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FATIGUE CRACK GROWTH INVESTIGATIONS ON SS PIPES SUBJECTED TO BLOCK LOADING, OVERLOADS AND UNDERLOADS

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ABSTRACT

The objective of the present study is to understand the Fatigue Crack Growth (FCG) behavior in stainless steel pipes by carrying out experiments and predictions. Experiments have been conducted on full scale pipes having part through circumferential defects subjected to pure cyclic bending moment. The test studies involve the investigation of fatigue behavior of cracked pipes under overload/ underload and different amplitude block loading conditions. The predictions for fatigue crack growth life of actual pipes under such loading conditions have been made using Paris law with Wheeler correction for after overload effects on crack growth. To carry out the analysis, Paris constants have been determined using Compact Tension (CT) specimens machined from the actual pipe material. On application of the single overload, crack acceleration occurs for a short time period followed by long term retardation of crack. A compressive overload (or underload) also results in short term crack acceleration. The Wheeler model requires the evaluation of the plastic zone size at overload event. The 3D-FE analysis of part through cracked pipe has been carried out to evaluate the plastic zone size. The predicted post-overload crack growth behavior is comparable with the test results. However, the crack acceleration during overloading is not assessed by Wheeler model. For block loding test case, the Paris law predictions are in good agreement with experimental results.

INTRODUCTION

Most of the failures in the piping components are due to the fatigue loading. This failure may occur well below the allowable stress limits even under normal operating conditions, which is attributed to the presence of flaws which may have either gone undetected during pre-service inspection or appeared in due course of its service. Such failures need a detailed stress/strain analysis to guarantee the integrity of piping component under fatigue loading. An alternate fail-safe design philosophy such as Leak-Before-Break (LBB) based on fracture mechanics concepts is adopted to demonstrate that piping component will not fail in catastrophic manner. Although, utmost care is taken to prevent catastrophic failure during the design, material selection and fabrication stage but some flaw may go undetected due to the inadequate sensitivity of Non Destructive Examination (NDE) instrument or poor workmanship. LBB philosophy calls for demonstration of insignificant crack growth from the postulated part through crack under cyclic loading in piping component during its design life. This requires investigations on FCG of piping components with postulated part through flaws for the qualification of LBB design criterion.

The piping components (with postulated part through flaw) in Nuclear Power Plant (NPP) experience normal fatigue cycling due to start up, shut down of NPP and other cyclic service loads. In addition to normal fatigue cycling, the piping components are subjected to overloads/ underloads which may be caused by pressure fluctuations and thermal transients. For correct prediction of FCG life of cracked component, it is required to study the crack tip behavior on application of overload/ underload and subsequent tip plasticity during normal fatigue cycling. In view of this, many studies have been carried out and various models on crack tip plasticity have been proposed to predict the fatigue crack growth life. The Wheeler (1972) model based on the engulfing area of residual compressive field due to overload, includes a retardation factor for assessment of subsequent crack growth. Carlson R. L. (1991) reviewed many theories based on residual stress, crack closure, strain hardening, and plastic blunting/ re-sharpening. Kalnaus S. et al. (2009) have carried out experimental and analytical studies on CT specimens of SS 304L material to investigate the effect of overload/ underload and two-step loading sequence on FCG life. They brought out that the predicted FCG life using corrected Wheeler model is comparable with test fatigue life. Recently, Smith K.V. (2011) has carried out finite element analysis to quantify FCG rate with dissipative energy.

The estimation of the crack growth rate is also important for evaluation of the residual life which helps in plant management program. In operating plants, especially the NPPs, when the components are put into service, their In Service Inspection (ISI) is possible at limited number of times. During the inspection, if cracks are detected, then the integrity of the component can be demonstrated by evaluating the time required for the growing crack to become critical is less than the next scheduled ISI the crack growth till the next inspection and showing that there is adequate margin with respect to critical crack size. This demonstration requires understanding and evaluation procedure of fatigue crack growth behavior in components under different loading scenario. Therefore, analytical methodology to predict realistic crack growth rate is essential for taking decision about repair/ replacement of the component or retaining it till the next ISI. In view of the above, the objective of the present study is to understand the fatigue crack growth behavior in austenitic stainless steel pipes by carrying out analysis/predictions and experiments.

