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C. Culver

R. Coston

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TESTS OF COMPOSITE BEAMS
WITH STUD SHEAR CONNECTORS

by

Charles Culver

and

Robert Coston

Fritz Engineering Laboratory
Lehigh University
Bethlehem, Pennsylvania

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C O N T E N T S

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I. Introduction

Composite beams, beams in which a concrete slab and steel beam act as an integral unit, are widely used in bridge and building construction. The essential elementof the composite section is the shear connection between the slab and steel beam. The function of this connection is to resist the horizontal shear between the slab and beam and to prevent uplift of the slab from the steel beam.

A variety of devices, including channels, Zee sections, and spirals have been used as shear connectors. Economic considerations have lead to the development and use of round studs in place of the above mentioned connectors. Simplicity and ease of installation make these studs advantageous.

The design of stud and other shear devices is based on an elastic analysis of the composite section and, for highway bridges, is governed by the AASHO specification.(1)

This specification lists formulas for determining the "useful capacity" of shear connectors or the maximum load which a shear connector can carry and satisfactorily perform its function.

The criterion used in establishing values for the "useful capacity" of a shear connector was a limiting value of residual slip or horizontal displacement between the slab and steel beam after unloading of the composite section.

The value of this residual slip was set at 0.003 in.[4] and it was stated that slip beyond this value, "causes an appreciable increase of both the stresses and deflections of the T-beam."[2]

This value of 0.003 in. is considerably below the slip at failure obtained from pushout tests of various types of connectors. Hence, the "useful capacity" is considerably below the ultimate connector strength. The resulting emergency reserve strength[7] $\left(\frac{\text{ultimate connector force}}{\text{"useful capacity" force}}\right)$ for the studs is therefore greater than the emergency reserve strength $\left(\frac{\text{ultimate moment}}{\text{yield moment}}\right)$ for the composite section. If increased slip did not alter the performance of the composite beam, then it seems feasible that larger values for the "useful capacity" of the connector could be used.

The objectives of this investigation were to determine:

1. The value of connector forces for studs such that the composite section will develop the ultimate moment.
2. The influence of slip on the load-deflection characteristics of a composite beam.
3. The effect of fatigue loading on a composite section.

II. Design and Fabrication of Test Specimens

Three specimens to be statically loaded and a fatigue specimen were designed for this series of tests. The design procedure used considers equilibrium of the concrete slab as a free body between sections of zero moment and ultimate moment and is based on the assumption that the shear connectors possess sufficient ductility so that a redistribution of the horizontal shearing forces is possible. This same assumption is used in the design of a riveted connection. Analysis of a previous test established the validity of this assumption.[5]

The shear connectors for the static tests were designed so that the connector forces at ultimate moment would be 1.6, 2.4 and 3.0 times the "useful capacity" according to the AASHO specification. The fatigue specimen was designed so that the shear stress, computed on the basis of a uniform distribution of shear stress on the cross section of the stud, would approach the fatigue strength, based on a fatigue life of 2×10^6 cycles, obtained in previous tests.[6] Design calculations are included in the Appendix.

Each of the four specimens consisted of a flat concrete slab connected to an 8WF17 beam by one-half inch diameter L shaped studs. Slab reinforcement consisted of a mesh of 5/16 and 3/16 inch diameter rods. Figure 1 gives the specimen dimensions and the connector spacings.

Forming and pouring of the specimens was done at Fritz Engineering Laboratory, Lehigh University. All beams were poured at the same time using a commercial ready mix concrete with a maximum aggregate size of 3/4 inch.

III <u>Test Procedure</u>

The specimens were simply supported over a span of 10 feet and loaded with two point loads spaced symmetrically with respect to the center of the beam. (See Fig. 2) Load was applied by means of an hydraulic jack.

In the static tests an Amsler pendulum dynamometer applied and measured the pressure in the jack. An Amsler pulsator was connected to the jack to produce the cyclic, sinusolidally varying load at 250 cycles per minute for the fatigue test.

The ultimate load at which crushing of the concrete slab will occur can be determined quite accurately. By stopping the tests short of this load, the loading positions can be changed to produce greater shearing forces for the same ultimate moment - in other words, increasing the spread "b" of the two concentrated loads. (See sketch Table 1) Thus a single specimen can be used for several ultimate load tests and connector failure insured.

The above mentioned procedure was followed in this series of tests with the load spacings designated as follows:

Spacing 1 (Test 1) --- 2b = 24"

Spacing 2 (Test 2) --- 2b = 36"

Spacing 3 (Test 3) --- 2b = 46"

Since all the specimens were similarly constructed, the only exception being the spacing and number of shear connectors, the value of M_p and hence P_p, for any given load spacing, should be the same for all specimens. Thus, the three static test beams are grouped according to the load spacing in Table 2, so that certain comparisons can be made later.

In the static tests load was applied in increments of five kips up to yielding of the steel beam and thence in increments of deflection equal to the deflection at this point.

Strain measurements in the slab and steel beam, center line and quarter point deflections, and end slip readings were taken after each load increment. After reaching the yield point of the steel beam, the load was released periodically and residual deflection and end slip readings taken. The arrangement of the recording gages and the test setup are shown in Fig. 2.

The fatigue test of specimen B4 was conducted as follows:

1. 1,000,000 load cycles alternating between a minimum of 3000 and a maximum of 30,000 lbs.
2. 500,000 cycles between 3000 and 36,000 lbs.
3. 500,000 cycles between 3000 and 42,000 lbs.
4. Cyclic loading between 3000 and 48,000 lbs. to failure of the specimen.

