Experiment and Analysis on Pressure Pulse Propagation in a Plastically Deforming Pipe (II)

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SUMMARY

This paper presents an experimental and analytical study on pressure pulse propagation phenomena in a plastically deforming pipe filled with water. In SMIRT-5, we concluded that (a) pressure pulse with peak over the yield pressure of the pipe are attenuated to the yield pressure at the pipe inlet (large deformation region), (b) the attenuated pressure pulse further reduces its height gradually while traveling through the pipe (small deformation region), (c) the pressure pulse attenuation rate at elbow depends on the pulse width. The objectives of this study are to clarify the mechanism of pressure pulse attenuation in the small deformation region and detailed behavior of the pressure pulse at elbow.

The experimental facility consists of a test pipe and a pulse gun filled with water at room temperature. The pressure pulse is generated in the pulse gun by the deflagration of low explosive (Sk Explosive). Experiments are performed on Type 304 stainless steel pipes with and without a 90 degree elbow. Pressure in pulse gun and test pipe, dynamic strain and deformation of the pipe wall and elbow displacement are measured.

In the small deformation region, the dependence of pipe material yield stress on the strain rate causes the pressure peak attenuation. The pressure in the pipe is controlled by the yield stress of the pipe material. At the large deformation region, the incident pressure pulse height is reduced to the pressure corresponding to the dynamic yield stress which is higher than the static yield stress. As the pressure pulse is propagated to the downstream, the strain rate is reduced. Therefore the pulse height approaches to the pressure corresponding to the static yield stress.

In the large deformation region, the pipe diameter expansion by the pulse incidence causes contraction in pipe axial direction. This contraction is propagated along the pipe in the form of stress wave. When the stress wave reaches the elbow, the whole elbow is pulled toward the pipe inlet. This displacement of the elbow generates a pressure pulse, which is propagated to both upstream and downstream direction.

For the water-propagated pressure pulse, no significant pulse height attenuation at the elbow is observed for such broad pulse as generated by Sk Explosive.

Calculated result by a computer code PISCES-2DELK agrees well with the experimental one in the predication of the pipe deformation.

I. Introduction

The behavior of pressure pulse traveling through fluid-filled thin-walled piping system is of great importance for safety evaluation of heat transport system of power plant where water hammer phenomena may occur. In SMIRT-5, we reported the results of experimental and analytical study [1] on pressure pulse propagation in a plastically deforming pipe filled with water and concluded that (a) pressure pulse with peak over the yield pressure of the pipe are rapidly attenuated to the yield pressure at pipe inlet (large deformation region), (b) the attenuated pressure pulse further reduces its height gradually while traveling through the pipe (small deformation region), (c) the pressure pulse attenuation rate at elbow depends on the pulse width. The objectives of this study with additional experiment and analysis are to clarify the mechanism of pressure pulse attenuation in the small deformation region and detailed behavior of the pressure pulse at elbow.

II. Experiment

Piping system

The experimental facility consists of a test pipe and pulse gun as shown in Fig. 1. Experiments have been performed on 165 mm outer diameter Type 304 stainless steel pipe with and without 90° elbow. Two sizes of pipe thickness are prepared, namely 3.0 and 3.4 mm. The test pipe is tilted 15° upwards in order to let air bubbles go out of the pipe. The downstream end of the pipe is covered by a rupture disk to fill up the pipe with water. A water filling nozzle and an air vent nozzle are installed on the rupture disk holder unit.

The test pipe is joined rigidly to the pulse gun which is fixed to a staff frame. The rupture disk holder unit weighing 46 kg is free in axial direction for straight pipe test. On the other hand the rupture disk holder unit of elbow pipe is fixed to the frame to make the piping system withstand the bending force acting on the elbow.

The pressure pulse is generated by Sk explosive, which is a double layered granular explosive composed of $KClO_4$ and Al with a small amount of soot and additive, and the total energy release is 8.8 KJ/g. The Sk explosive is mounted on a plug and loaded from the bottom of the pulse gun. Then the water is injected from the nozzle.

