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EXPERIMENTAL STUDY OF FILLET WELD UNDERCUT EFFECTS ON WELDED TUBING STRUCTURES UNDER CENTRIC AND ECCENTRIC CYCLIC LOADINGS

FRC Report No. 5896-10

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1. INTRODUCTION

Very limited amounts of experimental data are available relating to weld undercut effects on permanent deformation and performance of fillet welded structural members under centric and eccentric cycling loading. Undercutting of fillet welds is usually a result of a welding arc that is too long and can be eliminated with proper welding procedures. Nevertheless, weld undercutting does occur occasionally and the question to be answered in these cases is whether or not it is harmful to structural integrity.

Under a contract between Franklin Research Center (FRC) and the U.S. NRC's Engineering and Generic Communications Branch, Office of Inspection and Enforcement, FRC designed, fabricated, and tested six fillet welded tubing specimens under centric and eccentric cycling loading. The main purpose of this testing program was to evaluate the effects of fillet weld undercut on the permanent deformation, yield load, and ultimate load values of the tested specimens.

2. SUMMARY

FRC Report No.	Report Title:
5896-10	Experimental Study of Fillet Weld Undercut Effects on Welded Tubing Structures Under Centric and Eccentric Cycling Loadings
Conducted and Reported by:	Conducted for:
Franklin Research Center Division of Arvin/Calspan Twentieth and Race Streets Philadelphia, PA 19103	Engineering and Generic Communications Branch Office of Inspection and Enforcement U.S. Nuclear Regulatory Commission Washington, DC 20555
Report Date: November 26, 1985	Period of Test Program: June through September 1985

Objective:

To design, fabricate, and test six fillet welded tubing specimens under centric and eccentric cycling loading. The main purpose of this testing program was to evaluate the effects of fillet weld undercut on the permanent deformation, yield load, and ultimate load values of the tested specimens.

Equipment Tested:

Three centrically loaded weld specimens with 0, 1/32-, and 1/16-in undercuts.
Three eccentrically loaded weld specimens with 0, 1/32-, and 1/16-in undercuts.

Elements of Program:

Cyclically load each specimen to the ultimate load (Pu) of the specimen with no undercut, starting at 50% of Pu until failure occurs. Load was increased at 10% increments. Each load level was applied 10 times.

Results and Conclusions:

- For centric and eccentric specimens subjected to cyclic loading, the permanent deflection/load ratio relationship is nonlinear.
- For a centric specimen of 1/32-in fillet weld undercut, the deflection radio (d/do) varies randomly from 0.9 to 2.0 at load ratios (P/Py) between 0.6 and 0.9, whereas for an eccentric specimen of the same fillet weld undercut, it varies from 0.6 to 1.4 at load ratios between 0.5 and 0.9.
- The effect of 1/16-in fillet weld undercut on the permanent deflection ratio is significant. For a centrically loaded specimen, d/do varies from 10.0 to 12.0 after 1 load cycle between 0.5 and 0.8 load ratios, whereas after 10 load cycles, it varies from 3.7 to 9.2 at load ratios between 0.5 and 0.7. The effect on an eccentric specimen is less significant where d/do varies from 1.0 to 2.6 at P/Py between 0.5 and 0.9.
- The effect of a 1/32-in fillet weld undercut on reducing ultimate load values is negligible.
- The reduction of the ultimate load values of the 1/16-in fillet weld undercut specimens is noticeable (about 20% for centric specimen and 11% for eccentric specimen)

3. SCOPE OF WORK

The following presents the scope of work as indicated in the NRC's form "Request for Test or Analysis" and subsequent written correspondence and telephone communications between FRC and NRC:

1. Determine yield strength, Fy, of two standard 8-in tensile test specimens (T1 and T2) of base material cut from structural tubing (TS 4 x 4 x 0.25 in). The test specimens and procedures are based on ASTM, E8 specifications (see Appendix A for details).

2. To evaluate the adequacy of the welding quality, determine yield strength, Fy, of two standard 8-in tensile test specimens (W1 and W2). Each specimen consists of two plates cut from TS 4 x 4 x 0.25 in and welded together by complete penetration groove welds across the middle of the gage length.

3. Design, fabricate, and test a total of six fillet welded tubing specimens. Three of these specimens (S1, S2, and S3) will be subjected to centric cyclic loading (bending moment and shearing force), and the other three (S4, S5, and S6) will be tested under eccentric cyclic loading (bending moment, torsional moment, and shearing force).

Appendix B shows the details of the six specimens.

The main objective of the testing is to measure permanent deflection, d, after 1, 5, and 10 load cycles at 10% increments starting from 50% through 100% of the calculated yield load, Py, or to the ultimate load, Pu, whichever is greater. The collected data will be used to evaluate the effects of fillet weld undercut on the permanent deformation, yield load, and ultimate load values of defective specimens compared with the good welded specimens.

4. LITERATURE SEARCH

A comprehensive literature search was conducted using the Dialog Information Retrieval Service, WELDASEARCH, which is the database of The Welding Institute. The search produced 42 technical papers related to fillet weld undercut. The abstract of each of these papers was reviewed for initial screening and only three of them [1, 2, 3] were found to be directly related to the scope of work of this task. None of the 42 technical papers presented data or information of experimental testing of structural members under cyclic loading to evaluate the effects of fillet weld undercut.

In Reference 1, the fitness for service of fillet welded T-joints, with and without undercut, was investigated by computer calculations of weld stresses. The finite-element method was used for the analysis of T-joints in plane stress condition under static loads. Some photoelastic stress measurements were made to check the validity of the computer calculations. The effect of undercut was studied according to its size, shape, and location with respect to the loading directions. Stress concentration and local yielding caused by undercut were then determined. Some recommendations for the acceptance standard of weld undercut in fillet welded T-joints were presented.

Reference 1 concluded that undercut flaws on fillet welded T-joints can be related to three significant variables: size, shape, and location:

1. Undercut size. The size effect is reflected by the loss of cross-sectional area which is insignificant when compared to the shape effect.

2. Undercut shape. High stress concentration is expected when the toe radius of a flat fillet or the tip radius of an undercut is small. An undercut with a relatively large tip radius does not necessarily mean higher stress concentration than encountered with a flat fillet having sharp toes. Rounded undercut, in fact, reduces the actuity of fillet toe and relaxes the stress concentration.

3. Undercut location. The upper toes are subjected to higher stress when the load is applied at lower angles (from 0 to 70 degrees). The high stress location shifts toward the lower toes when the load angle becomes larger than 70 degrees. At a 90-degree loading angle, the highest stress appears at the lower toes. This implies that any undercut existing at noncritical fillet toes will not affect the joint integrity in any form.

Reference 2 described pulsating bending fatigue strength tests which were performed to investigate the effect of undercutting on the fatigue strength of machine-made submerged arc fillet welds (double-fillet welds at T-joints, material DH36 shipbuilding plate, plate thickness 25 mm). The number of stress cycles leading to incipient cracking was determined. The shape parameters for the undercut were depth, length, and radius of curvature. The mechanics of fracture were considered.

The basic conclusion of Reference 2 was that for cyclic bending stress, undercutting in machine-made fillet welds essentially reduces mechanical strength by shortening the crack propagation phase. In contrast to this, the incipient crack phase is largely unaffected. With regard to its effect on fatigue strength, undercutting can be evaluated by its depth, whereas the effects of axis of ratio and the radius of the bottom of the undercut are within the usual range of scatter. In other words, to lay down a limit on admissibility, it is enough to specify an admissible depth of undercut.

Reference 3 reports the results of an investigation of the influence of notching on the local stress value in the toe region of fillet welds. A distinction was made between "primary" and "secondary" notches. Although these do have an adverse effect on the weld, they are not defects in the true sense. In order to illustrate the disadvantages of notching (e.g., on fatigue strength), the results of a series of tests in which a distinction was drawn between undercut and edge notches were presented. The factors of notch depth and sharpness (notch radius) were considered to be of primary importance.

The effect of undercut, due to loss of cross-sectional area or stress concentration was studied by analyzing two types of undercut specimens: V-shape undercut (U-groove) and semicircular undercut (C-groove). It was concluded that the groove tip acuity plays a more significant role in the local stress concentration than the reduction of cross-sectional area.

5. TEST PROGRAM

5.1 TEST SPECIMENS

As shown in Appendix B, two types of test specimens were designed: one for centric load (three specimens S1, S2, and S3) and the other for eccentric load (three specimens S4, S5, and S6). Each one of the six specimens consists of a 1-in-thick middle plate (A588 steel) welded on both sides to a TS 4 x 4 x 0.25 member (A 500 B) by an all-around 1/4-in size, single pass, fillet weld (E7018). These fillet welded connections are at the critical sections of any specimen, and consequently were subjected to the highest stress level at any loading level. All fillet welds at the critical sections were inspected by dye penetrant testing to guarantee that they were good welds (free from defects such as cracks and porosity) before the testing was performed. Specimens S1 and S4 were reference specimens and represented a good solid fillet weld (i.e., no undercutting). Since the AWS code allowance for weld undercut size is 1/16 of an inch in depth regardless of the groove tip acuity, the semicircular machine-made undercut was chosen for use in this experimental study as representative of the man-made undercut. A machine-made semicircular undercut of 1/32 of an inch in depth for S2 and S5 and 1/16 of an inch in depth for S3 and S6 was made at the intersection of the fillet weld toe with the tubing section.

5.2 TEST SETUP

5.2.1 Testing Machine

A Baldwin Universal tensile-compression hydraulic testing machine of 120 kips capacity was used. The machine sensitivity was 0.2 kips. Based on a certified standard calibration test done at the beginning of the testing program, the machine accuracy across the capacity range was verified to be within a tolerance of $\pm 1\%$.

5.2.2 Deflection Measurements

Two identical deflectometers of 0.0005-in sensitivity and $\pm 1\%$ accuracy were mounted under the test specimens at equal distances from the center line. The deflectometers were used to measure maximum deflection values at the

mid-span section of the specimen. The average of the deflection values of the two readings were used in the evaluation of the data. The reason for using two deflectometers is to eliminate the possible rotational effect of the specimen on the deflection values, and to reduce the probability of having defective readings due to human error or deflectometer malfunction.

5.2.3 Test Specimens Supporting Fixtures

Two supporting fixtures were designed for the centric and eccentric test specimens. The basic function of each supporting fixture was to restrain the test specimens in the vertical direction at the support points only, while allowing them to rotate freely (i.e., to simulate simply supported boundary condition). In addition, as a recommended safety feature, the fixtures were designed to secure tested specimens against any lateral movement due to unbalanced loading.

5.3 TYPE OF LOADING

As described in Section 3, all test specimens were subjected to cyclic loading to measure permanent deflection, d, after 1, 5, and 10 load cycles at 10% increments of the calculated yield load, Py, starting at 50% of Py through the ultimate load, Pu.

