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Composite compression bottom flange for steel box girders, January 1986, EXECUTIVE SUMMARY

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16. Abstract

This report is the executive summary of the final report of a study on the use of composite steel-concrete compression flanges in the negative moment regions of continuous steel box girder bridges. Preliminary analyses of several bridge designs reveal the possibility of reducing or eliminating haunches, with significant ramifications on efficiency of design as well as on economy of fabrication and erection. Tests of small panel and box girder specimens show that with the use of concrete, the controlling mode of failure changes from the overall buckling of the bottom flange steel plate panel to local buckling between transverse anchor lines. The concrete slab shares in carrying compression force in the flange. Design guidelines are presented to insure the development of full yield strength of the steel plate and the full composite action of the materials. Proposed modifications to the AASHTO Specifications are included. Separately issued is the main report, of the same title and date, Fritz Engineering Laboratory Report 489.3, Government Report No.

17. Key Words

Box Girder, Composite Action, Local Buckling, Steel, Concrete, Continuous Spans, Testing, Design, Specifications

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INTRODUCTION

Steel box girders are frequently used for medium and long span continuous bridge superstructures. Typically, the highest longitudinal bending moment in the structure occurs over the piers. In these negative moment regions, it is often necessary to strengthen the bottom (compressive) flange by increased plate thickness or longitudinal stiffeners, or both. For long span bridges, it is also often necessary to increase the structural depth at the piers, resulting in a haunched profile.

Each of the special design features mentioned above increases the complexity and decreases the efficiency of the structure. The costs for material, fabrication and erection are increased. Furthermore, the increased complexity of the structure also renders it more difficult to predict its behavior under load. New design approaches to improve the structural efficiency in the negative moment regions are urgently needed. One such new approach involves the use of steel-concrete composite compression flanges in these regions. This is the topic of study for the research project reported herein.

PROBLEMS STUDIED

The objective of this study was to examine the possibility of using composite compressive bottom flanges in continuous steel box girders, with the goal of improving the structural efficiency of the flange system and eliminating the haunches.

The first task in this research undertaking was a feasibility study on the uses of fully composite steel-concrete compression flanges. Design plans of three continuous steel box girder bridges, with main span lengths up to 590 ft, were provided by the Federal Highway Administration. Figure 1 shows the distinct characteristics of the bridges. Alternate designs for these bridges were developed incorporating the use of fully composite compression flanges over the piers. Comparisons with the original designs were made on the basis of both strength and estimated cost. A large number of parameters were examined, including the thickness of steel bottom flange and web plates, the thickness and length of the concrete slab, the strength and density of concrete, the main span length, the span ratio, the midspan structural depth, the haunch ratio, and the procedure of fabrication and erection. Results of this study clearly established the feasibility of using composite compression flanges to eliminate the haunches completely.

The development of full composite strength of the steel-concrete compressive flange, corresponding to yielding of the steel plate and crushing of the concrete slab, depends upon the anchorage between the two materials and the bearing of the concrete slab at its ends. The material properties, the relative thicknesses, and the amount of anchorage are factors which influence the behavior of the composite flange. An analytical study on the strength of composite flange panels was made, utilizing existing solutions of buckling strength of steel plates. Special attention was given to the local behavior of the steel plate between two transverse rows of anchors, or among four anchors (see figs. 2 and 3). The effects of concrete shrinkage and creep, the bending of steel plate under the weight of fresh concrete, and the transmission of loads at the end of the panel were studied in detail. The pullout strength of anchors was also examined.

TEST PROGRAM

Four small specimens of composite compression panels were tested. Each specimen had a 62 by 50 by 3/8 in steel plate, combined with a 60 by 48 by 3 in concrete slab (fig. 4). The major factors examined in this experimental task included the spacing between anchors, the bearing condition at the ends of the concrete slabs, the distance between longitudinal supports simulating web plates, and the presence of out-of-plane loading. Table 1 gives the dimensions, material properties, and loading arrangements of the four panel specimens. The specimens were tested under an in-plane compressive load, either on the steel plate, or at the centroid of the composite cross section, as illustrated in figure 5. Table 2 summarizes the test results. Figure 6 shows a specimen in the test machine.

A 38 ft 3 in long box girder specimen, with a 3 by 4 ft cross section and a 3 in thick concrete slab, was tested in negative bending in four different arrangement of loading and supporting locations. Figures 7 and 8 show the dimension and details of the specimen. Figure 9 shows the various test arrangement and the respective ultimate bending moment diagrams. Parameters varied in these box girder bending tests were the strength of concrete, the bearing condition at the ends of the concrete slab (against the diaphragms), the anchoring at the ends of the concrete slab, and the moment gradient in the test panel. The combination of parameters for each test is summarized in table 3. Table 4 provides the predicted and observed moment strength for each test. Figure 10 shows the specimen in the test machine.

Based on the results of the analytical and experimental studies, practical design rules were developed for the composite compression flanges in continuous box girders. Appropriate specification provisions are proposed for consideration by the American Association of State Highway and Transportation Officials.

SUMMARY AND RECOMMENDATIONS

1. Summary of Findings

From the analysis of sample bridges, the testing of composite panels and box girder segments, and the evaluation of results, the following items of summary can be made:

(1) It is possible to reduce or eliminate haunches in the negative moment regions of the continuous steel box girders by using composite compressive bottom flanges in these areas. Adding of composite concrete slab is equivalent to having a thicker bottom flange plate, thus enabling the reduction or elimination of haunches.

(2) The required thickness and length of concrete slab over the bottom flange steel plate are influenced by the span length, by the adopted box girder depth at the piers and at the center of span, and by the chosen thickness of the bottom flange steel plate.

(3) Because constant depth box girder bridges are simpler for fabrication and erection, alternative designs of two sample bridges were made assuming constant depth throughout the entire length of each bridge. For a three span bridge with a maximum span of 590 ft and a depth of 27 ft at the piers, one of the alternative designs permitted a uniform depth of 16 ft with a concrete slab 18 in thick at the piers and tapering to zero at about 1/5 of the maximum span. For a five span bridge with a central span length of 450 ft and a maximum depth of 21 ft 4 in over two piers, a uniform depth box girder 10 ft 4 in deep with 18 in maximum thickness of concrete slab was among the possible alternative designs. The yield strength of the steel was 50 ksi and the concrete strength was assumed 4000 psi in these examples.

(4) Theoretically, for a chosen concrete slab thickness in a box girder, higher strength of concrete results in lower compressive stresses in the composite compressive bottom flange. Bearing of concrete slabs on box girder diaphragms, however, is essential to the development of the full strength of the composite compression flange. Results from testing box girder segments showed that the higher concrete strength was not fully utilized if the concrete slab was not in directed bearing.

(5) The procedures of construction and erection can have very strong influence on the utilization of strength of the composite compressive bottom flange. Cast-in-place concrete slab requires sufficient strength of bare bottom flange steel plate to resist in-plane compressive stresses and out-of-plane plate bending stresses due to wet concrete. Precast concrete planks can be attached before erection or attached on site to form the composite slab; the former provides strong box girder segments for transportation and erection and both procedures require grouting. The selection of a procedure obviously depends upon the geometry and location of the bridge as well as the capability of the fabrication and construction team.

