High Cycle Fatigue Improvements with Modified Root Weld Configuration

Technical Assessment

1007944

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Technical Update, December 2003

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This document describes research sponsored by EPRI.

The publication is a corporate document that should be cited in the literature in the following manner:

Vibration Fatigue Testing of Overlay-Repaired Cracked Socket Welds, EPRI-RRAC, Charlotte, NC: 2003. 1007944

ABSTRACT

Failures of small bore piping connections (2-inch and smaller) due to high cycle fatigue (HCF) continue to occur frequently at nuclear and fossil power plants in the United States, resulting in degraded plant systems and unscheduled plant downtime. Fatigue-related failures are generally detected as small cracks or leaks but, in many cases, the leak locations are not isolable from the primary reactor coolant system, resulting in extended outages. Outages associated with fatigue failures have resulted in extended shut downs and lost revenue. Consequently, improvements in socket weld installation methods and repair applications have become a prime target for plant cost reductions. In addition many utilities have modified or improved welder training and qualification procedures to include socket weld tests.

To reduce costs associated with these common failures of small bore piping and fittings, EPRI has conducted several studies to improve the understanding of fatigue failures, in small bore piping connections and reduce the costs associated with the failures. An early EPRI report (TR-104534) indicated that the majority of small bore piping connections (up to 80%) are caused by high cycle vibration fatigue of socket welds. These failures are often accelerated by poor weld quality at the weld root or toe of the fillet weld. Analytical results reported in EPRI TR-107455 have demonstrated that the socket weld profile can have an important effect on its high cycle fatigue resistance. Weld profiles with longer legs along the pipe side of the weld greatly increasing its predicted fatigue resistance. Other potentially important factors influencing fatigue life include residual stress, weld root and toe condition, pipe size, axial and radial gaps, and materials of construction. Solutions to the failures can be a combination of vibration control (i.e. dampening devices), improved weld quality and design criteria for replacement applications.

The objective of this program is to evaluate a modified socket weld configuration, under high cycle fatigue conditions. The modified socket weld, which consists of a chamfered fitting, improves weld root quality, increase cross sectional area of weld deposit and increase the effective throat of the fillet weld. The modified socket weld configuration will be directly compared to a standard socket weld (1x1), which meets minimum code requirements to determine improvements in high cycle fatigue resistance.

All test specimens have been fabricated and high cycle fatigue testing is in progress. The test matrix includes both standard and modified (chamfered) fitting socket welds under various loading conditions. Tests will be completed by the end of December 2003 with results tabulated in the first quarter of 2004. The data will be incorporated into a revision to EPRI 1003542, *Socket Weld Resolution Guidelines.*

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1 INTRODUCTION

To support an alternative method of welding socket welded connections for improved resistance to high cycle fatigue failures, a test matrix of modified socket weld configurations was established under an EPRI-RRAC program. The goal of the test matrix was to establish the fatigue performance of a modified socket weld compared to a standard 1x1 socket welded connection. The modified socket weld configuration consists of a chamfered fitting, which allows a root weld to be applied beneath the face of the socket weld fitting, improving the root weld quality, increasing the weld cross sectional area and effective throat.

The test program was tailored to demonstrate that, under a range of loads, the modified socket weld configuration would be more resistant to HCF than the standard 1x1 weld profile. Specimens are tested at various loads from a high stress range, selected to cause failure in approximately one million cycles to a low stress range selected to cause failure at approximately 10 million cycles. Table 1 shows the complete test matrix. A modified and a standard 2-in. NPS stainless steel test specimen is assigned to each stress range. Due to the quanitity of test specimens available for testing an additional standard configuration was added to the high and low stress range.

Table 1-1. Socket Weld Test Matrix.

