Chapter 1

Introduction

Stainless steel of AISI 304LN grade (hence forth referred as AISI 304LN SS) and its weldments are extensively used in primary heat transport (PHT) piping systems of advanced heavy water reactors (AHWR) of nuclear power plants. The PHT piping and pressure vessels are currently designed and operated on the basis of leak before break (LBB) concept. The LBB analysis involves careful application of fracture mechanics principles in order to ensure that stable extension of postulated cracks or flaws in piping components which usually lead to benign leakage occurs prior to the onset of unstable fracture. For implementation of LBB in structural integrity analysis of piping components, it is therefore imperative that ductile fracture characteristics of the material used for fabricating PHT piping be fully understood.

The integrity of all types of structural components specifically with the possibility of being subjected to seismic events is currently being considered as one of the critical issues in the design of nuclear power plants. The load fluctuations during seismic activity are usually random in nature. As a consequence existing cracks in an engineering component experience either tensile or compressive load amplitudes of considerable magnitudes during seismic activity and this leads to their extension or growth. In order to incorporate seismic factors in design, knowledge related to the resistance to fracture under cyclic loading conditions must be gathered for LBB analysis of piping components.

The operating temperature range of this structural component is usually 301-573 K. The pipes used in PHT system possess typically outer diameter of the order of 320 mm with wall thickness of 25 mm. So any attempt to determine plane strain fracture toughness of the material from specimens cut from this component gets limited by curved sections having maximum thickness of 25 mm. This limitation related to specimen thickness allows one to carry out only assessment of elastic-plastic fracture toughness of the steel. The *J*-integral fracture toughness values of a few steels having similar compositions are reported in the literature (Wilkowski *et al.*, 1990; Olson *et al.*, 1994; Rudland *et al.*, 1996), but similar toughness indices of AISI 304LN SS and its weldment at ambient temperature are not available. Hence an investigation on the *J*-integral fracture behaviour of AISI 304LN SS and its weldment was a-priori directed to understand their crack growth resistance behaviour. But the existing procedures for estimating fracture resistance of materials are considered inadequate to provide reliable information related to the fracture characteristics of component-materials subjected to seismic events because of the imposed uncertain nature of cyclic deformation. A component with an allowable defect size may be safe under conventional monotonic loading but may fail in a limited number of reversible load cycles as the latter may degrade the fracture resistance of the material in a significant manner. The effect of cyclic loading on fracture resistance of materials is currently not included in the design codes to assess the integrity of the PHT piping system. This problem has been recently realized by the engineering community, and thus attempts are being directed to assess the significance of superimposed cyclic loads for safe control of structural materials.

In order to incorporate seismic factors in design, the present design codes and practices (Scott, 2003) demand understanding of the deleterious effects of load reversals during conventional *J*-integral tests, often referred to as cyclic *J-R* test. However, the concept of cyclic *J-R* behaviour is of recent origin. Only a few laboratories over the world have directed efforts to understand this problem till now and the available literature on cyclic *J-R* behaviour of structural materials is scanty. There exists controversy over the applicability of *J*-integral test with compressive crack tip load-excursions that necessarily take place in cyclic *J-R* tests. The definition of *J* through crack extension is theoretically considered violated by unloading even in the standard *J*-integral tests (ASTM E 1820, 2009); but periodic partial unloading has been accepted in favour of an engineering solution by consensus (Landes *et al.,* 1979). So cyclic *J*-integral tests which incorporate higher unloading to different extents would cause severe violation of the theoretical definition of *J*, but at the present moment an understanding related to fracture resistance with superimposed load cycles possibly would emerge through this approach only for achieving engineering solutions (Tarafder *et al.,* 2003)**.**

The extent of deleterious effect due to superimposed cyclic load seems to depend up on the magnitude of the compressive load and the frequency of load cycle. Thus, to understand the nature of seismic effect on structural components, one must examine fracture behaviour of materials under both load and displacement controlled modes, a discipline of current interest with extremely limited available information. The primary objective of this study is to bring forward understanding related to fracture behaviour of AISI 304LN SS under cyclic loads involving both displacement and load control modes.

In addition, determination of initiation fracture toughness of ductile materials has always been a challenging task due to the ambiguity associated with the identification of the point of departure of the initial linear region of the fracture resistance curve which is considered to correspond to the initiation of cracking in a material. Acoustic emission (AE) is a technique that is capable of directly indicating this crack initiation point during fracture toughness tests using single specimen. A corollary objective of this investigation is also to illustrate some results related to monotonic and cyclic fracture resistance of the base metal and weldment of AISI 304LN SS estimated by 'combined acquisition of load-crack length data for *J*-integral analysis coupled with synergistic generation of acoustic emission data to assess the point of crack initiation'.

In summary, the objectives of this investigation encompass studies on monotonic and cyclic fracture behaviour and acoustic emission signal characteristics during the fracture tests supplemented by suitable characterizations of the microstructural aspects and determination of conventional mechanical properties.

1.1 Objectives

The major objectives and the pertinent work-plan to fulfill the objectives of this investigation can be categorized into four broad modules. These are:

Module (I) To characterize the microstructure and to determine the related mechanical properties of the selected steel.

This module consists of (a) microstructural characterization of AISI 304LN SS base metal and its weldment, (b) measurement of austenite grain size in base metal and determination of volume fraction of δ-ferrite in the weldment and (c) determination of hardness and tensile properties of the steel and its weldment at ambient temperature.

Module (II) To study the displacement controlled fracture behaviour of the steel at ambient temperature.

This module comprises of (a) generation of monotonic *J-R* curves of the base metal and weldment at ambient temperature, (b) examining the effect of specimen configuration

(CL and LC orientations) on the monotonic *J-R* curves of the base metal, (c) generation of a series of cyclic *J-R* curves of the steels at different test conditions, (d) investigation of the effect of stress ratio and plastic displacement on the *J-R* curve, and (e) examination of the micro mechanisms of crack propagation in the steels during various types of loading conditions.

Module (III) To study the load controlled fracture behaviour of the steel at ambient temperature.

This module consists of (a) examination of the number of cycles to failure of the investigated steels, and (b) comparison of the obtained results on laboratory samples with corresponding available component data.

Module (IV) Comparative assessment of acoustic emission and conventional load-displacement analysis for detection of crack initiation

This module consists of (a) examination of AE signals during monotonic *J*-integral test and (b) examination of AE behaviour during cyclic *J*-integral tests of both base metal and weldment.

All the cyclic fracture tests have been designed and performed following a few earlier investigations. Attempts have been made to assign reasons and explanations for the observed results and to illustrate the practical utility of the generated data. The thesis has been structured into seven chapters. The significance of the research and the motivation behind this investigation are briefed in Chapter-1. Some pertinent literature background related to the current investigation has been presented in Chapter-2 prior to the obtained results and their discussion. Chapter-3 to Chapter-6 includes the results and discussion corresponding to the above-mentioned four modules. An overview of the conclusions derived from this work has been summarized briefly in Chapter-7 together with some proposed future work related to this area. All references quoted throughout the dissertation have been compiled at the end of Chapter-7.