In-Plane Fatigue Strength of Plates with Laminar Discontinuities

R. L. BROCKENBROUGH AND D. E. OWENS

ALTHOUGH LAMINAR discontinuities in steel are of concern primarily in applications where through-thickness tension loads are applied to the plate (or shape), information was desired on the effects of repeated loadings on plates loaded parallel with the discontinuity. An example of such an application would be the flange of a girder (or rolled beam) of a bridge, which has a subsurface discontinuity that extends across part of the flange width and runs parallel to the flange surface for some length before terminating in sound material or in a welded flange splice. It was questioned whether the end of the discontinuity would propagate under repeated loadings.

Consequently, a series of fatigue tests were conducted on strap-type specimens with and without a midplane discontinuity. Two types of specimens, both with as-received mill surfaces, were tested: (1) an unwelded specimen and (2) a specimen with a transverse groove-welded joint. Specimens of both types, both with and without laminar discontinuities, were tested. All specimens were machined from the web of a rejected ASTM A572 Grade 50 steel beam.

This paper presents the results of the fatigue tests.* The work is part of Project 164, sponsored by the American Iron and Steel Institute through the Engineering Subcommittee of the Committee of Structural Steel and Steel Plate Producers.

MATERIALS AND EXPERIMENTAL WORK

Material—The fatigue specimens were fabricated from a 40-ft (12.2 m) length of a W36×150 beam that had a discontinuity at the midthickness of the ⅝-in.-thick (16 mm) web. This rejected beam had been produced for application on an order for ASTM A572 Grade 50 steel. Data on the tensile properties and chemical composition of the steel are given in Table 1.

As subsequently discussed, a laminar discontinuity extended over one-third of the web depth for the full length of the beam furnished. Figure 1 shows the location of the discontinuity within the beam cross section. The outside surfaces of the web were slightly bowed as a result of a separation, or gap, of up to about ⅛-in. (3 mm) at the discontinuity. In some areas, a layer of dark charred material

Table 1. Properties of A572 Steel Test Material

Tensile Properties[a,b]			
Specimen Orientation[c]	Yield Point, ksi	Tensile Strength, ksi	Percent Elongation
Longitudinal	62.9	87.6	—
Transverse	58.9	83.3	30.5 (in 2 in.)

Chemical Composition by Check Analysis, percent

C	Mn	P	S	Si	Cu	V	N	Cb
0.22	1.22	0.014	0.019	0.044	0.017	0.084	0.005	<0.005

[a] Average of 3 sheet-type specimens.
[b] Conversion factors: 1 ksi = 6.895 MPa
1 in. = 25.4 mm
[c] With respect to rolling direction of beam; fatigue specimens were oriented transversely.

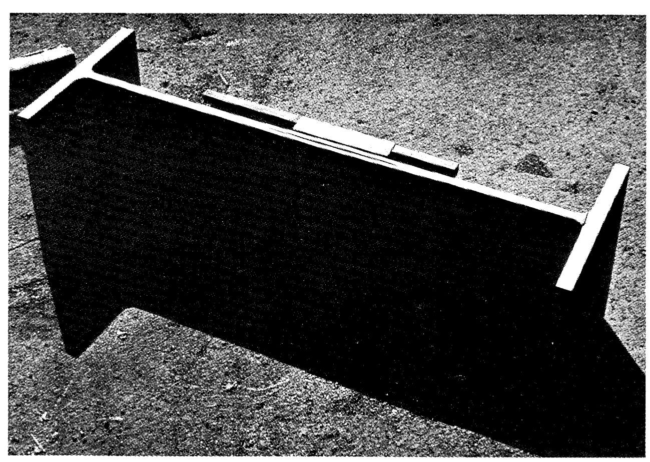


Fig. 1. Beam cross section, showing discontinuity at center of web

R. L. Brockenbrough is Associate Research Consultant, Research Laboratory, U.S. Steel Corporation, Monroeville, Pa.

D. E. Owens is Associate Research Engineer, Research Laboratory, U.S. Steel Corporation, Monroeville, Pa.

* *It is understood that the material in this paper is intended for general information only and should not be used in relation to any specific application without independent examination and verification of its applicability and suitability by professionally qualified personnel. Those making use thereof or relying thereon assume all risk and liability arising from such use or reliance.*

was found in this gap. An inspection by a scanning electron microscope showed that the material was mainly iron oxide with small amounts of iron and manganese silicate. Thus, the discontinuity is likely to have resulted from the oxidation of an open pipe at the top of the ingot which was rolled into the beam.

Specimen Fabrication—To properly locate the discontinuities within the test specimens and to locate material with no discontinuities for the "sound" specimens, it was necessary to accurately map the discontinuities within the beam web. This was accomplished with portable longitudinal-wave, pulse-echo ultrasonic testing equipment. The outlines of the discontinuities were marked on the beam web with paint.

The blanks for machining the specimens were located on the beam web so that the discontinuities were properly located within the specimens; the blanks were then marked with identification codes, as shown in Fig. 2. The unwelded specimens with a discontinuity (designation UD2 through UD11) were located so that a discontinuity approximately 12 in. (305 mm) long was in the center of the reduced test section. Figure 3 shows the specimen details and Fig. 4 shows an unwelded specimen with a discontinuity. As indicated, the specimens were typically bowed with a gap across the discontinuity.

