2 Literature Review

2.1 Introduction

This chapter deals with philosophy and methodology of designing pressurised piping for leak before break (LBB) condition; the terminologies of stability assessment of cracked pipes using elastic-plastic fracture mechanics, plastic collapse procedures and various parameters such as stress intensity factor (K), crack mouth opening displacement (CMOD), J-integral and tearing modulus T etc. have been defined and explained in brief. The currently used stability analysis procedures for leak-before break evaluation of pressure piping system is also described in brief.

The literature status on the following topic are covered: the LBB background and currently followed methodologies; investigations and consideration of the load history effects on the ductile fracture of pipe; the engineering need and the concepts behind development of cyclic J and ΔJ integral, cyclic J-R curves with their limitations; impact of geometric constraint, dynamic strain ageing, piping system compliance etc. on fracture assessment etc.. This section incorporates summary of outcomes from the two large programmes taken up by International Piping Integrity Research Group (IPIRG) and Central Research Institute for Electric Power Industry (CRIEPI), Japan in this area. Additionally many other associated issues like, impact of geometry / constraints, dynamic strain ageing, piping system compliance, and material’s cyclic plasticity behaviour on fracture stability assessment and LBB demonstration have been discussed.

Finally the limitation of presently available assessment methods and appraisal of the problem undertaken for present investigation are highlighted.
2.2 Leak-Before-Break (LBB)

Leak-before-break (LBB) is a term that has been used for decades in reference to a methodology that means that a leak will be discovered prior to a fracture occurring in service. LBB is most often used in high energy pipe lines of nuclear power plant piping and also being applied in many other places like gas and oil pipelines etc. The basic idea of LBB is to exclude any potential for pipe break and then prove that the critical crack which occurred in spite of the exclusion of all detrimental mechanisms will be safely detectable within reasonable time. Early detection enables shut down of the reactor in the case of a nuclear power plant.

Presently the primary piping of NPPs worldwide is demonstrated to meet LBB requirements. The LBB assessment of pressurized primary piping is done for two reasons. One is to provide assurance that there would be early warning before any major break in pressure boundary occurs. In this regard the calculations also help in serving design basis of leak monitoring devices, etc. The second important reason is to arrive at design simplifications to minimize design and operational penalty (i.e. the radiation exposure during in-service inspection). This is due to the fact that rupture of the pipe does not form design basis of pipe supports, jet shield, pipe whip restraints etc. This in turn leads to lesser operation stress and removal of jet shield, pipe whip restraints improves the accessibility to pipes which leads to lesser radiation exposure during in service inspection.

2.2.1 LBB Background

Historically, a hypothetical double-ended guillotine break (DEGB) of largest size high energy pipe line has been considered as the most severe accident namely loss of coolant accident (LOCA), while designing the NPP. Originally the postulation of DEGB was to
provide a design basis for sizing the reactor containment system. However, later it was extended to the design of the high energy piping system, resulting in the construction of massive pipe whip restraints and jet impingement shields, simply because no alternate acceptable design basis was available. The DEGB postulate was further extended to the design for environmental qualification and even in the sizing of the emergency core cooling systems (ECCS).

For many years, the commercial nuclear industry has recognized that a DEGB is highly unlikely even under severe accident loads and that a design basis LOCA based on DEGB is an unnecessary and undesirable design restriction. The LBB methodology has been accepted as a technically justifiable approach for eliminating postulated DEGB in high energy piping systems. This conclusion resulted from extensive research, development and rigorous evaluations in the area of fatigue, fracture, material and component tests, defect inspection and leak detection technologies, by the U.S. Nuclear Regulatory Commission (USNRC), the German Commission on Reactor Safety (RSK) and the commercial nuclear power industry since the early 1970s.

2.2.2 LBB Methodology

The methodology to demonstrate LBB compliance is based on advanced fracture / fatigue mechanics techniques and includes critical flaw size evaluation; leakage calculation; crack propagation analysis; ultrasonic flaw detection/sizing; leak detection; and service experience. “Modification of General Design Criterion 4 (GDC-4): Requirements for Protection against Dynamic Effects of Postulated Pipe Ruptures”, [2], released by the USNRC in 1984, uniquely defines the leak-before-break case. LBB assessment involves three levels. The complete LBB assessment calls for generation of complete material...
property database and understanding of material degradation mechanisms owing to ageing and environment (level-1), fatigue analysis (level-2), leak rate and fracture analysis (level-3). In level-1 it is ensured that material is ductile/tough and free from objectionable flaws/cracks. This is usually achieved by adhering to standard design codes, sound design and manufacture practices and rigorous quality assurance. In level-2 a credible sized part-through flaw is postulated, assuming it might have escaped detection during pre-service inspection. Assessments are done to assure that under different service loads it will not grow to a size where breakage may occur before the leak. In level-3, as a worst-case assumption, it is postulated that a through-wall crack exists with maximum credible size such that flow through can be detected using leakage monitoring system under normal operating conditions (NOC) loads. Such postulated crack is called as Leakage Size Crack (LSC). LSC is postulated, at all the potential locations and rigorous fracture assessment is performed for demonstration of LBB capability and safety margin against fracture failure, under postulated design basis accident event loading which in several countries, as in India also, is Safe Shutdown Earthquake (SSE). Presently LBB is applied worldwide in high energy piping of nuclear power plant and requirements and methodology are well documented in several guides/reports like USNRC LBB guide NUREG 1061 Vol-3 [1], Standard Review Plan, Section 3.6.3 of NUREG-0800 [3], IAEA-TECDOC [4, 5], Russian LBB guide[6], French LBB Guide [7], British R-6 method [8], German LBB concept [9-11], European LBB practices [12], NUREG-6765 on LBB technical basis [13], Korean practice [14], India [15], China [16,17] and recent developments in France [18, 19] etc..

