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Fatigue Crack Growth Behavior in Pipes and Elbows of Carbon Steel and Stainless Steel Materials

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Abstract

The objective of the present study is to understand the fatigue crack growth behavior and validate analytical procedures for austenitic stainless steel and carbon steel pipes, pipe welds and elbows. The study involved fatigue tests on actual components and specimens. The Paris law has been used for the prediction of fatigue crack growth life. Paris constants have been determined for pipe (base), pipe weld and pipe elbow materials by using Compact Tension (CT)/ Three Point Bend (TPB) specimens machined from the actual pipe, pipe weld and pipe elbow. Analyses have been carried out to predict the fatigue crack growth life of these piping components having part through cracks on the outer surface. In the analyses, Stress Intensity Factor (*K*) has been evaluated through two different schemes. The first scheme considers the '*K'* evaluations at two points of the crack front i.e. maximum crack depth and crack tip end at the outer surface. The second scheme accounts for the area averaged root mean square stress intensity factor (K_{RMS}) at deepest and surface points. In order to validate the analytical procedure/results, experiments have been carried out on full scale pipes, pipe welds with part through circumferential crack. The tests have also been conducted on the full scale carbon steel elbows having part-through circumferential notch at intrados location and axial notch at crown location on the outer surface. Fatigue crack growth life evaluated using both schemes have been compared with experimental results. Use of stress intensity factor (K_{RMS}) evaluated using second scheme gives better fatigue crack growth life prediction compared to that of first scheme.

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Keywords: Fatigue crack growth; stress intensity factor; Paris law; pipe weld; elbow

1. Introduction

Most of the failures in the piping components are due to the fatigue loading. These failures may occur well below the allowable stress limits even under normal operating conditions. This can be attributed to the presence of flaws which 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

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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 components during their design life. This requires investigation on Fatigue Crack Growth (FCG) of pipes and elbows with postulated part through flaws for the qualification of LBB design criterion.

Fatigue crack growth rate behavior in various materials has been widely studied [1-5] for understanding of the fatigue mechanisms and the FCG life predictions. The conventional Paris law [1] is based on crack growth in one direction perpendicular to the bulk maximum principal stress (σ_1) axis. Few studies are available on the plate specimens with part through crack [7-8]. The tests studies on 90^o elbows have also been conducted on LMFBR pipe elbows [9]. Bhandari et. al. [10] have also analyzed crack initiation, crack shape development with crack present at crown location of type 304 stainless steel material at operating temperature and with sodium as fluid environment. Singh et. al. [11] have shown crack growth behavior in carbon steel pipes with circumferential part through crack of large aspect ratio of 20-50. However, the crack aspect ratio and load combinations were such that crack growth occurred in thickness direction only. They have used stress intensity factor evaluated at two points of crack front i.e. maximum depth and crack tip ends. The effect of crack aspect ratio on fatigue growth behavior has also been studied by Engle [12] and Shang [13]. Cruse and Besuner [6] used an effective crack driving force parameter, K_{RMS} which accounts for the local stress intensity factors along the crack front, in an averaged sense. Fatigue crack growth on pipe welds has not been studied. In view of this, the objective of the present study is to understand the fatigue crack growth behavior in carbon steel and austenitic stainless steel pipes and pipe welds by carrying out analysis/predictions and experiments. The analyses have also been carried out on pipe elbows using the SIF at maximum depth and crack tip end points.

2. Analytical methodology

There are different schemes available for accounting the crack shape change during fatigue crack growth analysis. Some of these schemes have been listed down in terms of the equivalent fracture parameter to predict FCG life. This parameter in turn determines the capability of the scheme in exhibiting the degree of realistic fatigue crack growth behavior.

Scheme A: The most rigorous scheme can be the evaluation of local crack driving force or the local stress intensity factor (K) at many points on the crack front. This requires three dimensional finite element analyses for the evaluation of 'K' at each step. This multi-degree of freedom scheme is likely to render more realistic results but the use of this scheme is not preferred due to its high computational cost.

Scheme B: The simplest scheme accounts the local stress intensity factor values at the deepest and the surface points to be the governing parameters for fatigue crack growth evaluation. In this scheme the crack growths in depth and length directions are governed by local stress intensity factors at deepest and surface points respectively.