The load spacing was kept constant at 2b = 36". Maximum slip and deflection under the fatigue loading was recorded by special gages. The fatigue loading was stopped periodically and a load equal to the maximum cyclic load for that phase of the test was applied statically. Deflection, end slip, and strain readings were taken under this static load to determine the effect which the fatigue loading produced on the specimen.

Auxiliary tests included concrete cylinders tests and tensile coupon tests to determine the material properties of the composite section. The tensile coupons were taken from the unyielded portion of the flange of the steel beam after completion of testing. The results of these auxiliary tests appear in Tables 4 and 5.

IV Results and Interpretation

Static Tests

The results of the static tests are summarized in Table 2. The accuracy with which the ultimate load can be determined, assuming adequate shear connection, is shown by comparison of P_p and P_u for those tests in which bending failure occurred (failure type (A)). Values of P_u obtained for tests designated by failure type (B) are smaller than P_p because the tests were purposely stopped short of crushing of the slab and, strictly speaking, they are not really ultimate loads. In test B3-T3 the connectors failed before P_p was reached.

The average connector forces, computed by the same procedure used in the specimen design, are listed in Table 2. For those tests in which the ultimate moment was not reached, i.e., when the test was stopped short of crushing of the concrete or the connectors failed, the connector forces were computed by multiplying the calculated values for connector forces at ultimate (pg.27 of Appendix) by the ratio of the moment reached to the ultimate moment. All the values listed are greater than the "useful capacity" of the studs according to the AASHO specification. The values for residual end slip are also considerably larger than the value of 0.003".

Fig. 3 shows the load-slip curves for the three specimens. The load per connector in Beam 1 was close to the "useful capacity" load according to AASHO, whereas the maximum load per connector obtained in Beam 3, Test 3, was approximately 2.5 times the "useful capacity".

It is significant to note the large differences in slip which resulted from this increased connector loading.

Load deflection curves (shearing deflections included) for the various tests are presented in Fig. 4. Each test is plotted separately with residual deflections from a previous test indicated at the origin. In order to compare the load deflection characteristics for all the tests the non-dimensional graph of Fig. 5 was plotted. Despite the fact that there was a wide variation in connector forces between the various tests this plot shows that the effect on the load deflection characteristics was relatively small. Up to yielding of the steel beam the behavior of all the specimens was exactly the same. Beyond this point there is a small difference between the various specimens; however, it issignificant to note that all the curves tend to parallel the curve for B1-T1 and would have reached the same point at ultimate had they not been stopped short of crushing of the concrete. Only in B3-T3 in which the connector force reached 16 kips was there a reduction of M/M_y. It is evident that connector forces considerably in excess of the present AASHO "useful capacity" do not alter the performance of the composite section.

In summary, the following is to be noted:

1. The ultimate strength of stud connectors is considerably above the "useful capacity" according to AASHO.

2. Large values of slip between slab and beam do not significantly alter the ultimate moment or the load deflection characteristics of the composite section.

3. The emergency reserve strength of the studs $\left(\frac{\text{ultimate connector force}}{\text{"useful capacity" force}}\right)$ is considerably larger than the emergency reserve strength of the beam $\left(\frac{\text{ultimate moment}}{\text{yield moment}}\right)$.

Fatigue Test

The fatigue test results are presented in Table 3. It will be noted that there is a good correlation between the theoretical deflections and those obtained during testing. Calculations indicated that the dynamic effects of loading were negligible. The increase in deflection under cyclic loading over both the theoretical deflection and the deflection under static loading could possibly be due to overloading by the jack.

The fatigue strength of the studs in this beam test is larger than values obtained in fatigue tests of these connectors in pushout specimens.[6] This would indicate that there are certain effects which must be evaluated before a comparison between beam tests and pushout tests can be made. Frictional forces developed under the loading points in a beam test is one such effect. A comparison of beam tests and push-out tests does, however, seem feasible. Such a comparison would be advantageous because relatively small specimens (pushout specimens) could then be used to determine the strength of shear connectors.

These additional effects probably account for the increase in connector forces also observed in the static tests over connector forces observed in static pushout tests.[6]

V Conclusion

This series of tests has indicated that present specifications do not take into account the maximum useful strength of stud shear connectors. Further, it has been shown that loading these studs to ultimate does not alter the behavior of the composite section.

A design procedure for composite beams which would take into account the full strength of the elements of the composite section; i.e., plastic design, seems feasible. There are, however, many questions which must be answered before such a design code can be formulated. Further research is required to answer such questions as:

1. Distribution and spacing of shear devices along the beam.
2. Interaction created by bond and friction.

Even if an elastic analysis is adhered to these tests have shown that it is possible to increase the so called "useful capacity" shear connector force.

