Abstract

論 文 の 内 容 の 要 旨

論文題目　Development of Numerical Model for The Safety Design Against Unstable Ductile Fracture in Offshore Pipelines

（海底パイプライン不安定延性破壊防止設計のための数値モデル開発）

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1. Introduction

1.1 Background

Recently, world energy consumption has been growing rapidly with economic growth of developing countries in Asia and Africa [1]. Especially, supply of natural gas is increasing notably due to its rich deposit, low carbon dioxide emission, high heat efficiency. In addition, production of non-conventional natural gas such as shale gas and methane hydrate is expected to increase.

Provisional calculation clarified that transportation by pipelines is economical way as compared with transportation by ships as far as transportation distance is shorter than several thousand kilometers[2]. Laying cost of offshore pipelines is usually lower than that of onshore pipelines. Moreover, offshore pipelines are able to build shortest connection between countries across the sea. It follows that demand of offshore pipelines is expected to grow around the world.

1.2 Unstable ductile crack propagation and previous studies

Unstable ductile crack propagation is one of the important fracture types. Because ductile crack occurs at higher temperature at which almost existing pipelines are now in operation, controlling ductile crack propagation/arrest is so important in pipeline industry.

Mimura first pointed out that because both decompression velocity and crack velocity decrease with decreasing pressure at a crack tip, comparison between both velocities leads to the evaluation for unstable ductile crack propagation/arrest [3]. In 1960s and 1970s, Battelle memorial Institute (BMI) conducted a series of full-scale burst tests on natural gas pipelines and obtained much data for formulating the fracture velocity curve. W. A. Maxey proposed an empirical equation of the fracture velocity curve, and developed a predictive method for the evaluation of unstable ductile crack propagation/arrest, which is well-known as the Battelle Two-Curve Method (TCM) [4]. In the method, crack resistance curve and gas decompression curve are compared: unstable ductile crack is judged to occur if two curves have intersections, if not, the crack is judged to decelerate rapidly and be arrested.

TCM explained above have been applied to onshore pipelines, and the good applicability is well known in pipeline industry. However, a method for predicting fracture behavior in offshore pipelines is not established. W. A. Maxey surveyed offshore pipeline burst tests conducted ever, and proposed the modified crack resistance curve for offshore pipelines[5]. However, the applicability of the modified curve is definitely limited because there were only four full-scale offshore pipeline burst tests, which is not enough to propose an empirical method.

1.3 Unstable ductile crack propagation and previous studies

In the present study, the author developed a numerical model, which is called “UT offshore model” hereafter, to predict unstable ductile crack propagation/arrest in offshore pipelines. The features of the model are as follows:1) water effects such as delayed gas decompression by bubble generation/growth and constrained pipe deformation by surrounding water are incorporated in the model, 2) pipe deformation, gas decompression and bubble growth are formulated based on time dependent one-dimensional partial differential equations which are solved by finite difference method, 3) the model is weak two-way coupling model; the interaction among pipe deformation, gas decompression, bubble growth and crack propagation is considered and 4) the model has a potential to be an engineering tool for offshore pipeline design due to its low CPU cost as compared with three dimensional finite element based models.

The author also conducted underwater rupture tests especially to validate the bubble growth model by observing bubble growth behavior using high-speed camera. In addition, the model was applied to full-scale offshore pipeline burst test. Also, parametric study was conducted by changing parameters such as water depth, mechanical properties of a pipe and pipe geometry to discuss the effects of each parameter on unstable ductile crack propagation in offshore pipelines.

2. The UT offshore model

2.1 Overview

The UT offshore model describes pipe deformation, gas decompression, bubble growth and crack propagation which are shown in Fig. 1. These phenomena are formulated based on time dependent one-dimensional partial differential equations which are solved by finite difference method.

2.2 Pipe deformation model

Pipe deformation model is based on the Freund model in which the governing equation for pipe deformation is one-dimensional partial differential equation with a single parameter representing a deformed shape of a pipe [6]. In the present study, the relationship between deformed shape and shape parameter was determined based on experimental measurements [7].The governing equation for pipe deformation is obtained by using the principle of virtual work.

2.3 Water backfill effect

When a pipe is laid underwater, pipe deformation is constrained by surrounding water. In the present study, the water backfill effect is considered as an added density by calculating kinetic energy of surrounding water that is moved by pipe deformation. Added density is formulated as a function of pipe radius, pipe thickness, water density, water depth and shape parameter.