Instrumentation

Piezoelectric pressure transducers, strain gauges and an eddy current type displacement sensor are used as shown in Fig. 1. Two pressure transducers were mounted in the pulse gun to measure input pulse to a test pipe. Five pressure transducers are distributed along the straight pipe and eleven pressure transducers for the elbow pipe.

Strain in axial and circumferential direction at large deformation region and small deformation region of straight pipe is measured. For elbow test, strain gauges are mounted on outside and inside of the elbow in circumferential and axial direction. Displacement sensor is used to detect the movement of the elbow. The above measurements are recorded on magnetic tape.

The plastic radial deformation of the test pipe is measured with dial gauges mounted on a rotating ring into which the test pipe is inserted.

Experimental results

Pressure histories measured at the pulse gun in straight pipe test are shown in Fig. 2. As the pulse gun is thick-walled, the pressure pulse attenuation is negligible. Therefore the input pressure pulse and reflected wave from the test pipe can be separated from these data as shown in Fig. 3.

The pressure pulse generated by the explosion enters the test pipe and it is reflected by pipe expansion in the form of rarefaction wave. This rarefaction wave is again reflected by explosion product gas at the bottom of the pulse gun and re-enters the test pipe causing second peak in Fig. 3.

The pressure in the test pipe is truncated at the yield pressure of the pipe. Therefore the reflection by the test pipe deformation can be considered as a reflection at constant pressure boundary, where the reflected wave can be easily calculated as shown by the dotted line in Fig. 3. The calculated line agrees considerably well with the obserbed one.

The peak pressure of each transducer is plotted in Fig. 4, where the yield pressures of the pipe is also shown for both static and dynamic (strain rate is 200 s^{-1}) stress-strain relations. The pressure pulse is rapidly attenuated in the large deformation region (0 - 0.5 m) to the dynamic yield pressure. The attenuated pulse further reduces its height gradually in the small deformation region (0.5 - 1.5 m) asymptotically approaching to the static yield pressure, This means that the pressure pulse attenuation in the small deformation region is caused by the dependence of pipe material strength on strain rate. The mechanism of the attenuation is considered as follows.

At high strain rate, the limit of proportionality is extended as shown by A-B-C-D in Fig. 5. We assume that an internal pressure corresponding to the point C stress is loaded to the pipe with the high strain rate. When depressurization begins, strain rate and the yield stress decreases. If the strain rate is reduced to zero instantaneously at point C, the stress changes to the point expressed by E which is on the static stress-strain curve. After the internal pressure is removed, the strain A-F remains. Therefore the energy corresponding to the area surrounded by the points ABCEF is lost in this process. The experimental data are rearranged on the stress-strain diagram as Fig. 6, which demonstrates the above model except the instantaneous strain rate reduction. As the pressure decrease slowly and pipe wall has a mass, the absorbed energy is larger than the simplified model.

The observed strains along the pipe are shown in Fig. 7. Before the pressure pulse arrives, the pipe wall is strained in axial direction. These strains express a stress wave which is generated at pipe upstream. In the large deformation region, the pipe diameter expansion by the pulse input causes contraction in axial direction. This contraction is propagated along the pipe in the form of tensile stress wave, which propagates faster than the pressure pulse in the fluid. When pressure pulse passes through, the pipe wall is stretched in circumferential direction and shrinked in axial direction. It is noticeable that the axial negative strain is larger than that calculated from the hoop strain and Poisson ratio.

The pressure profiles obserbed in the elbow experiment are shown in Fig. 8. Pressure at point e' rises earlier than point d'. This means that a new pressure pulse is generated at the elbow. This pulse is also propagated to downstream and causes the first rise in point f' pressure. The pressure pulse propagated from pulse gun gives the second pressure rise at point e' and f'.

