Cyclic Tearing of Through Wall Cracked Pipes made of Carbon Steel

Suneel K. Gupta, V. Bhasin, J. Chattopadhaya, K. K. Vaze, A.K. Ghosh, H. S. Kushwaha

Reactor Safety Division, Bhabha Atomic Research Center, Mumbai, 400085, India,
e-mail: suneelkg@barc.gov.in

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1 ABSTRACT

The paper presents experimental and analytical investigation on the cyclic tearing of through wall cracked straight pipes made SA333Gr.6 carbon steel, subjected to large amplitude reversible cyclic loading as comes during an earthquake event. The present Leak Before Break (LBB) methodology uses monotonic ductile tearing and plastic collapse as failure modes to guarantee against instability of the piping with postulated leakage size through wall crack under design basis loading. Indian nuclear power reactors consider Operational-Basis-Earthquake (OBE) and Safe-Shutdown-Earthquake (SSE) event in the design of various structures, systems and components. The effect of cyclic loading has generally not been considered in the LBB 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 under reversible cyclic loading. In view it, a series of cyclic tearing test has been carried out on circumferentially through wall cracked straight pipes made of ASTM SA333 Gr.6 carbon steel material subjected to cyclic bending loading. The cyclic test results have been analysed in relation with the corresponding monotonic pipe test results. The test results and its comparison with corresponding monotonic tearing clearly illustrate the need of addressing the cyclic tearing damage and the number of safe load cycles in the LBB design. Further a methodology has been worked out in order to evaluate number of safe load cycles under cyclic tearing.

2 INTRODUCTION

In past the research in the area of LBB resulted in several publications like NUREG-1061 (1984) and IAEA-TECDOC (1994), which describe the piping flaw analysis procedures for LBB qualification. These procedure calls for rigorous fracture and plastic collapse assessment of piping components with postulated flaw. The pipe stability analysis, in presence of postulated through wall crack, considers the seismic loading as a onetime applied load of magnitude equal to peak load at the postulated flaw location during the earthquake event. The instability load of pipe with flaw is taken as equal to lower of the monotonic tearing instability or Net Section Collapse (NSC) load. There is no explicit consideration of the cyclic damage or the number of applied load cycles in both of these methods. However, in India like in many other countries also, the nuclear power plants consider earthquake event, in the design of piping components and other structures. During the typical earthquake event the nuclear power plant piping experiences around 10-20 cycles of large amplitude reversible load. It is a well-known fact that the reversible cyclic loading significantly accelerates the fracture process due to the cumulative damage by the compressive plasticity (i.e. void flattening and crack tip re-sharpening) and low cycle fatigue crack growth (fatigue crack growth under large scale yielding). As a result of combined damage there is significant decrease in the apparent fracture resistance of the material under reversible cyclic loading compared to monotonic loading. Unlike monotonic fracture, in cyclic fracture, the instability depends on the full load history and parameters such as loading ratio, loading range and number of load cycles. A cracked component, which is safe for monotonic load, may fail in limited number of reversible cyclic load of same amplitude.

In view of it to understand the fracture stability of cracked pipe under cyclic, a series of tests have been conducted, Gupta et. al. (2007) on circumferentially through wall cracked straight pipes made of SA333Gr.6 Carbon steel and subjected to reversible cyclic bending. All the tests have been conducted in four point bend configuration, at room temperature, under quasi-static i.e. slow loading rates and the dynamic effect is not considered. The tests have been conducted under both the load control conditions and the displacement controlled conditions. The load-controlled test was carried out with objective of investigating the importance of the number of cycles of loading (comparable to number of cycles in an earthquake) as a function of applied load amplitude (peak dynamic load). The load amplitude was kept constant between 60% and 95% of the predicted monotonic instability load for different tests. For all these tests, the load ratio was kept constant (R= –1). The displacement-controlled tests were carried out to quantify the reduction in the fracture resistance. In displacement-controlled tests, the displacement increment was controlled when the specimen was loaded in the crack opening direction and the load was controlled in the reverse direction loading in order to maintain the constant load ratio.

The results of above cyclic tearing tests have been investigated in detail and a methodology for evaluation of crack growth and instability under fully reversible cyclic loads has been developed. In this study, crack growth by both, fatigue and static fracture have been considered. The fatigue crack growth has been evaluated using, Dowling's ΔJ integral (based on the loading branch of cycle) along with the extrapolated high cycle fatigue law (Paris Law). The static crack growth has been calculated cycle by cycle from the monotonic J-R curve and a new proposed J'-integral which accounts for the cyclic damage. It is evaluated cycle-by-cycle, from area under the positive half of either load versus plastic Load Line Displacement (LLD) curve or load versus plastic Crack Mouth Opening Displacement (CMOD) curve (using CMOD based η and γ factors). The load controlled cyclic test results have been compared with the corresponding monotonic pipe fracture test and a cyclic tearing instability criteria have been proposed. Further the J-R curve has been evaluated from the envelope of displacement controlled cyclic tests and compared with corresponding monotonic tests. It has been observed that there is significant reduction in the fracture resistance under cyclic loading conditions.

