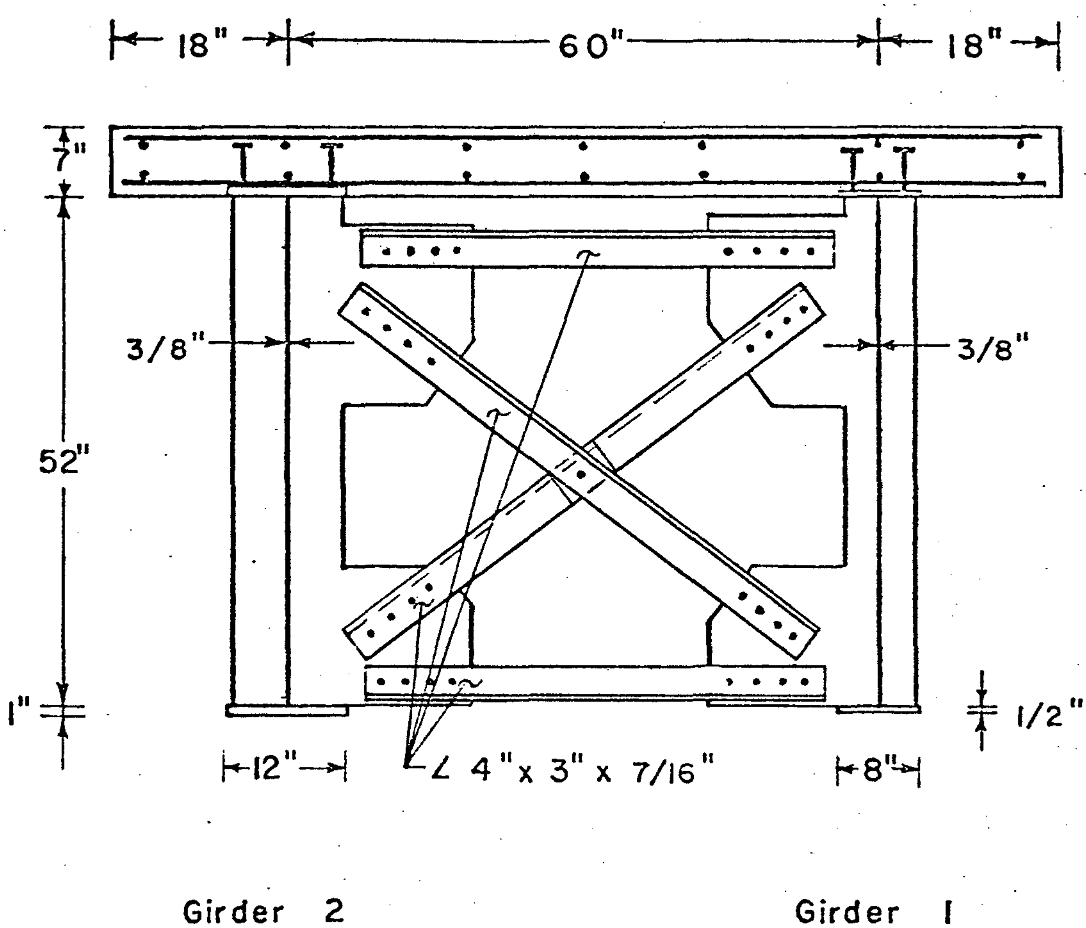


Fig. 4 Typical Diaphragm Section of Composite Assembly 5

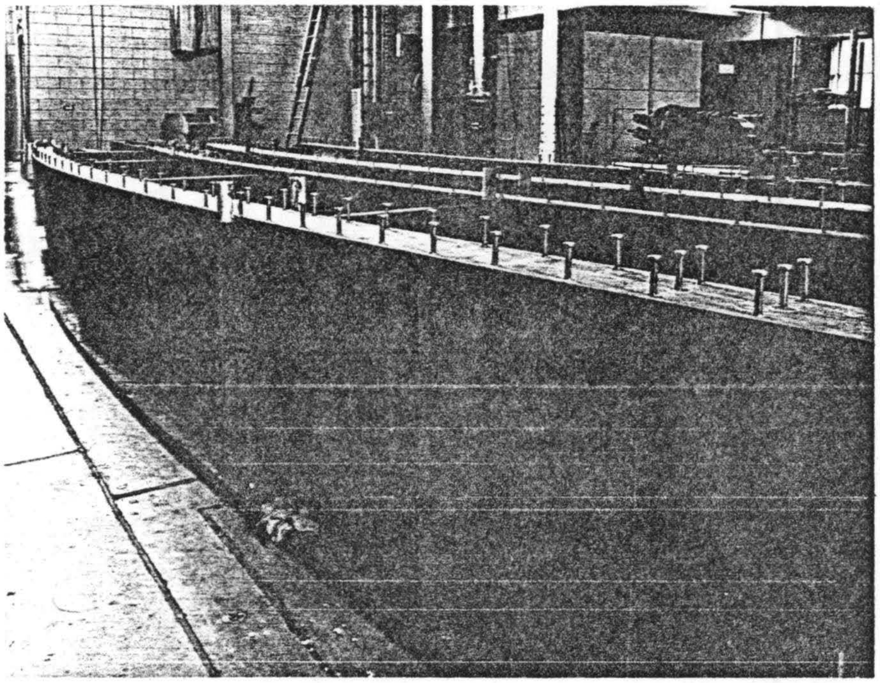


Fig. 5 Modification of Plate Girder Assemblies - Addition of Stud Connectors

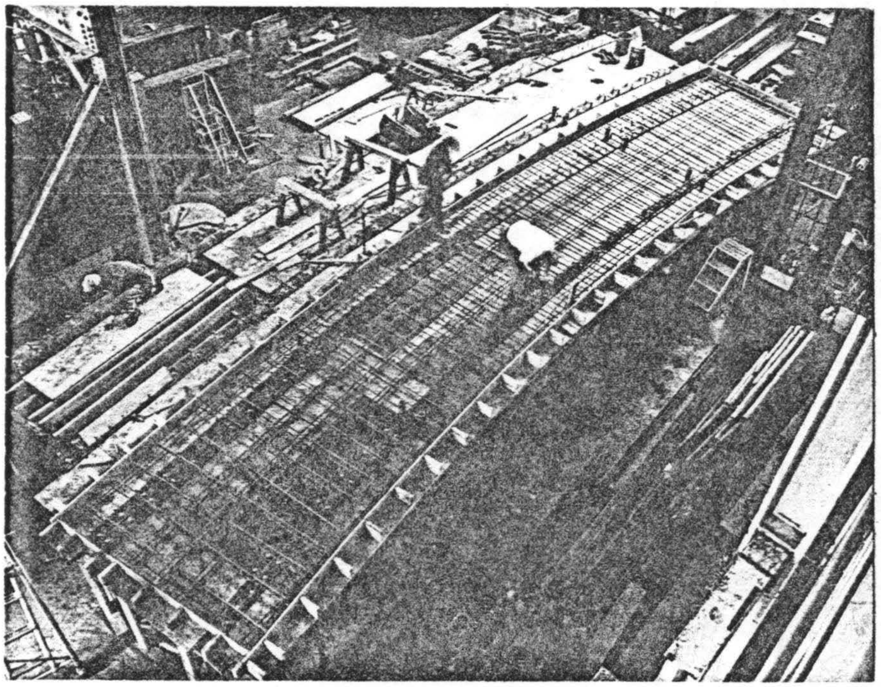


Fig. 6 Modification of Plate Girder Assemblies - Formwork and Placement of Reinforcing Bars