Figure 5-1 indicates a typical loading cycle (0-1-2-3-4) which is described as follows:

a. Loading Phase (0-1)

A constant load rate (r) of 40,000 lb/min was maintained steadily by the testing machine hydraulic control system throughout the loading phase. This loading rate was selected so the type of testing is still considered as static loading (i.e., non-inertia effect). The loading time t01 (sec) therefore depended on the load level, Pi (lb), at any particular time during the test. In other words,

$$t01 = \frac{Pi}{r} \times 60, \text{ sec}$$

b. Constant Load Phase (1-2)

This phase of the load cycle gave the specimen and welding materials enough time to react or respond to the imposed internal stresses under constant load Pi and meanwhile allowed enough time to record

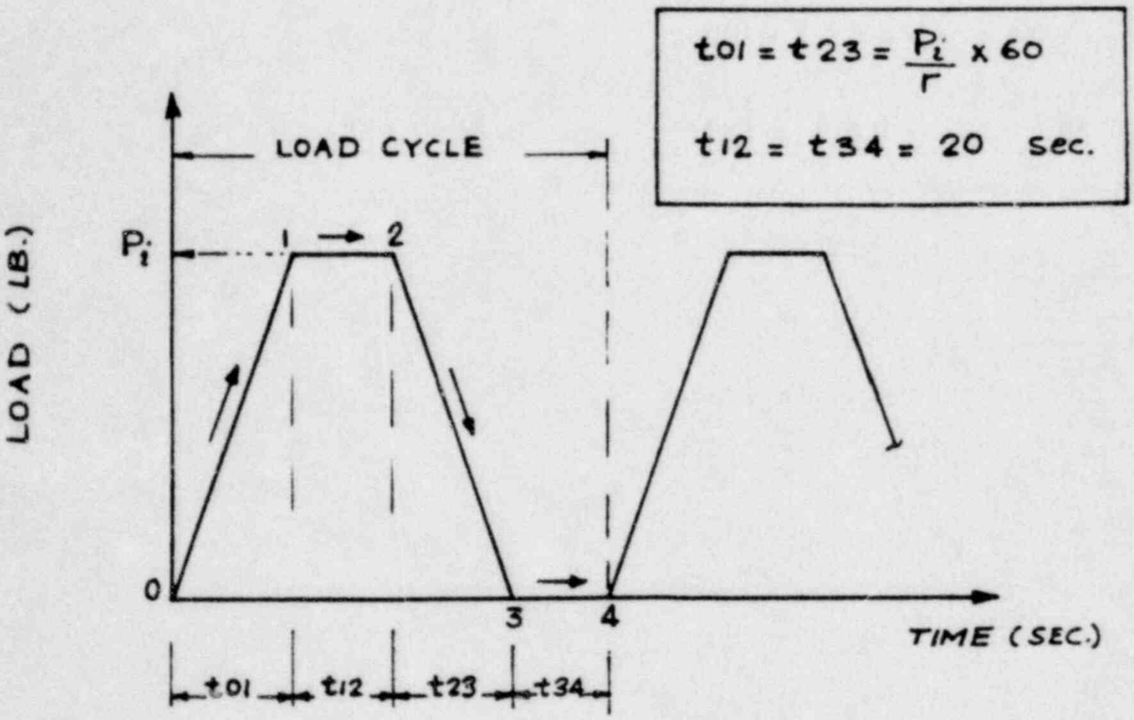

Figure 5-1. Typical Loading Cycle of All Tests

the deflectometer's readings. Based on observations of similar tests and previous experience, a 20-second period was chosen.

c. Unloading Phase (2-3)

The unloading rate of approximately 40,000 lb/min was maintained for the unloading phase. The unloading time t23 (sec), therefore, was approximately equal to the loading time to1.

d. Relaxation Phase (3-4)

During this phase, the deflectometer's readings which reflect the permanent deflection were recorded. The relaxation time, t34, was chosen to be equal to the length of the constant load phase (20 seconds).

5.4 MATERIAL PROPERTIES

Table 5-1 presents test results of four standard 8-in tensile test specimens cut from structural tubing section TS 4 x 4 x 0.25 in. Details of the tensile test specimens conform to the ASTM E8 specification as shown in Appendix A. Test specimens T1 and T2 are for base metal of the tubing section, and W1 and W2 are the complete penetration groove welded specimens. It should be noted that all tested specimens exhibit yield strength (Fy) and ultimate tensile strength (Fu) properties which exceed the ASTM minimum required value for the material of the structural tube specimen (ASTM A500 Grade B). Based on test results, the average yield strength value of the tensile test specimen 55,090 psi was used as the basis for calculating the yield load, Py, of centric and eccentric specimens.

The typical properties for the E7018 welding electrode used to prepare the specimens are 60,000 psi yield strength and 72,000 psi tensile strength.

It should be noted that when the tensile test specimens were cut from the rectangular tube, the outer surface had such a high tensile residual stress that the specimens took a camber of 1/8 inch in a length of 8 inches.

Table 5-1. Test Results of Four Standard 8-in Tensile Specimens

Specimen No.	Actual Dimensions of Critical Sections: Width (W), in	Thick. (T), in	Area (in^2) A = WT	Yield Strength, Fy: Load (lb)	Stress (psi)	Ultimate Tensile Strength, Fu: Load (lb)	Stress (psi)	Elongation (%)
T-1	0.500	0.242	0.1210	6,750	55,785	7,700	63,636	29
T-2	0.500	0.245	0.1225	7,200	58,776	8,225	67,143	26
W-1	0.500	0.241	0.1205	6,600	54,772	8,100	67,220	22*
W-2	0.500	0.243	0.1215	6,200	51,029	7,900	65,021	15**

*Failure in base metal.
**Failure in weld interface.

6. CALCULATION OF YIELD LOAD (Py)

6.1 CENTRIC LOADING SPECIMEN S1

- Yield moment based on the nominal section of modulus of the tube:

$$My = Fy \times S = 55{,}090 \times 4.11 = \underline{226{,}420} \text{ lb/in}$$

- Yield load:

$$Py = \frac{2 \times My}{11.5}$$

$$Py = \frac{2 \times 226{,}420}{11.5} = 39{,}377 \text{ lb}$$

6.2 ECCENTRIC LOADING SPECIMEN S4

The yield load, Py, is determined so that the principal stress at the critical section is equal to Fy.

Stresses at critical section due to Py:

<u>Bending</u>: $F_b = \frac{M}{S} = \frac{3.25}{4.11} Py = 0.79\ Py$

where: $M = 6.5 \times \frac{Py}{2} = 3.25\ Py$

$S = 4.11\ in^4$

<u>Shear</u>: $F_v = \frac{Mt}{2b^2t} = \frac{3.375\ Py}{2 \times 3.75^2 \times 0.25} = 0.48\ Py$

where: $M_t = 6.75 \times \frac{Py}{2} = 3.375\ Py$

$b = 3.75$ in

$t = 0.25$ in

From Mohr's circle of stress:

$$\text{Principal stress, } F_1 = \frac{F_b}{2} + \left[\frac{F_b}{2}^2 + F_v^2\right]^{1/2} = Fy$$

Substituting for F_b and F_v yields:

$$Fy = \frac{0.79}{2} Py + \left[(\frac{0.79}{2} Py)^2 + (0.48\ Py)^2\right]^{1/2}$$

$\therefore 55{,}090 = 1.106\ Py$

$\therefore Py = \frac{Fy}{1.106} = 49{,}810$ lb

7. TEST RESULTS

The test results of the six tested specimens S1 through S6 are shown on Tables 7-1 through 7-6, respectively. Each table presents deflection readings of deflectometers D1 and D2 at 10% increments of the calculated yield load, Py, starting at 50% of Py through the ultimate load, Pu. At each load level, the deflection readings recorded before unloading are given in columns marked "B" at 1, 5, and 10 load cycles. Likewise, columns marked "A" are deflection readings after unloading. It should be noted that the "A" deflection readings represent the permanent deflection of the tested specimen. The average deflection value, d, of D1 and D2 is presented in the tables along with the deflection ratios, d/do. The deflection ratio, d/do, represents the average deflection value of a defective specimen, d, versus that of the sound specimen (u = o) at the same load level and number of cycles. For centric test specimens S2 and S3, the do values used to determine deflection ratios d/do are those of specimen S1, whereas for eccentric test specimens S5 and S6, the do values used are those of specimen S4.

Visual examination of the welds indicated one weld on specimen S1 failed near the base plate where subsurface porosity was observed. On each of the other five specimens, one of the four welds failed at the weld to tube interface. Visual examination of these welds did not indicate cracks that were in existence prior to the load testing.

Table 7-1. Test Results for S1 Specimen

Load Ratio (P/Py)	Load Value (kips)	Deflectometer No.	Deflection Values (x10^{-3} in) C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Average Deflection Values (d) (x10^{-3} in) d/do C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Remarks
0.5	19.6	D1	37	0.5	38	2	38	2.5	37/1	1/1	38/1	2/1	38/1	3/1	
		D2	37	1.5	38	2.5	38.5	3							
0.6	23.6	D1	40	1.5	41	3	41	3.5	40/1	2/1	41/1	3/1	41/1	4/1	
		D2	40	2.5	41	3.5	41.5	4							
0.7	27.6	D1	50.5	6	51	7.5	50.5	8	50.5/1	6.5/1	51/1	8/1	51/1	8.5/1	
		D2	50.5	7	51.5	8.5	51	9							
0.8	31.5	D1	57	10	58.5	11.5	59.5	12	57/1	10.5/1	59/1	12/1	59.5/1	12/1	
		D2	57	11	59	12	59.5	12.5							
0.9	35.4	D1	69	18.5	73	21.5	75	23	69/1	19/1	73/1	22/1	75/1	23/1	Starting of yield
		D2	69	19	73	22	75	23.5							
Pu	39.0	D1													Deflection readings increased rapidly with decreasing load.
		D2													

B: Deflection readings before unloading
A: Deflection readings after unloading (i.e., permanent deflection)
Pu: Ultimate load
C: No. of load cycles
do: Average deflection value, d, of specimen S1.

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Table 7-2. Test Results for S2 Specimen

Load Ratio (P/Py)	Load Value (kips)	Deflectometer No.	Deflection Values ($\times 10^{-3}$ in) C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Average Deflection Values (d) ($\times 10^{-3}$ in) / d/do C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Remarks
0.5	19.6	D1	30.5	4	31	4	31	4	29.5	3	30	3	30	3	
		D2	28.5	2.5	29.5	2.5	29.5	2.5	0.8	3.0	0.79	1.5	0.79	1.0	
0.6	23.6	D1	37	5	37	5.5	37.5	5.5	36	4	36	4.5	36.5	5	
		D2	35	3.5	35	3.5	35.5	4	0.9	2.0	0.88	1.5	0.89	1.25	
0.7	27.6	D1	45.5	7.5	45.5	8	46	8.5	44	6.5	44	7	44.5	7.5	
		D2	42	5.5	42.5	6	43	6.5	0.87	1.0	0.86	0.88	0.87	0.88	
0.8	31.5	D1	58	13.5	59.5	15	58	15	56.5	13	58	14	56.5	14.5	
		D2	55	12	57	13.5	55	14	0.99	1.24	0.98	1.17	0.95	1.21	
0.9	35.4	D1	74	24.5	75.5	24.5	75	27	73	24	74.5	24	73	26	
		D2	71.5	23.5	73.5	24	71.5	25.5	1.06	1.26	1.02	1.09	0.97	1.13	
1.0	39.4	D1	90.5	40.5	96.5	45	100.5	48.5	89	39.5	95	44	99	50.5	d values do not exist
		D2	87.5	38.5	93.5	43.5	97.5	52.5	*	*	*	*	*	*	for S1 specimen.
Pu	42.7	D1													Deflection readings increased rapidly with decreasing load.
		D2													

B: Deflection readings before unloading
A: Deflection readings after unloading (i.e., permanent deflection)
Pu: Ultimate load
C: No. of load cycles
do: Average deflection value, d, of specimen S1.

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Table 7-3. Test Results for S3 Specimen

Load Ratio (P/Py)	Load Value (kips)	Deflectometer No.	Deflection Values (x10^{-3} in) C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Average Deflection Values (d) (x 10^{-3} in) / d/do C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Remarks
0.5	19.6	D1	41.5	10.5	42.5	11	42.5	11	41.5	10	42.5	11	42	11	
		D2	41.5	9.5	42.5	10.5	42	10.5	1.12	10.0	1.12	5.5	1.11	3.67	
0.6	23.6	D1	55	19.5	59.5	23	62	25	55	19	60	23	62	25	
		D2	54.5	18.5	60	22.5	62	24.5	1.38	9.50	1.46	7.67	1.51	6.25	
0.7	27.6	D1	102	61.5	112.5	69.5	121.5	78	102	60.5	112.5	69	121	78	
		D2	102.5	59.5	112.5	69	121	77.5	2.02	10.0	2.21	8.63	2.37	9.18	
0.8	31.5	D1	220.5	125.5					220.5	126					Failure at load 29.0 kip of the second loading cycle
		D2	220.5	126.5					3.87	12					
Pu	31.5	D1													
		D2													

B: Deflection readings before unloading
A: Deflection readings after unloading (i.e., permanent deflection)
Pu: Ultimate load
C: No. of load cycles
do: Average deflection value, d, of specimen S1.