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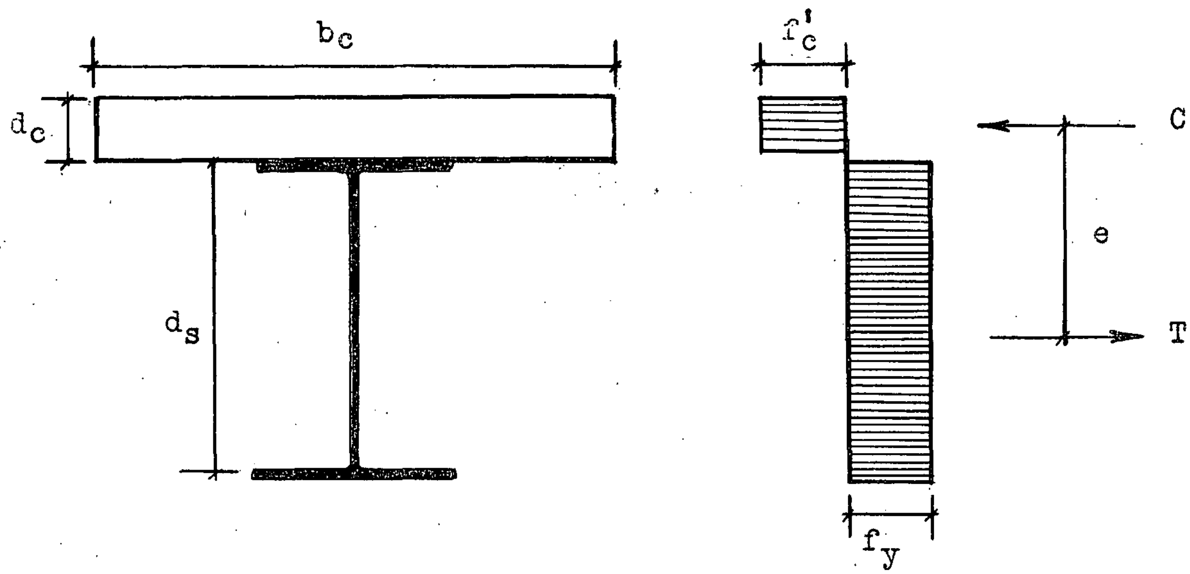
Nomenclature



A_s = steel area

a_{st} = distance from neutral axis of composite section to extreme fiber of steel in tension

b = distance from center line of beam to point of load

b_c = effective width of concrete slab

C = total compressive force = $f'_c b_c d_p$

c = number of connectors per transverse row

d_c = depth of concrete slab

d_p = depth of compressive stress block at M_p

d_s = depth of steel section

e = distance between resultant compression and tension forces at M_p

f_c = concrete stress

f'_c = cylinder strength of concrete at 28 days

f_s = steel stress

f_y = yield stress of steel beam

I = moment of inertia of composite section, concrete transformed to equivalent steel area

I_s = moment of inertia of steel section

L_s = shear span = distance between sections at which plastic moment and zero moment occur

m = statical moment of transformed compressive concrete area about the neutral axis of the composite section

M_p = theoretical plastic moment of composite section

M_u = experimentally observed ultimate moment

M_y = theoretical yield moment

n = $\dfrac{E_{steel}}{E_{concrete}}$

P = externally applied load

P_p = externally applied load at M_p

P_u = externally applied load at M_u

P_y = externally applied load at M_y

Q = connector force

s = connector spacing along longitudinal axis of beam

S = shear flow per unit length at interface of slab and steel beam

S_p = shear flow at M_p

T = total tensile force = $f_y \cdot A_s$

V = shear force

δ = deflection of beam in inches

δ_r = residual deflection of beam in inches

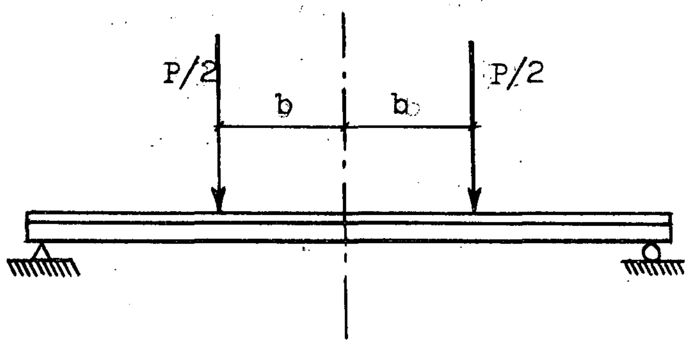


TABLE 1

Designation of Specimens

Specimen	Stud spacing c (in.)	Test No.	Load spacing 2b (in.)	Loading	Test Designation
B1	3 at 5.5"	1	24	Static	B1-T1
B2	2 at 5.5"	1 2	24 36	Static	B2-T1 B2-T2
B3	2 at 7.0"	1 2 3	24 36 46	Static	B3-T1 B3-T2 B3-T3
B4	3 at 5.5"	1	36	Fatigue	B4-T2

TABLE 2

SUMMARY OF STATIC TEST RESULTS

Specimen	Test	Load Spacing 2b (in)	Failure Type	Load P (kips) P_p	P_u	C_L Moment M (k-in) M_p	M_u	Connector Force Q (kips)	Maximum End Slip at P_u (inches)	Residual End Slip (inches)
B1	B1-T1		(A)		48.5		1164	7.0	0.0044	0.0028
B2	B2-T1	24	(B)	48.5	48.0		1150	10.6	.0089	.0060
B3	B3-T1		(B)		47.5		1140	13.4	.0218	.0165
						1160				
B2	B2-T2	36	(A)	55.5	55.0		1155	12.1	.0446*	.0453
B3	B3-T2		(B)		54.0		1132	15.4	.0712*	.0639
B3	B3-T3	46	(C)	63.0	58.0		1071	16.1	.0925*	--

Failure Type:

(A) Bending failure by crushing of slab

(B) Test stopped short of crushing of slab

(C) Shearing of studs

*Residual end slip from previous test included

TABLE 3

FATIGUE TEST RESULTS

Load Range P_{min} (kips)	Load Range P_{max} (kips)	No. of Cycles	Total Cycles	Deflection: Maximum During Cyclic Loading (inches)	Deflection: At P_{max} Applied Statically (inches)	Deflection: Theoretical (inches)	Maximum Shear Stress in Stud* (ksi)	End Slip at P_{max} Applied Statically (in.x10^{-4})
3	30	249 800	249 800	-	0.219	0.237	15.0	11
3	30	253 000	502 800	0.262	.218	.237	15.0	13
3	30	520 100	1 022 900	.272	.223	.237	15.0	17
3	36	250 900	1 273 800	.309	.267	.284	18.1	22
3	36	254 500	1 528 300	.311	.266	.284	18.1	22
3	42	619 900	2 148 200	.388	.328	.332	21.2	33
3	48	122 400	2 270 600	-	-	-	24.1	37

