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An experimental study on the stability of cracked piping system supported by a nonlinear support

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ABSTRACT: The stability of the cracked piping system supported by the nonlinear support under seismic conditions was investigated by the vibration test using 3-dimensional piping model. The elasto-plastic damper was used as a nonlinear support in this vibration test. From the experimental results, it is drawn that instable behavior of the piping model with a nonlinear support was not observed and the crack growth by dynamic excitation is also negligibly small. The elasto-plastic damper was failed by the fatigue at the estimated endurance limit.

1 INTRODUCTION

Recently, various types of supporting devices have been developed for piping systems in nuclear power plants by authors (Chiba 1990, Shibata 1992) or others. These supporting devices are designed intending to suppress the seismic response of piping systems by their energy dissipation capability. The energy dissipation capability in these new supporting devices is generated by nonlinear characteristics such as elasto-plastic behavior of metal or friction between metals so on. These have so called load constant or spring-softening type force-displacement characteristics. It is mentioned by Shibata (1990) that the piping system with supporting devices with such characteristics have possibilities of instable failures. Many reports were presented about the influence of crack size, loading condition and piping compliance on the static fracture behavior of the piping. Few reports discussed the effect of the nonlinear support on the instable failure of cracked piping (Ogawa, et al. 1988).

The aim of this study developed into two parts; one is to investigate a dynamic behavior of the cracked piping system supported by a nonlinear support, and another is to clarify the effect of the stiffness of piping support on the crack growth.

2 PIPING MODEL

In this experiment, a 3-dimensional piping model(dia. : 165.2mm, thickness : 7.1mm and length: 27.4m) was used. Fig. 1 shows the general view of the 3-D piping model. The material of this piping model is carbon steel, STS42.

This piping model was supported by two types of supports, one is the rigid restraint as a linear support and another is the elasto-plastic damper as a nonlinear support. The elasto-plastic damper is made of three layered steel plates. The force-displacement relationship, and equivalent stiffness and damping of the elasto-plastic damper is shown in Fig. 2 and 3. Damping ($c\omega$) was derived from following equation.

$$C\omega = \Delta E / \pi \delta^2$$

Where, ΔE is dissipation energy in the damper per one cycle and δ is damper displacement. As shown in these figures, its equivalent stiffness decreases in accordance with the damper displacement, while its damping increases with the damper displacement because the energy dissipation by elasto-plastic behavior of steel plates in the damper increases with damper displacement. As mentioned above, the elastic-plastic damper has spring-softening type nonlinear force-displacement characteristics.

The replaceable straight pipe element with crack was installed in the 3-D piping model as shown in Fig. 1. This pipe element was connected to the piping model through with flange by bolting joints. The bending moment under the seismic excitation becomes maximum at this crack position. This crack was made by the electrical discharge machining method (EDM). That is fully circumferential internal crack with about 0.5mm of width and 4.5mm of depth, which is about 63% of pipe body thickness as shown in Fig. 4. This pipe element was pressurized at 131.6kgf/cm^2. This internal pressure yields 14kgf/mm^2 of primary membrane stress in pipe body which is equal to design stress intensity Sm. The relationship between the collapse moment and crack depth obtained based on net section criterion (Kanninen 1984) is shown in Fig. 5. The yield stress and ultimate stress were measured from the tensile strength test. From this figure, collapse moment is obtained about 1.7 tonf-m.

