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Structural Integrity of Main Heat Transport System Piping of AHWR

K.K. Vaze[1]

Abstract: Advanced Heavy Water Reactor (AHWR) is a 920 MWth, 300 MWe vertical pressure tube type reactor, which uses boiling light water as a coolant in a high-pressure main heat transport (MHT) system. Structural integrity considerations have been a part of the design process right from selection of material. Among the various degradation mechanisms, low temperature sensitization and low temperature embrittlement were considered to be the life limiting material degradation mechanisms: In view of the proposed 100 year life of AHWR, these issues need to be addressed in a thorough manner. SS 304LN has been chosen based on its satisfactory low temperature sensitization behaviour and superior low temperature embrittlement behaviour. The material specification was optimized to gain maximum advantage in respect of intergranular stress corrosion cracking. The IGSCC behaviour can be further improved by adopting Narrow Gap Welding technique. The beneficial effect of this on residual stresses was demonstrated by measurements on conventionally and narrow-gap-welded pipes. The defect tolerance of the piping was demonstrated by carrying out a test programme showing compliance with Leak-before-break criterion. Fatigue tests were carried out on notched pipe and pipe weld under cyclic loading with different stress ratio. The results of fatigue tests show that for the typical stress range expected in the piping of AHWR, the number of cycles to crack initiation and growth (through thickness) is very large compared to the expected number of cycles. Aspect ratio (2C/a) at the point of through thickness lies in the range of 3 to 4 irrespective of the initial notch aspect ratio, thus favouring application of LBB. The use of the fatigue crack growth curve given in ASME Section XI will produce a conservative result. Fracture tests were carried out on through-wall cracked fatigue tested pipe and pipe weld under monotonic loading. The results of the fracture resistance properties of the pipe and pipe welds prepared by GTAW are comparable whereas that of pipe welds prepared by GTAW+SMAW is on lower side. A combination of narrow gap welding technique and GTAW will provide an added assurance against failure due to

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IGSCC/fatigue/fracture.
Tests carried out with large amplitude bending loads address new failure mechanisms such as fatigue-ratchetting and cyclic tearing whereas tests with fixed-fixed boundary conditions consider the effect of compliance on fracture integrity.

Keywords: Austenitic stainless steel, pipe welds, Fatigue crack growth, Fracture resistance, Leak-before-break, Residual stress, Gas Tungsten Arc Welding (GTAW) and Shielded Metal Arc Welding (SMAW), limit load, Low Temperature Sensitization, Low temperature Embrittlement, Narrow gap welding, fatigue-ratcheting, cyclic tearing, compliance effect

1 Introduction

Advanced Heavy Water Reactor (AHWR) is a 920 MWth, 300 MW vertical pressure tube type reactor, with boiling light water as a coolant in a high-pressure main heat transport (MHT) system. The MHT system consists of common circular inlet header from which 408 inlet feeders branch out to the coolant channel core. The outlets of the coolant channels are connected to the tail pipes carrying steam water mixture from the individual channels to the four steam drums. The steam is separated from steam water mixture in the steam drum and is supplied to the turbine. The condensate is heated in moderator heat exchangers and feed heaters and is returned to steam drum by feed pump. For each steam drum, four downcomers are connected to inlet header. The schematic of the MHT system piping is shown in Fig. 1.

AHWR is a new reactor being designed with a target life of 100 years. Ageing and structural integrity aspects of the MHT system piping are of concern considering the life of 100 years for which experience and material data are not available. When ageing processes are known they can be monitored through ageing management program and plant life management program and necessary preventive measure can be adopted. New or unknown degradation mechanism leads to failure or accident. Failures of austenitic stainless steel piping of boiling water reactors due to Intergranular Stress Corrosion Cracking (IGSCC), fatigue, embrittlement have been reported extensively in the available literature. Prevention of IGSCC in the operating plant and new plant is a great challenge to the design and material engineers. First step towards addressing the life related issues was selection of material. All the likely degradation mechanisms such as IGSCC, embrittlement and fatigue have been considered and described. In addition to this, issues related to structural integrity of the MHT system piping, which are of concern to the long life of the plant are also addressed.

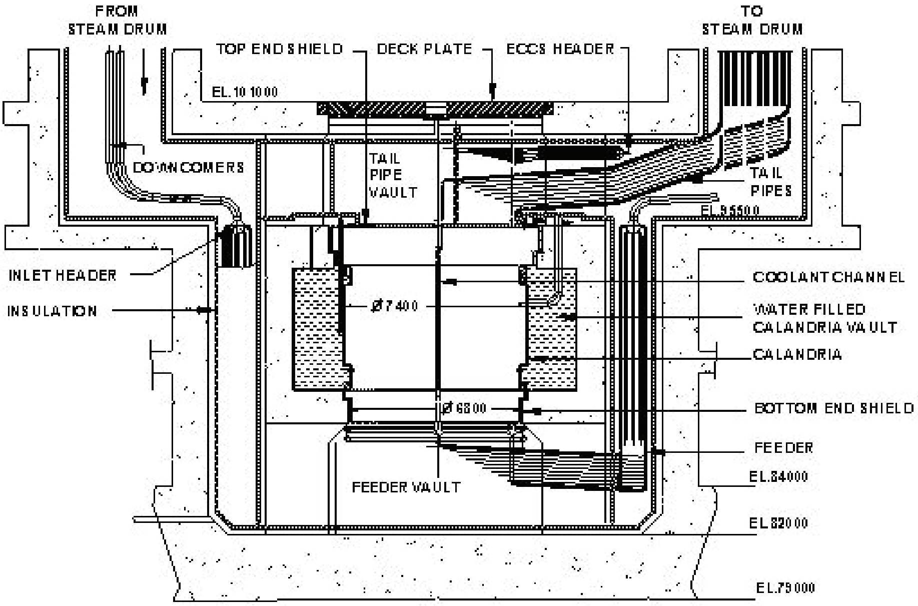


Figure 1: Schematic of the MHT system piping of AHWR

2 Selection of materials [AHWR (2005)]

Material for high energy MHT system components should have good corrosion resistance along with adequate strength and ductility. In addition to this, material should have good fabricability and be easily available. The selection of material is based on the literature survey, discussion with material experts, design codes and standards and the R&D activities carried out under component integrity testing program. Various factors considered in the selection of material for MHT system piping of AHWR are as follows:

- Operating conditions and plant life
- Material properties such as mechanical, metallurgical,
- irradiation and corrosion resistance.
- Availability of the material and data for design
- Ease of fabrication

- International experience
- Cost

Process fluid (coolant) in the MHT system is two-phase steam water mixture and the chemistry of the fluid would be similar to that of typical boiling water reactor. The operating temperature is 288^{o}C.