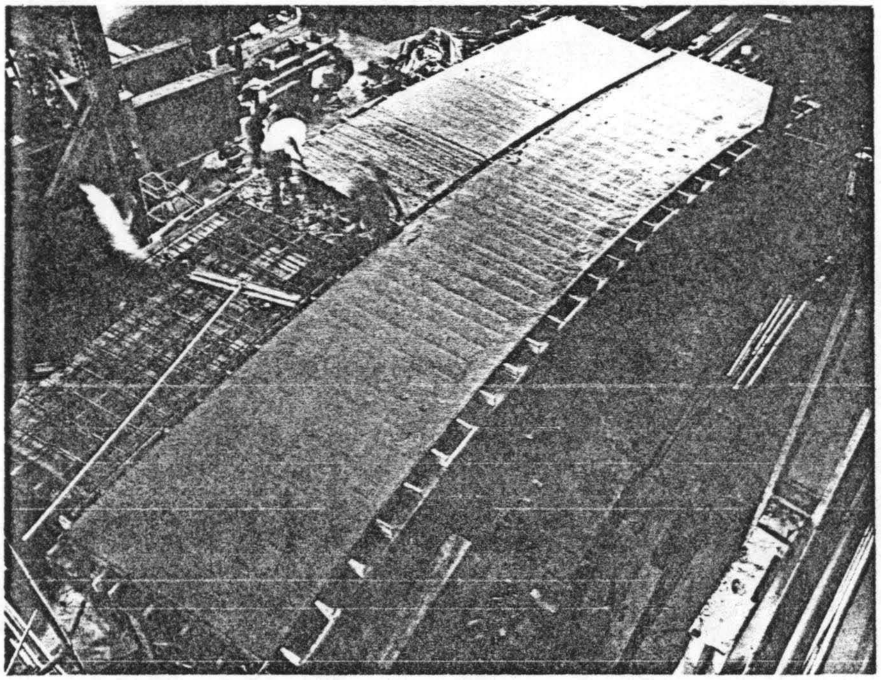


Fig. 7 Modification of Plate Girder Assemblies - Pouring the Concrete Deck

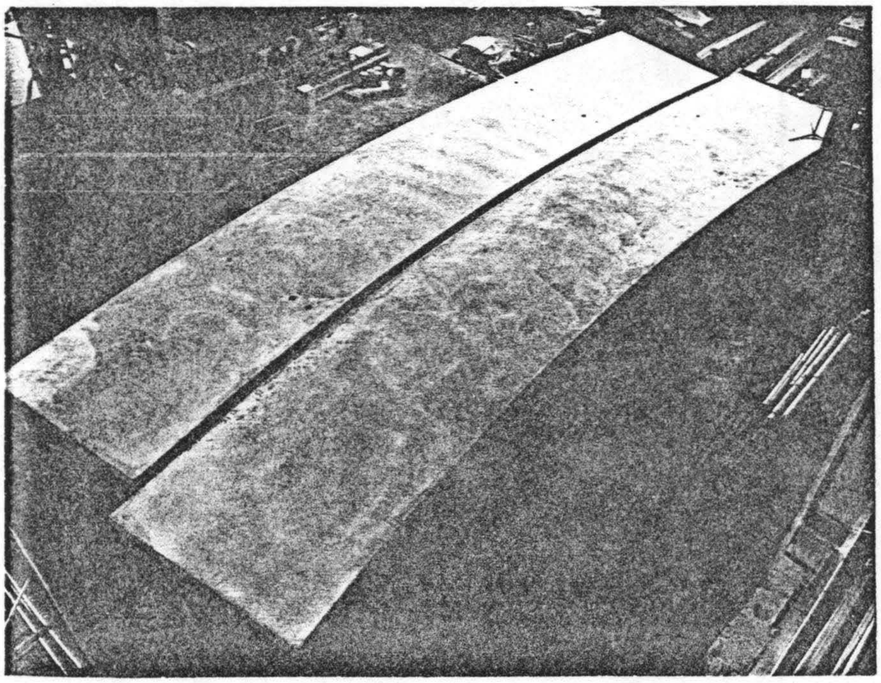


Fig. 8 Modification of Plate Girder Assemblies - Completed Assemblies with Formwork Stripped

