Pipe-whip experiment and numerical analysis

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1 INTRODUCTION

In a postulated guillotine-break of a pressure-tube-type heavy-water reactor's primary piping, there is a possibility that the ruptured pipe accelerated by escaping pressurized fluid will whip and form a hinge on itself. There is also a possibility that the ruptured pipe will strike the adjacent pipe causing severe local damage to the impacted zone. These situations may occur because the reactor consists of numerous, closely packed, small diameter pipes.

In order to assess the integrity of the primary piping system, two types of impact experiments, whip tests and pipe-to-pipe impact tests, were carried out with pipes of the same material and same size used in the reactor. Test pipes were accelerated by detonating powder installed at the free end of the pipes. The powder's thrust force simulates the blowdown force in a postulated pipe break accident.

Finite element analsis was also carried out to simulate the dynamic and highly nonlinear pipe behavior.

2 TEST CONDITIONS

Two types of impact tests were carried out: (a) unrestrained whip test, and (b) pipe-to-pipe impact test. In the unrestrained whip test for the inlet piping in the reactor's primary system, a 2-inch schedule 80 pipe, made of type 316 stainless steel, 4 m in length with one end fixed on the floor, was accelerated by the detonation of an explosive charge at the free end under room temperature conditions. The explosive used was chosen so that thrust force and duration time were 12.3 kN and 100 ms, respectively. Thrust force magnitude was determined from a blowdown analysis of the reactor's inlet piping in a postulated pipe rupture utilizing an envelope curve of the thrust history; Duration time was determined so that thermal reaction from the explosive would be finished before the pipe strikes the floor.

In the pipe-to-pipe impact test for the outlet piping in the reactor's primary system, a 3-inch schedule 80 pipe, made of type 316 stainless steel, 5.5 m in length with both ends simply supported, was impacted by another pipe of the same size and material, 5 m in length, charged with an explosive at the free end. The gap distance between impact and target pipe was 70 cm, and the test was carried out under room temperature conditions. The explosive was chosen so that thrust force and duration time

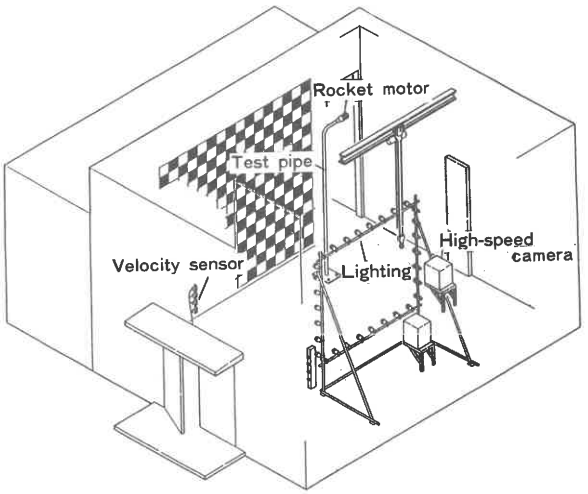


Figure 1. Test facility and instrumentation for 2-inch whip test.

Table 1. Test conditions

(a) Whip test

Pipe					Load
Outer diameter	Thickness	Material	Length	Support	
61.0mm	6.3mm	316s/s	4 m	Cantilever	12.3kN ×100ms

(b) Impact test

	Outer diameter	Thickness	Material	Length	Support	Load
Impact pipe	89.1mm	8.25mm	316s/s	5m	Cantilever	59kN ×27ms
Target pipe	89.5mm	8.4mm	316s/s	5.5m	Simply supported	——

would be 59 kN and 27 ms, respectively. Thrust force magnitude was determined from blowdown analysis of the reactor's outlet piping; Duration time was determined so that the thermal reaction from the explosive would be finished before impact. Test conditions are summarized in Table 1.

