FATIGUE CRACK GROWTH RATE BEHAVIOR IN CARBON STEEL ELBOWS OF INDIAN PHWRS

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ABSTRACT

The objective of the present study is to understand the fatigue crack growth behavior in carbon steel elbows by carrying out experiments and analysis/predictions. Experiments have been carried out on full scale elbows with part through circumferential/ axial crack. Three numbers of elbows have been tested to study the growth behavior of crack present at crown and intrados locations. The Paris law has been used for the prediction of fatigue crack growth life. To carry out the analysis, Paris constants have been determined for elbow materials by using Compact Tension (CT) specimens machined from the actual elbow. Analyses have been carried out to predict the fatigue crack growth life of the carbon steel elbows having part through cracks on the outer surface. In the analyses, Stress Intensity Factor (K) has been evaluated at two points of the crack front i.e. maximum crack depth and crack tip at the outer surface. Fatigue crack growth life predictions have been compared with experimental results. Multiple initiations of the cracks have been observed from inside surface of the crown followed by growth, although the nature of stress is compressive.

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 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 such as elbow during its design life. This requires investigation on Fatigue Crack Growth (FCG) of 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 [1-7] 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 [9-10]. Nagapadmaja et. al. [7] has carried out analysis to study the fatigue crack growth behavior of elbows using elastic-plastic J-integral range evaluated from FE analysis and RCC-MR code procedure. The tests studies on 90^o elbows have also been conducted on LMFBR pipe elbows [11]. Bhandari et. al. [12] 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.

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 Nuclear Power Plants (NPP), when the components are put into service, its In-Service Inspection (ISI) is possible at limited number of times. The American Society of Mechanical Engineers for Boiler & Pressure Vessel (ASME-B&PV) code section XI [13] recommends about four to five ISIs for the design life of a Nuclear Power Plant. During the inspection, if cracks are detected, then the integrity of the component can be demonstrated by evaluating the crack growth till the next inspection thereby 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. 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 elbows by carrying out experiments and analysis/predictions.

EXPERIMENTAL DETAILS

Material details

The carbon steel elbows were conforming to the specifications of ASME Section II and Section III of Boiler and Pressure Vessel (B&PV) Code. The chemical composition and tensile properties of the material are as tabulated in Table 1 and 2 respectively. The 90^o short elbows of 219 mm as outer diameter having 20 mm thickness, have been considered.

Table 1: Chemical composition (in wt%) of elbow material

C	Mn	Si	P	S
0.14	0.9	0.25	0.016	0.018

Table 2: Tensile properties at room temperature

σ_y (MPa)	σ_u (MPa)	% El
302	450	36.7

σ_y: yield strength, σ_u: tensile strength, %El: percentage elongation

Cyclic stress–strain has been obtained following ASTM E606 using smooth specimens of 4.5 mm gauge diameter machined from the same material. Tests have been conducted under fully reversible condition for different strain ranges at room temperature and air environment. The cyclic stress–strain curve is given by equation (1). The various constants in the equation have been obtained by fitting the test data points of the experiments.

$$\Delta\varepsilon/2 = 100\,(\Delta\sigma/2E) + (\Delta\sigma/2k)^{1/n} \quad (1)$$

k=354.27MPa n = 0.1523

where, $\Delta\varepsilon$(%) and $\Delta\sigma$(MPa) are the elastic-plastic strain range and stress range respectively.

Evaluation of Paris constants

A set of three fatigue crack growth rate experiments were conducted on CT specimens (machined from the same elbow material) using ASTM E647. The material constants have been evaluated after fitting the test data points in the form of Paris Law as given by equation (2) below,

$$da/dN=C(\Delta K)^m \quad (2)$$

The Fig. 1 shows nearly same value of Paris constants for all the three CT specimens (Specimen-A, B and C). The value of the CT specimen-B has been chosen due to wide test range of ΔK and has been used for predicting the growth behaviour of full scale notched elbows. The Paris constants are given by equation (3).

$$C = 3.982 \times 10^{-12} \text{ and } m = 3.188 \quad (3)$$

The values of Paris constants (C & m) are consistent with the units of da/dN and ΔK as m/cycle and MPa$\sqrt{m}$ respectively.