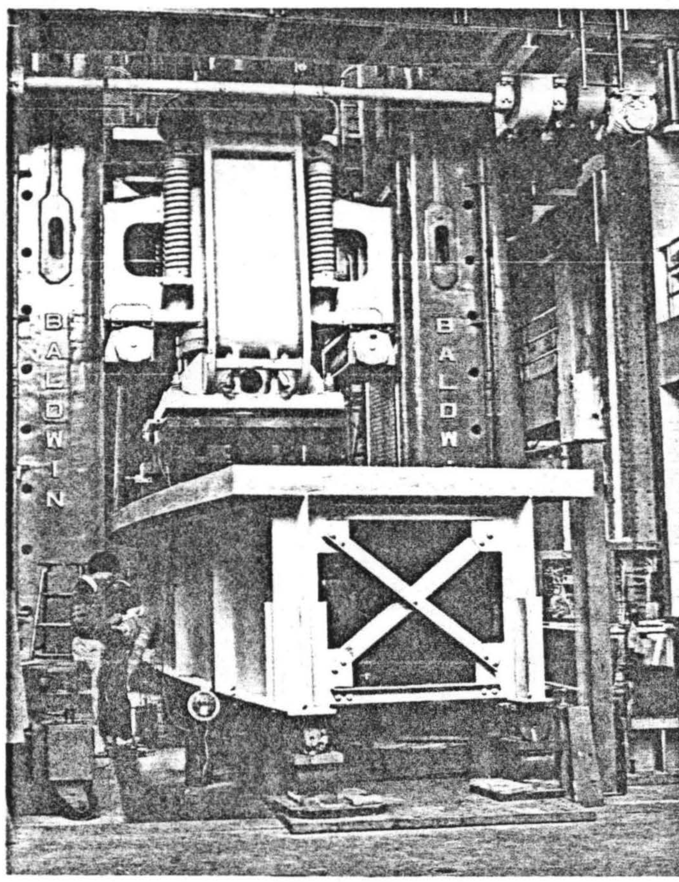


Fig. 9 Composite Assembly 4 under Test in the Baldwin Universal Testing Machine

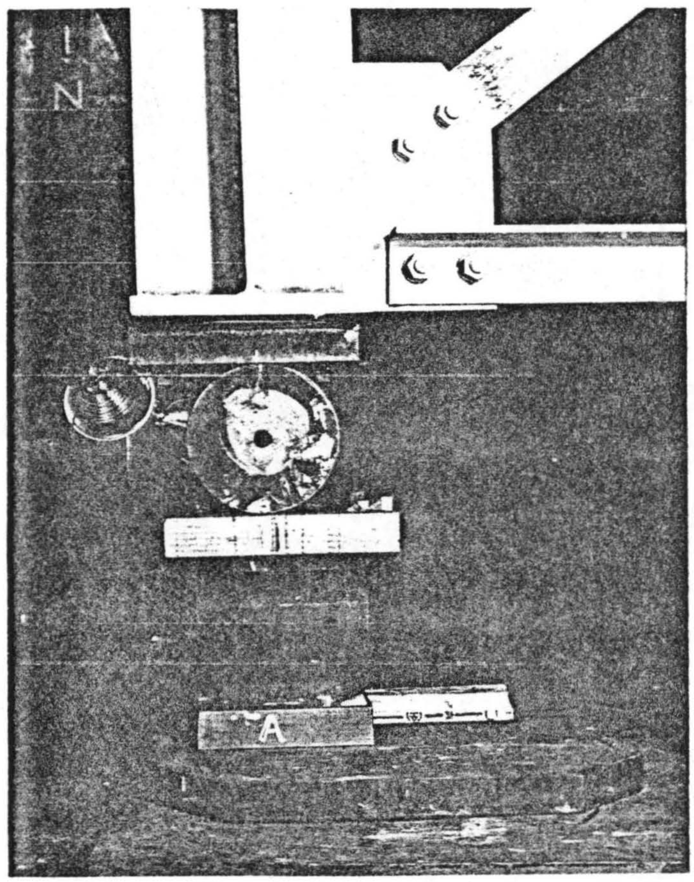