EXPERIMENTAL DETAILS

Piping material details

Piping material of austenitic stainless steel of SA312 type 304LN in solution-annealed condition, conforming to the specifications of ASME Section II and Section III of Boiler and Pressure Vessel (B&PV) Code has been used for studies. The pipes having outer diameter as 169 mm and 14.4 mm average thickness, have been used for tests studies. Typical microstructure of the pipe (equi-axed structure) is shown in Figure (1). The chemical composition and tensile properties are given in Table 1 and Table 2 respectively.

Table 1: Chemical composition of material in weight %

C	**Mn**	**Si**	**P**	**S**	**Cr**	**Ni**	**N**	**Balance**
0.013	1.57	0.38	0.035	0.001	18.6	8.45	0.11	Fe

Table 2: Tensile properties of SS 304L material

σ_y (MPa)	**σ_u (MPa)**	**% El**	**Elastic Modulus, E (GPa)**
340	670	65	195

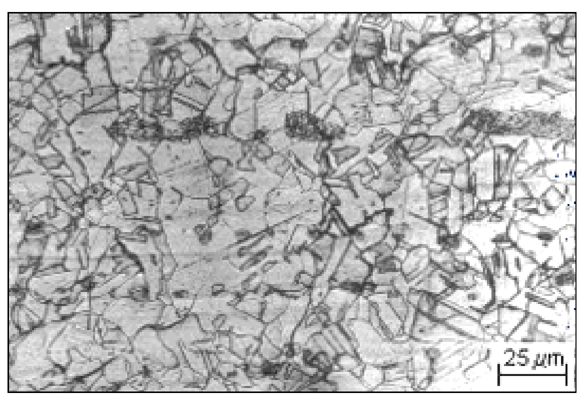


Figure 1. Typical microstructure of the investigated SS 304 LN material

Evaluation of Paris constants

The fatigue crack growth rate experiment was conducted on CT specimens (machined from the same seamless pipe) as per standard ASTM E647 test procedure. The material constants have been evaluated after fitting the test data points in the form of Paris Law as given by Equation 1.

$$\frac{da}{dN} = C(\Delta K)^m \qquad (1)$$

Here, *da/dN* is in m/cycle and ΔK is in $MPa\sqrt{m}$. *C* and *m* are the material constants which have been determined experimentally for SS 304LN pipe material.

Table 3: Paris constants (C & m)