Austenitic stainless steel is the choice for this application because of its ductility, good weldability, excellent corrosion and erosion resistance properties, adequate strength, availability of material data and above all vast experience in the use of this material in boiling water reactors. The experience indicates that Boiling Water Reactor (BWR) piping systems fabricated from AISI type 304 and 316 austenitic stainless steels have been susceptible to intergranular stress corrosion cracking in the heat affected zone of the pipe girth welds [Danko (1991)]. Extensive testing in BWR environment has demonstrated that reduction in carbon content in austenitic stainless steel reduces susceptibility to IGSCC. This is in conformity with plant performance, in which higher carbon material (more than 0.04%) has cracked in service [Sandusky, Okada and Saito (1990)].

In order to provide sufficient margin for the resistance to sensitization, for Advanced Boiling Water Reactor (ABWR) the maximum carbon content will be specified as 0.02%. For major reactor structures, preferred material is SS316L where lower allowable strength is acceptable. To compensate for lower carbon level, strength is maintained by adding nitrogen up to a maximum of 0.12 % [Sandusky, Okada and Saito (1990)].

Austenitic stainless steels of several grades such as SS 304, 316, 304L, 316L, 304LN, 316LN, 321, 347 and their equivalents were considered for the choice of the material. SS 304 and 316 are susceptible to sensitization and lead to weld decay. Stabilized austenitic stainless steel such as SS 321 and 347 are less susceptible to sensitization, but may be prone to knife line attack and hot cracking during welding.

Although all the low carbon grades of austenitic stainless steels viz. SS 304L, 316 L, 304LN and 316LN will satisfy the general structural integrity concerns such as fatigue, fracture, general corrosion and erosion; it was recognized that in view of the proposed design life of 100 years for AHWR, aspects such as LTS and LTE will influence the material choice. Resistance to LTS is comparable for SS 304LN and 316LN whereas, resistance to LTE is superior in case of SS 304LN. This is because the kinetics of LTE is faster in presence of Molybdenum. Since SS 316LN contains Molybdenum, this implies SS 316LN will embrittle faster than SS 304LN. Therefore, SS 304LN is the choice of material.

Identified life limiting ageing degradation mechanisms are:

1. IGSCC,
2. Embrittlement, and
3. Fatigue (crack initiation and crack growth).

3 Intergranular stress corrosion cracking (IGSCC)

3.1 Low temperatures sensitization

When austenitic stainless steels are heated or slowly cooled in the temperature range of 500 to 850^{o}C, Cr rich $M_{23}C_6$ carbides precipitate along grain boundaries leading to chromium depletion in the adjacent regions. This phenomenon is known as *sensitization*. When a stressed and sensitized material is exposed to corrosive media, it undergoes intergranular stress corrosion cracking (IGSCC). It has also been observed that carbides nucleated by short exposures in the critical temperature range without a detrimental degree of chromium depletion, can grow during service well below 500^{o}C causing a severe degree of chromium depletion. This phenomenon is known as *Low Temperature Sensitization (LTS)*.

Extensive research on the LTS in stainless steel suggests SS 304LN and 316LN as alternative materials to combat LTS likely to be encountered in service. This is because time required for the onset of sensitization in stainless steel with low carbon and extra nitrogen is quite high and critical cooling rate below which sensitization takes place is quite low. When carbon is low (<0.03%), very long ageing time at high temperature is required for the nucleation of chromium rich carbide precipitation in sufficient quantities, which may lead to LTS. When nitrogen is also present, the diffusion coefficient of chromium is low and chromium carbide precipitation kinetics becomes sluggish [Dutta, De and Gadiyar (1993)].

Low Temperature Sensitization (LTS) studies were carried out to confirm that austenitic stainless steel components (base and weld materials of SS 304LN will not have LTS problem during service of the plant. These studies were performed on materials subjected to accelerated ageing by simulating time and temperature in such a way that the kinetics processes remains unaffected. The ageing durations of 1300 and 8000 hours at temperatures 450^{o}C and 400^{o}C were worked out by considering the activation energy of carbide precipitation $\sim$ 150 kJ/mol. Material is also being subjected to thermal ageing at temperature of 350^{o}C for 50000 hours to verify the kinetics of the sensitization mechanism close to the operating temperature.

3.2 Welding process optimization

The issue of IGSCC can also be tackled by optimizing the welding process and technique, which will lead to reduction in heat input and residual stress. The propensity to sensitization can also be reduced using high deposition welding process and narrow gap welding. Existing welding process (as per ASME Section IX) [ASME (1991)] used in welding of pipes is GTAW for root pass and SMAW for filling passes. Although fracture toughness properties of the GTAW is comparable to that of base metal (good for LBB), GTAW is a low deposition process leading to high heat input which is detrimental for resistance to sensitization. Fracture toughness of the SMAW is inferior compared to that of base metal, although deposition rate is higher compared to that of GTAW. Welding process suitable for welding of pipes should have high deposition rate and comparable fracture toughness. A narrow gap technique gives additional margin against sensitization without compromising the fracture toughness. Hot Wire GTAW Process with Narrow Gap Technique is suitable for welding of pipes of austenitic stainless steel. Existing procedure and work carried out related to optimization of welding process and technique is described below:

3.3 Residual stress evaluation

In order to demonstrate the benefits of narrow gap welding, residual stress evaluation was performed on a welded pipe. Pipe of 300NB Sch 120 was welded (manually) using most widely and versatile welding process, GTAW as root pass (few initial passes) and SMAW as filling passes. These welding processes are currently being followed in Indian Nuclear Power Plants. Residual stress evaluations have been carried out on following weld joints.

Manual SMAW with various groove angles (324 mm outer diameter pipe) (a) Conventional groove with 75^0 included angle, (b) Narrow groove with 0^0 (width 16mm), (c) Narrow groove with 0^0 (width 13mm) and Manual GTAW with conventional groove (168 mm outer diameter pipe) were used for residual stress evaluation. Residual stress was measured using blind hole drilling method at weld root and top. Figure 2 shows the significant reduction in the residual stress resulting from narrow gap welding.

3.4 Minimization of sensitization in weld HAZ

Sensitization of austenitic stainless steel material can be reduced by material optimization and weld optimization. Weld HAZ is subjected to temperature range of 500-800^{o}C during heating and cooling. Increasing the cooling rate can reduce the chances of sensitization. Cooling rate (Fig. 3) of the weld HAZ in case of hot wire GTAW is 3 times faster compared to that of manual GTAW. This is because of the lower heat input of 0.9 KJ/mm for hot wire GTAW and 1.89 KJ/mm for manual GTAW.