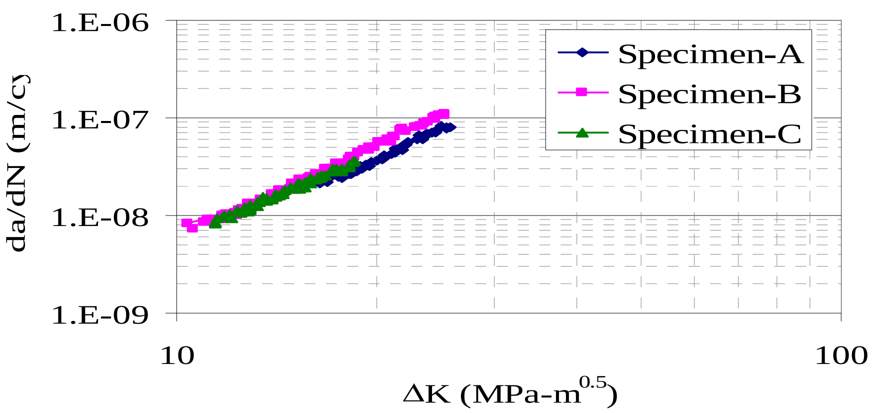
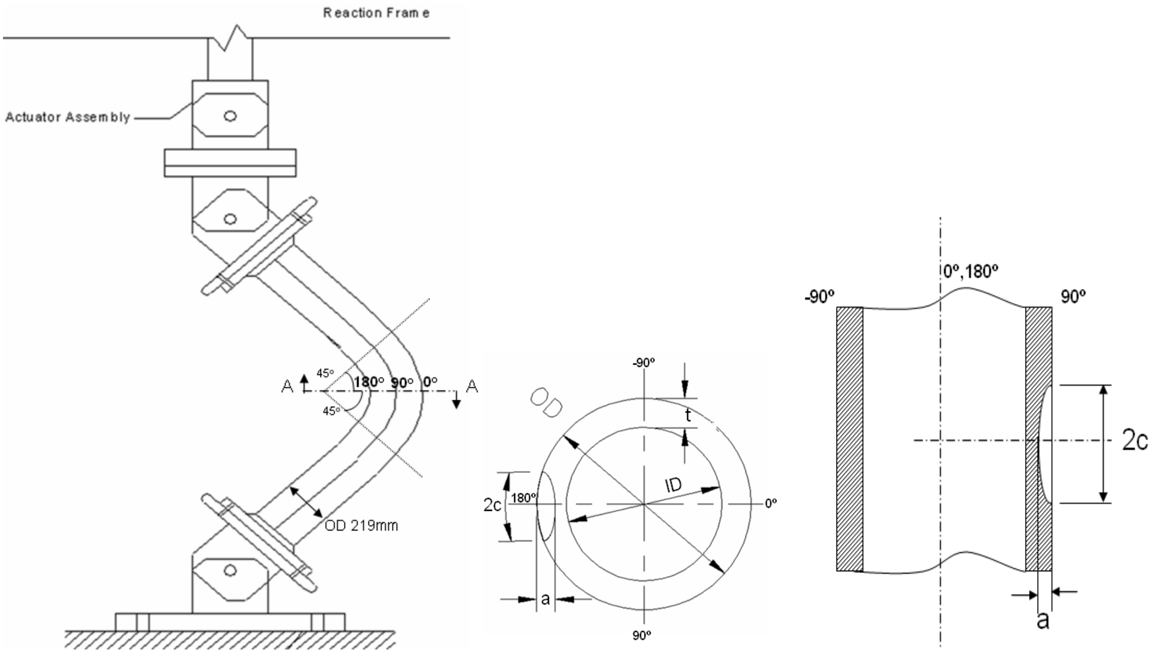


Fig. 1: Evaluation of Paris constants (C and m) from da/dN versus ΔK curve

Full scale elbow test

Fatigue crack growth tests on pipe elbows have been carried out under constant amplitude sinusoidal cyclic loading. The schematic of test set up and the notched sections with circumferential notch at intrados and axial notch at crown locations have been shown in Figs. 2(a), 2(b) and 2(c) respectively.



(a) (b) (c)

Fig. 2: (a) Schematic of test set up, (b) circumferential notch at intrados and (c) axial notch at crown

All the tests have been carried out at room temperature and air environment under load control condition. The loading frequency was within the range of 0.1Hz to 0.5Hz. Load was applied as shown in Fig. 2(a) to ensure that cracked location is subjected to combined membrane and bending stress. The stress ratio (R) i.e. the ratio of minimum nominal stress to the maximum nominal stress is maintained 0.1 for all the tests. The loading and notch geometrical details have been given in Table 3. Instrument based on the principle of Alternating Current Potential Drop (ACPD) technique was used to measure crack growth. The ACPD technique had an accuracy to measure the crack growth of 0.1mm. These gauges have been connected all along the length of the notch to obtain the evolving crack front with loading cycles. However, only one ACPD probe was connected at each crown location for un-cracked elbow (ELWC 8-2). The tests have been continued till the crack becomes through thickness size.