CT Orientation	***R***	***m***	***C***
LC	0.1	3.195	1.917×10^{-12}

R: Minimum load/ maximum load

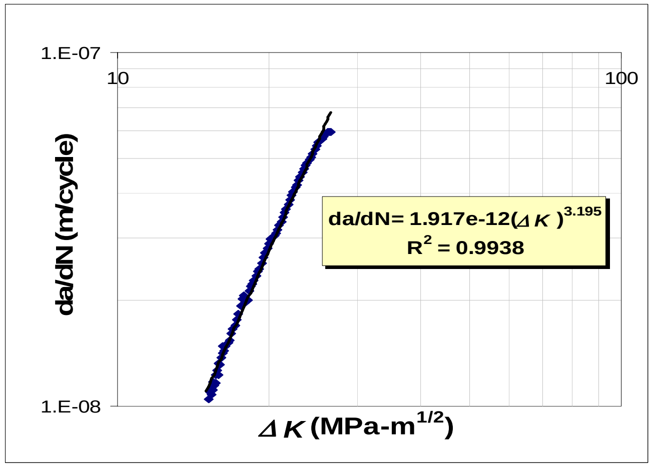
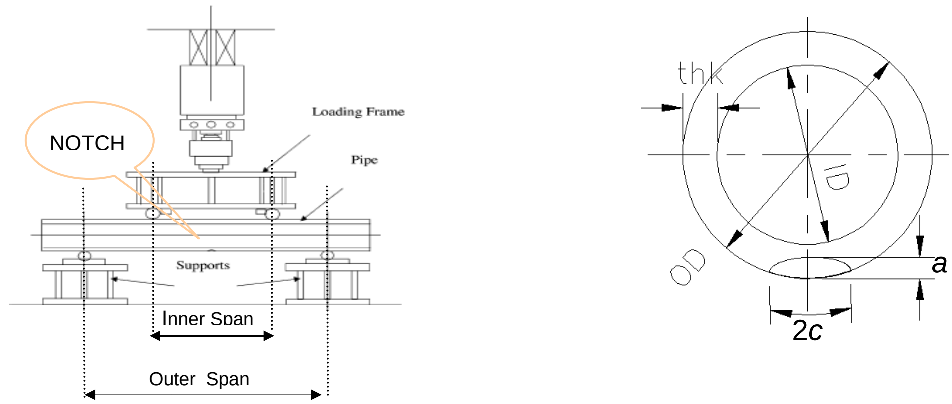


Figure 2. Evaluation of Paris constants (C and m) from da/dN versus ΔK curves for SS304LN

Full scale pipe test

Fatigue crack growth tests on pipes have been carried out under load control sinusoidal cyclic loading. The schematic of test set up and the notched section have been shown in Figure 3. All the tests have been carried out at room temperature and air environment under load controlled conditions. The loading frequency was kept within the range of 0.1Hz to 0.5Hz. Load was applied in four-point bend condition to ensure that cracked location is subjected to pure alternating bending stress. Instrument based on the principle of Alternating Current Potential Drop (ACPD) technique was used to measure crack growth. These gauges have been connected all along the length of the notch to obtain the evolving crack front with loading cycles.

During fatigue tests, beach marks produced due to change in either the maximum or minimum load of continuous load spectra. These beach marks on the fractured surface were used to compare the actual crack growth with the measured value using ACPD technique. The loading and crack geometrical details are given in Table 4. The fatigue tests were carried out until the crack grew through wall.



(a)Schematic of test set up (b) Notched section

Figure 3

Table 4: The notch geometry and loading details of pipe specimens

Pipe ID	OD (mm)	t (mm)	a (mm)	2C (mm)	Inner Span (mm)	Outer Span (mm)	Loading Details			
							Block No.	Max Load (kN)	R	ΔN (cycles)
SSPB 6-14	169	14.4	3.51	36	680	1700	1	258	0.1	0-6000
							2	387	0.67	6000-6001
							3	258	0.1	6001-8250
							4	258	-0.5	8250-8251
							5	258	0.1	8251-14250
							6	387	-0.33	14250-14251
SSPB 6-9	168	14.8	3.6	36	680	2000	1	185	0.1	0-27000
							2	240	0.08	27001-28000
							3	185	0.1	28001-47000
							4	240	0.08	47001-47500
							5	185	0.1	47501-50500
							6	240	0.08	50501-50800

OD: outer diameter of the pipe, t: thickness of the pipe, a: maximum initial crack depth, 2C: crack length, R: Minimum load/ maximum load, ΔN: cycle interval in a block

