Oct 19th, 12:00 AM

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Recommended Citation

Klippstein, K. H., "Fatigue Behavior of Sheet-steel Fabrication Details" (1980). *International Specialty Conference on Cold-Formed Steel Structures*. 1.
https://scholarsmine.mst.edu/isccss/5iccfss/5iccfss-session11/1

Fatigue Behavior of Sheet-Steel Fabrication Details

by

K. H. Klippstein

Abstract

To assist the ground-transportation and agricultural-equipment industries in their weight-, cost-, and energy-saving efforts, and to facilitate the use of new high-strength sheet steels and fabrication techniques, U. S. Steel Research is studying the fatigue behavior of typical sheet-steel fabrication details. Beams with welded and other fabrication details, made from sheet steels, were fatigue-tested at constant stress ranges with a minimum stress slightly greater than zero. Fabrication details studied included slit and sheared edges, cold-formed corners, rolled sheet-steel surfaces, drilled holes with and without screws, welded details such as web-to-flange welds, and plate attachments with transverse and longitudinal fillet welds. Steels with 60- and 80-ksi yield strengths, including American Society for Testing and Materials (ASTM) A715 Grade 80, were used to fabricate the test beam specimens and details. The beams were approximately four inches deep, consisting of cold-formed back-to-back channels and welded I beams.

This paper presents the fatigue-test results for 24 beam specimens with several different fabrication details, which provided 63 test-data points. The results are compared with conservative fatigue-design curves developed in previous studies on similar details in welded beams fabricated from plate steels or in hot-rolled beams. On the basis of the results obtained so far, it appears that the conservative fatigue-design curves used for plate-steel fabrication details can also be used for the fatigue design of sheet-steel fabrication details. Additional tests—including other details, materials, and stress ratios typical for the ground-transportation and agricultural-equipment industries—are in progress.

Introduction

During recent years, the ground-transportation and agricultural-equipment industries (car, truck, trailer, and agricultural equipment manufacturers) have made intensive efforts to reduce weight, cost, and energy requirements. As part of these efforts, new high-strength sheet steels such as American Society for Testing and Materials (ASTM) A715 and dual phase steels, and new fabrication methods such as high-frequency, electric-resistance welding (ERW) are being used. Although these materials and fabrication techniques often offer substantial savings, they also can occasionally provide the potential for fatigue problems in some parts or fabricated details that were previously not fatigue critical.

The project described in the present paper was initiated to assist engineers in assessing potential fatigue problems and in designing against fatigue. The objectives were to (1) test a limited number of typical fabrication details made with new high-strength and typical low-strength sheet steels, and (2) compare the results with existing stress-life fatigue-design provisions on similar details fabricated from structural-steel plates. Because of the similarity in the local stress conditions (caused by geometry and residual stresses) between a small sheet-steel specimen and a similar but larger plate-steel specimen, it was expected that the fatigue lives for both would be about the same. If this held true, existing fatigue-design provisions for bridges1)* and buildings2) could also be applied to the fatigue design of sheet-steel fabrication details without extensive testing. Additonal efforts could then be concentrated on details used only by the ground-transportation and agricultural-equipment industries.

Current Fatigue-Design Provisions

Comprehensive fatigue-design provisions (specifications) for beams, parts, or fabrication details made from sheet steel are currently not available to engineers in the ground-transportation and agricultural-equipment industries. Therefore, these engineers use a variety of fatigue-design approaches (strain life, stress life, crack-initiaton life, crack-propagation life) based on in-house or industry-supplied fatigue data, or on research conducted at universities. Often the fatigue data are proprietary, especially when derived from so-called "bogey tests" of parts, assemblies, or full-scale vehicles. Despite remarkable efforts by the Society of Automotive Engineers (SAE), American Society for Testing and Materials (ASTM) and governmental agencies, no uniform fatigue-design provisions are foreseeable in the near future.

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* See References.

On the other hand, fatigue-design provisions (specifications) do exist for bridges[1] and buildings[2] with a variety of fabrication details, as shown in Figure 1. The specifications for redundant* bridges and buildings are essentially the same because they are based on the same research.[3,4] For a given category of fabrication details the allowable stress ranges related to a specific number of stress cycles are as shown in Table I.

The highest stress ranges are allowed for details in Category A, which includes base metal with rolled or cleaned surfaces such as rolled plates with flame-cut edges and rolled sections (Examples 1 and 2, Figure 1a). Lower stress ranges are specified for details of increasing notch severity, such as Category B, consisting of built-up members with continuous longitudinal welds (Examples 3, 4, and 6, Figure 1a); Category C with welded transverse stiffeners or attachments less than 2 inches long (Examples 7 and 25, Figures 1a and 1b, respectively); Category D for welded attachments longer than 2 inches but equal to or less than 4 inches or 12 times the width or thickness of the attachment (Examples 15, 23 to 26, Figure 1b);and Category E, consisting of welded partial-length cover plates or attachments longer than 4 inches or 12 times the width or thickness (Examples 5 and 26, Figures 1a and 1b, respectively). Category F is for shear stresses on plug or slot welds (Example 27, Figure 1b).

The fatigue-design curves for Categories A through F of the current bridge and building specifications[1,2] are shown in Figure 2. The design concept is relatively simple because the number of stress cycles, N, depends only on the nominal stress range (stress-life approach); other variables such as minimum stress, mean stress, and maximum stress have been shown not to be significant for fatigue design of details discussed in this paper. Furthermore, the allowable stress ranges are not affected by the tensile strength of the material used. Calculation of stress-concentration factors for the various fabrication details is not required because their effects are considered during the categorization process. Finally, this fatigue-design approach is applicable to small and large steel components and fabrication details, and a complex analysis of the number of cycles required to initiate a crack or to propagate a crack until total breakage occurs is not required.

One of the reasons for this simplification is the presence of minute discontinuities existing in all welded details fabricated from any low-strength or high-strength steel. Thus, the number of stress or load cycles required to initiate a crack (crack-initiation life) is small compared to those required to

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* Where failure of a single element would not cause collapse.

propagate the crack (crack-propragation life). Because the rate at which a crack grows when exposed to a cyclic stess range is essentially the same for all structural steels with yield points of 36 to 100 ksi (248 to 689 MPa), the number of stress cycles required to propagate a crack to a given size (crack-propagation life) is also the same. The design curves shown in Figure 2 represent the approximate lower 95-percent confidence limit for 95 percent survival of the tested details.

Even though the fatigue-design strength does not vary with tensile or yield strength, higher strength steels still provide advantages because the maximum allowable stress under "static" conditions (usually a specified fraction of the yield point) is higher. Such static conditions frequently govern the design, particularly when the type and location of details are judiciously selected. Furthermore, some researchers feel that the allowable fatigue-stress ranges in Categories A and (possibly) B are too conservative for some high-strength steels.