From all above documents/reports it is clear that the most important and indispensable requirement for LBB is the stability demonstration of a leaking pipe.
“The piping system with a through wall crack, providing enough leakage for reliable detection by installed leak monitoring systems, shall remain stable during a severe earthquake event considered in design basis loading of piping system”

This requirement calls for integrity/stability demonstration of a through wall cracked (LSC size) pipe under normal operating conditions as well as under combined normal plus earthquake loading.

2.3 Stability analysis of cracked pipes

The nuclear power plant piping components are invariably made of ductile materials, like low C-Mn steel or austenitic stainless steel, and their failure is governed either by ductile fracture or by plastic collapse when they are subjected to large loading. Hence, the critical or ultimate load/moment (MU or MC) is taken as minimum of unstable ductile fracture/tearing load (MF) or plastic collapse moment (MP). The unstable ductile tearing load is assessed using the elastic plastic fracture mechanics while the plastic collapse load assessment is based on limit load analysis and net section plasticity. In the past huge effort were made to develop stability assessment procedures for the cracked pipe subjected to axial and bending loading. A brief background of these efforts in context of LBB is given below:

2.3.1 Background

The research and developments during 1960s, led to development of elastic plastic fracture mechanics parameters like CTOD [22] and J-integral [23] which later become the predominant method to characterize elastic-plastic fracture in the nuclear industry. During 1970s-80s, the research and developments efforts led to development of stability analysis
procedures specially J-integral based solutions for piping fracture analysis, standardization of the J-R curve testing method to develop elastic-plastic fracture toughness of piping materials, and validation of the J solutions for cracked pipe using pipe experiments typically done under simple quasi-static loading. The J-integral tearing modulus fracture instability methodology got recognised and came into use. The tearing modulus (T) is a dimensionless parameter that is proportional to slope of the J-integral vs. Crack length (or growth) curve, $T \propto \frac{dJ}{da}$.

2.3.2 Elastic Plastic Fracture Mechanics

Elastic Plastic Fracture Mechanics (EPFM) is used when large plastic zone is formed ahead of crack tip. EPFM demands a careful understanding of the crack tip plasticity and currently there are main two methods of ductile fracture assessment. These are: (i) Crack tip opening displacement (CTOD), suggested by Wells [22] and is popular in Europe (ii) J-integral proposed by Rice [23] and is widely used in the United States. Both these fracture parameters are discussed below:

2.3.2.1 J-Integral

In 1968, Dr. James Rice [23] first proposed the J-integral as an elastic-plastic fracture mechanics (EPFM) methodology. It provided the basis for EPFM fracture mechanics methodology well beyond the validity limits of Linear Elastic Fracture Mechanics (LEFM). Since then, this parameter has become the predominant method to characterize elastic-plastic fracture in the nuclear industry. The J integral has been used to characterise the crack driving force, crack tip stress field and the strain energy release rate during crack growth under elastic plastic. Thus the J integral can be viewed as both an energy parameter
and a stress intensity parameter for non-linear materials. The J-integral as energy parameter is defined as

\[ J = \frac{d\Pi}{dA} \]  

(2.1)

Where ‘\( \Pi \)’ is the potential energy and ‘A’ is crack area. The potential energy is given as difference of the strain energy stored in the body and the work done by external forces. The integral as a path independent parameter is defined as

\[ J = \int \left( w \, dy - T_i \frac{\partial u_i}{\partial x} \, ds \right) \]  

(2.2)

Where ‘w’ is the strain energy density and ‘\( T_i \)’ are component of traction vector. The ‘\( u_i \)’ is the displacement vector and the \( ds \) is a length increment along an arbitrary contour path ‘\( \Gamma \)’ taken as clockwise around the tip of the crack (see Figure 2.1(a)). The basic J-integral parameter was extended further to account for toughness changes with crack growth, resulting in what is known as the J-resistance curve.

Figure 2.1:(a) Schematic of an arbitrary contour around the crack tip of a CT specimen; (b) Schematic of a typical J-R curve of ductile material (Ref. [25])
2.3.2.2 **Crack Tip Opening Displacement (CTOD)**

Wells [22] proposed that the failure of a cracked component can be characterized by Crack Tip Opening Displacement (CTOD) theory based on the study of fracture specimens that degree of crack blunting in proportion of the material ductility. The CTOD or Crack Mouth Opening Displacement (CMOD) is defined as the opening of the crack faces in the vicinity of a sharp crack tip and is a measure for the plastic strain ahead of the crack-tip.

The Shih [24] analysis shows mat there is a unique relationship between J and CTOD/CMOD for a given material. Thus these two quantities are equally valid crack tip characterizing parameters for elastic-plastic materials.

2.3.2.3 **Tearing Modulus**

The J-integral is used with Tearing Modulus T (J-Tearing method) in elastic plastic fracture assessment [41]. The J-integral, as crack driving force or as material resistance to crack growth, changes with extension of crack. The rate of change of J-integral has significance while assessing stability of crack growth. The slope of J_{app} - \Delta a (or J_{R} - \Delta a) curve is usually quantified by a dimensionless parameter called Tearing Modulus. It is defined as:

\[
T = \frac{E}{\sigma_0^2} \frac{dJ}{da}
\]  

(2.3)

Where E is the elastic modulus and \sigma_0 is the flow stress of the material.

