Fatigue Crack Propagation behavior analysis of SA333 Gr.6 carbon steel material piping component a Comparative analysis

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Abstract:

In the present investigation, the fatigue crack growth behaviour of surface cracked piping component is analysis by using linear elastic fracture mechanics principles. The present analysis focuses the crack propagation behavior in both direction length as well as depth direction of the selected pipe specimen. He stresses intensity factors solution available in the literature (ASM, M-Bergman) is evaluated and compares them. The crack growth behaviour of the component using the specimen tested material data prediction is carryout using proposed approach. The present work has been carried out on SA333Gr.6 carbon steel pipe PBSC8-1 dimensions shown in table 3.1. The SIF position, crack length, cumulative life cycle is analysis.

1. Introduction:

The safety of nuclear reactors has always engaged the attention of designer. The nuclear reactor is the important part of nuclear plant in which large amount of heat energy is transferred then nuclear reaction takes place. A failure in the piping could lead to loss of fluid (i.e. steam, heavy water and other nuclear fuels), accidents and many leads to the release of radioactive materials. The financial losses due to the down time of the power plant have been expressed in the millions of dollars. Therefore, the assessment of the remaining life of the piping component under fatigue loading is important to be determined for the safety of power plants.

2. Methodology:

With the use of crack growth laws it is possible to predict the life of the piping components subjected to fatigue for a structure under repeating load. The crack growth rate can be related to the variation of Stress Intensity Factor (SIF) ΔK, during the lead cycle ΔK considerable influence an fatigue crack growth and if ΔK remains constant Paris has expressed the relationship between crack growth rate (da/dn) and ΔK in the following form .

$$da/ dN = C ((\Delta\ K_d)^m \qquad 2.1$$

Where C and M are material constant C & M are crack growth constant (Paris constant) depend upon material. And Δ K change in stress intensity factor $\Delta K = K_{max.} - K_{min}$, The K_{max} and $K_{min.}$ are the SIF value corresponding to the maximum and minimum stress level in fatigue load cycle. For the assume initial crack depth, the number of cycle required for the incremental increase in crack depth can be calculated as –

$$dN = da / C (\Delta K_d)^m \qquad 2.2$$

ΔK_d - SIF range at deepest point da = Assumed increase in crack depth.

The extension of crack length at the surface can be calculated by putting the numbers of cycle obtained from equation 2.1 is

$$dc = dn \times c\, (\Delta K_s)^{m} \qquad 2.3$$

Where dc = Extension of crack length and ΔK_s - SIF range at surface crack tip. The computation of crack propagation along the two directions has to be carried out simultaneously since 2.1 and 2.2 are not independent. Now the new dimension of the crack is calculated.

$$a_{New} = a_{old} + da \qquad 2.4$$

and $$2\,C_{New} = 2\,C_{old} + dc \qquad 2.5$$

The process is repeated until the crack reaches through - thickness or K reaches Kc, either at the surface or depth point. for every incremental increase in the crack depth, the life cycle are calculated using 2.2 and added upto through the thickness K reaches Kc to give the total life of the piping components correspondent thickness crack. For calculation of SIF, By using fracture mechanics approach to fatigue analyses.

SIF is measure if the stress surrounding the crack tip of a body and is –

$$K = f \times \sigma_b \times (\pi\, a)^{0.5} \qquad 2.6$$

Where f is the function that depend on the geometry of the crack and cracked part under consideration. A is the crack size and σ_b is the nominal stress action normal to the crack.

The geometry factor f find from ASM E - 647 and data book with the help of experimental tested solution available different problem. If the value of bending stress (σ_b) is more then 30 to 40 % yield strength of material (σ_y) in such a case i.e. pipe 8-1, σ_b = 158 MPa and yield strength of (SA333Gr.6 grade) steel 302 MPa. The $a_{ffective}$ crack depth is :

$$a_{eff.} = a + 1/3\,\pi\, (k_d / \sigma_y)^2 \qquad 2.7$$

$$2_{ceff} = 2c + 2/3\,\pi\, (\Delta k_s / \sigma_y)^2 \qquad 2.8$$

The process is repeated until the crack reaches through-thickness or *K* reaches fracture toughness of the material. For every incremental increase in crack depth, the life cycles are calculated using Eqn. 2.3 and added up-to through-thickness, to give the total life of the piping component corresponding to through-thickness crack.