(6) Shrinkage and creep may result in a gap between a concrete slab and the transverse member (diaphragm or stiffener) at the end of the slab. Evaluation of the alternative design of one sample bridge and the design of one practical thin composite panel showed that shrinkage and creep did not govern.

(7) The use of lightweight concrete had very little effect on the total weight of the sample bridge. The lower modulus of elasticity of the light-weight concrete resulted in smaller cross sectioned area of equivalent steel flange plate and correspondingly higher compressive stresses in the composite flange.

(8) By assuming wide ranges of unit costs for fabricated steel and concrete, it was found that the total cost of the alternative design for each of the two sample bridges was lower than the original design. Therefore, it is analytically possible and economically feasible to eliminate haunches or to strengthen the negative moment region of continuous box girders by using composite compression flanges.

(9) There is no readily available closed-form analytical solution for steel plates subjected to in-plane compression and out-of-plane bending simultaneously. The evaluation of strength of the bottom flange steel plate during erection and construction is therefore quite complicated and approximate. Caution must be taken in this regard.

(10) The strength of composite compression flange depends on the end conditions of the concrete slab. The slab may or may not be in bearing with the diaphragms or transverse stiffeners at the ends. The corresponding loading conditions for the composite compression flange are either concentric or eccentric loads, respectively.

(11) The first row of concrete slab anchors on the steel flange plate may be placed at or near the ends of the slab, or at a short distance away from the end. In the latter case, if the concrete slab is not in bearing, the steel plate alone carries the total compressive flange force in that region.

(12) Tests were conducted on box girder segments with the concrete slab not in bearing and not anchored to the steel plate near the ends of the slab. Failures were by local buckling of the steel flange plate between the first row of anchors and the end of the slab.

(13) Tests were conducted on composite flange panels with concrete slab not in bearing but with equivalent anchors at the ends of the slab. Failure was by cracking of concrete slab. The composite compression panels were subjected to eccentric load causing bending of the composite panel toward the concrete slab.

(14) For composite compression flange panels with concrete slabs in bearing, the strength of the flange panel depends on the spacing of concrete slab anchors. Small spacing between the transverse rows of anchors prevents local buckling of steel plate and permits development of full strength of the composite flange panel.

(15) The test specimens had 48 in wide panels with 3/8 in thick flange plates and 3 in thick concrete slabs. The anchor studs were 2 by 1/2 in arranged in different longitudinal spacing (pitch) and transverse distances (gage length). Failure of compression flanges was predominantly by local buckling between two rows of anchor studs. In two cases the ultimate strength of yielding the steel plate plus crushing the concrete slab was achieved. The failure modes were consistent with the predicted results.

(16) The strength of composite compressive flanges as governed by local buckling can be predicted approximately. The steel plate between two rows of anchors is considered simply supported at the boundaries. The lateral force of the concrete slab weight on the steel plate is not considered applicable between two rows of anchors because the concrete does not buckle with the steel plate. In all cases of test, the strength from testing was reasonably above the predicted values.

(17) The full strength of composite compression flange panel is dependent upon the strength of the concrete and the thickness of the slab. For a chosen concrete slab thickness, higher strength concrete contributes to a bigger transformed steel bottom flange and a higher cross sectional moment of inertia of the box girder. The resulting stresses in the composite flange is lower.

(18) The relative thickness of the concrete slab to the steel plate was about 8 and 9 for the test specimens and an alternatively designed bottom flange of a sample bridge respectively. A thickness ratio of 8 to 12 appears to be adequate.

(19) There was little transfer of forces between steel plate and concrete in the test specimens. The studs for anchoring the concrete slab appeared to be also sufficient for shear between the steel plate and the concrete slab. The approximately uniform distribution of stresses in the bottom flange steel plates confirmed the effectiveness of the anchored concrete slab in strengthening the steel plate.

(20) No fatigue test was planned or conducted. The anticipated low shear stresses at the anchors were not expected to cause any problem from fatigue.

2. Recommendations

Based on the results from analysis and testing, the following are recommended:

(1) That new rules and guidelines be introduced in design specifications to permit the use of composite compression flanges in negative moment region of continuous steel box girders.

- The thickness and length of concrete slabs of composite compressive bottom flanges should be determined by analyzing the bridge assuming full participation of the concrete slabs. Ordinary or high strength concrete can be used with appropriate consideration of the strength and modulus ratio in calculating the transformed steel flange area.

- The ratio of concrete slab thickness to steel flange plate thickness should be in the range of 8 to 10. The existing requirement of minimum thickness of concrete above anchor studs and the pullout strength of studs should be considered in determining concrete thickness.

- The concrete slab should be anchored to the steel flange plate by stud connectors. The maximum anchor spacing, a, in the longitudinal direction of the box girder should be calculated by the equation:

$$a = \frac{5120t}{\sqrt{F_y}} \leq 24 \text{ in.}$$

  in which t is the thickness of the steel flange plate. The first two anchore spaces at the ends of concrete slabs should not be more than half of the space calculated by this equation. The transverse distance between two longitudinal lines of anchors may be twice that of this computed value but not more than 24 in. These recommended rules are presented in specification language in the Appendix.

- The concrete slab should be of full length of the steel flange plate between box girder diaphragms and of full width between the webs of the box girder. The ends of the concrete slab should be in contact with the diaphragms.

(2) That additional research be conducted to examine further the behavior of composite compression flanges and to explore new applications.

   - Field measurements of stresses and displacements are needed of a bridge which has a composite compression flange or has a compressive bottom flange strengthened by a concrete slab.

   - Investigation is suggested on the possibility and advantages of applying concrete slabs to horizontally curved steel box girders.

Table 1 Composite Panel Specimens

Panel Specimen	A	B	C	D
Test Panel Dimensions	60- by 48 in			
Steel Plate Thickness	3/8 in			
Edge Plates	4 in by 3/8 in all around			
Concrete Thickness	3 in			
Anchor Studs	1/2 in dia. by 2 in			
Concrete Strength (psi)				
Design	4000			
Measured	4550	4220	4480	3730
Steel Yield Strength (ksi)				
Design	36			
Measured	46.0	32.3	45.3	42.1
Anchor Stud Spacings (in)	12 by 12	24 by 24	12 by 24	16 by 16
Lateral Support Spacing (in)	48	48	24,32,48	48
Lateral Load	No	No	No	Yes

Table 2 Limit State Loads of Composite Panels

Test	A1	A2	B1	B2	C1-1	C1-2	C1-3	C2	D
Load on	steel	steel & conc.	steel	steel & conc.	steel	steel	steel	steel & conc.	steel & conc.
Lat. Sup. Spacing (in.)	48	48	48	48	48	32	24	48	48
Initial Yielding [(1)(2)]	830^k	--	830	--	830	830	830	--	--
Cracking of Concrete	200^k	--	200	--	200	200	200	--	--
Full Strength [(3)]	--	1160	--	1160	--	--	--	1160	1160
Buckling between two rows of anchors [(4)]	520 [(5)]	1040	180 [(5)]	360	520 [(5)]	600 [(5)]	720 [(5)]	1040	640
Buckling between four studs	1100	2200	290	580	540	1450	2200	1080	1300

Notes: (1) First yield of steel plate in composite panel

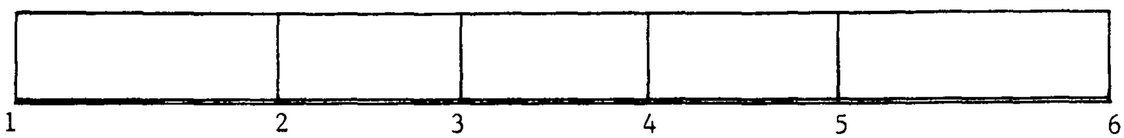
(2) Yielding of steel plate alone without concrete slab, 675^k

(3) Strength of direct compression of composite panel, yielding of steel plate (without buckling) and crushing of concrete.