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Table 7-4. Test Results for S4 Specimen

Load Ratio (P/Py)	Load Value (kips)	Deflectometer No.	Deflection Values ($\times 10^{-3}$ in) C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Average Deflection Values (d) ($\times 10^{-3}$ in) d/do C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Remarks
0.5	24.9	D1	53.5	8.5	53	9.5	53	9.5	53/1	9/1	53/1	9.5/1	52.5/1	9.5/1	
		D2	53	9	52.5	9.5	52	9.5							
0.6	29.9	D1	60.5	10	61	10	61.5	10.5	60/1	10/1	60.5/1	10/1	61/1	10.5/1	
		D2	59.5	10	60	10	60.5	10.5							
0.7	34.9	D1	71	14	73.5	15	74	16	71/1	14/1	73/1	15/1	74/1	16/1	
		D2	70.5	13.5	73	15	73.5	15.5							
0.8	39.8	D1	88	24	92.5	26.5	93.5	27.5	88/1	24/1	93/1	27/1	94/1	28/1	
		D2	88.5	24	93.5	27	95	27							
0.9	44.8	D1	120.5	48.5	127	54	129	56	122/1	49/1	129/1	55/1	131.5/1	57/1	
		D2	124	50	131	55.5	134	58							
1.0	49.8	D1	200.5	121.5	213	133	217.5	148	205/1	123.5/1	217/1	134.5/1	222.5/1	150/1	
		D2	209.5	125	221	136	227.5	152							
Pu	50.3	D1													Deflection readings increased rapidly with decreasing load
		D2													

B: Deflection readings before unloading
A: Deflection readings after unloading (i.e., permanent deflection)
Pu: Ultimate load
C: No. of load cycles
do: Average deflection value, d, of specimen S4.

Table 7-5. Test Results for S5 Specimen

Load Ratio (P/Py)	Load Value (kips)	Deflectometer No.	Deflection Values ($x10^{-3}$ in) C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Average Deflection Values (d) (x 10^{-3} in) / d/do C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Remarks
0.5	24.9	D1	51.5	6.5	53	7.5	53	7.5	47	5	49	6	49	6	
		D2	43	4	44.5	4	44.5	4.5	0.89	0.56	0.92	0.63	0.93	0.63	
0.6	29.9	D1	63	10	64	10.5	65	11	58	8.5	59.5	9	60	9	
		D2	53.5	7	55	7.5	55.5	7.5	0.97	0.85	0.98	0.9	0.98	0.86	
0.7	34.9	D1	76	15	78.5	16.5	79	17	71	13.5	74	15	74	16	
		D2	66.5	12	69	13.5	69.5	14.5	1	0.96	1.01	1	1	1	
0.8	39.8	D1	97.5	28.5	102.5	32	103	33	93	27	98	31	99	32	
		D2	88.5	26	93.5	29.5	95.4	30.5	1.06	1.13	1.05	1.15	1.05	1.14	
0.9	44.8	D1	143	70	151.5	74	154.5	77	140	68.5	148	73.5	151	76.5	
		D2	137	67	145	73	147.5	76	1.15	1.40	1.15	1.34	1.15	1.34	
1.0	49.8	D1	279	186					274	183					Weld failed at 49.4 kips on the fifth cycle.
		D2	268.5	179.5					1.34	1.48					
Pu	49.8	D1													
		D2													

B: Deflection readings before unloading
A: Deflection readings after unloading (i.e., permanent deflection)
Pu: Ultimate load
C: No. of load cycles
do: Average deflection value, d, of specimen S4.

5896-10

Table 7-6. Test Results for S6 Specimen

Load Ratio (P/Py)	Load Value (kips)	Deflectometer No.	Deflection Values ($x10^{-3}$ in) C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Average Deflection Values (d) ($x 10^{-3}$ in) d/do C = 1 B	C = 1 A	C = 5 B	C = 5 A	C = 10 B	C = 10 A	Remarks
0.5	24.9	D1	44	2	45	3	46	4	50	8.5	51	8.5	51.5	9	d/do less than 1.0
		D2	53	9	52.5	9.5	52	9.5	0.94	0.94	0.96	0.98	0.98	0.95	
0.6	29.9	D1	58	8	60	9	61	9	63	13	65	14	66	14	
		D2	68	18	70	19	71	19	1.05	1.30	1.07	1.40	1.08	1.33	
0.7	34.9	D1	76	19	80	21	81	22	81.5	24.5	86	26.5	86.5	27.5	
		D2	87	30	92	32	92	33	1.15	1.75	1.18	1.77	1.17	1.72	
0.8	39.8	D1	113	47	120	53	122	56	117.5	52	125	58	127	60.5	
		D2	122	57	130	63	132	65	1.34	2.17	1.34	2.15	1.35	2.16	
0.9	44.8	D1	193	119	206	132	213	141	197	124	211.5	137.5	221.5	148	
		D2	201	129	217	143	230	155	1.61	2.53	1.64	2.50	1.68	2.60	
Pu	44.8	D1													Specimen (weld) failed at 44.6 kips load (first) cycle of P/Py = 1.0
		D2													

B: Deflection readings before unloading
A: Deflection readings after unloading (i.e., permanent deflection)
Pu: Ultimate load
C: No. of load cycles
do: Average deflection value, d, of specimen S4.

8. EVALUATION OF TEST RESULTS

The test results for the centric and eccentric specimens shown in Tables 7-1 through 7-6 are used in this section to evaluate the effects of fillet weld undercut on the permanent deformation, yield load, and ultimate load values of the tested specimens.

8.1 PERMANENT DEFLECTION (d) VERSUS LOAD RATIO (P/Py)

The relationship between permanent deflection (d) and load ratio (P/Py) after 1, 5, and 10 load cycles is shown in Figures 8-1 through 8-3 for centric test specimens and in Figures 8-4 through 8-6 for eccentric test specimens. The behavior of the tested specimens as shown in Figures 8-1 through 8-6 can be summarized as follows:

1. Under cyclic loading starting from a load ratio of 0.5, the permanent deflection/load ratio relationship is nonlinear. The P/Py rate of change with respect to permanent deflection, d, decreases with increasing values of d.

2. For the centrically and eccentrically loaded specimens of 1/32-in fillet weld undercut (S2 and S5, respectively), permanent deflections after 1, 5, and 10 load cycles are generally slightly higher than that of the sound specimens (S1 and S4, respectively).

3. For the centrically and eccentrically loaded specimens of 1/16-in fillet weld undercut (S3 and S6, respectively), permanent deflections after 1, 5, and 10 load cycles are much higher than those of the sound specimens (S2 and S4). However, it should be noted that this behavior is more obvious for centric specimen S3 than for eccentric specimen S6.

8.2 EFFECT OF NUMBER OF LOAD CYCLES (C) ON PERMANENT DEFLECTION RATIO (d/do) AT DIFFERENT LOAD LEVELS

One of the main objectives of this assignment was to determine the effects of fillet weld undercut on the relative permanent deflection values of the defective specimens compared with the sound ones at various load cycles. Figures 8-7 through 8-10 present the load ratio to permanent deflection ratio relationship, (P/Py)/(d/do), for different load cycles of specimens S2, S3, S5, and S6, respectively. The figures indicate the following:

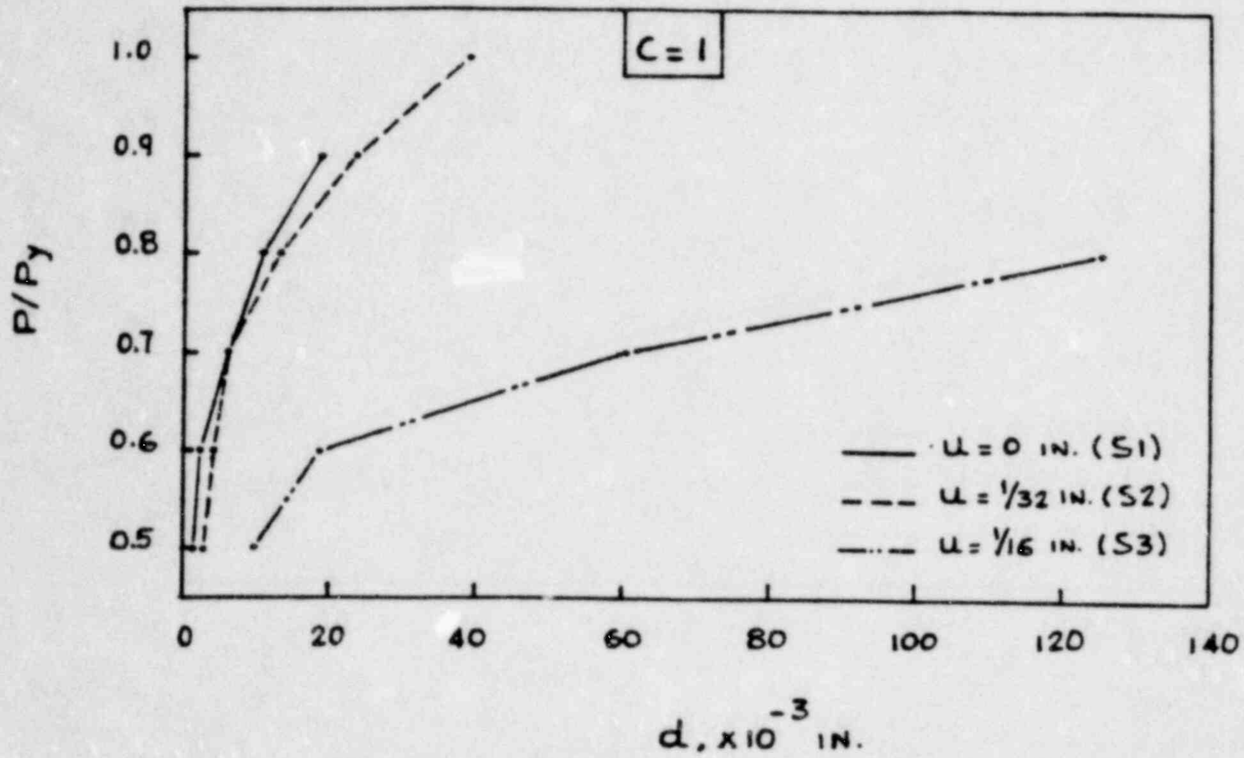


Figure 8-1. Permanent Deflection (d) Versus Load Ratio (P/Py) of Centric Test Specimens After One Load Cycle

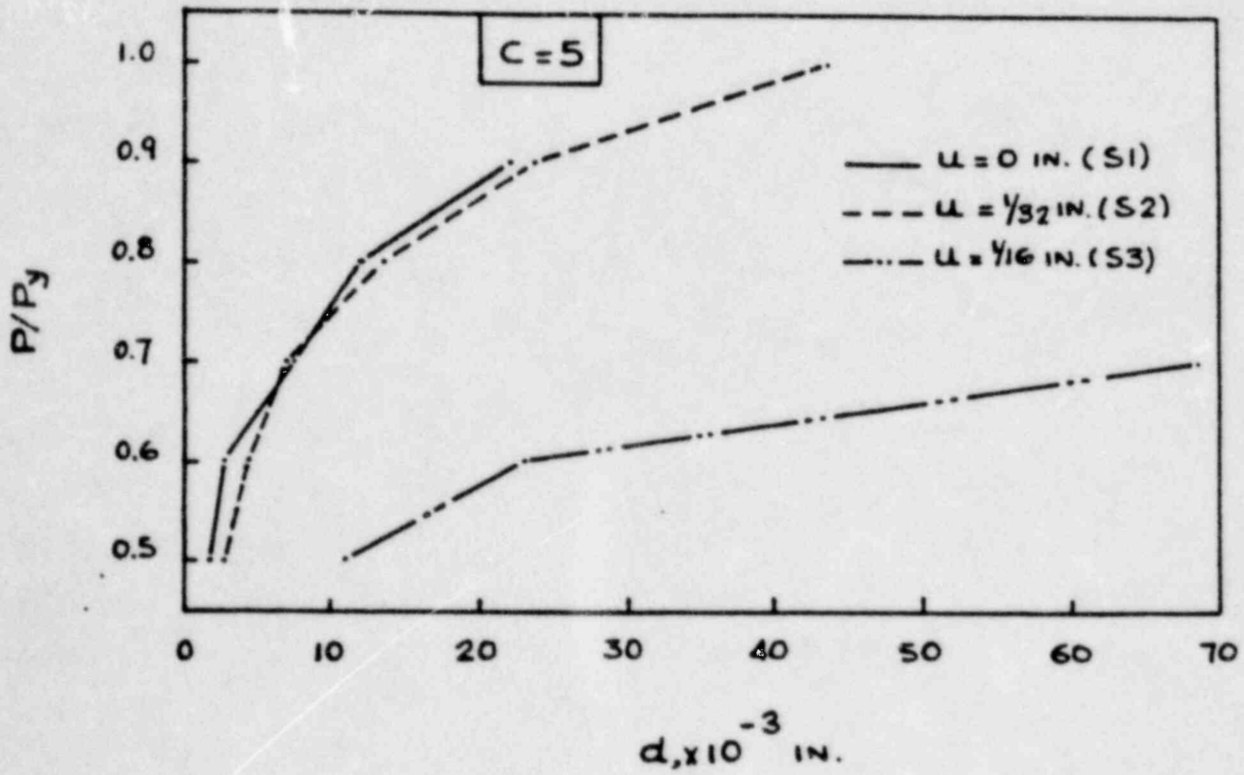


Figure 8-2. Permanent Deflection (d) Versus Load Radio (P/Py) of Centric Test Specimens After Five Load Cycles