2.3.2.4 **Crack growth resistance curve (J-R curve)**

Many materials with high toughness display increasing fracture resistance with crack growth characterized by a rising J-R curve. The material’s resistance to crack growth is
quantified by the J-resistance (J-R) curve and is evaluated by performing fracture tests on small sized cracked specimens such as compact tension, CT and single edge notch bend, SENB etc. or piping components such as cracked pipes or elbows etc.. A typical J_R-Δa curve plot is shown in Figure 2.1(b).

2.3.2.5 **J-Tearing Analysis**

In the application of elastic plastic fracture mechanics (EPFM) for fracture assessment of NPP piping, the J-tearing theory is an established concept for calculation of maximum load carrying capacity of the pipe. It is based on the ductile tearing i.e. on the fact that fracture instability occurs at higher applied loads and after some amount of stable crack growth in ductile and tough materials. The initiation of crack growth is characterised by following equation:

\[
J_a \geq J_i
\]  

(2.4)

Here ‘J_a’ is the applied J-integral and is obtained from the analysis of cracked component geometry under specified loading. The ‘J_i’ in the fracture crack initiation toughness and is obtained from standard fracture tests on small specimens made from same material. The fracture instability based on J-tearing theory is characterized by following equations.

\[
J_a(Δa) \geq J_R(Δa)
\]  

(2.5)

\[
T_a(Δa) \geq T_R(Δa)
\]  

(2.6)

To evaluate the instability load, the applied J-integral, ‘J_a’, and the tearing modulus, ‘T_a’, are respectively compared with those obtained from material J_R-Δa curve. The material J_R-Δa (or J_{mat}-T_{mat} ) curve can be extrapolated beyond the maximum Δa obtained in specimen
fracture test [26].

Figure 2.2: Schematic of ductile fracture assessment using J-tearing analysis

2.3.3 Plastic Collapse

The plastic collapse is a competing failure mode to ductile fracture for cracked components made of ductile material. Here the failure is characterised when gross plasticity deformation or yielding occurs in the section containing crack which leads to unbounded / large deformations in the structure component leading to instability (see Figure 2.3). The plastic collapse assessment methods are well developed [27-31]

Figure 2.3: A schematic showing plastic collapse
2.3.4 Stability Analysis Methods: LBB level-3

Current leak-before-break analyses involve assessing the load-carrying capacity of through-wall cracked pipe. These assessments assume that the load is increased in a quasi-static fashion until the instability owing to fracture or plastic collapse occurs. The load carrying capacity of a pipe is taken as minimum of the critical load obtained for two competing mode of failures namely unstable ductile tearing and plastic collapse. In case of ductile materials, ductile tearing failure mode based critical load may be higher than that evaluated based on plastic collapse. Hence for ductile materials, both ductile fracture and plastic collapse mode of failure are considered in stability analysis of cracked piping components for demonstration of their compliance to LBB. Currently several methodologies of stability assessment are available in literature, codes and guides [6-8, 32-42]. The material’s tensile, fatigue and fracture properties required in these methodologies are obtained by performing small specimen tests following the testing standards [43-45]. These stability assessment methodologies can be grouped into three broad categories as given below:

(a) J-integral based methods: This is a fracture mechanics based methodology which does not implicitly consider the possibility of plastic collapse mode of failure. Here, the criterion is primarily derived based on ductile tearing mode of failure with the calculation of J-integral by following methods:

(i) GE-EPRI J-Tearing Method

(ii) A-16 method

(iii) LBB-NRC Method
(iv) LBB.BCL1 Method
(v) LBB.BCL2 Method
(vi) Finite Element Method

The technical basis of above (iv and v) analyses methods was developed in the Degraded Piping Program of USNRC. Other methods GE/EPRI [32, 36-37 ] and LBB.NRC [42] analyses are based on the J-integral/tearing modulus theory. The A-16 [7] method is developed by French CEA as part of RCC-M code appendix. As such, (i - v) fall under the category of J-estimation schemes. These J-estimation schemes are relatively simple to use compared to finite element analysis.

b) Plastic collapse/instability based methods: Here, the criterion is primarily derived based on net section plastic collapse or the plastic instability mode of failure.

(i) Limit Load Method
(ii) Modified Limit Load Method
(iii) Moments Method

c) Double criteria approach: Here, the criterion considered both fracture as well as plastic collapse mode of failure.

(i) R-6 method [8]
(ii) ASME Section XI, Z-Factor method [38]
(iii) ASME Section XI, FAD method [38]
2.4 Load history effects on fracture stability cracked piping

The discussions in previous section have shown that the fracture stability assessment of cracked piping under quasi-static monotonic loading conditions is well understood and the analyses procedures / methodologies are well developed, validated and have been used in LBB analysis worldwide since last 2-3 decades. However these analyses/methodologies do not explicitly account for load history and load cycle effects on stability of cracked piping. In this section the existing literature has been reviewed in context of impact of load history effects onto fracture stability assessment of cracked piping. An earthquake event, which is considered in designing and LBB demonstration of the piping system of NPPs, induces reversible dynamic cyclic loading. In view of this the effects of load history and the number of loading cycles, on stability analysis of piping is a very important aspect of LBB compliance. A leaking pipe, which is considered safe based on monotonic load stability analysis procedures (sec.2.3.4), may fail in very few cycles of repetitive dynamic loading.

