Experimental and Analytical Studies on Fatigue Crack Growth and Fracture Behaviour of Carbon Steel elbows

P.K.Singh[1], K.K.Vaze[1], H.S.Kushwaha[1], D.M.Pukazhendi,[2] S.Seetharaman[2], D.S.R. Murthy[2]

1. Bhabha Atomic Research Centre, Mumbai-400085, INDIA
2. Structural Engineering Research Centre, Chennai-600113, INDIA

Abstract: *Experimental and analytical investigation has been carried out for crack initiation, crack growth and the fracture behavior of notched elbows to demonstrate the Leak-Before-Break (LBB) concept design criteria for the high energy piping system of Nuclear Power Plants. The tests have been carried out on 90^o large radius elbows of 219 mm outer diameter and 15.1 mm nominal thickness with a notch at locations such as crown, intrados and without notch. Initiation of crack has been observed from both the surface of wall thickness at the crown of the elbow. Number of cycles for crack initiation obtained experimentally and analytically have been found to compare well. Crack growth and number of cycles have been obtained experimentally and analytically for a/t <0.6 by evaluating stress intensity factor at the crack tip and the Paris constants obtained from the specimen test. Analytically and experimentally obtained crack growth has been found to compare well. Net section collapse has been found to be dominant failure mode under monotonic loading in the elbow having through wall crack at the crown.*

INTRODUCTION

Elbows in the piping system increases the flexibility and helps in reduction of the reaction forces and moments within the system by virtue of their elastic deformation. Now a days safe design criteria such as Leak-Before-Break (LBB) based on fracture mechanics concept is being adopted which requires the demonstration of integrity of the piping system by showing that unstable crack growth should not occur before crack penetrates the wall thickness, nor should it occur for through-wall leakage size flaw [1]. The demonstration of LBB design criteria of the piping components requires information on the size of initial defect, initiation of crack from the inherent defect, subsequent propagation rate of the initiated crack till the crack penetrates the wall thickness under fatigue loading and stable crack growth of the through wall cracked pipe till the acceptable leakage size flaw under monotonic or cyclic loading. Therefore, various tests have been conducted for the determination of fatigue crack initiation, fatigue crack growth and the behavior of cracked component under monotonic loading.

EXPERIMENTAL DETAILS

The chemical composition and tensile properties of the material have been shown in tables 1 and 2 [2].

Table 1: Chemical composition (in weight %).

C	Mn	Si	P	S	Al	Cr	Ni	V	N
0.14	0.9	0.25	0.016	0.018	<0.1	0.08	0.05	<0.01	0.01

Table 2: Room temperature tensile properties.

Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	% Elongation
302	450	36.7

Cyclic stress strain curve obtained by fitting the data points is given below:

$$\Delta\varepsilon/2 = 100/E \times (\Delta\sigma/2) + (\Delta\sigma/581.04)^{1/0.168} \qquad (1)$$

Low cycle fatigue curve obtained by fitting the data points is given below:

$$\Delta\varepsilon/2 = 58606/E\ (2N_i)^{-0.0757} + 24.06\ (2N_i)^{-0.4814} \qquad (2)$$

Where $\Delta\varepsilon$ is in % and $\Delta\sigma$ in MPa, N_I is number of cycles, E is Modulus of Elasticity in MPa.

Paris law constants in fatigue crack growth rate equation have been obtained from specimen test as per ASTM E647 [3]. The Paris law equation is given below, where da/dN is in mm/cycle and ΔK is in MPa$\sqrt{m}$.

$$da/dN = 3.807 \times 10^{-12}\ (\Delta K)^{3.03445} \quad \text{for } R=0.1 \qquad (3)$$

90^o short radius elbows of 219 mm outer diameter and 15.1 mm nominal thickness of piping system in Indian PHWRs have been used for tests. The details of the notch dimension have been shown in table 3

Table 3: Details of the loading and notch dimensions in the elbows.

Test no.	t mm	2C mm	a mm	P_{max} (KN)	R	Type of Moment	Notch location
ESCBC8-1	15.58	80	2.0	-150	0.1	Closing	Both crown
EWC8-2	15.38	-	-	-120	0.1	Closing	No notch
ESCC8-3	15.12	87	2.0	-150	0.1	Closing	One crown
ESCI8-4	15.38	106	4.0	+80	0.1	Opening	Intrados

t - Nominal thickness, 2C - Initial crack length, a - Initial crack depth, P_{max} - Maximum load, R - load ratio

Tests have been conducted in three stages. In first stage, the elbow has been loaded monotonically to obtain the stresses at various locations of the elbow. In second stage, the elbow has loaded under constant amplitude cyclic loading till the crack has penetrated through wall. In third stage, through wall cracked elbow has been subjected to monotonic load till the failure of the elbow.