Fig. 10 Detail - Roller Bearing Assembly

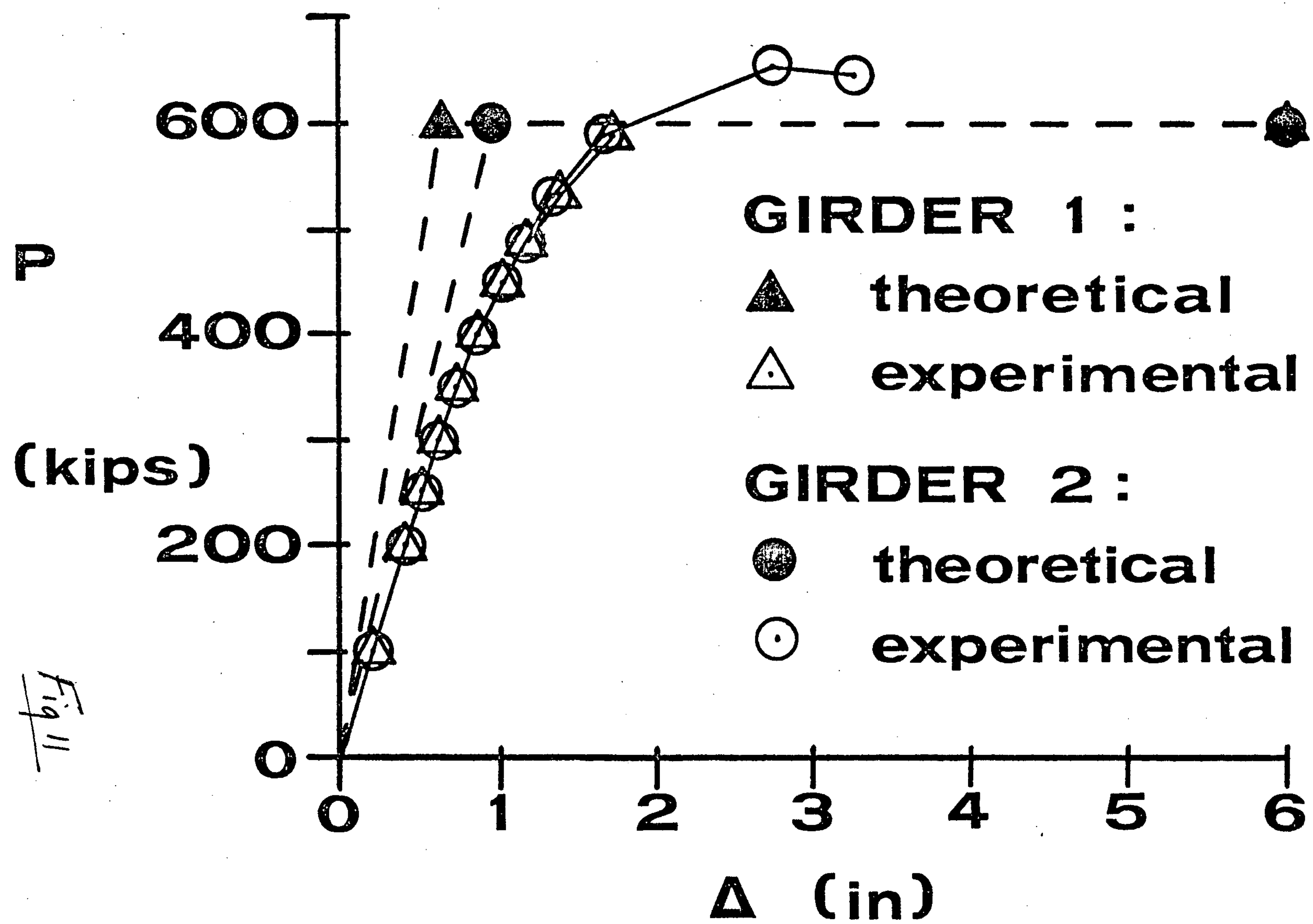

P
(kips)
600
400
200
0
0
1
2
3
4
5
6
Δ (in)
GIRDER 1 :
theoretical
experimental
GIRDER 2 :
theoretical
experimental