3 TEST DETAILS AND RESULTS

The pipes were made SA-333 Gr.6 Carbon Steel material. The carbon steel grade is same as that of the Indian 500 MWe Pressurised Heavy Water Reactor's (PHWR) Primary Heat Transport (PHT) system. The tensile properties of pipe material i.e. yield stress, tensile strength and Young's modulus is 288 MPa, 420 MPa and 203 Gpa correspondingly. These pipes have 219 mm outer diameter and 15.5 mm average wall thickness. All the pipes had initially machined a through wall circumferential notch of size ranging from 60^o - 90^o.

3.1 Test procedure

The tests had been conducted under quasi-static cyclic loading conditions. The four point bending loading has been used for both direction of loading. The schematic layout is shown in Fig. 1. All the test pipes were fatigue pre-cracked by a small amount of 1^o-2^o at each crack tip to produce a sharp crack front, before carrying out the actual cyclic fracture test. The fatigue pre-cracking was carried out under four-point bending by applying sinusoidal cyclic loading of constant amplitude with a load ratio of 0.1 at a frequency of 2Hz. The maximum load for fatigue pre-cracking was within 20% of the theoretical plastic collapse load of the pipe. The quasi-static cyclic load tests are divided into two categories, namely tests under Load Control conditions for different load amplitude and load ratios and tests under displacement control conditions for different displacement increment and load ratios.

Constant Amplitude Load Controlled Tests: In these tests the pipe was subjected to cyclic loading with constant load amplitude and constant load ratio. The load amplitude was kept between 60% and 95% of the predicted collapse load.

Incremental Displacement Controlled Tests: In these experiments, a constant displacement increment is applied after every cycle and the load ratio was kept constant throughout the experiment. In this category of tests displacement increment was controlled when the specimen was loaded in crack opening direction and load was controlled in the reverse direction loading in order to maintain the constant load ratio. The loading scheme for the incremental displacement controlled test has been given in Fig. 2.

The detail of the geometry, crack size and applied loadings for all the cyclic tearing experiments has been given in table 1. These tests have been conducted at Fatigue Testing Laboratory (FTL) of Structural Engineering Research Centre (SERC) Chennai, India. During the test load, LLD, CMOD and crack growth were continuously monitored and recorded. Four LVDTs had been placed to capture the displacements of the pipe at different points along its span and in the direction of loading. The CMOD data had been recorded using the clip gauge. In addition to this the actuator controller had recorded the applied Load (using strain gauge based load cell of actuator) and the load line displacement (using in-built LVDT of the actuator). The image processing technique consisted of four CCD cameras and a frame grabber card connected with a PC had been used for crack growth measurements at the two crack tips along with the crack mouth opening displacement at centre.

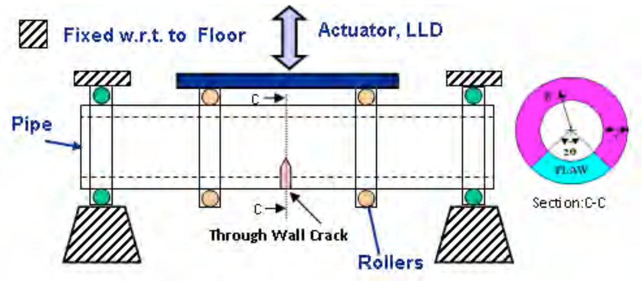

Figure 1. Schematic Diagram of the Cyclic Tearing Test on Circumferential Through Wall Cracked Straight Pipes

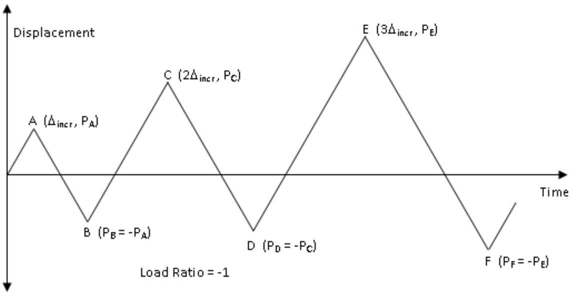

Figure 2. The schematic of the loading for the incremental displacement controlled loading cyclic experiment

Table 1. Details of the Cyclic Tearing Tests conducted on circumferential through wall cracked Straight Pipes made of SA333 Gr.6 Carbon Steel

Sr. No.	Name of Cyclic Experiment	Outer Diameter (mm)	Thickness (mm)	Total Crack angle (2θ°)**	Inner span (mm)	Outer span (mm)	Load Ratio	Applied Load Amplitude (kN)	% of Monotonic Failure Load (M_{cr})	Cycles to Fail Nc
1	QCSP-8-60-L2-CSB	220	15.31	67.82	2500	860	-1	325	86.60	18.5
2	QCSP-8-60-L3-CSB	219	15.4	67.50	2500	860	-1	344	91.89	4.6
3	QCSP-8-60-L4-CSB	219	15.66	67.45	2500	860	-1	262	68.98	156.5
4	QCSP-8-60-L5-CSB	219.9	15.6	67.48	2500	860	-1	280	73.33	71.5
5	QCSP-8-90-L6-CSB	219	15.51	97.02	2500	860	-1	226	75.87	61.5
6	QCSP-8-60-D1-CSB	219	15.63	65.23	2500	860	-1	2.6 mm/cycle		22
7	QCSP-8-60-D2-CSB	219	15.23	64.65	2500	860	-1	0.65 mm/cycle		60