ANALYTICAL PREDICTIONS

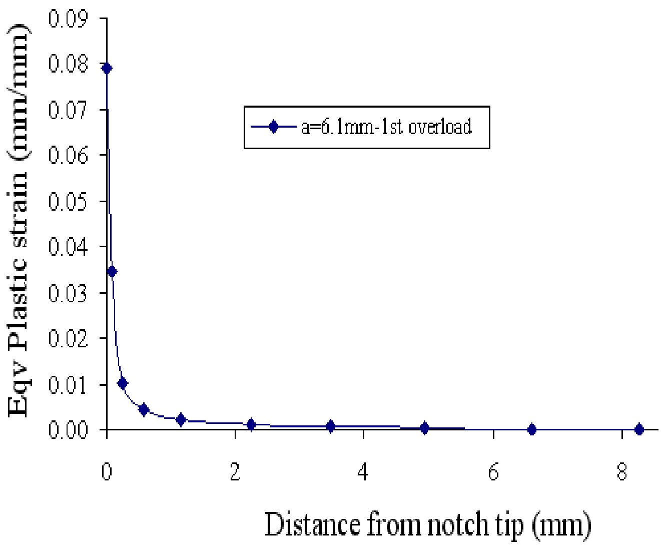
The Paris type power law as given by Equation 1 is applicable for measurable stable crack growth under constant amplitude loading. In order to account the variable amplitude history, a correction factor as proposed in the Wheeler model should be used and is given by Equation 2.

$$\left(\frac{da}{dN}\right)_V = C_{pi} \bullet \left(\frac{da}{dN}\right)_C$$
$$C_{pi} = \left(\frac{r_{pi}}{a_{OL} + r_{OL} - a_i}\right)^p \qquad (2)$$

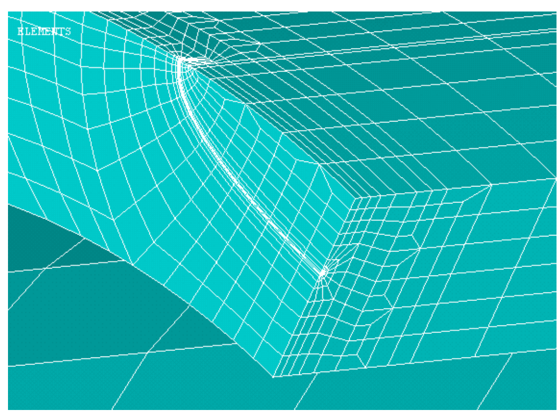
where, C_{pi} is the retardation factor, r_{pi} is the plastic zone size corresponding to *i*th loading cycle, a_{OL} is the crack depth at overload event, r_{OL} is the plastic zone size after overload, a_i is the current crack depth and *p* is the material parameter which can be determined from the best fit of tests data. In this study, *p* parameter has been taken from tests carried by Kalnaus S. (2009) on similar material (SS304L). The value of *p* was considered as 0.72 for the material in study.

After the application of overload, the residual compressive field does not allow the crack to grow at its normal rate viz. retardation occurs and is predicted by the model (Equation 2). Thus the value of retardation factor (C_{pi}) will be minimum just after the application of overload. Once the current plastic zone comes out of the residual plastic zone created due to overload, the crack resumes growing at the normal rate. At this time, C_{pi} becomes unity. The Wheeler model (Equation 2) reduces to conventional Paris law for constant amplitude loading.

For correct prediction of the retardation caused by overloading, the plastic zone size of growing crack (r_{pi}) should be evaluated. Certain approximations can be made to determine the plastic zone size using Irwin's method (1957) for plane stress and plane strain geometries. However, the cracked pipe would have plastic zone which lies between the two extreme cases of plane stress and plane strain. Therefore, a 3D finite element model of the cracked pipe (SSPB6-14) was made with crack depth (a) of 6.1mm (i.e. a_{OL}) and crack length (2c) as 36mm, at overload event. The plastic zone size of the pipe at maximum crack depth location was determined on the basis of equivalent plastic strain versus distance from crack tip (Figure 4(a)). The quarter symmetric 3D FE model of cracked pipe is shown in Figure 4(b).