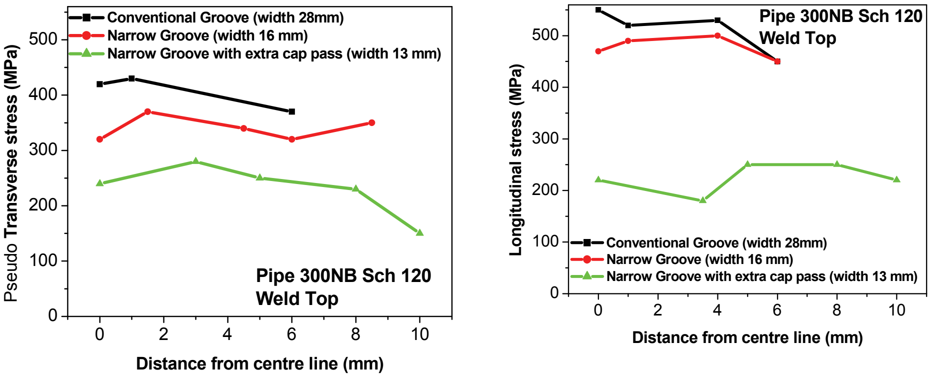


Figure 2: Reduction in residual stress due to narrow gap welding

Figure 3: Time-Temperature curve for material and cooling rate in weld HAZ

4 Embrittlement

4.1 Low temperature thermal ageing embrittlement

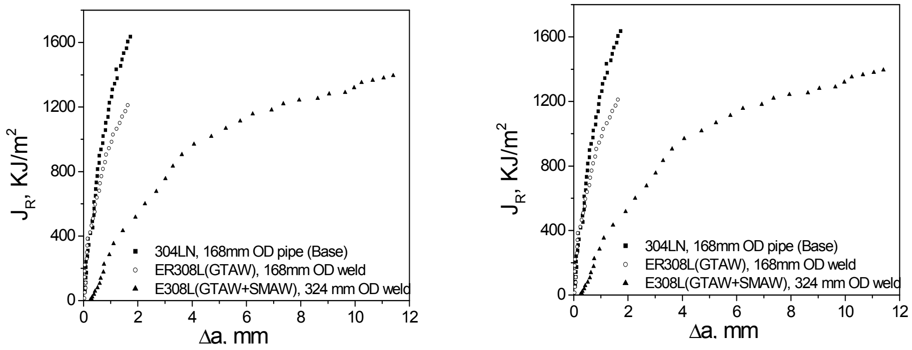
The phenomenon of hot cracking or solidification cracking is of concern in austenitic stainless steel welds. The solidification cracking results from the segregation of low melting point liquid along the grain boundaries during last stage of solidification. If sufficient stresses are generated before the final solidification, boundaries may separate to form a crack. It has been known that presence of retained ferrite in the austenitic stainless steel weld effectively prevents hot cracking. The higher solubility of impurities in ferrite than austenite results in less segregation of low melting impurities, which helps in preventing hot cracking. Delta ferrite has lower thermal coefficient of expansion (α), which helps in reduction of thermal stresses. ASME Boiler and Pressure vessel code calls for minimum of 5% δ-ferrite (or 5 FN) in austenitic stainless steel weld to avoid solidification cracking.

Transformation of this δ-ferrite into a brittle phase due to prolonged exposure to temperature of about 300 deg C can cause Low Temperature Embrittlement. It is well known that the kinetics of low temperature embrittlement is faster in presence of Molybdenum [Chopra (1991)].

LTE studies were carried out to confirm that austenitic stainless steel (SS 304LN) welded by E308L/ER308L would not have problem of loss in toughness during service of the plant. The ferrite content in the weld metal was in the range of 5-8 FN. These studies were performed on materials subjected to accelerated ageing by simulating time and temperature in such a way that the kinetics of the processes remains unaffected. The ageing durations planned are of 5000, 10000, 20000 and 50000 Hours at temperatures 400^{o}C, 350 and 300^{o}C. Loss in toughness has been quantified by carrying out the impact test. At present, work has been completed for 5000 hours of ageing. The result indicates no reduction in toughness for the ageing duration of 5000 hours at various temperatures.

4.2 Fracture Toughness

Embrittlement in material can also be quantified by fracture toughness. In this section, fracture toughness of the weld and base materials has been evaluated to quantify the available toughness to prevent failure due to embrittlement. Advantage of GTAW over SMAW is described in this section.



(a) (b)

Figure 4: (a) Comparison of J-R curves for SMAW & GTAW. (b) J-R curves for conventional groove and narrow gap using SMAW

Fig. 4a shows that crack resistance of GTAW weld is comparable to that of base metal and is much higher as compared to SMAW. Fig. 4b compares the J-R curves of conventional and narrow grove weld joints. Weld geometry has no effect on J-R curve.

5 Leak-Before-Break

The next step towards ensuring structural integrity was demonstration of the ability of the piping to tolerate defects.

One of the ways of showing this is the demonstration of leak-before-break. A combination of ductile material, not so hostile environment and a reliable leak detection system is necessary for this.

This concept aims at the application of fracture mechanics principle to demonstrate that pipes are very unlikely to experience sudden catastrophic break without prior indication of leakage. LBB evaluation is divided in three stages:

In the first level, it is shown that in view of the stringent specifications in material, design, fabrication, inspection and testing, there will be no crack initiation, thus avoiding the possibility of crack propagation. In this program, material specification (as detailed in section 2) and fabrication (as detailed in section 4) were optimized to improve quality of the material and weld to fulfill intended purpose. In addition to the mechanical properties, fatigue and fracture properties were evaluated.

In the second level of LBB evaluation, we postulate that a crack of certain length and depth has escaped detection. But, it can be shown that for the duration of plant life this crack will not grow enough to penetrate the wall, let alone cause catastrophic failure. This has been demonstrated by carrying out tests on actual pipes and pipe welds with postulated part through crack to show that there is not significant crack growth for the anticipated loading cycle during the plant life. This is described in detail in section 5.2.

In the third level, we postulate forced crack propagation to penetrate the wall and show that the resultant through-wall crack is stable, produces leakage in sufficient quantity to enable detection and corrective action can be taken before it becomes critical. This has been demonstrated by carrying out tests on actual pipes and pipe welds with postulated through crack to show that there is no unstable crack growth. This is described in detail in section 5.3.