** The crack angle includes the fatigue pre-cracking

3.2 Test results

The applied load history and the response load line displacement for one of the pipe test, namely 'QCSP-8-60-L5-CSB', have been plotted in Fig. 3. The hysteresis record of load versus CMOD has been shown in Fig. 4. These figures show that the area of the hysteresis loop or the hysteresis becomes larger as the number of load cycles increase. It is observed that contribution of the crack closure on these global parameters is insignificant. Further, the crack extension versus cycles of the load controlled tests has been plotted in Fig. 5. The moment versus rotation histories for the displacement controlled cyclic tearing tests and their envelope curve along with the corresponding of the monotonic fracture test, Chattopadhaya et. al. (2000) have been plotted in Fig. 6. The area under the load displacement envelope curve for cyclic test is less than that of the monotonic test curve (Fig. 6). This shows the loss of the energy absorbing capacity of the pipe when subjected to the reversible cyclic loading. The maximum moment for the cyclic test has found slightly lesser than the corresponding monotonic tests. However the pipe rotation at peak load point for the cyclic test was found significantly lower than the monotonic tests.

4 EVALUATION OF J-R CURVES

In this section, the J-Integral based method available in literature, have been used to analyse the cyclic tearing tests. The corresponding monotonic test, Chattopadhaya et.al. (2000), has also been analysed for comparison purpose. From the experimental load, load point displacement and corresponding crack growth data, the J-R curves for the pipes have been evaluated.

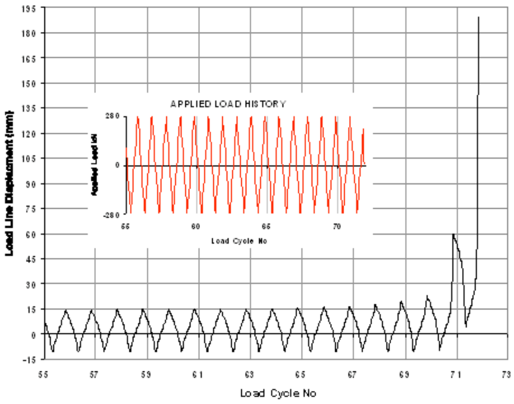

Figure 3. applied load history and the response load line displacement for the ‘QCSP-8-60-L5-CSB’ load contolled cyclic tearing test

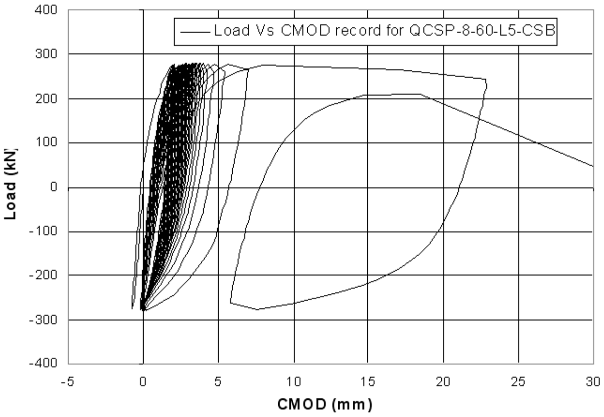

Figure 4. The hysteresis records of load versus CMOD for the ‘QCSP-8-60-L5-CSB’ load controlled cyclic tearing test

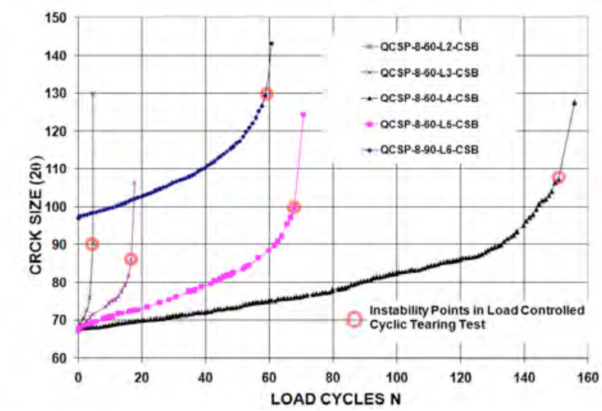

Figure 5. applied load history and the response load line displacement for the load controlled cyclic tearing test on 200 NB pipes