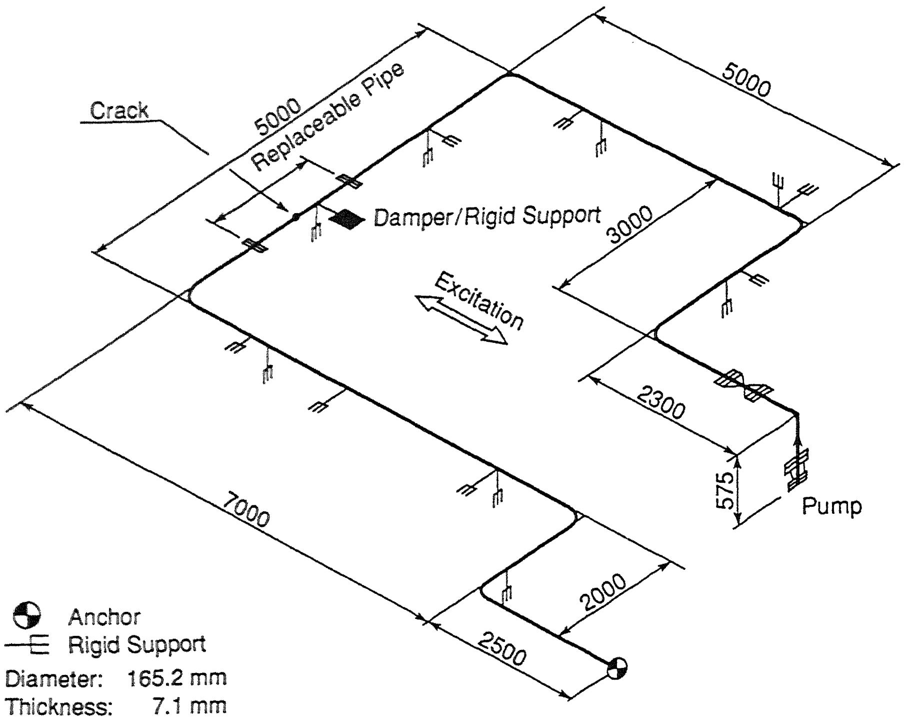

Fig. 1 Piping model.

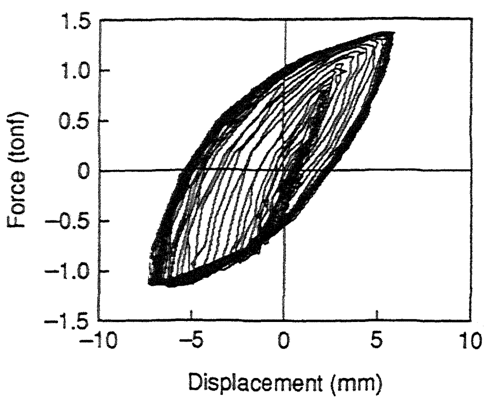

Fig. 2 Hysteresis loop of damper.

3 TEST METHOD

The piping model was fixed on the large shaking table of 12m × 12m. It was excited by sinusoidal wave whose frequency corresponds to the first natural frequency of the piping model in order to make bending moment above collapse moment at the crack position of the pipe element. The estimated deformation of the piping model is shown in Fig. 6.

In the first test, the piping model without crack was excited. The resonant frequency, damping, acceleration, and bending moment were obtained. In order to clarify the effect of the stiffness of pipe support on crack penetration, 2 types of Supporting condition were examined. One is rigid supports only. Another is rigid supports and one elasto-plastic damper. The elasto-plastic damper was installed in stead of the rigid support whose reaction force becomes maximum at the vibration test of rigid supports only.

Second, the piping model was excited by each resonant frequency obtained from the vibration test of the piping model without crack. he test was conducted under the two types of the supporting condition.

4 RESULTS OF VIBRATION TEST

Fig. 7 shows the frequency response function of response acceleration of the piping model without crack to input acceleration. In case of rigid supports only, response acceleration becomes large in proportion as excitation frequency comes near to resonant frequency. The peak of frequency response function was observed clearly. The frequency response function of the piping model with elasto-plastic damper has not a clear peak and its maximum gain is smaller than that with rigid supports only. This is reason why the energy dissipation in the damper increases the equivalent damping ratio and decreases the dynamic response of the piping model.

Table 1 shows the summary of test results of the piping model with crack. The piping model supported by rigid

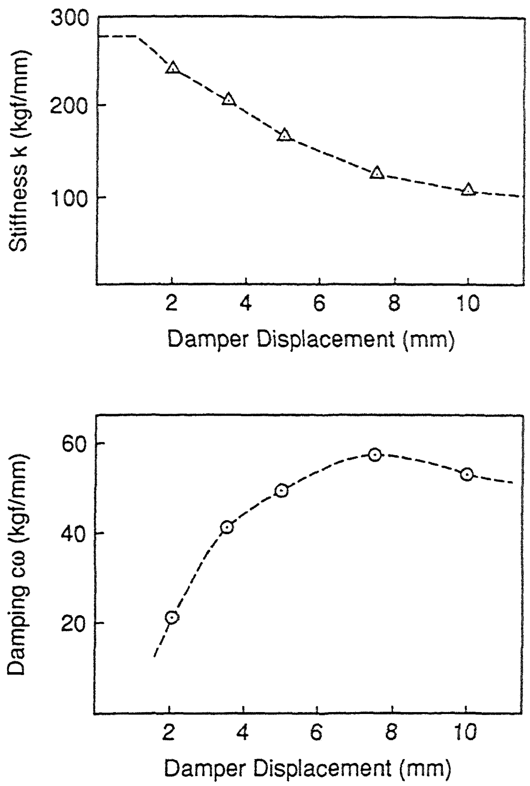

Fig. 3 Stiffness and damping of elasto-plastic damper.