3. Dimension and Material Properties (Pipe case PBSC 8-1):

Present work selected Pipe case PBSC 8-1 for the analysis its dimensions and material properties are shown in table 3.1 and 3.2 respectively.

Table - 3.1 Details of the experimental results of surface cracked pipe

S.No	Notch location	Outer diameter (mm)	Thickness t (mm)	Outer Span (mm)	Inner span (mm)	Load (KN)		Stress Range (MPa)	Crack Length (2C) mm	Crack Depth (a) mm	Through wall crack cycles	Accept ratio 2 C/a at through wall
						Max	Min					
PBSC 8-1	Base metal	219	15.58	2500	80	200	20	158	114.3	2.01	220000	7.3

3.2 Tensile Properties of pipe base material at room temperature:

Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation %	Percentage reduction in area	Young's Modulus (GPa)	Poisson's Ratio
302	450	36.7	72.96	203	0.3

Table 3.3 Paris constant values for the material studied

Pipe case	Stress ratio	Notch location	Paris constant	
			C (mm)	m
406mm pipe	**0.1**	**Base**	**8.87×10^{-10}**	**3.80**
219mm pipe	0.1	Base	3.807×10^{-9}	3.034

4. FEM analysis Data:
Table 4. Comparative results of spur gear assembly for design-1

Torque N/mm²	Vonmises stress MPa	Min. Life Cycle	Safety Factor	Max Life Cycle	Hysteresis Stress MPa	Hysteresis Strain mm/mm	Contact Pressure MPa	Penetration mm
350	919.99	65861.0	0.1838	1.47E+6	389.18	0.0109	447.21	0.0188
400	1048.60	38734.0	0.1613	7.76E+5	408.74	0.0135	508.98	0.0214
450	1177.40	24439.0	0.1437	4.52E+5	426.53	0.0163	570.77	0.0240
500	1306.20	16270.0	0.1295	2.83E+5	442.92	0.0193	632.56	0.0266
550	1435.10	11301.0	0.1179	1.87E+5	458.16	0.0225	694.36	0.0290
600	1564.20	8123.6	0.1081	1.30E+5	472.42	0.0259	756.17	0.0318

5. LEFM Analysis:

The Stress Intensity Factor (SIF) solution (ASM and Bergman) available in the literature, the extreme point SIFs (depth and surface) are determined at initial crack depth of 2.10 mm for the pipe case PBSC 8-1**.** The yield strength for the material is 302MPa. In this case, the applied nominal stress range is 158 MPa, which is 0.52 times the yield strength of the material. Therefore, for the particular case the plastic zone correction is applied.

Table 5.1 Predicted results using ASM SIF solution for pipe case PBSC 8-1

Crack size a (mm)	Length of span 2C (mm)	Effective crack length a_f (mm)	Effective Crack length 2 C_{eff} (mm)	a_{eff}/t	2 C_{eff} / a_{eff}	K_s MPa $\sqrt{m}$	K_d MPa $\sqrt{m}$	$K_{s(eff)}$ MPa $\sqrt{m}$	$K_{d(eff)}$ MPa $\sqrt{m}$	dN	Cumulative dN
2.10	114.3	2.26	112.52	0.145	50.67	9.685	14.664	10.47	15.615		
4.79	115.26	5.279	116.72	0.33	21.91	13.95	21.14	15.1138	22.334	156079	156079
7.72	116.48	8.65	118.46	0.55	13.58	20.6	27.359	18.35	26.67	54036	210115
10.22	118.27	12.23	120.53	0.78	9.77	23.38	30.46	24.5	36.41	31000	241115
15.88		15.58	121.20	1	7.71					11474	252859