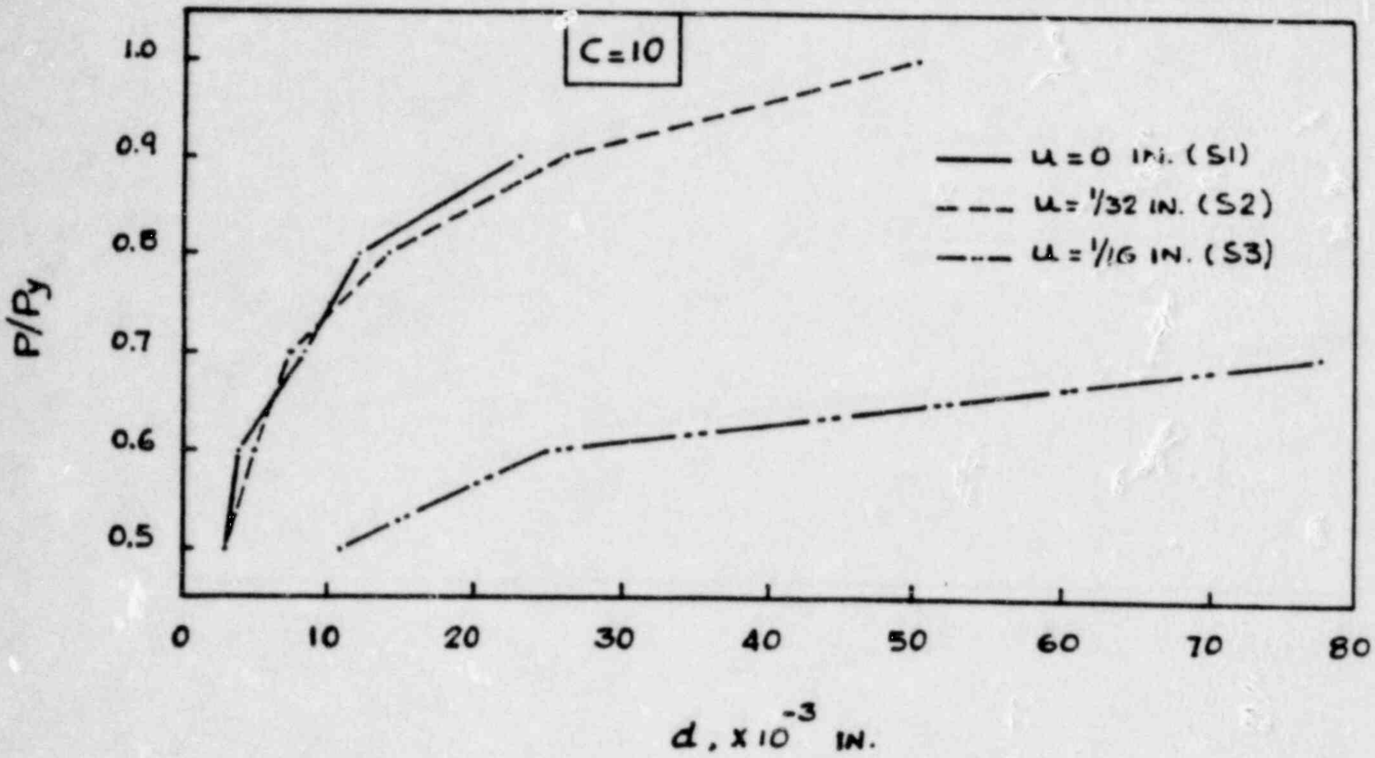


Figure 8-3. Permanent Deflection (d) Versus Load Ratio (P/Py) of Centric Test Specimens After Ten Load Cycles

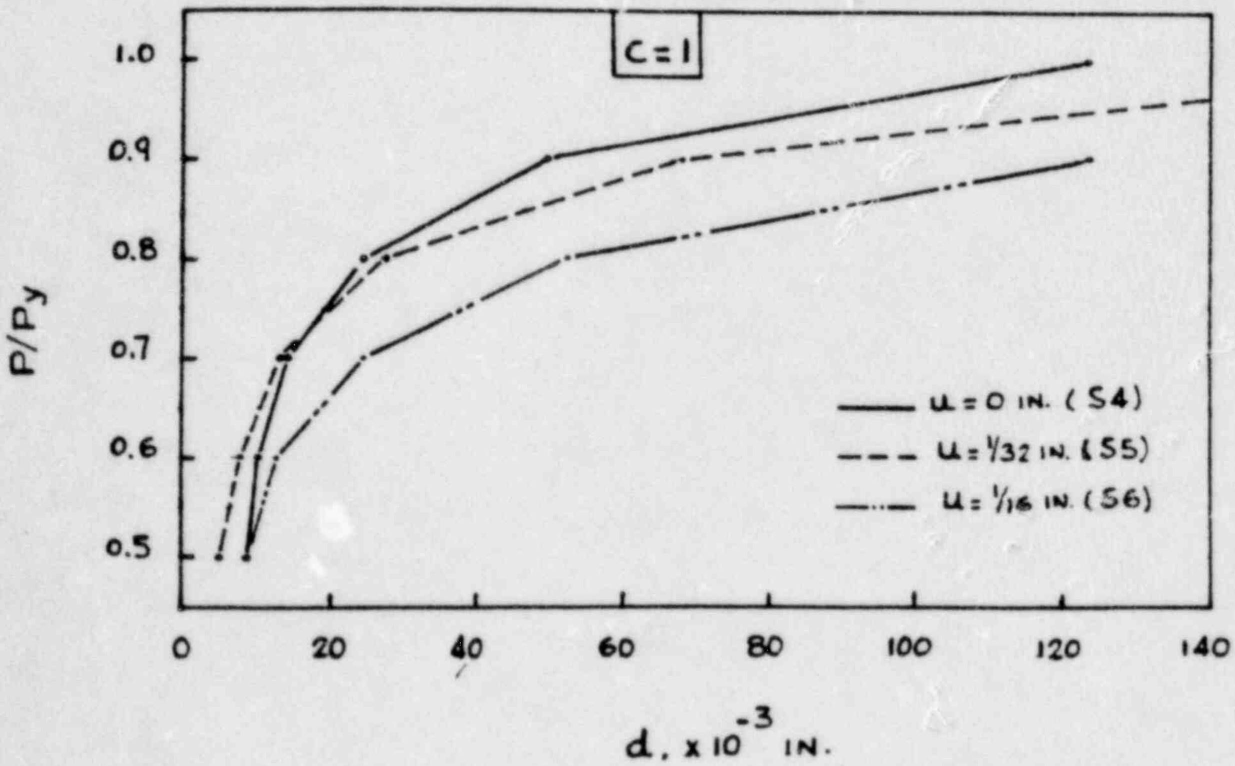


Figure 8-4. Permanent Deflection (d) Versus Load Ratio (P/Py) of Eccentric Test Specimens After One Load Cycle

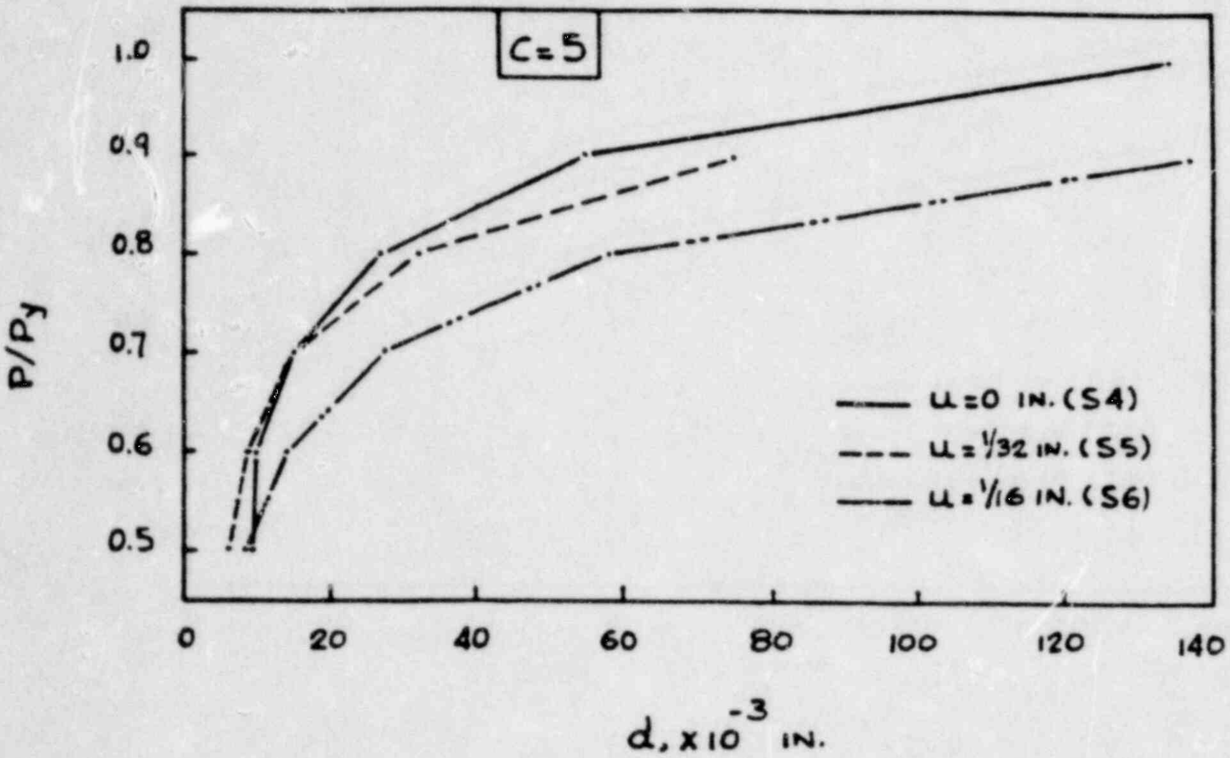


Figure 8-5. Permanent Deflection (d) Versus Load Ratio (P/Py) of Eccentric Test Specimens After Five Load Cycles

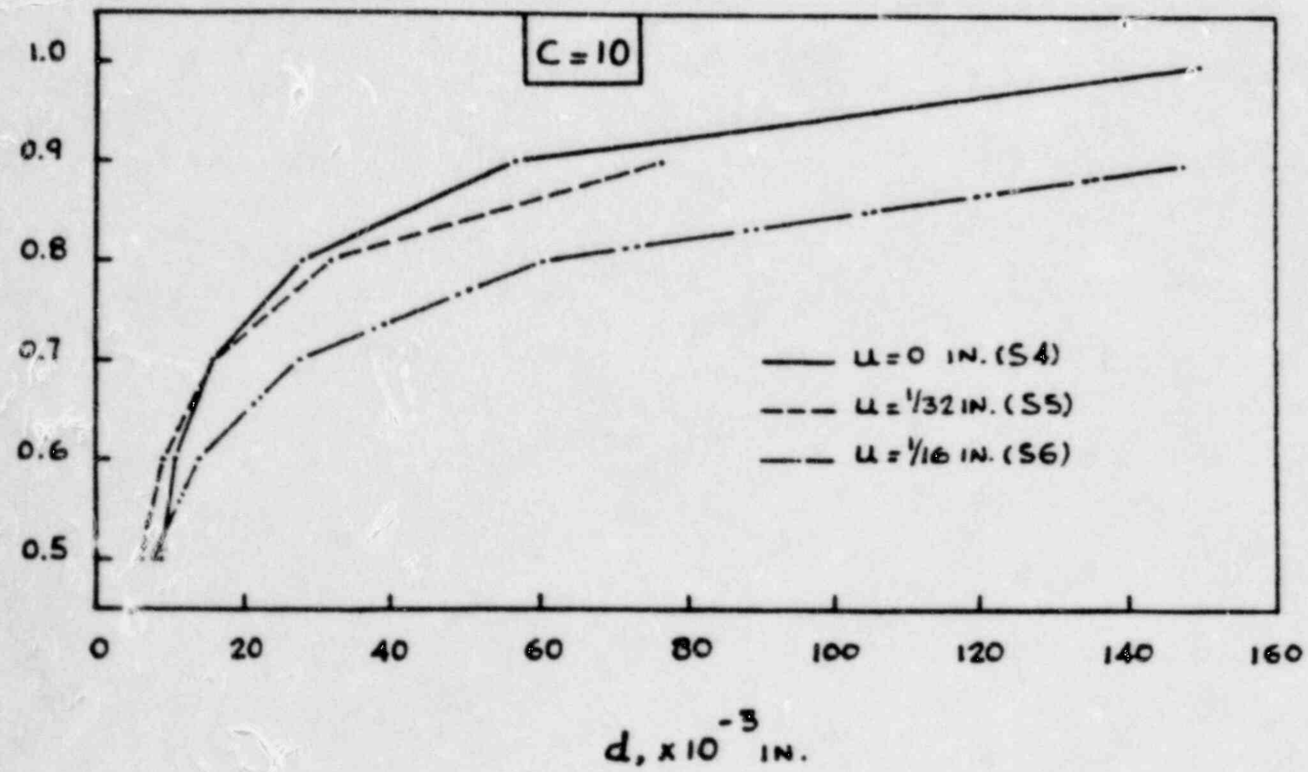


Figure 8-6. Permanent Deflection (d) Versus Load Ratio (P/Py) of Eccentric Test Specimens After Ten Load Cycles