Scheme C: A powerful method as proposed by Cruse and Besuner [6] which accounts the area averaged root-mean-square effective stress intensity factor (K_{RMS}) at maximum depth and tip end points, can be used for FCG life prediction. This is a coupled 2-DOF scheme which indirectly considers the effect of 'K' values at all the points along the crack front.

The present study utilized the values of K along the crack front from a handbook of American Petroleum Institute (API) [14]. The analytical studies on straight pipes/ pipe welds have been carried out using *Scheme B* and *Scheme C* till the ratio of the crack depth to thickness (a/t) reaches 0.8. However, the predictions of fatigue crack growth for carbon steel elbows have been carried out using FE analyses. FE analyses have been carried out on the full scale un-cracked elbow to determine the distributions of hoop and axial stresses along thickness direction. Hoop stress distribution along thickness direction in the un-cracked elbow governs the fatigue growth behavior of axial crack present at crown location. The Stress Intensity Factor (K) has been evaluated for a plate having an edge crack of the same crack geometry subjected to same remote stress distribution as obtained from

FE analyses for un-cracked elbow. The SIF has been determined at two points of the crack front i.e. maximum crack depth and crack tip end at the outer surface (*Scheme-B*). The fatigue crack growth life predictions have been compared with experimental results.

3. Experimental details

Piping materials of carbon steel (SA 333 Gr 6) in normalized and tempered condition and 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 have been used for studies. Welding of pipes has been carried out as per the procedure given in ASME Section IX of the B&PV code. Quality assurance and acceptance of the weld joints were as per the requirement of ASME Section III. The details of the chemical composition and tensile properties of the pipes and pipe welds for each size are as detailed by Arora et. al. [15].

3.1. Evaluation of Paris constants

A set of experiments were conducted on CT/ TPB specimens of base and weld materials (machined from the same seamless pipe, pipe welds and elbow) as per standard ASTM E647 test procedure to evaluate fatigue crack growth rate constants as per Paris Law (eq. (1)). The Paris constants are tabulated in Table 1.

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

Here, *da/dN* is in m/cycle and ΔK in $MPa\sqrt{m}$. *C* and *m* are the material constants. The Paris constants as derived for the base material (Table 1) have been used for the fatigue crack growth predictions of pipe welds of Gas Tungsten Arc Welding (GTAW) because of their comparable fracture toughness and tensile properties [16].

Table 1. The Paris constants (C& m) for pipe, pipe weld and elbows

Specimen	Material	Orientation	R	m	C
CT (from pipe)	SS304LN	LC	0.1	3.195	1.917×10^{-12}
CT (from pipe weld)	E308L	LC	0.1	4.4	2.29×10^{-14}
TPB (from pipe)	SA 333 Gr 6	LC	0.1	3.94	2.597×10^{-13}
TPB (from pipe weld)	E 7018	LC	0.1	4.08	1.959×10^{-13}
CT (from elbow)	SA350LF2	LC	0.1	3.188	$3.982 \text{ x } 10^{-12}$

3.2. Full scale pipe, pipe weld and elbow test

Fatigue crack growth tests on pipes and pipe welds have been carried out under constant amplitude sinusoidal cyclic loading. The schematic of four point bend test set up for straight pipes and pipe welds has been shown in Fig. 1(a). The test set up for elbow has been shown in Fig. 1(b). All the tests have been carried out at room temperature under quasi-static load control condition. The fatigue crack growth was measured along the crack front using Alternating Current Potential Drop (ACPD) technique. The tests were conducted under load ratio (R) (ratio of applied minimum load to maximum load) as 0.1.