Once a fatigue crack is visible, the number of additional stress cycles needed to fail the entire member or connection is relatively small. Therefore the fatigue life is essentially unaffected by the size of a specimen. Consequently, one of the objectives of this study was to determine whether the fatigue-design provisions developed for the large details in bridges and buildings would also be applicable to small details fabricated from sheet steels, as used in the ground-transportation and agricultural-equipment industries.

Test Program

To provide a basis of comparison with previous fatigue studies on details made with structural-steel plates,[1,2,3,4] the program for sheet-steel applications had to include a spectrum of steel grades, a variety of typical fabrication details, and representative test conditions. The chosen parameters are summarized in Table II.

The steel grades tested were ASTM A715 Grade 80 steel (80-ksi yield strength), ASTM A607 Grade 60 (60-ksi yield strength), and the low-strength SAE 1008 hot-rolled drawing-quality (HRDQ) steel (30-ksi yield strength). These materials were used to fabricate test beams with U- and I-shaped cross sections. Other cross sections may be added for future tests. The test beams included details such as rolled surfaces, slit and sheared edges, cold-formed corners, open drilled holes, and welded details (including flange-to-web welds and plate attachments with transverse welds, and with short or long longitudinal welds). Other test parameters considered for future tests include holes with self-drilling screws, stress ranges up to 100 ksi, stress ratios (min. stress/max. stress) of -1, and constant-amplitude as well as limited variable-amplitude tests.

Test Setup and Procedure

Figure 3 shows the overall test setup used for the present study. Three beams in a set were tested simultaneously at approximately the same stress range for each beam. One 50-kip hydraulic jack was used to apply the required loads to the quarter points of each beam through the spreader beams and rods shown in the figure. Thus, a four-foot-long region about the center of each beam was exposed to a uniform moment (and nominal stress) during the test. The jack load was controlled by an MTS command module and a digital programmer. The cyclic stresses in the center region of each beam were continuously monitored through strain gages and a VISHAY 220 multipurpose data-logging system equipped with minimum/maximum peak detectors.

During each test the controls were adjusted as required to maintain the desired stress range. Jack-load and deflection limit switches were used to assure that the beams were not overloaded, and the tests were halted as soon as one of the beams in a set had a significant crack. Thus, each beam specimen was considered to have failed when a crack large enough to activate a limit switch had developed. Such cracks ranged from about 1/4 inch across the flange to cracks across the entire flange. Cracked or failed details were weld-repaired, and the test for the remaining details was continued. After the last detail in a beam failed, the beam was replaced by a dummy beam, and the test was continued until all test beams in the set failed.

The present test setup allows for unidirectional forces (acting upwards) resulting in stress ranges with a stress ratio greater than zero. For future fatigue tests with reversed loads or negative stress ratios, the test setup will be modified.

Results

The beam types and detail types for the current study are described in Table II. So far, eight sets or 24 beams have been tested (Set 1 failed during calibration); the results are summarized in Table III. This table indicates the beam-set number, beam type, detail type, stress levels, number of cycles to failure, and location of failure. The stresses are nominal stresses measured on the outer fiber of the tension flange away from regions influenced by stress concentrations. For details with holes, the nominal stresses monitored at locations away from the holes were converted to the nominal stresses based on the net section properties at holes.

A test was discontinued when a crack was observed or when the increased deflection of a beam with a cracked detail triggered a limit switch. The resulting cracks varied in length from cracks approximately 1/4-inch long to cracks extending over the width of the beam flange. The number of cycles required to propagate a visible crack (say 1/4 inch long) to a crack across the width of the flange is only an insignificant portion of the number of cycles recorded in Table III.

As seen from Table III, the minimum stresses applied were slightly greater than zero. These stresses were the lowest attainable without unloading or racking the specimens. Because none of the strain gages were rezeroed at any time after the test commenced, the minimum stress readings shown probably represent mainly changes in the residual stresses at the outer fiber of the test specimens. Residual stresses in beams are caused by rolling, forming, or welding. Slight amounts of strain-gage drifts were observed during the tests; however, this did not affect the cyclic strain or stress range of a test.

Discussion

To evaluate the performance of the tested sheet-steel specimens, results are compared with the fatigue-design curves for hot-rolled and welded-plate beams in bridges and buildings, shown in Figure 2. The design curve for Category A details (rolled beams and plates) is shown in Figure 4 as Curve A. Also shown are the results for sheet-steel beams consisting of I beams fabricated from back-to-back channels (set No. 5, beam type G with 80-ksi yield strength, see Tables II and III). As seen from the results shown in Figure 4, sheet-steel beams with sheared edges, typical rolled surfaces and cold-formed corners can be considered as Category A because their test lives exceed the lives represented by the design curve.

Welded plate-steel beams produced by the shielded-metal-arc or submerged-arc process fall under Category B, and have a lesser fatigue life for a given stress range than beams with Category A details. The design curves for both categories are shown in Figure 5, along with the results for the ERW detail, a 9/32-inch drilled hole, and slit edges using sheet steels. Only one test result (a 9/32-inch hole) is below the Category B design curve, and another test result exceeds the Category A design curve. Thus, it is concluded that the tested details represent Category B details.

The fatigue life of ERW beams fabricated from high-strength sheet steel is the same as that of previously investigated low- and high-strength welded plate-steel beams. Figure 5 also demonstrates that the fatigue life of an ERW beam, like that of any welded beam is less than that of a hot-rolled or cold-formed beam. However, in many applications, fabrication details (welded or mechanical attachments) will limit welded, hot-rolled and cold-rolled beams to the same fatigue life. For three beams tested at stress ranges near 60 ksi; the fatigue cracks initiated at the slit edges. On the basis of the number of cycles to failure, slit edges are represented by Category B. Because of the limited test data obtained so far, no explanation can be offered why slit edges are Category B, whereas sheared edges are Category A. Caution is also suggested regarding the information presented on holes because the roughness of a hole may vary considerable and reduce the fatigue life accordingly.

Category C includes "short" attachments with welds transverse to the direction of stress. An 0.1-inch-thick plate welded to the tension flange of an ERW beam was chosen to represent this category for sheet-steel beams; however, the tests had to be discontinued because additional, but more severe, details (Categories D and E, discussed below) were also attached to the same specimens and repeatedly failed. As seen from Figure 6, the detail would probably have behaved as Category C if the test could have been continued.