The displacement of the elbow is shown in Fig. 9. When stress wave generated in the large deformation region reaches elbow, the whole elbow is pulled toward the pipe inlet. This sudden displacement generates the new pressure pulse.

The peak pressure of each transducer is plotted in Fig. 10, which shows no significant pulse height attenuation at the elbow for such broad pulse as generated by Sk explosive.

The hoop strain at inside of the elbow is larger than that of outside, as shown in Fig. 11. This is because both hoop and axial tensile stresses result from internal pressure at the outside, and on the contrary tensile hoop stress and compressed axial stresses are generated at inside.

If the strain is elastic, this difference in stress direction has small effect, i.e. the circumferential strain is affected by the axial strain as much as calculated with Poison ratio. In this experiment, however, the hoop stress is at almost yield point, as the pressure pulse is automatically kept as yield pressure of the pipe. Therefore even a little axial stress can cause a large circumferential strain change.

III. Analysis

The experimental results of straight pipe test is analyzed by using PISCES-2DELK [2]. The system is modeled including pulse gun, test pipe and rupture disk holder unit. The pulse gun is expressed by rigid wall and the test pipe is calculated with thin shell option and the rupture disk holder is given as a movable rigid mass. As the boundary conditions for fluid, pressure history are given at exit and point "a" where input pulse is measured. The reflected wave from test pipe is automatically cancelled out because both calculation and experiment account the reflected wave.

The circumferential strain profile in large deformation region is shown in Fig. 12. The calculated results agree well with the experimental one. Figure 13 shows the dynamic strain at the downstream of the pipe. The calculated results agree very well with the observed values.

When the stress wave reaches the pipe exit, the rupture disk holder unit is accelerated toward the pulse gun. Then the holder unit compresses the pipe in axial direction because of its momentum. In this calculation, the holder unit moves 8 mm. This displacement is considered to cause the rather large negative axial strain.

IV. Conclusions

Pressure pulse propagation experiments have been performed on water filled thin-walled type 304 stainless steel pipe with and without an elbow. The experiments reveal :

(a) The rarefaction wave reflected by the pipe deformation can be estimated as the reflection at boundary of constant pressure which is yield pressure of the pipe.

(b) The input pulse is rapidly attenuated to the yield pressure giving large deformation. The attenuated pulse further reduces its height gradually while traveling through the pipe. This gradual attenuation is caused by the dependence of pipe material yield stress on strain rate.

(c) In the large deformation region pipe diameter expansion by the pulse causes contraction in axial direction. This axial deformation is propagated along the pipe in the form of stress wave.

(d) The stress wave causes the elbow displacement which generates another pressure pulse.

(e) No significant pulse height attenuation at elbow is observed for such broad pulse as generated by Sk explosive.

(f) Calculation by a computer code PISCES-2DELK gives good agreement with the experimental results in pipe deformation and strain.

References

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/ 2 / Hancock, S. L., "Application of a Coupled Euler-Lagrange Computer Program to the Structural Response of LMFBR", Nucl. Eng. Des., 42, 69 (1977).