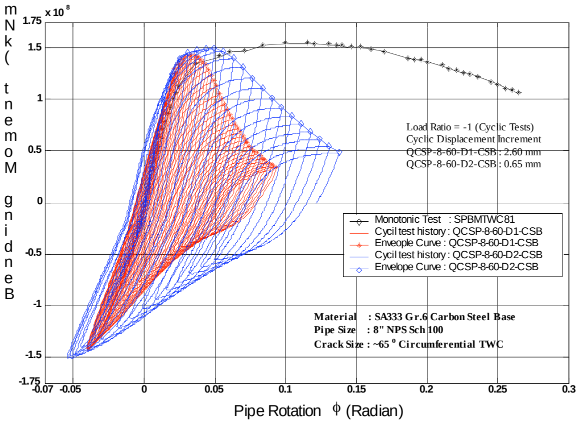

Figure 6. The hysteresis records and envelop curve of moment versus rotation for the two displacement controlled cyclic tearing tests and corresponding monotonic fracture test

4.1 Monotonic Fracture Tests Analyses

One of the monotonic tests conducted was for similar pipe with same crack size (66.5^o) and heat material, under four point bend loading. For this experiments the J-R curves had been calculated using the ‘η factor approach’ Zahoor et. al. (1989). The J integral can be derived from the following equations

$$J = J_{EL} + J_{PL} \tag{1}$$

Here the subscript J_{EL} and J_{PL} are elastic and plastic components of the J-integral. The elastic part of the J integral is given by following equation

$$J_{EL} = f_b^2 \left(\frac{\theta}{\pi}\right)\left(\frac{M^2}{ER^3t^2}\right) \tag{2}$$

Here the function f_b is geometry function and available in Zahoor et. al. (1989). The M is total bending moment and given as P(Z-L)/4. The E is the Young’s modulus. The Plastic Part of the J-integral

$$J_{PL} = \int_0^{\phi_{PL}} \eta(\theta) M d\phi_{PL} + \int_{\theta_o}^{\theta} \gamma(\theta) J_{PL} d\theta \tag{3}$$

Where, ' θ_o' is initial half crack angle , 'θ' is current half crack angle and ϕ_{PL} is plastic load point rotation.

$$h(\theta) = \left[\cos(0.5\theta) - 0.5\sin(\theta)\right] \tag{4}$$

$$\eta(\theta) = -\frac{h'(\theta)}{2Rth(\theta)} \quad \text{and} \quad \gamma(\theta) = \frac{h''(\theta)}{h'(\theta)} \tag{5}$$

The plastic load point rotation (ϕ_{PL}) is evaluated from the total rotation (ϕ_{tot}) by substrating the rotation of un-cracked pipe, the elastic rotation due the presence of crack and the rotation due to machine compliance corresponding to the moment M.

4.2 Cyclic Tearing Tests Analyses

It has been reported Miura et. al.(1994, 1997) that the cyclic maximum J-integral, J_{max} and cyclic J-integral range, ΔJ can be used for describing the crack growth behaviour in a large scale yielding region and also the ΔJ along with monotonic J-R curve can be used to determine the instability point. In cyclic fracture experiments the envelope curve of the load displacement history had been used for evaluation of the J_{max} and the ΔJ. J_{max} and the ΔJ evaluation using experimentally measured load displacement is discussed in following sections. Cyclic J_{max}-integral is defined as the J-integral corresponding to the peak load points (envelop curve) under cyclic loading conditions.

4.2.1 Load Controlled Tests

The cyclic J_{max}-integral has been evaluated as sum of the elastic J-integral and plastic J integral using following equations, Miura et. al. (1994)

$$J_{max,\,i} = J_{max,\,EL,\,i} + J_{max,\,PL,\,i}$$

$$J_{max,EL,i} = f_b^2 \left(\frac{\theta}{\pi}\right)\left(\frac{M_i^2}{ER^3t^2}\right) \tag{6}$$

$$J_{max,PL,i} = \frac{1 + \frac{\Delta a}{R}\gamma(\theta_i)}{1 - \frac{\Delta a}{R}\gamma(\theta_i)} J_{max,PL,i-1} + \frac{2\eta(\theta_i)}{1 - \frac{\Delta a}{R}\gamma(\theta_i)} U_i \tag{7}$$

$$U_i = \int_{\Delta_{PL,i-1}}^{\Delta_{PL,i}} P d\Delta_{PL} \tag{8}$$

The U_i is the area under the envelop load versus load line displacement curve between two subsequent cycle peaks as shown in Fig. 7. The Cyclic ΔJ-integral has been evaluated as sum of the elastic ΔJ-integral and plastic ΔJ integral using following equations

$$\Delta J_i = \Delta J_{EL,\,i} + \Delta J_{PL,\,i} \tag{10}$$

$$\Delta J_{EL,i} = f_b^2 \left(\frac{\theta}{\pi}\right)\left(\frac{\Delta M_i^2}{ER^3t^2}\right) \tag{11}$$

$$\Delta J_{PL,i} = \frac{2\eta(\theta_i)}{1 - \frac{\Delta a}{R}\gamma(\theta_i)} \Delta U_i \tag{12}$$

ΔU_i = total area under the P-Δ_{PL} curve as shown in Fig. 7.