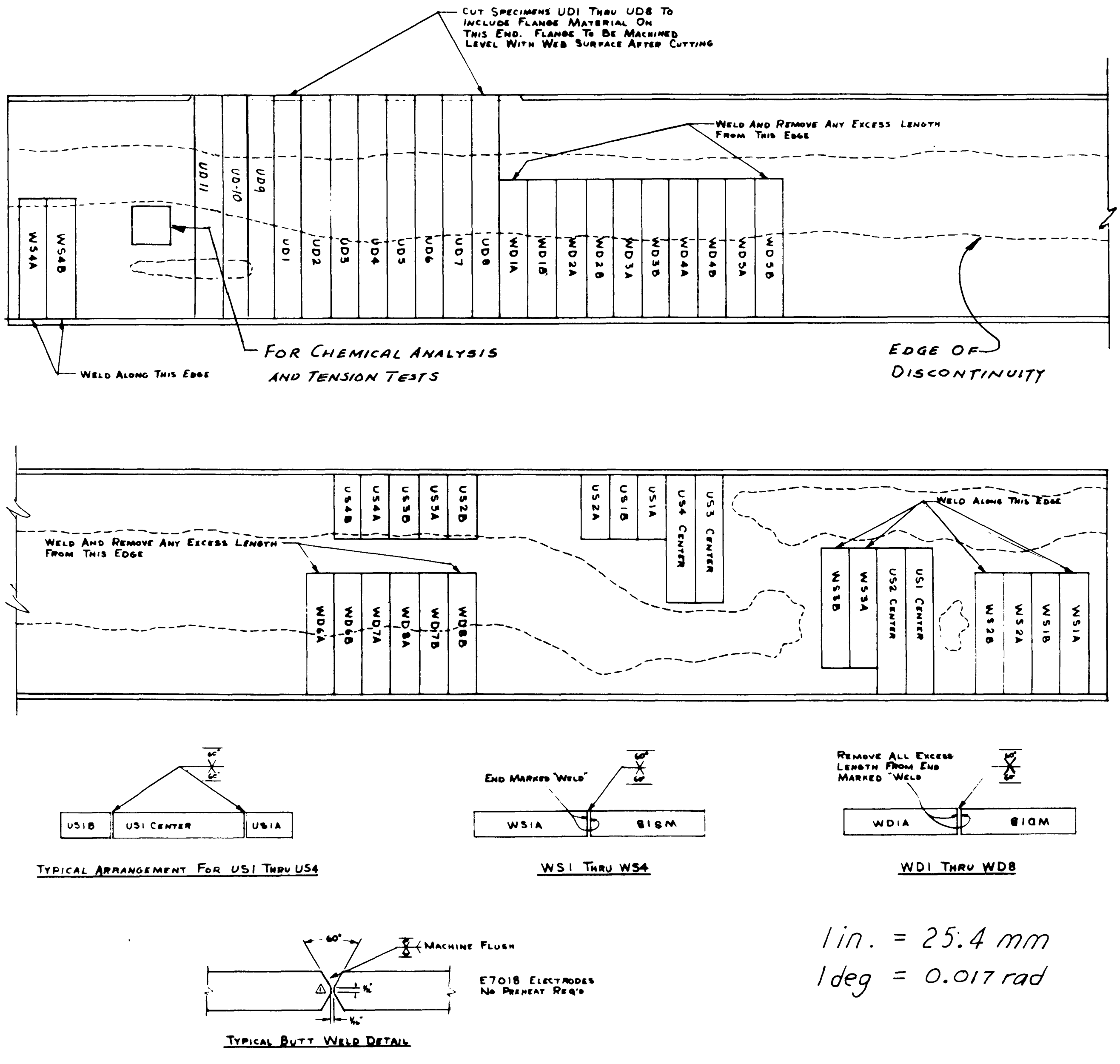


Fig. 2. Layout of beam, showing outline of discontinuity and location of specimen blanks