While reviewing various regulatory guides and documents on LBB [1-19] practised in different countries, it is observed that most of these documents are silent on consideration of the load history effects on the fracture/tearing stability assessment of a cracked pipe. Although some of them (e.g. NUREG-1061 vol.3 [1]) have identified its importance, however, no suggestions have been made to account for the degradation during cyclic loading. Below is an extract from NUREG 1061 [1]

….“The ductile fracture mechanics and experimental J-R curve techniques discussed in the report assume that loads are applied in a monotonically increasing fashion. In reality, under seismic loading conditions fully reversed cyclic loading could be anticipated. To date little work has been performed to evaluate the load history effects
The review of all the current leak-before-break (LBB) [1-19] documents and in-service flaw stability evaluation criteria [38], showed that the fracture evaluations are typically based on a quasi-static monotonic J-R curve data. The earthquake loading, however is dynamic cyclic in nature.

2.4.1 Background

In view of above, in recent past two large experimental and analytical programmes, namely International Piping Integrity Research Group (IPIRG) programme (from 1986 - 1997), [46 to 61], and a programme (1991-1997) by Central Research Institute of Electric Power Industry (CRIEPI) Japan, [62-66], have put huge effort to understand and develop procedures to account for loading history effects in crack growth and stability analysis in the tearing – fatigue region. The IPIRG tests [13, 56-58] have shown that seismic inertial loading can produce complete fracture instability. The reversible cyclic nature of the earthquake load was found to have substantial deleterious effects on fracture, rather than its dynamic nature. IPIRG programme presented two approaches to account for the cyclic loading effect on ductile tearing assessment of cracked pipe. First one is based on the low cycle fatigue crack growth using the Dowling’s $\Delta J$-integral while the other modifies the J-R curve, named as Cyclic J-R curve, to account for load-history effects. In CRIEPI programme a procedure for crack growth calculation and stability assessment was proposed. This was based on cyclic $J_{\text{max}}$ and $\Delta J$ integrals, evaluated from load - displacement envelope curve of the cyclic tearing test.

In addition to above research programmes, limited work was reported by other investigators
which are primarily based on tearing fatigue tests on CT specimen to study material behaviour under cyclic loading. Salient observations from these research works are discussed in following sections:

2.4.2 IPIRG Program (1986-97)

The International Piping Integrity Research Group (IPIRG) [46 to 61] who shared a common interest, was an international group formed and managed by the U.S. Nuclear Regulatory Commission and funded by a consortium of organizations from nine nations: Canada, France, Italy, Japan, Sweden, Switzerland, Taiwan, the United Kingdom, and the United States. One of the objectives of the IPIRG programs was to investigate the behaviour of circumferentially flawed piping systems subjected to high-rate repetitive loadings typical of seismic events.

Prior to IPIRG-1 program, the nuclear piping fracture research in the international community had focused on relatively large cracks in straight pipe and welds joining straight pipe under simple monotonic loading. As a result, the technology for predicting the behaviour of such cracks is relatively established. However, no efforts had been undertaken to determine if using quasi-static material properties was appropriate to use for integrity assessment of components subjected to cyclic type of loading e.g. earthquake. Under IPIRG-1 program there were three main experimental efforts undertaken in the area of load history effects on fracture resistance. These are:

(1) The simplest involved through-wall-cracked pipe tests conducted under four-point bending under different loading conditions. The IPIRG-1 Program evaluated the separate and combined effects of dynamic and single-frequency cyclic loading on
circumferentially cracked pipe in four-point-bending experiments and in pipe system experiments. During the IPIRG-1, a series of circumferential through-wall-cracked pipe fracture experiments were conducted with the intent of investigating the separate effects of dynamic and cyclic loading on the fracture toughness of typical ferritic carbon and austenitic stainless steels. The results from both the load-history effects on fracture and the piping system evaluations showed that reversed cyclic loading during ductile tearing had a large effect on the apparent toughness of the material. The dynamic load effects were negligible for the TP304 steel, but tended to marginally reduce the toughness and load-capacity of the A106 B pipe material [35]. The investigations attempted to quantify the effect of cyclic and dynamic nature of loading on quasi-static monotonic fracture toughness of material. The quasi-static cyclic J (for fully reversed loading) and the dynamic monotonic J were related (see Figure 2.4) with the corresponding quasi-static monotonic J data [60].

(2) The second type pipe tests, slightly complicated, were conducted with internal pressure, an initial dead-weight load, and inertial loads. In these tests, once the pipe reached the maximum load, it only took two to four cycles to reach DEGB [35].

(3) The third type was major fracture tests of the IPIRG-1 program. These were conducted on piping system conducted at PWR conditions with a relatively large diameter pipe [59]. Here, in all the experiments, the surface crack penetrated the pipe wall and grew unstably until it got arrested at the ends of the surface crack. Subsequent cyclic loading caused additional through-wall crack growth to produce a double-ended break [59]. The comparison of the maximum loads from
the pipe system and the quasi-static pipe experiments were also investigated in IPIRG-1 program [58]. The ratio of the maximum loads of the system experiments to the quasi-static experiments versus the quasi-static yield-to-ultimate strength ratio is shown in Figure 2.5(a) (reproduced from [58]). Here it may be noted that, in most cases, the pipe system maximum loads are lower than the quasi-static monotonic bend tests maximum loads. The effect of the different stress components (i.e., primary membrane, Primary bending, secondary thermal expansion, and secondary seismic anchor motion) in pipe system tests test and the comparison of the total maximum loads with that in the quasi-static experiments is shown in Figure 2.5(b) (reproduced from [58]). These tests were analysed and the margins were evaluated using various popular fracture analyses methods, like NSC, ASME Sec-XI, R-6 and J-Tearing etc. The fracture margins, defined as the ratio of maximum stress measured in the test and predicted by analytical methods, for both the IPIRG pipe system experiments as well as the companion quasi-static experiments, are shown in Figure 2.5(a and c) (reproduced from [58, 59 and 62]).