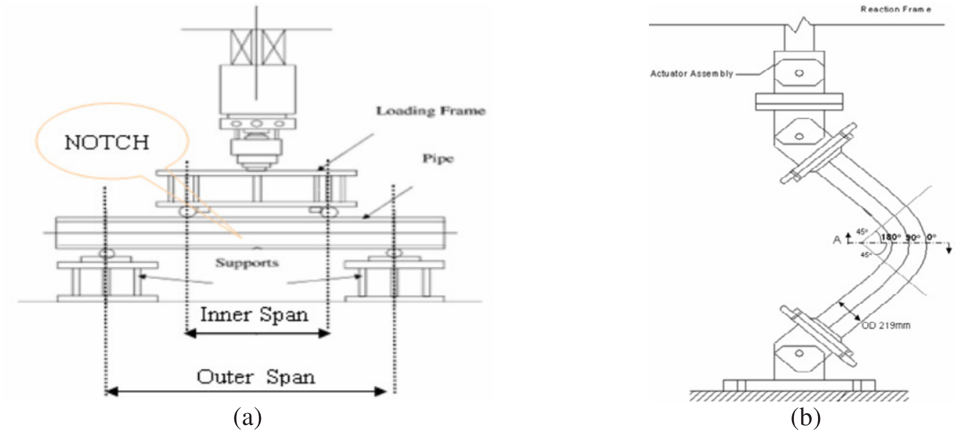


Fig. 1. The test set up for (a) straight pipe/ pipe welds and (b) elbow.

4. Results: experiments and analytical

4.1. Straight pipe and pipe welds

This section details the results of the analysis and experiments for the pipe and pipe welds. The crack growths in depth and circumferential directions and the crack shape have been considered for the comparison of experimental and analytical results.

In all the cases, the growth in maximum crack depth (a) and crack length ($2c$) directions have been plotted with respect to number of cycles. Crack growth in depth and length directions for pipe welds SSPW 6-3 has been shown in Figs 2(a) and 2(b) respectively. Fig 2 shows that the crack growth predictions using Scheme C compare reasonably well with experimental values for depth and circumferential directions. However, Scheme-B resulted in over-estimation of crack growth.

Figure 3(a) shows that crack growth predictions using both the schemes compare well with experiments for SSPB 6-9. However, Scheme C gives marginally lower crack growth in depth direction. In length direction (Fig. 3(b)), both the schemes marginally underestimate the crack growth. This marginal under estimation could be due to the use of Paris constants evaluated from the pipe of different sizes and different heat.

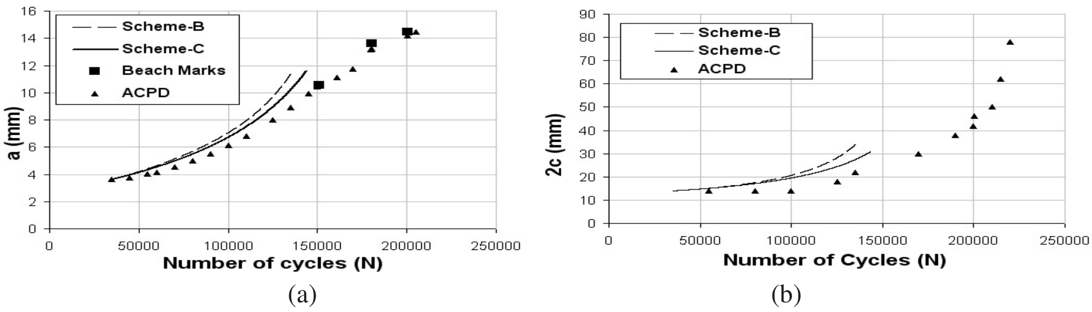
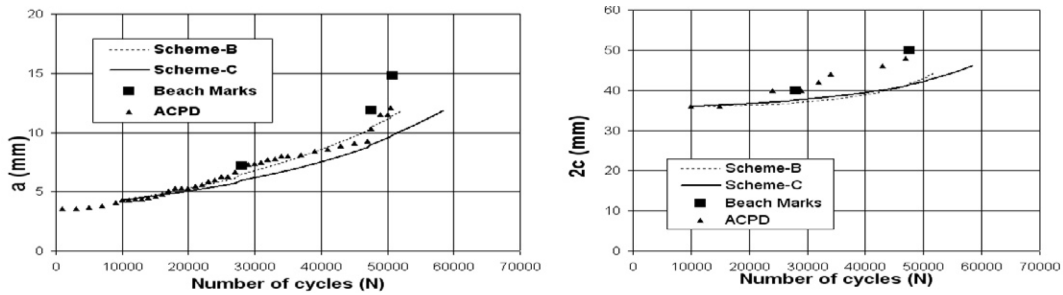


Fig. 2. (a) Crack depth (a) growth with loading cycles (N), (b) Crack length (2c) growth with loading cycles (N) for SSPW6-3 pipe test.