(a) The von-Mises equivalent plastic strain versus distance from notch root at maximum crack depth location



(b) Quarter symmetric 3D FE model of pipe

Figure 4

The FE analysis helped in finding the constraint effect for actual pipe geometry. The cyclic stress strain diagram as obtained from the standard LCF specimens on the same material was used in FE analysis (Gupta S.K. et al. (2011)). The plastic size as evaluated from FE analysis is correlated with Irwin's approximation as specified in Equation 3.

$$r_{OL}^{FE} = (1-\zeta)\bullet\left(r_{OL}^{Irwin}\right)_{p\sigma} + \zeta\bullet\left(r_{OL}^{Irwin}\right)_{p\varepsilon} \tag{3}$$

where, ζ is the weighting parameter and $0 \le \zeta \le 1$. r^{FE}_{OL}: the plastic zone as determined from FE analysis, $(r^{Irwin}_{OL})_{p\sigma}$: plastic zone size of plane stress geometry, $(r^{Irwin}_{OL})_{p\varepsilon}$: plastic zone size of plane stain geometry. The values of $(r^{Irwin}_{OL})_{p\sigma}$ and $(r^{irwin}_{OL})_{p\varepsilon}$ are given by Equation 4 and Equation 5 respectively.

$$\left(r_{OL}^{Irwin}\right)_{p\sigma} = \frac{1}{\pi}\left(\frac{K_{OL}}{\sigma_y}\right) \tag{4}$$

$$\left(r_{OL}^{Irwin}\right)_{p\varepsilon} = \frac{1}{3\pi}\left(\frac{K_{OL}}{\sigma_y}\right) \tag{5}$$

The r_{OL} as evaluated from FE analysis is 6.6mm and ζ as evaluated from Equation 3 is 0.49. Further, the value of r_{pi} is determined for the same geometry weighting factor (ζ) and is given by Equation 6.

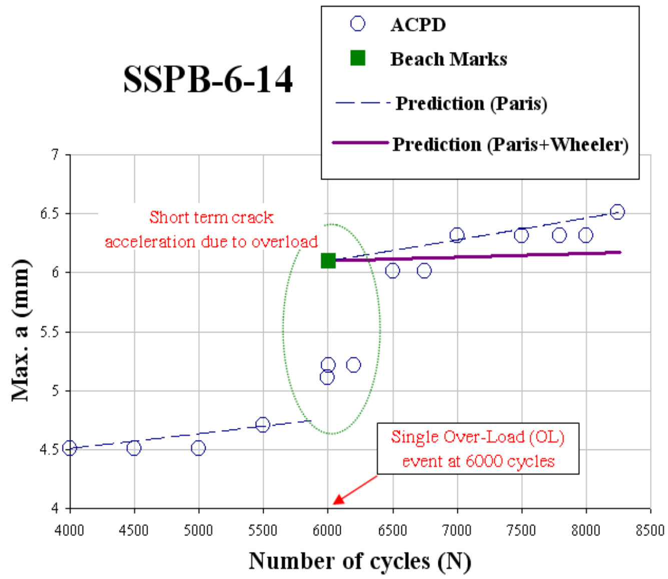
$$r_{pi} = (1-\zeta)\bullet\left(\frac{1}{\pi}\bullet\left(\frac{\Delta K_i}{2\sigma_y}\right)^2\right) + \zeta\bullet\left(\frac{1}{3\pi}\bullet\left(\frac{\Delta K_i}{2\sigma_y}\right)^2\right) \tag{6}$$

The calculations have been performed for the increasing r_{pi} due to growing crack. The increasing value of C_{pi} (or diminishing retardation effect) as the loading continued, was evaluated to account post-overload history effects. Numerical integration was carried out to evaluate crack depth increment (Δa) for a given small interval of loading cycles (ΔN).

