DEPARTMENT OF THE NAVY
NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
BETHESDA, MD. 20034

# A DECADE OF LOW-CYCLE FATIGUE TESTING OF LARGE-SCALE HIGH-STRENGTH STEEL WELDMENTS
## A Summary Report

by
J. G. Macco



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## ABSTRACT

Information and data, accumulated over the past decade, on low-cycle fatigue behavior of large-scale HY-80, HY-100, and HY-130 steel weldments and on the effects of various postweld treatments are presented. Baseplate, tee- and butt-welded fatigue specimens are covered, in addition to postweld treatments such as mechanical peening, shot peening, stress relieving, grinding, and overstressing. The information will be especially useful to designers of welded structures that are subjected to repeated loads such as submarines and surface ships.

ADMINISTRATIVE INFORMATION

This report was prepared under Work Unit 1-2814-104-45, Task Area SF43-422-210, Task 15055, covering fatigue strength of structures for combatant submarines. The investigation was sponsored by NAVSHIPS (SHIPS 0342). Mr. C. H. Pohler, NAVSHIPS (SHIPS 03423), was the program manager and Mr. A. Malakhoff, NAVSEC (SEC 6129C), was the technical agent. The report constitutes milestone 1 (fiscal year 1973) in the 1 July 1972 Program Summary.

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## INTRODUCTION

In the past decade considerable research has been conducted at NASL and this laboratory on low-cycle fatigue of high-strength steel structural weldments used in submarine hull construction. Voluminous reports covering this work have been issued and are listed in appendix A. It is the purpose of this report to consolidate significant data and findings from these reports into a single convenient source for future reference in designing advanced military submarines. The information presented covers low-cycle fatigue behavior of large-scale HY-80, HY-100, and HY-130 steel weldments and the effects of various postweld treatments.

## DESCRIPTION OF FATIGUE MACHINES

The low-cycle fatigue data presented herein were obtained from tests conducted in plate- and beam-type pneumatic fatigue machines. Photographs of the machines and specimens used appear as figures 1 through 6. The operating characteristics of each machine are given below.

- Two-edge support uniformly loaded plate machine (figure 1)
  - Loading mode - bending, constant load
  - Operating mode - zero to maximum flexure
  - Speed range - 12 cpm,* maximum
  - Stress, maximum - 140,000 psi on 1 1/2-inch-thick plate
  - Specimen size - 32 x 29 1/2 x 1 1/2 inches thick (figure 2).
- Four-edge support uniformly loaded plate machine (figure 3)
  - Loading mode - bending, constant load, 2:1 biaxial
  - Operating mode - zero to maximum flexure

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*Abbreviations used in this text are from the GPO Style Manual, 1967, unless otherwise noted.

- Speed range - 12 cpm, maximum
- Stress, maximum - 120,000 psi on 1 1/2-inch-thick plate
- Specimen size - 56 x 28 x 1 1/2 inches thick (figure 4).

- Uniform moment beam machine (figure 5)
  - Loading mode - bending, constant load
  - Operating mode - all ranges of stress
  - Speed range - 20 cpm, maximum
  - Bending moment, maximum - 800,000 in-lb
  - Deflection, maximum - 16 inches
  - Specimen size - 32 to 36 x 5 x 1 1/2 inches thick (figure 6).

In addition to constant cyclic-load fatigue tests, the above machines were also used for spectrum cyclic-load fatigue tests under various spectra proposed for tests on submarine models. The results of this work are not presented herein because of its confidential nature and since the intent of this report is to cover results of constant cyclic-load fatigue tests only. A separate summary report on spectrum tests is being prepared for submission at a later date.

## DETAILS OF INVESTIGATION

### WELDMENTS

#### Conventional Welds

Joint design details for conventional tee and butt weldments are given in figure 7. All welding was done parallel to the direction of roll by either the gas metal arc welding (GMAW) or the shielded metal arc welding (SMAW) process.

#### 40% Efficient Welds

Joint design and welding details for 40% efficient double-fillet-welded joints are given in figure 8. Efficiency, as used in this connection, was defined as the ratio of the static strength of the weld to the strength of the steel.

Subsurface Weld defects

The two types of weld defects deliberately produced in the weldments were slag inclusions, approximately 1/2 inch long, and lack of fusion, approximately 1/4 inch long. The lengths of the particular defects and their locations in the plate, shown in figure 9, were determined so as to conform to existing acceptance-rejection limits. The weld defects were produced in each weldment as described below:

- Normal welding was stopped at the locations selected for the defects.

- The current was reduced approximately 50% to 115 amperes for 3/16-inch-diameter electrodes.

- A high crowned, convex head approximately 1 inch long was deposited at each selected location.

- Additional small weld passes were deposited alongside and on top of the convex head to box in each defect. For the slag inclusion defect only, slag was deliberately tamped into each boat-shaped crevice formed before covering the defect.

- The welds were completed with normal welding current and speed, except that at the flaw locations a faster speed was used to avoid penetration and washing out of the defects. Upon completion of each weldment, radiographic inspection was performed which ensured that the defects were of the desired size and correctly located along the length of the plate.

## WELD TREATMENTS

### Weld Grinding

**Tees**

The toes of these welds were ground to a radius of 3/8 inch using a tapered-cup grinding wheel whose bottom edge had a radius of approximately 3/8 inch. Rotation of the wheel was such as to leave scratches parallel to the weld length. These scratches were then removed by grinding with a small tapered stone, leaving the finishing scratches normal to the weld.

Butts

Both faces of these weldments were ground flush by means of a 6-inch portable disk sander, using 180-grit paper for the top face finish and 240-grit paper for the bottom face finish. Grinding was done so that all grinding marks ran normal to the weld length. A smoother finish was given to the bottom face to assure that failure would occur at the top face on which the required stress conditions are imposed.

## Shot Peened Welds

The apparatus employed for shot peening weldments is shown diagrammatically in figure 10 together with details of the peening procedures. Intensity of shot peening was measured by means of Almen strips. In brief, the principle involved is that shot peening deforms the metal on the surface and produces a layer of residual compressive stresses. This in turn produces a curvature in the strip which is proportional to the intensity of shot peening.

## Mechanically Peened Welds

The mechanical peening procedures used for tee and butt weldments are described in detail in reports of NASL[3,4]*. A size 2, type 2, pneumatic chipping hammer, conforming to federal specification OO-H-116a, was used for the peening operations. A hemispherical nose-contouring tool was used for major metal removal and a dressing tool for removing the spherical impressions made by the contouring tool. On butt weldments a flattening tool was used for removing any sharp ridges that might appear at the baseplate edge of the peened area.

## Stress-Relieved Welds

The specifications for stress relieving HY-80 steel weldments were as indicated below:

- Place in furnace at a temperature not exceeding 300° F.
- Raise temperature to 1025° F and hold for 2 hours.
- Furnace cool to a temperature not exceeding 300° F and remove.

*Superscripts refer to similarly numbered entries in appendix A.

• Temperature rise and fall not to exceed 150° F per hour.

• Temperature difference between coolest and hottest points on weldment not to exceed 100° F.

## REVIEW OF FATIGUE RESULTS

Significant data culled from the mass of low-cycle, large-scale specimen fatigue data generated over the past decade at NASL and this laboratory are summarized in figures 11 through 20. An index is provided in table 1 indicating the bibliography report numbers from which the fatigue data, shown on the respective figures, in this report were obtained.

TABLE 1
INDEX TO LOW-CYCLE FATIGUE DATA

| Type of Data | Report Figures | Bibliography No. |
|---|---|---|
| | Base Metal | |
| HY-80 | 11, 14 | 40 |
| HY-100 | None available | - |
| HY-130 | 11 | 37 |
| | Butt Welds | |
| HY-80 | 12, 14, 15 | 15-17, 39, 47 |
| HY-100 | 12 | 44 |
| HY-130 | 12, 14 | 32, 45 |
| | Tee-Fillet Welds | |
| HY-80 | 13-16, 18 | 3, 9, 19-22 |
| HY-100 | 13, 17 | 44 |
| HY-130 | 13, 14 | 28, 34, 46 |
| | Effect of Grinding | |
| HY-80 | 13, 15, 16, 18 | 4, 5, 22 |
| HY-100 | 13, 17 | 44 |
| HY-130 | 12, 13 | 33, 43 |
| | Effects of Shot and Mechanical Preening and Stress Relieving | |
| HY-80 | 15, 18 | 5, 8, 9, 22, 47 |
| HY-100 | None available | - |
| HY-130 | None available | - |
| | Others (HY-80) | |
| Castings | 12 | 12-14 |
| Subsurface weld defects | 14 | 26 |
| 40% efficient welds | 15 | 27 |
| Effect of overstress | 19, 20 | 6, 7, 25, 42 |

The fatigue data as presented in the figures are discussed below:

- Figures 11 through 14 - Fatigue data are presented for baseplate and tee- and butt-welded plate specimens for HY-80, HY-100, and HY-130 steel. It may be observed from these figures that:

  - The scatter for baseplate specimens is considerably less than for welded specimens and that the scatter for all tends to increase as the applied stress is reduced. In general, the scatter factor for the fatigue data presented herein varied from about 2 to 10.

  - The fatigue life of higher yield strength baseplate is significantly longer than that of baseplate with lower yield strength. However, the fatigue life of similar types of weldments is essentially the same, regardless of yield strength.

  - The fatigue life of butt welds is at least two times that of tee welds.

  - The fatigue life of butt welds with subsurface weld defects, within the range of current acceptance/rejection limits, is equal to that of sound butt welds.

  - The fatigue life of weldments is considerably improved by grinding; and the degree of improvement tends to increase as the applied stress is decreased. In general, the improvement varied from about a factor of 2 at the higher stresses to a factor of 10 at the lower stresses.

- Figure 15 - Fatigue data demonstrating the effects of fabrication variables on low-cycle fatigue properties of HY-80 plate specimens are presented graphically. Giving due consideration to the inherent scatter found in the fatigue resistance of weldments, figure 15 indicates that:

  - There is no substantial difference in the fatigue life of welds prepared by the GMAW or SMAW processes.