The results from IPIRG-1 program, both the load-history effects on pipe fracture and the piping system evaluations gave significant insight into the real behaviour needed to realistically assess the leak-before-break (LBB) and in-service flaw evaluations. These experiments showed that reversed cyclic loadings caused a significant decrease in the apparent toughness of the cracked pipe.
Figure 2.4: (a) The effect of cyclic loading on fracture toughness; [ref. 60] (b) the effect of dynamic loading rate on fracture toughness [ref. 60]
(a) Ratio of IPIRG-l pipe system maximum loads to the companion quasi-static pipe test maximum load versus quasi-static yield-to-ultimate strength, all data at 288C (ref. [58])

(b) Bar chart showing the fracture behaviour of the IPIRG-I pipe-system experiments (ref. [58]) Comparison of maximum loads for IPIRG-l pipe system tests and companion quasi-static tests (CSBM=AI06 B base metal, SSBM=TP304 base metal, ACS=aged CF8M, CSW= carbon steel SAW, SSW=stainless steel SAW)

(c) Range of inherent fracture margins for pipe system and quasi-static experiments (ref. [59])

Figure 2.5: Salient results from IPIRG piping system and standalone pipe fracture tests
Second International Piping Integrity Research Group (IPIRG-2) Program was built on what was learnt during the IPIRG-1 program. The task 1 and task 3 of IPIRG-2 program were on further studies on dynamic cyclic fracture assessment of cracked pipe and piping system. These are briefly

(a) IPIRG-2 Task 1: In this task tests were conducted on pipe system (loop) with flaws in straight pipe / welds, under a simulated seismic loading history as opposed to the single-frequency loading used in the IPIRG-1 program. The investigations were focused on the effects of complex load histories with variable amplitudes and multiple frequency content such as in a seismic event.

(b) IPIRG-2 Task 3: This task dealt with cyclic and dynamic load effects on fracture toughness. The investigations were focused on the resolution of differences in toughness values observed between laboratory specimen and full-scale pipe experimental data resulting from load history effects, such as the cyclic and dynamic loading effects that can occur during a seismic event.

2.4.2.1 Summary of outcomes from IPIRG program in context of present study

The salient observations reported from IPIRG programme [46-61] related to stability assessment under seismic load are given below:

(a) NUREG 6233-1 [57], NUREG 6233-4 [56], NUREG 6452 [61], G. Wilkowski et al. [58] and NUREG 6765 [13] reported that the inertial loading produced complete fracture instability in only a few cycles past maximum load. The inertial stresses produced in these experiments were similar to load-controlled stresses for fracture stability analyses. The load-carrying capacity of a cracked pipe subjected to a
simulated seismic load history is no worse than that of a cracked pipe subjected to the single-frequency excitation. In IPIRG-1 program, the ratios of maximum loads obtained in the system experiments to that obtained in the quasi-static monotonic bend tests [58], in most cases, are less than 1, see Figure 2.5 (a and b).

(b) The stress ratio (minimum/maximum stress) for a cracked pipe system at SSE loading should conservatively be assumed to be -1, because cracked pipe has a more negative stress ratio than uncracked pipe. [61]

(c) The investigations, NUREG-6440 [53] showed weak interaction between the dynamic and cyclic effects. NUREG-6438 [50] reported that the cyclic nature of the loading has substantial effect on the fracture resistance of the material than that of dynamic nature. Hence the deleterious damage due to cyclic nature of load dominates. NUREG 6233-2 [54] reported reduction in the load-carrying capacity, and apparent toughness under quasi-static incremental displacement loading test with load ratio equal to -1.

(d) Marschall et. al. [51], compared the monotonic static and monotonic dynamic strength and J-R curve from IRIRG-1 programme and have shown that the quasi-static material property data are adequate for in-service and LBB analysis of SS and CS pipes. In other word the dynamic nature of load, in general is found to have insignificant effect on fracture resistance.

(e) In IPIRG program, NUREG 6765[13], a set of curves were developed which relate the ratio of cyclic J to monotonic J-integral ($J_{cyc}/J_{mono}$) with applied load ratio and material toughness. These studies showed that $J_{cyc}$ depend on loading history as
well as material toughness.

(e) The cyclic plastic loading prior to crack initiation and during ductile crack growth causes a toughness degradation effect [53]. The toughness of all nuclear piping materials reduced under cyclic loading. The stress ratio, displacement increment, cyclic plasticity, cyclic crack growth, and initial toughness govern the amount of degradation. A correction factor was developed between yield/ultimate strength ratio versus toughness under dynamic and with \( R = -1 \) cyclic loading relative to the toughness under quasi-static monotonic loading [53, 61] (see Figure 2.4 and Figure 2.6). The effect of the R-ratio on the J-R curve appears to saturate to a minimum value at an R-ratio of -1. At \( R = 0 \), there is negligible effect, i.e., equal to the monotonic J-R curve. The transition of the J-R curve from \( R = 0 \) to -1 appears to be sensitive to the material toughness [53, 58].

(f) In order to obtain comparable J-R curves from CT specimens and TWC pipe under cyclic loading, the CT tests should be conducted with the same stress ratio and the same normalized cyclic plastic displacement. During crack growth, the cyclic plastic displacement needs to be changed to account for geometry effects in order to provide similitude between cracked pipe and specimens.