*Computed on the basis of a uniform distribution of shear stress on the cross section of the stud

TABLE 4

Static Yield Strength of Material in 8WF17

Coupon No.	Material	Location of Coupon	Static Yield Stress (Ksi)
1	ASTM		36.0
2	A-7	Flange	38.1
3	Structural		36.8
4			36.7
		Average	36.9

TABLE 5

Cylinder Strength of Concrete in Slab

Cylinder No.	Age at Test (days)		Strength (psi)
B-1	28		5800
B-2-A	28		5480
B-3-A	28		5390
		Average	5556
B-2-B	35		5670
B-3-B	35		5540
		Average	5605
B-3-C	42		5720
B-4-A	42		5390
B-4-B	42		5480
		Average	5530
		Cumulative Average	5563

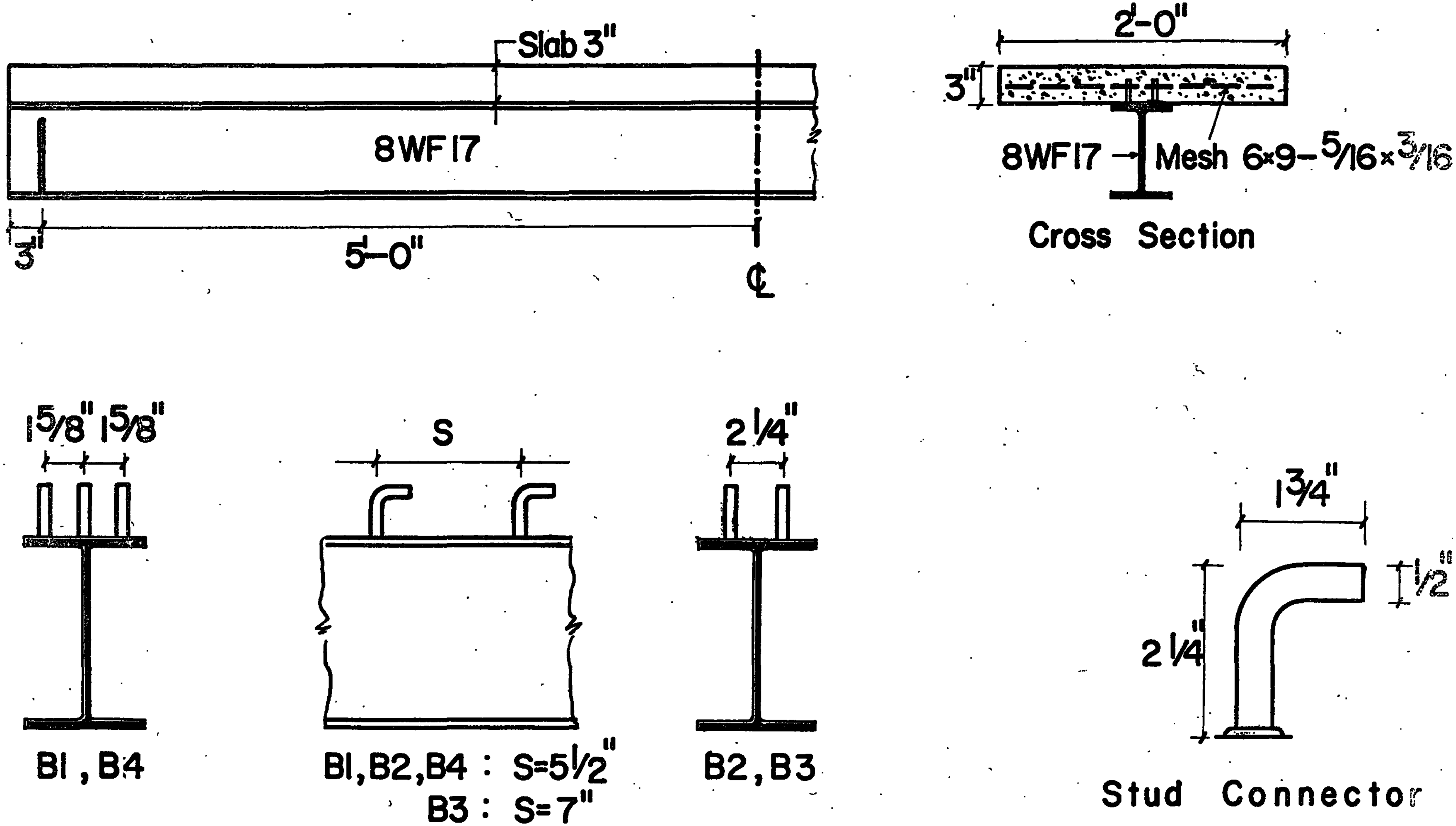


Fig. 1 - Dimensions of Test Specimens

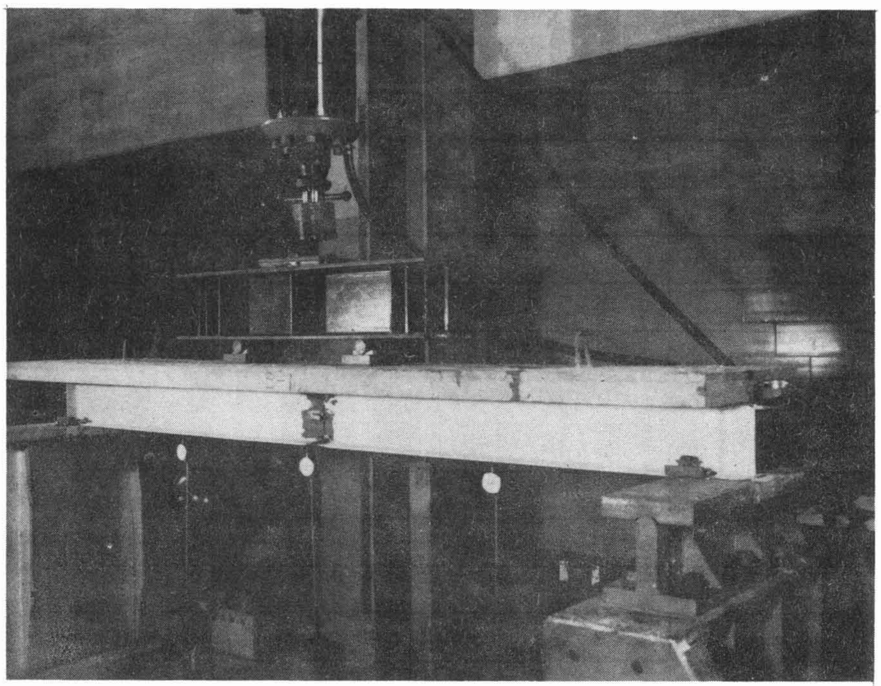


Fig. 2 - Test Setup

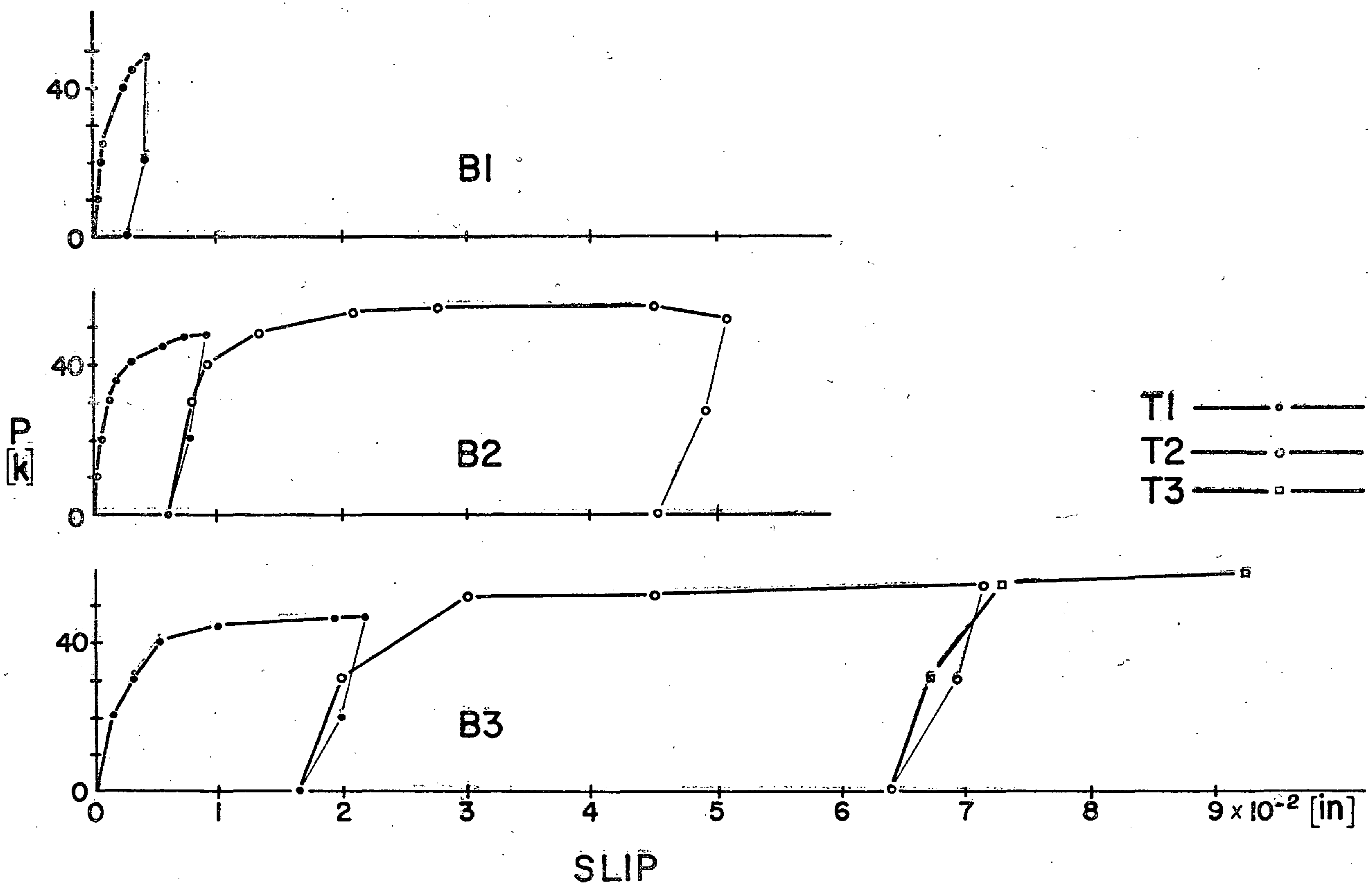


Fig. 3 - Load-Slip Curves for Static Tests

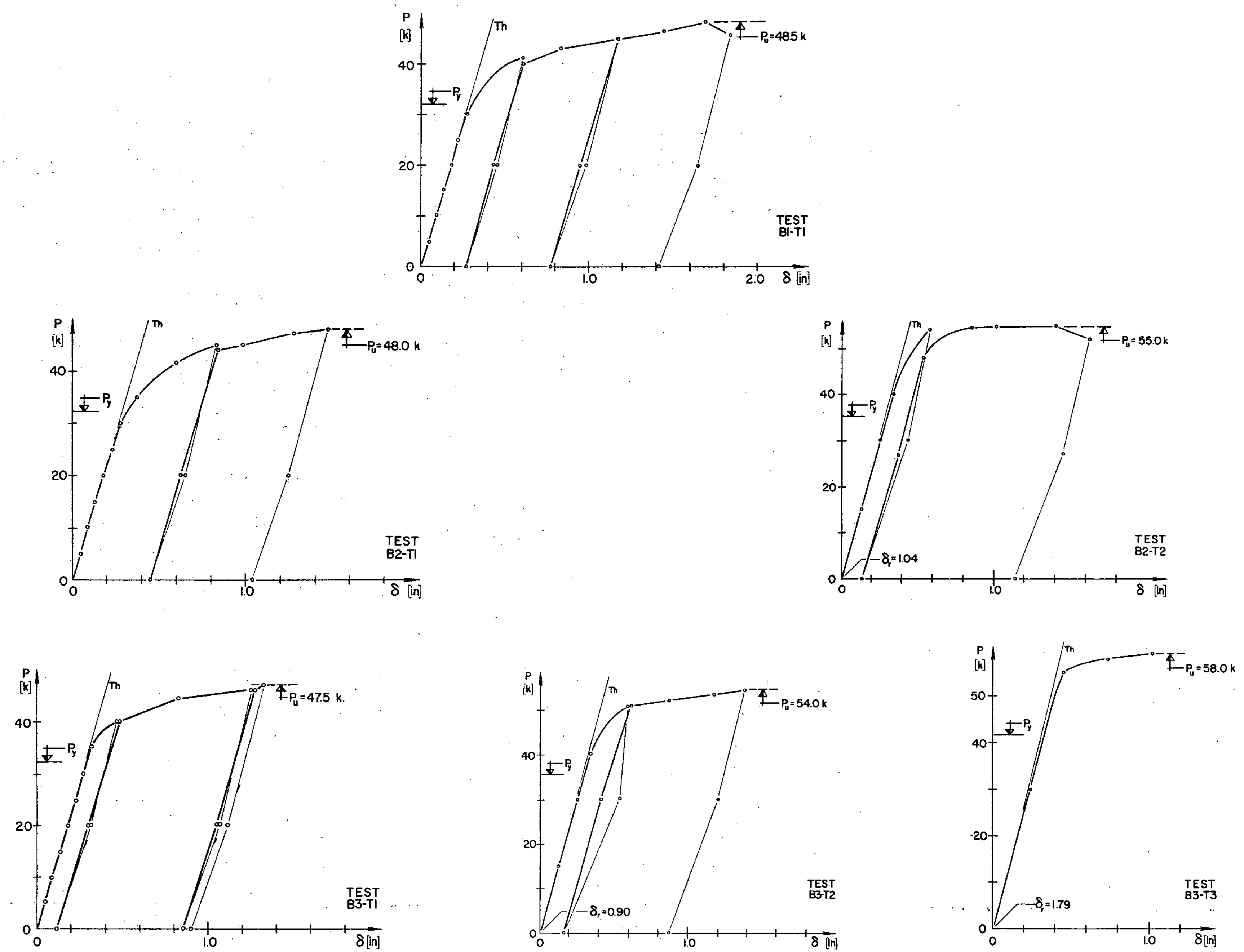


Fig. 4 - Load Deflection Curves for Static Tests

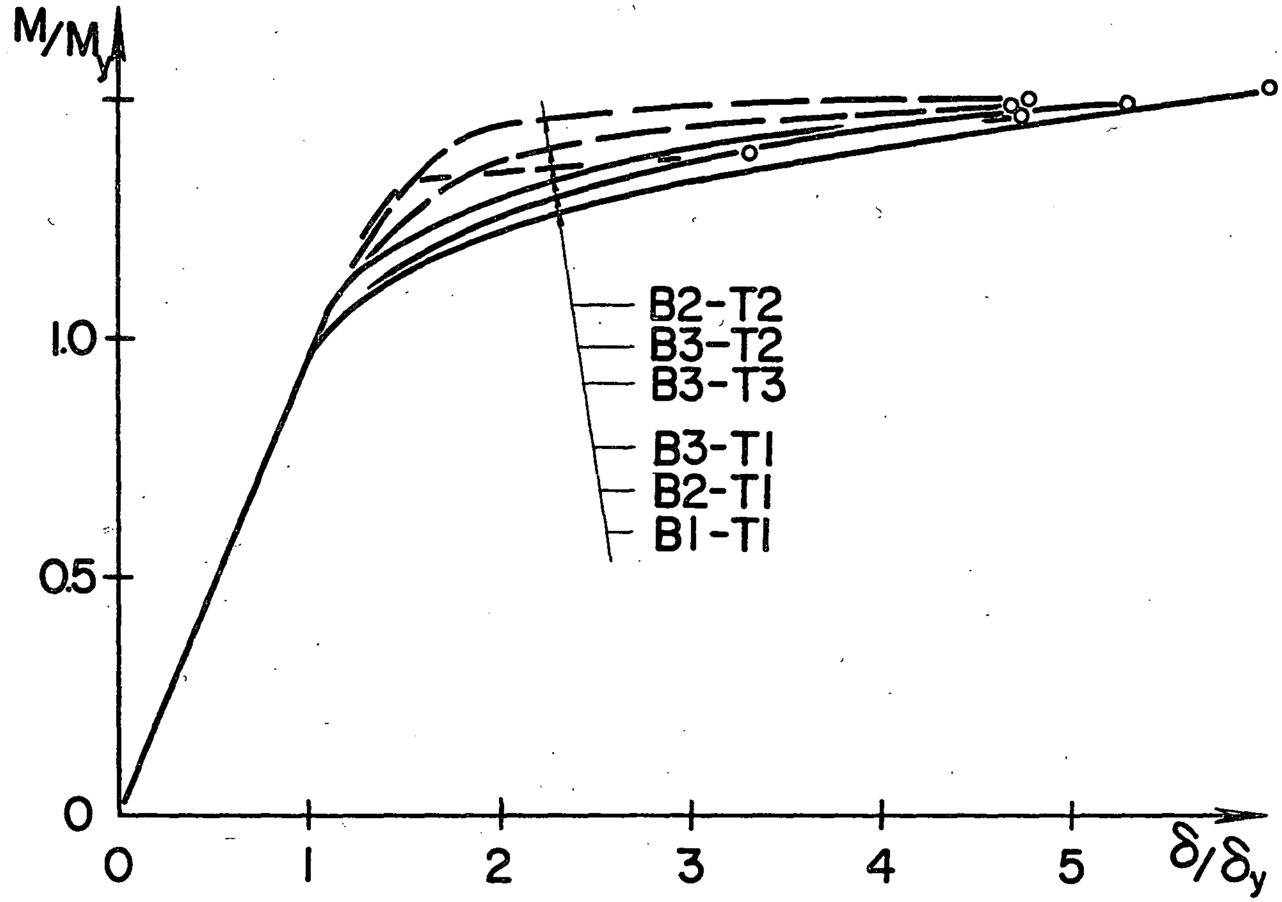


Fig. 5 - Comparison of Static Tests

APPENDIX

A. Section Properties

1. Concrete Slab

