Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Dynamic Collapse Test of Cracked Pipes

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ABSTRACT

In order to clarify the behavior of cracked pipes under seismic events, cyclic four point bending tests were conducted on the straight pipes with flaws. In the tests, real stress corrosion cracks(SCC) and artificial electric discharge machining(EDM) notches were induced on pipes as flaws. The specimens were subjected to the constant amplitude loading wave or the random amplitude wave. In comparison with the natural crack as SCC and the artificial crack as EDM notch, the EDM notch was easier to cause the leak of water than SCC. For the estimation of the failure on the cracked pipes, Net Section Collapse Failure Criterion (NSCFC) has been proposed and widely used under the monotonic loading condition. To extend the thought of NSCFC to the cyclic loading condition, the method using NSCFC and fatigue life prediction was found to be useful.

1. INTRODUCTION

Pressurized piping systems used in nuclear power plants are supposed to be degraded by aging effects, such as wall thinning or stress corrosion cracks. To maintain the plants in safe condition, it is important to estimate the effects of such degradation on dynamic behavior of piping systems under destructive earthquakes. In order to clarify such effects, the authors have planned an experimental research program of pipe elements and piping systems with some degradation parts. As the first stage of this study, cyclic bending tests for straight pipes and shaking table tests for 2-D piping models have been conducted. In this paper, the results of four-point bending tests for straight pipes with cracks are described. The results of pipes with wall thinning and 2-D piping models are described in another paper[1].

2. OUTLINE OF THE TEST

2.1 Pipe Specimens

The aims of the cyclic bending tests for cracked pipes are to clear the effect of two different loading types (sinusoidal and random) and compare between real stress corrosion cracks (SCC) and artificial electric discharge machining (EDM) notches. In this series of the experiments, 10 specimens with circumferential flaws were used in total, 4 of them were with SCC and 6 with EDM notches. All flaws were on the inside surface of the pipe specimens. The material of specimens is type-304 stainless steel. The yield stress of the material is 311MPa and the ultimate tensile stress is 617MPa. The length of the test part was 200mm for

SCC models, and 400mm for EDM notched models. The thicker pipes for reinforcement were welded at the both end of the test part pipe, so that the total length of the pipes became 3010mm. The size of the pipe in the test part was 100A - Sch80, that is 114.3mm of outer diameter and 8.3mm of thickness, and the size of the pipe for reinforced part was 100A - Sch160, that is 114.3mm of outer diameter and 13.5mm of thickness.

To induce SCC to the specimens, pipes with welded line were subjected to tensile loading in an elevated temperature and high pressure water environment[2]. The initial crack shapes were checked after the bending tests by the observation of the fracture surface (shown in Fig.1-(a) and (b)). As for EDM notched pipes, the initial angle of the notches were 360deg. for 4 specimens and 90deg. for 1 specimen. The depth of these notches were 4.3mm (0.5t) for all these 5 specimens. Besides these specimens, one specimen with a half-oval shape EDM notch which depth and area were equal to SCC shown in Fig.1-(a) was made in order to compare SCC and EDM notch. Fig.2 shows the geometry and dimensions of the EDM notched pipe specimens. All of these specimens are shown in Table 1.

All specimens were pressurized up to 7.8MPa with room temperature water. An accumulator was used to maintain the pressure during the bending test.

2.2 The Condition of Loading

The test equipment shown in Fig.3 was used for the four-point bending tests. This system used shaking table and the bending load was applied by the relative displacement between the anchor and the shaking table. The bending tests were displacement-controlled test and the specimens were subjected to 2 types of displacement wave, which were the constant amplitude sinusoidal wave and the random amplitude wave. The pattern of the input displacement waves are shown in Fig.4-(a) and (b), respectively. The frequency of the waves were both 1Hz. The number of steady amplitude waves in the sinusoidal wave were 26. The amplitudes were modulated from 0 to the steady state at the beginning and the ending 10 sec..