5.1 Description of Tests

Pipe material was austenitic stainless steel of SA312 type 304LN. Tests were carried out on seamless pipe and pipe weld of nominal outer diameter 324 mm and 168 mm having thickness of 27 mm and 14.3 mm respectively. The pipes were in solution-annealed condition. Gas Tungsten Arc Welding (GTAW) was used for welding of 6”NB pipe. GTAW (for root pass and few passes) and Shielded Metal Arc Welding (SMAW) (filling passes) were used for welding of 12”NB pipe.

The test set up consists of servo hydraulic loading system, support for the pipes and various instruments for the measurement of the data during the test. The support system for the pipe tests consists of two pedestals with pairs of rollers, at outer span and inner span which simulates four point bending condition (Fig. 5).

Figure 5: Actual experimental set up for pipe test

This type of loading ensures that notched section of the pipe is subjected to pure bending stress.

Pipes with part through and through-wall notch were subjected to fatigue loading till the crack has grown through thickness. Thereafter fracture tests were carried out on through-wall cracked pipes. The final through-wall crack size after fatigue test was taken as the initial crack size for the fracture tests.

During the test the crack growth at either tips of the through-wall crack, the load, angular rotation of the pipe about the support on either end and vertical deflection of the pipe at four locations along the length of the pipe were measured.

5.2 Fatigue tests (Level II of LBB)

In these tests, the pipes containing machined notch were subjected to cyclic loading. Number of cycles to crack initiation and the evolution of crack shape during crack growth were monitored. The results of these studies on crack resistance behaviour of the austenitic stainless steel pipe and pipe welds can be summarized as:

For the typical stress range expected in the piping of AHWR, the number of cycles to crack initiation is very large compared to the expected number of cycles (Fig. 6).

Fatigue crack growth also depends on the aspect ratio. Aspect ratio (2C/a) at the point of through thickness lies in the range of 3 to 4 irrespective of the initial notch aspect ratio (Fig. 7-8). This provides justification for the usual assumption in LBB that for a reasonable part through crack the length at break out (leakage size crack) is not likely to be more than that is normally assumed. Crack growth in surface direction is more for the aspect ratio greater than 4 compared to thickness direction. Notch of semi circular front (aspect ratio is crack length by crack depth=2) maintains its shape till through thickness (Fig. 8). Number of cycles required for crack to grow through thickness is very large compared to those expected during plant life.

The use of the fatigue crack growth curve given in ASME Section XI [ASME (1989)] will produce a conservative result (Fig. 9).

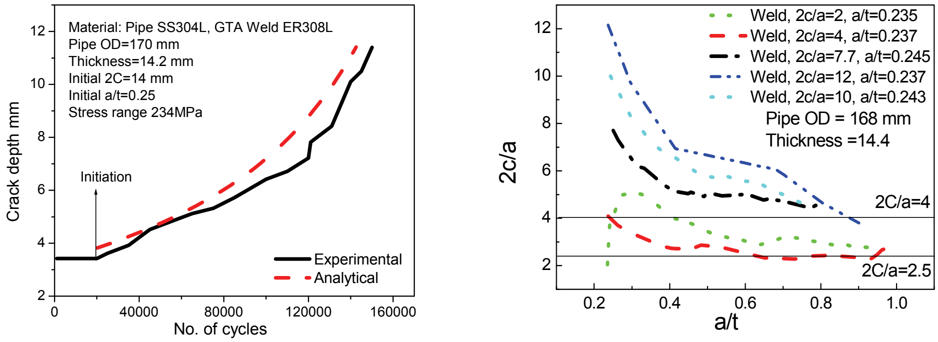


Figure 6: Crack initiation and growthwith no. of cycles

5.3 *Fracture Tests (Level III of LBB) [Singh, Vaze, Ghosh, Kushwaha, and Pukazhendi (2006)]*

The fatigue test was continued till the crack grew through-wall. The pipe containing through-wall crack was subjected to monotonically increasing load till collapse. Applied bending moment versus bending rotation, applied moment versus crack extension and fracture resistance (J-R) curves for the pipe and pipe weld are shown in Figs. 10-12 for the 168 mm OD pipe and in Figs. 13-15 for 324 mm OD pipe. Figs. 16-17 are the photographs of the 168 mm OD pipe weld and base respectively.

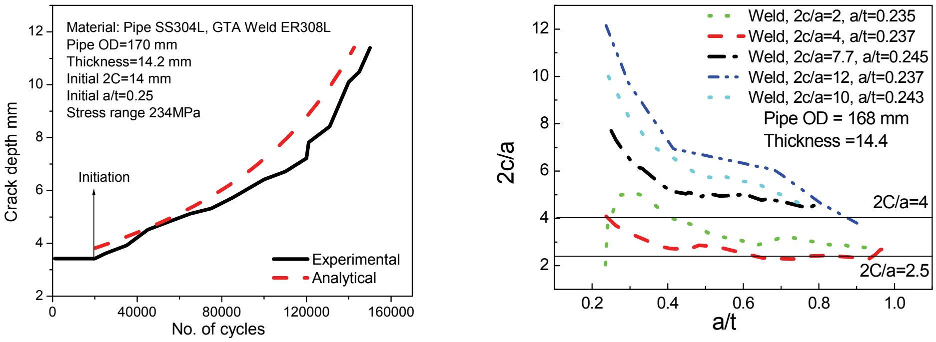


Figure 7: Variation of aspect ratio with crack growth

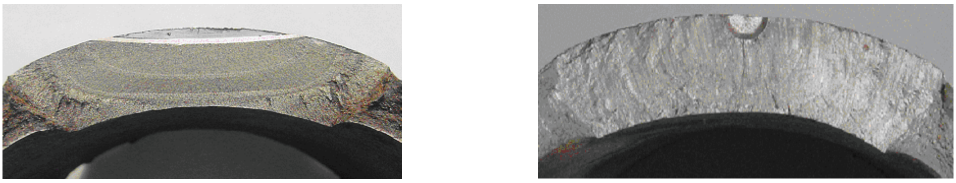


Figure 8: Fracture surface showing crack shape during fatigue crack growth

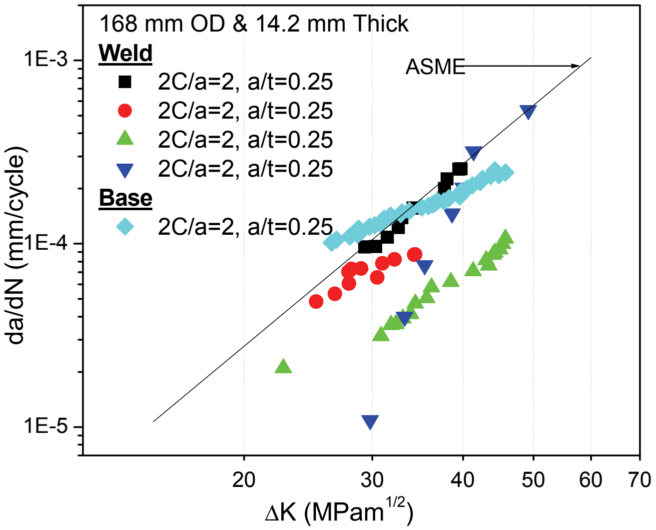


Figure 9: Comparison of crack growth rate curve from pipe tests and ASME

Similarly, Figs. 18 and 19 show the photographs of the 324 mm OD pipe weld and base.