(a) (b)

Fig. 3. (a) Crack depth growth with loading cycles (N), (b) Crack length (2c) growth with loading cycles (N) for SSPB6-9 pipe test.

Crack growths in depth direction for pipe weld SSPW 12-10 and pipe SSPB 12-12 have been shown in Figs 4 and 5 respectively. These figs indicate that Scheme-C compares well with experimental results and Scheme B resulted in over estimation of crack growth in depth direction.

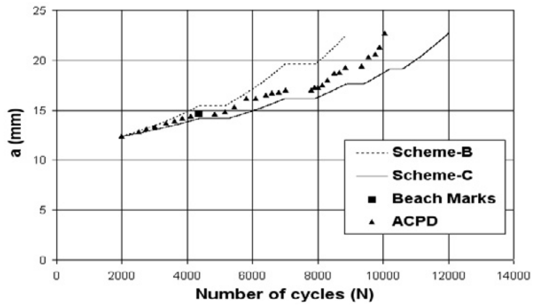


Fig. 4. Crack depth (a) growth with loading cycles (N) for SSPW-12-10.

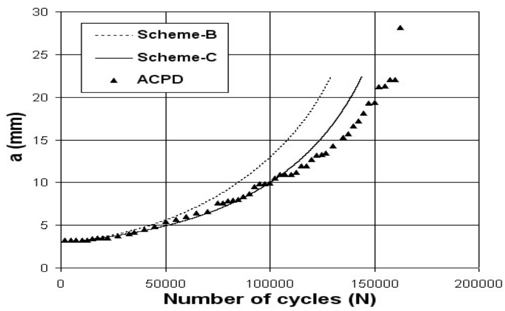


Fig. 5. Crack depth (a) growth with loading cycles (N) for SSPB-12-12.

Crack growths in depth direction for pipe weld (SPBMSC 16-4) and pipe (SPBMSC 16-1) have been shown in Figs 6 and 7 respectively. These figs indicate that Scheme-C compares well with experimental results and Scheme B resulted in over estimation of crack growth in depth direction. The overestimation of crack growth after the crack grew nearly half thickness in case of pipe weld could be due to use of Paris constants of SMAW in the region of GTAW (root pass).

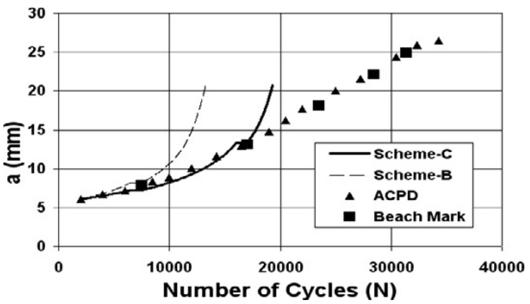


Fig. 6. Crack depth (a) growth with loading cycles (N) for SPBMSC-16-4 (CS-SMAW).

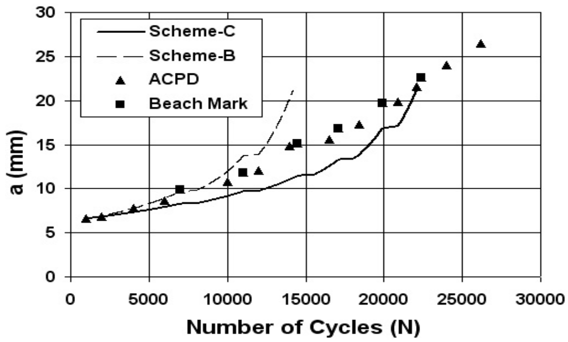


Fig. 7. Crack depth (a) growth with loading cycles (N) for SPBMSC-16-1 (CS-Base).

4.2 Elbows

The remote axial and hoop stress variations are required along thickness direction for the evaluation of stress intensity factor at maximum depth and crack tip end points. The variation of hoop stress for ELASCC 8-3 elbow is shown in Fig. 8.