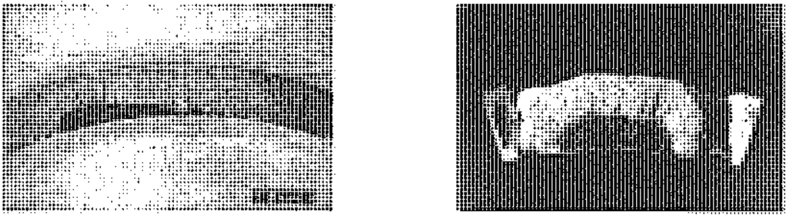
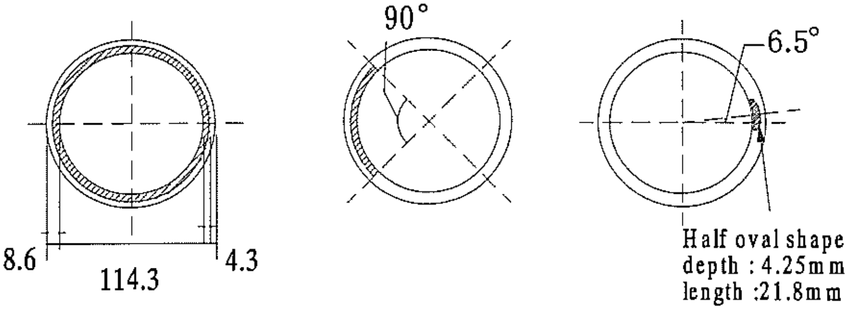

(a) SC01 (b) SC03

Fig.1 The initial crack shape of SCC (dark colored part)



(a) EM01~ EM04 (b) EM05 (c) EM06

Fig.2 The geometry and dimensions of the EDM notched pipe specimens

The number of cycles in the random wave were 47. The level of the input displacement was decided from the bending moment predicted by Flow Stress Criterion(FSC, described later). The bending load was applied to the specimen repeatedly until the crack penetrated and the specimen could not maintain the internal pressure because of the leak of water.

The specimen with the 90deg. EDM notch was installed in the direction so as to the maximum bending load was applied on the notch. As to the specimens with SCC, the largest SCC was detected by the ultrasonic inspection and specimens were installed as the SCC was sited in the maximum bending position. The specimen with EDM notch corresponding to the real SCC was installed so that the notch was in the same position on the pipe section as the original SCC.

2.3 Measurement

The following data were recorded by digital data acquisition system with sampling frequency 500Hz.

(1) Displacement of the shaking table as the input to the specimen
(2) Reaction force of the specimen

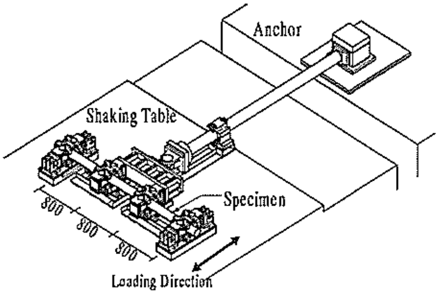
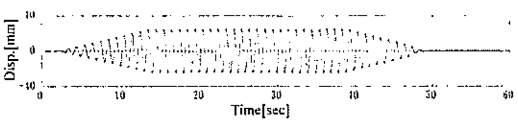
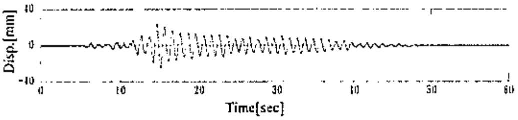