Fracture resistance of pipe is superior compared to pipe weld (Figs. 11 and 12, 14 and 15).

Initiation of crack growth occurred at a load lower than the maximum load bearing capacity of the pipe, e.g. the crack extension at maximum bending moment, in pipe and pipe weld for 168 mm OD pipe, are 4.5 and 8.5 mm respectively (Figs. 11, 14). This shows that failure is not due to plastic collapse alone and therefore fracture mechanics has a role in prediction of instability condition in pipes.

Drop in bending moment after maximum moment is faster in weld (Figs. 16 and 19).

In the case of 168 mm OD pipe (GTAW weld), the crack extension in pipe (base) and the pipe (weld) is comparable (Figs. 17, 18). But in case of 324 mm OD pipe (GTAW + SMAW) weld, the crack extension is much more than that in base (Figs. 14, 15). This indicates that fracture resistance of pipe and SMAW weld differs considerably whereas in case of GTAW weld this difference is not significant. Thus there is a substantial incentive towards employing GTAW for welding of SS pipes.

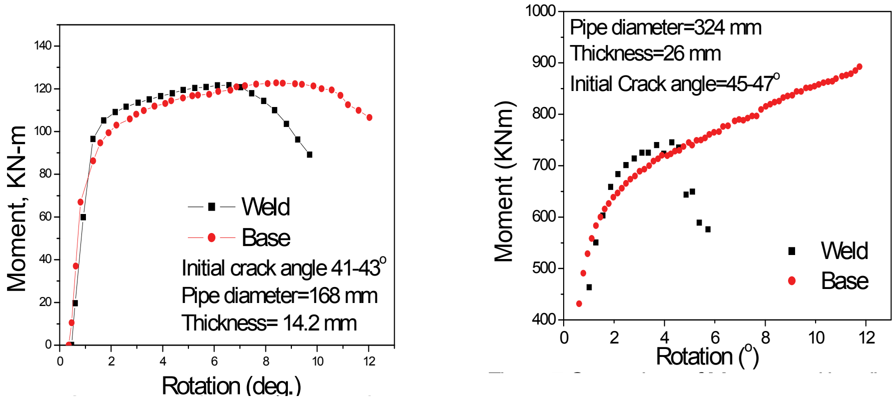


Figure 10: Moment rotation curve – 168 O

6 Fatigue-Ratchetting

The Nuclear Power Plant (NPP) piping components, which are under high pressure, are subjected to large amplitude reversible cyclic loading during an earthquake event. During this event the pressurised piping may deform significantly or fail due to excessive accumulation of plastic strain by ratchet action in addition to

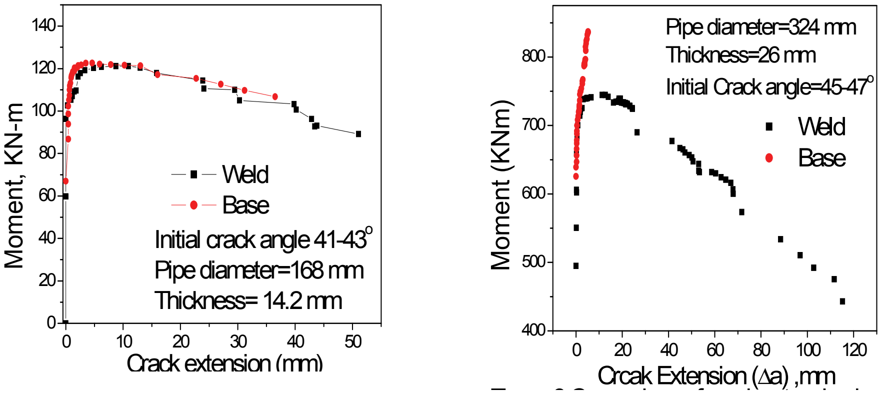


Figure 11: Moment-crack extension 168 OD

the low cycle fatigue damage. Fatigue ratcheting has been recently addressed by piping design codes. The 1995 ASME Code increased the piping allowable primary stress to 4.5 times the allowable stress intensity, S_m applicable to level D service loads. The new limits are intended to ensure plastic shakedown, defined as the event when ratcheting ceases to occur after a few cycles. These limits assume fatigue and ratcheting as a failure mode rather than a structural collapse with reversing dynamic loads. However, there were a lot of uncertainties and unresolved issues related to these failure mechanisms. In further revision of ASME sec III issued in 2001, the increased limit ($4.5S_m$) of primary stress was again brought back to $3S_m$ but with modification of B_2 indices. The modified B_2 indices are refered as B_2' indices. To understand the fatigue ratcheting failure mechanism and to assure the real safety margins vis-a‘-vis the new design rules related to fatigue-ratcheting a number of the ratcheting experiments on pipe-elbows were conducted under constant internal pressure and large amplitude cyclic displacement loading.

The fatigue ratcheting tests have been conducted at Structure Integrity Testing and Analysis Centre (SITAC) of IIT Bombay, on large radius 8” NB Sch.100 elbows made of carbon steel material. The experimental setup for fatigue-ratcheting testing on pipe-elbow assembly under in-plane bending is shown in Fig. 20.