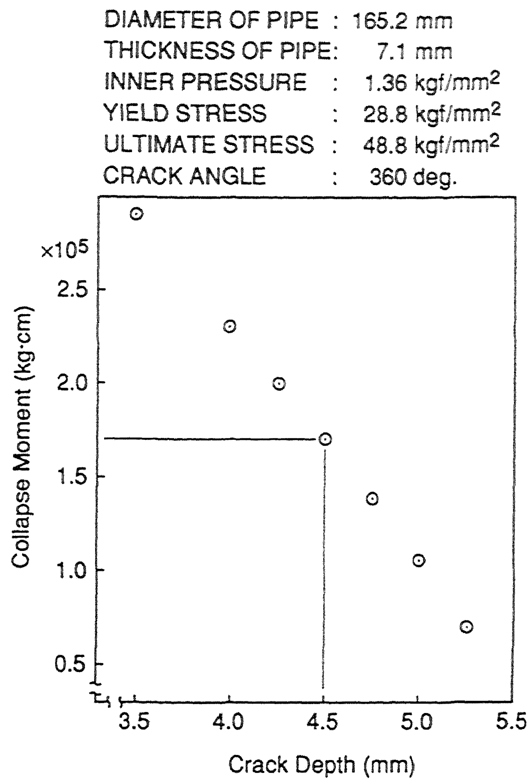

Fig. 5 Collapse moment by net section criterion.

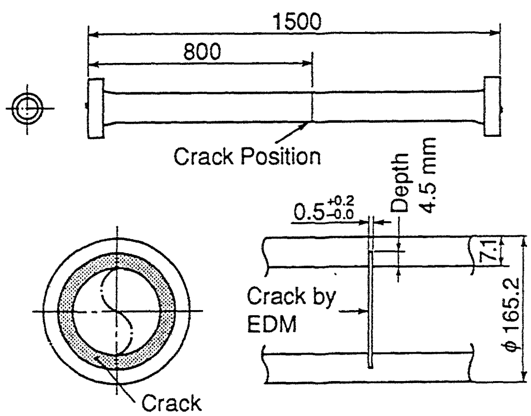

Fig. 4 Detail of crack.

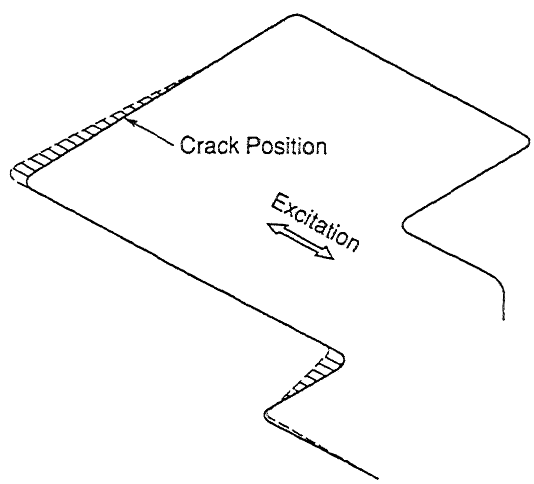

Fig. 6 Deformation of piping model.

supports only was excited by sinusoidal wave of 1st resonant frequency and crack penetration was caused after 4th test run. Total excitation cycle is 3755 and generated bending moment at the crack position is 0.98×10^5 kgf-cm which is about 52% of leak moment by net section criterion. It was supposed that this crack penetration was caused by the fatigue crack growth and opening length of the crack is about 10.7 mm as shown in Fig. 8.

The piping model with crack supported by a damper was also excited by sinusoidal wave of its 1st resonant frequency. However, crack penetration was not caused as

Table 1 Summary of test results.