Fig.3 Test equipment



(a) Sinusoidal wave



(b) Random wave

Fig.4 Time histories of input displacement

Table 1 Results of the Cyclic Bending Test

Specimen	Type of flaw	The full angle of the notch [deg.]	Internal pressure [MPa]	Type of loading	Max. input disp. [mm] & number of loading	Failure Type
EM01	EDM	360	7.8	random	±15mm ×35 times ±30mm ×2 times	Full circumferential break
EM02				sinusoidal	±25mm ×1 times (at 16th cycle)	
EM03				random	±25mm ×10 times	
EM04				sinusoidal	±21mm ×1 times (at 18th cycle)	
EM05		90		random	±35mm ×4 times	Crack penetration
EM06		25.73		sinusoidal	±50mm ×2 times	
SC01	SCC	–	7.8	sinusoidal	±50mm ×5 times	Crack penetration
SC02		–			±50mm ×21 times	
SC03		–			±50mm ×5 times	
SC04		–			±50mm ×6 times	

(3) Internal pressure
(4) Axial and circumferential strain of the specimen
(5) Acceleration of the specimen

Crack-opening displacement was also recorded for the EDM notched pipe specimens.

3. TEST RESULTS AND DISCUSSION

3.1 The Outline of the Results

Table 1 shows the names of the specimens, initial crack type, loading conditions and the test results. The fracture mode according to the initial crack type was as following;

(1) Specimens with SCC

4 specimens were used for the bending test, but for two of them, crack penetration occurred at the section changing part for the connection of the test pipe to reinforcement pipe. For the other two specimens, the initial SCC progressed by fatigue, caused the crack penetration and the leak of water. The shape of the initial SCC at the penetration part were shown in Fig.1. The test specimens did not show the unstable crack growth to the circumferential direction.

(2) Specimens with EDM notches

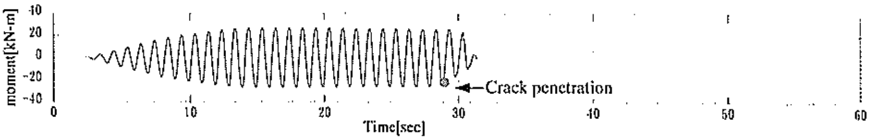
For 4 specimens with the full circumferential EDM notch, the crack penetrated at the point where the largest bending moments were applied. After the penetration occurred, the crack progressed in the circumferential direction and ended in full circumferential break. The failure mode did not differ in the wave type, whether it was the sinusoidal wave or the random amplitude wave. The specimen with 90deg. partial circumferential EDM notch(EM05) and the specimen with EDM notch corresponding to the real SCC(EM06) showed only crack penetration and the leak of water.

3.2 Comparison between Real SCC and Artificial EDM Notch

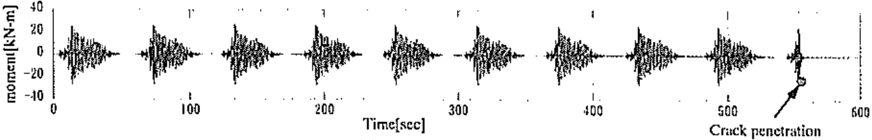
The EDM notch in EM06 had the same depth and area of SCC in SC01. These specimens were subjected to the same internal pressure and loading wave. Though the failure mode was similar to each other, the number of the waves required the initial crack to penetrate were 108 in SC01 and 32 in EM06. As compared with the EDM notch, the SCC required more than 3 times loading cycles until the crack penetration occurred. There is a difference that the SCC existed near the welded line and the EDM notch existed on the base metal, but the main reason of the difference in the number of the loading cycles is considered that the SCC had the three-dimensional shape, though the EDM notch had the two-dimensional shape.

3.3 Comparison between Constant Amplitude Loading and Random Amplitude Loading

In order to find the difference between the constant amplitude sinusoidal wave and the random amplitude wave, two EDM notched pipes were subjected to the bending loads in the same condition except the loading wave. The maximum amplitude of the input displacement was 25mm in both tests. Fig.5 shows the time histories for moment of these specimens throughout the tests. For the specimen subjected to the constant amplitude wave(EM02), the crack penetration occurred at the 16th cycle of the constant amplitude part and through-wall crack progressed in the circumferential direction. For the specimen subjected to the random wave(EM03), the crack penetrated during the 10th loading block and progressed in the circumferential direction by the following cycles in this block. This result shows that 1 block of the random wave used in this tests is equivalent to about 1.5 cycle of the same maximum amplitude sinusoidal wave. This result suggests that the smaller amplitude cycles also influence the propagation of the crack in the random amplitude wave.