Fatigue crack growth tests have been carried out at room temperature and air environment under load control mode using sinusoidal waveform loading. The constant amplitude method with stress ratio of 0.1 and the frequency of 0.1 Hz has been followed during the test. Through wall cracked elbow has been subjected to monotonic loading under displacement control mode with the displacement rate 2.16 mm/min.

RESULTS AND DISCUSSIONS

Static test

The stresses obtained at various locations along the circumference at 45^o to the elbow axis such as crowns or flanks, intrados and extrados are given in table 4.

Table 4: Principal stresses at various locations measured by strain gauges

Test no.	Load (KN)	Intrados (MPa)		Extrados (MPa)		Crown 1 (MPa)		Crown 2 (MPa)	
		σ_1	σ_2	σ_1	σ_2	σ_1	σ_2	σ_1	σ_2
ESCBC8-1	-150	-233	-781	-23	-247	428	343	431	315
EWC8-2	-98	-318	-335	-7	-167	294	203	292	77
ESCC8-3	-150	-423	-502	-11	-220	334	300	-	-
ESCI8-4	+100	269	141	177	6.12	-191	-252	-10	-80

Fatigue Crack Initiation

Minimum surface crack depth of 0.1 mm was possible to measure by Micro-gauge. Therefore, initiation of crack has been assumed when crack has grown by 0.1 mm. Cycles for crack initiation have been given in table 5. Initiation of crack in healthy elbow was detected by scanning the highly stressed regions of the elbow. It has been observed that crack initiated from the inside as well as outside surface of the wall thickness at the crown. Crack initiated at several locations along the longitudinal axis subsequently they merge to form single crack. Initiation of crack in the elbow having notch at the outer surface of the crown was detected at the notch tip and also from the inside surface of the wall thickness opposite to the notch tip at several locations along the longitudinal axis. The similar behavior has been also observed for other elbows. Initiation of crack in the elbow having notch at the outer surface of the intrados was detected from the notch tip at maximum crack depth. Initiation of crack has been observed from the inside surface of the crown although, the nature of stress is compressive for closing moment. The absolute magnitude of stress at the inside surface is more than that of outside surface as per the stress analysis carried out [4]. The phenomena of initiation of crack from the region of compressive stress may be due to the fact that initiation of crack is a local phenomena and depends on the development of slip planes in the material due to plastic straining. These slip planes can be formed under compressive or tensile stress. These slip planes coincide with the maximum shear stress and become the source of crack initiation site when subjected to tensile stress.

Table 5: Cycles for crack initiation and the crack to grow through-wall

Test no.	Cycles for crack initiation		Cycles for through wall (experimental)
	Experimental	Analytical	
EWC8-2	249000	240180	400000
ESCC8-3	2000	2556	64100
ESCI8-4	8000	13629	147000

Markl et al. [5], Heald and Kiss [6], Kussamaul [7] have found that for in plane bending condition under pressurized or unpressurized condition failure of the elbow started at the crown and progressed longitudinally. In some cases crack has been found at both surfaces. Shimakawa [8] and Sakakibara [9] has similar observation of crack initiation from both the surfaces and subsequently joins to form through thickness crack.

The fatigue crack initiation analysis involves evaluation of strain range and number of cycles. Strain range has been evaluated using Creager formula [10]. It has been assumed that the state of stress is plane 2D type. For the notch having tip radius, ρ and the remote stress range, $\Delta\sigma^0$, the approximate value of maximum pseudo elastic stress range $\Delta\sigma^{pe}$, at any distance, d (known as characteristic distance) from the notch tip, $r = d + \rho/2$ (ρ = 100 μm and d=70 μm for present case) can be evaluated by creager formula given below:

$$\Delta\sigma^{pe} = (\Delta K / \sqrt{2\pi\, r}) \times (1.0 + \rho/2r) \quad (4)$$

$$\Delta K = (\Delta\sigma_m . M_m + \Delta\sigma_b . M_b)\sqrt{\pi a} \times F_G \quad (5)$$

$\Delta\sigma_m$ is Membrane stress range, M_m is Correction factor for membrane stress $\Delta\sigma_b$ is Bending stress, M_b is Correction factor for bending stress, a is depth of the notch, F_G is Geometry factor [11]. After evaluation of $\Delta\sigma^{pe}$, the pseudo elastic stain range has been evaluated by equation given below:

$$\Delta\varepsilon^{pe} = \Delta\sigma^{pe} \times [\, 2(1 + \mu)/3] \quad (6)$$

where μ is the poisson ratio =0.3. Knowing the cyclic stress-strain equation and pseudo elastic strain range, the total strain range has been evaluated using Neuber’s rule [10]. The number of cycles to crack initiation have been evaluated using fatigue life curve equation (2) and are given in table 5

Experimental and analytical results shown in table 5 for the elbows has been found to be in good agreement. Differences in the experimental and analytical results may be due to the various assumptions.