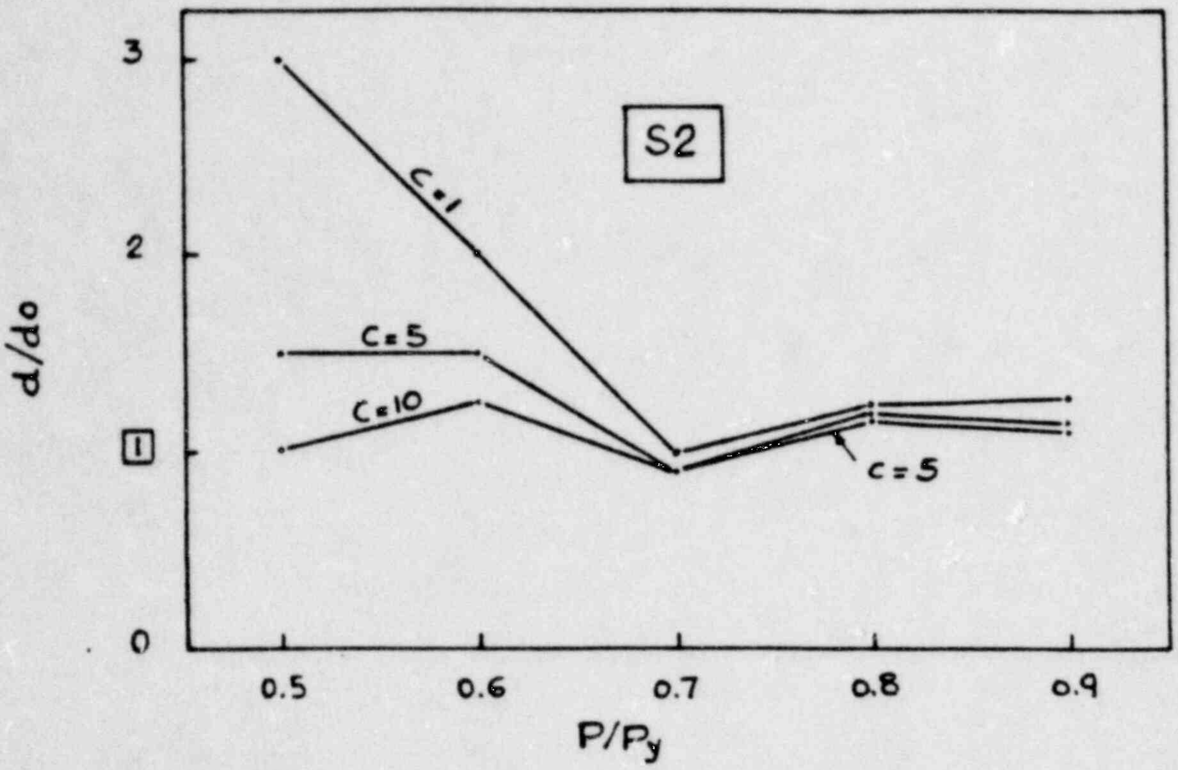


Figure 8-7. Effect of Number of Load Cycles (c) on Permanent Deflection Ratio (d/do) for Specimen S2

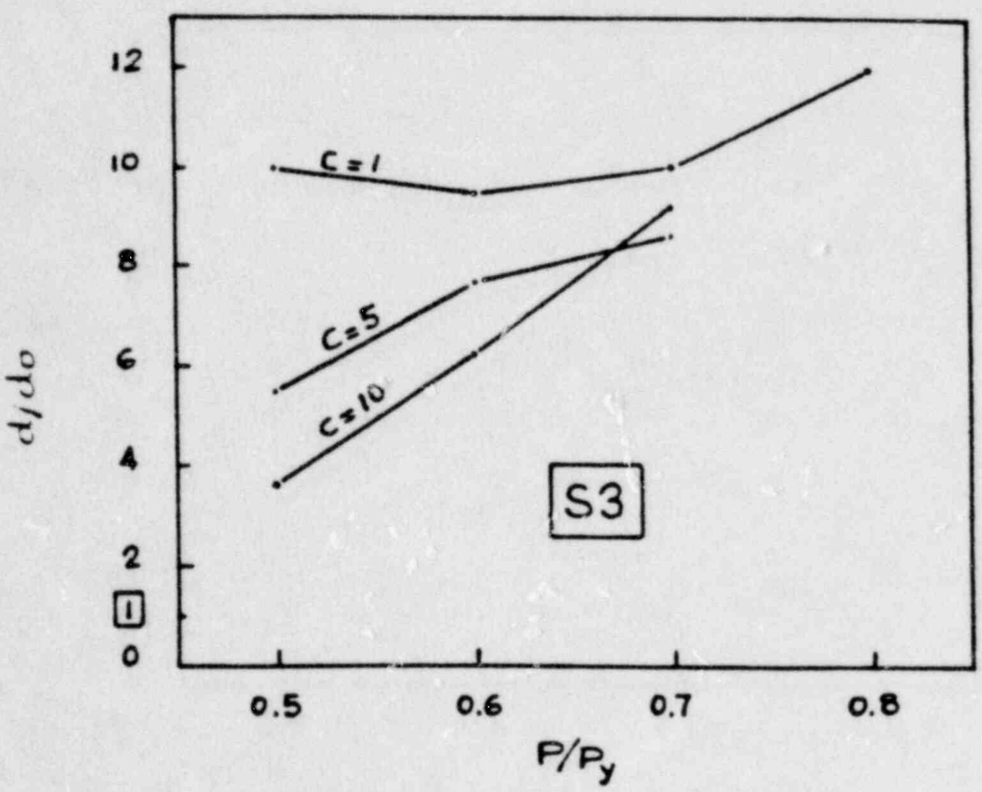


Figure 8-8. Effect of Number of Load Cycles (c) on Permanent Deflection Ratio (d/do) for Specimen S3

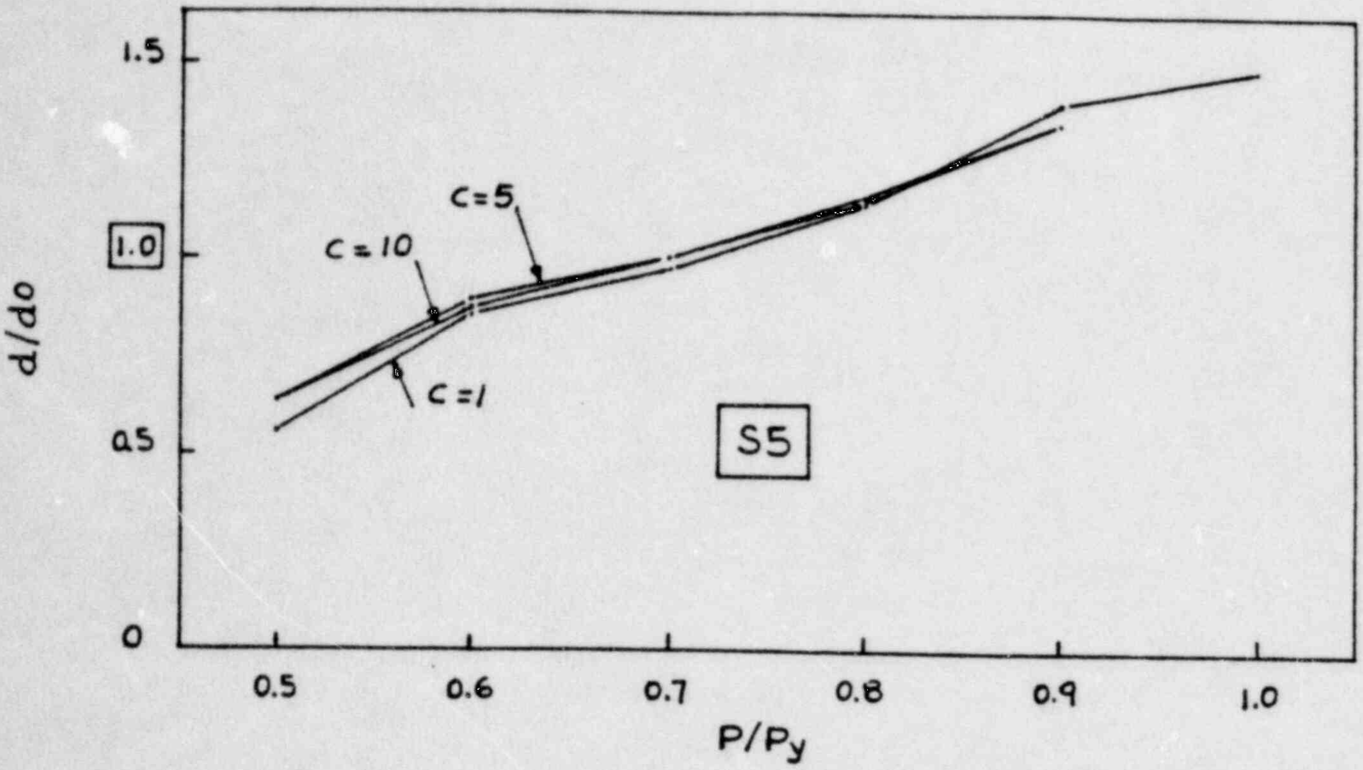


Figure 8-9. Effect of Number of Load Cycles (c) on Permanent Deflection Ratio (d/do) for Specimen S5

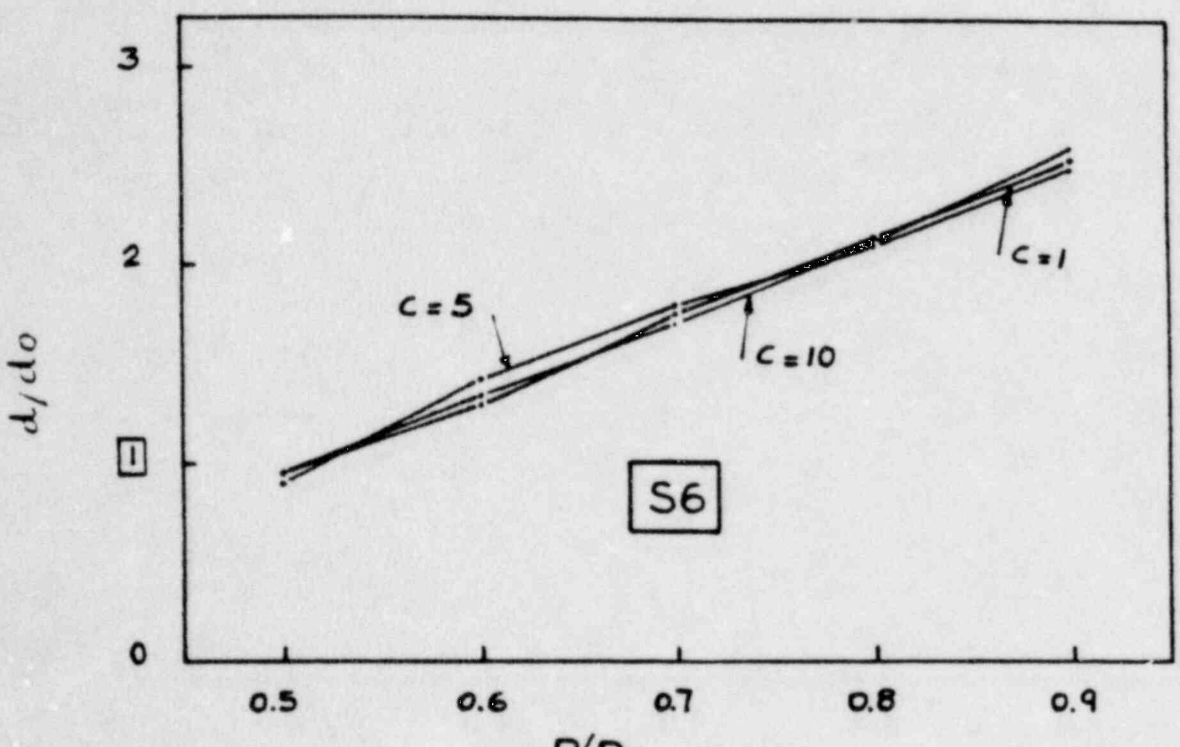


Figure 8-10. Effect of Number of Load Cycles (c) on Permanent Deflection Ratio (d/do) for Specimen S6

1. For centric specimen S2, which had a 1/32-in weld undercut, the deflection ratios shown in Figure 8-7 range from 3.0 for C = 1 to 1.0 for C = 10 at 0.5 load ratio. At higher load ratios between 0.7 and 0.9, d/do values generally decrease and reach a value slightly higher than 1.0 for all number of load cycles.