  - In general, stress relieving does not affect the fatigue life of welds; however, stress relieving after mechanical peening has a significant detrimental effect.

- Shot peening produces no significant effect on the fatigue life of welds.

- Grinding welds produces an appreciable increase in fatigue life. The fatigue lives of ground tee welds were at least six times longer than those for tee welds in the as-welded condition.

- The most dramatic improvement in the fatigue life of welds was achieved by mechanical peening. Mechanically peened welds exhibited fatigue lives of at least 20 times greater than those for welds in the as-welded condition.

- The fatigue life of 40% efficient tee welds is similar to that of double-bevel full penetration tee welds.

- The fatigue life of HY-80 cast tees that are butt welded to rolled plate is similar to that of cast plate butt welded to rolled plate and that of rolled plate butt welded to rolled plate.

- The fatigue life of cast tee plates is at least five times greater than that of tee and butt welds and about equal to that of as-rolled baseplate.

- Figures 16 through 18 - Fatigue data and S-N curves are presented for both beam- and plate-type specimens tested under similar stress conditions. It may be seen that the fatigue results obtained with beam-type specimens corroborate corresponding results obtained on plate-type specimens. Sufficient additional confirming evidence that has been gathered over the years indicates that the considerably less expensive beam tests can be substituted for the two-edge plate tests without adversely affecting the results.

- Figures 19 and 20 - Data demonstrating the effect of overstress on fatigue and residual stresses of HY-80 steel tee-welded beam specimens are presented. The various effects of overstressing are as follows:

  - Tensile overstressing causes a reduction in the high initial tensile residual stresses usually found at the toe of the weld, even introducing beneficial compressive stresses.

  - Tensile overstressing produces a significant increase in the fatigue life of tee-welded beams that are cyclically stressed in tension.

• Compressive overstressing has no significant effect on the initial tensile residual stresses at the toe of the weld nor on the fatigue life of tee-welded beams that are cyclically stressed, either in tension or compression.

## SUMMARY

The primary objective of this report, as originally defined, was to accumulate and review fatigue data on HY-80, HY-100, and HY-130 steel weldments generated over the past decade, and to provide information for use in designing advanced military submarines. Such information has been furnished in the text and will not be restated; however, the most noteworthy observations are summarized below:

- The scatter factor for the fatigue data covered herein ranges from 2 to 10, increasing in magnitude as the applied stresses decrease.

- HY-130 and HY-100 steel weldments show no advantage over HY-80 steel weldments in fatigue behavior at design stresses applicable to HY-80.

- Mechanical peening produces a substantial improvement in the fatigue behavior of HY-80 steel weldments. Tests recently completed on two contour-peened tee weldments indicate that this may also be true for HY-130 weldments.

- Grinding significantly enhances the fatigue behavior of HY-80, HY-100, and HY-130 steel weldments.

- The fatigue life of butt-welded plates is at least twice that of tee-welded plates.

- The fatigue life of HY-80 cast tees butt welded to rolled plate equals that of rolled plate butt welded to rolled plate.