2.4 Gas decompression model

In the present study, it is assumed that gas flow is one-dimensional and thermodynamic behaviour is based on isentropic change. The governing equations are derived based on mass conservation and momentum conservation. Gas leak from the pipe to the bubble through the crack opening is considered in mass conservation equation.

2.5 Bubble growth model

Bubble is assumed as one-dimensional gas flow with increasing cross sectional area, but gas is supplied from the pipe through the opened crack, see Fig. 2 where ρ_{B}, u_{B}, p_{B}, p_{∞}, $\dot{m}$, R and v are bubble density, flow rate inside bubble, bubble pressure, hydrostatic pressure, mass flow rate from a pipe to a bubble, bubble radius and bubble growth rate, respectively. The governing equations are derived based on mass conservation, momentum conservation and modified Rayleigh-Plesset equation in bubble dynamics[8].

2.6 Crack propagation model

Crack propagation is formulated based on dynamic energy balance where work done by gas to the pipe wall, strain energy generated by pipe deformation behind a crack tip, Kinetic energy of the pipe wall and the surrounding water and strain energy generated by crack tip singularity ahead of a crack tip are considered. In the present study, crack speed dependency of strain energy generated by crack tip singularity is determined based on experimental measurements[9].

2.7 Example of calculation result

The UT offshore model is able to calculate time histories of crack propagation, pipe deformation, pressure inside a pipe, gas flow rate inside a pipe, bubble pressure, gas flow rate inside a bubble, bubble radius and bubble growth rate. Figure 3 shows a calculated example of 3D view of pipe and bubble at each time after the burst, where colors represent value of pressure.

3. Underwater rupture test

3.1 Testing condition

Aluminum pipes with surface notch was located at the bottom of the water tank and pressurized by pure nitrogen until burst happens. Pressurizing system and measurement instruments are shown in Fig.4.

3.2 Testing condition

Figure 5 shows photos of bubble captured by high-speed camera. Changes of bubble radius with time was successfully observed as shown in Fig. 6. Also, internal and external pressure changes were measured by pressure transducers.

3.3 Calculation results by the UT offshore model

Calculation for the rupture tests was conducted using the UT offshore model by inputting the same conditions as the experimental ones. Figure 7 shows calculated bubble radius at each time together with experimental results. Because both of the calculated results show good agreements with the experimental ones, the bubble growth model of the UT offshore model was successfully validated.

4. Calculation for full-scale burst tests

For the validation of the whole UT offshore model, the author conducted calculation for full-scale underwater pipeline burst test performed by C. S. M [10]. The detailed testing conditions are described in Reference 10. The UT offshore model predicted internal pressure changes and crack propagation history well. It follows that the UT offshore model is successfully validated.

5. Parametric study

Parametric study was conducted by changing water depth, pipe thickness, pipe outer diameter, pipe grade and pipe toughness. Reference condition is set to the same condition as the full-scale burst test conducted by C.S.M[10]. Fig. 8 shows the dependence of crack propagation/arrest and pressure distributions inside a pipe on water depth. It was clarified that increasing water depth makes a crack more likely to be arrested mainly because increasing hydrostatic pressure and water backfill have strong effect on crack propagation in offshore pipelines. Also, it is clarified that increasing pipe thickness, decreasing outer diameter and increasing toughness make a crack more likely to be arrested.

6. Conclusions

The conclusions from the present study are presented below:

1) The UT offshore model, which describes pipe deformation, gas decompression, bubble growth, crack propagation and interactions among them, was developed.
2) Underwater rupture tests were conducted, where bubble growth behavior was successfully captured by high-speed camera. Bubble growth model in the UT offshore model was validated by comparing the calculated results with the experimental ones.
3) Calculation for full-scale offshore pipeline burst test performed ever by C. S. M was conducted. Because the UT offshore model predicted well the experimental data, applicability of the model was reasonably ensured.
4) Parametric study clarified that increasing water depth makes a crack more likely to be arrested by the effect of water backfill effect and hydrostatic pressure.