A three-inch-long attachment welded to three sets of beams (a total of nine beams) was chosen to represent Category D in the present study. The welds for the attachments were parallel to the direction of stress, along the edges of the beams. Three beams were gas-metal-arc welded (only on one side of the web) by using steel with 60-ksi yield strength, and six beams were fabricated by the ERW process by using steel with 80-ksi yield strength. Because each welded attachment can fail at either end in a constant-moment region, 18 test points were obtained. Each failed end was weld-repaired, and the fatigue test was continued until all ends had failed. As seen from the results shown in Figure 7, the sheet-steel details performed as expected. Nearly all test lives fall within the region defined as Category D, and no significant differences in the fatigue lives could be found for the different welding processes or the different steel grades.

An attachment with welds exceeding four inches in a direction parallel to the applied stresses is Category E. Such attachments were placed on the same beams described above, with Category D details. The two details were located aproximately 12 inches apart. The fatigue results for the six-inch-long weldments (9 beams, 18 test points) are shown in Figure 8. The test points fall into the Category E region, without significant differences for steel grades or welding processes.

Conclusions

The initial fatigue tests conducted on 24 beam specimens fabricated from sheet steel with several different fatigue details provided 63 data points. This study included steels with different yield strengths and different welding processes. The data for sheet-steel details indicate that conservative design curves previously developed by others for similar plate-steel details are suitable for sheet-steel details. Further tests of different typical details, steels, stress ranges, and stress ratios are planned.

Future Work

For the supplemental tests related to the various fatigue categories described above, other stress ratios (R = -1), additional steels (dual-phase steels), and possibly variable-amplitude stresses will be considered.

Acknowledgement

Many of the tested beams were produced and donated by Fruehauf, Great Dane, and the Welded Beam Corporation. The cooperation and generosity of these companies are greatfully acknowlledged. R. E. Leffler designed the fixtures used in the test program.

References

1. American Association of State Highway and Transportation Officials, Standard Specifications for Highway Bridges, Twelfth Edition, 1977.

2. American Institute of Steel Construction, Specification for the Design, Fabrication, and Erection of Structural Steel for Buildings, November 1, 1978.

3. Fisher, J. W., Frank, K. H., Hirt, M. A., and McNamee, B.M., "Effect of Weldments on the Fatigue Strength of Steel Beams," National Cooperative Highway Research Report 102, 1970.

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Table I

Allowable Range of Stress* (F_{sr}), ksi

Category	20,000 to 100,000 Cycles	500,000 Cycles	2,000,000 Cycles	More than 2,000,000 Cycles
A	60	36	24	24
B	45	27.5	18	16
C	32	19	13	10[a]
D	27	16	10	7
E	21	12.5	8	5
F	15	12	9	8

[a] Flexural stress range of 12 ksi permitted at toe of stiffener welds on webs or flanges.

* According to References 1 and 2.

Table II

Sheet-Steel Test Program

Beam Types

A - I-beams, gas-metal-arc welded on one side, FY = 60 ksi.
B - I-beams, electric-resistance welded, FY = 80 ksi.
production butt-welded splice in flange.
C - Same as Type B without splice.
D - I-beams, hot-rolled, symmetric, FY = 60 ksi.
E - I-beams, hot-rolled, unsymmetric, FY = 80 ksi.
F - Cold-formed channels, back to back, FY = 30 ksi.
G - Cold-formed channels, back to back, FY = 80 ksi.

Detail Types

A1 - Sheared edge.
A2 - Cold-formed corners.
B1 - High-frequency resistance weld.
B2 - Gas-metal-arc weld.
B3 - Slit edge.
B4 - 9/32-in.-diameter drilled hole.
B5 - 9/32-in.-diameter drilled hole with self-tapping screw at flange quarterpoint.
C1 - Transverse-welded, short (3-in.-long) flange attachment.
C2 - Spot weld.
D1 - 3-in.-long longitudinally welded flange attachment.
D2 - Partial 9/32-in.-diameter hole at edge of flange.
E1 - 6-in.-long longitudinally welded flange attachment.
F1 - Production butt weld.

Test Parameters

Stress ranges - 15 through 60 ksi, nominal
Stress ratios - 0, -1
Amplitudes - Constant and variable.

Table III

Fatigue Results for 4-Inch-Deep Beams

Set No.	Beam No.	Beam Type*	Detail Type*	Stress, ksi Min.	Stress, ksi Max.	Stress, ksi Range	Cycles	Failure Location/Initiation
2	2	C	D1	1.0	21.9	20.9	249,475	South End of Plate/Weld Toe
2	2	C	D1	1.0	21.9	20.9	293,650	North End of Plate/Weld Toe
2	1	C	D1	1.9	23.7	21.8	341,540	North End of Plate/Weld Toe
2	1	C	D1	1.9	23.7	21.8	386,690	South End of Plate/Weld Toe
2	3	C	D1	0.7	21.1	20.4	394,480	North End of Plate/Weld Toe
2	3	C	D1	0.7	21.1	20.4	545,915	South End of Plate/Weld Toe
3	1	B	D1	6.6	48.0	41.4	24,520	North End of Plate/Weld Toe
3	3	B	D1	9.5	49.6	40.6	28,185	North End of Plate/Weld Toe
3	3	B	D1	9.5	49.6	40.6	28,185	South End of Plate/Weld Toe
3	2	B	D1	14.8	55.1	40.3	33,545	South End of Plate/Weld Toe
3	1	B	D1	6.6	48.0	41.4	33,990	South End of Plate/Weld Toe
3	2	B	D1	14.8	55.1	40.3	42,515	North End of Plate/Weld Toe
4	3	A	D1	11.3	52.5	41.2	31,535	North End of Plate/Weld Toe
4	3	A	D1	11.3	52.5	41.2	31,535	South End of Plate/Weld Toe
4	2	A	D1	11.1	51.8	40.7	34,495	North End of Plate/Weld Toe
4	2	A	D1	11.1	51.8	40.7	34,495	South End of Plate/Weld Toe
4	1	A	D1	12.4	54.1	41.7	39,120	North End of Plate/Weld Toe
4	1	A	D1	12.4	54.1	41.7	39,120	South End of Plate/Weld Toe
2	2	C	E1	1.0	21.9	20.9	150,300	North End of Plate/Weld Toe
2	2	C	E1	1.0	21.9	20.9	166,115	South End of Plate/Weld Toe
2	3	C	E1	0.7	21.1	20.4	167,250	South End of Plate/Weld Toe
2	1	C	E1	1.9	23.7	21.8	183,900	North End of Plate/Weld Toe
2	1	C	E1	1.9	23.7	21.8	219,105	South End of Plate/Weld Toe
2	3	C	E1	0.7	21.1	20.4	244,940	North End of Plate/Weld Toe
3	3	B	E1	9.5	49.6	40.6	13,800	South End of Plate/Weld Toe
3	2	B	E1	14.8	55.1	40.3	24,970	South End of Plate/Weld Toe
3	1	B	E1	6.6	48.0	41.4	28,185	North End of Plate/Weld Toe
3	3	B	E1	9.5	49.6	40.6	32,450	North End of Plate/Weld Toe
3	2	B	E1	14.8	55.1	40.3	33,545	North End of Plate/Weld Toe
3	1	B	E1	6.6	48.0	41.4	36,860	South End of Plate/Weld Toe
4	2	A	E1	11.1	51.8	40.7	18,810	North End of Plate/Weld Toe
4	1	A	E1	12.4	54.1	41.7	21,370	North End of Plate/Weld Toe
4	1	A	E1	12.4	54.1	41.7	21,370	South End of Plate/Weld Toe
4	2	A	E1	11.1	51.8	40.7	23,255	South End of Plate/Weld Toe
4	3	A	E1	11.3	52.5	41.2	23,255	North End of Plate/Weld Toe
4	3	A	E1	11.3	52.5	41.2	23,255	South End of Plate/Weld Toe
5	1E	G	A1	5.2	46.5	41.3	483,855	Near North Load Point
5	1W	G	A1	5.2	46.5	41.3	523,435	Near South Load Point
5	3E	G	A1	8.5	46.2	37.7	760,225	Near South Load Point
5	2E	G	A1	10.1	51.0	40.9	760,225	Near Midlength, Surface Scar
5	3W	G	A1	8.5	48.7	40.2	891,140	Near North Load Point
5	2W	G	A1	8.5	48.7	40.2	891,140	DISCONTINUED
2	1	C	B1	1.9	23.7	21.8	2,010,120	DISCONTINUED
2	2	C	B1	1.0	21.9	20.9	2,010,120	DISCONTINUED
2	3	C	B1	0.7	21.1	20.4	2,010,120	DISCONTINUED
9	1	C	B1	2.0	17.1	15.1	3,121,250	DISCONTINUED
9	2	C	B1	3.3	18.4	15.1	3,121,250	DISCONTINUED
9	3	C	B1	1.9	17.0	15.1	3,121,250	DISCONTINUED
7	1	C	B1	13.8	43.8	30.0	484,705	Near North Load, Weld
7	2	C	B1	12.3	43.0	30.7	707,000	Near North Load, Weld
7	3	C	B1	15.5	46.2	30.7	655,415	Near South Load, Weld