The elbow assembly was pressurized to a constant pressure and then subjected to large amplitude reversible cyclic displacement loading at the free end. The crack initiation event was detected using online Acoustic Emission Technique (AET) and offline (holding test after few cycles for UT scanning) using Ultrasonic Testing (UT). Number of cycles in which the crack initiated and cycles when the elbow has failed (i.e. initiated crack grows to through wall and results in leakage) were

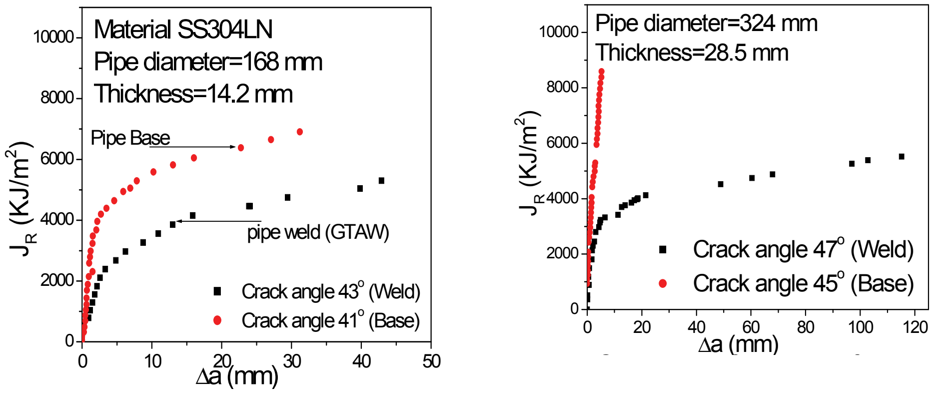


Figure 12: J-R curve 168 OD

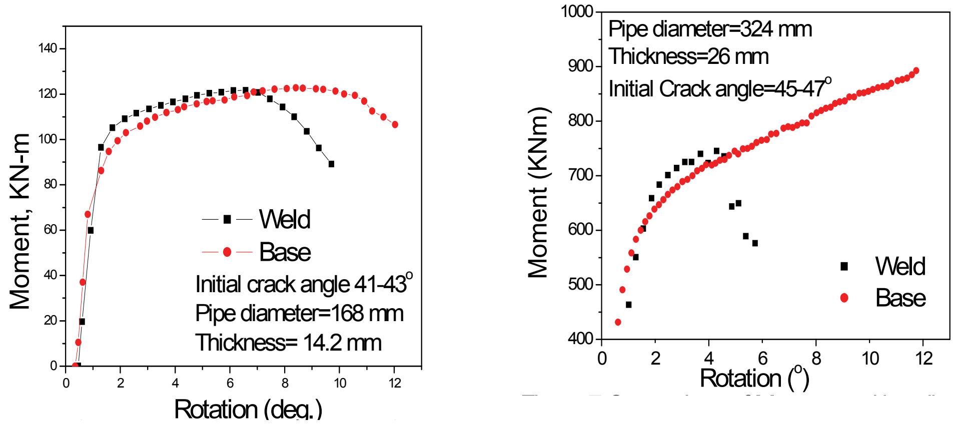


Figure 13: Moment rotation curve – 324 OD

noted. The experiment was stopped on appearance of leakage. In all the tests the elbows have failed, following an appearance of a through wall axial crack, near the crown location. There was significant ballooning (8-10% increase in diameter), with simultaneous fatigue damage followed by crack initiation on inside surface at crown location and subsequent growth till it becomes through wall thickness. Fig. 21 shows a photograph of fatigue ratcheting failure of ERT-2 test. Fig. 22 shows the typical hoop strain versus number of load cycles at intrados.

The test results demonstrate that the likely failure mode is indeed fatigue-ratchetting and justify the higher allowable limits. They also point to the shortcomings in the existing material models and strain-life equations for predicting fatigue crack initiation.

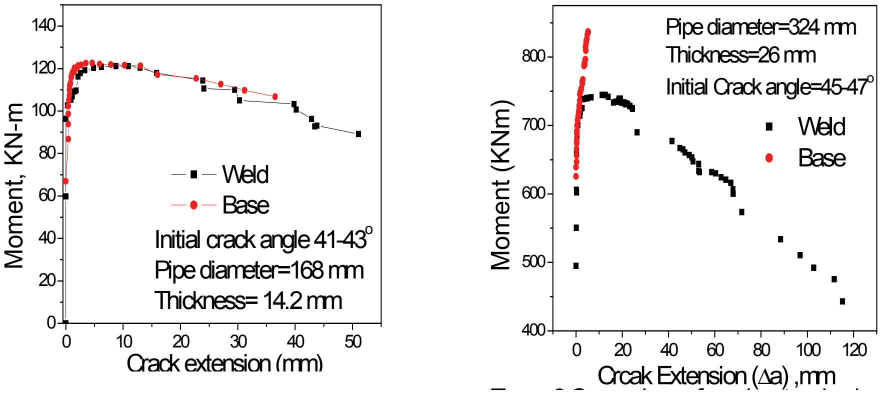


Figure 14: Moment-crack extension 324 OD

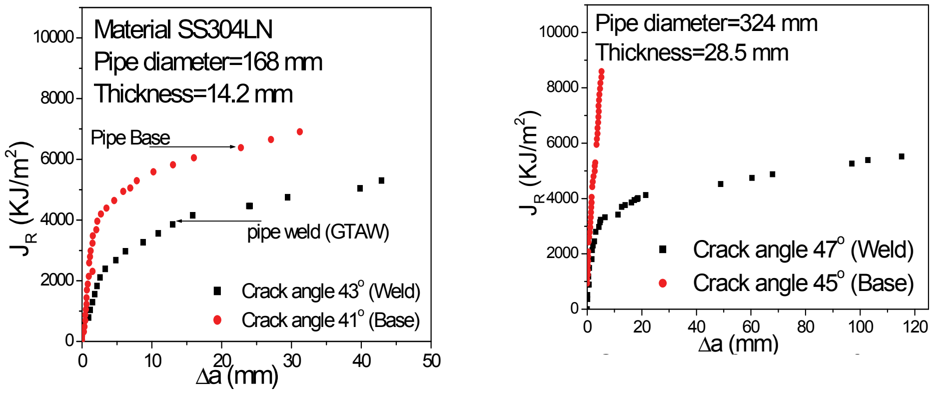


Figure 15: J-R curve 324 OD

7 Cyclic Tearing

The current Leak Before Break (LBB) assessment is based primarily on the monotonic fracture tearing instability. The maximum design accident load is compared with the fracture-tearing resistance load. The effect of cyclic loading has generally not been considered in the fracture assessment of nuclear power plant piping. It is a well-known fact that the reversible cyclic loading decreases the fracture resistance of the material, which leads to increased crack growth. A cracked component, which is safe for monotonic load, may fail in limited number of cycles when subjected to fully reversible cyclic load of same amplitude. Keeping this in view a series of tests have been carried out on circumferentially through wall cracked seamless and circumferential seam welded straight pipes under reversible cyclic bending loading. The cyclic test results have been compared with the cor-