Support Condition	Test Run	Bending Moment at Crack (kgf·cm)	Ratio(*)	Excitation Cycle	Residual Strain at crack ($\times 10^{-6}$)
Rigid Supports only	1	0.73×10^5	0.41	650	5500
	2	1.00×10^5	0.53	925	4200
	3	1.13×10^5	0.59	880	4700
	4	1.00×10^5	0.53	1300	Leak
Rigid Supports + Damper	1	0.82×10^5	0.43	300	1400
	2	0.78×10^5	0.41	470	70

(*) : Ratio of Bending moment at crack to Collapse moment

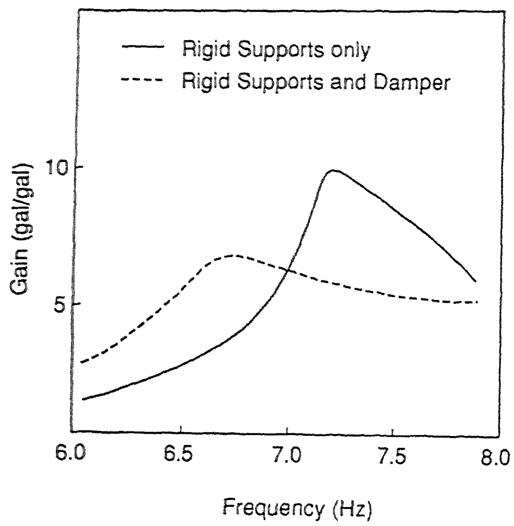

Fig. 7 Frequency response function of piping model without crack.

shown in Fig. 9. The steel plate which was installed to dissipate energy by elasto-plastic behavior in the elasto-plastic damper, was broken by fatigue at the estimated excitation cycle. Fig. 10 shows the strain time history of the outer surface og pipe on the crack position. The strain at crack position did not drift during each test and residual strain was also negligible small after excitation of each test.

5 DISCUSSIONS AND CONCLUSIONS

On the vibration test of the piping model with crack supported by the rigid supports only, input vibration energy from shaking table was converted to the vibration energy of the piping model or the energy dissipation at the rigid support joints or the energy to produce the crack. It was already clarified that energy dissipation in the rigid support joints used in this vibration test is negligibly small. Therefore, it is judged that some amount of input energy was flowed into and concentrated on the weakest region in the piping model. That is the crack tip in the pipe element, and crack was grew gradually by this vibration energy concentration.

On the other hand, the piping model with crack supported by a elasto-plastic damper has two weak points; one is a crack in the pipe element, and another is the steel plates in the elasto-plastic damper. In case of the piping model with rigid supports only, crack in the pipe element is the only weak point. Because the elasto-plastic damper has larger energy dissipation capability by elasto-plastic behavior of steel plates than crack penetration, some amount of energy flowed into the elasto-plastic damper. That energy was dissipated by elasto-plastic behavior of steel plates in the damper instead of the energy dissipation through penetration of crack in the pipe. This dissipation of vibration energy accumulates the fatigue damage in the steel plates of damper.

In this paper, only the experimental results were described that the instable crack growth in the piping model supported by an elasto-plastic damper (spring-softening type nonlinear support) was not observed. It is difficult to obtain the conditions to predict the instability on the piping model by an analytical approach. It will be estimated by only numerical simulation on the piping model. The knowledge on nonlinear behaviors of a pressurized pipe element and nonlinear supports is extremely important to estimate the behavior of a piping system with nonlinear supports under a seismic event.