The test facility and configuration are shown in Figure 1 for the 2-in whip test. Pressure history measured by a pressure transducer mounted inside the rocket motor's combustion chamber, was converted into thrust force history, using a calibrated relation between pressure and thrust force. Acceleration history, obtained from an accelerometer mounted on the pipe near the free end, was time-integrated to generate the pipe's velocity history. A high speed motion picture (1500 frames per second) was also used for evaluating overall velocity distribution of the pipe. Dynamic and residual pipe strain on the outer surface was also measured with strain gauges.

Local strain near the fixed end of the pipe was also measured after sectioning the pipe. The same facility slightly modified in the configuration was used for the pipe-to-pipe impact test.

3 NUMERICAL ANALYSIS

Pipe impact behavior was analyzed using a nonlinear finite element code ADINA with a beam element after adding the following capabilities to the original version: (i) Follower load capability, necessary for the large rotation analysis in which force direction is built in the deforming body. (ii) Capability to take account of rigitity-decrease relation caused by pipe ovalization. The relation was obtained from a static three point bending test of a 2-inch pipe, shown in Figure 2. The elastic stiffness matrix used in the analysis was multiplied by the rigitity-decrease ratio, which was given as a function of bending angle. (iii) Explicit computation of kinetic energy, elastic strain energy, and dissipation due to plastic deformation energy, to be used in the evaluation of the results.

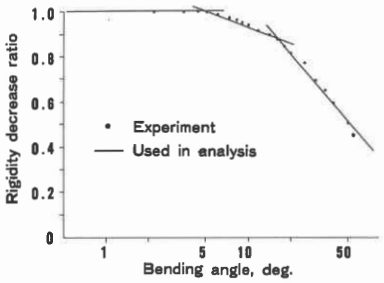


Figure 2. Rigidity decrease effect obtained from static 3-point bending test of a 2-in. pipe.

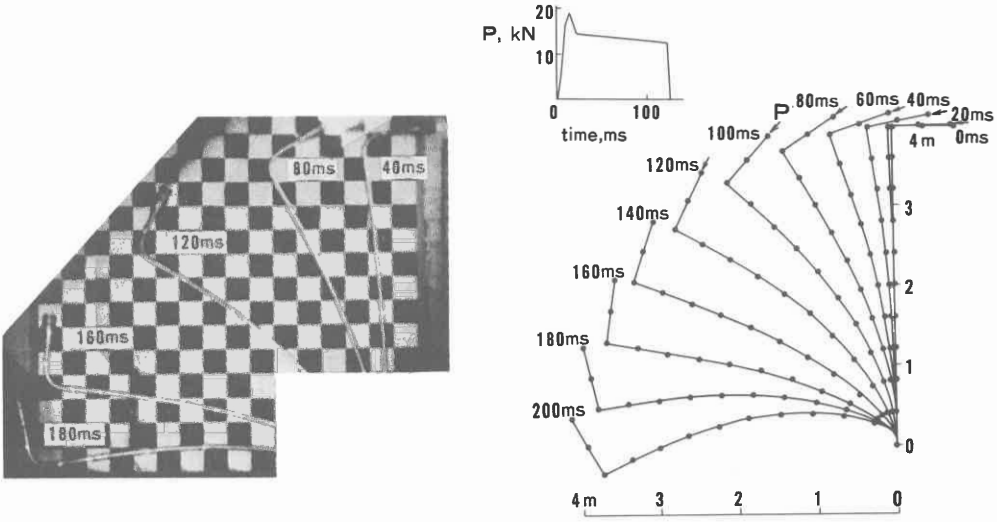
4 TEST RESULTS COMPARED WITH CALCULATED RESULTS

4.1 Whip test

The overall pipe deformation is shown in Figure 3 at a 40 ms interval compared with the calculated configuration. The pipe was crushed against the floor at 184 ms; In the calculation, time passing the floor line was 190 ms. From the comparison it can be said that overall deformation of the pipe is well simulated by the calculation.

Velocity history, obtained from time-integration of the measured acceleration in the rotating direction of the pipe, is shown in Figure 4. Calculated velocity, corresponding to the same component as experimental one, is also shown in the figure.