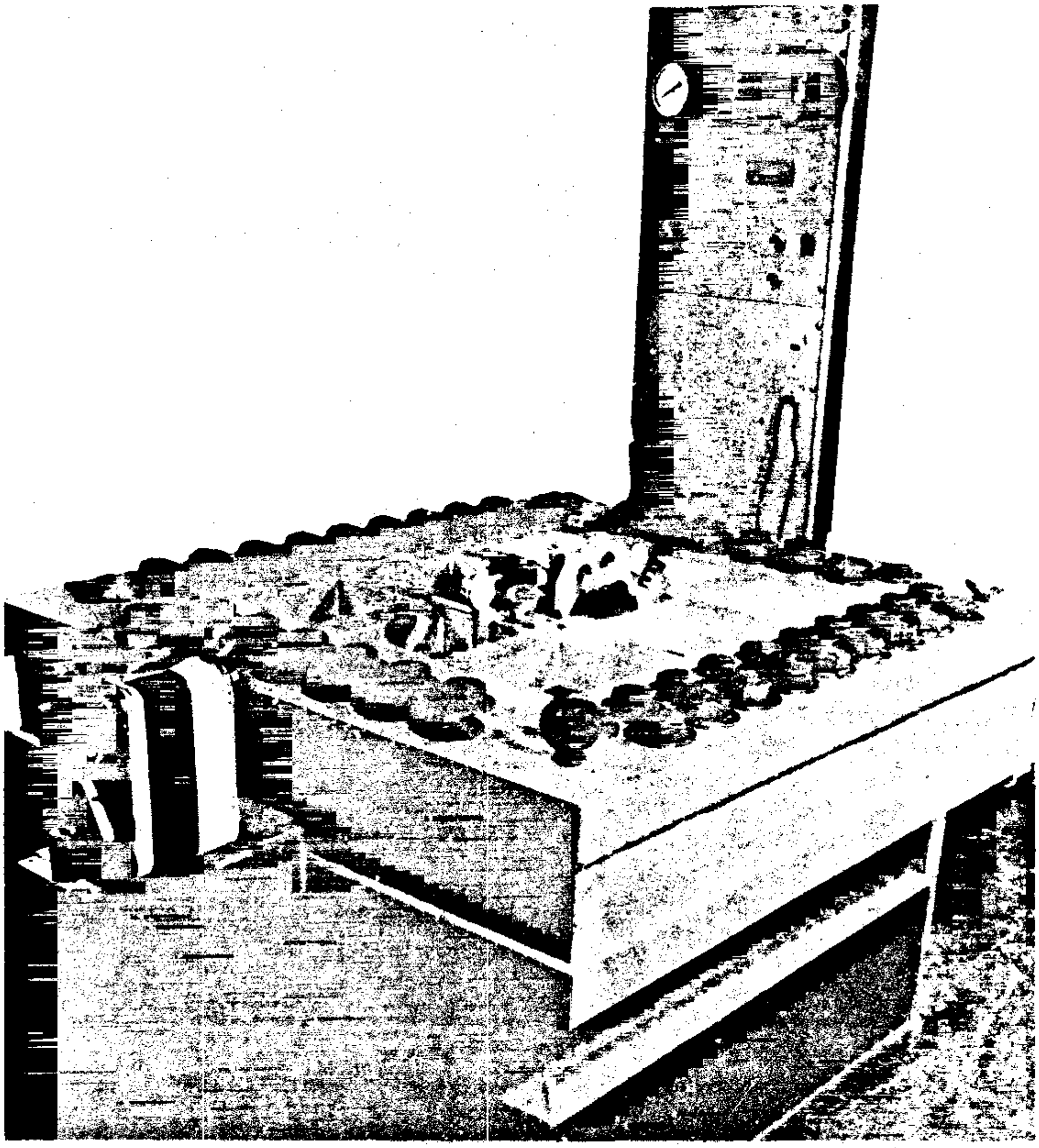


Figure 1
Two-Edged Support Uniformly Loaded Plate Machine

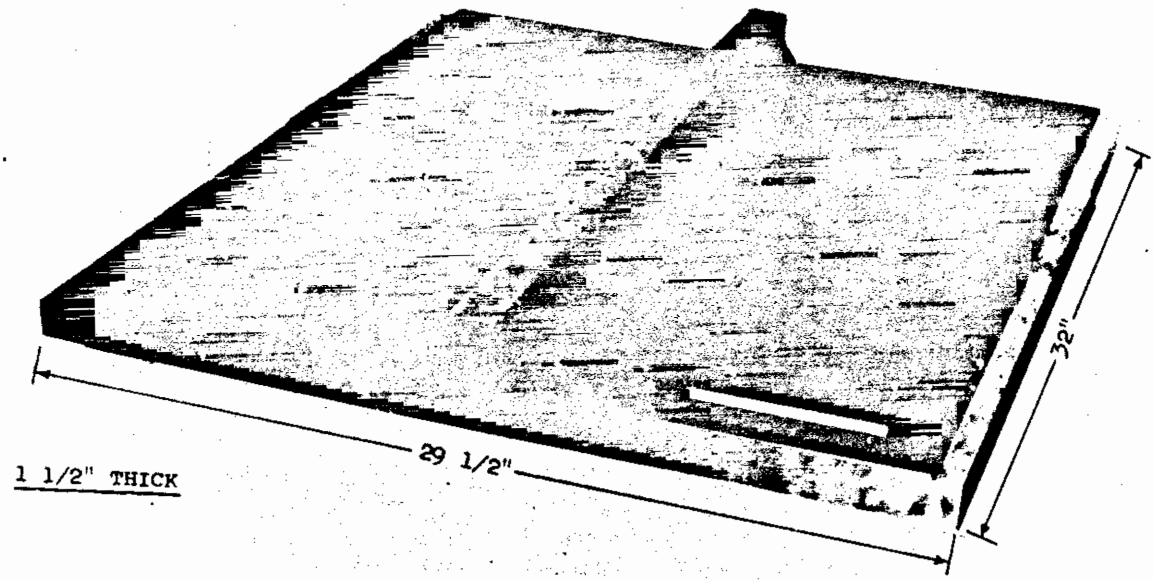



**Figure 2**
**Typical 32- x 29 1/2- x 1 1/2-Inch**
**Tee-Fillet-Welded Plate Specimen**

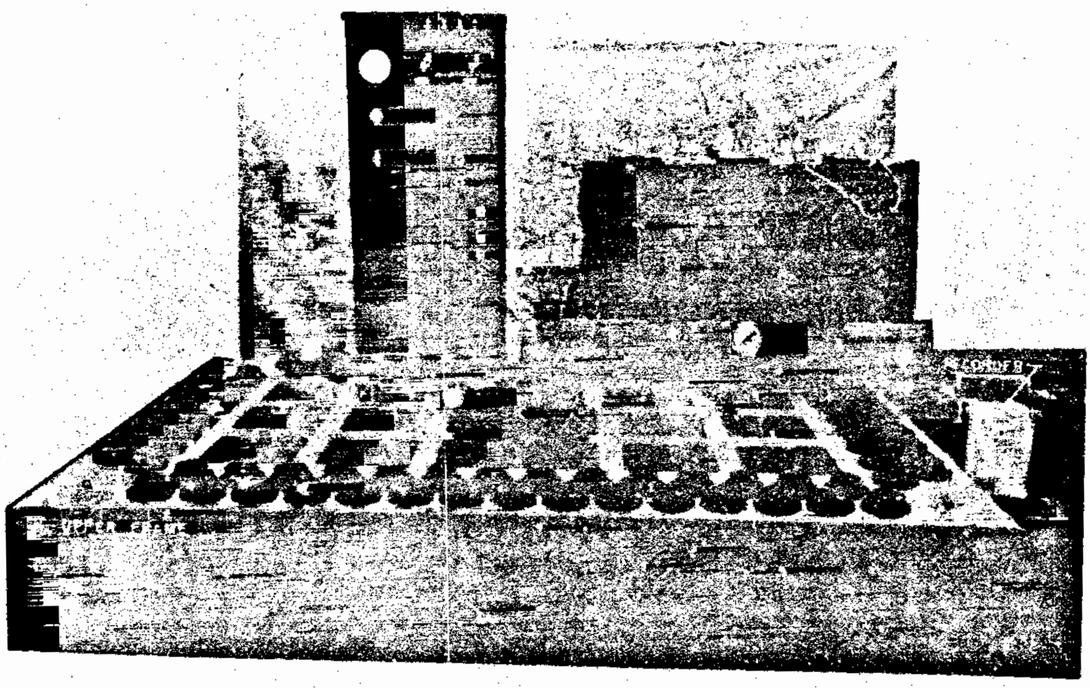


**Figure 3**
**Four-Edge Support Uniformly Loaded Plate Machine**

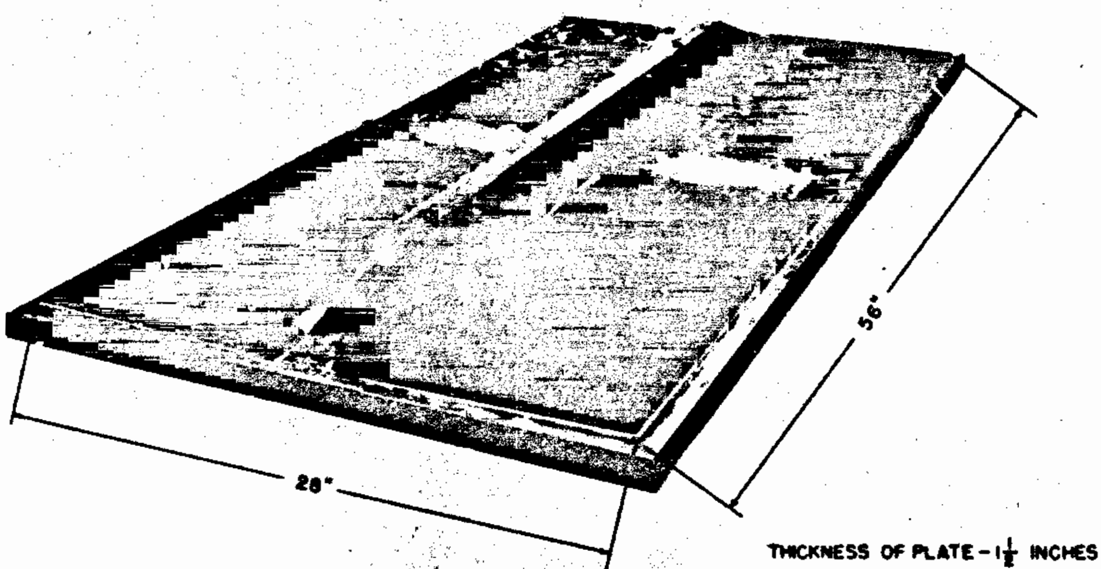



Figure 4
Typical 56- x 28- x 1 1/2-Inch
Tee-Fillet-Welded Plate Element

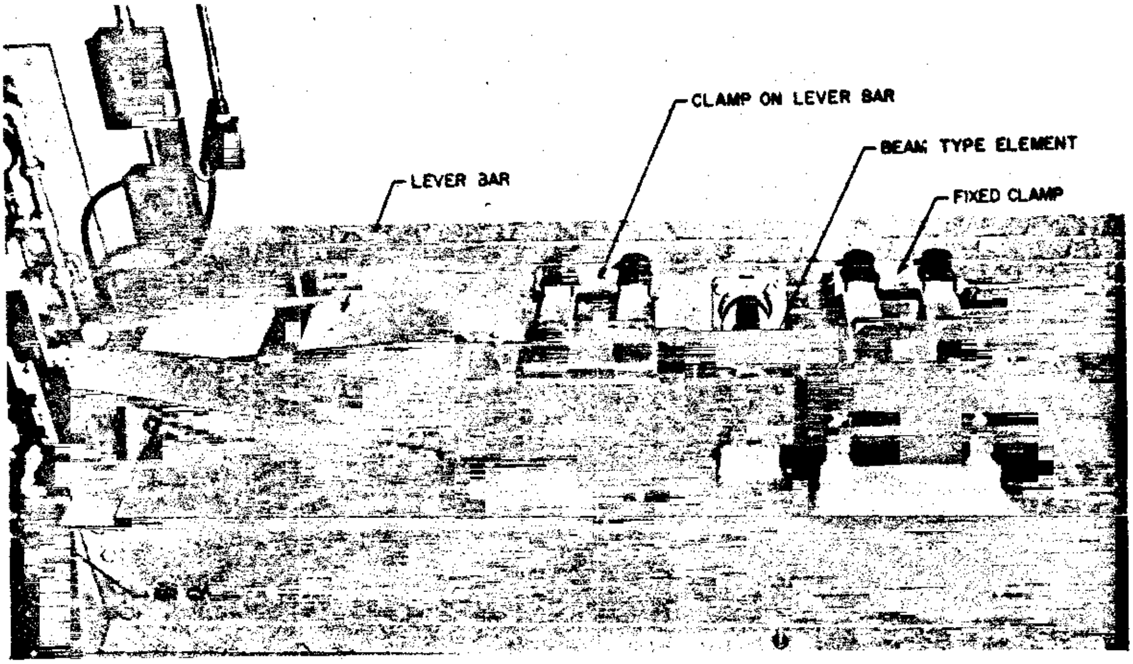



Figure 5
Uniform Moment Beam Machine

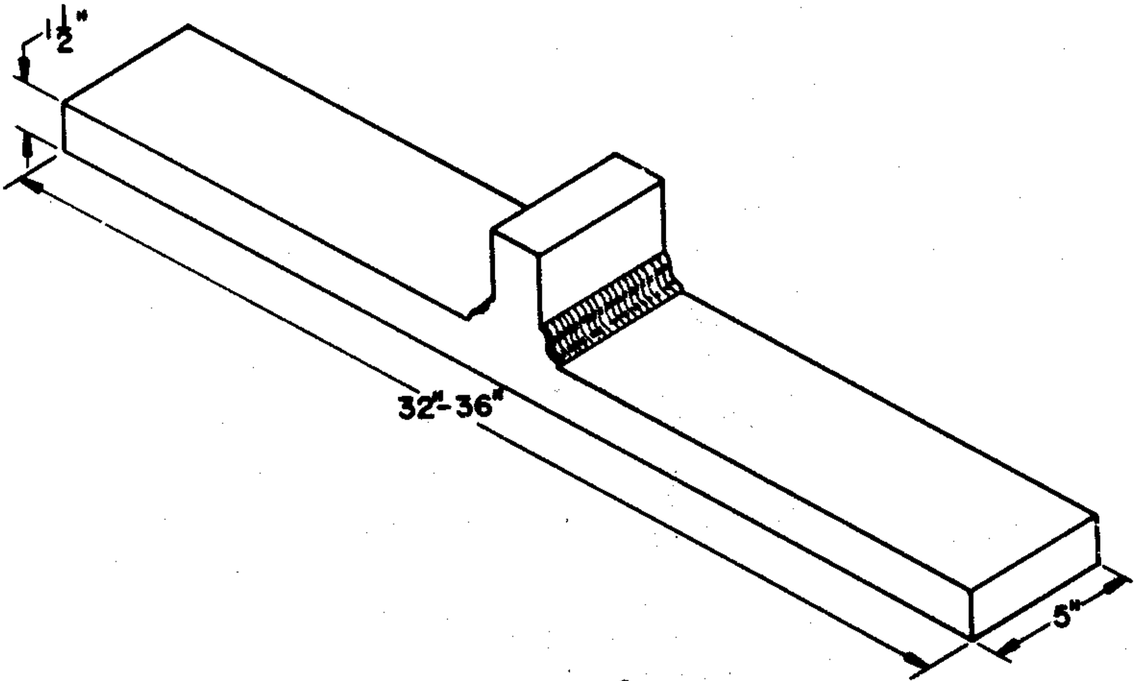



Figure 6
Typical Tee-Welded Beam-Type Specimen

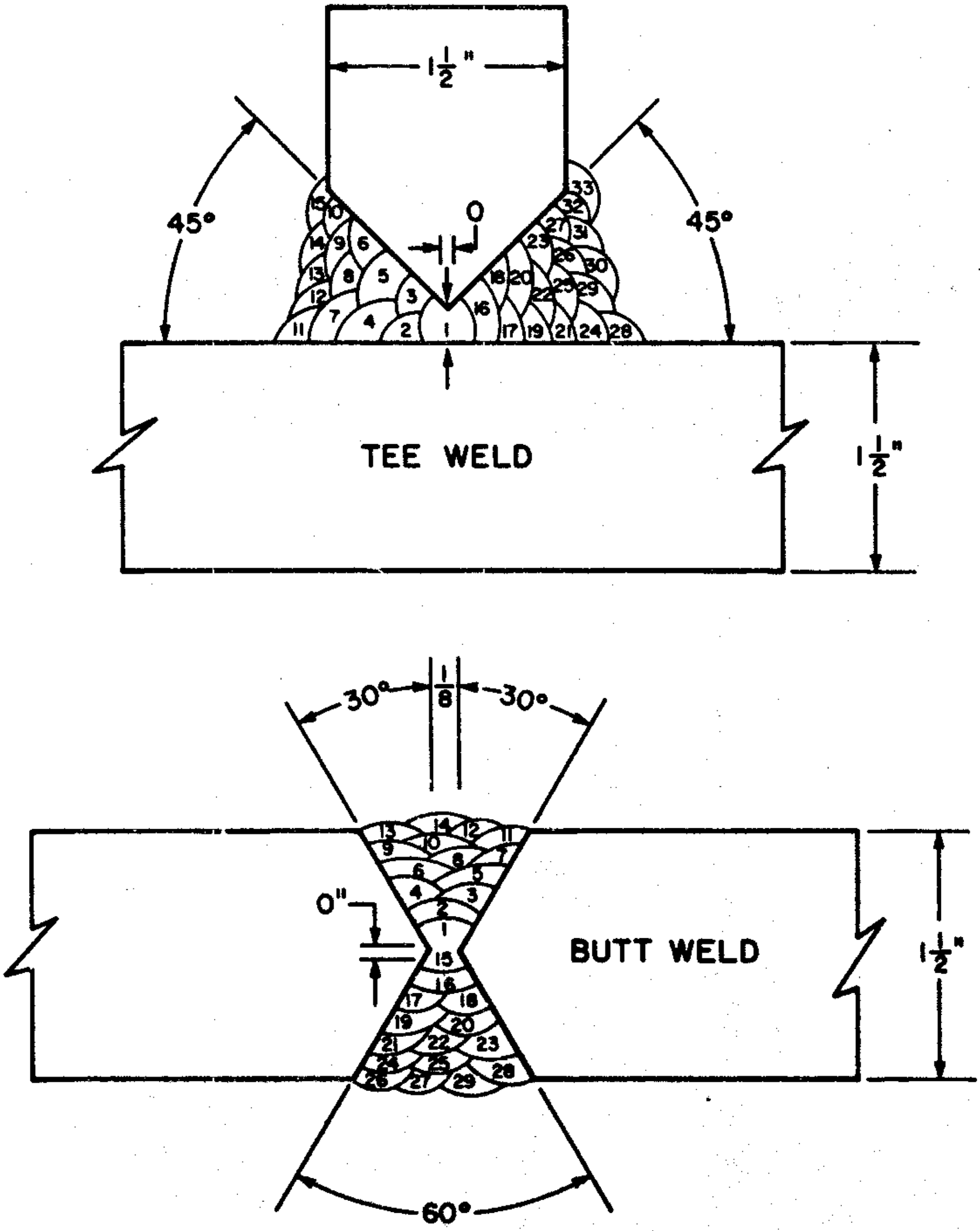
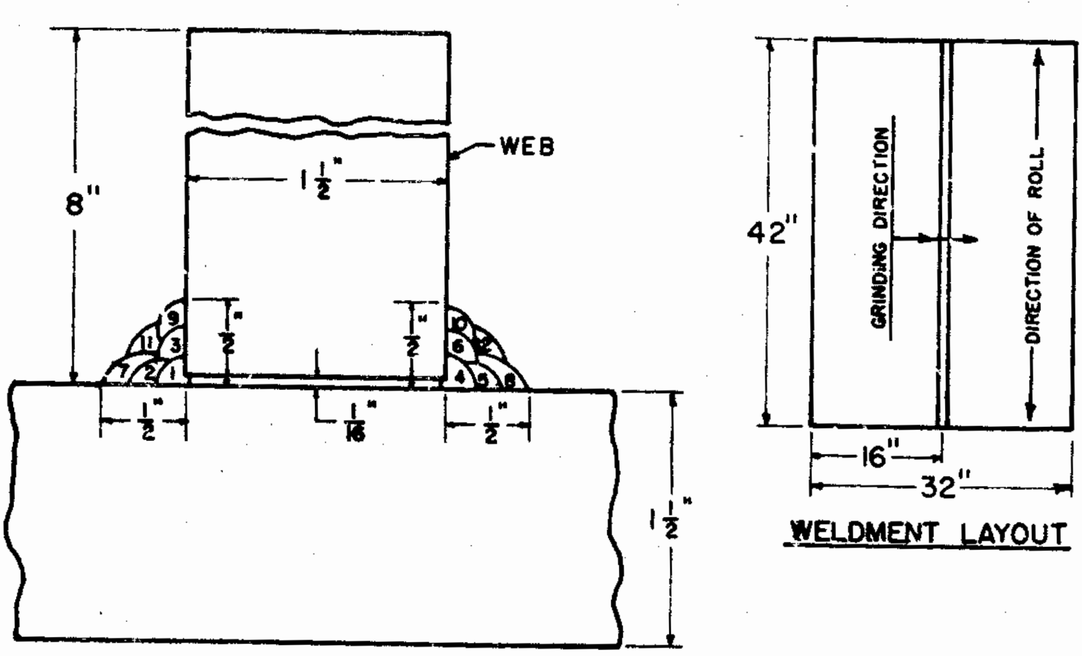



Figure 7
Joint Design for Conventional Tee- and Butt-Weldments




## PROCEDURE

| | |
|---|---|