Material	Size	Configuration	Stress Range	Number of Specimens
Stainless Steel	2-in. Schedule80	Modified	High	1
		Standard		2
Stainless Steel	2-in. Schedule80	Modified	Medium-High	1
		Standard		1
Stainless Steel	2-in. Schedule80	Modified	Medium-Low	1
		Standard		1
Stainless Steel	2-in. Schedule80	Modified	Low	1
		Standard		2

2

SOCKET WELD MODIFICATION

The design of the modified socket weld considered that the majority of the HCF socket weld failures originate at the root of the socket weld due to root defects, and that past HCF tests have verified that a greater weld deposit cross sectional area improves the resistance to HCF. The fitting modification maintains or exceeds the fillet weld size (throat and leg size) required by various codes while increasing the cross sectional area of the weld. Figure 2-1 illustrates the weld profile of resulting from the chamfered fitting compared to the standard 1x1 code minimum weld profile.

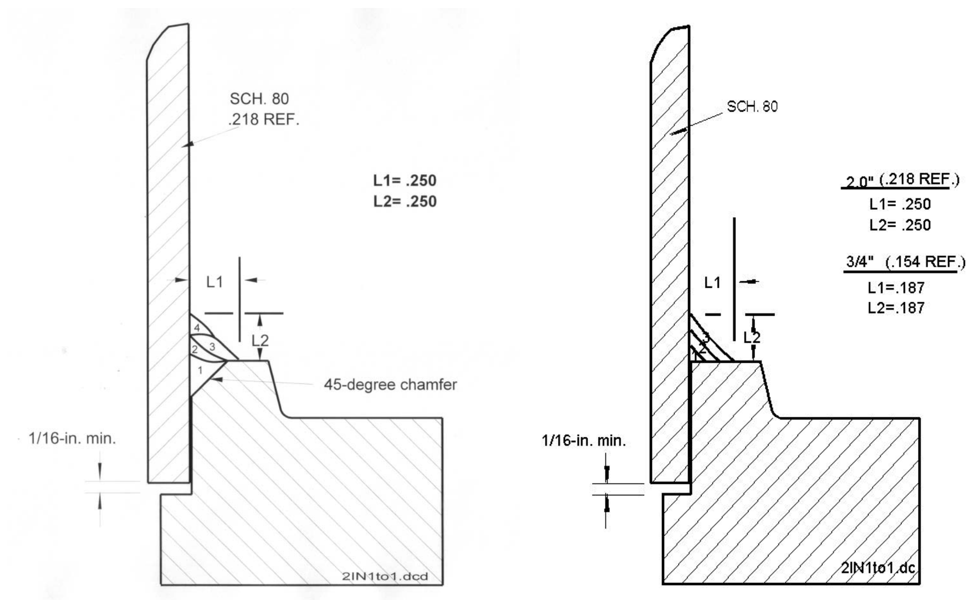


Figure 2-1.
Socket Weld Dimensions for Modified Weld Profile compared to standard weld profile.

For welds made in accordance with ASME Section III, socket weld leg size for a fitting must be a minimum of 1.09 times the nominal wall thickness of the connecting pipe for fittings and 1.4 times the nominal wall thickness of the connecting pipe for flanges. Assuming an equal leg fillet weld (1x1), the throat dimension is 0.71 times the leg size or 0.77 times the nominal wall of the connecting pipe for fittings and 0.98 times the nominal wall of the connecting pipe for flanges.

The chamfered fitting does not increase the leg lengths, when measured from the face of the fitting, although increases the overall weld leg length along the pipe by increasing the profile of the root weld. The effective throat length also, when measured after the weld is applied with a weld throat gage is unchanged, although in reality the weld cross section and effective throat is increased by the depth of the fitting chamfer.

3
TEST SPECIMEN

Figure 3-1 shows the geometry of the 2-in. NPS test specimen ready for high cycle fatigue testing. The pipe is schedule 80 and the fittings are Class 3000. The pipe is ASTM A312, Type 304 stainless steel and the fittings are ASTM A182, Type 304 stainless steel. The test weld is the lower fitting to pipe weld shown in Figure 3-1. The modified configuration utilized a 45-degree by 3/16-in. chamfer on the fitting adjacent to the pipe. The weld joining the coupling to the blind flange is a partial penetration weld with a reinforcing fillet weld. The 2-in. NPS specimens are 18-in. long. The upper end of the specimen is closed with a blind flange and O-ring seal to ensure leak tightness during the test. During the test, the specimen is pressurized with air at about 50 psig. Specimen failure is indicated by a loss of internal pressure.