Table 5.2 Predicted results using Bergman solution for pipe case PBSC 8-1

a (mm)	2c (mm)	a_{eff} (mm)	2 c_{eff} (mm)	a_{eff}/t	2 c_{eff} / a_{eff}	K_s MPa $\sqrt{m}$	K_d MPa $\sqrt{m}$	$K_{s(eff)}$ MPa $\sqrt{m}$	$K_{d(eff)}$ MPa $\sqrt{m}$	dN	Cumulative dN
2.10	114.3	2.271	114.30	0.145	50.33	1.10	14.68	1.71	15.86		
4.79	115.26	5.556	114.40	0.356	20.59	6.46	26.11	7.818	29.22	155232	155232
7.72	116.48	12.73	114.77	0.817	9.01	12.5	63.41	26.6	54.73	24463	179695
10.22	118.27	15.58	114.91	1	7.37					1806	181501

a - Crack size, 2C - Crack length, a_{eff} - effective crack depth, $2C_{eff}$ - effective crack length, a_{eff}/t - crack depth/thickness, K_s - stress intensity factor for surface, K_d - stress intensity factor in depth, $K_{s(eff)}$ - effective stress intensity factor for surface, $K_{d(eff)}$ - effective stress intensity factor in depth, dN – number of fatigue cycles . From Fig. 5.1, it can be seen that in PBSC 8-1 pipe using Bergman solution the SIF results at the deepest point is higher as compare to ASM solution. It can also be observed that Bergman solution predicted lower value of surface SIF as compared to ASM solution.

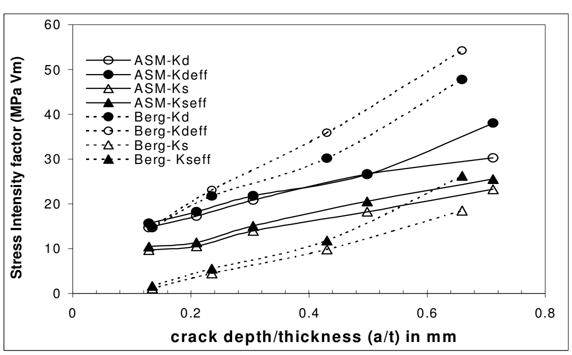

Fig. 5.1 SIF range with crack depth

Fig. 5.2 showed the comparison of predicted crack growth behaviour with experimental results. It can be seen that the crack growth behaviour predicted by ASM SIF solution over predicts (12.9%) the experimentally determined crack growth behaviour of the component. In the present case it can also be observed that Bergman SIF solution under predicts (21.22%) the fatigue crack growth life of the component.

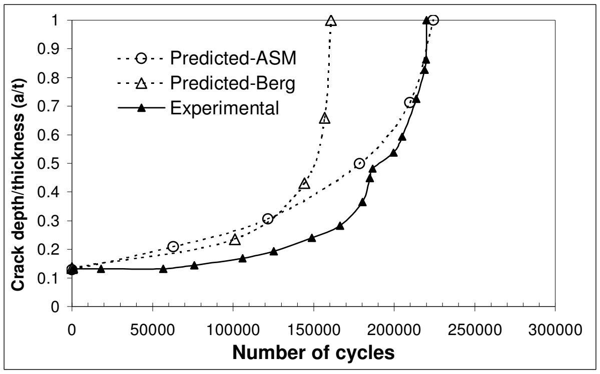

Fig. 5.2 Crack depth/thickness with cycles

The comparison of predicted and experimentally determined increase in length on the outer diameter of the pipe surface is shown in Fig. 5.3 for the pipe case PBSC 8-1. In this case, it can be seen that the increase in crack length during the process when surface crack becomes through-wall is negligible. The increase in crack length predicted by Bergman SIF solution (0.53% over prediction) is better than that predicted by ASM solution (5.1% over prediction).

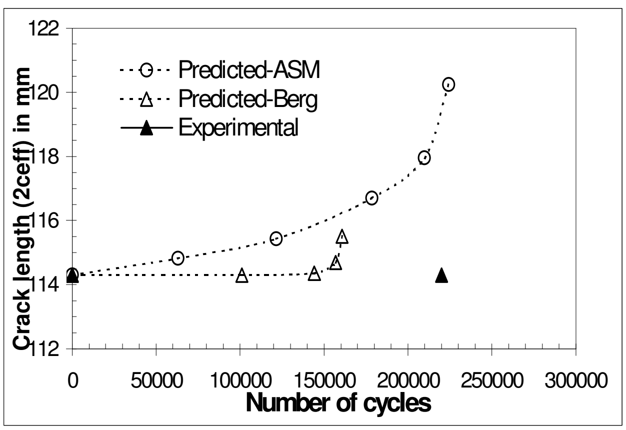

Fig. 5.3 Crack length with fatigue cycles

In case of pipe PBSC 8-1, the variation in aspect ratio of crack profile under fatigue loading is shown in Fig. 5.4. It can be appreciated that ASM SIF solution better connects the two experimental points.