(4) Buckling of steel plate alone without concrete slab 290^k

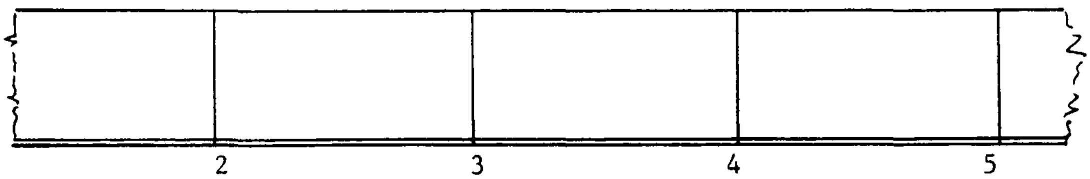
(5) Assuming steel plate alone carries load

Table 3 Box Girder Specimen Design and Material Properties



Box Segment	2-3	3-4	4-5	5-6 and 1-2
Steel Yield Strength (ksi)				
1 in plate (top flange)	34.9			
3/8 in plate (all other)	42.7			
Concrete Strength (psi)	5580	3820	3820	4100
Bottom Flange Design:				
Panel Dimension (in)	72 by 48			109 1/2 by48
Steel Plate Thickness (in)	3/8			
Concrete Thickness (in)	3			
Anchor Spacing (in)	16 x 16			
Concrete Slab In Bearing	No	Yes	No	No

Table 4 Summary of Box Girder Specimen Failure Tests



Test	3	4		1	2
Test Segment	2-3	2-3	3-4	3-4	4-5
Concrete Slab	Not bearing	Bearing		Not Bearing	Not Bearing
Failure Location	2	2-3	3-4	4	5
Predicted Failure Moment (k-ft)	2290	2400	2220	2290	2290
Observed Failure Moment (k-ft)	2580	2840	3415	2420	3010
Failure Mode	Buckling of Steel Plate				
	(1)	(2)	(2)	(1)	(1)

Note:

(1) Buckling upward between diaphragm and first row of studs

(2) Buckling downward between two rows of studs

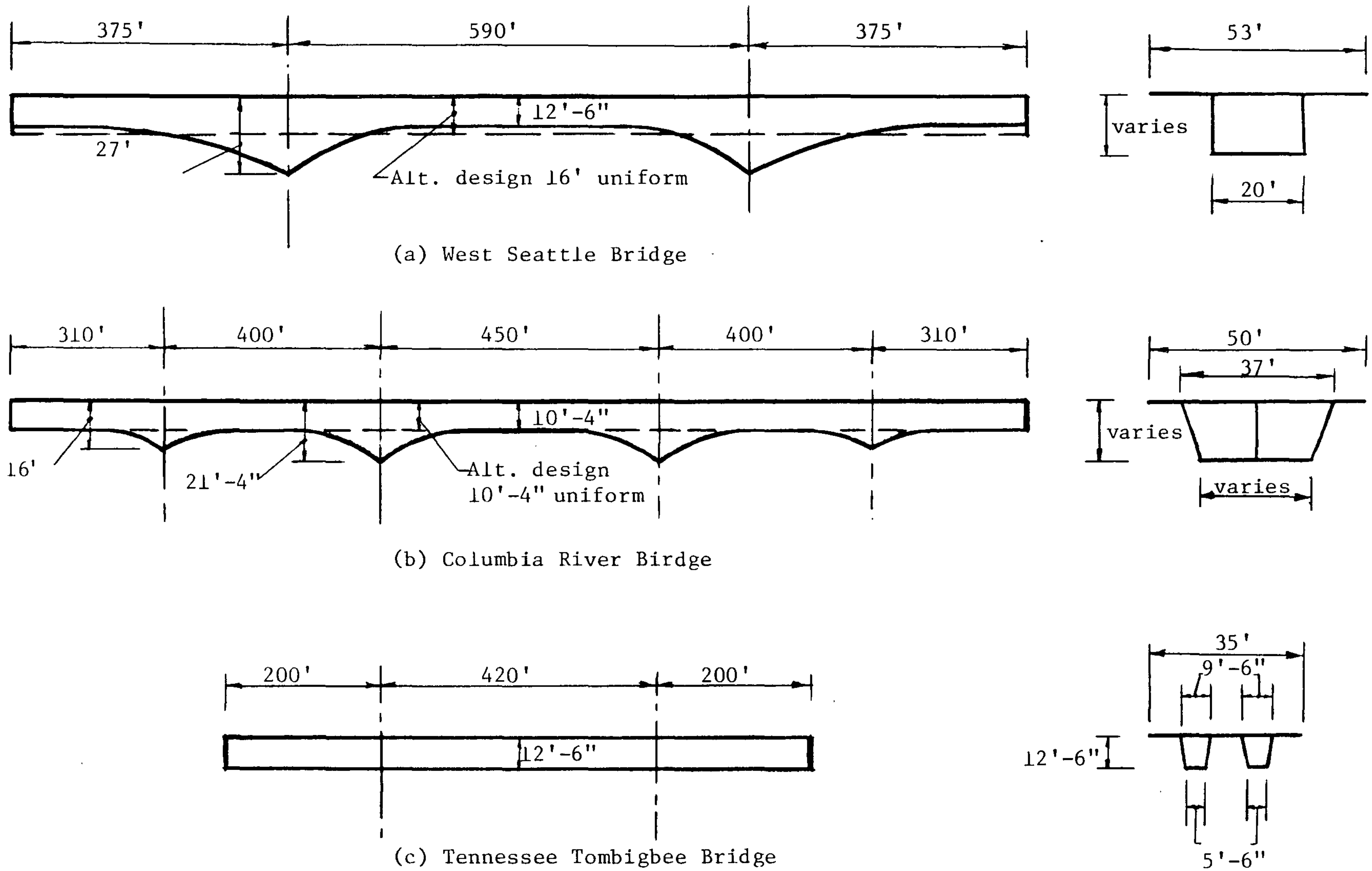


Figure 1 Characteristics of Three Bridge Structures (Schematic)