Table 3: Loading and notch geometrical details of pipe elbow specimens

Description	**Test ID**		
	ELWC 8-2	**ELASCC 8-3**	**ELCSCI 8-4**
Notch Orientation	No notch	Axial	Circumferential
Notch location	--	crown	intrados
OD (mm)	219	219	219
t (mm)	19.6	19	19.11
a_0 (mm)	0	2.5	2.9
$2c_0$ (mm)	0	86	112
$^*P_{max}$ (kN)	-120	-150	80
$^*P_{min}$ (kN)	-12	-15	8
N_i	249000	8000	64000
a_i (mm)	1.0	3.1	4.0

OD: outer diameter of elbow, t: average thickness of elbow, a_0: initial blunt notch depth, $2c_0$: initial blunt notch length, P_{max} : maximum applied load, P_{min}: minimum applied load, N_i: initiation life in component tests, a_i: crack depth at initiation.

* **Note:** The negative and positive load cause closing and opening of elbow respectively.

ANALYTICAL PREDICTIONS METHODOLOGY

The predictions for fatigue crack growth life have been made using local stress intensity factor values at the deepest and the surface points of the crack. The crack growths in depth and length directions are governed by local stress intensity factors at deepest (K_a) and surface points (K_c) respectively. The Paris constants as derived from the CT specimens were used to predict the growth life of the tested elbows.

The predictions for FCG life have been made for two numbers of elbows having semi-elliptical axial crack at crown location and circumferential crack present at intrados location on outer surface of the elbow. The elbow was subjected to combined membrane and bending cyclic loading. The remote stress distribution across thickness has been evaluated from three dimensional FE analyses on un-cracked elbows. The elbow and the connected straight pipes were modeled with 20 node hexahedral elements. Five numbers of element divisions were taken in thickness direction to capture the remote stress distribution across thickness. In order to validate FE model, analyzed strain values were compared with the strain gauge values as recorded during the monotonic test conducted before the actual fatigue test. The strains as obtained from FE analyses compare well with the test values during monotonic test on elbow.

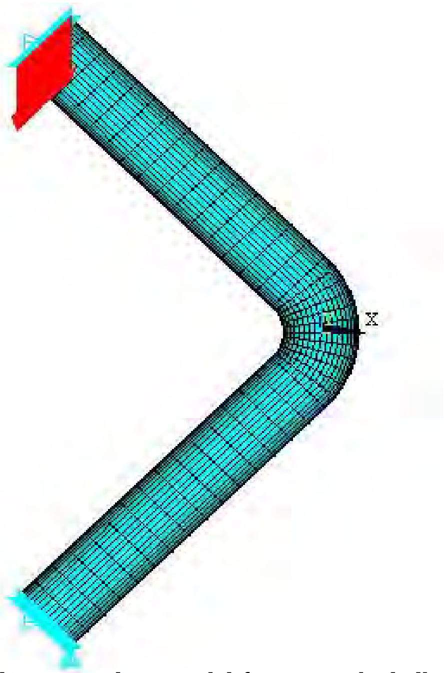
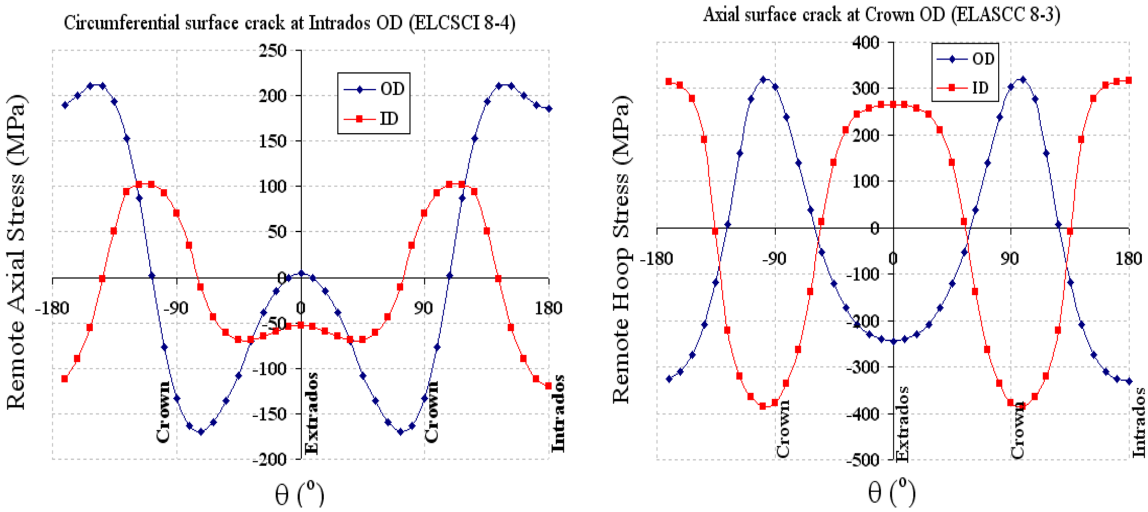