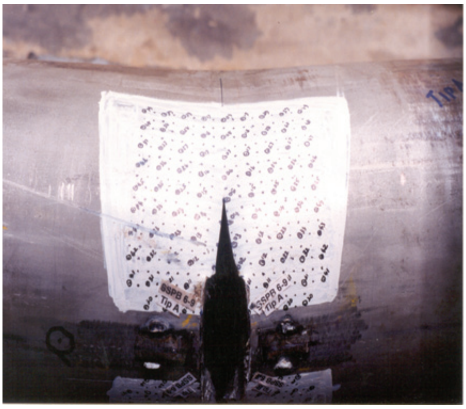


Figure 16: Pipe weld of 168 mm OD

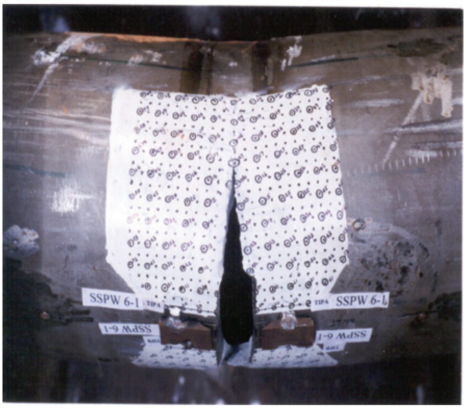


Figure 17: Pipe base of 168 mm OD

Figure 18: Pipe weld of 324 mm OD

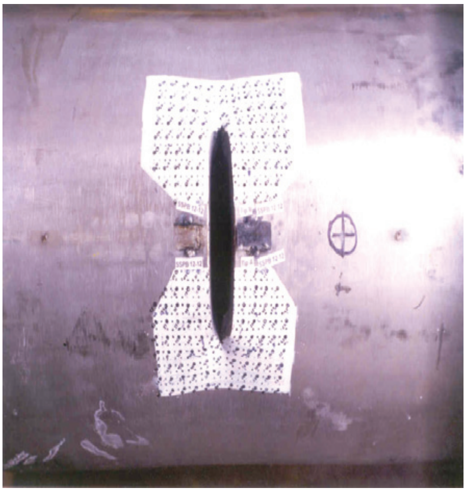


Figure 19: Pipe base of 324 mm OD

responding monotonic pipe fracture test results. And it is seen that the pipes may fail in limited number of load cycles with the load amplitude significantly below the monotonic fracture/collapse load. A simplified master curve has been generated directly from these pipe cyclic tearing tests. The master curve is the plot of the cyclic load amplitude (given as % of maximum load recorded in corresponding monotonic fracture test) versus number of load cycles to fail (N_f) and has been shown in Fig. 23. This curve can readily be used in the current practice for LBB

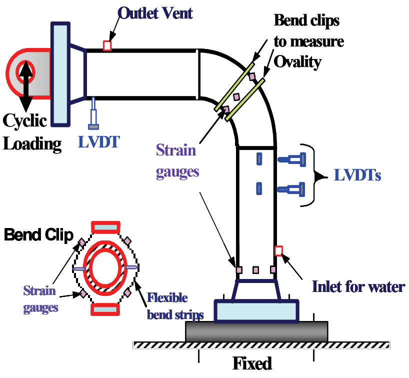


Figure 20: Schematic of setup for Fatigue-Ratcheting Test

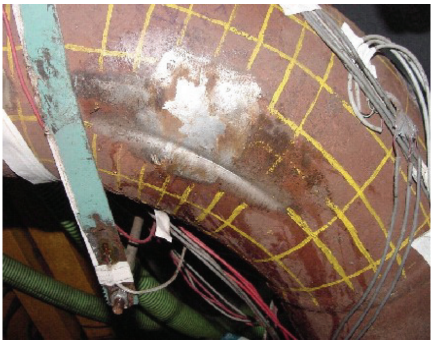


Figure 21: Axial through wall crack as a result of fatigue ratcheting failure

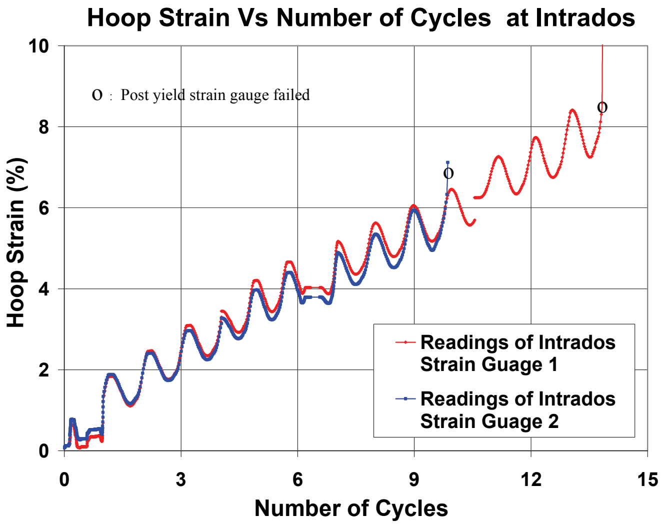


Figure 22: Hoop strain at Intrados versus loading cycles for ERT-2 Test

qualification for evaluating the critical load (which accounts for cyclic damage and number of load cycles) in term of the percent of monotonic critical load. For the postulated 50 cycles of high amplitude loading, the failure load reduces to 75% of the monotonic failure load.

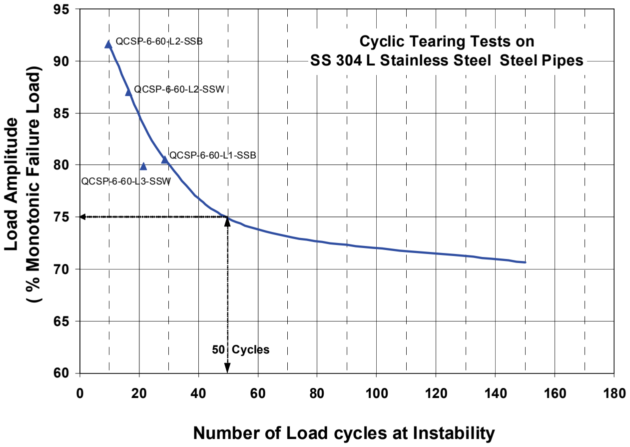


Figure 23: Master Curve: summary of load controlled cyclic tearing tests

8 Compliance effect

Level-3 LBB assessment requires integrity of piping system under the most severe loading conditions, which, typically for most of the nuclear power plants is safe shut down earthquake (SSE). Applied loads for such events are usually evaluated via a linear elastic dynamic analysis assuming that the piping system is uncracked. However, the presence of crack increases the local compliance resulting in reduction of load at the cracked section. During integrity assessment the uncracked loads are then compared with the maximum critical load that the cracked piping section can sustain. Again the evaluation of critical load is done by means of fracture test performed on cracked stand-alone pipe and not on the cracked piping system. These simplifications lead to a lot of conservatism in the LBB evaluation.