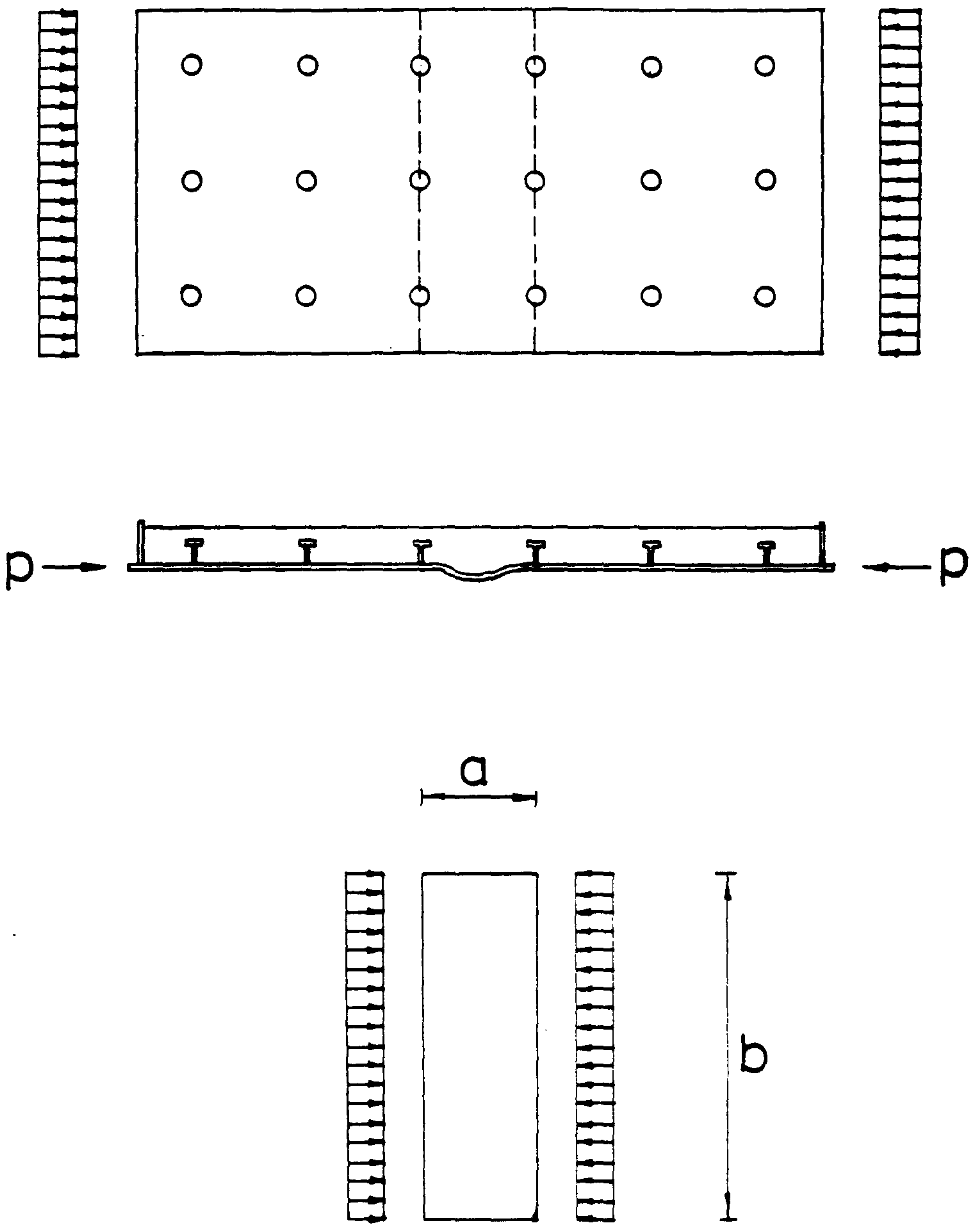


Figure 2 Local Buckling Between Anchor Rows

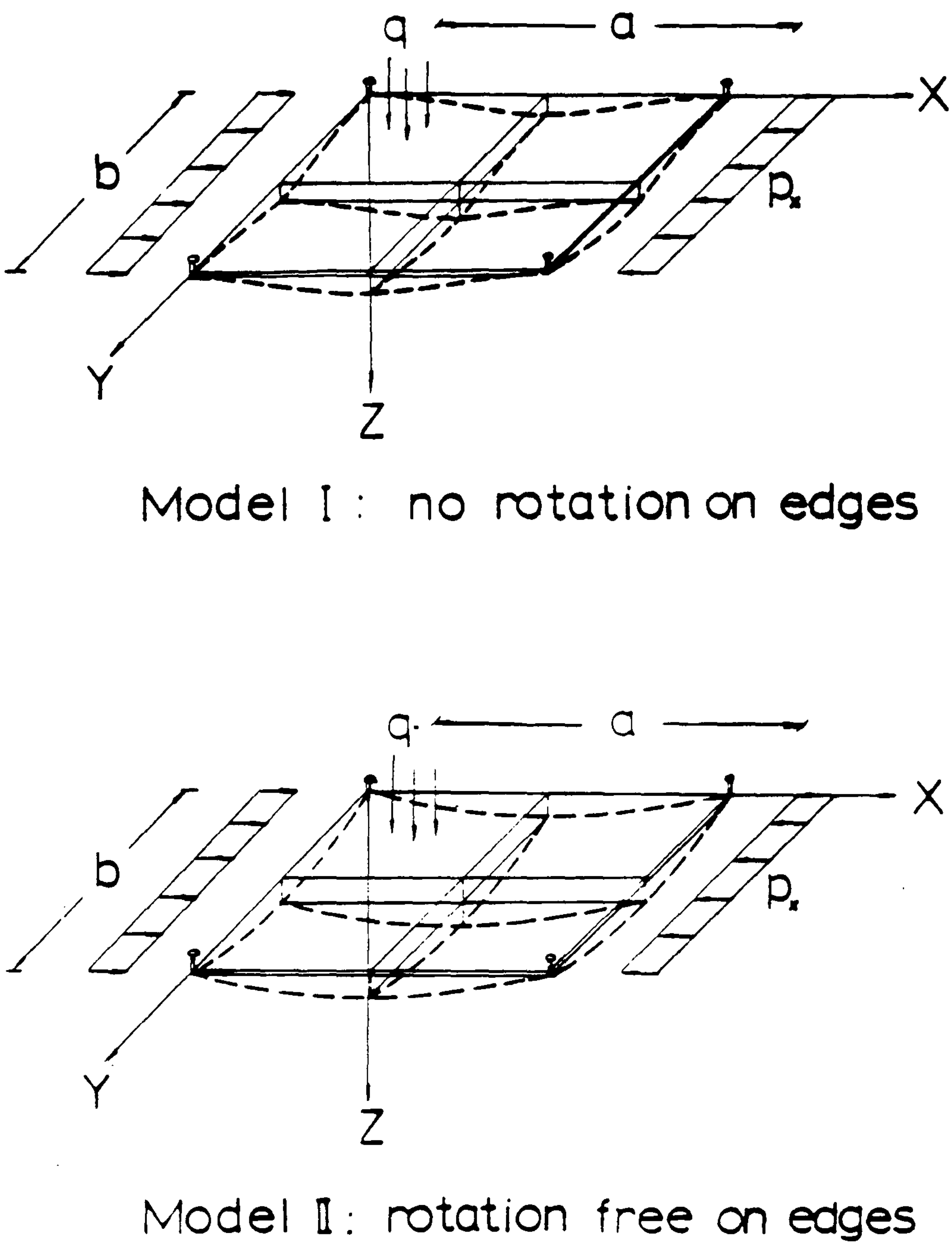