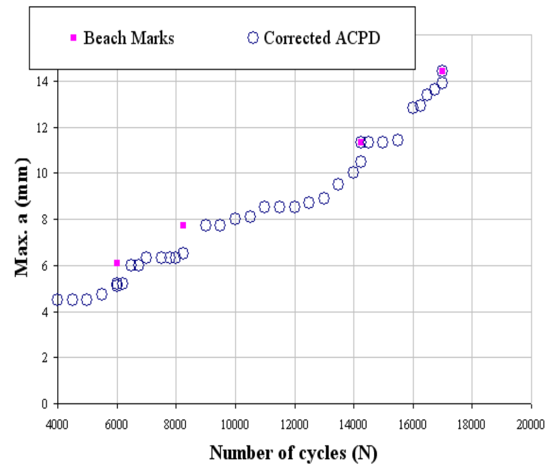
RESULTS

The results for SSPB 6-14 have been shown in Figure 5 after the crack has initiated from blunt notch. The initial crack size (a_i) has been taken as 4.5mm corresponding to fatigue crack initiation life as 4000 cycles. The FCG calculations for constant amplitude loadings were carried out till the overload event (6000th cycle). After this, sudden rise in crack growth is evident from the ACPD data and beach mark as seen on actual fractured pipe specimen. This short term acceleration of crack can be due to cracking from voids within the overload plastic zone. Wheatley G. et al. (1999) have also observed similar behavior at overload event in SS 316L material. Since the Wheeler model targets only the post-overload retardation effect, it can not predict acceleration in crack growth during overloading. The predictions using Wheeler corrected Paris law were made from 6001 cycles to 8250 cycles. Figure 5 (a) shows that Wheeler corrected Paris law predicts retardation effect reasonably well. However, the constant amplitude Paris law over-predicts FCG life after overload event.

After 8250th cycle, an underload was applied and a sudden growth in fatigue crack growth rate can also be seen from test data (Figure 5(b)). However, the FCG life predictions have not been carried out after underload event as *p* exponent of Wheeler model is different for underload and is not known.



(a) Comparison for tested FCG behavior with predictions



(b) Tests data for fatigue crack growth life

Figure 5. Results of SSPB 6-14

As there is not much difference between peak loads of one block to the next block (Table 4). The FCG life for SSPB 6-9 was predicted using conventional Paris law for constant amplitude loading without considering the effect of any post overload retardation. Figure 6 shows the fatigue crack growth life predictions are comparable with the tests results.

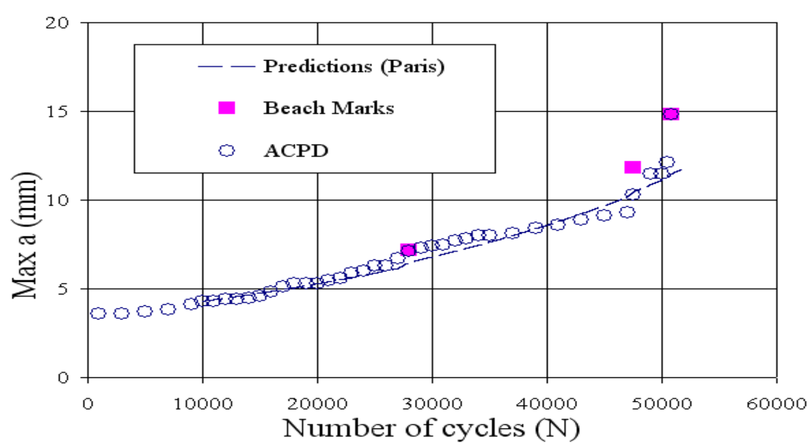


Figure 6. Comparison for tested FCG behavior with predictions for SSPB 6-9

CONCLUSIONS

The predicted life with Wheeler correction on conventional Paris law compare well with test life after overload. However, fatigue crack growth life is over-predicted if Paris law (without considering retardation effects) is used in the analyses. Tests life shows short term crack acceleration at the time of overload and underload. Wheeler model can not predict the damage occurring in the plastic zone due to overload. The predicted fatigue life using conventional Paris law for block loading compares well with the tests results as the ratio of the peak loads in different cycle blocks is near to one.

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