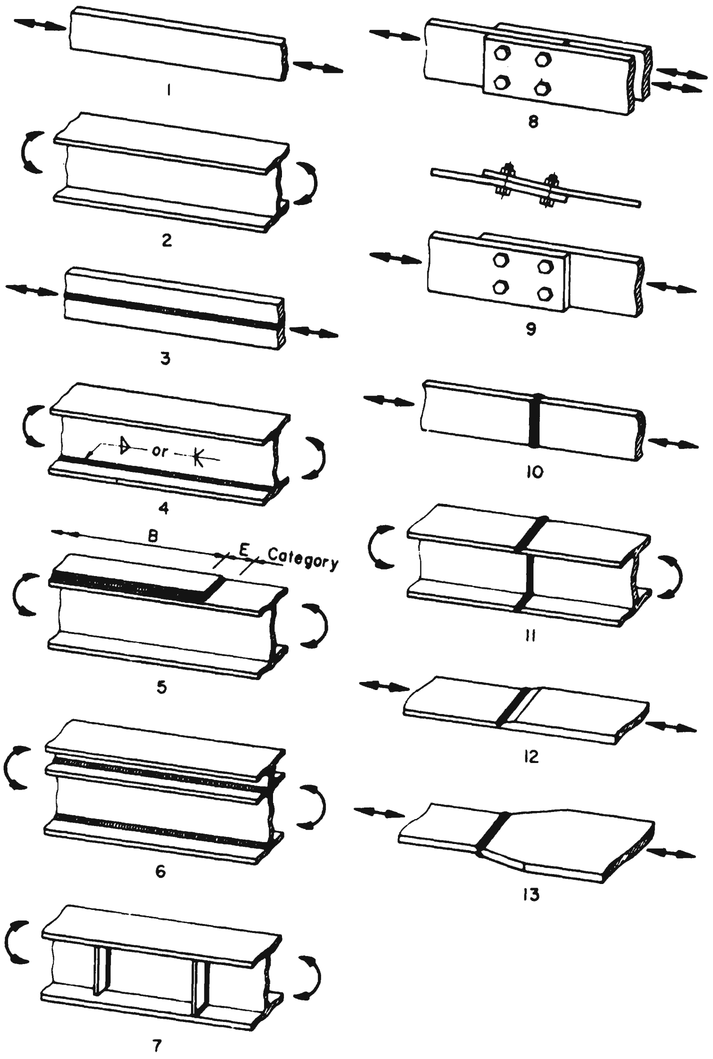
(Continued)

Table III (Continued)

Fatigue Results for 4-Inch-Deep Beams (Continued)