| BASE METAL: | HY-80 |
| ELECTRODE: | MIL-E-11018, 1/8" DIAMETER |
| PROCESS: | MANUAL METAL ARC |
| PREHEAT: | 225° F |
| INTERPASS TEMPERATURE: | 225°-250° F |
| CURRENT AND POLARITY: | DIRECT CURRENT, REVERSED POLARITY |
| POSITION: | VERTICAL |
| HEAT INPUT: | 30,000 JOULES/INCH AVERAGE |
| VOLTS: | 22 |
| AMPS: | 110 |

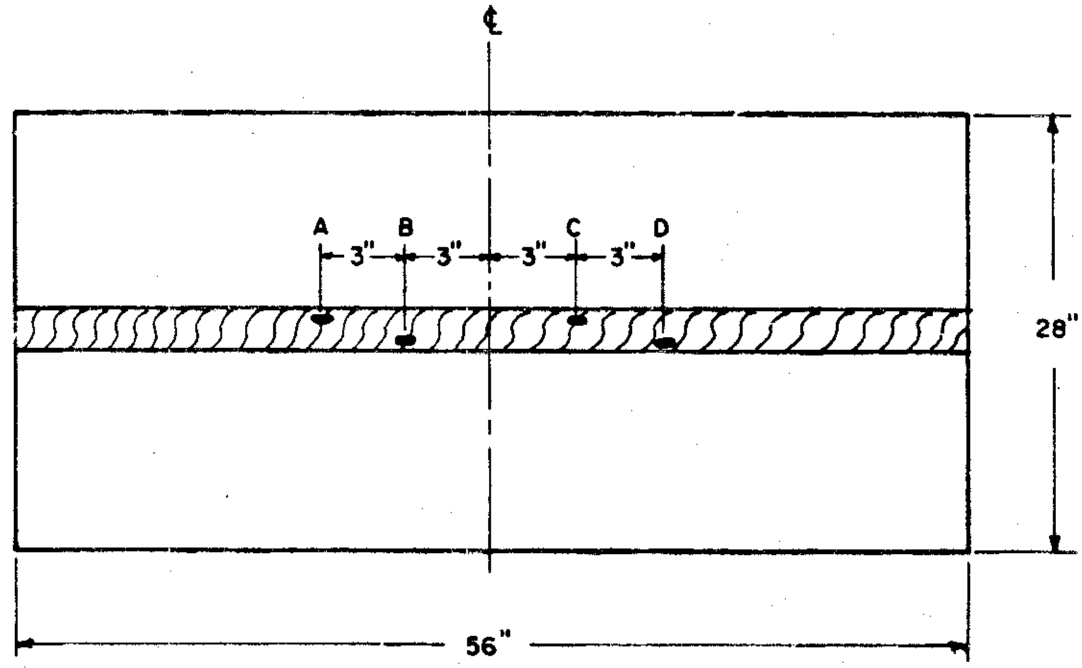
## WELDING TECHNIQUE

BACK STEP FROM TOP DOWN, IN 9" TO 12" INCREMENTS. WELDING BALANCED ON BOTH SIDES OF WEB TO PREVENT PULLING OFF CENTER

## INSPECTION

MAGNETIC PARTICLE INSPECTION OF SECOND AND FINAL WELD LAYERS.

Figure 8
Joint Design and Welding Details for 40% Efficient 1 1/2-Inch-Thick HY-80 Tee-Fillet-Welded Plates




LEGEND:

A AND D: SLAG INCLUSIONS, APPROXIMATELY $\frac{1}{2}$ IN. LONG.

B AND C: LACK OF FUSION, APPROXIMATELY $\frac{1}{4}$ IN. LONG.