(a) EM02



(b) EM03

Fig.5 Time histories for moment of EM02 & EM03 throughout the tests

3.4 Application of the Engineering Type Method

3.4.1 Estimation by Net Section Collapse Failure Criterion

Net Section Collapse Failure Criterion(NSCFC) has been proposed for the prediction of the load which cause the leak of water for a pipe with a part-through crack. Though this method is usually used in the monotonic loading condition, the results of the tests are compared with the prediction in order to know the relation between the prediction and the experimental load. There are some kind of estimation for this method (Kanninen[3], Kurihara[4], Hasegawa[5], for example). Among them, the estimation called Flow Stress Criterion(FSC), a variety of the method proposed by Kanninen, and the estimation proposed by Kurihara are used in this paper.

In this method, the applied bending moment required for rupture of the ligament is expressed as the leak moment (M_L) and it is given by the following formula in relation to the property of the pipe and flaw. In the following, β_L means the neutral angle of the stress when the pipe is subjected to the internal pressure and bending moment.

(1) Flow Stress Criterion

Provided that the flow stress acts evenly on the pipe section with the crack when the leak of the water occurs on the pipe. From the equilibrium of the axial forces and that of the bending moments, M_L is given as;

(i) In case of $\beta_L \leq \pi - \theta$

$$M_L = 2R^2 t\sigma_0 \left(2\sin\beta_L - x\sin\theta\right) \quad , \quad \beta_L = \frac{\pi - x\theta}{2} - \frac{\pi R p}{4t\sigma_0} \tag{1-a}$$

(ii) In case of $\beta_L > \pi - \theta$

$$M_L = 2R^2 t\sigma_0 \left\{2(1-x)\sin\beta_L + x\sin\theta\right\} , \; \beta_L = \pi + \frac{1}{1-x}\left(\frac{x\theta - \pi}{2} - \frac{\pi R p}{4t\sigma_0}\right) \tag{1-b}$$

where

R : average radius
t : thickness of the pipe wall
d : depth of the crack
x : ratio of the depth ($= d/t$)
θ : half angle of the crack
p : internal pressure
σ_y : yield stress
σ_u : ultimate tensile stress
σ_0 : flow stress ($= (\sigma_y + \sigma_u)/2$)

(2) Estimation method by Kurihara

Provided that the flow stress acts on the cracked ligament area and tensile and compressive stresses defined by $\pm m\sigma_0$ ($m \leq 1.0$) act evenly on the remaining area. From the equilibrium of the axial forces and that of the bending moments, M_L is given as;

(i) In case of $\beta_L \leq \pi - \theta$

$$M_L = 2R^2 t\sigma_0 \{2m\sin\beta_L + (1-x-m)\sin\theta\},\ \beta_L = \frac{\pi}{2} + \frac{\theta(1-x-m)}{2m} - \frac{\pi Rp}{4tm\sigma_0} \qquad \text{(2)-a}$$

(ii) In case of $\beta_L > \pi - \theta$

$$M_L = 2R^2 t\sigma_0 (1-x+m)\sin\beta_L\ ,\ \beta_L = \frac{m\pi}{1-x+m}\left(\frac{1-x}{m} - \frac{Rp}{2tm\sigma_0}\right) \qquad \text{(2)-b}$$