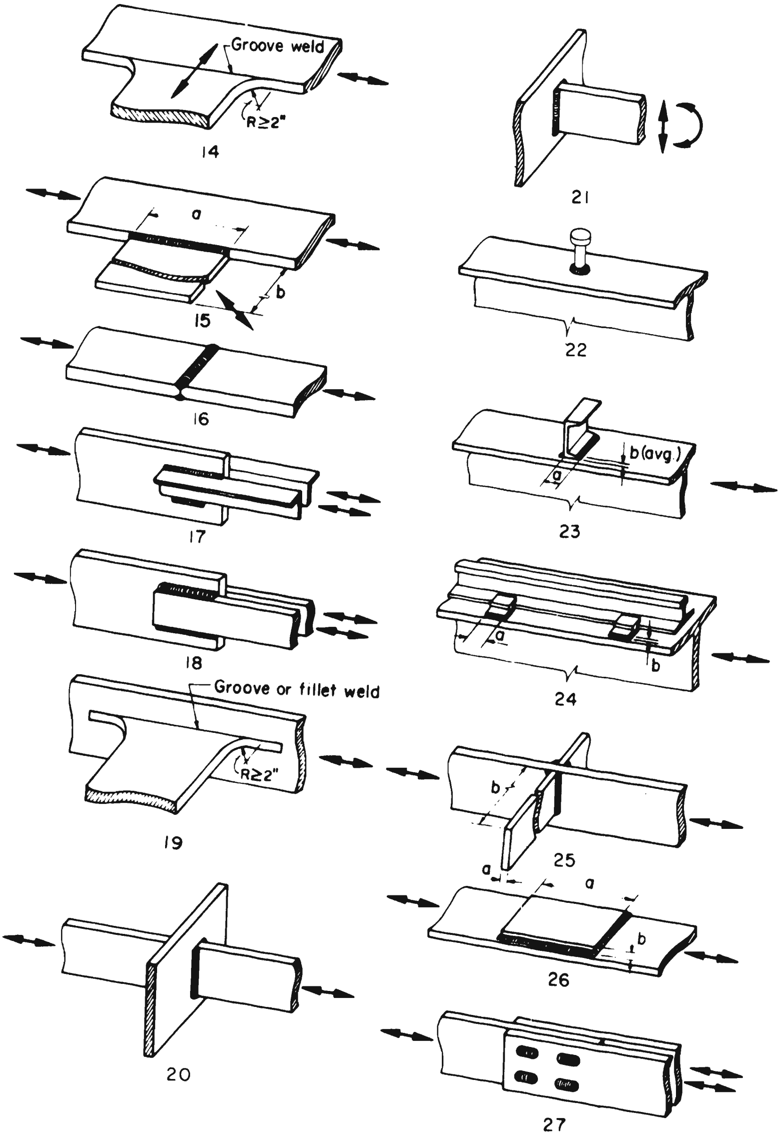
Set No.	Beam No.	Beam Type*	Detail Type*	Stress, ksi Min.	Stress, ksi Max.	Stress, ksi Range	Cycles	Failure Location/Initiation
8	1	C	B1	5.6	50.8	45.2	290,600	Near North Load Point, Weld
8	2	C	B1	4.7	50.2	45.5	270,055	11-In. North From Center, We
8	3	C	B1	4.9	50.1	45.2	268,910	Near South Load Point, Weld
6	1	C	B3	17.7	75.1	57.4	72,810	Near South Load Point, Edge
6	3	C	B3	20.4	78.1	57.7	74,525	At North Load Point, Edge
6	2	C	B3	19.2	77.0	57.8	101,335	Near South Load Point, Edge
2	1	C	B4	2.1	26.1	24.0	731,425	Through/At Hole
2	3	C	B4	0.8	23.2	22.4	1,626,415	Through/At Hole
2	2	C	B4	1.1	24.1	23.0	2,010,120	DISCONTINUED
3	1	B	C1	6.6	48.0	41.4	44,000	DISCONTINUED
3	2	B	C1	14.8	55.1	40.3	44,000	DISCONTINUED
3	3	B	C1	9.5	49.6	40.6	44,000	DISCONTINUED

*Defined in Table II.



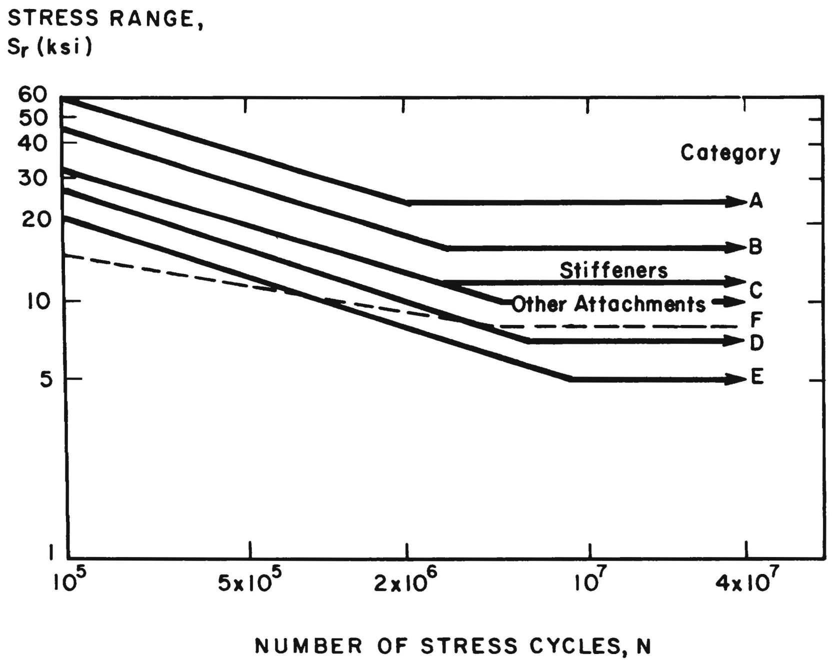
ILLUSTRATIVE EXAMPLES

FIGURE 1a



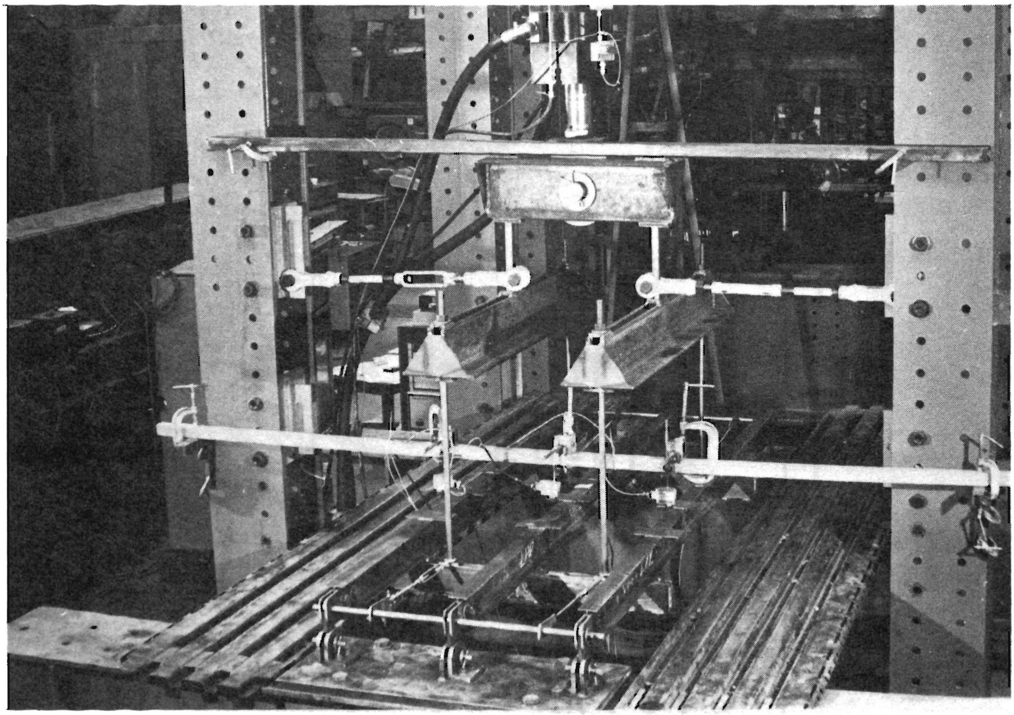
ILLUSTRATIVE EXAMPLES (CONTINUED)