(g) The IPIRG programme [53] presented basic analysis approach to account for cyclic tearing. Here two approaches were presented to predict the effect of cyclic loading effect on ductile tearing and load carrying capacity of cracked pipe. The first one was based on the low cycle fatigue crack growth using the Dowling’s \( \Delta J \)-integral method along with the extrapolated Paris law. The other was based on the modification of J-R curve, named as Cyclic J-R curve which accounts for load-
(h) The analytical assessment of cyclic tearing tests in the IPIRG programme had used procedures similar to monotonic fracture assessment except replacing the load-displacement curve with the envelope curve which was obtained from the incremental displacement controlled cyclic fracture tests.

![Graph showing experimental J versus calculated J for dynamic, cyclic (R=-1) experiments](image)

Figure 2.6: Experimental J versus calculated J for dynamic, cyclic (R=-1) experiments (ref. [35])

2.4.3 CRIEPI program (1991-97)

The Japanese participants in the above IPIRG program were CRIEPI. CRIEPI, as a Japanese representative, played a major role in managing the program among Japanese members. CRIEPI has carried out several tasks additional to the IPIRG program, on Japanese piping material and to look at some of the aspects which are not covered in IPIRG.
program. The CRIEPI programme [62-65] also confirmed the IPIRG finding of significant influence of fully reversed loading on the cyclic fracture stability. The salient observation / outcome of CRIEPI programme is given below:

(a) A series of fracture tests was conducted on circumferentially cracked carbon steel (STS410) pipes at high temperature (285°C) under the four-types of dynamic bending loadings (monotonic load, cyclic loads with constant amplitude, increasing amplitude and random amplitude, see Figure 2.7).

(b) Monotonic pipe tests showed that the dynamic (strain rate) effect was negligible for this material and fracture load was well predicted by the tensile properties of the material.

(c) CRIEPI proposed an evaluation method for dynamic pipe failure to predict the crack initiation, stable crack propagation and unstable pipe failure, based on the fracture mechanics approach, the J-integral based parameter.

(d) A cyclic $J_{max}$ integral and cyclic $\Delta J$ integral based procedure was proposed for crack growth calculation and stability assessment. Both the $J_{max}$ and $\Delta J$ integral were

Figure 2.7: CRIEPI Test Facility and Loading Conditions (Ref. [62])
evaluated from the load - displacement envelope curve of the cyclic tearing test.

2.4.4 Other investigations

Salient observations from the limited work by several other investigators, in area of fatigue-tearing under cyclic loading other investigators which are primarily based on tearing fatigue tests on CT specimen, have been given below:

(a) I. Milne [68] has studied ductile tearing in presence of fatigue associated with variable amplitude loading and in conjunction with R-6 provisions. It is suggested that in fatigue-tearing regime, tearing should be regarded as causing an acceleration of the fatigue crack growth rate, than the fatigue causing a reduction in the material's resistance to tearing. The ductile instability condition is still determined by the pure tearing resistance curve, but the fatigue crack growth to that state is more rapid.

(b) Marschall and Wilkowski, [69], Chang et al [70, 71] and other investigators, have reported that the cyclic J-R curve based on load-displacement envelope of cyclic test strongly depends on loading parameters such as load ratio, displacement increment etc..

(c) Recently Singh et al [72], Roy et al [73, 74], have discussed cyclic fracture studies on CT specimens. These studies clearly brought out; i) the significant drop in cyclic J-R curve under fully reversing loads and ii) the dependence of cyclic J-R curve on loading history. Qualitatively these observations are in agreements with that from components cyclic tearing tests of IPIRG programme. However the quantitative observations have to be verified in view of issues of transferability of the J-R curve from the specimen fracture test to components level
2.4.5 Summary of past research on load history effect of fracture behaviour

The recent LBB document (2002), NUREG 6765 [13] has presented comprehensive review and compiled nearly all the developments of technical basis for LBB evaluations, lessons learned from past LBB applications and the research results (1985-2001) in area of Leak-Before-Break evaluation procedures. In addition to several other aspects, this report has thoroughly reviewed all the salient work (1985-2001), in the area of load history or cyclic load effects on the fracture stability behaviour of typical nuclear pipes, piping system and also on the fracture toughness J-R curve of typical nuclear piping materials. Below is an extract from NUREG 6765 [13]

"In summary, although cyclic loads can be detrimental to fracture resistance, there is no clear way as to how to account for them. Perhaps the best way would be to conduct a probabilistic study on seismic load functions, and use that to assess the magnitude of the degradation effect versus frequency of occurrence. One could then establish a cyclic toughness correction based on the mean result of that study."........ (Section 5.3.3.2 of [13])

This clearly indicate that despite the huge efforts to develop procedures to account for the loading history effects in stability analysis, the cyclic tearing failure mode is not explicitly taken care of in present guides/practices [1-19] of stability demonstration of a cracked pipe. This also indicate the un-availability of simple, reliable and easily implementable procedure to demonstrate the fracture stability of cracked pipes including the load history effects and for specified number of cycles as required in level-3 of LBB analysis
2.5 Cyclic J and $\Delta J$ Integral

The IPIRG and CRIEPI programmes and other past investigators have used Cyclic J and $\Delta J$ integrals to develop analysis methodologies for assessing the crack growth and fracture behaviour of materials under cyclic loading conditions.