Thus, for a realistic fracture assessment it becomes necessary to include the effect of piping system compliance. Detailed analytical investigations have been performed to investigate the phenomenon and a simple formula has been proposed to evaluate the actual moment at the cracked section considering the piping system compliance.

In addition, 15 full-scale fracture tests have been conducted on 8” NB reactor grade pipes (Fig. 24) to demonstrate the effect of piping system compliance on fracture loads. Through-wall cracks of different sizes were machined in the pipes (followed by fatigue pre-cracking) and the system compliance was varied in terms of length of piping system. These experimental studies have revealed that

The critical load of a cracked piping system (with even large through-wall crack of about 120°) is of the order of 85-90% of the collapse load of uncracked piping system where as the critical load of a simply supported pipe (which simulates piping system with infinite compliance) drops to 43% of collapse load of uncracked pipe (Fig. 25).

There exists a large margin between the crack initiation load and the maximum load that a piping system can sustain.

These experimental results have clearly demonstrated that the current LBB assessment procedure is too conservative. There is a large inherent factor of safety due to system indeterminacy.

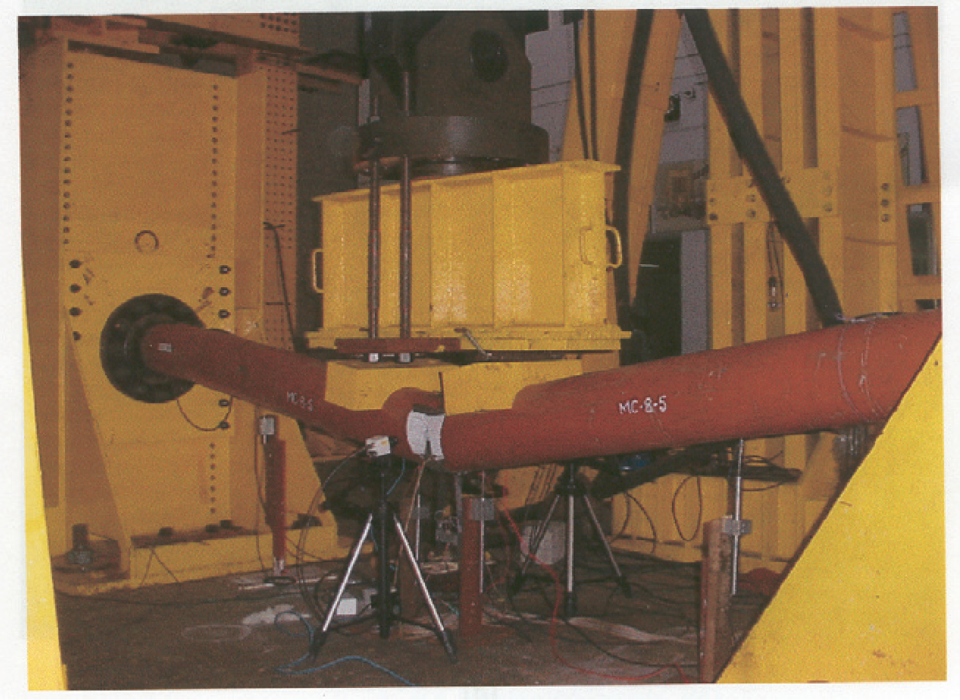


Figure 24: Schematic of piping system Test Setup

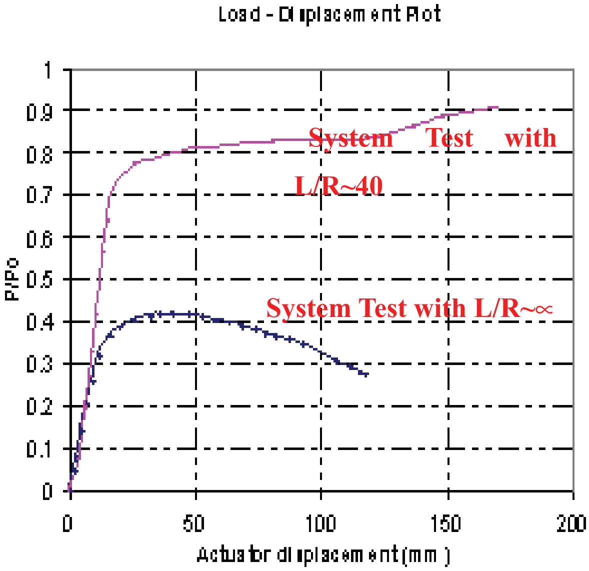


Figure 25: Reduction in load carrying capacity of piping system due to crack

9 Conclusions

Issues and outcome of the studies related to ageing and structural integrity aspects can be summarized as below:

1. Selection of material based on the available knowledge should be given due consideration. Here, among the various low carbon grades of austenitic stainless steels viz. SS 304L, 316L, 304LN and 316LN, choice of SS 304LN is based on its satisfactory low temperature sensitization behaviour and superior low temperature embrittlement behaviour which are important for targeted life of 100 years.

2. IGSCC, embrittlement and fatigue are the main degradation mechanism, which may affect the longevity of the piping system. In this study, LTS and residual stress in the pipe weld joints have been quantified and the use of superior welding process technique has been suggested. The IGSCC resistance can be improved by adopting high deposition rate (hot wire GTAW) process and narrow gap technique, which has shown reduced residual stresses compared to conventional welding. Further during welding, the margin on sensitization in terms of time temperature (cooling rate) is higher in case of hot wire GATW.

3. Gas Tungsten Arc Welding gives much better fracture resistance compared to Shielded Metal Arc Welding. Use of GTAW will lead to the reduction in chances of failure due to embrittlement.
4. A combination of narrow gap technique and hot wire GTAW will provide an added assurance against failure due to IGSCC/fatigue/fracture.
5. Number of cycles for crack initiation in AHWR piping is considerably higher than the number of cycles anticipated during the design life.
6. Crack growth in depth direction is more than that in length direction. Aspect ratio (2C/a) at the point of through thickness lies in the range of 3 to 4 irrespective of the initial notch aspect ratio, thus favouring Leak-before-break.
7. The load carrying capacity of a through-wall cracked pipe is higher than the maximum credible loading due to a Safe Shutdown Earthquake. Thus, AHWR piping has been shown to satisfy the Leak-before-break criterion.
8. Ratchetting-fatigue is the likely failure mode under large amplitude cyclic loading.
9. ASME code limits have sufficient conservatism to guard against this failure mode.
10. Cyclic loading is likely to cause damage due to cyclic tearing phenomenon.
11. Factors to account for the same have been evaluated.
12. Compliance effect is the beneficial effect due to which the failure load of a cracked pipe is very nearly same as uncracked pipe.

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