Figure 3 Model of Steel Plate Buckling Between Anchor Points

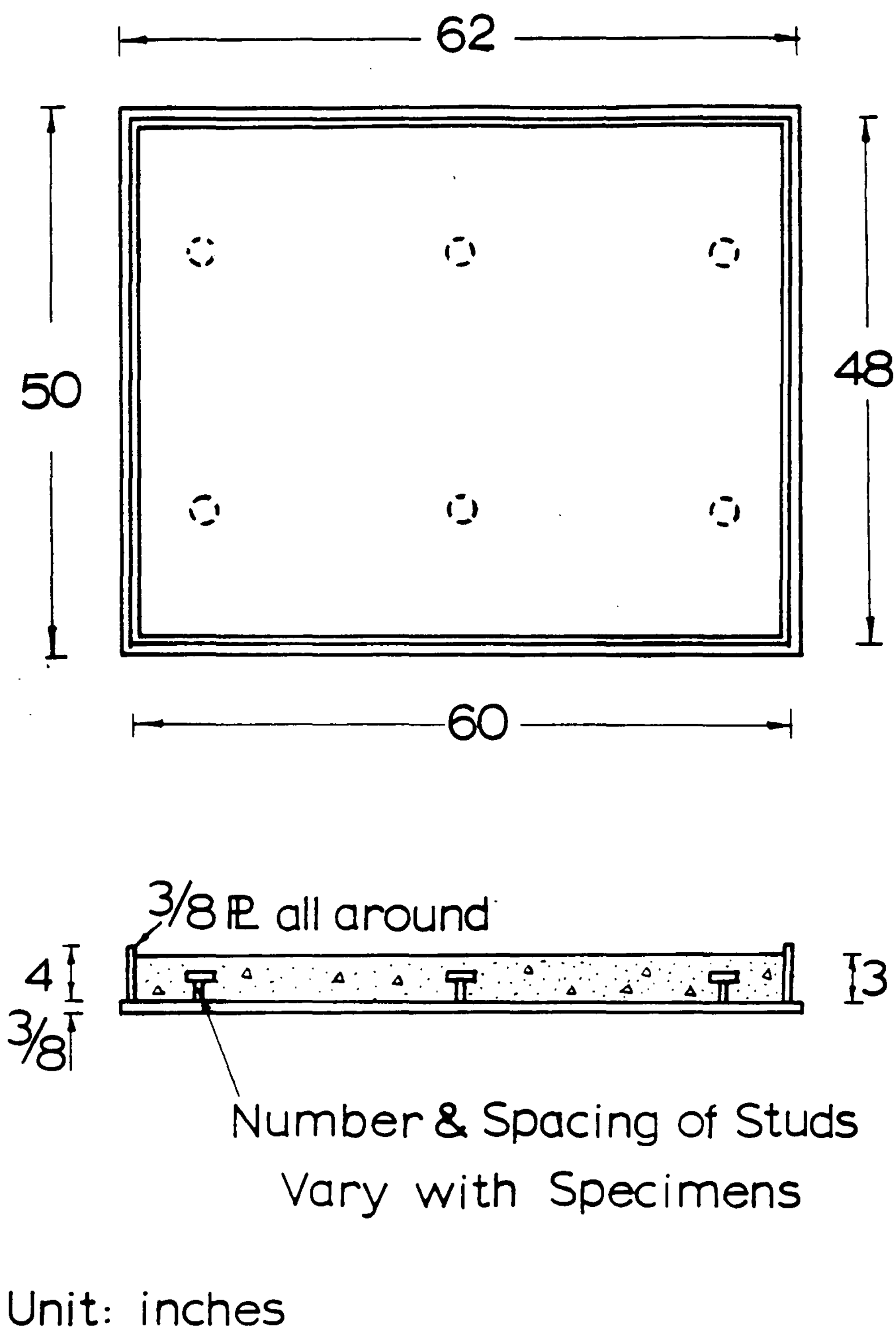


Figure 4 Small Panel Specimens