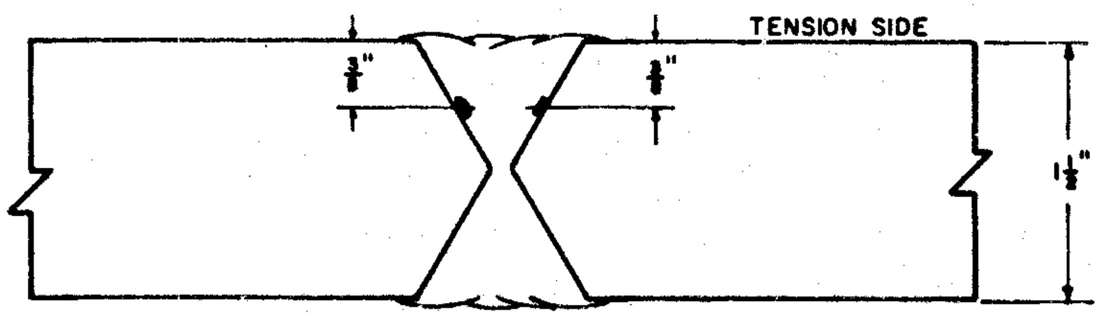



Figure 9
Location of Subsurface Weld Defects

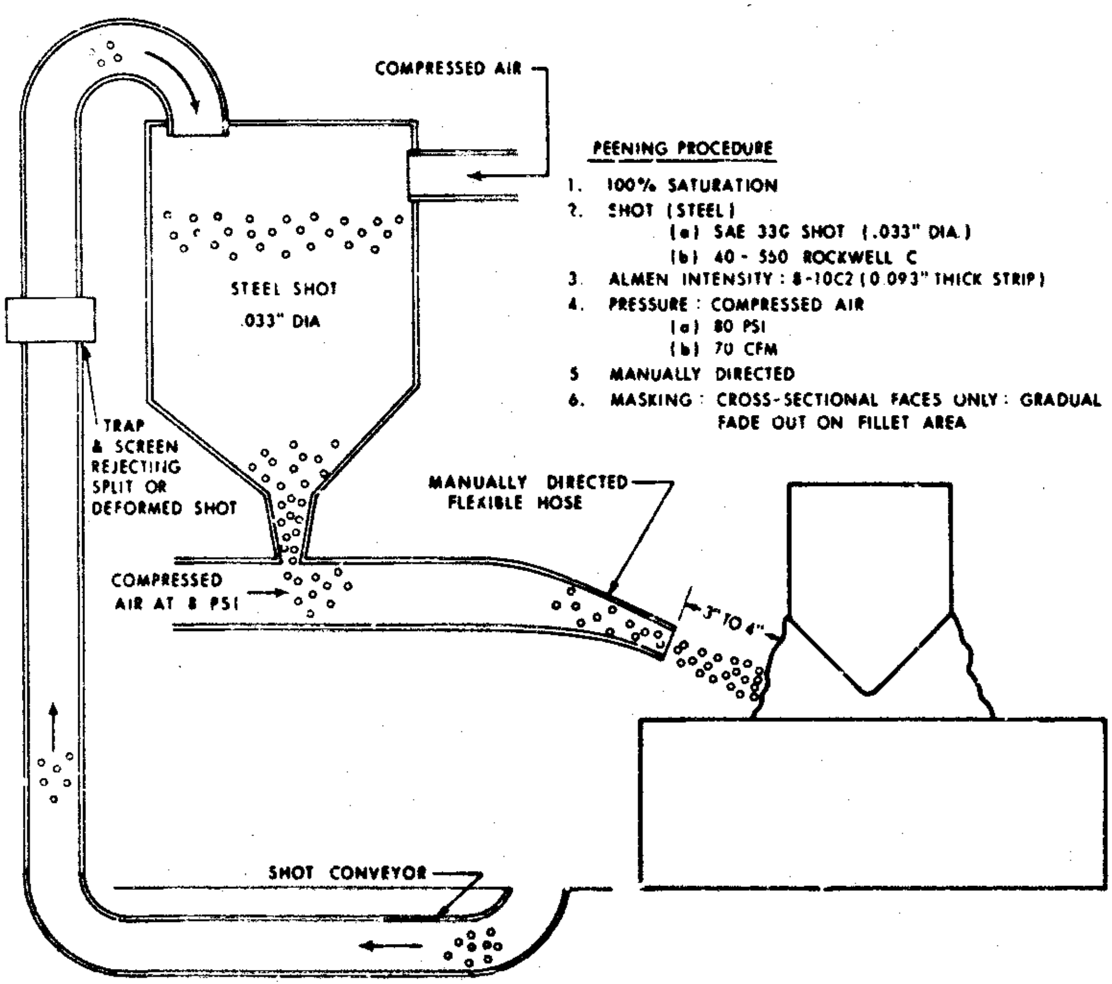



Figure 10
Shot Peening Apparatus and Procedure

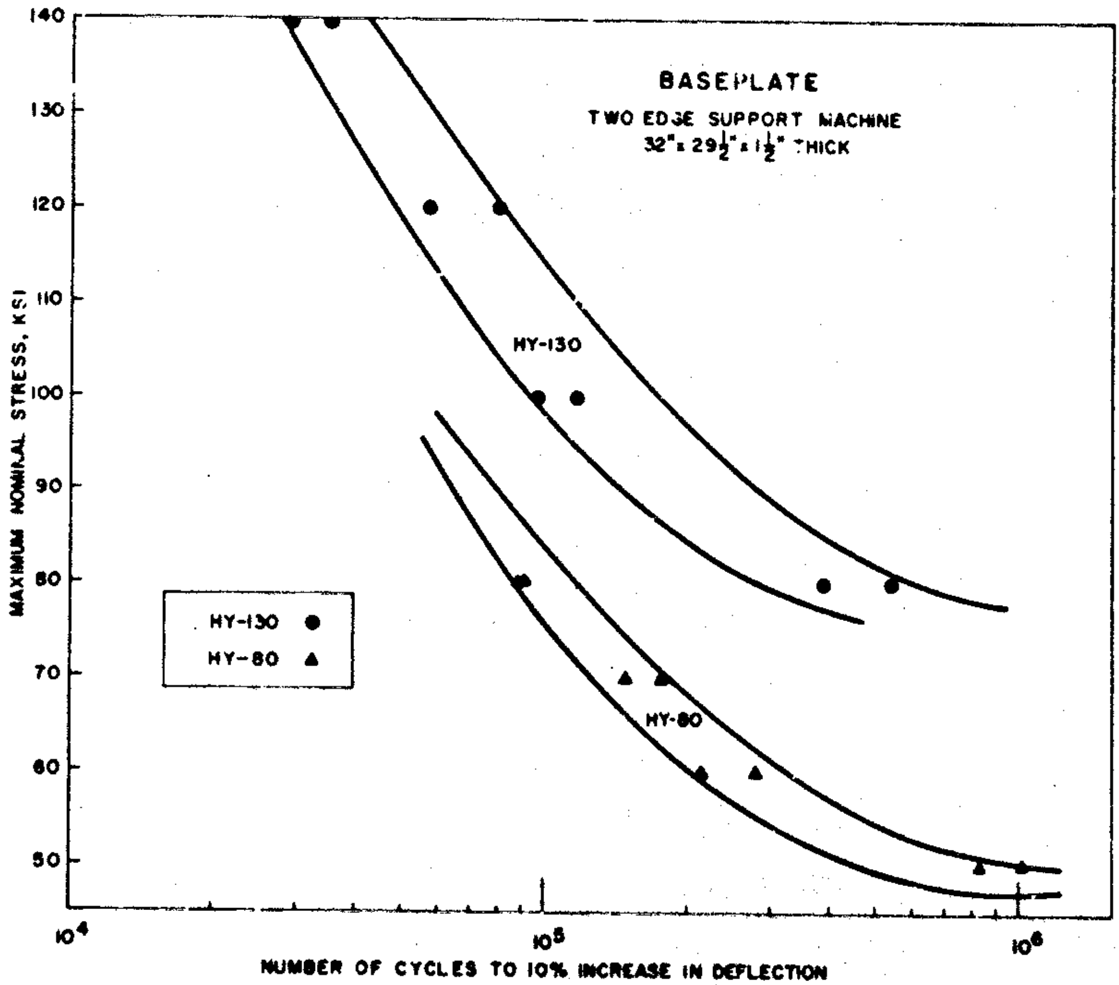



**Figure 11**
**Baseplate Fatigue Data on HY-80 and HY-130**
**Two-Edge Support Plate Specimens**

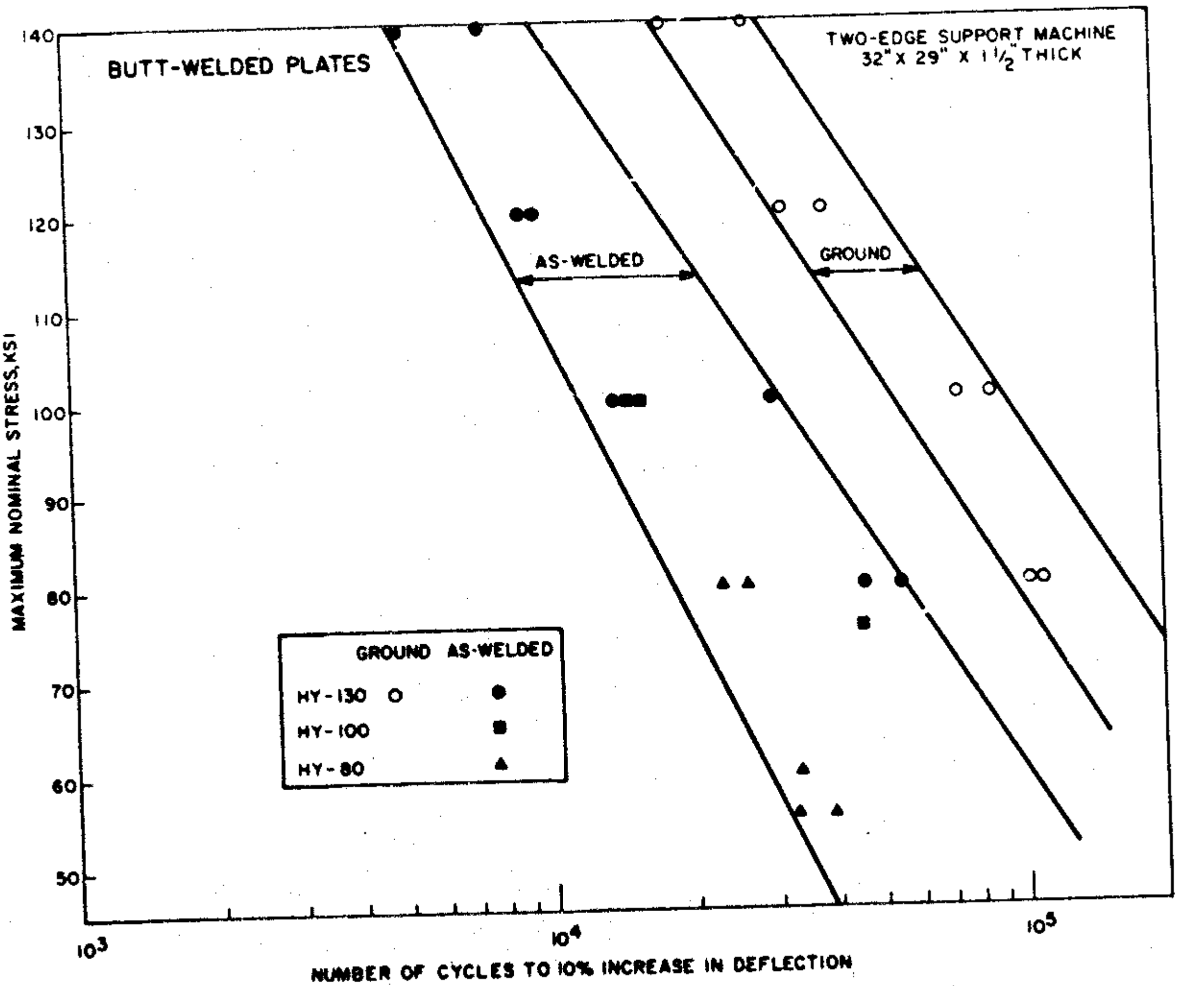



Figure 12
Butt-Weld Fatigue Data on HY-80, HY-100, and HY-130
Two-Edge Support Plate Specimens