where $m = 1.0 - x^a y^b\ ,\ y = \theta/\pi$

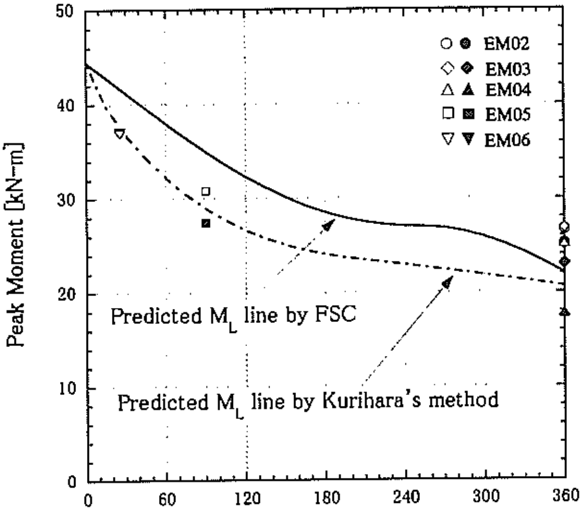
From the static and dynamic unstable fracture tests of stainless steel pipe and carbon steel pipe, *a* and *b* are decided as 0.8 and 0.65, respectively[4)].

Fig.6 shows the relation between the predicted leak moment M_L and the maximum moment M_{exp}. The open marks denote the maximum moment which appeared first time in the bending tests and the solid marks denote the moment when the leak of water occurred. EM01 is not used because the input level was changed during the bending tests before the crack penetration occurred.

In comparison with the M_L predicted by FSC and the maximum moment that first applied to the specimen, the ratio of M_{exp}/M_L is about 0.9 - 1.2 for all specimens. If the idea of the NSCFC is applicable to the cyclic loading test, the leak of water should occur in the three specimens, EM02, EM03 and EM04 at the first time the maximum moment applied. But the crack penetration did not occur then and more than 10 cycles of the maximum moment were required to cause the crack penetration in these specimens. This result suggests that the first excursion failure would not occur in the dynamic cyclic loading if the amplitude of the applied moment is about 10% larger than the predicted M_L. The moment when the leak of water occurred better agreed with the predicted M_L by Kurihara than M_L by FSC, especially for specimens with narrow crack angle(EM05 and EM06).

3.4.2 Estimation Considering the Effect of cyclic loading

For the life assessment of the cracked pipe subjected to the cyclic load, a method like fatigue life prediction is proposed by Kurihara[4)]. This method uses NSCFC, and the relation between the applied peak-to-peak moment (ΔM_{app}) and the number of cycles to crack



*Open marks denote the max. moment applied to the specimen for the first time. Solid marks denote the moment when the leak occurred

Fig.6 The relation between the predicted leak moment and test results penetration (N_p) is determined experimentally. The way to estimate is as following;

(1) Using the FSC

The amplitude of the predicted leak moment is determined as

$$\Delta M_{L1} = M_{L1} + M'_{L1} \tag{3}$$

where M_{L1} is the moment applied to the direction to open the crack and given by the Eq.(1). M'_{L1} is the moment applied to the direction to close the crack and given as following;

(i) In case of $\beta_L \leq \pi - \theta$

$$M'_{L1} = 2R^2 t\sigma_0 (2\sin\beta_L - x\sin\theta),\ \beta_L = \frac{\pi - x\theta}{2} + \frac{\pi Rp}{4t\sigma_0} \tag{4-a}$$

(ii) In case of $\beta_L > \pi - \theta$

$$M'_{L1} = 2R^2 t\sigma_0 \{2(1-x)\sin\beta_L + x\sin\theta\},\ \beta_L = \pi + \frac{1}{1-x}\left(\frac{x\theta - \pi}{2} + \frac{\pi Rp}{4t\sigma_0}\right) \tag{4-b}$$

The Eq.(1) and Eq.(4) differ in the sign in front of the internal pressure p. The relation between the applied moment and the number of cycles to crack penetration is determined as following;