Fig. 3: Three dimensional FE model for un-cracked elbow

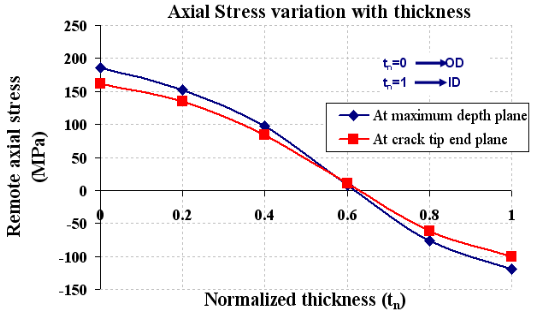
The axial stress causes crack opening for circumferentially cracked elbow ELCSCI 8-4. However, the hoop stress is the key parameter for the crack growth in axially cracked elbow ELASCC 8-3. The cyclic stress-strain curve (equation (1)) as obtained from uniaxial LCF tests has been considered for FE analyses. The axial stress and the hoop stress variations have been plotted along the circumferential direction for ELCSCI 8-4 and ELASCC 8-3 in Figs. 4(a) and 4(b) respectively. The axial stresses as obtained from FE analysis are tensile in nature on OD side and compressive stresses exist on the inner surface at intrados. Similarly, the hoop stresses are tensile on OD side and compressive on the inner surface at crown location.



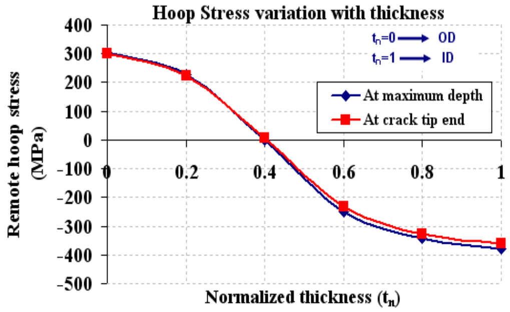
(a) (b)

Fig. 4: FE results at P_{max}: The variation of (a) axial stress for ELCSCI 8-4 and (b) hoop stress for ELASCC 8-3, in circumferential direction of un-cracked elbow.

Further, 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 axial stress and hoop stress for ELCSCI 8-4 and ELASCC 8-3 elbows are given in Figs. 5(a) and 5(b) respectively. The remote stress field at notch tip end point location has been compared with that at maximum depth location for both the elbows. There exists marginal difference between the remote stresses at these locations. The remote stress variation in thickness direction at maximum depth location has been used to evaluate the stress intensity factors at maximum depth and tip end points.



(a)



(b)

Fig. 5: FE results at P_{max}: (a) The axial stress for ELCSCI 8-4 and (b) The hoop stress for ELASCC 8-3 along thickness of elbow

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 [14] for plate with semi-elliptical edge crack subjected to the same remote stress distribution.

RESULTS: EXPERIMENTS AND ANALYTICAL PREDICTIONS

In elbows, crown location is the highly stressed region under in-plane membrane and bending load condition. A test has been conducted on an un-cracked elbow to validate the initiation location and to understand the behavior of the growing crack after initiation. The crack initiation in ELWC 8-2 elbow occurred at the crown location. The crack growth data has been presented in the form of growth in thickness direction with respect to number of load cycles as shown in Fig. 6. It can be inferred from this Fig. that the growth rate decreases with increase in crack depth/ load cycle. This has happened due to change in the tensile hoop stress from OD to the compressive hoop stress field on inner surface. A similar behavior has been observed in elbow with axial crack at crown location and is apparent from the ACPD test data as shown in Fig. 8.