FIGURE Ib

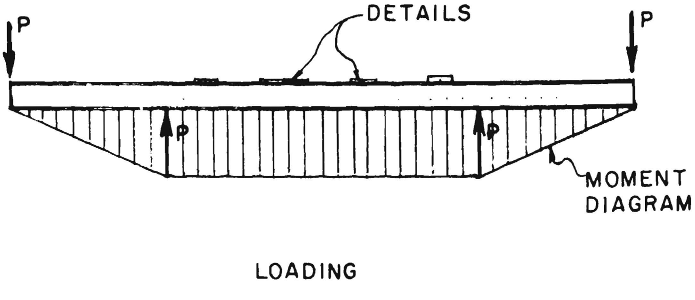


S_r-N FATIGUE-DESIGN CURVES FOR BRIDGES AND BUILDINGS

FIGURE 2



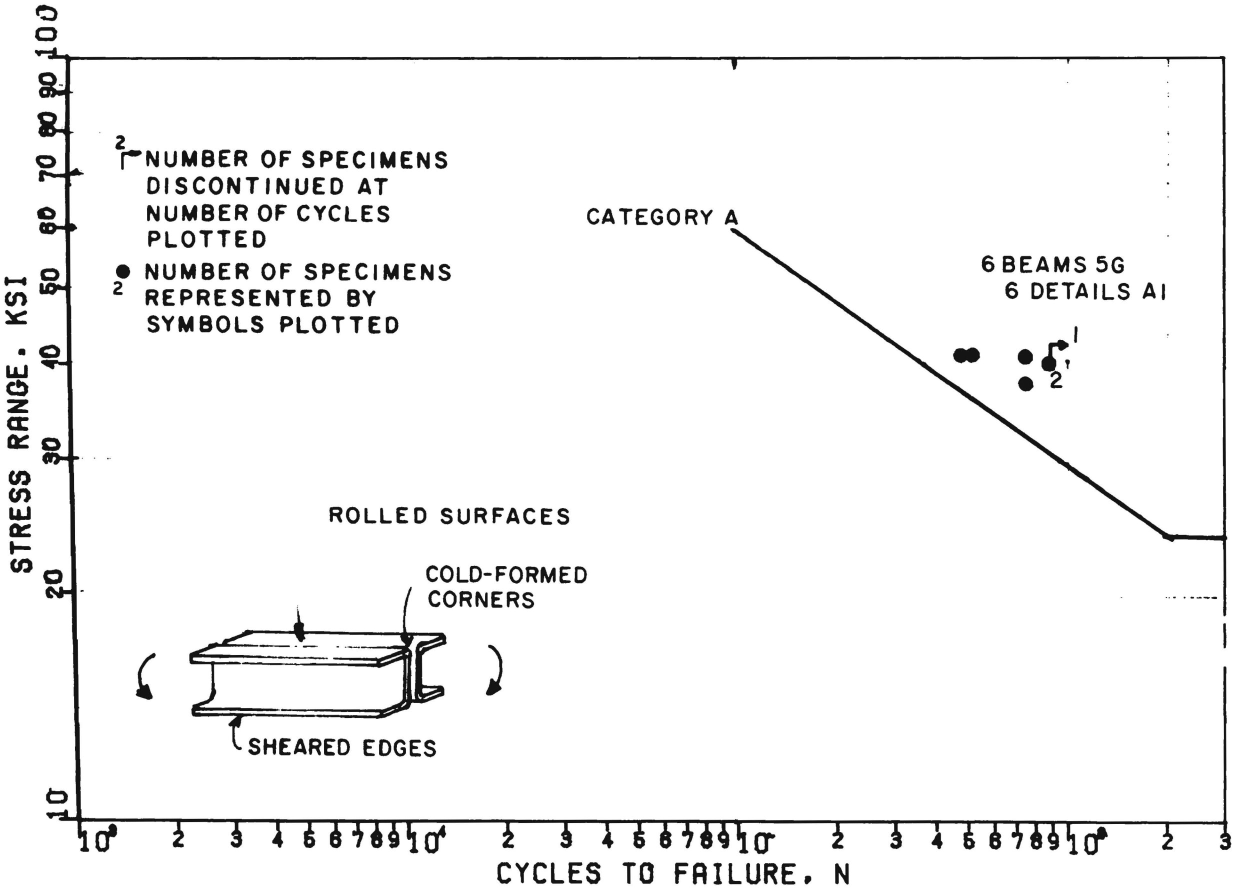
OVERALL VIEW