The test welds (modified with chamfer or standard) were conventional, equal leg fillet welds made with the gas tungsten arc welding (GTAW) process. The leg size for the 2” NPS specimens was ¼-in. made with 3-5 weld passes. All specimens were welded with 1/8-in. or 3/32-in. ER 308L filler material. Table 3-1, lists the weld parameter for the 10 specimens included in the test matrix.

Table 3-1.
Weld Data Sheet for Stainless Steel Test Specimens

Specimen	Amps	Volts	Filler Material	No. Of Passes	Travel Speed
0	141	10.9	1/8-in. ER308L	4	2-in./34sec. (3.5ipm)
1	135	10.9	1/8-in. ER308L	4	2-in./33sec. (3.6 ipm)
2	140	11.0	1/8-in. ER308L	4	2-in./34sec. (3.5ipm)
3	142	10.7	1/8-in. ER308L	4	2-in./32sec. (3.7ipm)
4	138	10.8	1/8-in. ER308L	4	2-in./37sec. (3.2ipm)
5	136	11.0	1/8-in. ER308L	4	2-in./34sec. (3.5ipm)
6M	115	10.9	3/32-in. ER308L	5	2-in./36sec. (3.3ipm)
7M	115	11.0	3/32-in. ER308L	5	2-in./32sec. (3.7ipm)
8M	143	11.0	1/8-in. ER308L	5	1.5-in./33sec. (2.7ipm)
9M	140	10.9	1/8-in. ER308L	5	1.5-in. /36sec. (2.5ipm)

M – Modified socket weld profile

Testing Arrangement

Fatigue cracks in the test specimens are initiated and propagated with an electro-hydraulic shaker that drives a 3-ft. x 3-ft. shaker table, shown in Figure 3-2. Each specimen is mounted to the table with four 5/8" high strength bolts torqued to 100 ft-lbs. Each specimen is tuned so that the first mode of vibration was slightly below the adjustable driving frequency of the shaker. Various stress levels for different specimens are accomplished by tuning the specimen closer or further from the driving frequency. As the driving frequency approaches the resonant frequency, amplification of the table vibration will increase the vibration at the top of the specimen as well as the stress at the weld. Tuning is done by the addition or subtraction of mass, e.g., nuts and washers, at the top of the specimen.

Each specimen is instrumented with an accelerometer cemented onto the upper welded flange. A blind flange with an o-ring seal is bolted to the upper flange to allow for internal pressurization of specimen. The blind flange is fitted with a Swaglock fitting to pressurize the specimen with 40-50 lbs of air. A pressure transducer is used to monitor the pressure of each specimen.