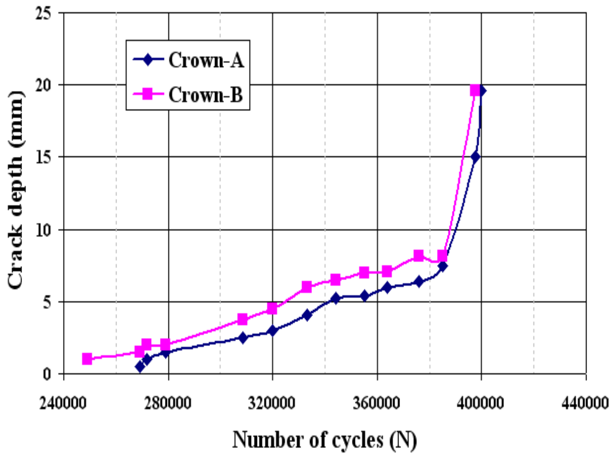
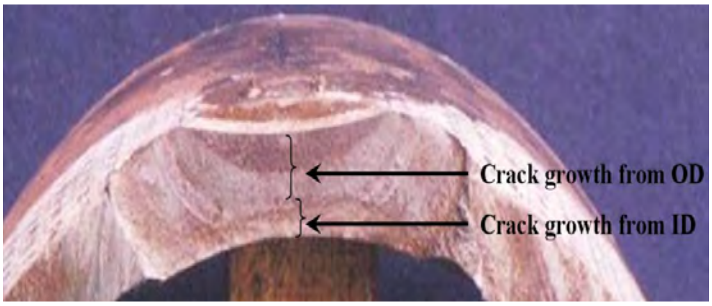


Fig. 6: Test data on crack depth with number of cycles for ELWC 8-2



(a)

(b)

Fig. 7: Fatigued surfaces of elbows having (a) circumferential notch at intrados and (b) axial notch at crown locations

The fatigued elbows were cut open after the crack became through thickness size. Figs. 7(a) and 7(b) show the fatigued surfaces of ELCSCI 8-4 and ELASCC 8-4 specimens respectively. These Figs. indicate 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. [15] and Chu et. al. [16] 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.

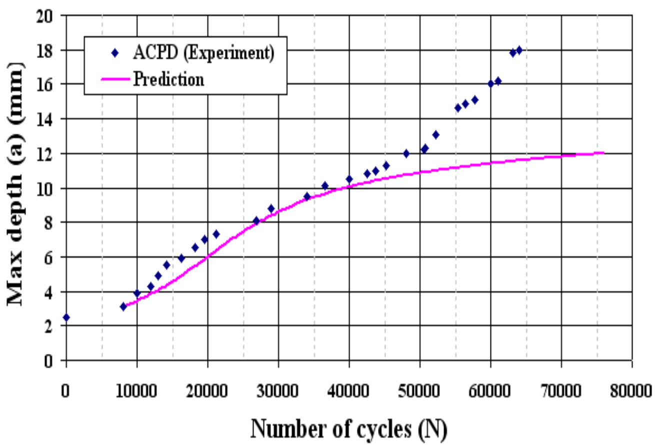


Fig.8: The maximum crack depth with number of cycles for ELASCC 8-3

Fig. 8 shows that the predicted crack growth for elbow having axial notch at crown location 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 prediction for crack growth behavior in elbow with circumferential notch at intrados is in agreement with the test results as shown in Fig. 9. However, the predicted growth rate decreases after a/t as 0.6. This is due to evaluated remote compressive axial stress at ID side. The crack growth from inside the surface was also observed for this test specimen as indicated in Fig. 7(a). However, the sudden change in the slope of the growth rate from ACPD test data is not apparent from Fig. 9.

The study infers that the fatigue crack growth life of the elbows 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.