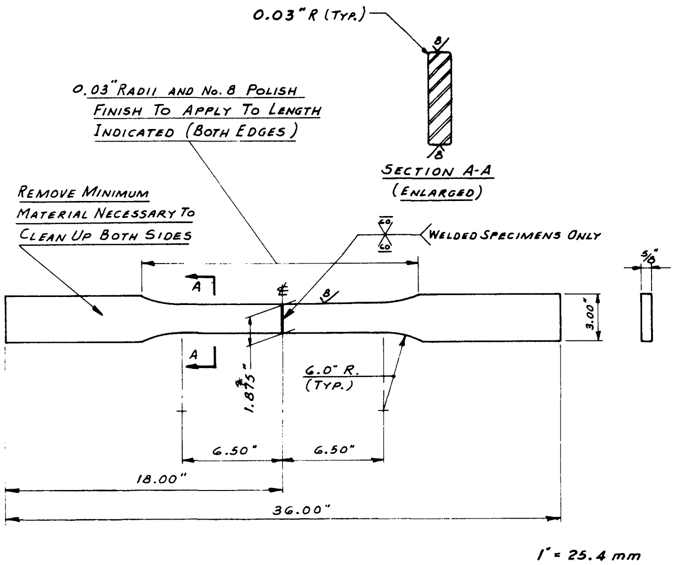


Fig. 3. Specimen details

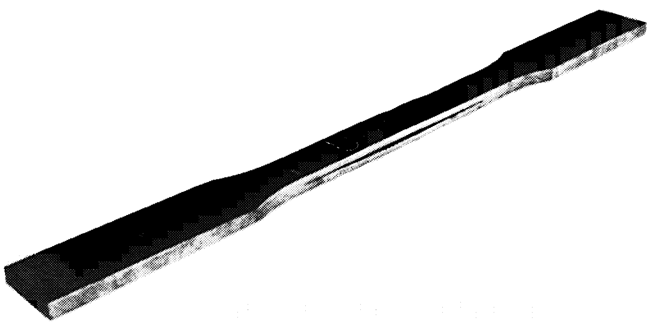
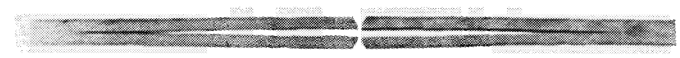


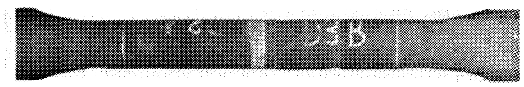
Fig. 4. Unwelded specimen with discontinuity before testing

The welded specimens with a discontinuity (designation WD1 through WD8) were fabricated so that the specimen halves would be joined by welding at the ends containing the discontinuity. This provided specimens with discontinuities that terminated in a double-vee-groove weld at midlength. Figure 5 shows a specimen with a discontinuity before and after welding. After the center of the specimen was prepared for the groove weld, the specimen halves were clamped to the welding bench. This closed the gap across the discontinuity so that a proper full-penetration weld could be made.

As previously discussed, the discontinuity extended over the entire beam length. Consequently, there was no area of sound material large enough to make the unwelded sound specimens (designation US1 through US4) in one piece. Therefore, these specimens were fabricated in three pieces by locating one blank large enough to contain the entire reduced test section, and groove welding additional sound pieces to both grip ends for additional length before machining the specimen to finished size.



(*a*) *Edge view before welding*



(*b*) *Plan view after welding*

Fig. 5. Welded specimen with discontinuity before testing

The welded sound specimens (designation WS1 through WS4) were located so that two pieces of sound material could be joined with a groove weld to form one specimen blank with a transverse groove weld at midlength.

Specimens Tested—The specimens tested are listed in Tables 2 and 3. As indicated, the tests included a total of 14 unwelded specimens (4 of "sound" material and 10 having a discontinuity) and 11 welded specimens (4 of "sound" material and 7 having a discontinuity). (The material available was not sufficient to permit testing of a large number of sound specimens.) Each of these 25 specimens was tested under alternating axial loads that varied the nominal stress on the net section of the specimens from zero to either 40 or 50 ksi (276 or 345 MPa) tension. [A stress range of 58 ksi (400 MPa) was used for one specimen, as indicated in Table 2.] These stresses are higher than permitted by design specifications (even for static loads), but were selected to reduce the time required for testing. Most of the specimens were tested on an Amsler alternating 200-kip (890 kN) fatigue-testing machine (designated by "A" in Tables 2 and 3), and the rest were tested on a 100-kip (445 kN) servo-hydraulic fatigue-testing machine (designated by "M" in Table 2).

As previously mentioned, the unwelded specimens with discontinuities were typically bowed along the length of the discontinuity. Also, some overall bowing was present in the unwelded specimens from sound material. Thus, it was apparent that in addition to the axial stresses, the specimens would be subjected to bending stresses that develop when an axial load is applied to a member with an initial out-of-straightness. Therefore, to account for the effect of these stresses in the test results, axially oriented strain gages were mounted on the opposite outside faces of most of the unwelded specimens so that strains could be monitored and used to calculate the maximum stress. The procedures used are described in Appendix A. It was not necessary to monitor strains on the welded specimens, since a check showed that any out-of-straightness in these specimens was negligible.

Table 2. Test Results for Unwelded Specimens

Specimen Desig-nation[a]	Test Machine[b]	Stress Range, ksi[c]		Cycles to Failure	Type of Failure[d]
		Nominal	Calculated		
US1	A	50.0	53.0	148,800	FS
US2	A	50.0	54.0[e]	89,300	FS
US4	A	50.0	55.1	172,600	FS
US3	A	58.0	62.6[e]	40,600	FS
UD2	A	40.0	49.6	221,600	F
UD3	A	40.0	48.4	111,100	F
UD7	A	40.0	47.7	149,500	F
UD10	M	40.0	48.5[e]	114,300	F
UD11	M	40.0	48.5[e]	210,300	F
UD4	M	50.0	55.1	103,440	F
UD6	A	50.0	56.7	66,900	F
UD8	A	50.0	55.4	59,000	F
UD5	M	50.0	55.7[e]	69,200	F
UD9	M	50.0	55.7[e]	101,330	F

[a] U indicates unwelded, S indicates sound material, and D indicates discontinuity.
[b] A indicates Amsler and M indicates MTS.
[c] Conversion factor: 1 ksi = 6.895 MPa.
[d] FS indicates fracture across half of the specimen thickness, with some midplane splitting; in some tests the specimen also fractured across the remaining ligament. F indicates fracture across one or both ligaments with no extension of the discontinuity.
[e] Strains not monitored; average value calculated from similar specimens.