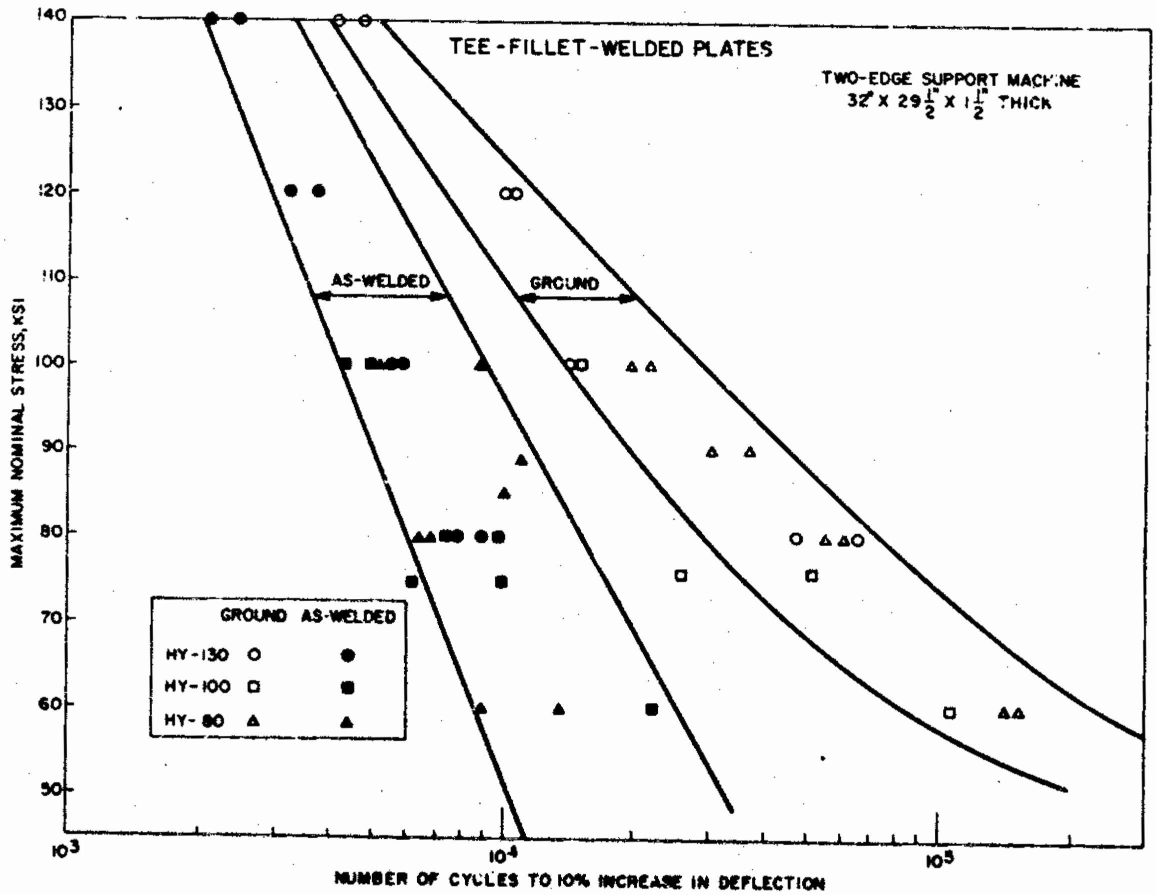



Figure 13
Tee-Fillet Weld Fatigue Data on HY-80, HY-100, and HY-130
Two-Edge Support Plate Specimens

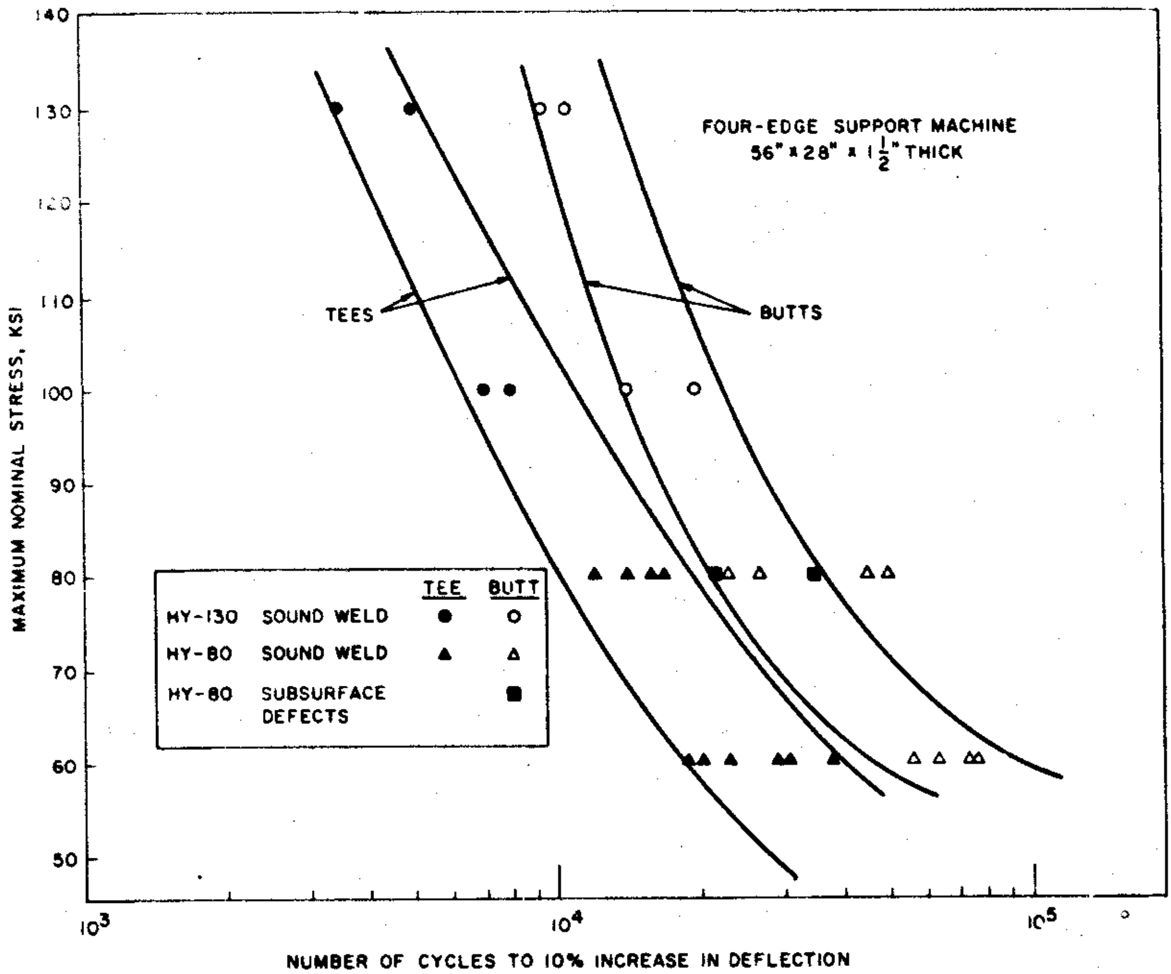



Figure 14
Butt- and Tee-Weld Fatigue Data on HY-80 and HY-130
Four-Edge Support Plate Specimens

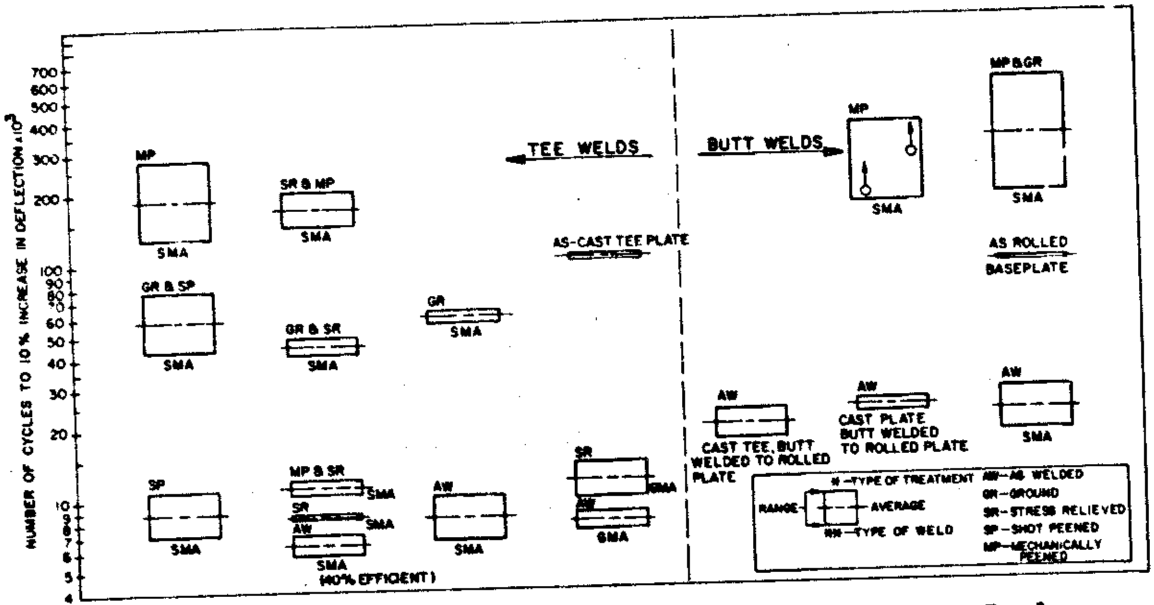


Figure 15 - Effects of Fabrication Variables on Low-Cycle Fatigue Properties of 1 1/2-Inch-Thick HY-80 Two-Edge Support Plate Specimens Under a Nominal Cyclic Flexural Stress of 0-80,000 Psi