The stress intensity factor at deepest point (K_a) and tip end point (K_c) have been evaluated using the procedure given in A16 guide of RCC-MR [17] for plate with semi-elliptical edge crack subjected to the same remote stress distribution.

The fatigued elbows were cut open after the crack became through thickness size. Fig 9 shows the fatigued surfaces of ELASCC 8-3 elbow. This Fig. indicates the crack growth from inner and outer surfaces. The formation of persistent slip bands can occur even under compressive stress field that may cause the fatigue crack initiation on inner surface at crown location. This observation is supported by the studies carried out by Hsua et. al. [18] and Chu et. al. [19] on the fatigue crack initiation under compressive stress state. The growth from the inner surface at crown region may have occurred due to coalescence of multiple initiated cracks.

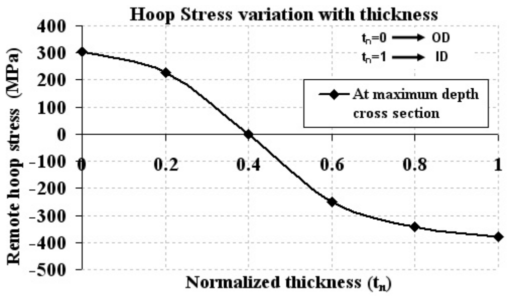


Fig. 8. FE results at P_{max}: The hoop stress for ELASCC 8-3 along thickness of elbow.

Fig. 9. Fatigued surfaces of elbows having axial notch at crown location.

Figure 10 shows that the predicted crack growth for elbow having axial notch at crown location (ELASCC 8-3) is comparable with the test results till a/t becomes 0.6. However, the test growth rate increases after a/t 0.6 due to interaction between the stress fields of the growing cracks from inside and outside surfaces. The crack growth from inside the surface was also observed for ELCSCI 8-4 specimen. However, the sudden change in the slope of the growth rate from ACPD test data is not apparent from Fig. 11.

This study on elbows infers that the fatigue crack growth life can be well predicted by Paris law till a/t 0.6. However, prediction of the crack growth behavior under compressive stress needs different approach because crack tip is closed and the mechanism of growth differs.

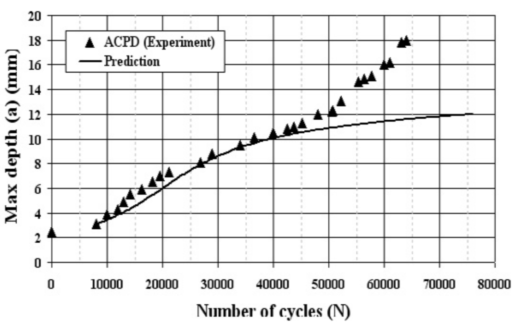


Fig. 10. The maximum crack depth with number of cycles for ELASCC 8-3.

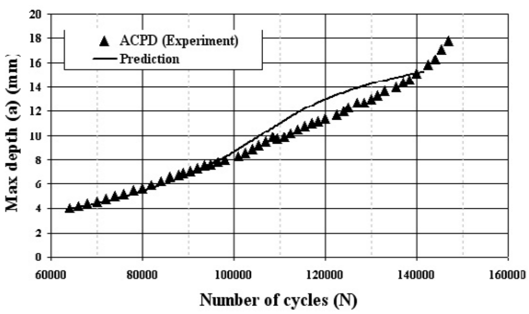


Fig. 11. The maximum crack growth with number of cycles for ELCSCI 8-4.

5. Conclusions

Present study on FCG behavior on pipe/ pipe welds and elbows can be summarized as

- Two schemes based on the evaluations of effective stress intensity factors, result in marginally different fatigue crack growth life predictions. Scheme-C based on K_{RMS} gives comparable results w.r.t. experiments whereas scheme-B gives marginally conservative predictions.
- Use of FE analyses and Paris Law result in comparable predictions till a/t as 0.6 for axial and circumferential crack orientations at crown and intrados locations respectively.
- Multiple initiations of the cracks have been observed from inside surface under compressive stress state. The crack growth predictions under compressive stress field needs different analytical approach.

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