LOADING

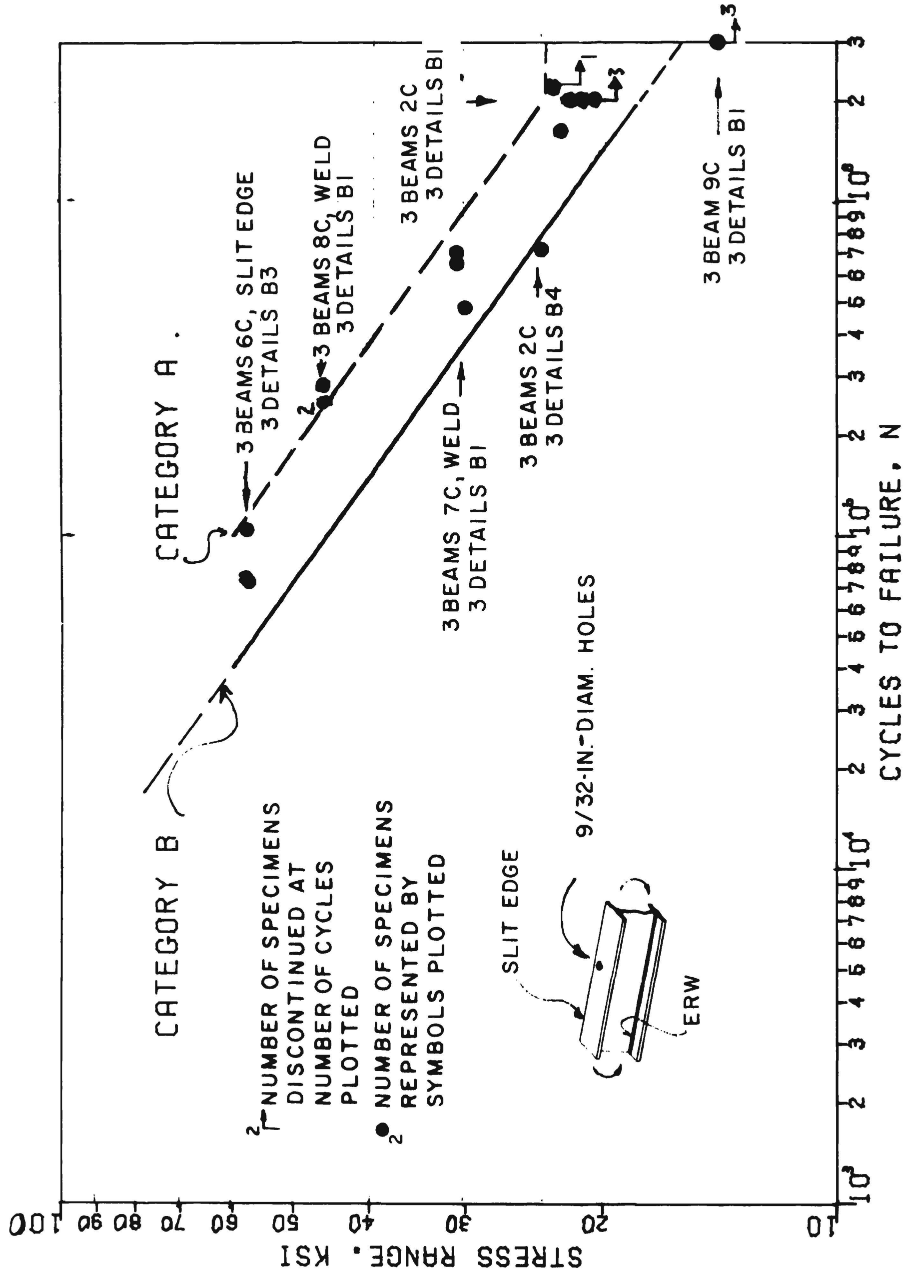
TEST SETUP

Figure 3



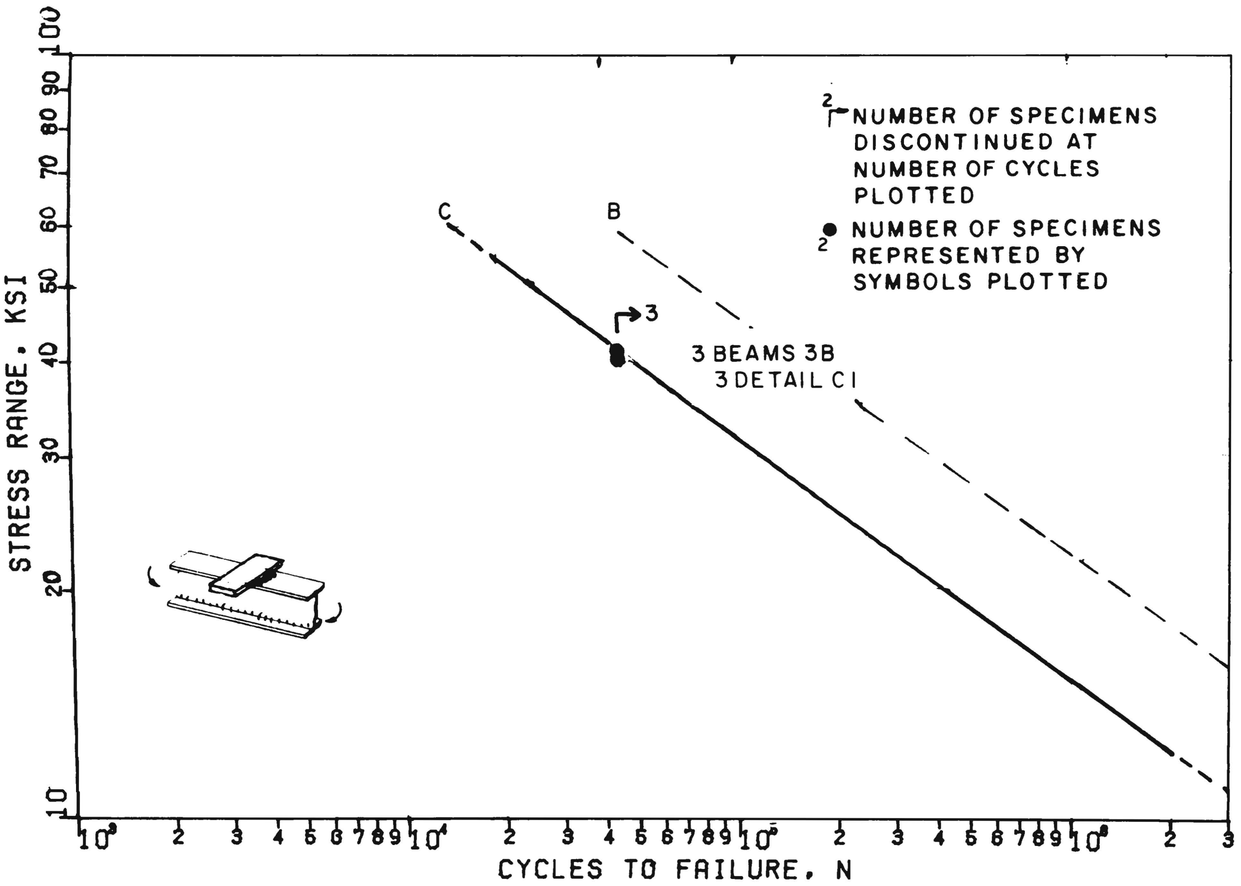
FATIGUE TESTS ON 4-INCH-DEEP BEAMS
(CATEGORY A)