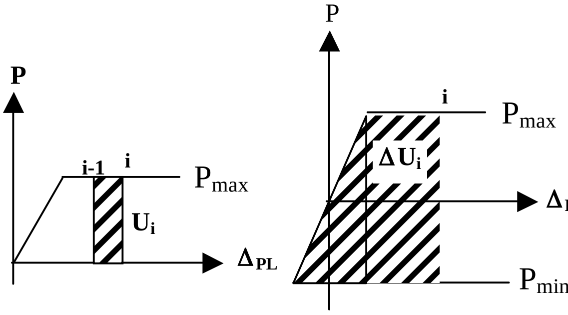

Figure 7. Schematic of Ui and ΔUi Calculations from the envelope P-Δ_{PL} curves

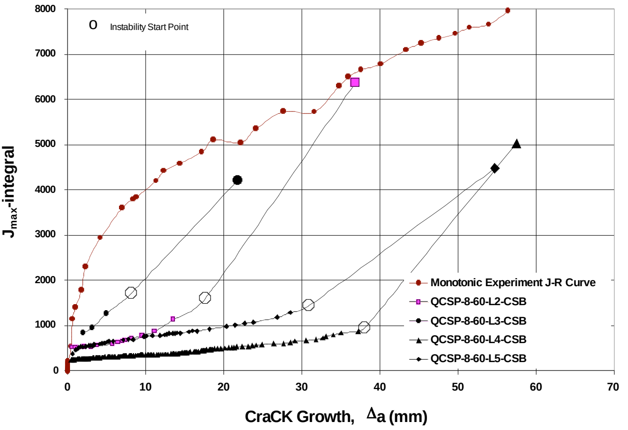

Figure 8. The J_{max} (load control cyclic tearing test) and J-integral (monotonic test) versus crack extension plot

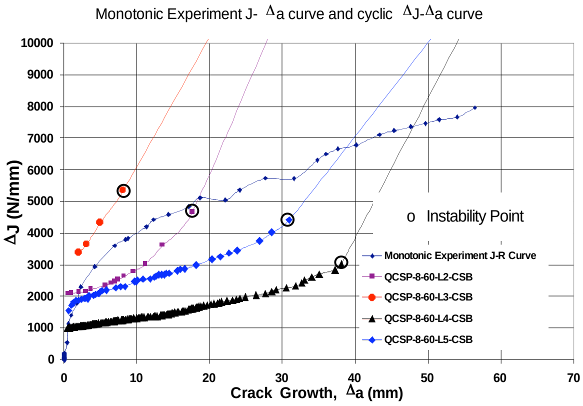

Figure 9. The ΔJ (load control cyclic tearing test) and J-integral (monotonic test) versus crack extension plot

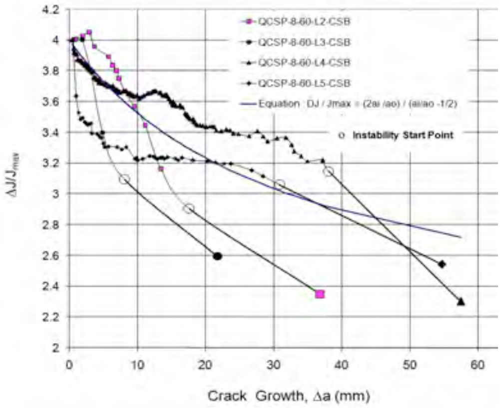

Figure 10. The ΔJ / J_{max} versus crack extension curves of load controlled cyclic tearing tests conducted on circumferential TWC straight pipes

Miura et. al. (1994) has also suggested following equation for calculation of the ΔJ from the Jmax .

$$\Delta J = \frac{2a/a_o}{a/a_o - 1/2} J_{\max} \tag{13}$$

Where 'a' is the current crack length and 'a_o' is the initial crack length. Here J_{max} can be evaluated using standard analytical schemes such as GE/EPRI method etc. For the cyclic tests the maximum J-integral, J_{max} and cyclic J-integral range, ΔJ had been evaluated for the crack growth behaviour analysis as per above equations and plotted in Fig 8 and Fig 9. The $\Delta J/J_{max}$ ratio plotted in Fig. 10, has always remained between 2 and 4 for all the experiments. However, the $\Delta J/J_{max}$ ratio calculated from above given equation (plotted in Fig. 10) does not have good correlation with test and depends on the loading parameters in addition to a/a_o. Further the instability criteria proposed (Instability occurs when ΔJ becomes equal or more than the monotonic J for current crack extension) also does not holds good for all the current load controlled cyclic tearing tests.

4.2.2 Displacement Controlled Tests

The incremental displacement cyclic tearing tests, have been analysed using the load displacement envelope curve (Fig. 6) and the 'η factor approach' similar to monotonic was used for J-R curve evaluation. The Cyclic J-R curve evaluated from these tests have been plotted along with the corresponding monotonic test J-R curve in Fig. 11. This clearly shows that there is significant the loss of the fracture resistance under the cyclic loading conditions. The area under the load displacement envelope curve for cyclic test is less than that of the monotonic test curve (Fig. 6). However, it may be noted here that, J-R curve evaluation procedure does not excludes the additional crack growth taking place due to fatigue.