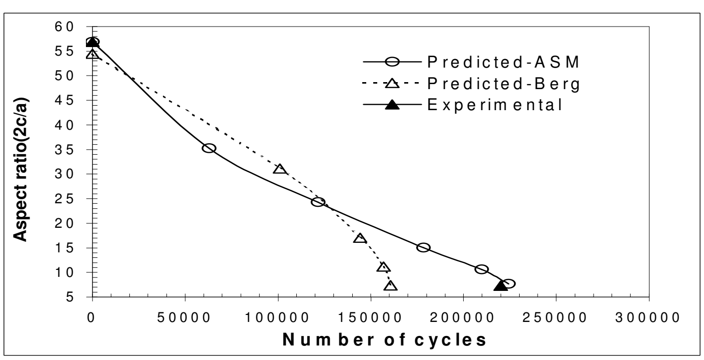

Fig. 5.4 Aspect ratio with cycle

The variation of aspect ratios with the increase in crack depth has been shown in Fig. 5.5 for the pipe case PBSC 8-1. It can be seen that the two SIF solutions predicts well the results as shown in figure.

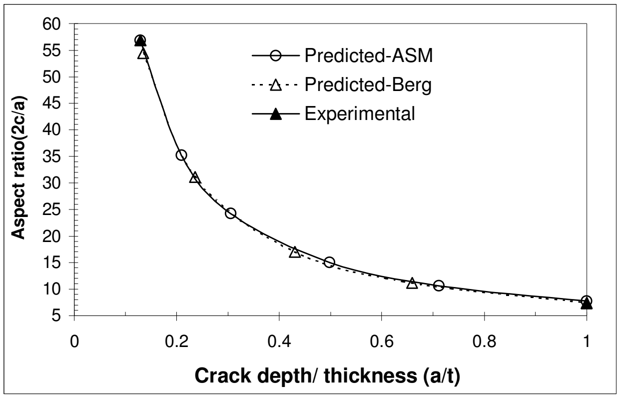

Fig. 5.5 Aspect ratio with crack depth

6. Results and discussion:

6.1 The depth position SIF position prediction by ASM solution is lower than that predicted by Bergman SIF solution

Pipe case	Predicting surface SIF value		Predicting depth SIF value	
	ASM Result	Bergman Result	ASM	Bergman
PBSC 8-1	Higher	Lower	Lower	Higher

6.2. **Comparison of final fatigue cycle:**

The comparison of fatigue cycle at through-thickness crack depth is given in below

Comparison of predicted with experiments results for final fatigue cycle

Pipe case	Experimental	Prediction method		% error	
		ASM	Bergman	ASM	Bergman
PBSC 8-1	220000	252859	181501	-12.9%	+21.22%

Note: + tive sign Under prediction; - tive sign Over prediction

6.3 Comparison of final crack length: Comparison of predicted with experiments results for final crack length:

Pipe case	Experimental	Prediction method		% error	
		ASM	Bergman	ASM	Bergman
PBSC 8-1	114.3	121.22	114.91	-5.70%	-0.522%

7. Conclusion: Concluded remark shown in the table below

It is analysis that in the depth direction SIF position prediction by ASM solution is lower than that predicted by Bergman SIF solution. Similarly, the surface position SIF solution predicted by Bergman solution is lower as compared to ASM solution. It can be concluded that in the present case these SIF solutions are not suitable to predict the fatigue crack growth life of the component hence analysis value of SIF are over predicted.

Case	Parameter	ASM- solution	Bergman- Solution	Conclusion
PBSC- 8-1	Fatigue cycles	Over predicts but compared well	Under predicted	ASM -better
	Crack length (2C)	Over predicted	Compares well	Bergman - better

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