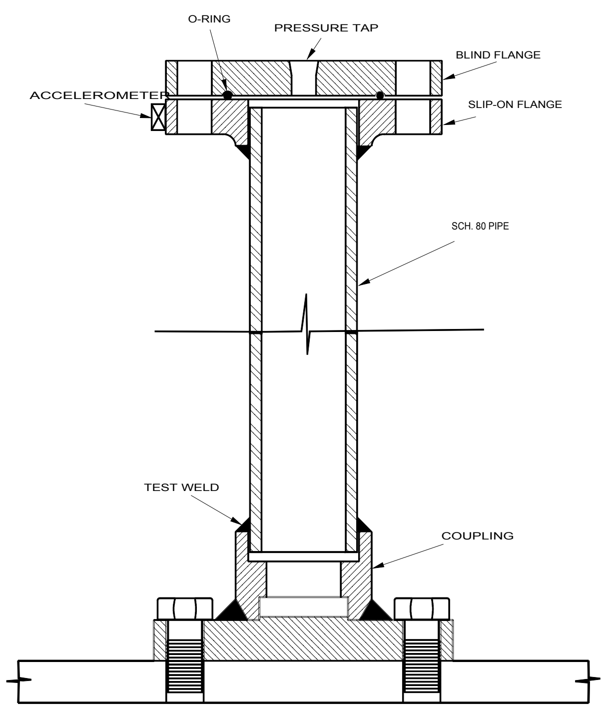


Figure 3-1.
Configuration of Test Specimen Ready For Shaker Table

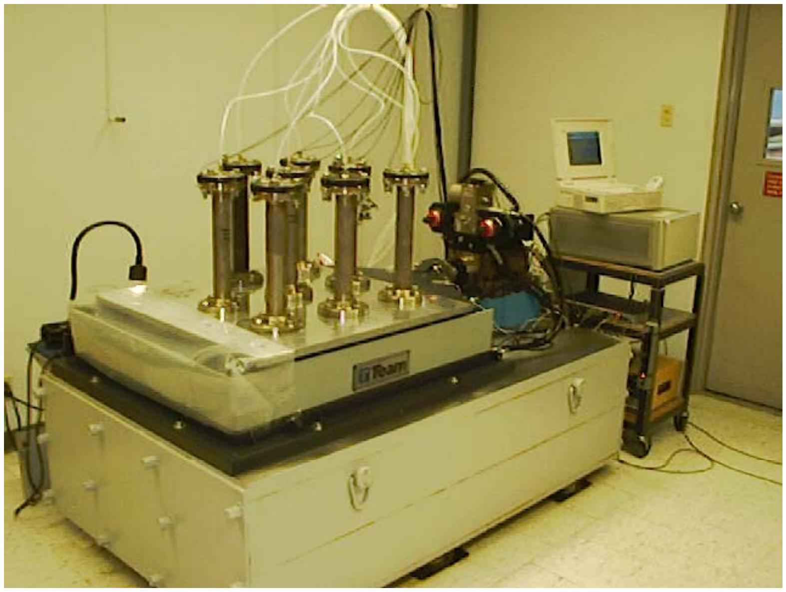


Figure 3-2.
Electro-Hydraulic Shaker Table With Eight Specimens On Breadboard (PG&E)

A computer program controlled an HP 3566A spectrum analyzer that simultaneously acquired all data. The system recorded total accumulated cycles, table acceleration, specimen acceleration, and specimen pressure every five minutes. The system also stored the spectra and time signatures of all channels every hour for diagnostic purposes. A crack is indicated when the pressure decreased by a minimum of 20% from its baseline. The shaker is then shut down and the crack located with soap solution. The socket welds are tested until failure or run-out on the shaker table.

The stresses at the weld are calculated based on the standard beam formula below with modifying factors:

$$\sigma = a\left[\frac{1.5}{(2\pi f)^2}\frac{gED_o}{L^2}\right]K_{Stiffness}K_{MassLoading}K_{location}$$

Where:

σ = Stress (psi)
a = Acceleration of top mass plus shaker table input (g's)
f = shaker table frequency (Hz)
g = Acceleration due to gravity = 386.4 (in/s^2)
E = Young's modulus (psi)
D_o = Pipe outside diameter (in.)
L = Distance from base of weld to accelerometer centerline (in.)
$K_{Stiffness}$ = Factor correcting for the stiffness difference between a cantilever beam and the actual specimen geometry (2-in SS, 0.897).
$K_{MassLoading}$ = Since the mass of the pipe is not small relative to the end mass, a correction is needed to attribute the mass effects (2-in SS, 1.067).

$K_{Location}$ = All stresses were calculated at the toe of the weld. This factor adjusts for the difference in the applied moment at the base of the weld to the toe of the weld (2-in SS, 0.983).