Fatigue Crack Growth

Crack growth in healthy elbow has been observed from the inside as well as outside surface of the crown and is shown in figure 3. Crack growth from the inside and outside surface has been observed till the a/t=0.35 and a/t=0.6 respectively. Crack from the inside and outside surface coalesced to form a through wall crack. The crack growth from the inner and outer surface has been shown in figure 2. The crack length at the outer and inner surface of the elbow at the time of through wall have been shown in table 6. Crack growth in the elbow having notch at the outer surface of the crown has also been observed from the inside as well as outside surface and is shown in figure 4. The relation between crack growth rate and crack depth has been shown in figure 5. Crack growth rate remains almost constant for the growth of crack from outside surface till a/t =0.5. Fatigue crack growth rate in the elbow having notch at one side of the crown has been found to be higher than that having notch at both side of the crown. This can be inferred from figure 6. Crack growth in the elbow having notch at the intrados has been observed from the notch tip in thickness as well as in circumferential direction and is shown in figure 7. In all the cases, crack growth from the outer surface has been observed till a/t = 0.6 and is almost constant. This may be due to the fact that stress intensity factor which is the driving force for the growth of crack does not vary significantly. Crack grows from the inside surface, although nature of stress is compressive for closing moment. This may be due to the fact that the stress range magnitude is more than that of the outer surface which helps in formation of slip planes due to the shear stress. Due to cyclic nature of stress, there is weakening of the material at the crack initiation sites and crack grows. Since there is no tensile stress available for the crack to open, crack growth is due to shear stress only. The rate of crack growth from inner surface has been observed to be slower that that of the outer surface.

Table 6: Details of the crack length and depth at the time of through wall

Test no.	Inner surface		Outer surface		Notch location
	2C (mm)	a (mm)	2C (mm)	a (mm)	
ESCBC8-1	100	5.5	103	13.0	Both crown
EWC8-2	120	6.5	140	13.5	No notch
ESCC8-3	95	5.0	130	13	One crown
ESCI8-4	70	0	173	19	Intrados

2C- Crack length, a - Crack depth

Fatigue crack growth analysis has been carried out based on the Paris law. Stress intensity factor range [11] has been calculated as per the equation 5. Maximum crack depth and number of cycles calculated analytically using constants C and m in Paris equation obtained from the TPB specimens have been shown in figures 4 and 7. The results for the crack growth in thickness direction have been observed to be in good agreement till a/t= 0.8 for the elbow having crack at the intrados and a/t=0.6 for crown crack.

Behavior of Cracked elbow under monotonic loading

Load–Load line displacement (LLD) plot for the tests have been shown in figure 8. It has been observed that the elbow subjected to more number of loading cycles prior to fracture test attains the maximum load earlier than those subjected to less number of loading cycles. It can be seen from figure 6 that elbow subjected to 400,000 cycles, with maximum principal stress 294 MPa, attains maximum load at LLD of 20 mm whereas elbow subjected to loading cycles 97000, with maximum principal stress 455 MPa attains maximum load at LLD of 39 mm during monotonic loading. Maximum load and corresponding displacement for each elbow have been shown in table 7. Similar observation has been seen for CMOD and angular rotation also. No crack growth has been observed during monotonic loading before attainment of maximum load for the elbow having through wall crack at the crown. It can be said that net section collapse is the governing mode of failure of the elbow.