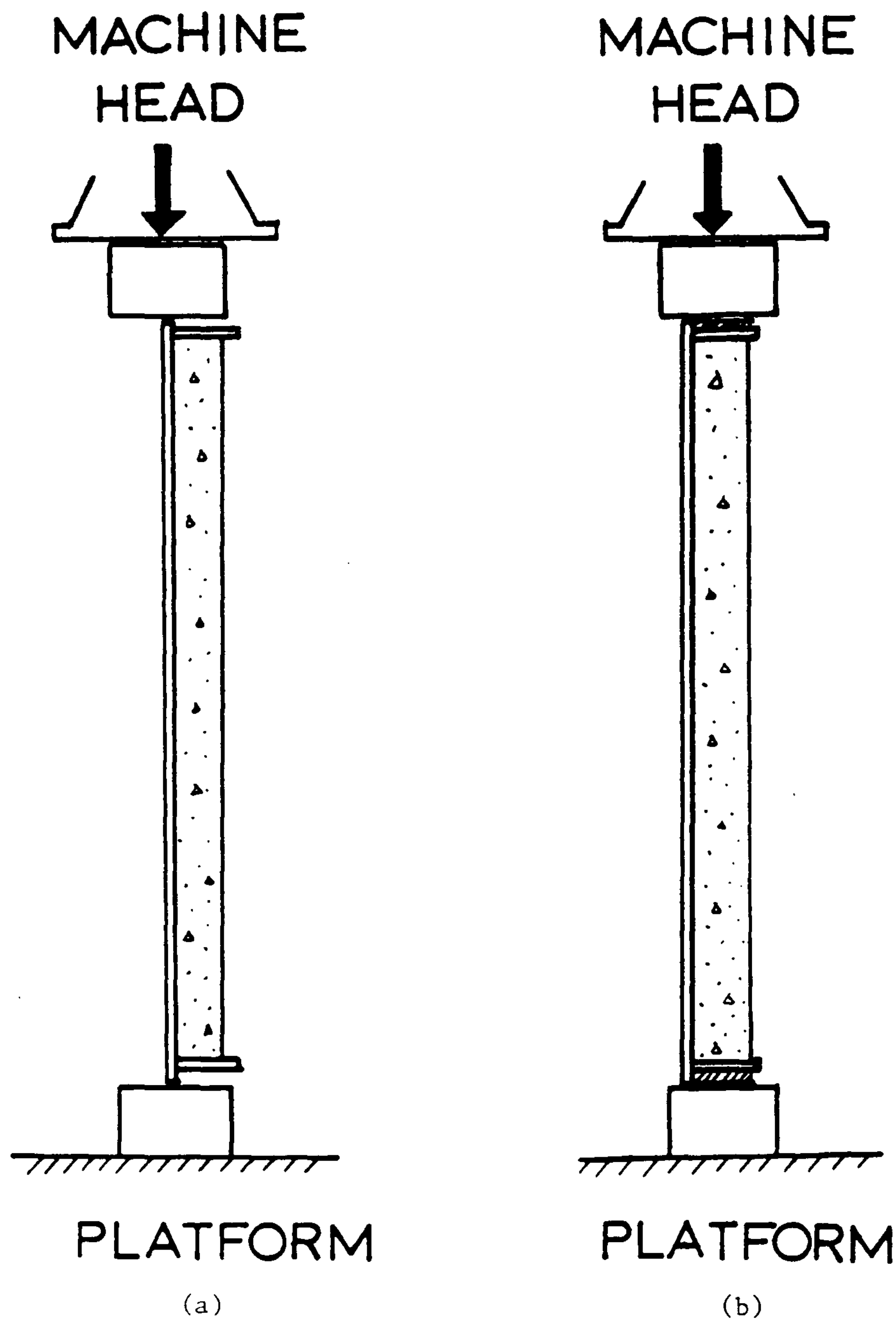


Figure 5 Loading Conditions of Panel Specimen

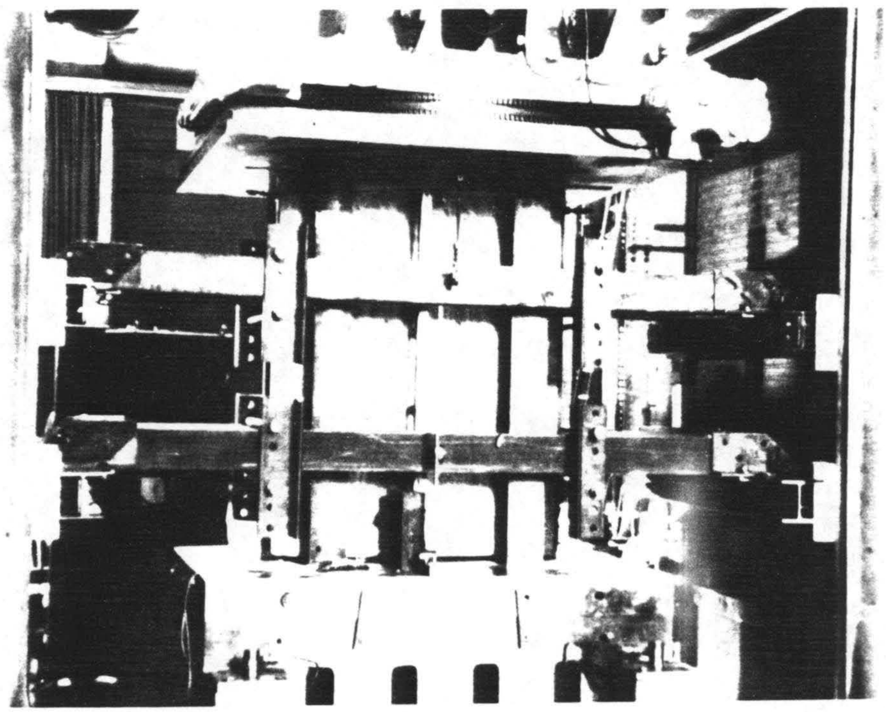


Figure 6 Panel Specimen in Test Machine