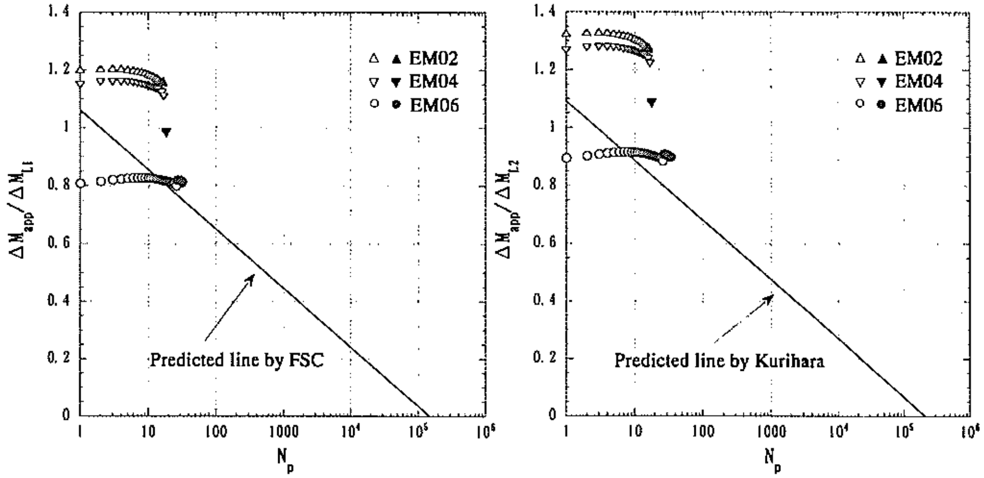
$$\frac{\Delta M_{app}}{\Delta M_{L1}} = -0.205\log N_p + 1.06 \tag{5}$$

(2)Using the estimation of NSCFC by Kurihara

The amplitude of the predicted leak moment is determined as

$$\Delta M_{L2} = M_{L2} + M'_{L2} \tag{6}$$

where M_{L2} is given by Eq.(2) and M'_{L2} is given by reversing the minus sign in front of the internal pressure p in Eq.(2). The relation between the applied moment and N_p is determined as following;



(a) Using the FSC

(b) Using the NSCFC proposed by Kurihara

(* Open marks denote intermediate loading steps.
Solid marks denote the point when the leak occurred.)

Fig.7 The life predicted line and test results

$$\frac{\Delta M_{app}}{\Delta M_{L2}} = -0.205\log N_p + 1.09 \quad (7)$$

It is noted that the method can predict N_p unless the initial crack angle becomes about 360deg. or the depth of the crack is over 90% of the thickness.

Fig.7 -(a) and (b) show the predicted fatigue life and the test results. The blank marks denote intermediate loading steps. The solid marks denote the point when the leak occurred. The specimens subjected to the constant amplitude wave are used in this figure, because the estimation of the random wave is not decided.

For the specimens with the full circumferential crack, the predicted life and the results of experiment are not so close. But for the specimen with narrow crack angle(EM06), the number of cycles to crack penetration is rather close to the predicted life by Eq.(5) or Eq.(7). Though there is only one case to compare the prediction and the experimental result, such idea proposed by Kurihara using NSCFC and fatigue life may be useful to life prediction of the pipe with crack under the cyclic loading condition.

4. CONCLUSION

Four point bending tests were carried out on the pipes with cracks. The pipes with the full circumferential crack ended in full circumferential break but the pipes with actual SCC and with narrow crack angle smaller than 90deg showed only the crack penetration and the leak. In comparison with the real SCC and the artificial EDM notch, the crack propagation is easier to occur in the EDM notch if the depth and area are equivalent to the real SCC. For the estimation of the failure on the cracked pipes, NSCFC is widely used under the monotonic loading condition. But under the cyclic loading condition, a number of cycles are required to cause the crack penetration though the applied moment was about 10% larger than the leak moment predicted by this method. Under the cyclic loading condition, the method using NSCFC and fatigue life prediction might be useful to estimate the life of the cracked pipe.

Acknowledgment

The authors would like to express their appreciation to Dr. H. Shibata, the Emeritus Professor of the University of Tokyo, for his support and precious advice for this study. They also appreciate Mr. S. Aida of IHI and Mr. H. Uchida of Ishikawajima Inspection and Instrumentation Co., Ltd. supporting the accomplishment of these tests.

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