Fig 11

(Prepared as original for slide.)

Fig. 11 Composite Assembly 4 - Load-Deflection Curve

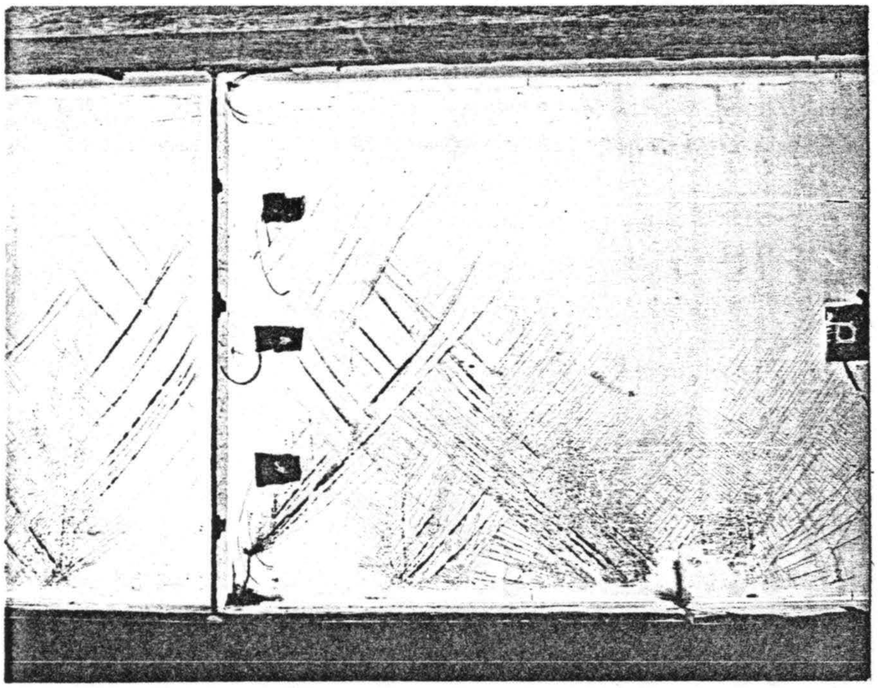


Fig. 12 Composite Assembly 4 (Midspan of Girder 2) - Location of Fracture at Bottom Right

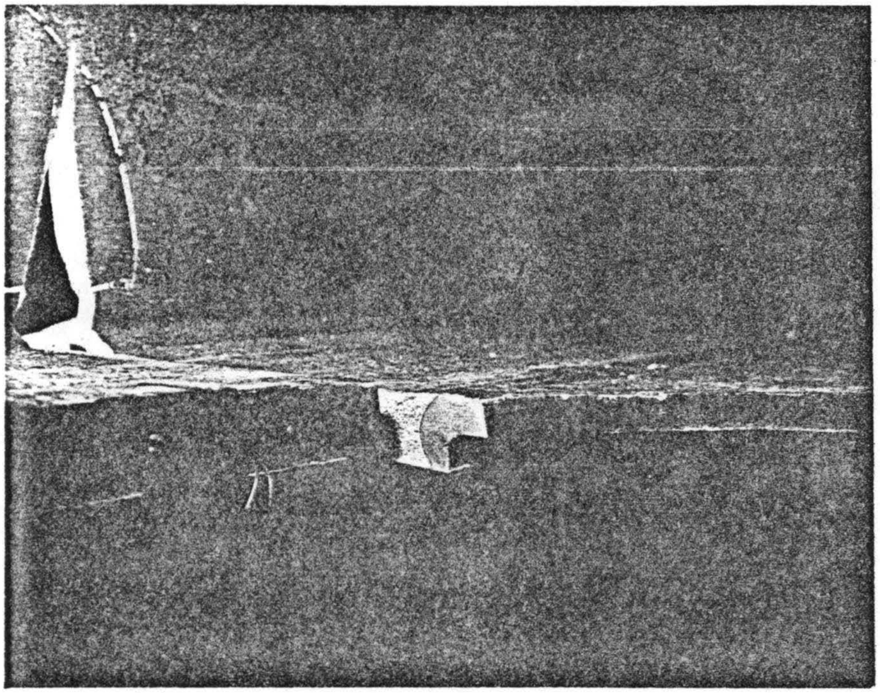


Fig. 13 Composite Assembly 4 - Fracture Surface showing Fatigue Crack at Gusset Plate Detail

