FATIGUE CRACK GROWTH OF CCT SPECIMEN UNDER SPECTRUM LOADING OF A STEAM LINE

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ABSTRACT

As part of failure analysis for a high temperature and pressure steam line this paper presents a study on fatigue crack growth of center–cracked tension(CCT) specimen to which 17–block spectrum loading is applied.Generalized Willenborg model was chosen to evaluate the overload retardation effect of crack growth under the spectrum loading with high–low load sequences.To verify the calculated fatigue crack growth life, three CCT specimens were tested by using MTS 810 System. The test data agreed well with the calculated life.

KEYWORDS

Spectrum loading, CCT specimen, overload retardation effect, retardation model, fatigue crack growth life

INTRODUCTION

Having investigated a failure of a high temperature and pressure steam line at a large petro–chemical corporation in China, it is found that several circumferential cracks among the butt welding of an eccentric reducer causes leaks. The first thing has been done is to carry out stress analysis for the welding zone of the reducer among which cracks are located. From the stress analysis it is quite clear that temperature is a dominant load other than pressure to produce axial force that exerts on the welding zone.

In order to obtain temperature fluctuations of the line in service about 20,000 data were collected from which temperature load spectrum was compiled by the method commonly used in the aerospace and automotive industries. Furthermore, 17–block load spectrum for CCT specimen was converted from it.

Based on the 17–block load spectrum, this paper has completed the following tasks: (1) to calculate fatigue crack growth life by employing Generalized Willenborg model,(2) to carry out crack growth test under both constant and spectrum loading, and (3) to give a comparison between calculated value and test data.

TEMPERATURE LOAD SPECTRUM AND 17–BLOCK LOAD SPECTRUM

This steam line is under operation with working conditions of temperature, 530℃,and pressure, 12 MPa. A computer,PDP–11, was placed at central control room to record hourly temperature fluctuations for more than two years, giving a total of about 20,000 random readings.

In evaluating the data the authors deleted a temperature reading when its value differed from proceeding temperature by less than 1.1 percent of the temperature amplitude of the start–up and shut–down.

The cycles were counted by the rainflow method (ASTM E1049–85) and grouped in intervals of temperature amplitude and mean temperature as listed in Tab. 1.

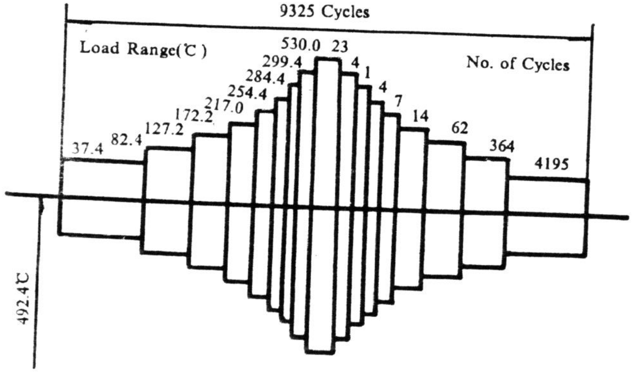

Fig.1 17–block temperature load spectrum

In considering experiences and special operating conditions for compiling load spectrum of pressure vessels and process equipment proposed by Cheng et al (1986,1990a,b),[9] 17–block temperature load spectrum was established which involved all cycles of start–up and shut–down as well as temperature fluctuations in the line. The spectrum can reflect the real temperature load in service, as shown in Fig. 1.

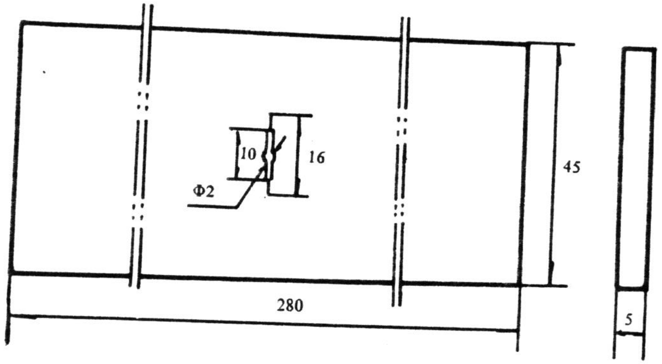

Fig.2 Center–cracked–tension (CCT) specimen

Table 1. Temperature amplitude and mean temperature of the line, after rainflow counting