5 DEVELOPMENT OF METHODOLOGY FOR CYCLIC TEARING ANALYSIS

In this section, the developed method for cyclic tearing tests analyses and evaluating the safe number of load cycles before instability has been discussed.

5.1 Evaluation of Crack Growth Behaviour

As discussed earlier, the crack growth in cyclic tearing is consists two parts, one is crack growth due to fatigue under large plasticity and the other is due static tearing. So in the cyclic tearing crack growth evaluation procedure, calculation has been made for the crack growth by the fatigue mechanism with consideration of plasticity and also for the static fracture mode. The J-integral based on envelope curve does not represent that actual energy dissipated in fracture process / plasticity in a particular cycle. Hence a new parameter J′-integral has been proposed which is evaluated cycle by cycle using η and γ factors.

The static ductile tearing crack growth has been calculated cycle by cycle from the monotonic J-R curve and a new proposed J'-integral which same as J-integral but calculated from area under the positive half of the load and plastic displacement. The total crack extension in let us say ith cycle can be given by the following equation.

$$\frac{da}{dN}_i = \left(\frac{da}{dN}\right)_{i,Fatigue} + \left(\frac{da}{dN}\right)_{i,Teraing} \tag{14}$$

5.1.1 Evaluation of Fatigue Crack Growth.

It is reported, Dowling (1976) that the cyclic J-integral range, ΔJ is effective to describe the crack growth behaviour in a large scale yielding region. Several experimental studies based on the ΔJ parameter, Miura et al. (1994), Rahman et al. (1997), Skallerud et al.(2001) have been made under excessive cyclic loading, for both the specimen and component testing. The ΔJ value versus the fatigue crack growth Δa under large scale yielding, was found to be in agreement with a linear extrapolation of Paris law. The LCF crack growth has been evaluated using, ΔJ approach (based on the loading branch of hysteresis Load-Displacement along with η factor) along with the extrapolated high cycle fatigue law (ie. Paris Law). The elastic part of ΔJ-integral for ith cycle is evaluated using eqn. (11) and the plastic part is evaluated cycle by cycle using below equation.

$$\Delta J_{i,pl} = \int_{\phi^A_{i,pl}}^{\phi^C_{i,pl}} \eta \,(M - M_A) d\phi_{pl} + \int_{\theta_{i-1}}^{\theta_i} \gamma \,\Delta J_{pl}\, d\theta \tag{15}$$

Here point 'A' corresponds to the minimum load and point 'C' corresponds to the maximum load of the ith cycle hysteresis as shown in Fig 12. Further for fatigue crack extension evaluation the ΔJ_i value is converted into equivalent ΔJ_i using following relation.

$$\Delta K_i = \sqrt{\Delta J_i . E} \tag{16}$$

The crack growth in this cycle is evaluated using the effective ΔK_i and fatigue crack growth law.

$$\frac{da}{dN} = C(\Delta K_i)^m \tag{17}$$

The constant C and m can be determined from the low amplitude cyclic tearing experiments where the applied load was well kept below the predicted initiation load for static (monotonic) tearing. It has been reported that a linear extrapolation of typical high cycle fatigue crack growth data gives good prediction. So in the present study the constants 'C 'and 'm' has been calculated from the past investigations Singh et. al. (2003) on cracked specimens of SA333 Gr.6 carbon steel. The C is 3.982×10^{-12} and m evaluated is 3.01. In above equation unit of da/dN is m/cycle and of the ΔK is in MPa√m. These constant has been obtained as per the ASTM Standard E647 using three-point bend specimen machined from the pipe material stock. These tests have been carried out for stress ratios of 0.1, 0.3 and 0.5. The stress ratios have negligible effect in the Paris region.

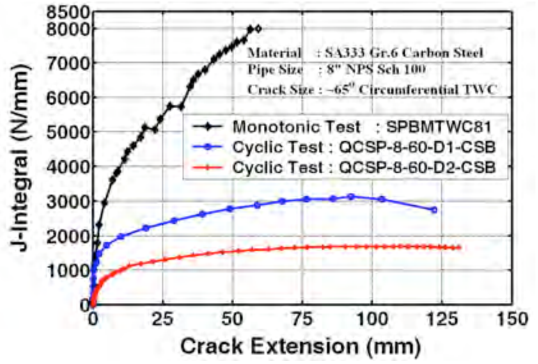

Figure 11. The J-R curve evaluated from displacement control cyclic tearing tests and also from corresponding monotonic fracture test

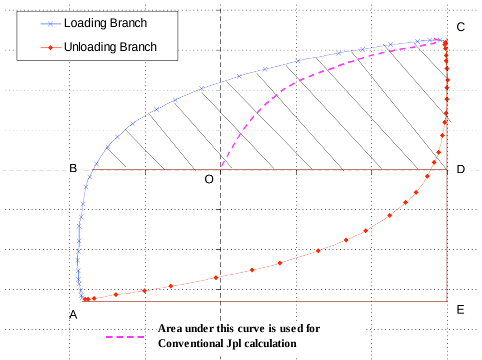

Figure 12. A salient load versus plastic displacement hysteresis showing points A, B and C in loading path

5.1.2 Evaluation of Static Crack Growth (Ductile Tearing)

The calculation of static crack growth using J-integral based on the upper half envelope curve of load vs. plastic displacement record does not accounts for the plastic deformations from the compressive loading and hence does not account for the damage occurred due to the compressive plasticity. For cyclic loading with positive load ratios (e.g. monotonic pipe fracture test with several un-loading), the compressive plasticity is insignificant and hence the calculation of the J-integral from the envelope curve gives good predictions since on reloading the specimen to its maximum (previous from where unloading is done) load level, the plasticity ahead of the crack in the specimen does not differs much from the condition before unloading. Only precaution is required is, if there are large number of cycles then it is necessary to account for the fatigue crack growth.