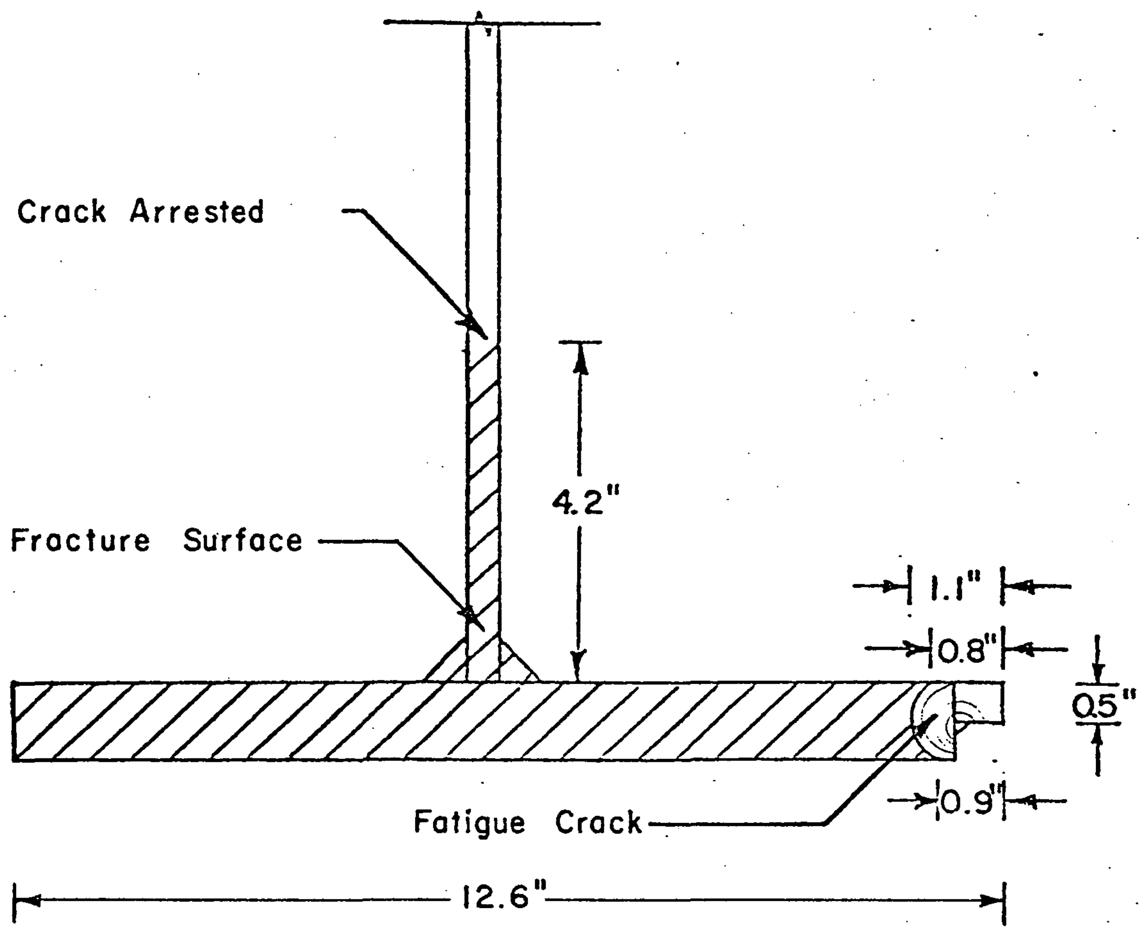
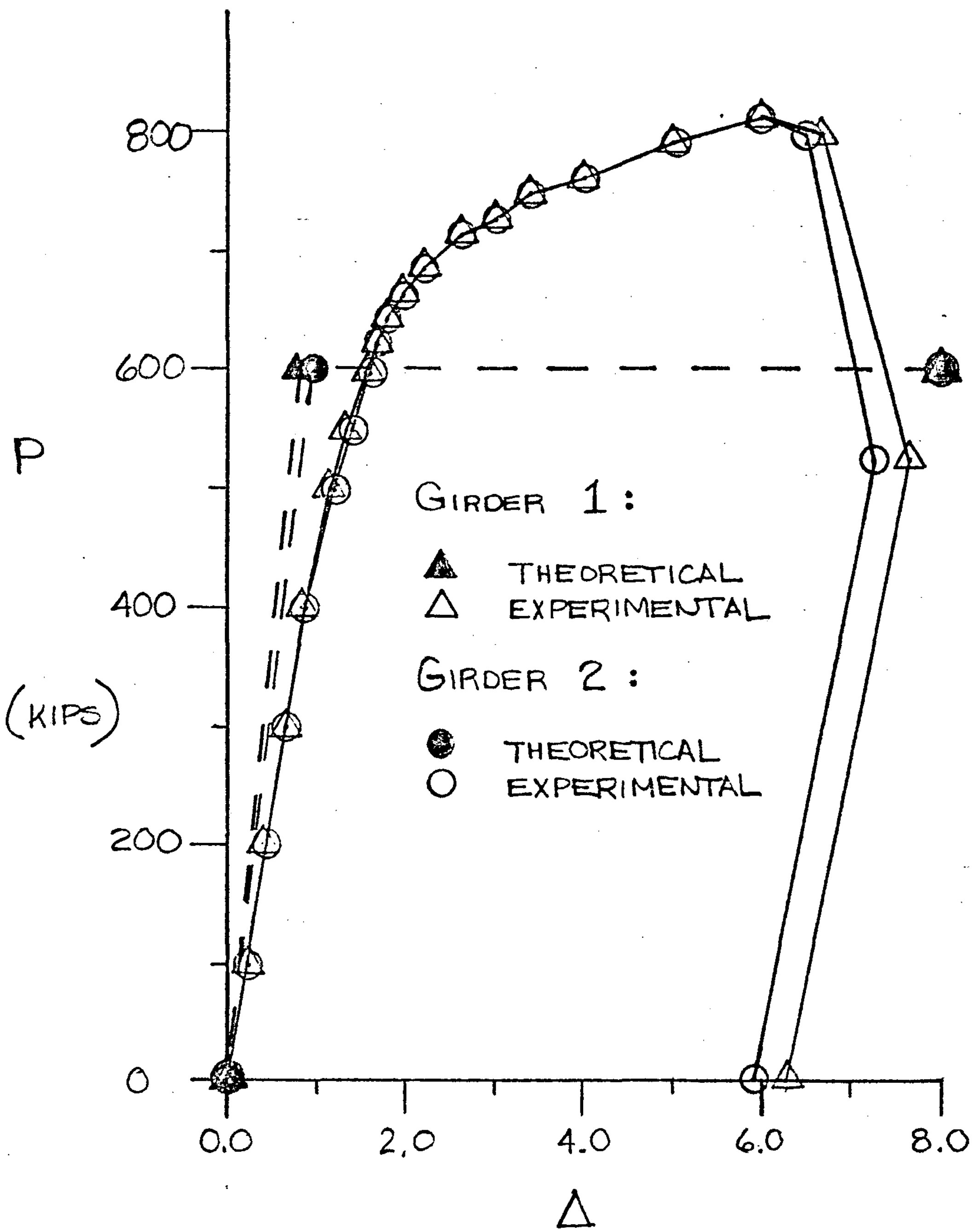


