Experimental Verification for Application of Fracture Mechanics to Failure of Pressure Vessel

J. Imamasa and T. Miki

Results of two series of experiments, which were conducted to verify the application of Facture mechanics to the catastrophic failure of pressure vessel, were reported in this paper.

1. Test models

Six model vessels as shown in Fig. 1 were fabricated by 18 Ni marage steel with 28,000 psi tensile strength. After initial surface flaw was cutted by electric discharge on half-cylindrical plate, and developed to fatigue crack by applied load, then two parts were welded to cylinder. Fracture tonghness (K_{IC}) and growth rate of flaw were measured as shown in Fig. 2 by test specimen with penetrated flaw at center.

2. Test Result

Three models were subjected by internal pressure until failure occured with measurements of stress, deformation, crack opening displacement and acoustic emission.

Size of initial flaw, experimental result and predicted burst pressure are shown in Table 1. Burst pressure is calculated from condition the stress intensity factor of flaw (K) shown by equ. (1) attain to critical value (K_{IC}).

$$K = 1.1 \cdot \sigma \cdot M_K \sqrt{a/Q}$$

where a, $2C$: flaw depth and lenth

$\sigma = pR/t$: normal hoop stress

Q : Flaw shape parameter shown in Fig. 3.

M_K : Stress intensity magnification factor for thin wall thickness vessels shown in Fig. 4.

1.1 : for surface flow, 1.0 for submerged flaw

M_K was affected by flaw shape, but max. value was used for estimation. Estimations of burst pressure shows the good agreement to experimental results. Vessels were failed catastrophically as shown in Pho. 1, but fracture surface did't show the feature of brittle fracture as Chevron pattern. As example, outbreak of acoustic emission was shown in Fig. 5, which shown the possibility for foreknowledge of fracture.

Other three models were subjected internal cyclic pressure in expectation of two types of failure.

Predication of number to failure is calculated by

$$N_a = \int_{a_0}^{a_{cr}} \frac{1}{A(\Delta K_v)^n}\, da$$

where $A = 1.52 \times 10^{-8}$, $n = 2.19$ for this material

$a_{cr} = K_{IC}^2 \cdot Q_v / (1.1 \cdot \sigma \cdot M_{kv})^2$

K_v, Q_v, M_{kv} : The value corresponded to developing flaw size a_v and C_v

In case $a_{cr} < t$ (plate thickness), vessel failed catastrophically at above cycle after flaw grew to a_{cr}. But in case $a_{cr} > t$, vessel failed by leakage when flaw

penetrated through thickness at following cycle.

$$N_t = \int_{a_0}^{t} \frac{1}{A(\Delta K_v)^n}\, da$$

Predicated failure cycles and experimental results are shown in table 2 and example of predicated growth of flaw is in Fig. 6 with breadth of scattering corresponding to that of Flaw growth rate of Fig. 2. Predicated cycles is over-estimated in comparison with experimental results, one of reasons is considered as the last layer of fracture surface is failed by ductile fracture before penetration of flaw as shown in Pho. 2. No.3 model shown brittle fracture at remarkably lower cycle at where 10mm apart from initial flaw. In this case fracture initiated at repaired section by welding because of miscutting of flaw and can be explain by decrease of the fracture toghness at welded part and the equivalent flaw size where transformed part of material structure. Although the results of test may be satisfactory in engineering use considering the safety factor for fatigue test in the number of cycles, investigation must be continued for more exact estimation.

Reference

Tiffany : Some Fracture Consideration in the Design and Analysis of Space craft Pressure Vessels (Nat. Met. Cong. 1966)