The results of the fatigue testing are reported as cycles to failure at a given stress range. Generally, the stress range at which the specimens are tested is not a single, constant value. The initial stress range is selected by adjusting the mass of the top of the specimen as described earlier. During testing, the initial stress range declines as cycles are accumulated. This is a result of testing multiple samples at varying stress levels simultaneously on the shaker table. Since the shaker table was controlled on table acceleration, as the stiffness of each specimen changes due to crack formation, the resonant frequency shifts downward ever so slightly. This shift in the resonance away from the shaker driving frequency causes a reduction in the amplification factor. The only way to solve this is to control the vibration of each specimen. This would require that each specimen be tested separately.

This variation in stress range throughout the test is accounted for by averaging the stress range at five-minute intervals. The variation over each five-minute interval is very small, so an average of the segments was representative of the stress history. This is the same approach used in the previous EPRI socket weld testing programs. (2)

4

TEST RESULTS

Data for the socket welds will be tabulated in Tables 4-1 and plotted in Figures 4-1 at the completion of the tests and will include data accumulated from prior EPRI tests of similar socket weld configurations.

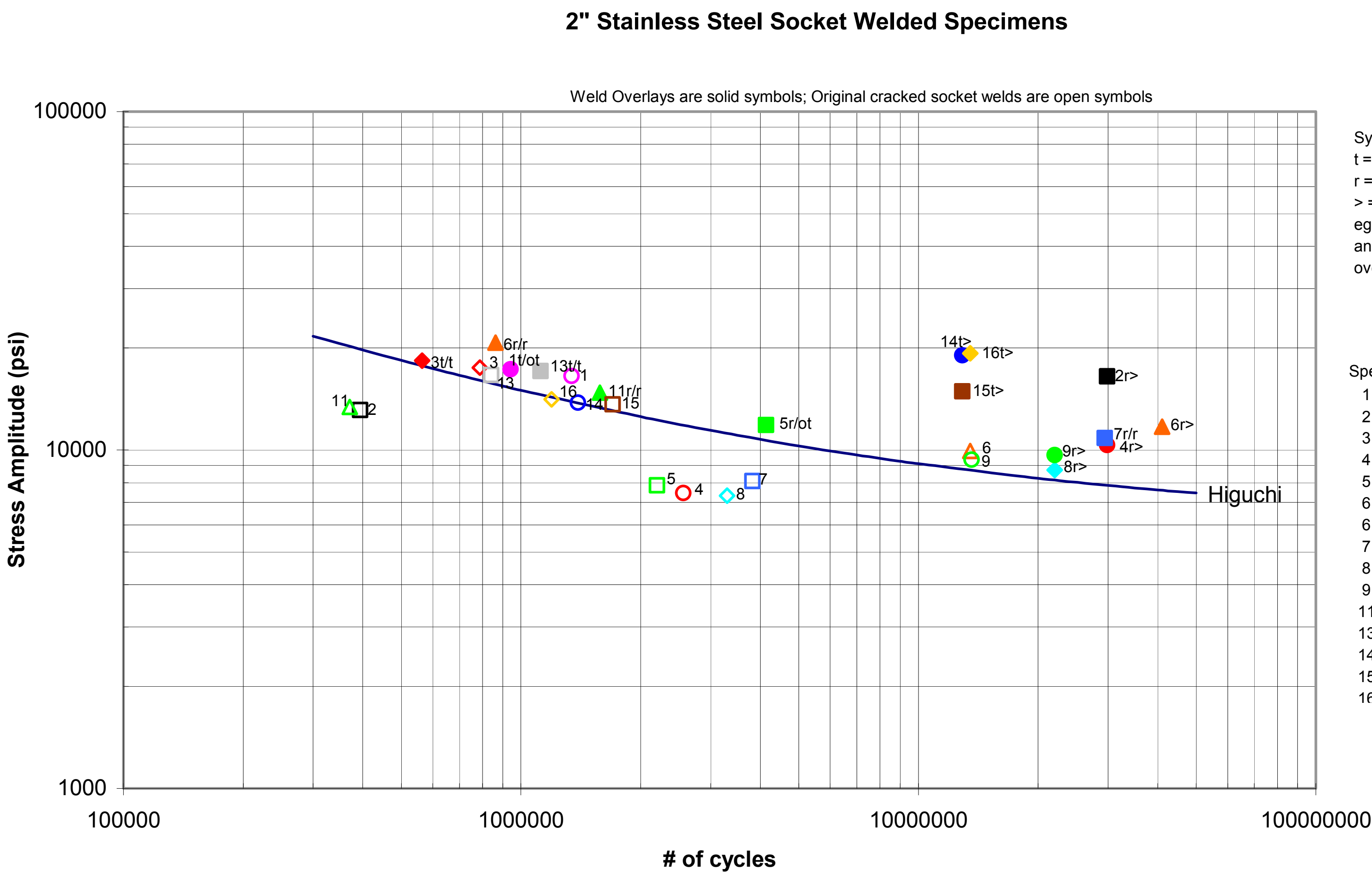
In Figures 4-1, each datum will be labeled with specimen number and labeled with a code that indicates the crack location, root (r) or toe (t). Specimens with a ">" symbol will indicates that the test was stopped before the socket weld cracked and is referred to as a "runout". In the past, testing was stopped after reaching about 10 million cycles. The Higuchi trend curve is also plotted to serve as a comparison with data for similar socket welds developed by other researchers (1). The Higuchi trend curve represents the mean failure line for a series of standard equal leg socket welds loaded in four point bending. Data points for the modified socket weld configuration that fall above the Higuchi trend curve indicate that the performance is better than the mean of the data set used by Higuchi.