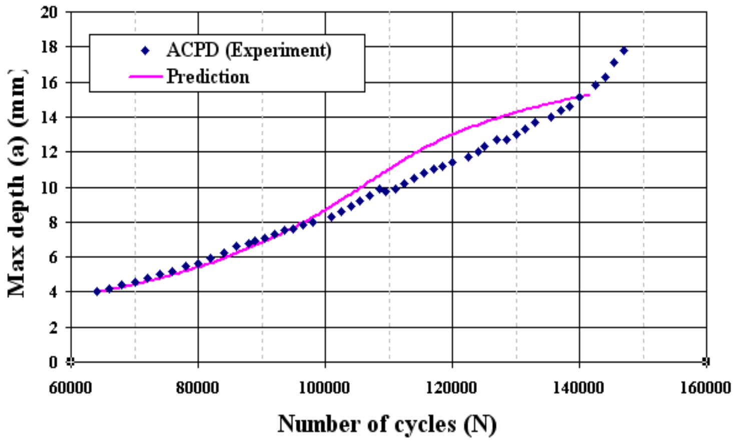


Fig. 9: The maximum crack growth with number of cycles for ELCSCI 8-4

CONCLUSIONS

Present study on FCG behavior in carbon steel elbows can be summarized as

1) 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.

2) 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.

REFERENCES

[1] P Paris and F Erdogan (1963), “A critical analysis of crack propagation laws”, *Journal of Basic Engineering, Transactions of the American Society of Mechanical Engineers*, December 1963, pp.528-534.

[2] Małgorzata Skorupa, Andrzej Skorupa, “Experimental results and predictions on fatigue crack growth in structural steel”, *International Journal of Fatigue*, Volume 27, Issue 8, August 2005, Pages 1016-1028.

[3] S. Kalnaus, F. Fan, Y. Jiang, A.K. Vasudevan, “An experimental investigation of Fatigue crack growth of stainless steel 304L”, *International Journal of Fatigue*, Volume 31, Issue 5, May 2009, Pages 840-849.

[4] K. Sadananda, A. K. Vasudevan, “Fatigue crack growth mechanisms in steel”, *International Journal of Fatigue*, Volume 25, Issues 9-11, September-November 2003, Pages 899-914.

[5] Vibhor Chaswal, G. Sasikala, S.K. Ray, S.L. Mannan, Baldev Raj, "Fatigue crack growth mechanism in aged 9Cr–1Mo steel: threshold and Paris regimes", *Materials Science and Engineering A*, Volume 395, Issues 1-2, 25 March 2005, Pages 251-264.

[6] L. W. Tsay, Y. C. Liu, M. C. Young, D. -Y. Lin, "Fatigue crack growth of AISI 304 stainless steel welds in air and hydrogen", *Materials Science and Engineering A*, Volume 374, Issues 1-2, 15 June 2004, Pages 204-210.

[7] P. Nagapadmaja, V. Kalyanaraman, S.R. Satish Kumar, B.N. Rao, "Fatigue crack propagation analysis of surface cracks in pipe elbows", *International Journal of Fatigue*, Volume 30, Issue 4, April 2008, Pages 734-744.

[8] Cruse TA, Besuner PM. *J Aircraft* 1975;12(4):369–75.

[9] Bhargava R.Y., V. Bhasin, H.S. Kushwaha, "Assuring It is safe", *International conference on Integrating Structural Integrity, Inspection, Monitoring, Safety and Risk Assessment*, Institution of Mechanical Engineers, U.K., May 1998.

[10] F.P. Brennan, S.S. Ngiam, S.S. Ngiam, "An experimental and analytical study of fatigue crack shape control by cold working", *Engineering Fracture Mechanics*, 75 (2008) 355–363.

[11]P. Nagapadmaja, V. Kalyanaraman, S.R. Satish Kumar, P. Chellapandi, "Experimental study on LBB behaviour of LMFBR pipe elbows", *International Journal of Fatigue*, 30 (2008) 574–584.

[12]S. BHANDARI, M. FORTMANN, L. GRUETER, J. HELIOT, P. MEYER, B. PERCIE DU SERT, A. PRADO and H. ZEIBIG, CRACK PROPAGATION IN A LMFBR ELBOW, Nuclear Engineering and Design 91 (1986) 107-119.

[13] Rules for in-service inspection of nuclear power plant components. ASME Boiler and Pressure Vessel Code, Section XI, New York;2001.

[14]A16 guide of RCC-MR for defect assessment and leak before break analysis. Edition 2002.

[15]Tzu-Yin (Jean) Hsua, Zhirui Wanga, "Fatigue crack initiation at notch root under compressive cyclic loading", *Procedia Engineering* 2 (2010) 91–100

[16]Wu-yang Chu, Chin Mei Hsiao, Liun-Jiang Jin, Tian-Hua Liu,"FATIGUE CRACK INITIATION FROM A NOTCH TIP UNDER A CYCLIC COMPRESSIVE LOAD", *Scripts METALLURGICA*, Vol. 17, p p . 993-990, 1983