FIGURE 4



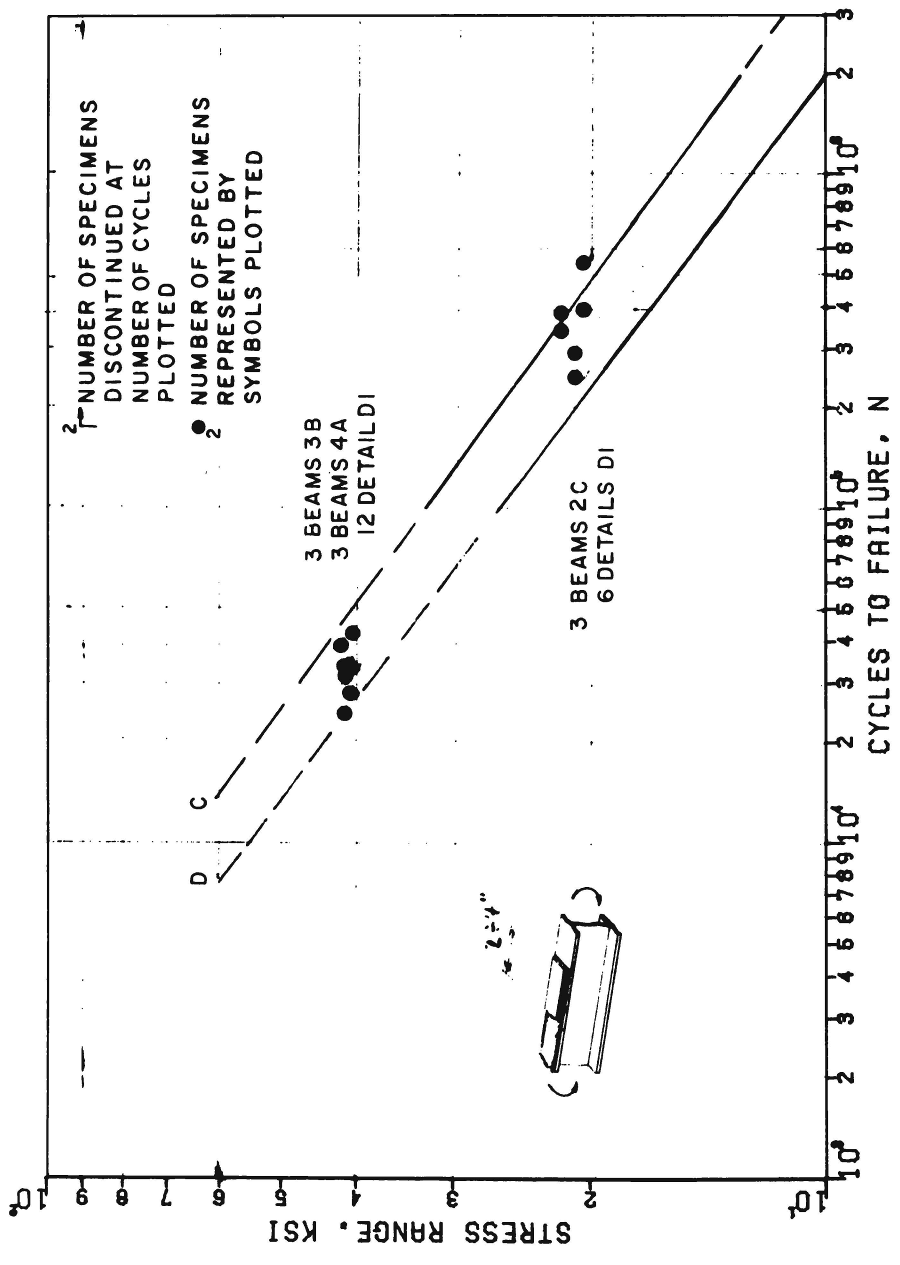
FATIGUE TESTS ON 4-INCH-DEEP BEAMS (CATEGORY B)

FIGURE 5



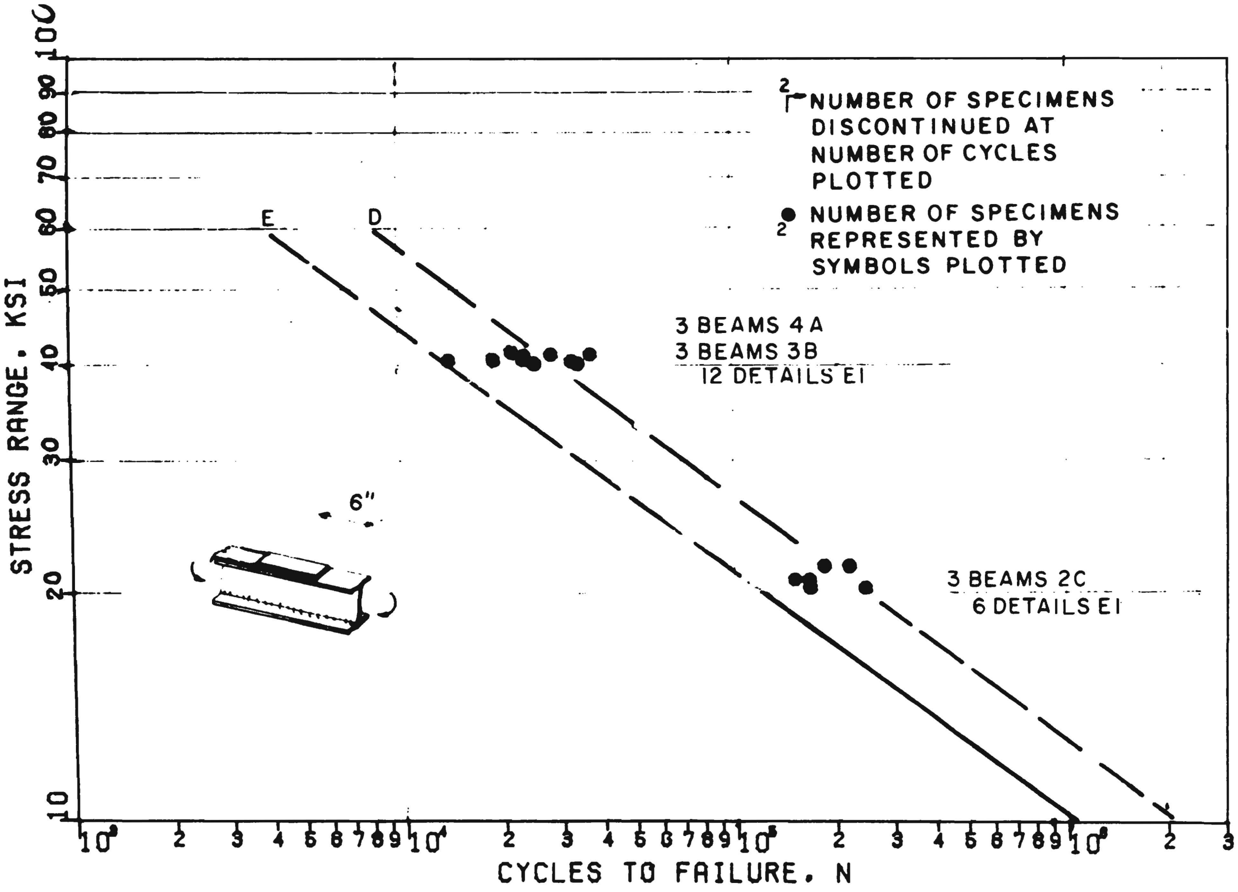
FATIGUE TESTS ON 4-INCH-DEEP BEAMS
(CATEGORY C)

FIGURE 6



FATIGUE TESTS ON 4-INCH-DEEP BEAMS
(CATEGORY D)

FIGURE 7



FATIGUE TESTS ON 4-INCH-DEEP BEAMS
(CATEGORY E)

FIGURE 8