ASME Section III design rules provide another method of comparison. Section III, Subsection NB uses stress indices to compare the severity of the reduction in fatigue strength for various types of fittings and welds. For Class 1 piping, the stress indices C_2 and K_2 are used to assign a fatigue strength reduction factor of 3.9 to a standard, equal leg socket weld. Stress Indices for specific configurations may also be determined by test. A reasonable comparison of the performance of a standard socket weld and a modified socket weld can be made by comparing their calculated stress indices. A smaller numerical value of C_2 K_2 indicates better fatigue performance. Table 4-1 will show this comparison.

Table 4-1.
Results For Stainless Steel Specimens

Specimen	Crack Location	Stress Range, psi	Cycles	C_2K_2 (1)
0				
1				
2				
3				
4				
5				
6M				
7M				
8M				
9M				
			Average C_2K_2	

1. Calculated using stress range and cycles from tests.



Symbols:
t = toe failure
r = root failure
> = runout
eg. 5rt = Specimen 5 with an initial root failure and an overlayed toe failure.

Specimen	Original C_2K_2	Overlay C_2K_2
1	1.8	1.8
2	2.8	0.9
3	1.9	1.9
4	3.4	1.5
5	3.4	2.0
6 runout	1.8	1.3
6	1.8	1.5
7	2.9	1.5
8	3.3	1.9
9	2.0	1.7
11	2.9	1.9
13	1.9	1.8
14	2.1	1.0
15	1.0	1.2
16	2.1	1.0

Figure 4-2.
2" NPS Stainless Steel Standard and Modified Weld Profile with Higuchi Trend Line

5
CONCLUSIONS

Conclusions will be based on the test results and documented in the final report.

6 REFERENCES

1. M. Higuchi, M. Hayashi, T. Tamauchi, K.Iida, and M.Sato. *Fatigue Strength of Socket-Welded Pipe Joints*. PVP-Vol. 313, ASME, 1995.

2. P. Hirschberg, P.Riccardella, S. Pan, M. Sullivan, J.Schletz and G. Frederick. *Vibration Fatigue Testing of Socket Welds.* EPRI, 1999. TR-113890.

3. "Criteria of the ASME Boiler and Pressure Vessel Code for Design by Analysis," Sections III and VIII, Division 2, ASME, 1969.

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