   $b_c = 24$ in.

   $d_c = 3$ in.

   $f'_c = 5500$ psi

2. Steel Beam (8WF17)

   $A_s = 5.00\ in^2$

   $d_s = 8.00$ in.

   $I_s = 56.0\ in^4$

   $f_y = 37.0$ ksi

3. Studs

   diameter = 1/2 in.

   height = 2.25 in.

   area = $0.196\ in^2$

4. Composite Section

   $a_{st} = 7.25$ in.

   $I = 151.3\ in^4$

   m (inner face of slab) = $16.2\ in^3$

Note:

In the design of the test specimens values for f'_c and f_y were assumed to be 3 ksi and 38 ksi respectively. The cylinder tests and coupon tests gave average values of f'_c = 5563 psi and f_y = 36.9 ksi. The design calcualtions were then revised using rounded off values of f'_c = 5500 psi and f_y = 37 ksi and only these revised calculations appear here.

B. AASHO Design *

1. Conventional design (allowable stress in bottom flange 18 ksi)

a. Studs

$H/d \geq 4.2$

$$Q_{uc} = 330\ d^2\sqrt{f'_c}$$

$$= 330\ (0.5)^2\sqrt{5500}$$

$$= 6110 \text{ lbs.}$$

b. Factor of Safety

$$F.S. = \frac{2.7\ (1 + C_{mc} + C_{mi}\ C_s) - (C_{mc} + C_{mi}) + C_v}{(1 + C_v)}$$