Fig. 14 Composite Assembly 4 -
Fracture Surface (schematic)



800
600
400
200
0
P
(KIPS)
GIRDER 1:
THEORETICAL
EXPERIMENTAL
GIRDER 2:
THEORETICAL
EXPERIMENTAL
0.0
2.0
4.0
6.0
8.0
Δ

FIG. 15

(Prepared for drafting room.)

Fig. 15 Composite Assembly 5 - Load-Deflection Curve

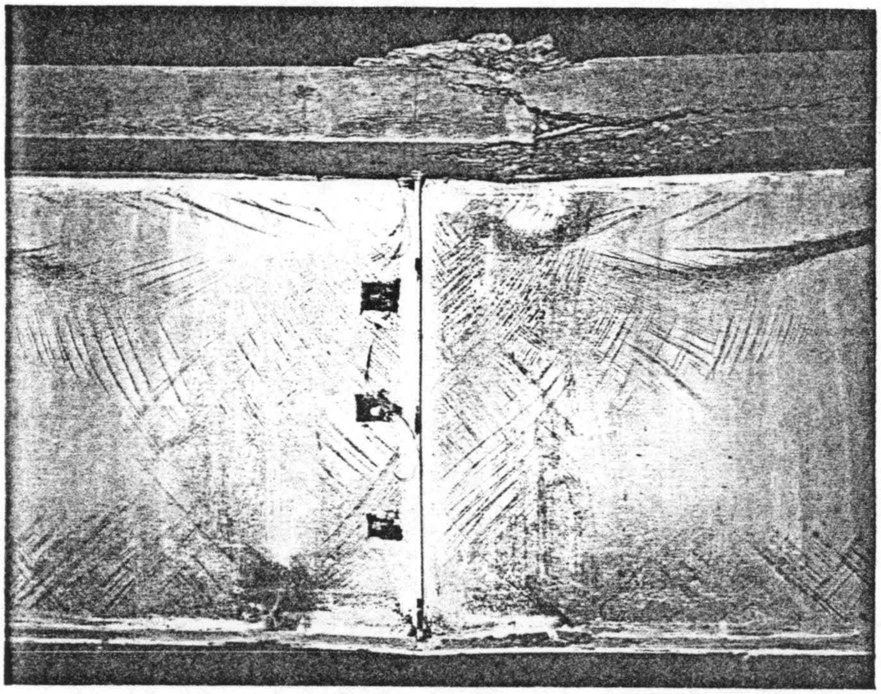


Fig. 16 Composite Assembly 5 (Midspan of Girder 1) -
Concrete Deck Crushing and Web Buckling
under Concentrated Load