Table 3. Test Results for Groove-Welded Specimens

Specimen Desig-nation[a]	Test Machine[b]	Stress Range, ksi[c]	Cycles to Failure	Type of Failure[d]
WS1	A	40.0	235,200	FS
WS3	A	40.0	160,000	FS
WS2	A	50.0	111,100	W/S
WS4	A	50.0	90,000	W/S
WD2	A	40.0	140,200	W/S
WD3	A	40.0	142,000	W
WD5	A	40.0	96,600	W/S
WD8	A	40.0	301,900	W/S
WD1	A	50.0	72,600	W/S
WD4	A	50.0	102,700	W
WD6	A	50.0	139,500	F

[a] W indicates groove weld, S indicates sound material, and D indicates discontinuity.
[b] A indicates Amsler.
[c] Conversion factor: 1 ksi = 6.895 MPa.
[d] FS indicates fracture away from the weld, with some midplane splitting. W/S indicates fracture at weld with subsequent midplane splitting at weld. W indicates fracture at weld with no splitting. F indicates fracture away from weld with no splitting. For both types of welded specimens, the fractures occurred across one or both of the specimen half-thicknesses.

RESULTS AND DISCUSSION

Unwelded Specimens—The test results for the unwelded specimens are listed in Table 2. Typically, the fatigue crack for the unwelded sound specimens originated on the as-received surface in the reduced section, and propagated through half the specimen thickness; the specimen then split along the midthickness plane, and in some cases, fractured across the remaining ligament. This suggests that a weakness existed in the plane of the discontinuity, even though no physical separation was present. Figure 6 shows a typical failure mode. The sound specimen with the greatest fatigue life (US4) failed in the grip at the welded extension to a connection plate, and split along the midthickness plane.

For the unwelded specimens with a discontinuity, the failures typically originated on the inside surfaces (surfaces of discontinuity) and propagated across one or both ligaments. (This behavior agrees with the stress analysis given in Appendix A, which shows that because of the bending in the bowed ligaments of the discontinuity, the highest stresses are on the inside surfaces.) The failure initiation on the inside surface may also have been influenced by the greater roughness of the surface of the discontinuity as compared with the roughness of the as-received surface. Surface-roughness measurements were made on both types of surfaces of a typical specimen with a Brush surface indicator. The measurements were made both parallel and at right angles to the specimen axis. The parallel readings were 210 microinches (5.33 μm) for the as-received surface and 250 microinches (6.35 μm) for the surface of the discontinuity. The transverse readings (rolling direction of the beam) were 217 microinches (5.51 μm) for the as-received surface and 287 microinches (7.29 μm) for the surface of the discontinuity. Figure 7 shows a typical failure mode. The fatigue loadings did not cause extension of the end of the discontinuity.