Lamba [75] in 1975, first proposed J-integral application under cyclic loading and presented its formulation. Dowling and Begley [76] in 1976 first proposed use of $\Delta J$-integral for fatigue crack growth modelling in presence of gross plasticity. K Tanaka, 1983 [77], Lambert, 1988 [78], have provided mathematical frame work to estimate cyclic J and $\Delta J$ integral for 2D and its physical significance for fatigue crack growth was discussed using Dugdale model. However, the applicability of the J-integral to cyclic loadings conditions is questioned and controversial. The J-integral evaluation procedure, prescribed in ASTM E 1820-09 [44] and other standards, violated the theoretical definition of J-integral due to periodic partial unloading, however to have an engineering solution it has been accepted by consensus [79]. Afterward, in IPIRG, CRIEPI and several other investigations used cyclic J and $\Delta J$ integral for fatigue crack growth modelling under elastic-plastic conditions.

2.5.1 Cyclic J-R curve for fracture and Cyclic $\Delta J$ Integral for FCG assessment

As reported above, the concept of cyclic J and $\Delta J$ integral was developed during 1975-1990, [75-79]. However, the concept of cyclic J-R curve characterizing material’s fracture resistance under cyclic loading is of recent origin [74, 80-85]. Only a few international laboratories have worked on this problem and the available literature on cyclic J-R behaviour of materials is very limited. Mogami et al. [80] have first proposed cyclic
J-integral tests to simulate the deleterious effects of periodic load reversals. K. Mogami et al. [80] have studied the fatigue crack growth and tearing instability behaviour of STS 42 carbon steel and A508 low alloy steel under cyclic loading. Here the $\Delta J$ and $J_{\text{max}}$ were used for modelling of crack growth.

Several investigators [69-74] have reported that the cyclic J-R curve strongly depends on loading parameters such as load ratio ($R$), displacement increment ($\delta$). To understand the impact of cyclic loading on cyclic J-integral, the studies generally divided broadly into two categories viz., tests conducted with a load ratio, $R \geq 0$ and $R < 0$.

S. Kaiser [81], B K Neale and E K Proddle [82] have studied the fatigue-crack growth and stable tearing under cyclic loading with positive load ratio, $R \geq 0$. S. Kaiser [81] has conclusively shown the influence of number of unloading cycles on the J-R curve obtained from CT specimens tests (see Figure 2.8). The J-R curve is strong function of cyclic displacement increment and number of loading cycles. However, when this data is corrected for the fatigue part of the crack growth during unloading (fatigue crack growth in each cycle subtracted from the total crack extension of that cycle), the resulting J-R curves (see Figure 2.9), now fall into the scatter band of monotonic J-R tests.

B. Skallerud and Z L Zhang [84] have investigated failure of structures due to fatigue-tearing crack growth, under severe cyclic loading. Here the fatigue part of the crack growth was computed using Dowling’s cyclic $\Delta J$ integral while the ductile tearing crack growth computed using Gurson-Tvergaard model. All these have studies [81-84] observed significant increase in crack growth due to concurrent fatigue cycling. The crack growths were found in reasonable agreement with the sum of predicted fatigue crack growth and stable tearing component for the tests conducted with a load ratio, $R \geq 0$. 
C.W. Marschall and G. Wilkowski, [69] have reviewed several experimental and analytical studies carried out to understand effect of cyclic loading on ductile fracture resistance. It is shown that the crack tearing under cyclic loading with R-ratio greater than 0, the total crack extension is just summation of crack extension due to monotonic ductile tearing, $\Delta a_{\text{mono}}$ (obtained from a monotonic J-R curve test) and fatigue crack growth, $\Delta a_{\text{cyc}}$ (estimated using fatigue crack growth analysis). While for negative R-ratios the total crack extension exceeded the $d \Delta a_{\text{mono}} + \Delta a_{\text{cyc}}$. The difference in measured tearing with that of estimated tearing clearly showed additional tearing/degradation taking place due to compressive loading which is not being accounted for in the above calculation procedure.

During 1990s, in the IPIRG programme, CRIEPI investigations and several other studies reported above, the cyclic J-R curve was considered in cyclic fracture assessment studies. Rahman et al.[85] have shown that the cyclic $\Delta J$ is an effective parameter to describe the low cycle fatigue crack growth in cracked pipe fracture analysis.

### 2.5.2 Limitations of Cyclic J-R curve

The above literature review has clearly brought out that the cyclic J-R curves following limitations of cyclic J-R curves:

(a) The cyclic J-R curve is found dependent on loading parameters such load ratio, displacement increment etc. The loading history at a location in piping depends on several factors such as, input earthquake spectra, piping layout etc. Hence development of generalised procedure or rule is difficult.
Figure 2.8: Influence of the numbers of unloading on the J-R-curve. CT-specimen of material OX 812. (Ref. S Kaiser [81])

Figure 2.9: Data of Figure 2.8 but with the crack growth during unloading subtracted from the total crack extension. (Ref. S Kaiser [81])
Most of the studies on cyclic J-R are performed on the small size specimens. The application of cyclic J-R curves generated from specimens to large size piping components in view of difference in their constraints, have not been investigated. Hence application of the quantitative observations from the CT specimen tests have to be verified in view of issues of transferability of the J-R curve from the specimen fracture test to components level

2.6 Effects of geometry constraint on J-R curves

The crack initiation toughness and J-R curve used in J-Tearing analysis are, in general, obtained from standard fracture specimens following ASTM standard-1820 [44]. Here the J-integral is assumed to characterize the crack-tip stress field and one unique J-R curve is assumed sufficient to characterize the material. However, now it is well understood and established [86-90] that the J-R curves are geometry dependent. In view of the influence of crack-tip constraint or stress triaxiality on ductile fracture, the transferability of specimen J-R curve data to a component level is an issue. In most cases, standard ASTM specimens are such; they maintain high level of constraint, to ensure predominantly plane strain conditions at the crack tip. However, real structures generally be low-constraint geometries and hence use of the specimen J-R curve lead to conservative assessment. However if the real component geometry have higher constraints than that of specimen used to obtain J-R, the fracture assessment would lead to un-conservative condition.
2.7 Dynamic Strain Ageing

