STUDY ON THE LOW CYCLE FATIGUE OF SUPER–HIGH PRESSURE VESSELS BY MEANS OF TENSION–TORSION TEST

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Third International Conference on Biaxial / Multiaxial Fatigue, April 3–6, 1989 Stuttgart, FRG

ABSTRACT

In this paper, stress state of thin wall tube sample under tension–torsion biaxial load and the stress state of thick wall tubular vessel under internal pressure were analysed and compared with each other. A new biaxial low cycle fatigue method of super–high pressure vessel that is based on the theory of principal stress–strain was proposed, in which internal pressure load was replaced by tension–torsion load and so that the test became much easier. By means of this method, low cycle fatigue of one kind of high pressure vessel steel 37CrNi3MoV was holded. Test results were compared with that of uniaxial test in the same steel.

INTRODUCTION

Fatigue of high pressure vessel is a very important aim of fatigue study. Many work have been done in this field. But researches on some vessels which undergo super–high internal pressure, such as linking tube of chemical reactor and gun tube etc. was rarely published. Main reason to it is that the fatigue machines can hardly simulate such load on the laboratory samples as to what the actual structures undergo in service, i.e. super high internal pressure. For example, the peak pressure reached by MTS 809 series machine is only 20.7 MPa, which is one grade lower than what we needed. In the laboratory such a high internal pressure is realized by means of using manual handed pressure pump, which is very slowly and unaccurately, so it cann't meet the need of fatigue test.

Fortunnately, load method is only the form, actual factor influencing fatigue characters of materials is the stress–strain state. Brown and Miller[1] proposed that maximum shear strain amplitude $\hat{\gamma}$ governed plastic deformation and thus, crack initiation, they postulated that

$$\hat{\gamma} + f(\varepsilon_n) = constant \qquad [1]$$

NOMENCLATURE

A	material coefficient
a	internal radius
B	coefficient of Bauschinger effect
b	external radius
c	fatigue plastic exponent
E	Young's modulus
G	modulus of rigidity
k,l,m,n	constants
l	fatigue crack length
N	fatigue life
P	pressure
r	radius
w	ratio of external radius to internal radius
γ	shear strain
ε	normal strain
μ	Poisson's ratio
σ	normal stress
τ	shear stress

SUPERSCRIPTS

w	work
R	residul

SUBSCRIPTS

a	actual
b	ultimate
eq	equal
e	elastic
m	mean
p	plastic
r	radial
s	yield
t	total, transversal
z	axial
1,2,3	principal values

Similarly, Socie, Wail and Dittmer[2] proposed a Manson–Coffin type equation to estimate fatigue life under biaxial loading by

$$\hat{\gamma}_p + \hat{\varepsilon}_{np} = 1.75\varepsilon_f'(2N_f)^c \qquad [2]$$

For crack propagation under biaxial loading, Moguerou et al[3] proposed that

$$\frac{dl}{dn} = A(\triangle\varepsilon_{Tresca} / 2)^m l^n \qquad [3]$$

From these published works mentioned above and not mentioned here, we can conclude that ε_1, ε_3 and ε_{eq} are the main factors governing biaxial low cycle fatigue life of materials. So we can propose reasonablely that fatigue life will keep unchanged if the principal stress–strain state keeps constant in spite of various loading forms. Based on the hypothesis and on the analysis of stress–strain states of thick wall tubular vessel under super high internal pressure and thin wall tube samples under tension–torsion load and comparison of the states, a new method of biaxial fatigue test of vessel, in which internal pressure load was replaced by tension–torsion load, was postulated. By means of the method, we have made the biaxial low cycle fatigue experiment of 37CrNi3MoV steel.

STRESS–STRAIN ANALYSIS AND COMPARISON

1. Stress State of Thick Wall Tube under Internal Pressure

Stress state of a unit on thick wall tube under internal pressure was shown in Fig.1. On the intersurface of the tube, stress arrived at maximum. From Lame's equation under planar stress condition .

$$\begin{cases} \sigma_t^w = \dfrac{P}{w^2 - 1}(1 + w^2) \\ \sigma_Z^w = 0 \\ \sigma_r^w = -P \end{cases} \qquad [4]$$

So that $\sigma_t^w > \sigma_z^w > \sigma_r^w$, and these three stresses are perpendicular to one another, actually they are three principal stresses.

$$\sigma_t^w = \sigma_1; \quad \sigma_z^w = \sigma_2; \quad \sigma_r^w = \sigma_3 \qquad [5]$$

Stress analysis is very simple as above if there is only internal pressure, but in the actual usage, "Autofrettaged" technology is usually used to make use of reverse elastic stress range and to enhance ability of materials to undergo pressure. The induced residul stress can be expressed as follows

$$\sigma_t^R = m(1 + ln\frac{r}{a}) - n(\frac{1}{a^2} + \frac{1}{r^2})$$

$$\sigma_r^R = m \ln\frac{r}{a} - n\left(\frac{1}{a^2} - \frac{1}{r^2}\right) \qquad [6]$$

Where m and n are the material constants depended on strength. From equation[6], we can calculate σ_t^R *and* σ_r^R on the intersurface of the tube. Considering the influence of Bauschinger effect, actual residul stress is lower than calculated value

$$\sigma_{ta}^R = B\sigma_t^R \qquad [7]$$

Coefficient B varies between 0 and 1. By the equations [4], [6] and [7], we can determine stress range varied during loading internal pressure.