Temperature amplitude interval (℃)	Mean temperature interval (℃) 417.6 to 446.9	446.9 to 476.3	476.3 to 505.6	505.6 to 535.0	Total No. of cycles	Frequency (percent)	Cumulative frequency (percent)
3.0 to 7.9	2	161	208	0	371	59.65	99.51
7.9 to 12.8	0	60	58	0	118	18.97	39.86
12.8 to 17.7	0	28	24	0	52	8.36	20.89
17.7 to 22.6	0	13	12	0	25	4.02	12.53
22.6 to 27.5	1	15	8	0	24	3.86	8.51
27.5 to 32.3	0	4	2	0	6	0.96	4.65
32.3 to 37.2	0	7	0	0	7	1.13	3.69
37.2 to 42.1	0	3	3	0	6	0.96	2.56
42.1 to 47.0	1	1	1	0	3	0.48	1.6
47.0 to 51.9	0	2	0	0	2	0.32	1.12
51.9 to 56.8	1	1	0	0	2	0.32	0.80
56.8 to 61.7	1	0	0	0	1	0.16	0.48
61.7 to 66.6	0	0	0	0	0	0.00	0.32
66.6 to 71.5	0	0	0	0	0	0.00	0.32
71.5 to 76.4	1	0	0	0	1	0.16	0.32
76.4 to 81.2	1	0	0	0	1	0.16	0.16
No. of cycles	8	295	316	0	619	99.51	

EXPERIMENTAL WORK

The experimental work was carried out with CCT specimens 280 mm long, 45 mm wide, and 5 mm thick (Fig. 2) which are designed according to both Chinese National Standard GB 6398–86 and American Standard ASTM E647–86. The 10–mm–long cut was extended about 16.2 mm by fatigue precracking. The steel for the specimens was Chinese designation 12Cr1MoV piping steel having the following chemical composite in percentage: 0.12 C, 0.60 Mn, 0.27 Si, 1.1 Cr, 0.30 Mo, 0.23 V, less than 0.04 S, and less than 0.04 P. The mechanical properties of the steel were 330 MPa yield strength, 450 MPa tensile strength, and 20.9 percent elongation, which were tested using round specimen. Three CCT specimens also were tested under constant amplitude loading with 14.8 KN load amplitude and zero load ratio, from which the material constants of the steel for Paris formula can be obtained as: $c = 2.322 \times 10^{-16}$ and $n = 6.061$ when all quantities are substituted into ISO unit.

Table 2. 17–block load spectrum

Block no.	Normalized load amplitude	Load range (KN)	No. of cycles	Ratio of load	Mean load (KN)
1	0.125	0.75	4195	0.93	10.64
2	0.275	1.67	364	0.85	10.64
3	0.425	2.57	62	0.78	10.64
4	0.575	3.47	14	0.72	10.64
5	0.725	4.38	7	0.66	10.64
6	0.850	5.14	4	0.61	10.64
7	0.950	5.74	1	0.58	10.64
8	1.000	6.04	4	0.56	10.64
9		10.72	23	0.33	10.64

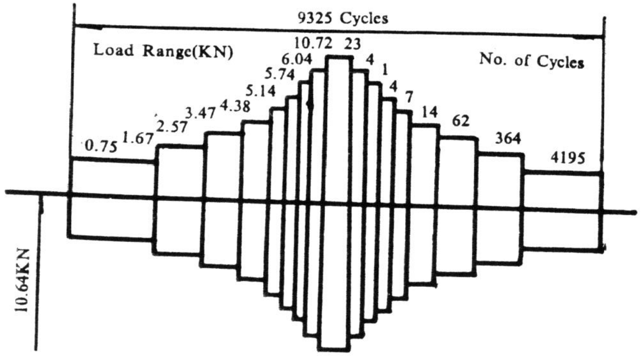

Fig. 3. 17–block load spectrum for CCT specimen

By using 17–block temperature load spectrum, 17–block load spectrum for CCT specimen was converted in proportion to temperature amplitude as shown in Fig. 3 and it can be utilized for calculation and testing herein.The load amplitude and cycles per block of the spectrum were given in Tab. 2.

Another three specimens, CCT4, CCT5, and CCT6, were subjected to 20 times repeating cycles of 17–block load spectrum. The crack growth for each specimen was measured and given in Tab. 3.