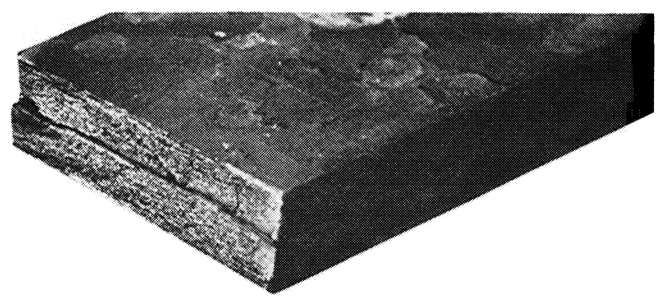


Fig. 6. Typical failure of sound unwelded specimen

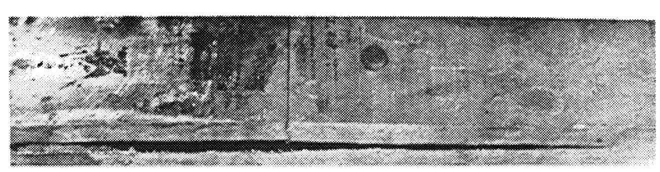


Fig. 7. Typical failure of unwelded specimen with discontinuity

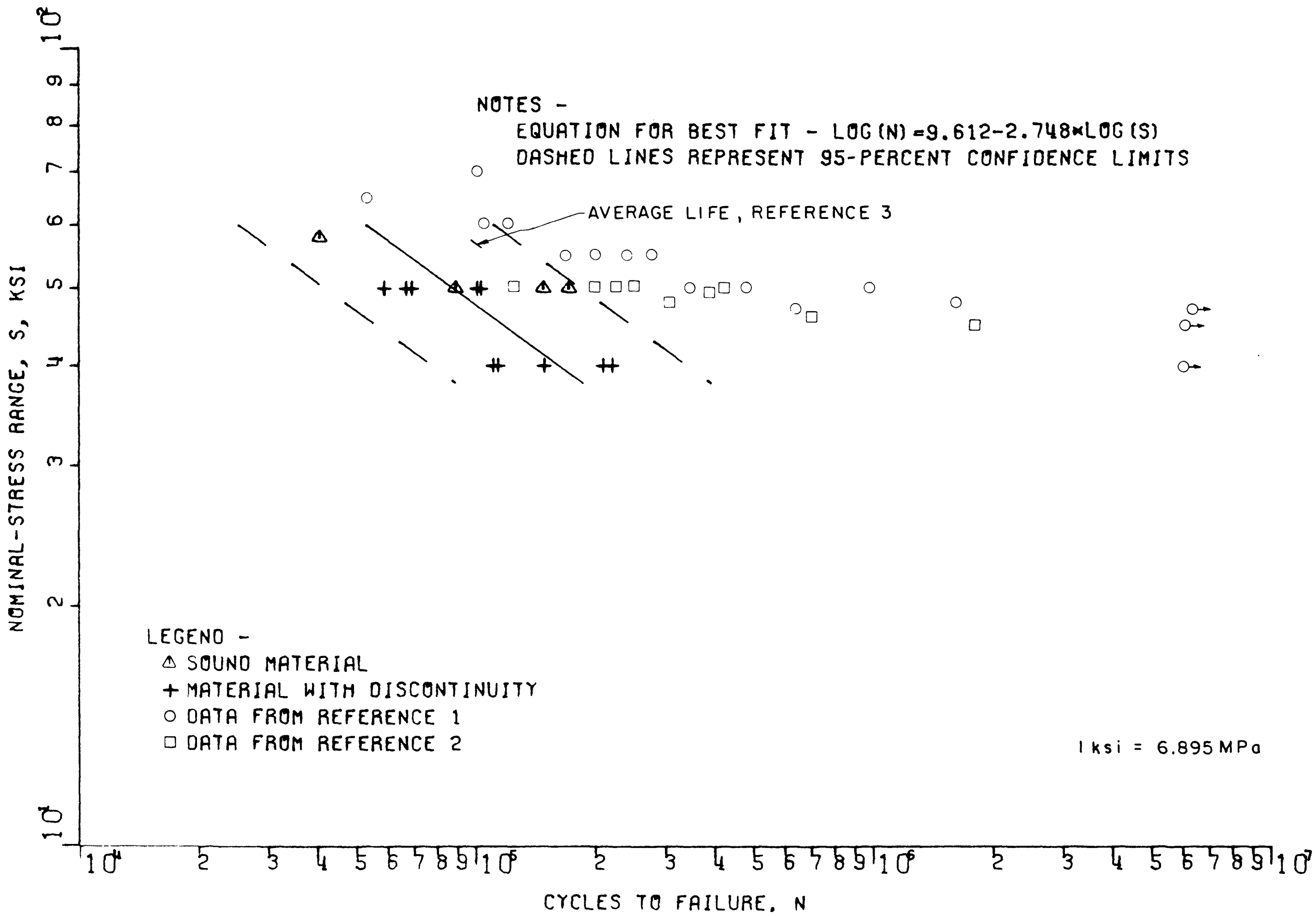


Fig. 8. Fatigue diagram for as-received material based on nominal-stress range

The fatigue lives obtained for the unwelded specimens are shown in the log-log S-N diagrams (stress vs. number of cycles) of Figs. 8 and 9, based on the nominal-stress range and the calculated maximum-stress range, respectively. Since the difference in fatigue life for the sound specimens and the specimens with a discontinuity did not appear to be significant, a statistical curve fit was made for all the present test data on unwelded specimens. The resulting equations for fatigue life are shown in the figures. Previous data for steels having approximately the same tensile strength are also shown for comparison. Reference 1 describes tests conducted earlier at U.S. Steel's Research Laboratory, and Ref. 2 describes tests conducted at the University of Illinois. These data were used to develop specifications for bridges.[3,4]

The correlation with previous data is more favorable in Fig. 9 than in Fig. 8, since the calculated maximum stresses averaged about 10 percent higher than the nominal stresses. It appears that the fatigue life of the present unwelded specimens is somewhat less than that determined in previous tests, although the scatter bands from the various sets of data overlap.

Welded Specimens—The test results for the welded specimens are listed in Table 3. The failures for the welded sound specimens originated on the outside surface in the reduced area; the crack initiated away from the weld for two specimens and near the weld for the other two specimens. The crack propagated through half the specimen thickness, split along the midthickness plane, and in some cases, fractured across the remaining ligament. Thus, the typical failure mode was similar for the welded sound specimens, Fig. 10, and for the unwelded sound specimens.

A typical failure mode for the welded specimens with a discontinuity is shown in Fig. 11. As indicated in Table 3, most of the failures initiated at the weld, and subsequent midplane splitting through the weld often occurred. No extension of the discontinuity away from the weld was observed.