Dynamic strain ageing (DSA) is a phenomenon observed in many carbon steels at light-water reactor operating temperatures ranges, 150-450°C [91-96]. The DSA involves interactions between highly mobile nitrogen and carbon atoms dissolved in the steel and moving dislocations associated with plastic strain. At certain combinations of strain rate and temperature, these interactions can lower the crack-growth resistance and can cause a stably growing crack to become temporarily unstable. In general, an increase in the ultimate tensile strength and a decreasing trend of ductility properties with increase in temperature is observed. Dynamic strain aging is a time and temperature dependent phenomenon. Alteration in the strain rate can shift the occurrence of DSA phenomenon from one temperature range to another. It has been observed by these investigators that DSA has detrimental effect on fracture toughness behaviour of a material. Both the fracture initiation toughness and the resistance to crack propagation are found to decrease in the DSA operative range. DSA occurs under specific combination of temperature and strain rate and such test conditions must prevail for the degradation of fracture toughness properties.
2.8 Piping system compliance effects on fracture assessment

In conventional fracture stability assessment, the cracked pipe is assumed to have free rotations at its ends (infinite compliance of the connected piping), and subjected to the bending load. However, in reality the piping system is indeterminate since the ends of the pipe are connected to the rigid pressure vessels etc. Hence, the piping on the either side of the cracked section has finite compliance or non-zero stiffness (rotational). In piping system, the presence of crack causes moment redistribution and may result in some reduction of moment at its location. The reason for the moment redistribution is the indeterminacy of the piping system. This leads to change in the applied J-integral, crack mouth opening displacement (CMOD) and applied tearing modulus (T) curve. Nestell and Coward [97] had first included the effect of compliance in the stability criteria and derived an equation for applied tearing modulus. Afterward several investigators [98-100] studied the effect of piping system compliance on J-Tearing analysis. Simplified equations / graphs were developed to account for the piping compliance into stability assessment. These studies have also shown that any beneficial effect due to compliance is strong function of the system stiffness at crack location. However, the piping system experiments carried out as part of IPIRG programme (see 2.4.2) have not shown any significant advantage in the maximum load capacity of the piping system with respect to stand alone pipe.

On the other hand E Smith [102-103] have shown the deleterious effect of the piping compliance on assessment of crack opening area which is important in evaluation of leakage size crack, LSC. Estimation of the size of the crack that gives a measureable leakage under normal operating condition is a key requirement of LBB. It requires calculations of crack opening area which, in general, is performed on cracked pipe (ends free) and subjecting it to elastically calculated loads for the untracked piping system.
However, E Smith [102-103], has shown that this procedures does not account for the effects of piping system stiffness (owing to facts that a piping system is restrained, i.e. built in at its ends into large sized components) and leads to under-prediction of leakage size crack associated with a specific leakage area and therefore this has potential to jeopardise any leak-before-break argument.

The above literature has shown that considerations of the piping system compliance may be favourable in stability assessment but un-favourable in assessment of leakage size crack.

2.9 Appraisal of the problem and key issues

In designing the nuclear components [38], a minimum of 10 cycles of equivalent maximum magnitude of induced load during an earthquake event, are considered. In Indian NPP, one Safe Shutdown Earthquake (SSE) event (comprising of 10 cycles) and five Operating Basis Earthquake (OBE) events (comprising of 10 cycles per event) are considered in design. In view of this, the fracture stability or LBB assessment of the candidate pipe should be demonstrated for reasonable number of cycles and the load history effects on failure shall be considered. Currently used crack tearing and fracture assessment method as outlined in several LBB documents [1-19] does not explicitly account for damage due to the repeated cycles of such load. These consider the earthquake load as once applied non-cyclic load, which monotonically increases up to its maximum magnitude. The ductile fracture load or the critical crack size evaluation is based on the monotonic ductile fracture and uses the J-R curves evaluated under monotonic loading conditions. However it is known that under the large magnitude reversible cyclic loads (during SSE), the realistic failure mode is due to combined tearing-fatigue damage. Such failure is termed as Cyclic Tearing.

The literature survey (discussed in section 2.4) has shown that significant work was done
in area of fracture stability assessment under cyclic loading conditions. These investigators have recognized the deleterious cyclic tearing damage under a cyclic loading event. Although, these proposed a cyclic J-R curve approach to account for cyclic loading damage effects but it could not be widely used/practised due to following key reasons;

(a) The Cyclic J-R curve has strong dependence on the loading history: The loading history at a location in piping depends on several factors such as, input earthquake spectra, piping layout etc. Hence development of generalised procedure or rule is difficult.

(b) The Cyclic J-R curve is independent of number of loading cycles of a cyclic loading event

(c) The transferability of the cyclic J-R curve from the specimen level fracture test to component level test is not verified/established yet. Application of the quantitative observations from the CT specimen tests have to be verified in view of issues of transferability of the J-R curve from the specimen fracture test to components level.

(d) Analytical assessment would involve modelling of the cyclic plasticity and combined tearing-fatigue regime crack growth under reversible cyclic loading. These are yet not well developed, nor widely validated.

In view of these issues, there is a need to develop an independent, alternative assessment approach to consider cyclic tearing damage for a specified number of cycles of a cyclic loading event and which could directly be implemented in existing fracture stability assessment procedures.