However, if the load ratio is negative then there will be significant compressive plasticity at the crack tip of specimen. On subsequent tensile cycle the material behaves as it has reduced fracture resistance. This is due to the compressive plasticity. During the compression loads the voids ahead of the crack tip were flattened and sharpened. The sharpening of voids makes the voids easier to link together upon the subsequent tensile loading. Further due to the compressive loading the crack tip gets re-sharpened so on subsequent tensile loading, the stress intensification ahead of the crack tip will be more. Combining these effects ie. void flattening and crack tip re-sharpening makes the crack growth faster. The J integral is relevant for tensile plastic strains ahead of crack tip. While, Chang-Sung Seok et al. (2000) has shown for fully reversible loading ie. R=-1, at the minimum load, the crack tip positive plastic strains due to previous tensile load vanishes, and the compressive plastic strains are generated at tip. However, reloading to maximum load in tensile direction will generate fresh tensile plastic strains ahead of the crack tip. This points that for R=-1 loading, the crack tip tensile plastic strain are generated as results of current load cycles. In view this a new J'-integral has been proposed which is calculated cycle-by-cycle from the positive half of the hysteresis loop of Moment – rotation ϕ_{pl} hysteresis and for a circumferential trough wall cracked pipe subjected to cyclic bending, is given below.

$$J_i^{'} = J_{i,el}^{'} + J_{i,pl}^{'} \tag{18}$$

$$J_{i,el}^{'} = \mathrm{f}_\mathrm{b}^2 \left(\frac{\theta}{\pi}\right)\left(\frac{\mathrm{M}_{i,\max}^2}{\mathrm{E}\mathrm{R}^3\mathrm{t}^2}\right) \tag{19}$$

The plastic part of J' integral is expressed as below, for i^{th} cycle.

$$J_{i,pl}^{'} = \int_{\phi_{i,pl}^{B}}^{\phi_{i,pl}^{C}} \eta \, M d\phi_{pl} + \int_{\theta_{i-1}}^{\theta_i} \gamma \, J_{i,pl}^{'} \, d\theta \tag{20}$$

Here point 'B' corresponds to the zero load and point 'C' corresponds to the maximum load of the i^{th} cycle loading branch of the hysteresis as shown in Fig 12. In Fig. 12, it has been observed that the area 'BCDB' is more than the area 'OCDO', one would have used in envelope curve based J_{max} integral calculation. The additional area is coming due to loading on compressive side so it seems to be accountable for the damage due to compressive loading. Since the cyclic plasticity has been accounted in the J' integral, the crack growth resistance during the cyclic loading has been assumed to be same as under monotonic loading. Hence the static crack extension, corresponding to J'_i obtained directly from the monotonic J-Δa curve. Here if the J'_i is less than the J-initiation then there will not be any growth due to ductile tearing. However the crack will grow only due to fatigue.