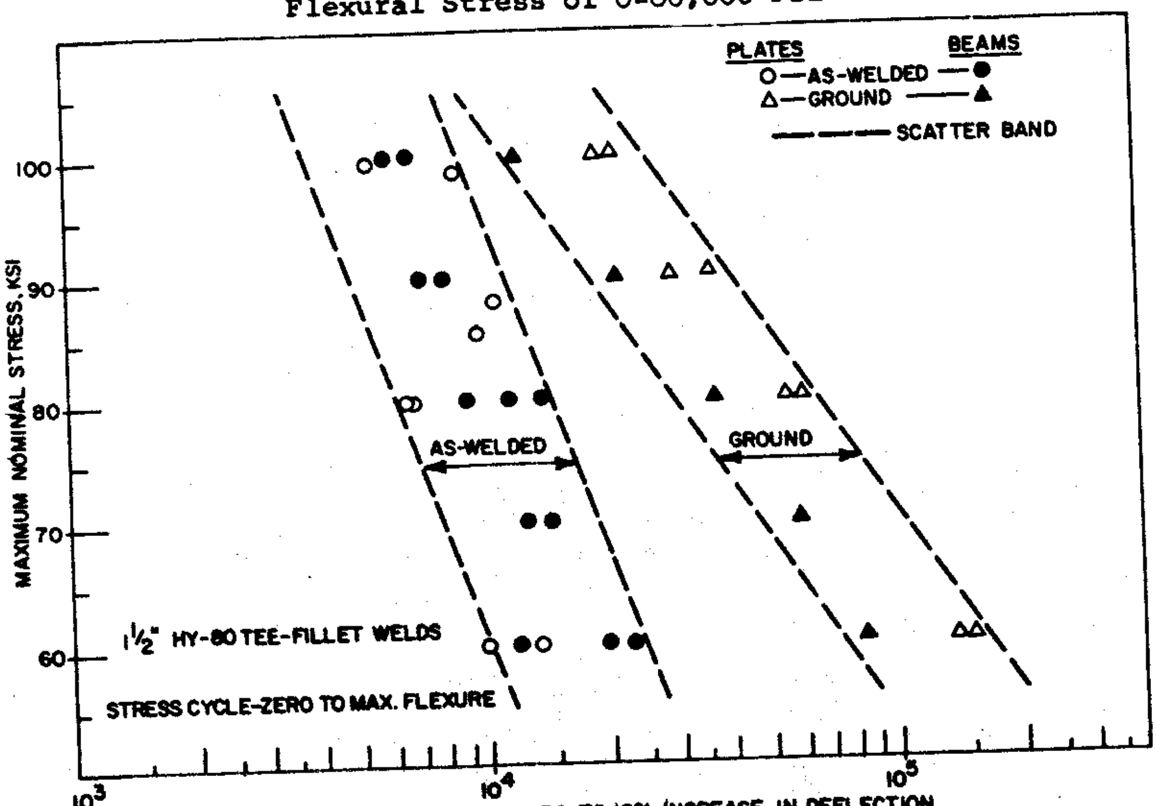


Figure 16 - Comparison of Fatigue Data for HY-80 Steel Beam- and Plate-Type Specimens

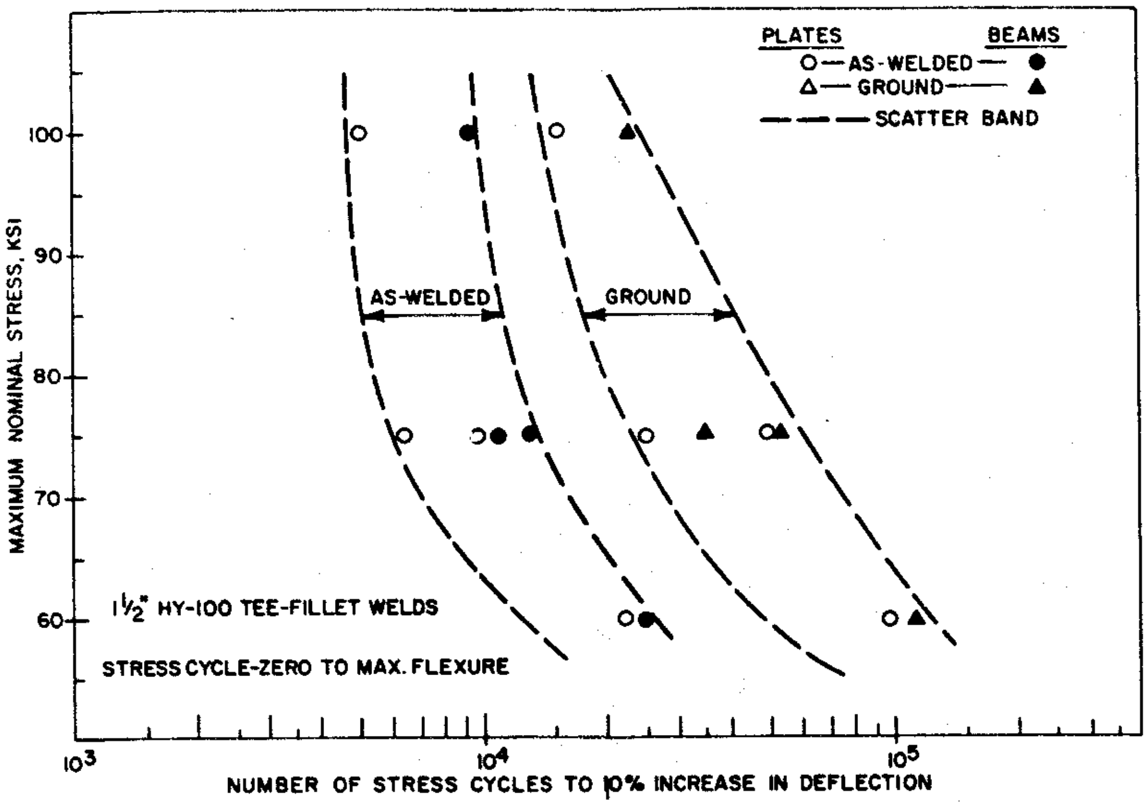



Figure 17
Comparison of Fatigue Data for HY-100 Steel
Beam- and Plate-Type Specimens

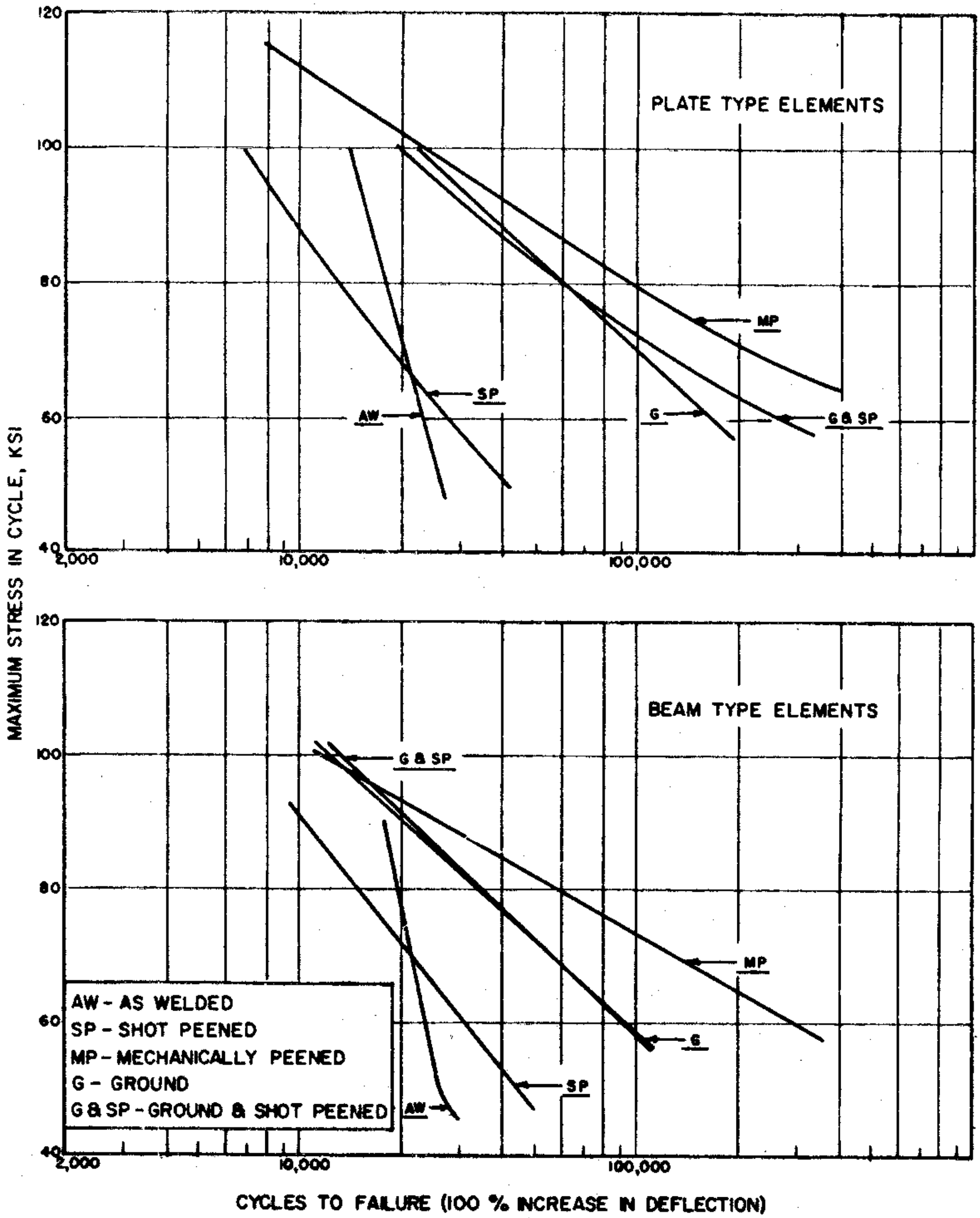



Figure 18
Comparison of Fatigue Curves for 1 1/2-Inch HY-80 Steel Tee-Fillet Welds Beam- Versus Plate-Type Elements (Stress Cycle-Zero to Maximum Flexure)

| Specimen Number | Nominal Overstress psi | Residual Stresses at Weld: σy psi | Residual Stresses at Weld: σx psi |
|---|---|---|---|
| 131M5 reference (e) | 0 | 119,300 | 101,600 |
| 307-2-12 | 75,000 Tension | 106,000 | 93,400 |
| 307-2-3 | | 43,000 | 30,750 |
| 307-2-4 | | 77,400 | 67,400 |
| 307-2-11 | | 57,900 | 71,500 |
| 307-3-11 | 110,000 Tension | -13,000 | 20,700 |
| 307-3-5 | | -11,200 | 52,500 |
| 307-4-4 | 110,000 Compression | 110,960 | 51,120 |
| 307-4-6 | | 101,700 | 90,500 |