The fatigue lives obtained for the welded specimens are shown in the log-log S-N diagram of Fig. 12. The fatigue life does not appear to be significantly affected by the absence or presence of the discontinuity. A statistical curve fit was made for all the present test data on welded speci-

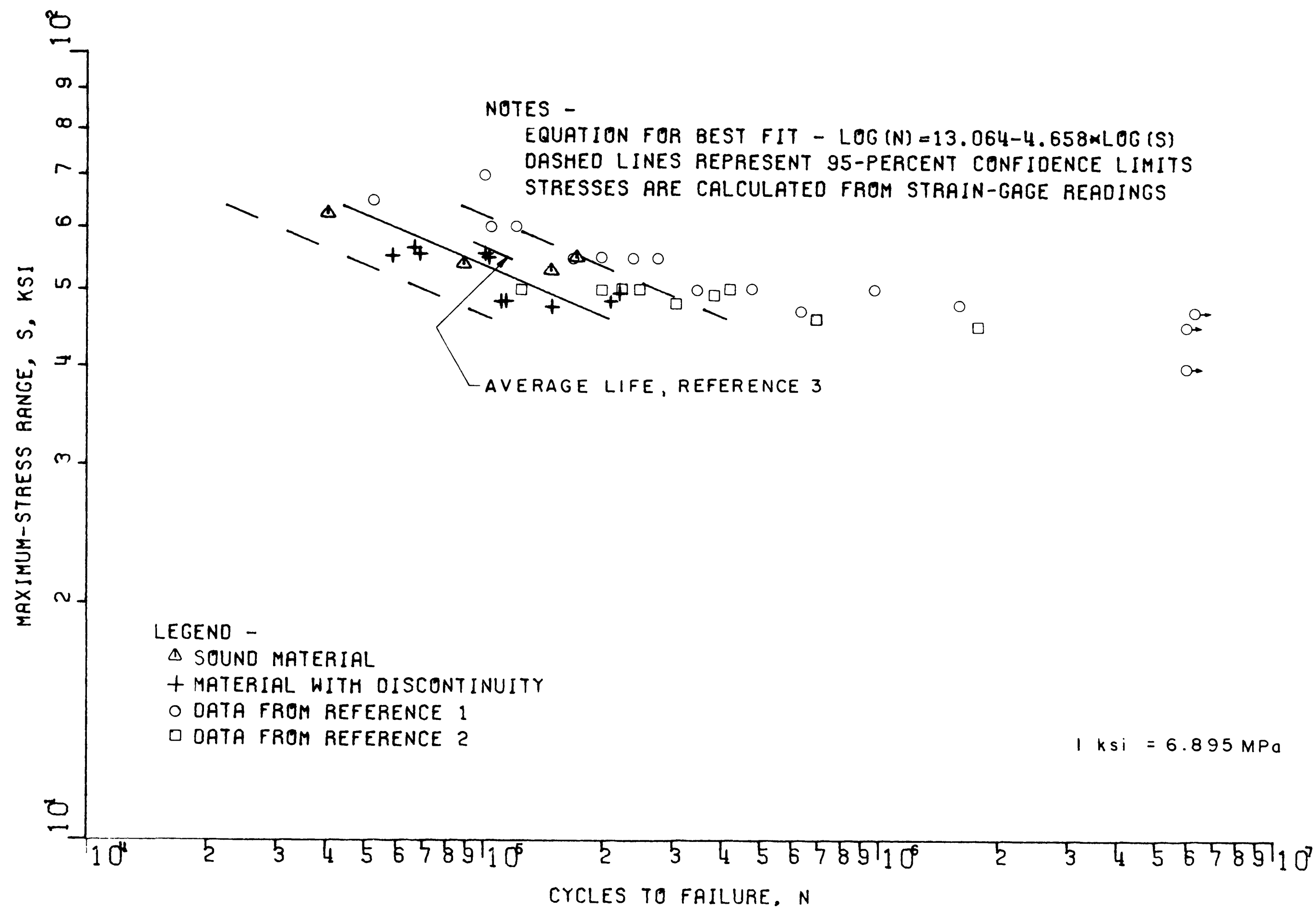


Fig. 9. Fatigue diagram for as-received material based on maximum-stress range

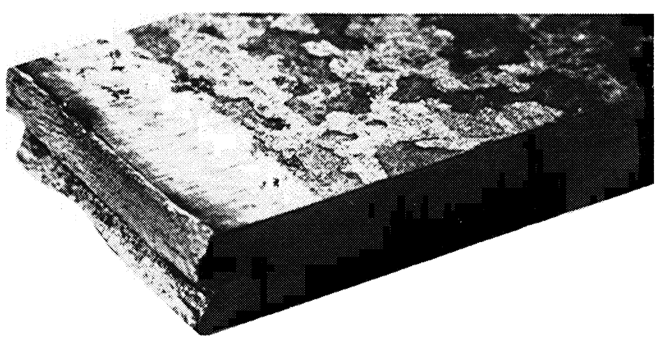


Fig. 10. Typical failure of sound welded specimen

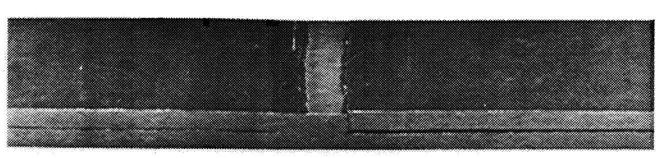


Fig. 11. Typical failure of welded specimen with discontinuity

mens and the resulting equation for fatigue life is shown. The data generally fall above the average of data from previous tests of as-welded (not ground) specimens, and somewhat below the average of data from previous tests of specimens with as-received (unwelded) surfaces. The scatter bands from the various sets of data would overlap. Thus, these results indicate that the presence of the discontinuity in welded specimens has little, if any, effect on fatigue life.