2. For centric specimen S3, which had a 1/16-in weld undercut, Figure 8-8 indicates that the deflection ratios range from 10 for C = 1 to 3.7 for C = 10 at a load ratio equal to 0.5. At higher load ratios, d/do generally increases for all load cycles. The deflection ratio reaches a maximum value of 12.0 for C = 1 at P/Py = 0.8 and a value of 9.2 for C = 10 at P/Py = 0.7.

3. For eccentric specimen S5, which had a 1/32-in weld undercut, Figure 8-9 indicates that d/do values are almost the same for different load cycles at any particular load ratio. The permanent deflection ratios increase gradually with increasing load ratios and range from 0.6 at P/Py = 0.5 to 1.4 at P/Py = 0.9.

4. For eccentric specimen S6, which had a 1/16-in weld undercut, Figure 8-10 indicates that for all load cycles, the deflection ratios increase linearly with the load ratios. It should be noted that d/do values are almost identical for different load cycles at any particular load ratio. The permanent deflection ratios increase linearly from 1.0 at P/Py = 0.5 to 2.6 at P/Py = 0.9.

8.3 EFFECT OF FILLET WELD UNDERCUT (u) ON PERMANENT DEFLECTION RATIO (d/do)

Figures 8-11 through 8-13 show the effect of fillet weld undercut (u) on the permanent deflection ratio (d/do) of centric specimens after 1, 5, and 10 load cycles, respectively; Figures 8-14 through 8-16 show the same relationship for the eccentrically loaded specimens. The figures indicate the following:

1. The effect of 1/32-in fillet weld undercut on the permanent deflection ratio, d/do, after 1, 5, and 10 load cycles is generally small. For centric specimen S2, d/do varies randomly from 0.9 to 2.0 at load ratios between 0.6 and 0.9, whereas for eccentric specimen S5, it varies from 0.6 to 1.4 at load ratios between 0.5 and 0.9.

2. The effect of 1/16-in fillet weld undercut on the permanent deflection ratio of the tested specimens is significant, especially for the centrically loaded specimen. For centric specimen S3, at C = 1, d/do varies from 10.0 to 12.0 between 0.5 and 0.8 load ratios (Figure 8-11), whereas at C = 10, it varies from 3.7 to 9.2 at load ratio ranges between 0.5 and 0.7 (Figure 8-13). The effect on eccentric specimens, as shown in Figures 8-14 through 8-16, is somewhat less significant than that on the centric specimen; at C = 1, 5, and 10, d/do varies from 1.0 to 2.6 at P/Py values ranging between 0.5 and 0.9.

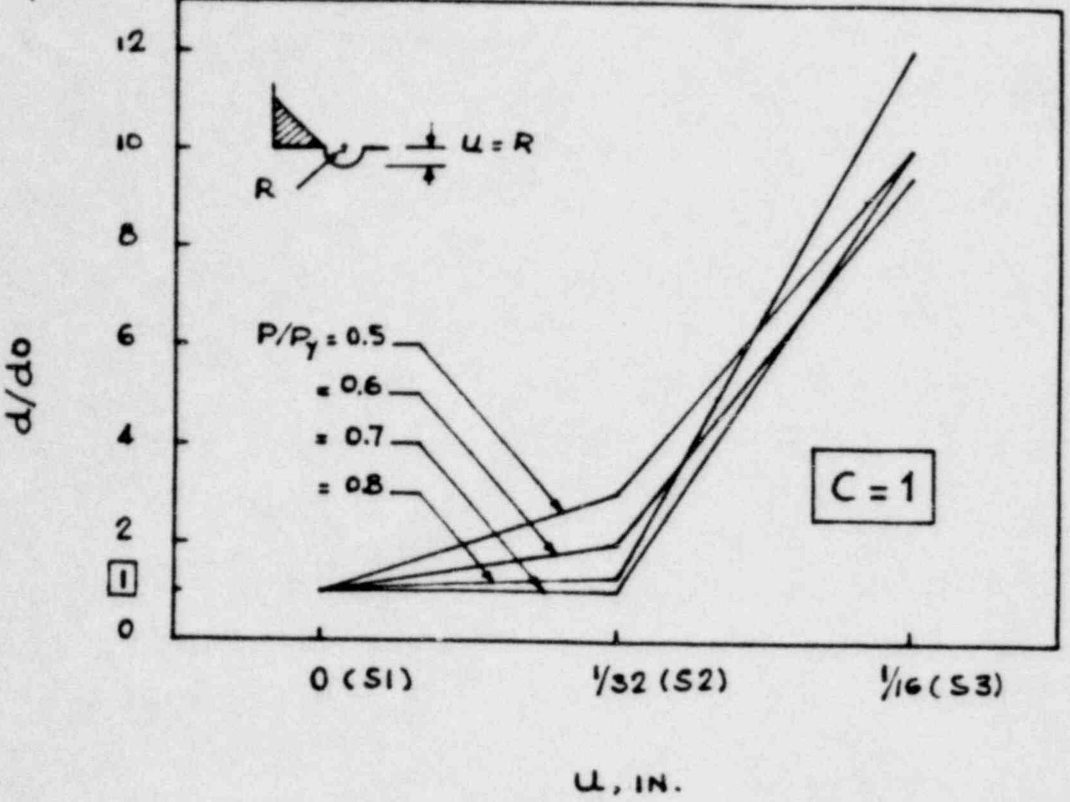


Figure 8-11. Effect of Fillet Weld Undercut (u) on Permanent Deflection Ratio (d/do) of Centric Specimens After One Load Cycle

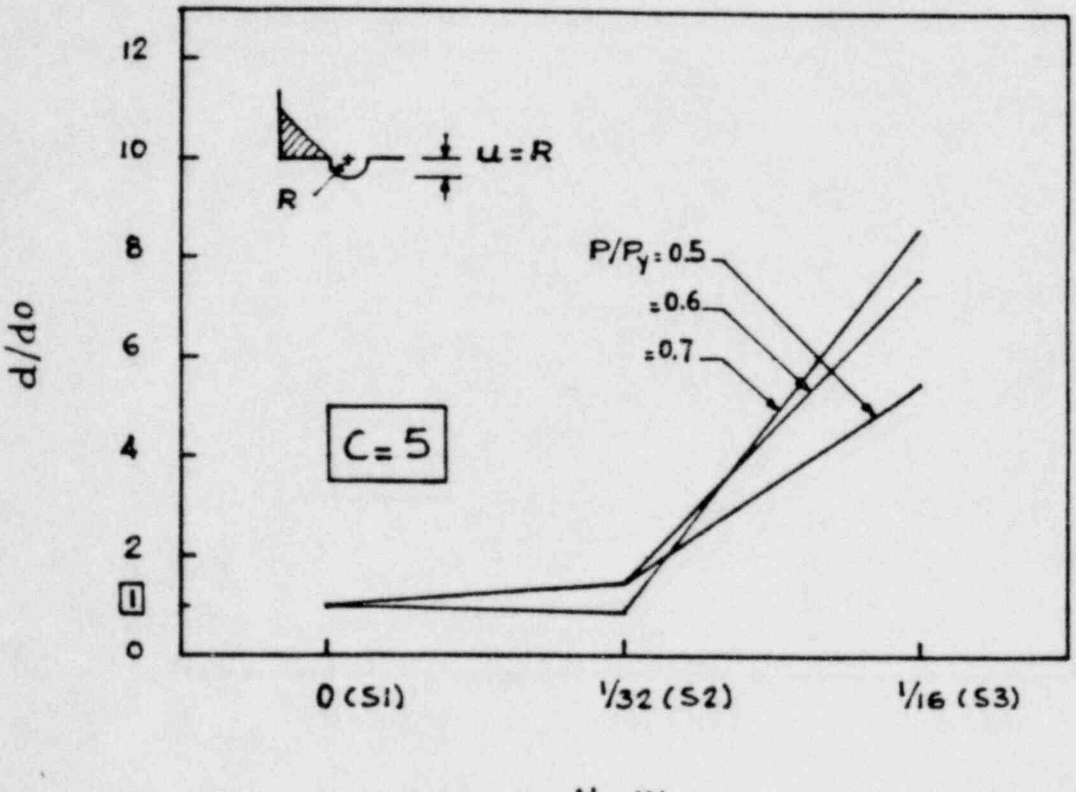


Figure 8-12. Effect of Fillet Weld Undercut (u) on Permanent Deflection Ratio (d/do) of Centric Specimens After Five Load Cycles

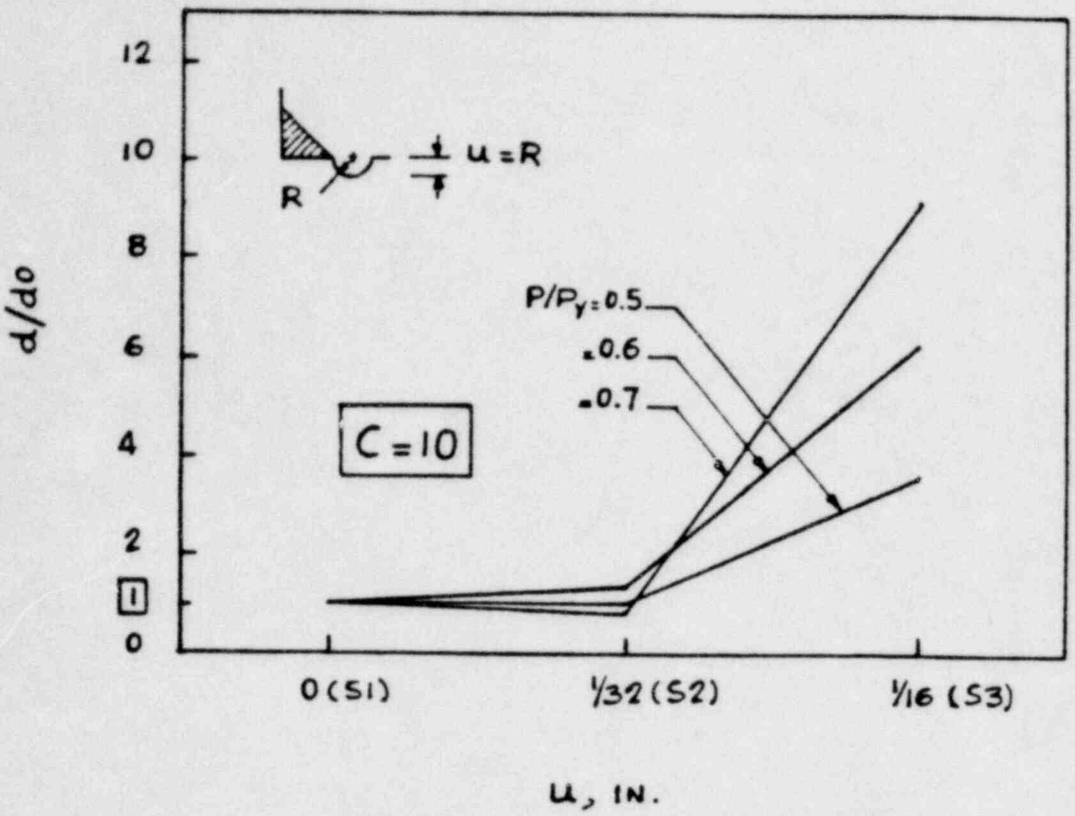


Figure 8-13. Effect of Fillet Weld Undercut (u) on Permanent Deflection Ratio (d/do) of Centric Specimens After Ten Load Cycles