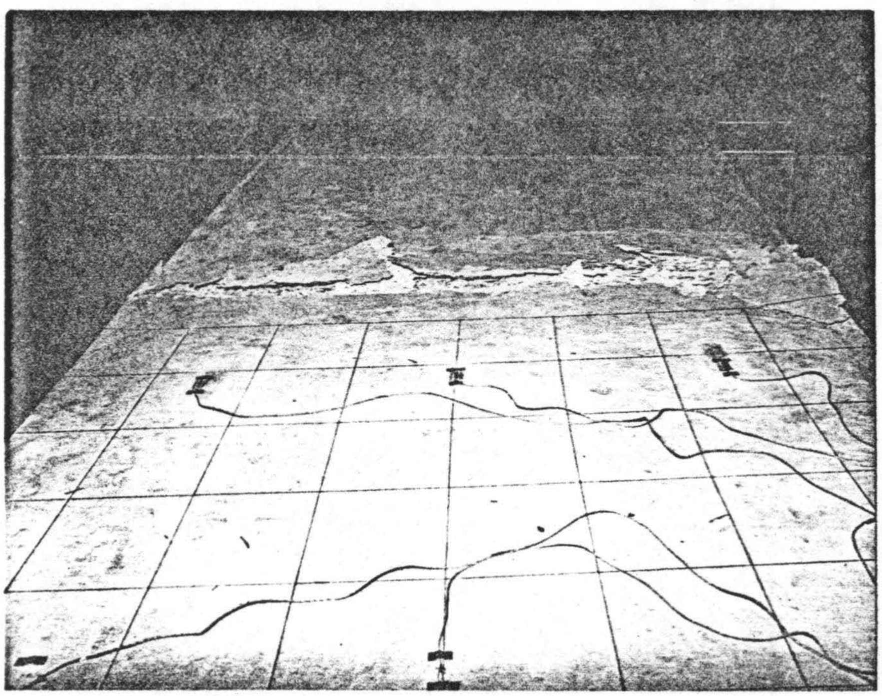


Fig. 17 Composite Assembly 5 -
Concrete Deck at Midspan Viewed from above

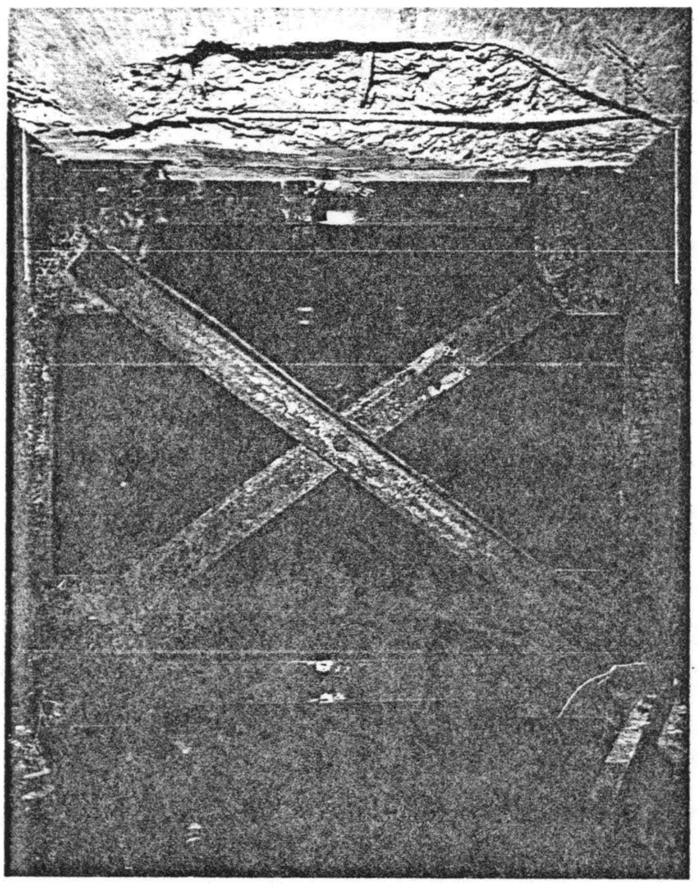


Fig. 18 Composite Assembly 5 -
Midspan Diaphragm and Concrete Deck Viewed from inside the assembly

Fig. 19 Composite Assembly 5 -
Midspan Diaphragm Viewed from inside the assembly (looking toward Girder 1)

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