2. Stress State of Thin Wall Tube under Tension–Torsion Load

Stress state of a unit on the thin wall tube loaded by tension–torsion was shown in Fig.2. From elastic theroy, we have

$$\sigma_1 = \frac{\sigma}{2} + \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2}$$
$$\sigma_2 = 0 \qquad [8]$$
$$\sigma_3 = \frac{\sigma}{2} - \sqrt{\left(\frac{\sigma}{2}\right)^2 + \tau^2}$$

Comparing equation [8] to equation [4], we can see that they are very similar to each other, thus, if we would make σ_1, σ_2 and σ_3 equal to σ_t^w, σ_z^w and σ_r^w respectively, only the ratio of σ / τ and the value of $\sigma / 2$ should be controlled.

Strain controlling is usually used in low cycle fatigue testing, so we must translate stress into strain.

$$\sigma_1 / \sigma_3 = \sigma_t^w / \sigma_r^w = k \qquad [9]$$

$$[\sigma / 2 + \sqrt{(\sigma / 2)^2 + \tau^2}\,] / [\sigma / 2 - \sqrt{(\sigma / 2)^2 + \tau^2}\,] = k \qquad [10]$$

$$\sigma / \tau = 2 / \sqrt{[(1-k)/(1+k)]^2 - 1} \qquad [11]$$

$$\varepsilon / \gamma = 2G / E \cdot \sqrt{[(1-k)/(1+k)]^2 - 1} \qquad [12]$$

loading path in ε–γ plane is determined now, and it is shown in Fig.3. The dot line is the loading path when the residul stress introduced by Autofrettaged process is considered, and it shows one kind of out–of –phase loading path. There is only a little change in phase angle if residul stress isn't very large. For simplification, we extended the line of ε / γ reversely into the third phase field, and then determined values of ε^R and γ^R.

All the samples were tested along the path shown in Fig.3 by real line.

EXPERIMENT AND RESULTS

Material used in experiment is 37CrNi3MoV steel. Table 1 is the mechanical properties of the steel.

Table.1 Mechanical Properties of 37CrNi3MoV steel

σ_s MPa	σ_b MPa	δ%	ψ%	E GPa	G GPa	μ
1127.69	1225.75	16	53	213.78	82.5	0.27

For the comparison to the results of uniaxial tension–compression LCF test, ε^R and γ^R were kept constant, only the maximum ε_{eq} in the first phase field varied, as shown in Fig.3.

$$\varepsilon_{eq} = \sqrt{\varepsilon^2 + \gamma^2 / 3} \qquad [13]$$

Cyclic deformation was peformed in a tension–torsion mode in MTS 809 type machine, samples were tested at constant total tension and torsion strain amplitude to fracture. A triangular waveform commend signal from a digital function generator was used for total strain control. The frequency in test was o.2 HZ for all samples. Test were holded in air under room temperature

Table.2 and table.3 were respectively fracture life of biaxial and uniaxial LCF tests.

Table.2 Fracture Life of Biaxial LCF Test

sample number	ε_{eq}%	ε%	γ%	ε^R%	γ^R%	$2N_f$
1	0.47	0.215	0.721	−0.0837	−0.280	15000
2	0.65	0.229	1.000	−0.0837	−0.280	8624
3	0.80	0.368	1.230	−0.0837	−0.280	1888
4	1.00	0.460	1.538	−0.0837	−0.280	1120
5	1.20	0.552	1.846	−0.0837	−0.280	834
6	1.35	0.621	2.076	−0.0837	−0.280	784

Table.3 Fracture Life of Uniaxial LCF Test

sample number	$\varepsilon_t/2$ %	$\varepsilon_e/2$ %	$\varepsilon_p/2$ %	$2N_f$
1	1.00	0.48	0.52	576
2	0.80	0.475	0.325	802
3	0.70	0.44	0.26	1468
4	0.55	0.43	0.12	3548
5	0.50	0.41	0.09	5380
6	0.40	0.36	0.04	19104

It should be noticed that the value in table.3 was obtained at constant stress ratio of R=−1, i.e. full reverse tension–compression load[4]. From the data in table.3, we can deduced a Morrow type equation as follows

$$\varepsilon_t / 2 = 8.42 \times 10^{-3}(2N_f)^{-0.077} + 0.508(2N_f)^{-0.728} \qquad [14]$$

If considering the effect of mean stress and mean strain on the fatigue life, equation[14] can be modified to

$$\varepsilon_t / 2 = 8.42 \times 10^{-3}(1 - \frac{\sigma_m}{\sigma_b})(2N_f)^{-0.077} + (0.508 - \varepsilon_m)(2N_f)^{-0.728} \quad [15]$$

Based on above equation, uniaxial LCF life, in condition of equal–strain state being same to that of biaxial test respectively, can be calculated. Data needed in calculation can be obtained by output during biaxial LCF test. In table.4, fatigue life of two loading methods was compared.