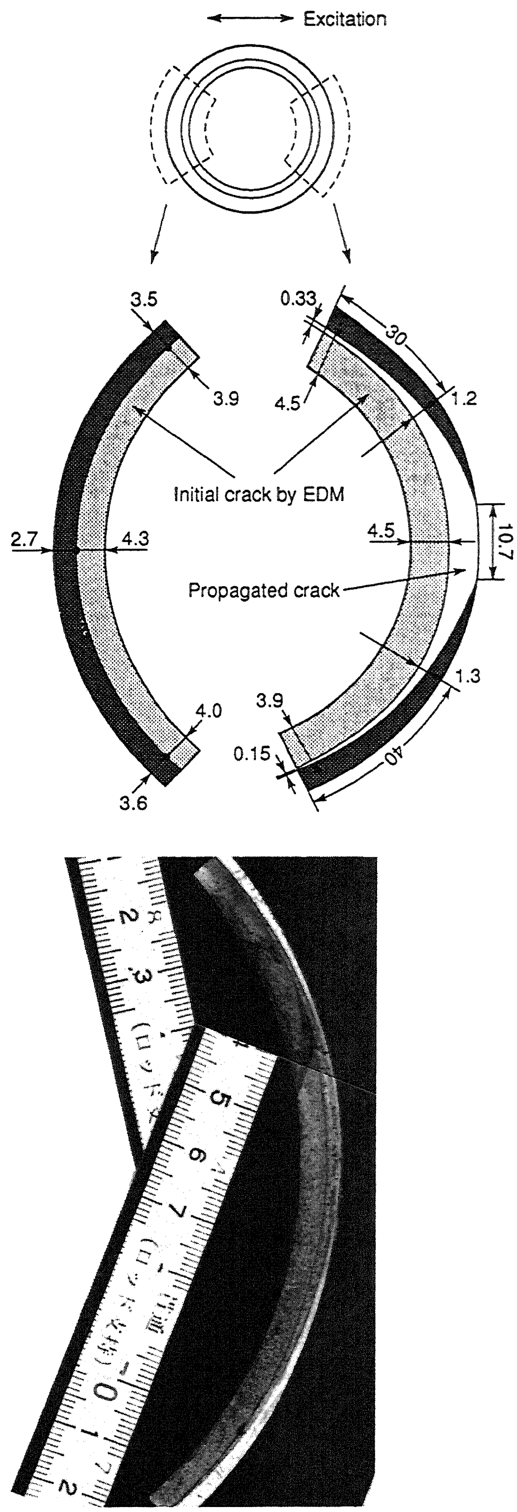

Fig. 8 Post test crack section in case of rigid support only.

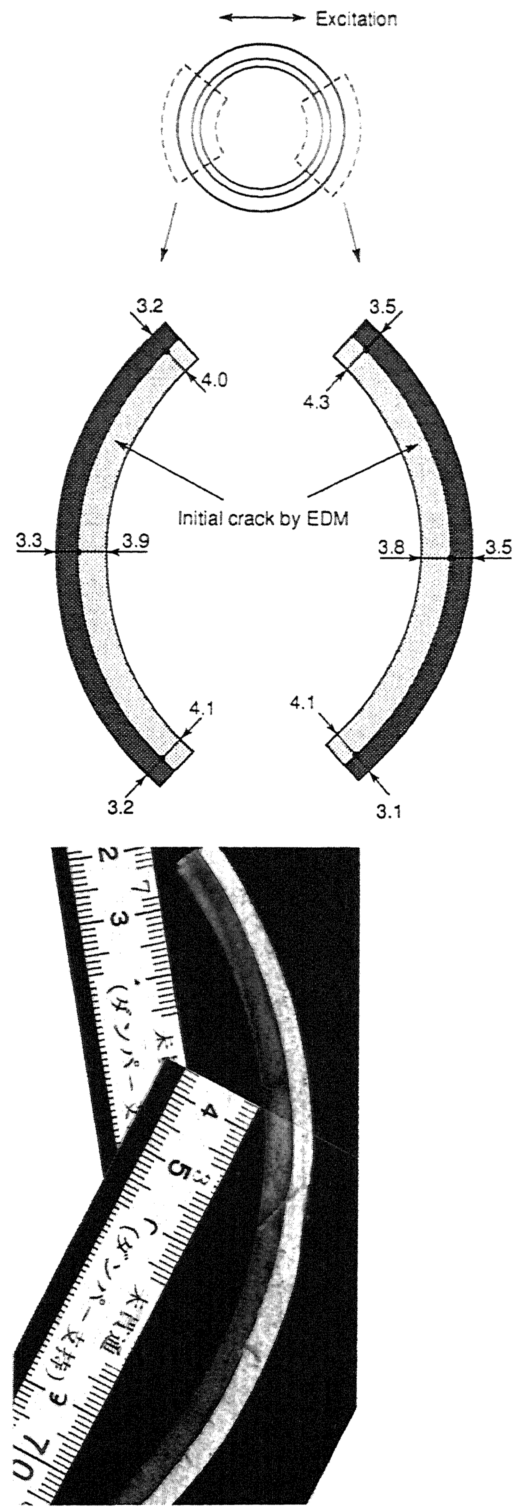

Fig. 9 Post test crack section in case of damper.

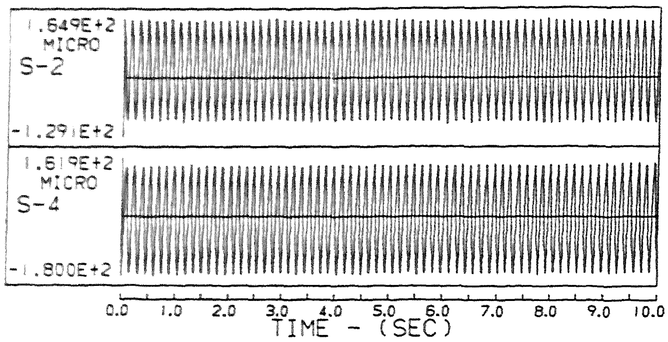

Fig. 10 Strain time history of outer surface of pipe at crack.

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