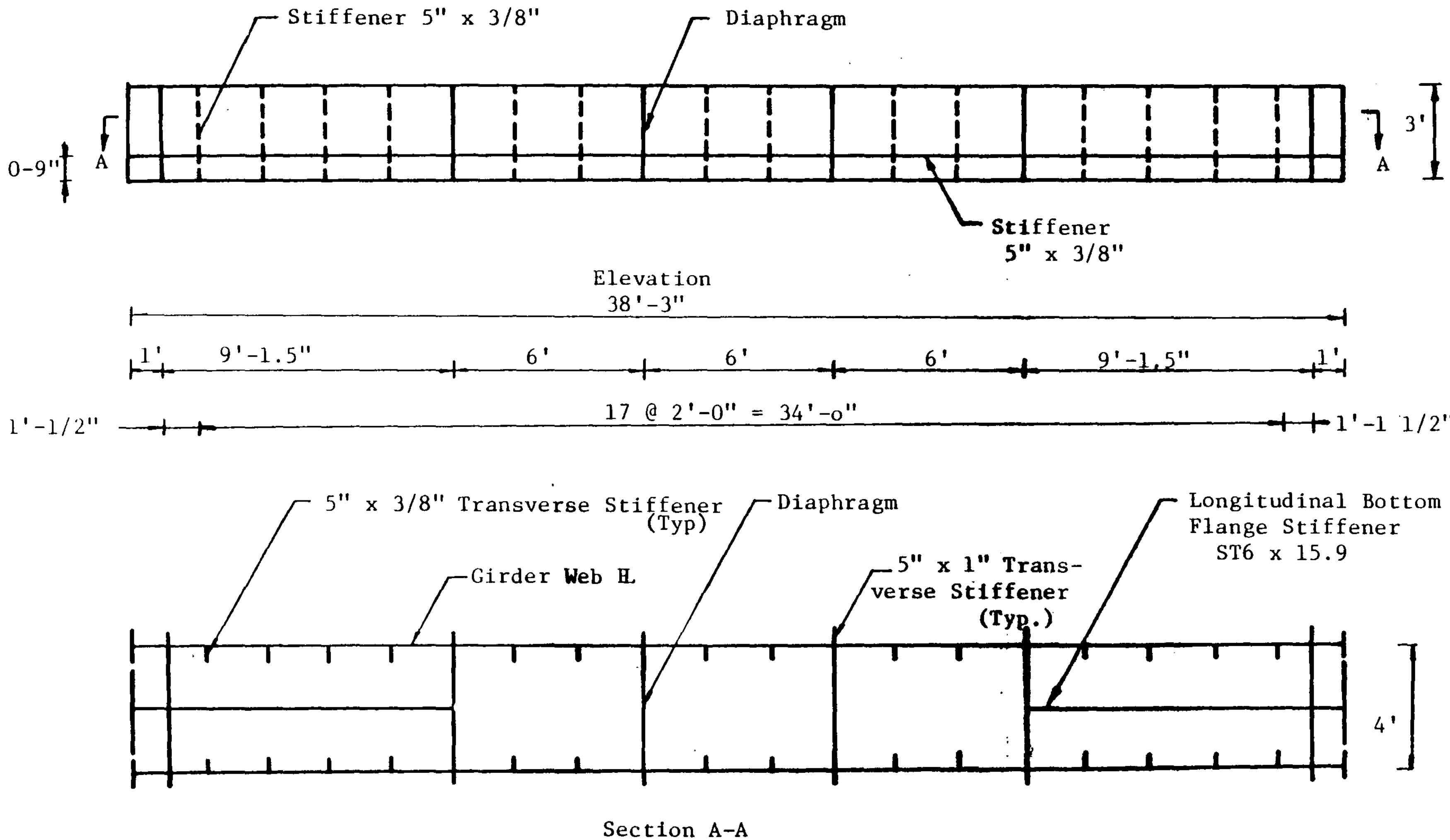
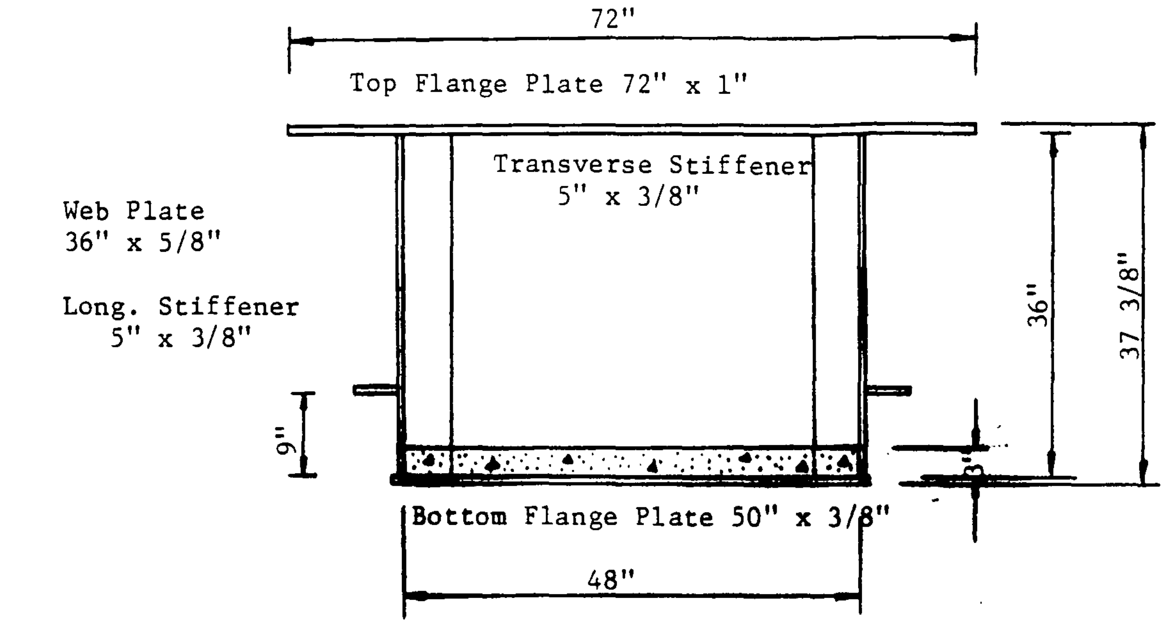
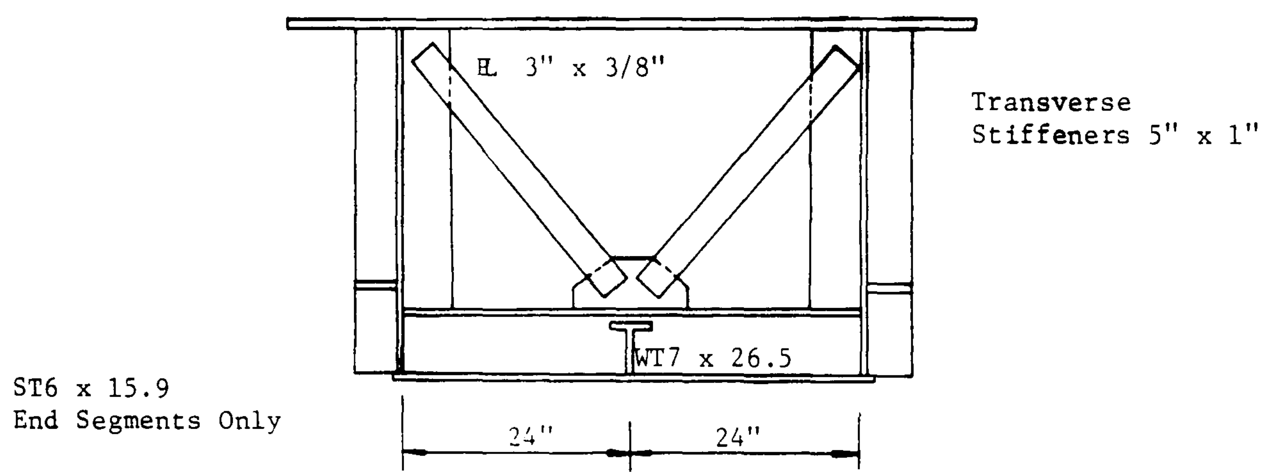