Measured and calculated acceleration histories are shown in Figure 5. Component in the rotating direction, same as the velocity history, is plotted in the figure.



(a) High speed photograhs (b) Calculated

Figure 3. Deformation of 2-in. pipe accelerated by detonation at free end of the pipe.

Figure 4. Velocity history of 2-in. whipping pipe measured at free end.

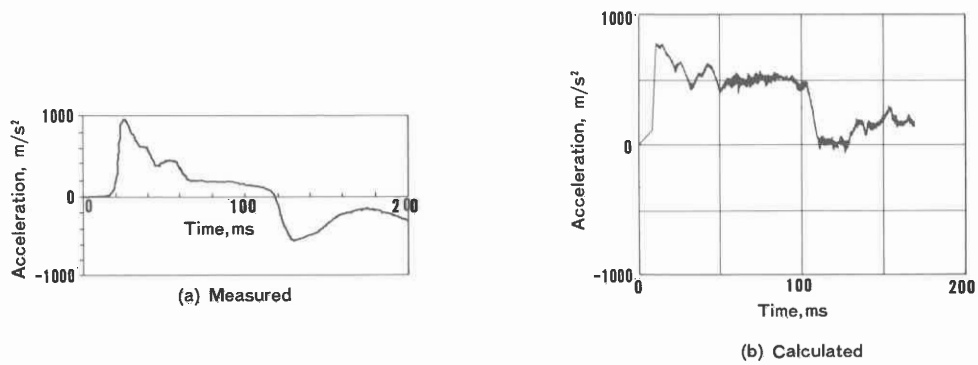


Figure 5. Acceleration history of 2-in. whipping pipe measured at free end.

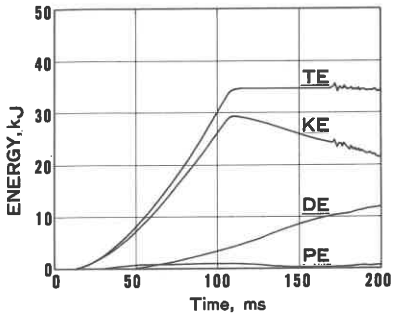


Figure 6. Calculated energy history for 2-in. whip test. TE,KE,DE and PE mean total, kinetic, dissipation, and elastic strain energies, respectively.

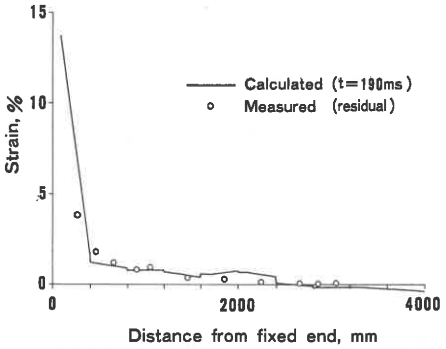


Figure 7. Residual strain measured at outer surface in axial direction of 2-in pipe.