Table 3. Test data for CCT specimen

Specimen no.	CCT plate size (mm)		No. of blocks	Crack size (mm)			No. of applied spectra
	width	thickness		a_i	a_f	$\triangle a$	
CCT4	45.11	4.86	17	7.947	8.145	0.1980	20
CCT5	44.72	4.92	17	7.953	8.252	0.2985	20
CCT6	44.77	5.66	17	8.356	9.008	0.6524	20

CALCULATION OF CRACK GROWTH LIFE UNDER 17–BLOCK SPECTRUM LOADING

A few typical retardation models are practically used in engineering fields which are: Wheeler model (Wheeler,O.E.,1972), Willenborg model (Willenborg,J.,et al,1971), Matsuoka model (Matsuoka, S., 1979) and others. Generalized Willenborg model,proposed by Gallagher (1974), was based on the concept of yield–zone and it has been widely employed in aerospace industries in U.S.A.

Generalized Willenborg model was chosen to evaluate overload retardation effect for calculating crack growth life of CCT specimen subjected to 17–block spectrum loading shown in Fig. 3. All formulas dealing with the calculation of crack growth life under the spectrum loading are written as:

$$K = \frac{P}{B}\sqrt{\frac{\pi\alpha}{2W}\sec\frac{\pi\alpha}{2}} \tag{1}$$

in which

$$\alpha = \frac{2a}{W} \tag{2}$$

$$K_{max,eff} = K_{max} - \Phi\left[K_{max,ol}\left(1 - \frac{\triangle a}{Z_{ol}}\right)^{\frac{1}{2}} - K_{max}\right] \tag{3}$$

$$K_{min,eff} = K_{min} - \Phi\left[K_{max,ol}\left(1 - \frac{\triangle a}{Z_{ol}}\right)^{\frac{1}{2}} - K_{max}\right] \tag{4}$$

in which

$$\Phi = \frac{1 - \dfrac{\triangle K_{th}}{K_{max}}}{S - 1} \tag{5}$$

$$R_{eff} = \frac{K_{min,eff}}{K_{max,eff}} \tag{6}$$

$$Z_{ol} = \frac{1}{2\pi}\left(\frac{K_{max,ol}}{\sqrt{3}\,\sigma_b}\right)^2 \tag{7}$$

and

$$R_{eff} = 0 \quad , \qquad if \quad R_{eff} < 0$$

$$\frac{da}{dN} = c\left[(1 - R_{eff})^m * K_{max,eff}\right]^n \quad , \qquad if \quad R_{eff} > 0 \tag{8}$$

For 12Cr1MoV domestic piping steel, the material properties in all equations above were tested by authors unless quoted from related references, which are:

$\sigma_b = 48.1$ Mpa

m = 0.15 (Chang, J. B., et al, 1981)

c = $1.926065 * 10^{-16}$

n = 6.0613

S = 3 (Chang, J. B., et al, 1981)

$\triangle K_{th} = 2.2$ Mpa$\sqrt{m}$ (Sheng, Z. X., 1990)

With the model, crack growth life of three CCT specimens with individual sizes of initial and final crack was calculated. The values are listed in Table 4.

Table 4. Calculated value and test results for three CCT specimens under 17–block spectrum loading.

Specimen no.	No. of blocks	Crack growth(mm)	No. of applied spectra		Error (percent)
			Experiment	Calculation	
CCT4	17	0.1980	20	14.5	−27.5
CCT5	17	0.2985	20	21.5	7.5
CCT6	17	0.6524	20	26.5	32.5

To verify the accuracy of the calculation by the model, the test data also were compared with the calculated values, which are written in Table 4. The comparison shows that the average error for the three specimens is 22.5 percent and the maximum error of specimen CCT6 is just 32.5 percent, which means that the model chosen and the method employed as well as the test procedure are acceptable.

SUMMARY

1. The result of the study shows that fatigue crack growth for the pipe line subjected temperature loading should be evaluated according to variable amplitude load based on its expected service history. A constant amplitude fatigue design and safety assessment for a number of start–up and shut–down cycles is not adequate.
2. Generalized Willenborg model can be used to evaluate fatigue crack growth life under variable amplitude loading, especially under spectrum loading for the steam line.
3. Based on this study, a further investigation on failure analysis for an eccentric reducer of the line can be followed by using the same method proposed in this paper.

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