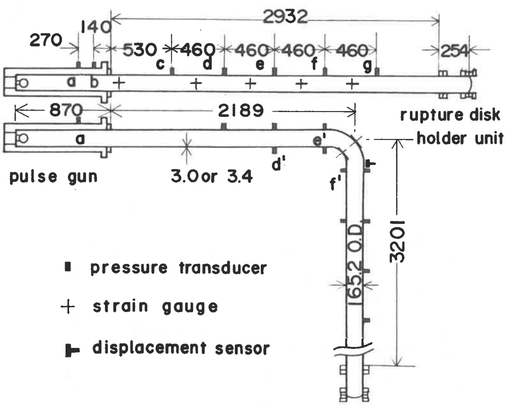


Fig.1 Schematic of Test Pipe and Instrumentation

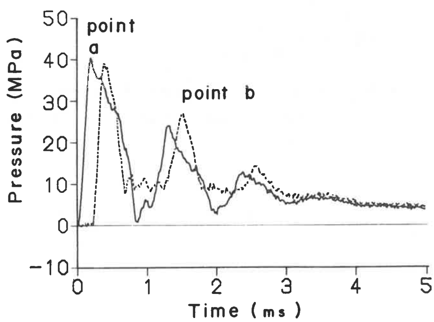


Fig.2 Pressures in Pulse Gun

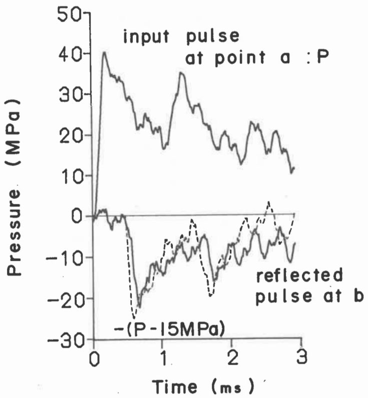


Fig.3 Input Pressure Pulse and Reflected Pulse

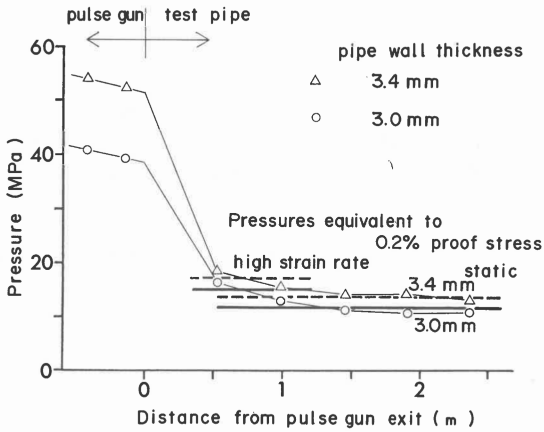


Fig.4 Peak Pressure Distribution

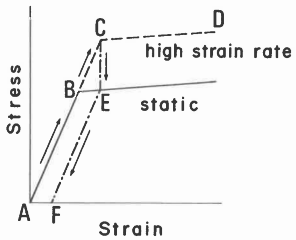


Fig.5 Model of Energy Absorption in Small Deformation Region

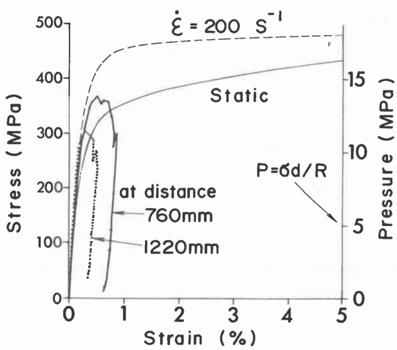
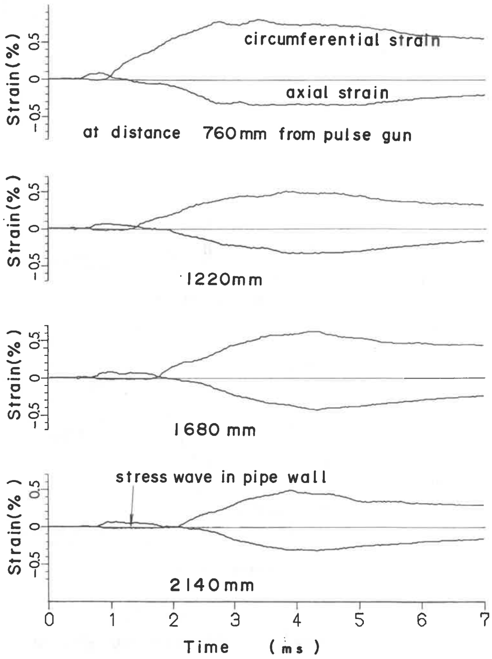