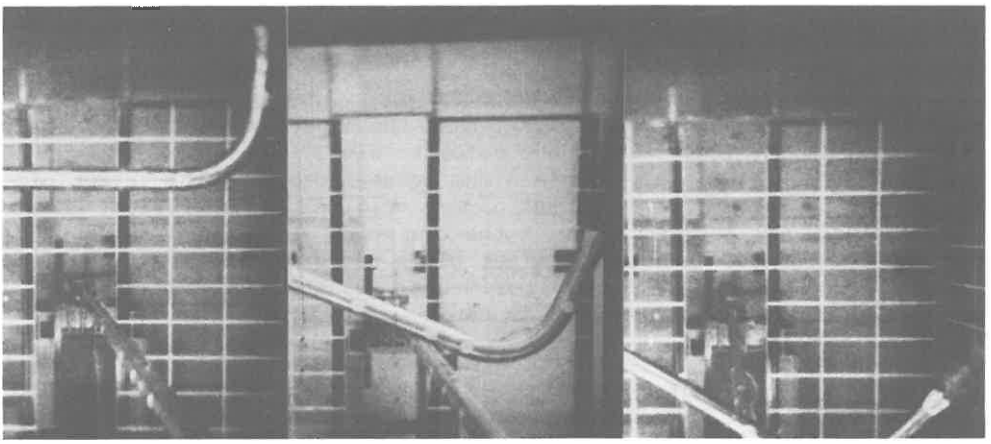


Figure 8. Movement of impact and target pipes of 3"-3" impact test. (a) 0 ms (left), (b) 29 ms (center), and (c) 40 ms (right).

Table 2. Summary of calculated results for 2-inch whip test.

	Calculation	Experiment
Displacement	Passed floor line at 190ms	Crushed against floor at 184ms
Max. velocity	47.2m/s at 108ms	43.2m/s at 130ms
Max. acceleration	781m/s² at 11ms	951m/s² at 11ms
Max. residual strain	13.4% at 10cm from fixed end	3.89% at 25cm from fixed end
Bending angle at fixed end	70.6°	71°
Max, kinetic energy	29kJ at 110ms	——

Table 3. Summary of calculated results for 3"-3" impact test.

		Calculation	Experiment
Displacement	Impact pipe at free end	1600mm (100ms)	1141mm (residual)
	Target pipe at impacted zone	1000mm (100ms)	700mm (residual)
Max. Velocity	Impact pipe at free end	39m/s at 29ms	37m/s at 29ms
	Target pipe at impacted zone	40m/s at 33ms	17m/s at 35ms
Kinetic energy of impact pipe		30kJ	31.4kJ
Bending angle	Target pipe at impacted zone	13°	12°

Calculated energy history is shown in Figure 6, where TE, KE, DE and PE stand for total, kinetic, dissipation, and elastic strain energies, respectively. Total energy reaches its maximum of 34 kJ at 124 ms. After completion of explosion, no energy is supplied from outside the system, and energy is maintaind at the same level. Kinetic energy reaches its maximum of 29 kJ at 110 ms, and subsequently decreases monotonically. Dissipated energy due to plastic deformation increases with time, indicating 34% of total energy has been consumed in plastic deformation at 190 ms (when the pipe was crushed against the floor). Elastic strain energy accouts for only 3% of total energy.

Residual strain distribution in the axial direction both measured and calculated at the outer surface of the pipe is shown in Figure 7. It can be said that agreement between them is fairly good execpt for strain near the fixed end, where local constraint effect could not be ignored. The minimum cross-section of the pipe near the fixed end was found 83% of the original cross-section. Calculated and experimental results are summarized in Table 2. Agreement between them is satisfactory except for local deformation of the pipe.

4.2 Pipe-to-pipe impact test

Movement of impact and target pipes, near the impact zone, of 3in.-to-3in. test is shown in Figure 8. Impact velocity was 37 m/s, remaining no cracks in the target pipe. The minimum cross-section of the target pipe at the impacted zone was found 90% of the original cross-section. Numerical analysis was carried out with the same code as in the whip test. The gap between the impact and target pipes was simulated by a nonlinear truss element. Calculated and experimental results are summarized in Table 3. Agreement between them is good.

5 SUMMARY AND CONCLUSION

Pipe-whip and pipe-to-pipe impact experiments and their numerical analyses were performed in order to assess the integrity of the primary piping system of a pressure-tube-type heavy-water-reactor in a postulated guillotine pipe break. Test pipes, whose size and material were the same as those used in the actual plant, were accelerated by means of an explosion caused by detonating powder installed at one end of the pipe. Pipe impact behavior was analyzed using a finite element code ADINA with beam elements for overall pipe behavior. Calculated results were compared with experimental results in terms of deflection, velocity, acceleration and strain, showing good agreement between them. Therefore, overall pipe behavior upon impact could be well simulated by numerical analysis.