Table 7: Details of the parameters during monotonic loading

Test no.	Max. load KN (1)	Load ratio (1)	Number of cycles (1)	LLD mm (2)	Angular rotation (^{o}) (2)	COD (mm) (2)	Experim-ental load KN (3)
ESCBC8-1	150	0.1	97000	37.9	2.52	0.730	150.87
EWC8-2	120	0.1	400000	20.1	1.90	0.442	132.85
ESCC8-3	150	0.1	64100	39.8	2.46	0.951	131.69
ESCI8-4	80	0.1	147000	148	9.25	24.0	180.8

(1) Test Parameters during fatigue test prior to fracture test
(2) Parameters at maximum load during fracture test
(3) Experimental Maximum load sustained by the elbow

CONCLUSIONS

1. Fatigue crack initiation has been observed from the inside as well as outside surface of the crown region of the elbow irrespective of the nature of stress (i.e. tensile or compressive).
2. Fatigue crack growth has been observed from the inside as well as outside surface of the crown region of the elbow. Crack growth from the outer surface in thickness direction is faster than those from the inside surface. The elbow having notch at the intrados grows from inside to the outside surface similar to pipe.
3. There is no crack growth under monotonic loading for the elbow having through wall crack at the crown. Failure of the elbow has been observed by net section collapse. Load carrying capacity of the elbow depends on the prior load histories to which it has been subjected.

References

1. Report of USNRC piping review committee, NUREG 1061, Vol.3, USNRC, Washington DC.

2. Singh P.K., Chattopadhyay, Kushwaha H.S., Tarafder S., Ranganath V.R., (1998), International Journal of Pressure Vessel and Piping 75 271-280.
3. E647-93, 1995, Annual book of ASTM standard, vol. 03.01, pp 569-596.
4. Shah V.N., Ware Arthur G., (1994), ASME PVP, Vol. 286,.
5. Markl A.R.C, (1947), Transaction of ASME November, pp 869-879.
6. Heald J.D., Kiss E., (1974), ASME Journal of Pressure Vessel Technology, pp 171-176.
7. Kussaumal K., (1989), Third international Conference on Biaxial /Multiaxial fatigue, stuttgart, Germany.
8. Shimakawa T, Takahashi H., Doi, H, Watashi, K, Asada, Y, (1993), Nuclear Engineering Design, Vol. 139
9. Sakakibara Y., Imazu A., Nagata T., Okabayashi K., International conference on Structural Mechanics in Reactor Technology, pp E 7/3.
10. Kassir M.K., Park Y.J., Hofmayer C.H., Badyopadhyay K.K., Shteyngart S., NUREG/CR-6078, BNL-NUREG-52383, USNRC, Washington DC 20555-0001.
11. ASME Boiler and Pressure Vessel Code, (1989) Section XI, New York.