Figure 7 Box Girder Specimen



(a) Typical Cross Section



(b) Typical Diaphragm Section

Figure 8 Box Girder Specimen Cross Section

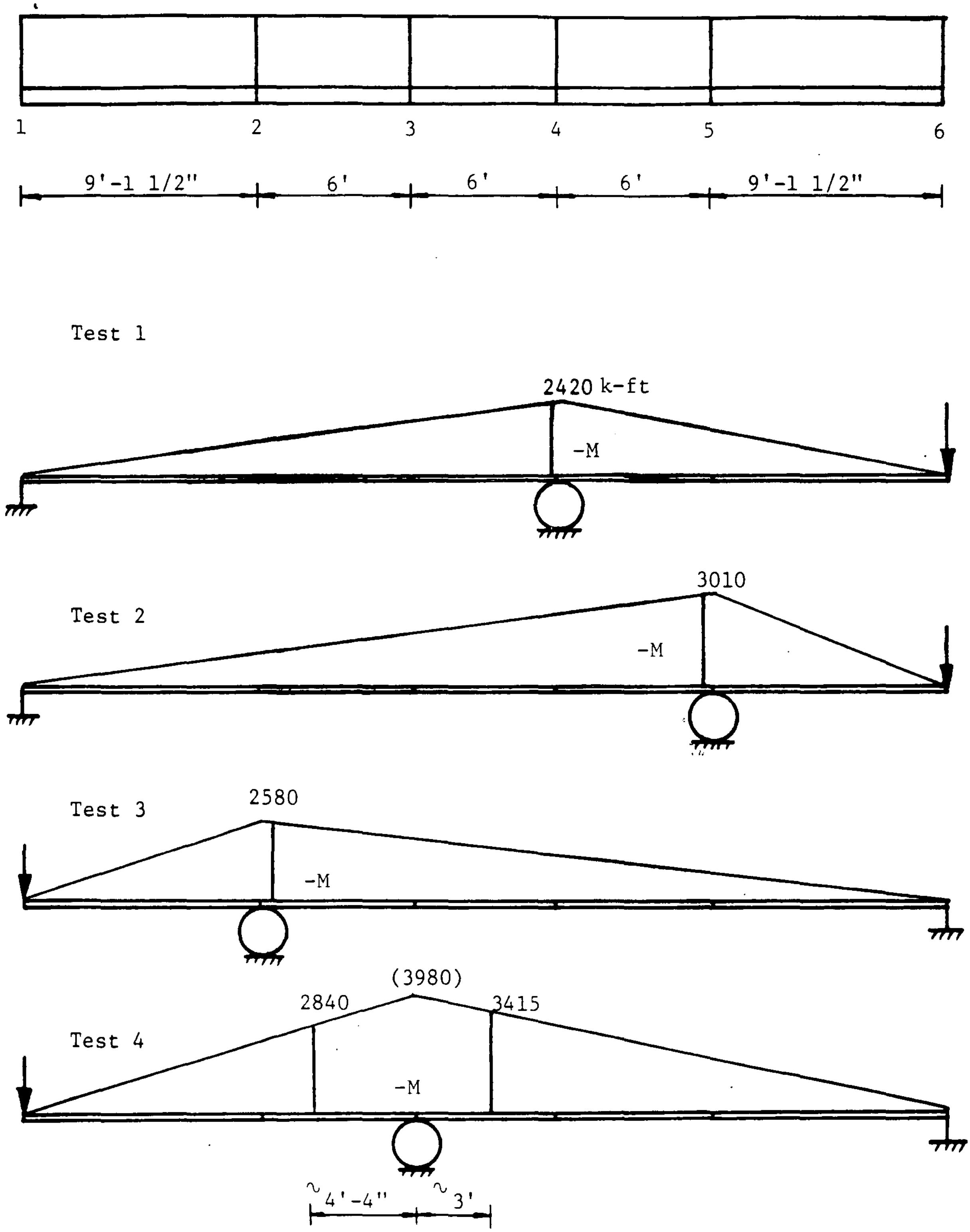


Figure 9 Support Locations and Moment Diagrams of Box Girder Specimen Tests

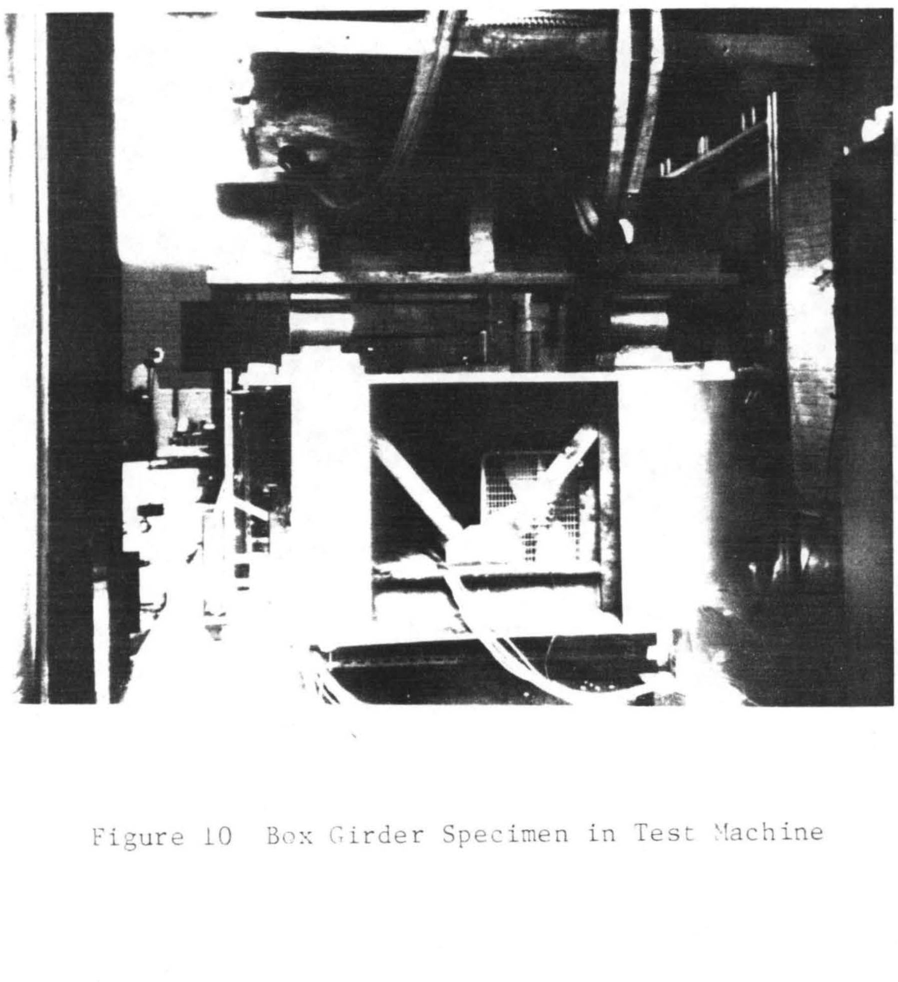


Figure 10 Box Girder Specimen in Test Machine

APPENDIX

A. Proposed addition to AASHTO Standard Specifications for Highway Bridges.

10.39 Composite Box Girders

10.39.4 Design of Bottom Flange Plates

10.39.4.6 Composite Compression Flanges

10.39.4.6.1 Concrete slab may be anchored to the steel bottom flange plate to form a composite compression flange. Anchorage shall be provided by anchor studs or other mechanical connectors.

10.39.4.6.2 The concrete slab on the bottom flange plate shall extend full length between transverse diaphragms or stiffeners, and full width between webs.

10.39.4.6.3 The design of the composite compression flanges, and the computation of stresses therein, shall be based on the concept of transformed cross-section, employing the modular ratio of the concrete and steel materials.

10.39.4.6.4 The minimum clear depth of concrete over the tops of anchor connectors shall conform to the requirements of Article 10.38.2.

10.39.4.6.5 The spacing of stud anchors, a, in the longitudinal direction shall not exceed the value determined by the formula:

$$a = \frac{5120t}{\sqrt{F_y}} \leq 24 \text{ in.} \qquad (10\text{-xx})$$

Where t is the thickness of the steel flange plate. Near the ends of a concrete slab in a composite flange panel, the first two spaces between rows of anchor studs shall be limited to half of the value computed by Eq. 10-xx, with a maximum distance of 12 in. The transverse distance between longitudinal lines of anchor studs may be twice of the value by Eq. 10-xx, but not more than 24 in.

10.51 Composite Box Girders

10.51.5 Compression Flanges

10.51.5.6 Composite Compressive Bottom Flanges

The conditions and provision of Article 10.39.4.6 for the allowable stress design method are also applicable here for the load factor design method.

B. Commentary on Proposed Article 10.39.4.6 and 10.51.5

10.39.4.6.1 Concrete slab anchored to the steel bottom flange plate can act compositely with the steel plate to form a composite compression flange. The strength of the compression flange is increased from that of overall buckling of the steel plate to that of local buckling of the plate between rows of anchors.

10.39.4.6.2 If the concrete slab is not in bearing at its ends, the composite compression flange is subjected to eccentrical load with respect to its centroidal plane. Full length slab in bearing permits direct transmittal of forces into the slab and its direct participation in resisting compression. Full width slab is also specified so as to provide restraint along the flange-to-web junction. The thickness of the concrete slab is to be determined through the analysis of bridge bending moments and compressive stresses in the steel flange plate.

10.39.4.6.3 The analysis and design of the box girder with composite bottom flange should be made on the basis of transformed cross section where the two materials are converted into one by means of modular ratios as specified in Article 10.38.1.2 and 10.38.1.3.

Dependent upon the fabrication and erection procedures, the critical stress condition in the composite box section may occur at a stage before the completion of the bridge construction. Appropriate considerations must be given to these early stage conditions, such as: (1) bare steel plate bottom flange supporting the weight of fresh concrete, (2) bare steel plate bottom flange supporting partial bridge weight and fresh concrete in segmental construction.

10.39.4.6.4 A minimum thickness of concrete is specified, similar to that for composite I-beams, in order to provide anchorage between the concrete and steel.

10.39.4.6.5 The limit for stud anchors spacing is derived on the basis that local buckling between two transverse rows of stud anchors will not occur prior to yiedling of the steel plate. The maximum spacing of 24 in. is imposed because no distance of more than 24 in. existed in test specimens of the study leading to this rule. An end space of half the value from Eq. 10.xx is specified to cover uncertainties such as the bearing of concrete slab and the condition of splice plates in this area for field connections. In all cases, direct bearing of the slab at its ends is recommended.

10.51.5 See commentary for 10.39.4.6.