Table.4 Comparision of fatigue life of two loading methods

ε_{eq}%	$2N_f$(uniaxial)	$2N_f$(biaxial)	decrese factor = 2Nf(uniaxial) / 2Nf(biaxial)
0.47	42832	15000	2.9
0.65	14667	8624	1.7
0.80	8737	1888	4.6
1.00	3281	1120	2.9

From table.4, we can see that life of biaxial test is always lower than that of uniaxial test at condition of equal–strain being same value, in the test strain range, decrese factor varied between 1.7 and 4.6. Decrese in fatigue life is obviously due to difference in principal strain states.

CONCLUSIONS

1. Tension–torsion loading method can be used in researching low cycle fatigue life of super–high pressure vessels, as the principal strain and equal strain being the same values for two loading forms. It's a simple and practical method.

2. For 37CrNi3MoV steel, fatigue life of biaxial test is always lower than that of uniaxial test at same equal–strain condition.

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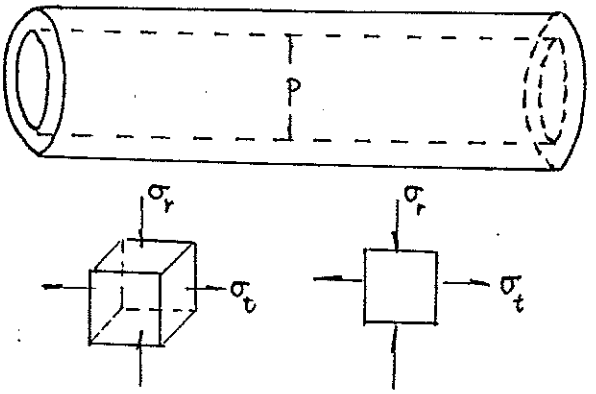

Fig.1 Stress state of thick wall tube under internal pressure

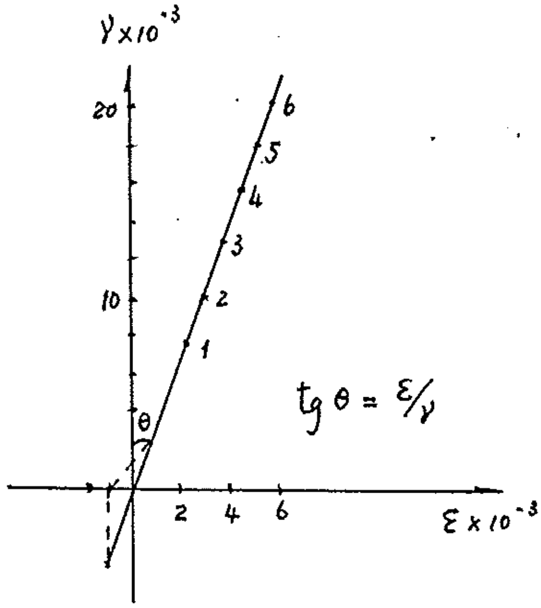

Fig.3 Loading path

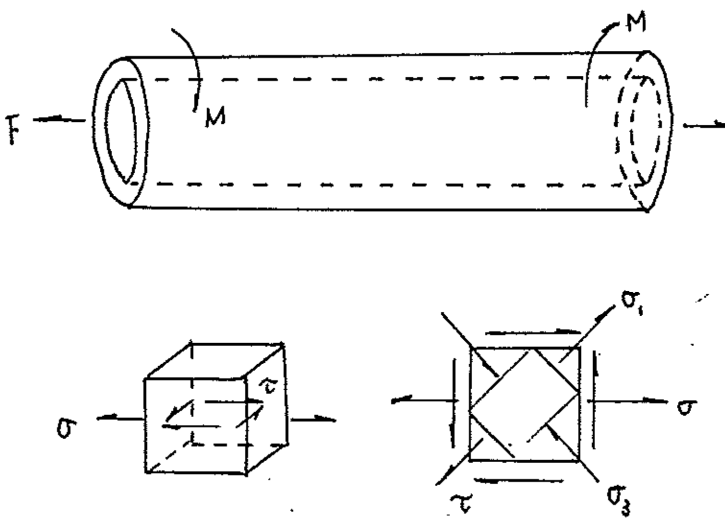

Fig.2 Strees state of thin tube under tension–torsion load