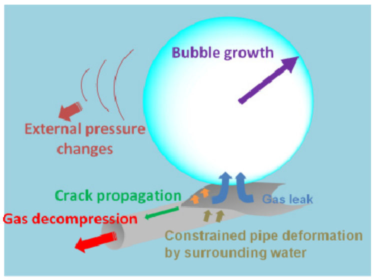


Figure 1 Fracture in offshore pipelines

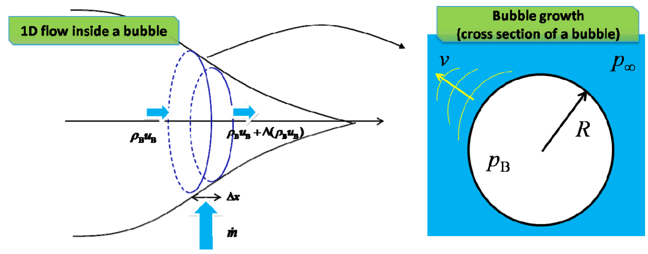
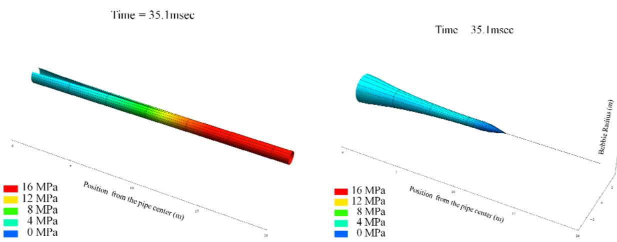


Figure 2 Bubble modeling



(a) pipe (b) bubble

Figure 3 Calculation example, 3D view

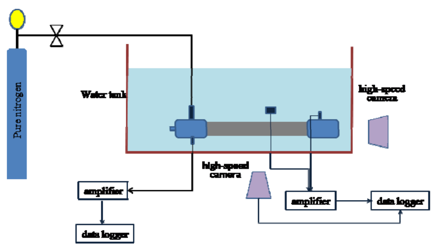
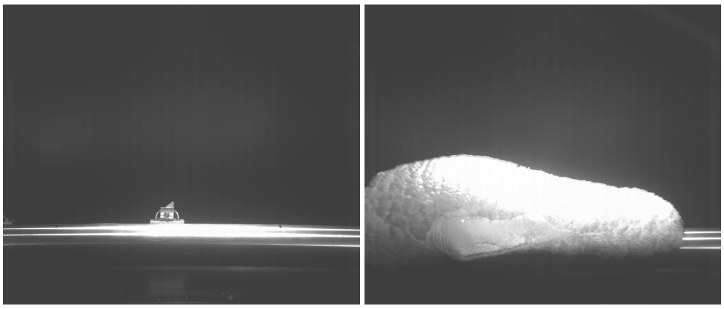


Figure 4 Test arrangement



(a)before the burst (b)after the burst

Figure 5 Bubble growth behavior

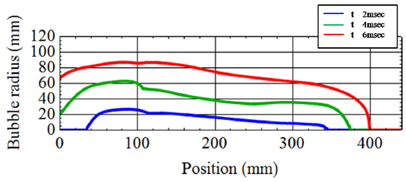


Figure 6 History of bubble radius

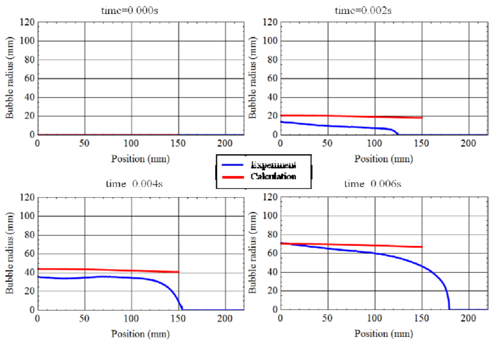
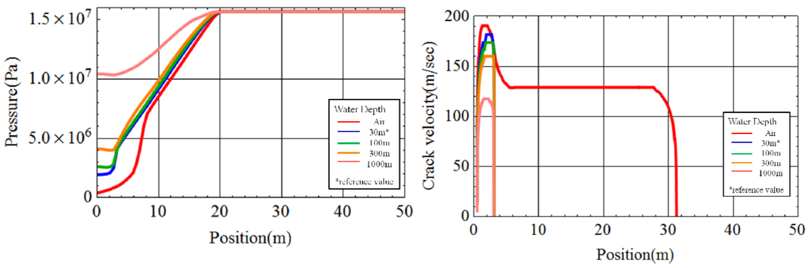


Figure 7 Calculated bubble radius



(a) pressure distribution (b)crack propagation

Figure 8 Water depth effect on gas decompression and crack propagation

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