Investigation of Fatigue-Induced Socket-Welded Joint Failures for Small-Bore Piping Used in Power Plants

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Nuclear power plants typically experience two or three high-cycle fatigue failures of stainless steel socket-welded connections in small bore piping during each plant-year of operation. This paper discusses fatigue-induced failure in socket-welded joints and the strategy Texas Utilities Electric Company (TU Electric) has implemented in response to these failures. High-cycle fatigue is invisible to proven commercial nondestructive evaluation (NDE) methods during crack initiation and the initial phases of crack growth. Under a constant applied stress, cracks grow at accelerating rates, which means cracks extend from a detectable size to a through-wall crack in a relatively short time. When fatigue cracks grow large enough to be visible to NDE, it is likely that the component is near the end of its useful life.

TU Electric has determined that an inspection program designed to detect a crack prior to the component leaking would involve frequent inspections at a given location and that the cost of the inspection program would far exceed the benefits of avoiding a leak. Instead, TU Electric locates these cracks by visually monitoring for leaks. Field experience with fatigue-induced cracks in socket-welded joints has confirmed that visual monitoring does detect cracks in a timely manner, that these cracks do not result in catastrophic failures, and that the plant can be safely shut down in spite of a leaking socket-welded joint in a small bore pipe.

Historical data from TU Electric and Southwest Research Institute are presented regarding the frequency of failures, failure locations, and the potential causes. The topics addressed include 1) metallurgical and fractographic features of fatigue cracks at the weld toe and weld root; 2) factors that are associated with fatigue, such as mechanical vibration, internal pulsation, joint design, and welding workmanship; and 3) implications of a leaking crack on plant safety. TU Electric has implemented the use of modified welding techniques for the fabrication of socket-welded joints that are expected to improve their ability to tolerate fatigue.

Keywords: failure analysis, fatigue, piping, stainless steel, welding

Introduction

The Electric Power Research Institute (EPRI), Report TR-107455, “Vibration Fatigue of Small Bore Socket-Welded Pipe Joints,”[1] states that approximately 80% of the fatigue failures in the nuclear power industry have been associated with high-cycle vibration fatigue of socket-welded connections in small-bore piping. These fatigue-induced failures occur at the rate of two or three per plant-year. With over 100,000 socket-welded joints in TU Electric’s Comanche Peak Steam Electric Station (a typical nuclear generating plant), it is difficult to know where to look for the next failure. EPRI has studied socket-welded joints[1] and assessed their ability to resist high-cycle fatigue, but this report does not provide recommendations on ways to improve the performance of these joints.

The maintenance database at Comanche Peak Steam Electric Station (CPSES) was searched for suspected fatigue-induced failures of small-bore piping systems (2 in. or smaller) between March 1990 and March 1998. This eight year period represents 13 plant-years of operation. A total of 28 leaks considered likely to have been caused by fatigue were identified. The majority of the suspected fatigue failures occurred in socket-welded fittings, but some of the failures (fewer than 10%) were observed in threaded joints. Socket-welded joints at CPSES appeared to experience about two fatigue-induced failures per plant year, and this is consistent with EPRI’s reported failure rate.

Fatigue failures in socket-welded joints are not rare, but relatively few of them are subjected to a full metallurgical failure analysis. Consequently, plant personnel have complete information on only a very few failures, and this makes it difficult to develop the broad perspective needed to respond to the issue. Southwest Research Institute (SwRI) has been...
Patigue-Induced Socket-Welded Joint Failures (continued)

investigating and documenting field failures of socket-welded joints in small-bore piping for its utility customers during the last 10 years. Individual case studies reported in this paper have been thoroughly analyzed, and only those small-bore socket weld failures that are high-cycle, low-stress fatigue are included here. The names of individual utilities are not used.

By studying the characteristics of the failures known to be included in the target population, it is possible to more accurately characterize failure mechanisms, objectively assess consequences of a failure, and to formulate appropriate corrective actions. TU Electric has implemented a strategy to respond to the issue of fatigue-induced failures of socket-welded joints in small-bore piping systems. The risk factors that are associated with fatigue-induced failures of socket-welded joints are also associated with threaded joints. Threaded joints, however, are subject to unique risks like overtightening, and the built-in stress concentration sites at the thread roots.

Joint Configuration

A typical socket-welded joint is shown in Fig. 1 along with the identifying terminology used to describe various features in the socket joint and the weld. The weld in this figure would be considered desirable because the fillet has satisfactory throat thickness, a slightly concave profile, a long axial leg, and a smooth transition of the weld metal to the base metal at both weld toes.

Joint Design

Socket-welded joints are very common because they can be assembled easily, a major benefit in field installations, but the design of socket-welded fittings contributes to their susceptibility to high-cycle fatigue failure. The annular gap formed when the pipe is inserted into the fitting creates an unavoidable stress riser at the weld root. This annular gap also forms a crevice (or slot) where stagnant, potentially corrosive fluid comes in contact with the weld root. Butt-welded joints are more resistant to fatigue-induced damage than socket-welded joints because the annular gap is eliminated.

Experience shows the vast majority of socket-welded joints (in excess of 99%) perform reliably, so socket-welded joints will continue to be used at CPSES. They are cost effective to install in the field and the fact that they can be assembled quickly is important where minimizing the radiation dose is a consideration in the repair process. Enhanced field fabrication methods can be expected to result in even better reliability.

Experiments performed by the Japanese suggest that eliminating the axial gap makes socket-welded joints more tolerant of fatigue, however the ASME Boiler and Pressure Vessel Code, §III, requires an axial gap. Socket welded joints at CPSES are now, and will continue to be, installed in accordance with ASME Code.

Field Failures

Only six specimens, from the 28 suspected high-cycle fatigue failure incidents at CPSES, were subjected to detailed metallurgical examination. Failures originated at the OD pipe surface at the axial weld toe and at the weld root. This observation is consistent with investigations conducted at SwRI. Evidence of macroscopic plastic deformation is totally absent in the vicinity of the fracture face when the damage mechanism is high-cycle (>10E5 cycles) low-stress fatigue.

SwRI has records of their investigations of field failures in socket-welded joints in small bore piping dating from 1988. They have investigated 13 fatigue-related failures of small-bore, socket-welded fittings from nine different nuclear plants. These failures occurred in vent lines, drain lines, sample lines, and instrument lines. The following systems were affected:

![Fig. 1 Typical socket fitting with a fillet weld](image)