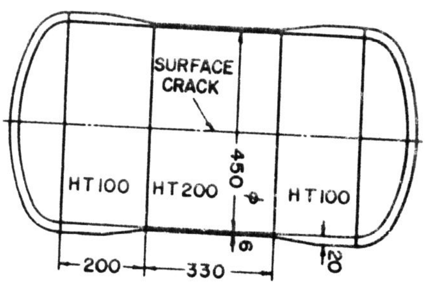


Fig. 1 Model Shape

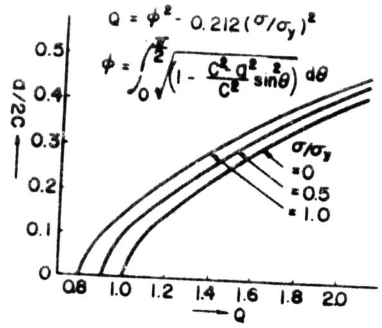


Fig. 3 Flaw Shape Parameter

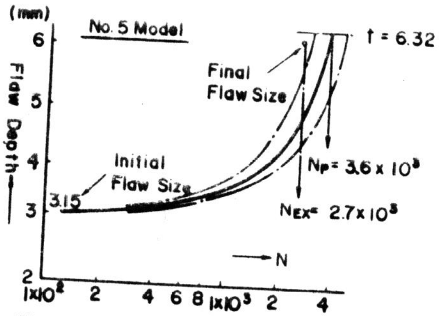


Fig. 7 Predicted Growth of Flaw

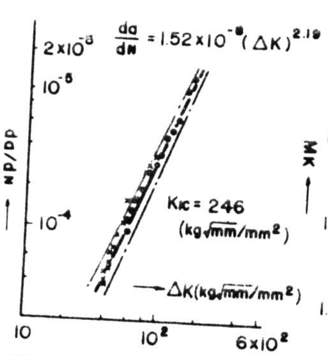


Fig. 2 Flaw Growth Rate

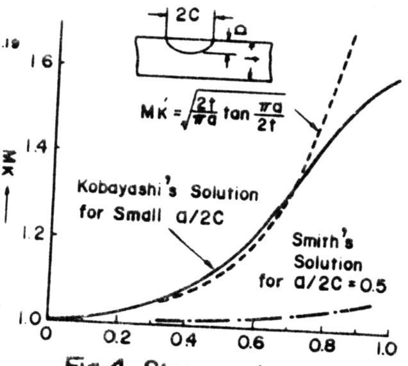


Fig. 4 Stress Intensity Magnification Factor

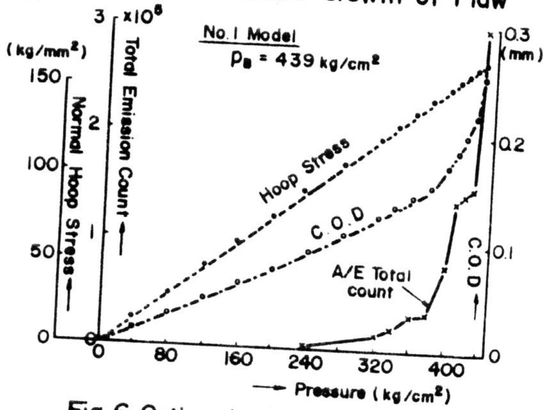


Fig. 6 Outbreak of Acoustic Emission

Table 1 Flaw Size and Experimental Results

Model No.	1	2	3
a/2C (mm)	2.87/10.50	3.57/17.27	3.82/20.91
a/t (mm)	2.87/6.38	3.57/6.40	3.82/6.28
Q, Mk	1.39, 1.12	1.22, 1.19	1.17, 1.23
$(\sigma_{cr})_P$ kg/mm²	139	110	100
$(P_B)_P$ kg/cm²	387	308	275
$(\sigma_{cr})_{EX}$ kg/mm²	158	108	97
$(P_B)_{EX}$ kg/cm²	439	300	267
$(P_B)_{EX}/(P_B)_P$	1.13	0.98	0.97

σ_{cr} : Critical Normal Hoop Stress
P_B : Burst Pressure
P, EX : Predicted and Experimental Value

Table 2 Flaw Size and Experimental Results

Model No.	4	5	6
$(a)_I$ $(a)_E$ (mm)	1.82, 2.63	3.15, 6.11	3.05, 5.89
$(2C)_I$ $(2C)_E$ (mm)	6.47, 8.25	10.71, 20.84	14.48, 23.06
t (mm)	6.40	6.32	6.38
ΔP (kg/mm²)	196	167	133
Δσ (kg/mm²)	70	60	48
$(K)_{NP}$ (kg/mm^1.5)	$\boxed{246}$	212	184
$(N)_P$	5700	3610	4416
Failure Type	Brittle F.	Leakage	Leakage
$(N)_{EX}$	(765)	2682	2359

I, E : Initial and Final Value
ΔP, Δσ : Cyclic Pressure and Hoop Stress
$(K)_{NP}$: Stress Int. Fac. at $(N)_P$

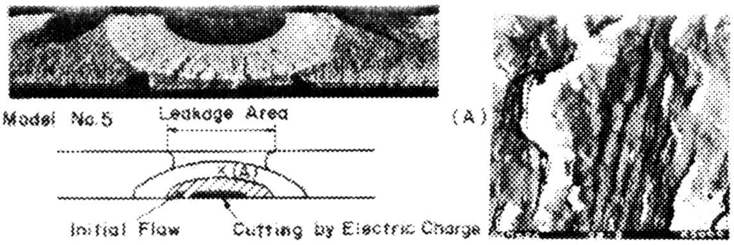
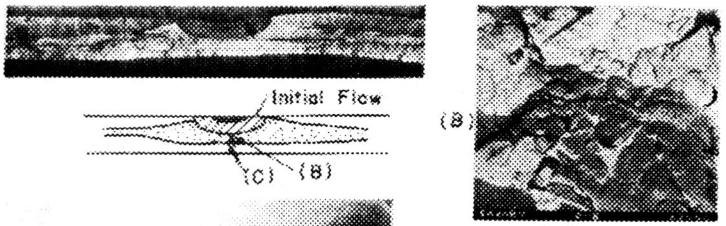
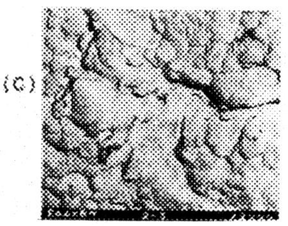


Photo 2 Fracture Surface at Fatigue test





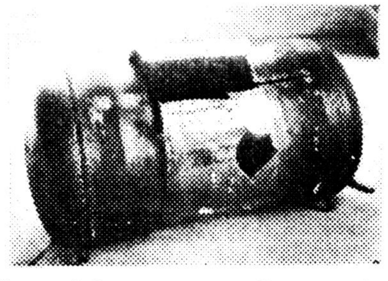


Photo 1 Catastrophic Fracture by Statical Test (Model No. 1)