Fig 1: Experimental set up for fatigue and fracture test

Fig 2: Fracture surface of fatigue tested elbow

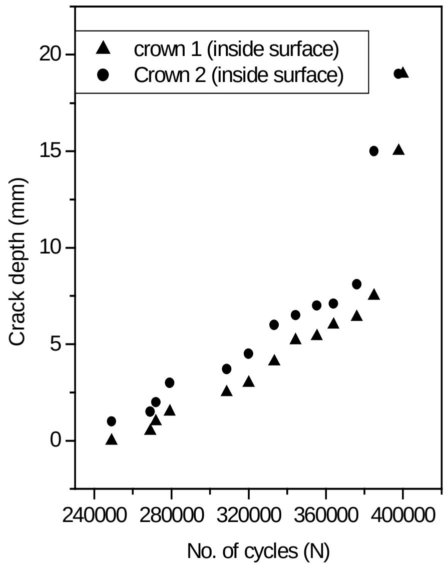

Figure 3:Crcak growth in healthy elbow from inside surface of the crown

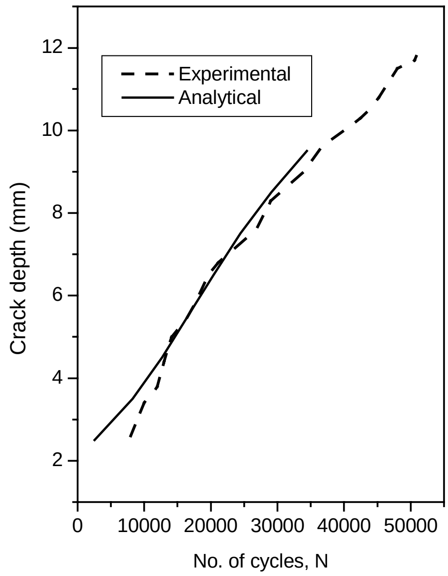

Figure 4:Comparison of experimental and analytical results for crown crack elbow

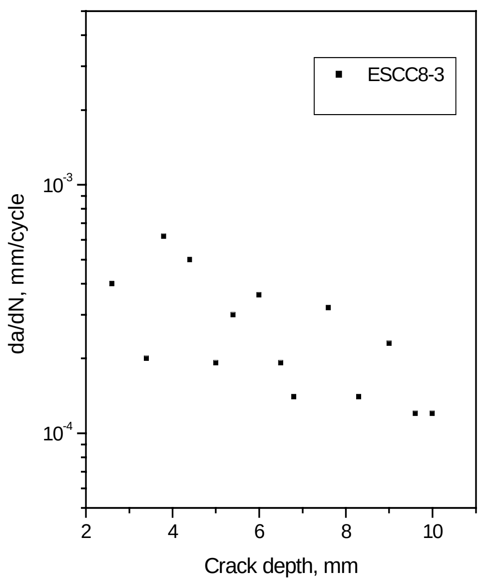

Figure 5 :Relation between crack growth rate and crack depth

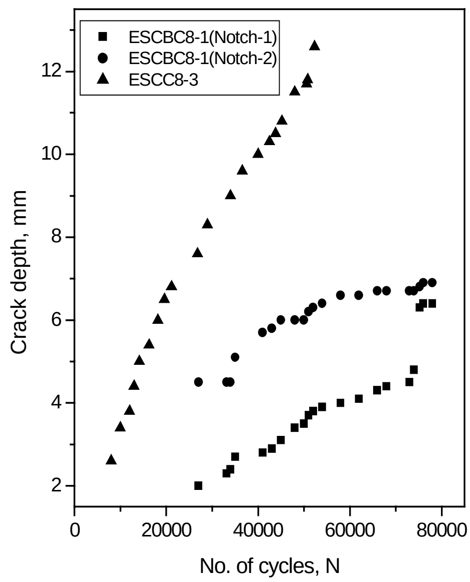

Figure 6: Comparison of crack depth and Number of cycles (experimental) for specimens having crack at the crowns

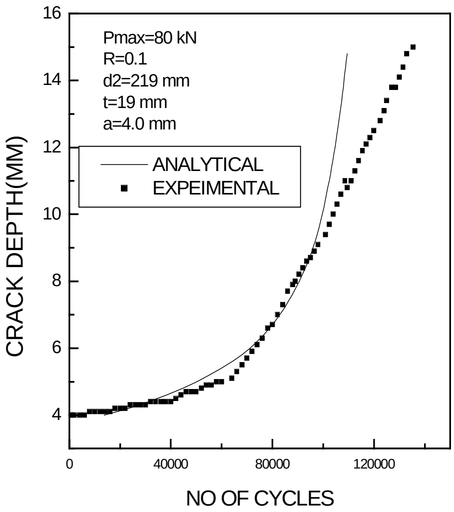

Figure 7: Comparison of analytical and experimentalresults for crack at Intrados

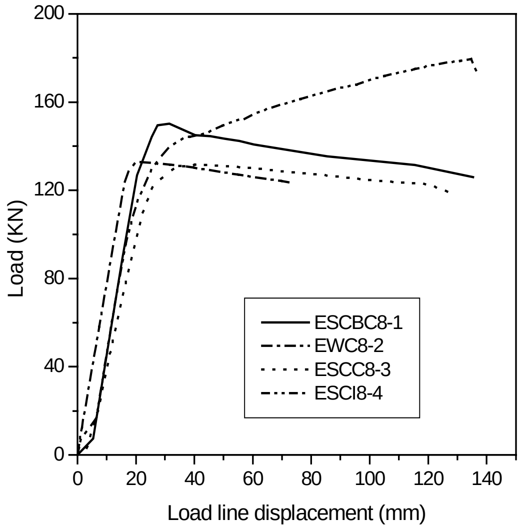

Figure 8: Comparson of load and load line displacement under monotonic loading

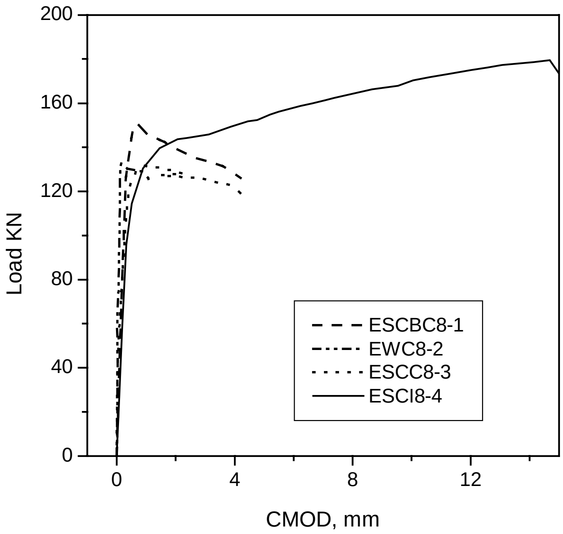

Figure 9: Comparison of Load and CMOD of elbows under monotonic loading