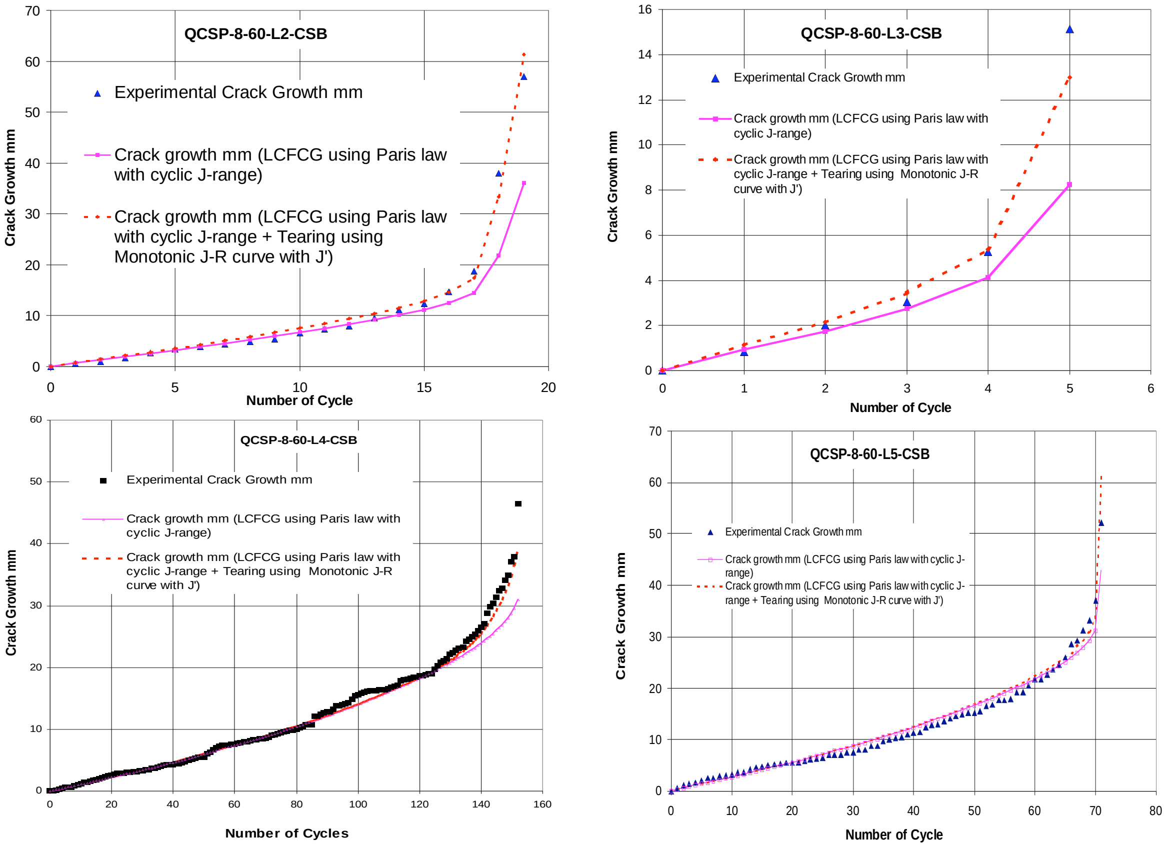

Figure13. Crack growth 'Δa' versus number of cycles for load controlled cyclic tearing tests QCSP-8-60-L2-CSB, QCSP-8-60-L3-CSB, QCSP-8-60-L4-CSB and QCSP-8-60-L5-CSB

5.2 Evaluation of Instability in Load Controlled Tests

In Fig. 14, the maximum moment points of the 5 load controlled cyclic tearing test have been plotted versus the current crack size. In the same figure the moment versus crack size for 3 monotonic fracture tests on similar pipes have also plotted. The figure also plots the monotonic failure line which joins the maximum load point of the monotonic fracture test load versus crack size record. The figure clearly shows that there is large crack growth in cyclic tests before the instability point. However in monotonic tests, there is very small crack growth up to the maximum moment (instability load). Further it also shows that the instability point of cyclic tearing tests lie close to the monotonic failure line. Hence, instability occurs when the current crack θ in cyclic tests reaches to a critical size θ_c for the given loading amplitude (evaluation based on the monotonic ductile tearing and plastic instability assessment). Using this criteria along with above described cycle by cycle crack growth calculations, the safe number of cycles before instability can be evaluated.

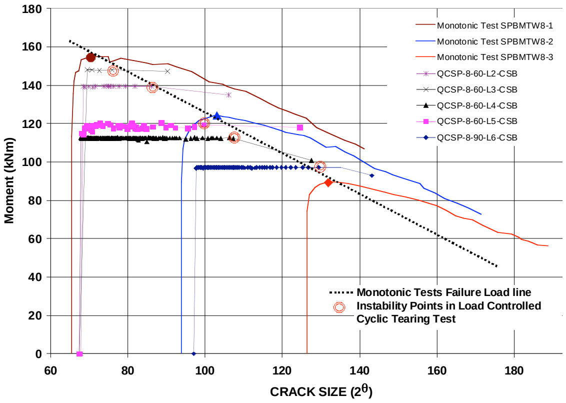

Figure 14. Moment Versus Crack Extension plots for the three Monotonic Fracture Tests and five Cyclic Tearing Tests

6 CONCLUSION

From the comparison of the displacement controlled quasi-static cyclic test and the corresponding quasi-static monotonic test results it has been concluded that the cyclic loading has less influence on the maximum load carrying capacity than expected but there is significant loss in the energy absorbing capability of the piping during the cyclic loading. This leads to significant reduction in the fracture resistance if evaluated using envelop curve under cyclic loading conditions. From the load controlled quasi-static cyclic tests the importance of the number of the load cycles in the fracture assessment of piping subjected to cyclic loading event has been highlighted. The cyclic fracture tests have shown that the pipes will fail in a limited number of load cycles with the load amplitude sufficiently below the monotonic fracture/collapse loads. In the cyclic tearing crack growth evaluation procedure, contribution of both crack growth modes shall be considered, i.e. Fatigue and Static Mode. The fatigue crack growth can be evaluated using, Dowling ΔJ approach (based on the loading branch of hysteresis loop) along with the extrapolated high cycle fatigue law (ie. Paris Law). The static crack growth has been calculated cycle by cycle from the monotonic J-R curve and a new proposed J'-integral. However, further investigation and validation of J' is required . Also the present analyses has shown that the envelope curve based schemes does not work for reversible loading or high negative load ratios.

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