$$C_s = \frac{151.3/7.5}{56.4/4} = 1.48$$

$$C_v = \frac{0.46 \text{ k.}}{20 \text{ k.}} = 0.023 \cong 0$$

$$C_{mc} = \frac{24.8 \text{ kin}}{1080 \text{ kin}} = 0.023 \cong 0$$

$$C_{mi} = \frac{4.6}{1080 \text{ kin}} = 0.004 \cong 0$$

$F.S. = 2.7$

c. Q allowable

$$Q_{all} = \frac{Q_{uc}}{F.S.}$$

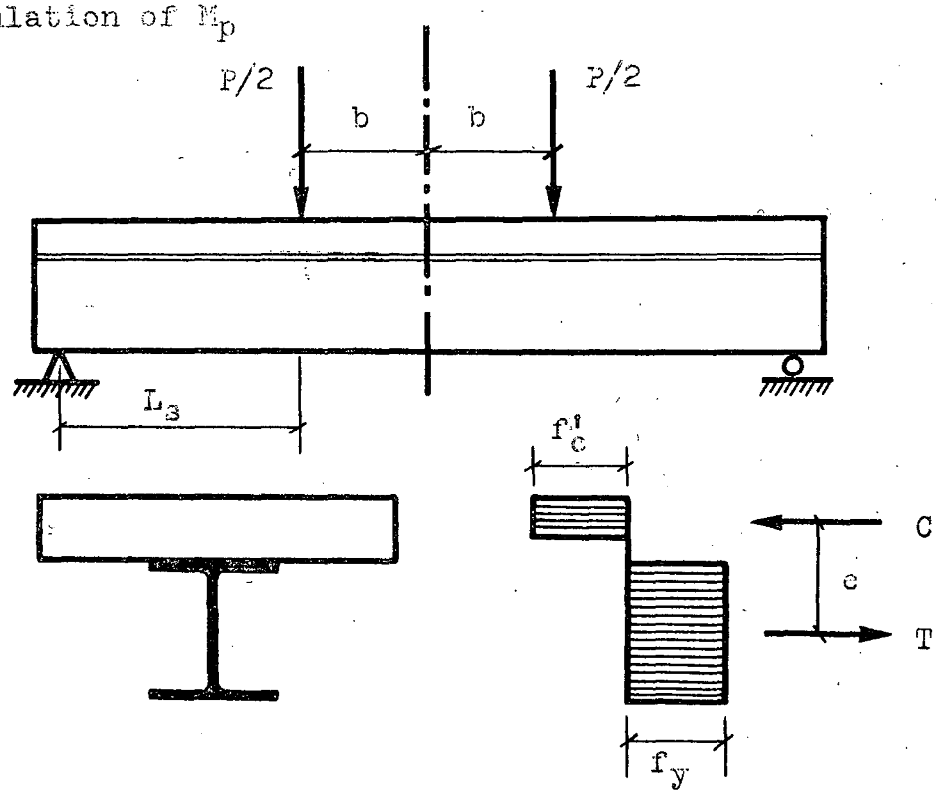
$$= \frac{6110}{2.7}$$

$$= 2260 \text{ lbs}$$

* reference 1

C. Specimen Design

1. Calculation of M_p



$$T = f_y \cdot A_s = 37.0 \cdot 5.00 = 185 \text{ k}$$

$$d_p = \frac{T}{f'_c b_c}$$

$$= \frac{185}{24.5500}$$

$$= 1.40 \text{ in.}$$

$$e = 4.0 + 3.0 - \frac{1.40}{2}$$

$$= 6.30 \text{ in.}$$

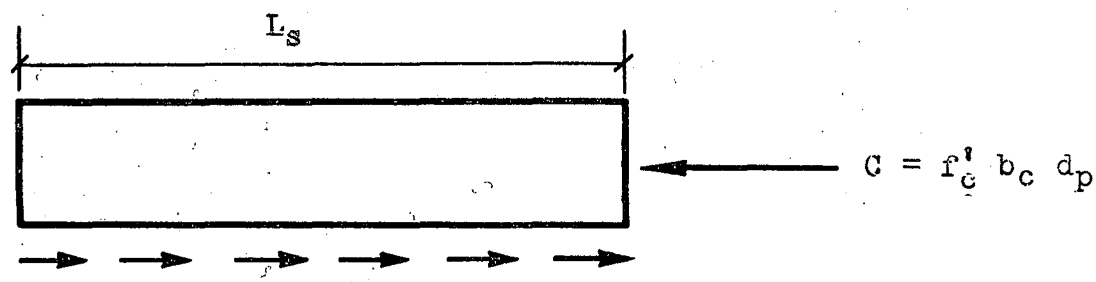
$$M_p = T \cdot e$$

$$= 185 \cdot 6.30$$

$$= 1165 \text{ k-in.}$$

2. Calculation of shear flow

Considering the length L_s as a free body and assuming uniform connector forces



$$S_p = \frac{C}{L_s}$$

Spacing 1 (Test 1) 2b = 24"

$$P_p = \frac{M_p}{24} = \frac{1165}{24} = 48.5\text{k} \qquad S_p = \frac{C}{L/2-12} = \frac{185}{60-12} = 3.85 \text{ k/in.}$$

Spacing	2b (inches)	P_p (kips)	S_p k/in.
1	24	48.5	3.85
2	36	55.5	4.40
3	46	63.0	5.00

3. Calculation of connector forces

$$Q = \frac{s \cdot S_p}{c} \quad \text{(Force per stud)}$$

B-1 (3 studs per row at 5.5 in.)

$$Q = \frac{5.5 \cdot 3.85}{3} = 7.05 \text{ k}$$

τ = 35.9 ksi (Average Shearing Stress in Stud)

	Test 1		Test 2		Test 3	
Beam	Force per stud (kips)	τ (ksi)	Force per stud (kips)	τ (ksi)	Force per stud (kips)	τ (ksi)
B-1	7.05	35.9	-	-	-	-
B-2	10.6	54.0	12.1	61.7	-	-
B-3	13.4	68.4	15.4	78.5	17.5	89.1

4. Fatigue Specimen

Max. fiber stress in WF section = 30 ksi

$$f_s = \frac{Ma_{st}}{I}$$

$$M = \frac{30.151.3}{7.25}$$

$$= 625 \text{ k-in.}$$

$$P = \frac{M}{21}$$

$$= \frac{625}{21}$$

$$= 29.8 \text{ k}$$

$$V = 15.0 \text{ k}$$

$$S = \frac{Vm}{I}$$

$$= \frac{15.0 \cdot 16.2}{151.3}$$

$$= 1.60 \text{ k/in}$$

$$Q = \frac{1.60 \cdot 5.5}{3}$$

$$= 2.94 \text{ k}$$

$$\tau = \frac{2.94}{0.196}$$

$$= 15 \text{ ksi}$$

D - Deflection Calculations

1. Static Deflections

a. Due to Bending

$$\delta_B = \frac{Pa}{24EI}(3L^2 - 4a^2)$$

where

L = 10' - 00"

E = 30×10^3 ksi

I = 151.3 in^4

$$a = \begin{cases} T1 - 48" \\ T2 - 42" \\ T3 - 37" \end{cases}$$

b. Due to Shear

$$\delta_S = \frac{\tau a}{G} = \frac{Pa}{2A_wG}$$

where

A_w = 1.84 in^2 (web area of steel beam)

G = 11.5×10^3 ksi

c. Total Static Deflection

$$\delta = \delta_B + \delta_S$$

		T1	T2	T3
Load (P)	(k)	30	30	40
Deflection dut to Bending δ_B	(in.)	0.224	0.208	0.256
Deflection dut to Shear δ_S	(in.)	0.034	0.030	0.035
Total Deflection $\delta_B + \delta_S$	(in.)	0.258	0.238	0.291