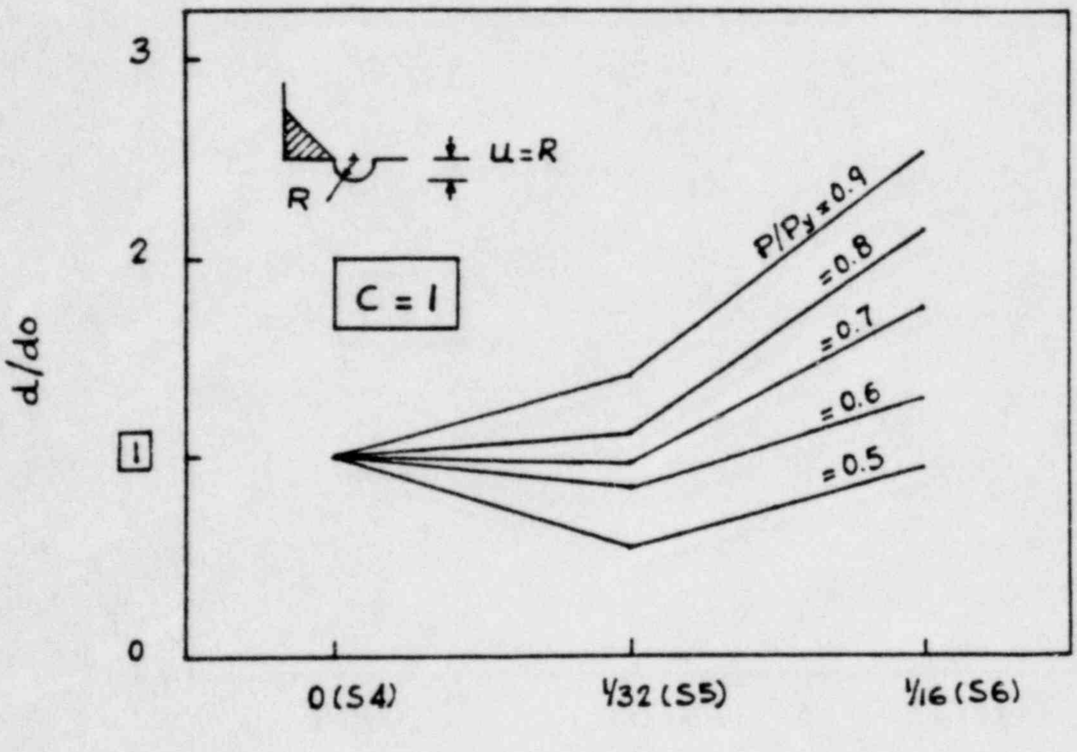


Figure 8-14. Effect of Fillet Weld Undercut (u) on Permanent Deflection Ratio (d/do) of Eccentric Specimens After One Load Cycle

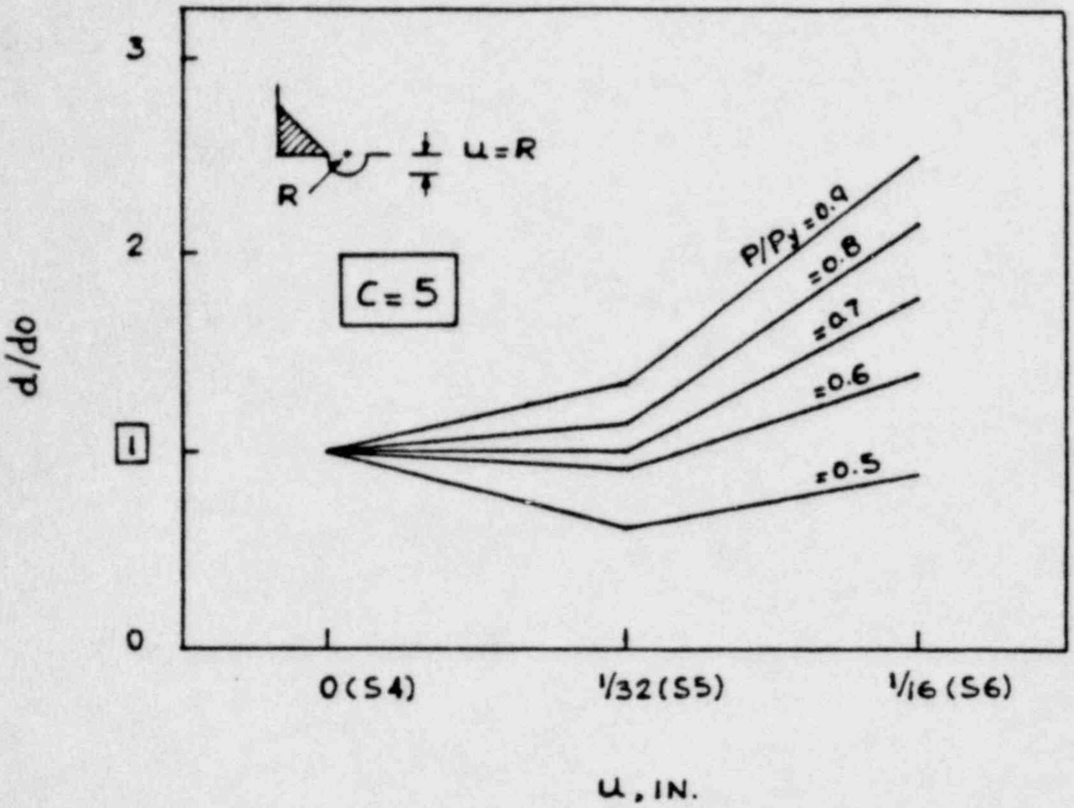


Figure 8-15. Effect of Fillet Weld Undercut (u) on Permanent Deflection Ratio (d/do) of Eccentric Specimens After Five Load Cycles

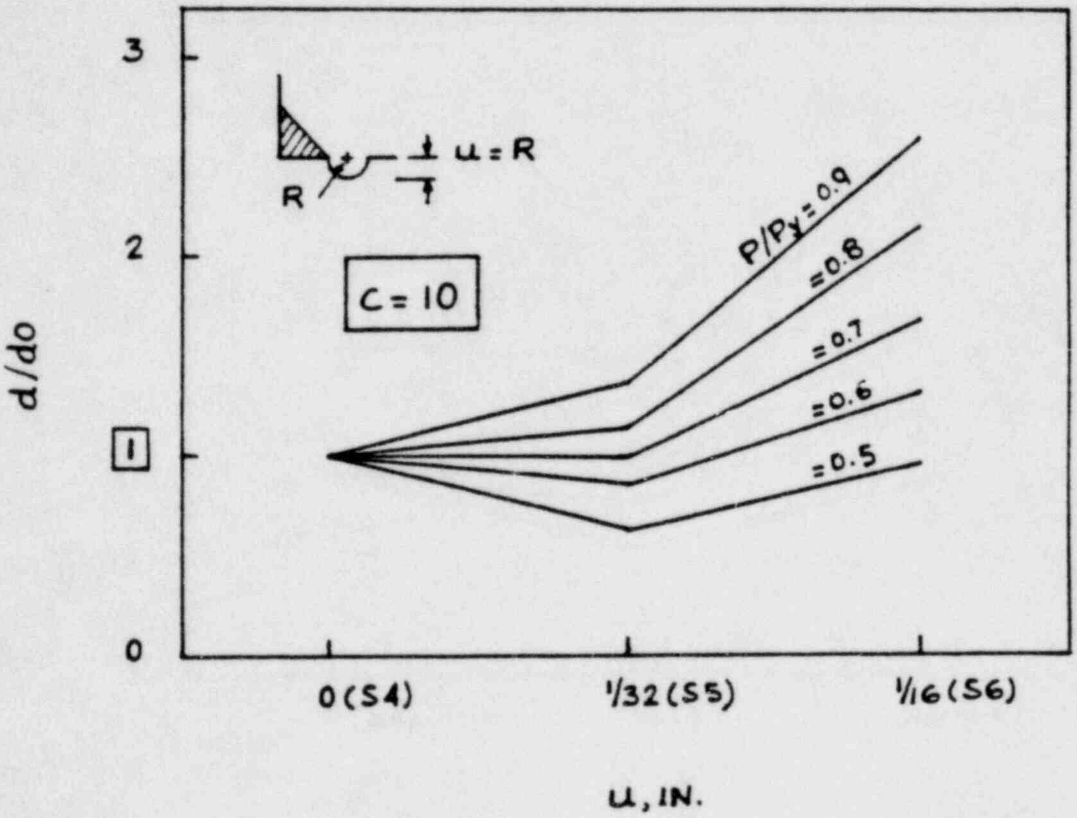


Figure 8-16. Effect of Fillet Weld Undercut (u) on Permanent Deflection Ratio (d/do) of Eccentric Specimens After Ten Load Cycles

8.4 EFFECT OF FILLET WELD UNDERCUT (u) ON THE ULTIMATE LOAD VALUES (Pu) OF TESTED SPECIMENS

The ultimate load values (Pu) shown in Tables 7-1 through 7-6 present the highest applied load during tests which in all cases correspond to the instance of the critical weld failure at the mid-span section of the tested specimens. It should be noted that in all cases the failure was abrupt and started at the bottom of the specimen, which indicates a typical shear failure between the fillet weld and the tubing section of the welded connection. The effect of fillet weld undercut (u) on the ultimate load values of tested specimens can be summarized as follows:

1. The ultimate load values (Pu) of centric and eccentric test specimens of 1/32-in fillet weld undercut are very comparable to those of the corresponding sound specimens. For the centric specimen S2, the ultimate load value of 42.7 kips is 9% higher than that of the sound specimen S1. This can be attributed to a better quality of weld and/or a slight increase in the actual weld size of specimen S2, which might offset the anticipated slight reduction of the ultimate load value due to weld undercutting. The ultimate load of eccentric specimen S5 (49.8 kips) is slightly lower (1%) than that of the sound specimen S4 (50.3 kips).

2. The ultimate load values of the 1/16-in fillet weld undercut specimens are lower than the corresponding values of the sound specimens. For the centric specimen S3, the ultimate load of 31.5 kips is about 20% lower than that of the sound specimen S1. On the other hand, for the eccentric specimen S6, the ultimate load of 44.8 kips is 11% lower than that of the sound specimen S4.

9. CONCLUSIONS

The analysis of test results, described in Section 8, yields the following conclusions:

1. For centric and eccentric specimens subjected to cyclic loading starting with a load ratio (P/Py) equal to 0.5, the permanent deflection (d)/load ratio relationship is nonlinear.

2. The effect of a 1/32-in fillet weld undercut on the permanent deflection ratio, d/do, after 1, 5, and 10 load cycles is relatively small. For the centric specimen, d/do varies randomly from 0.9 to 2.0 at load ratios between 0.6 and 0.9, whereas for the eccentrically loaded specimen, it varies from 0.6 to 1.4 at load ratios between 0.5 and 0.9.

3. The effect of a 1/16-in fillet weld undercut on the permanent deflection ratio is significant, especially for centrically loaded specimens. For specimen S3, d/do varies from 10.0 to 12.0 after one load cycle between 0.5 and 0.8 load ratios, whereas after 10 load cycles it varies from 3.7 to 9.2 at load ratios that range between 0.5 and 0.7. The effect on the eccentric specimen (S6) is somewhat less significant than that on the centric specimen S3; after 1, 5, and 10 load cycles, d/do varies from 1.0 to 2.6 at P/Py values between 0.5 and 0.9.

4. The effect of a 1/32-in fillet weld undercut on reducing ultimate load values of centrically or eccentrically loaded specimens is negligible (about 1%).

5. The reduction of the ultimate load values of the 1/16-in fillet weld undercut specimens is noticeable. For centric specimen S3, the ultimate load is about 20% lower than that of the similar but sound specimen S1, whereas for eccentric specimen S6, the ultimate load is 11% lower than that of sound specimen S4.