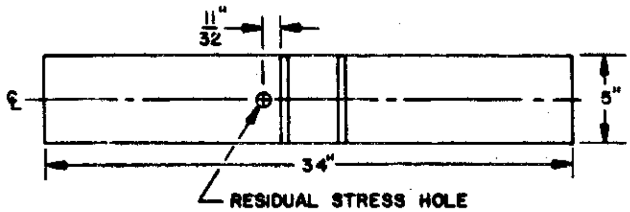



Figure 19 - Effect of Overstress on Residual Stresses at the Toe of HY-80 Steel Tee-Fillet Welds

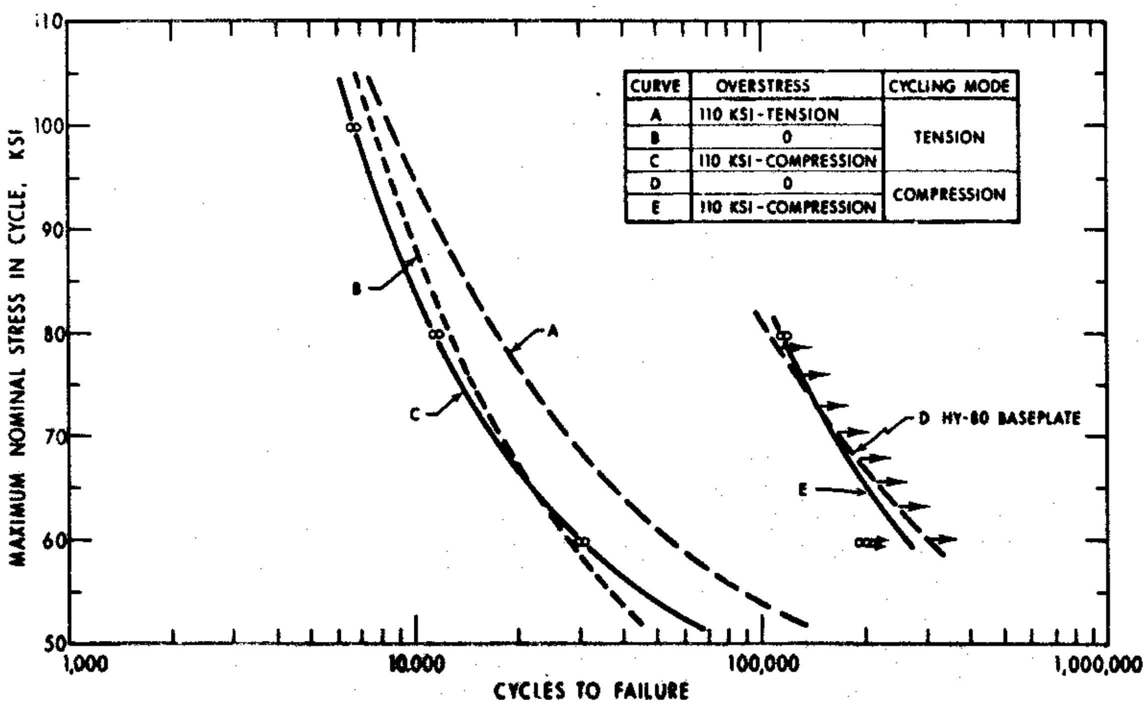



Figure 20 - Effect of Overstress on Fatigue Life of As-Welded HY-80 Steel Tee-Fillet-Welded Beam Specimens

APPENDIX A

BIBLIOGRAPHY OF FATIGUE REPORTS HY-80, HY-100, AND HY-130 STEEL BEAM- AND PLATE-TYPE SPECIMENS

1 - "Crack Growth Properties of Welds in HY-80, HY-100, and HY-130/150 High Strength Steels in a Sea-Water Environment," NASL Lab proj 9300-1, Tech Memo 39 (16 Sep 1965)

2 - "Development of Economical Beam Type Structural Element for Simulated Fatigue Evaluations (HY-80 Tees), "NASL Lab proj 930-23, Tech Memo 9 (18 Oct 1967)

3 - "Development of NASL Mechanical Peening Procedure for Improvement of Fatigue Properties of HY-80 Welds," NASL Lab proj 9300-1, Prog Rept 1 (15 Apr 1964)

4 - "Effect of Grinding on Fatigue Life of Tee Weldments," NASL Lab proj 9300-1, Tech Memo 11 (8 July 1964)

5 - "Effects of Grinding and Shot Peening on Fatigue Life of Tee-Weldments (HY-80)," NASL Lab proj 9300-1, Tech Memo 18 (30 Sep 1964)

6 - "Effect of Overstrain on Fatigue and Residual Stresses; HY-80 Steel Tee-Fillet Welded Beam Type Elements; NASL Lab proj 930-23, Tech Memo 11 (20 Feb 1969)

7 - "Effect of Overstress on Fatigue and Residual Stresses; HY-80 Tee-Fillet Welded Beam Type Elements," NASL Lab proj 930-23, Tech Memo 12 (22 Apr 1969)

8 - "Effects of Shot Peening on Fatigue Life of HY-80 Tee-Fillet Weldments," NASL Lab proj 9300-1, Tech Memo 15 (25 Aug 1964)

9 - "Effects of Stress Relieving on Manual Metal Arc (MMA) and Metal Inert Gas Spray Arc (MIG) HY-80 Tee Weldments;" NASL Lab proj 9300-1, Prog Rept 6 (27 Apr 1967)

10 - "Effects of Welding on Fatigue Properties of HY-80 Steel," NAVSHIPYDNYK MATLAB proj 6160-2, Prog Rept 2 (15 Apr 1960)

11 - "Fatigue Machine for Large Scale Uniformly Loaded, Simply Supported Rectangular Plates," NASL Lab Proj 9300-23, Tech Memo 3 (3 Feb 1966)

12 - "Fatigue of Iron Base Alloys; HY-80 Steel Cast Tees," NAVSHIPYDNYK MATLAB proj 6160-2, Prog Rept 7 (28 June 1963)

13 - "Fatigue of Iron Base Alloys HY-80 Steel Cast Tees Butt-Welded to Rolled Section, Single and Double Weld Joint Design," NASL Lab proj 9300-1, Tech Memo 19 (14 Dec 1964)

14 - "Fatigue of Iron Base Alloys, HY-80 Steel, Rolled Plate to Cast Plate, Butt-Welds; Peened Tee-Fillet and Ground Tee-Fillet Welds," NAVSHIPYDNYK MATLAB proj 6160-2 (16 Sep 1963)

15 - "Fatigue of Large Scale, Uniformly Loaded, Simply Supported Butt-Welded Rectangular Plates (HY-80)," NASL Lab proj 930-23, Prog Rept 6 (5 Feb 1968)

16 - "Fatigue of Large Scale, Uniformly Loaded, Simply Supported Butt-Welded Rectangular Plates (HY-80)," NASL Lab proj 930-23, Prog Rept 9 (20 Nov 1968)

17 - "Fatigue of Large Scale, Uniformly Loaded, Simply Supported Butt-Welded Rectangular Plates (HY-80 Butts)," NASL Lab proj 9300-23, Tech Memo 8 (23 June 1967)

18 - "Fatigue of Structural Elements; Measurement of Residual Stresses at Tee-Fillet Welds in HY-80 Steel," NASL Lab proj 9300-23, Tech Memo 2 (19 Oct 1964)

19 - "Fatigue of Large Scale Uniformly Loaded, Simply Supported Tee-Fillet Welded Rectangular Rib-Stiffened Plates (HY-80)," NASL Lab proj 9300-23, Tech Memo 6 (30 Dec 1966)

20 - "Fatigue of Large Scale, Uniformly Loaded, Simply Supported Tee-Fillet Welded Rectangular Rib-Stiffened Plates (HY-80)," NASL Lab proj 9300-23, Tech Memo 7 (11 Mar 1967)

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13. ABSTRACT

Information and data, accumulated over the past decade, on low-cycle fatigue behavior of large-scale HY-80, HY-100, and HY-130 steel weldments and on the effects of various postweld treatments are presented. Baseplate, tee- and butt-welded fatigue specimens are covered, in addition to postweld treatments such as mechanical peening, shot peening, stress relieving, grinding, and overstressing. The information will be especially useful to designers of welded structures that are subjected to repeated loads such as submarines and surface ships.

(Author)

| 14 KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| Low-cycle fatigue | | | | | | |
| Steel weldments | | | | | | |
| Postweld treatments | | | | | | |
| Peening | | | | | | |
| Stress relieving | | | | | | |
| Grinding | | | | | | |
| Overstressing | | | | | | |
| Loading | | | | | | |