Fig.6 Comparison of Stress-Strain Relation with Loci of Measured Strain and Pressure



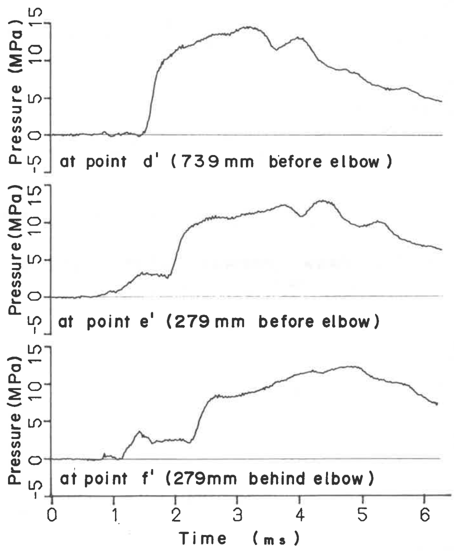


Fig.7 Strains on Straight Pipe **Fig.8 Pressure before and behind Elbow**

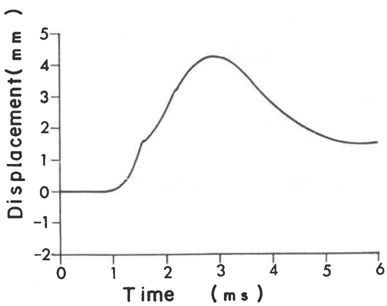


Fig.9 Displacement of Elbow

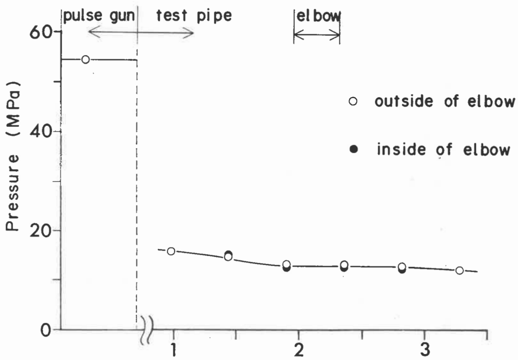


Fig.10 Peak Pressure Distribution for Elbow Test

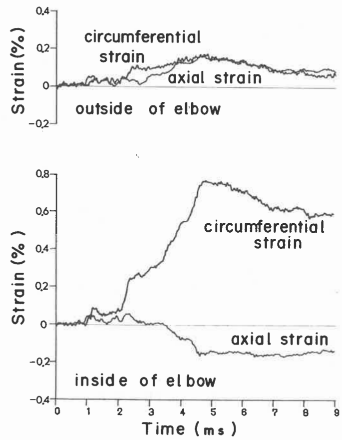


Fig.11 Strain at Elbow

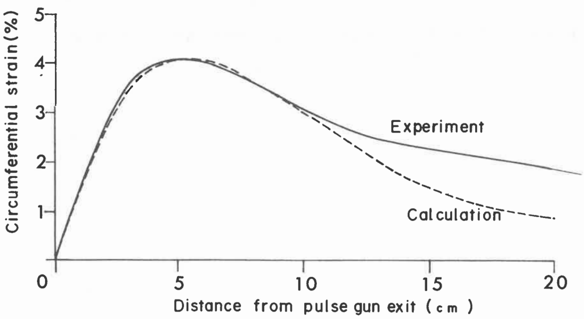


Fig.12 Profile at Large Deformation Region

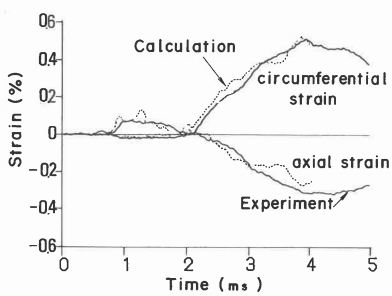


Fig.13 Strain at Downstream of Straight Pipe