6. The overall effects of fillet weld undercut on increasing permanent deflection and reducing ultimate load values of welded tubing structures are generally more severe for centrically loaded structures than for eccentrically loaded ones.

10. REFERENCES

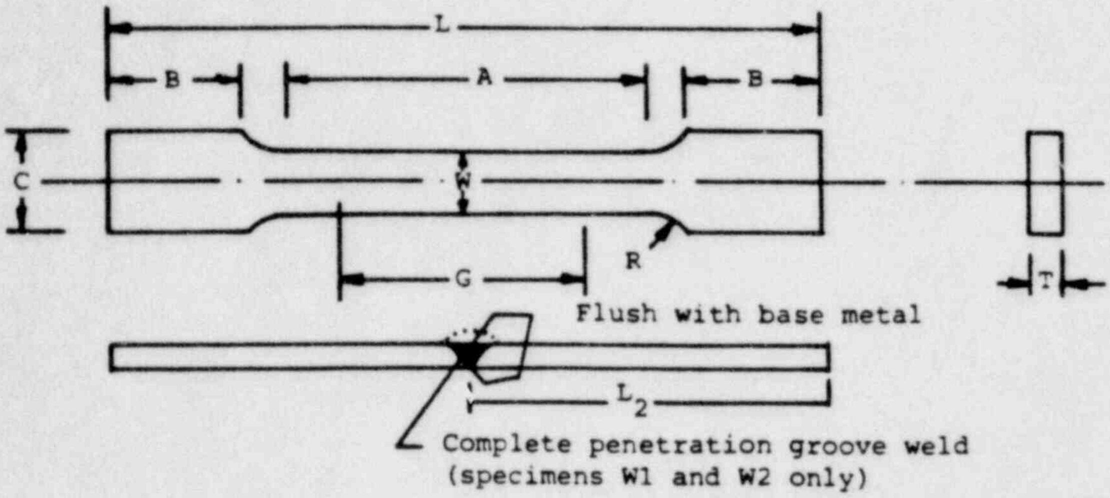
1. Tsai, C. L. and Tsai, M. J., "Significance of Weld Undercut in Design of Fillet Welded T-joints," Welding Journal, Vol. 63, No. 2, February 1984, pp. 64S-70S

2. Petershagen, H., "The Effect of Undercut on the Fatigue Strength of Machine-Made Fillet Welds," Schweissen Und Schneiden, Vol. 33, No. 4, April 1981, pp. 165-168 (English Translation of Text and Captions: pp. E54-E56)

3. Krieg, J., "Hints and Recommendations on Notches in Fillet Welds," Prakiker, Vol. 33, No. 6, June 1981, pp. 152-154

APPENDIX A

DETAILS OF TENSILE TEST SPECIMENS



Dimensions (in)*							
G	W	T	R	L	A	B	C
2.000±0.005	0.500±0.010	As provided	1/2	8	2¼	2	3/4

*All specimens (T_1, T_2, W_1, and W_2)

Notes: 1. Total number of specimens is 4 (2 from solid piece, T_1 and T_2; 2 from welded piece, W_1 and W_2).

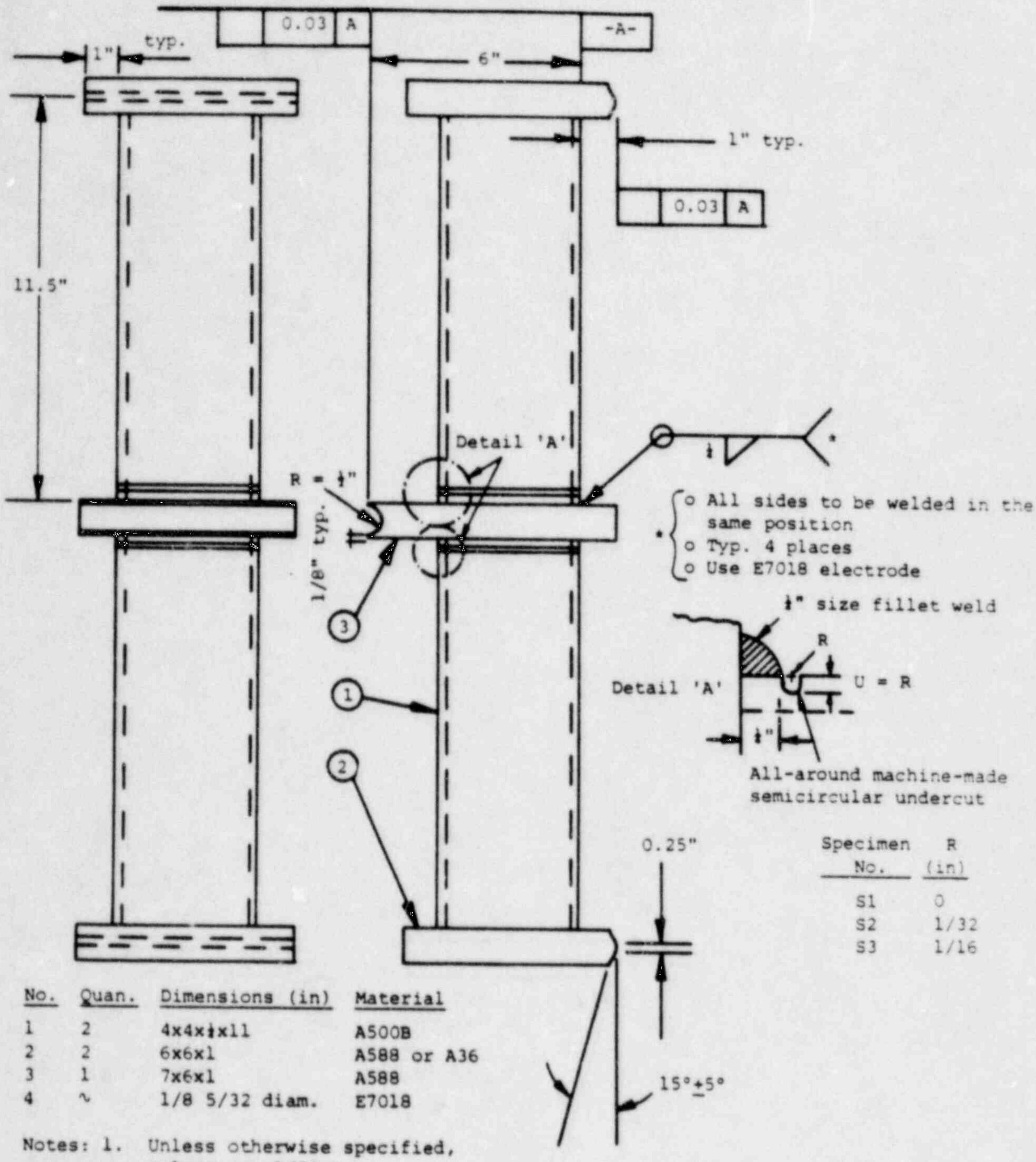
2. Required tensile properties:
tensile strength, F_u (psi)
yield point, F_y (psi)
elongation percent

Figure A-1. Details of ASTM 8-in Standard Tensile Test Specimens

APPENDIX B

DETAILS OF CENTRIC AND ECCENTRIC TEST SPECIMENS

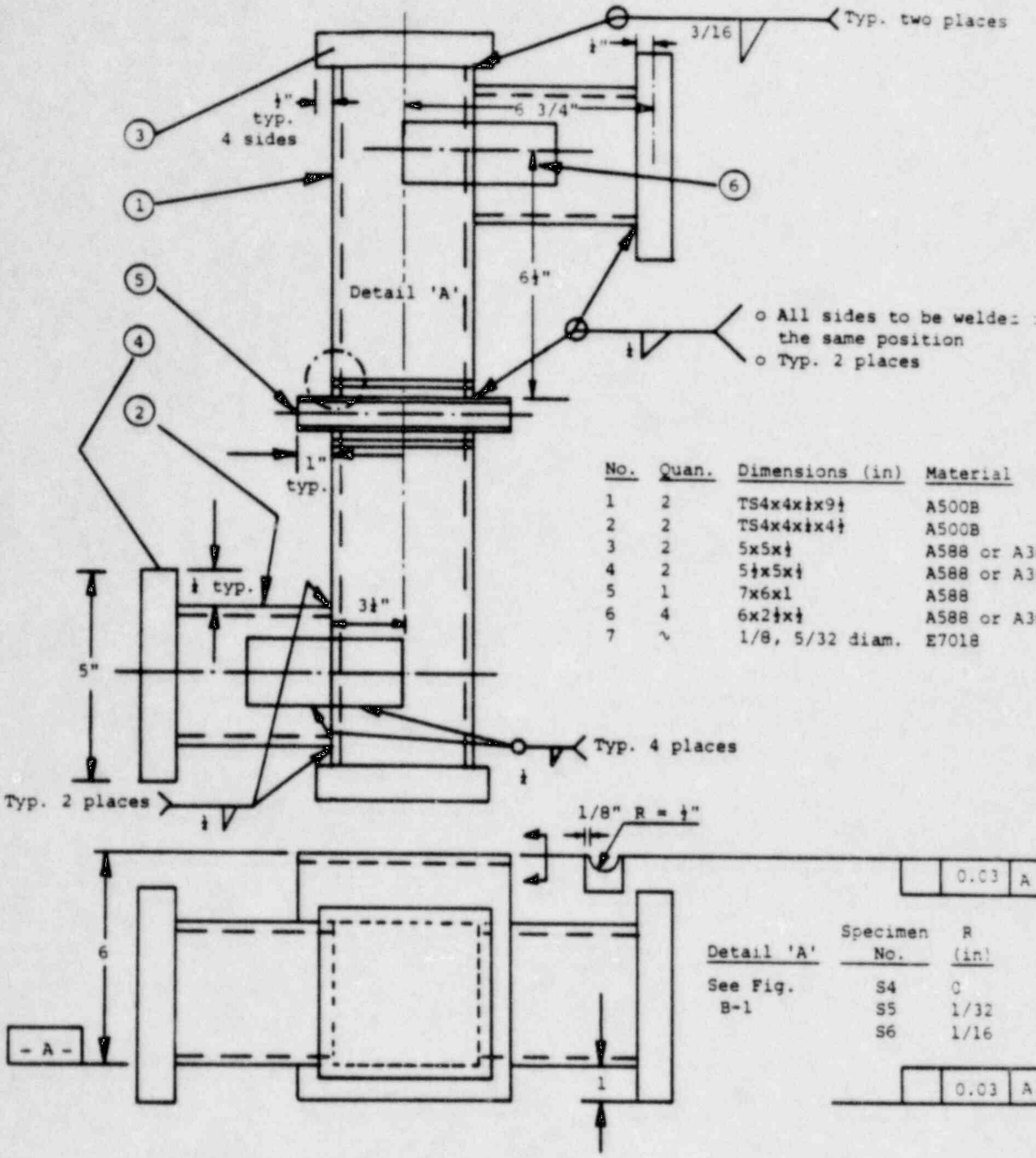
FRANKLIN RESEARCH CENTER
DIVISION OF ARVIN/CALSPAN
20th & RACE STREETS, PHILADELPHIA, PA 19103



No.	Quan.	Dimensions (in)	Material
1	2	4x4x¼x11	A500B
2	2	6x6x1	A588 or A36
3	1	7x6x1	A588
4	~	1/8 5/32 diam.	E7018

Notes: 1. Unless otherwise specified, tolerance ±1/32 in
2. Estimated weight 45 lb
3. Paint all surfaces with inorganic zinc primer except welds

Figure B-1. Details of Centric Specimens (S_1, S_2, and S_3)



No.	Quan.	Dimensions (in)	Material
1	2	TS4x4x¼x9½	A500B
2	2	TS4x4x¼x4½	A500B
3	2	5x5x½	A588 or A36
4	2	5½x5x½	A588 or A36
5	1	7x6x1	A588
6	4	6x2½x½	A588 or A36
7	~	1/8, 5/32 diam.	E7018

Detail 'A'	Specimen No.	R (in)
See Fig. B-1	S4	0
	S5	1/32
	S6	1/16

Notes:
1. Unless otherwise specified, tolerance ±1/32 in
2. Estimated weight 75 lb
3. Paint with inorganic zinc primer except welds

Figure B-2. Details of Eccentric Specimens (54, 55, and 56)