SUMMARY

Axial-load fatigue tests over stress ranges of 40 and 50 ksi (276 and 345 MPa) were conducted on specimens having a laminar midthickness discontinuity that terminated either in plain material or in a transverse double-vee-groove weld. The as-received surface was left intact and the reinforcement of the groove welds was removed by grinding. A few comparison tests were conducted on specimens of the same material not having an apparent midplane discontinuity, and data from previous tests on material with approximately the same tensile strength were reviewed.

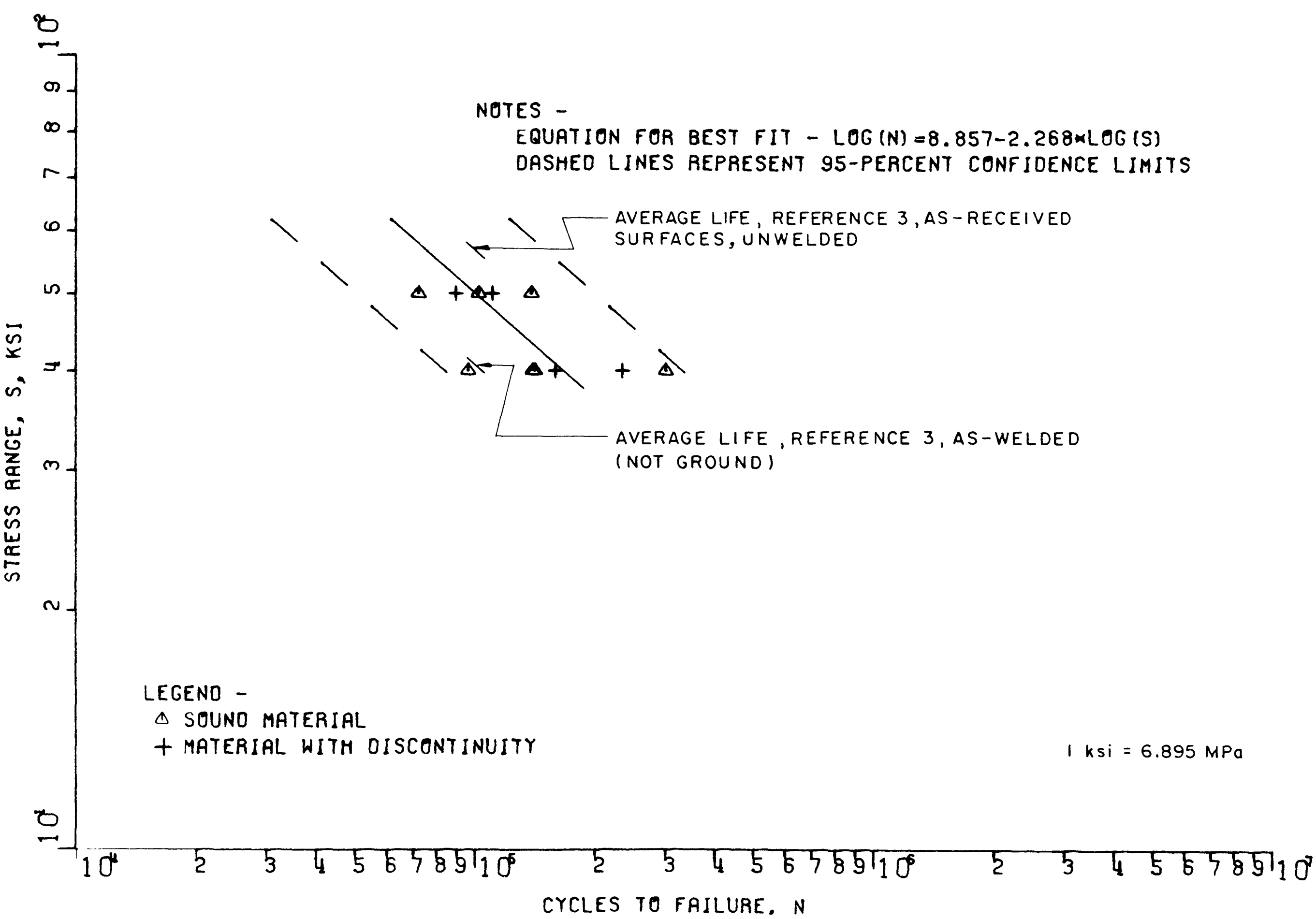


Fig. 12. Fatigue diagram for transverse groove-welded specimen

Although the discontinuity was severe, in that the half-thicknesses were visibly separated and bowed along the length of the discontinuity, no failures were initiated by extension of the discontinuity. For both the welded and the unwelded specimens, the fatigue life of specimens with and without a discontinuity was similar. The fatigue life of both types of welded and unwelded specimens was slightly less than that determined in previous tests, but the scatter bands from the various sets of data overlap.

Since the specimens tested had severe discontinuities, but did not fail by extension of the discontinuity, and had fatigue lives only slightly less than those determined in previous tests, a laminar discontinuity does not appear to significantly affect the fatigue life of a plate loaded in tension parallel with the discontinuity.

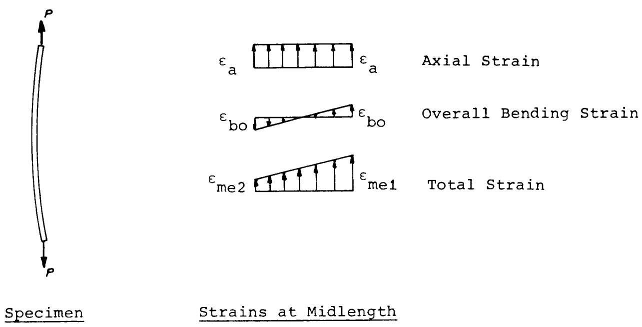
REFERENCES

1. Shuck, R. R. Fatigue Strength of ¾-Inch-Thick USS TRI-TEN High-Strength Low-Alloy Steel Plates *U.S. Steel Applied Research Laboratory Report 57.19-903(1), August 26, 1963.*
2. *Stallmeyer, J. E., G. E. Nordmark, W. H. Munse, and N. M. Newmark* Fatigue Strength of Welds in Low-Alloy Structural Steels *Welding Journal, Research Supplement, June 1956.*
3. *Fountain, R. S., W. H. Munse, and R. D. Sunbury* Specifications and Design Relations *Journal of the Structural Division, Proceedings ASCE 94, No. ST12, December 1968.*
4. *American Association of State Highway Officials* Standard Specifications for Highway Bridges 1973.

APPENDIX A

OUT-OF-STRAIGHTNESS EFFECTS

It was necessary to determine the magnitude of stresses caused by the combined effects of axial stress and bending stress due either to bowing of the specimen in the area of the discontinuity or to out-of-straightness of a plain specimen. To accomplish this, electric-resistance strain gages (type EA-125BB-120, resistance 120 ohms, gage factor 2.07 at room temperature, K_t = +0.5%) were applied to both as-received surfaces at the centerline on several of the specimens. Each strain-gaged specimen was then loaded in tension in a universal testing machine to a load approximately equal to the maximum load that would be subsequently applied in the fatigue test. The specimen was then unloaded and reloaded once or twice to assure that the strains measured at a given load were repeatable. The measured strains were then used to calculate the maximum



$$\sigma_{max} = E \times \varepsilon_{me1}$$

where σ_{max} is maximum stress

E is modulus of elasticity

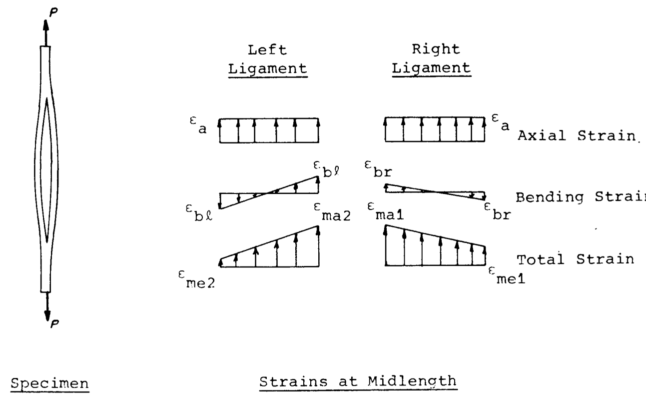
ε_{me1} is larger of measured strains

Fig. A1. Stress calculation for sound specimen

stresses at the fatigue-test loads as explained in the following section. For each specimen checked in this manner, out-of-straightness and bowing effects were approximately the same for a given type of specimen and maximum load. Consequently, strain gages were not used on all the specimens.

Figures A1 and A2 show the equations used to calculate maximum stresses for the specimens. For the sound specimen with an overall out-of-straightness, Fig. A1, the maximum stress is on the outside surface and is simply the larger measured strain multiplied by the modulus of elasticity (29,000 ksi or 200 GPa).

Figure A2 shows a specimen that is bowed along the discontinuity; the specimen does not have an overall out-of-straightness, but one side (the left side) is bowed more



$$\varepsilon_a - \varepsilon_{b\ell} = \varepsilon_{me2}$$

$$\therefore \varepsilon_{b\ell} = \varepsilon_a - \varepsilon_{me2}$$

$$\varepsilon_{ma2} = \varepsilon_a + \varepsilon_{b\ell} = 2\varepsilon_a - \varepsilon_{me2}$$

$$\varepsilon_a = P/AE$$

$$\therefore \sigma_{max} = \frac{2P}{A} - E \times \varepsilon_{me2}$$

where σ_{max} is maximum stress

P is axial load

A is net area of specimen

E is modulus of elasticity

ε_{me2} is smaller of measured strains

Fig. A2. Stress calculation for specimen with discontinuity

than the other. For this condition, the maximum stress occurs on the inner surface (surface of discontinuity) and is equal to twice the axial (nominal) stress minus the product of the smaller measured strain and the modulus of elasticity.