Reliability analysis of pipes suffering wall thinning based on extreme value analysis of ultrasonic thickness measurement

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Abstract This study proposes to use extreme value analysis to characterize the uncertainty in estimating the wall thickness of carbon steel pipes by ultrasonic testing. The goodness of fit has been examined using experimental data measured from plate samples processed by corrosion test. A model is subsequently developed for predicting the failure probability of carbon steel pipes suffering wall thinning based on Bayesian theorem. In this model, the wall thinning rate predicted by KWU-KR model can be updated by offering measurement results and corresponding distributions of measurement error. Compared with the results from extreme value analysis, the failure probability predicted in terms of normal distribution could underestimate the risk of pipe failure.

Keywords: pipe wall thinning, risk analysis, ultrasonic testing, extreme value analysis, Bayesian theorem, measurement uncertainty

1. Introduction

Carbon steel pipes are prone to wall thinning due to corrosion or erosion in various applications. Ultrasonic testing (UT) serves as a common technique to measure pipe wall thickness to maintain the integrity. However, measurement results are inevitably affected by stochastic error. Reasonable quantification of error distribution is important for the reliability analysis of the pipes. Prevalent practices to characterize measurement error are based on guide to the expression of uncertainty in measurement[1] or normal distribution. Large error could occur with a certain probability, especially in overestimation of thickness, resulting in misleading pipe reliability analysis. However, this cannot be correctly accounted for by the normal distribution with light tails.

Therefore, this study proposes to use extreme value analysis to characterize the distribution of error in the overestimation of pipe wall thickness by UT. By incorporating the results of extreme value analysis, reliability analysis of pipe suffering wall thinning is performed using a developed Bayesian model.

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2. Materials and methods

2.1 UT experiment

Grooves of semi-ellipse cross section with different depths (d) and widths (w) were machined on each of 63 plates (carbon steel, S50C) as shown in Fig. 1(a). Their surfaces were processed by corrosion test by soaking for 100 hours in iron (III)-chloride-based etchant whose temperature was kept as 50 °C by water bath to simulate realistic wall thinning as demonstrated in Fig. 1(b).

The thickness of the plates was measured by micrometer and pulse-echo UT, respectively, at two positions on the centerline of the grooves. The instrument, UI-25 (RYOSHO Electronics Co Ltd, Japan), was employed and the measurements used 5 MHz frequency, two bandwidths (narrow and wide), three beam path methods (up, first echo and zero-cross), and two probes (5C5N

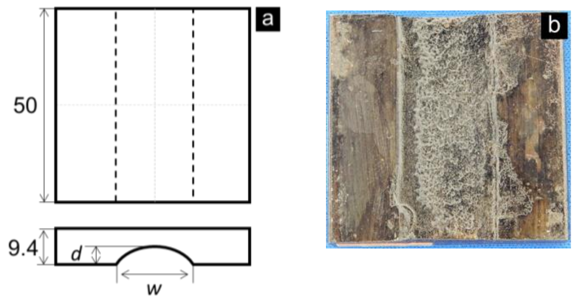

Fig.1 Illustration of plate samples, unit: mm

and 5C10N, Japan Probe Co Ltd). Calibrations and measurements based on 12 different combinations of the conditions were performed.

2.2 Extreme value analysis (EVA)

Measurement error of UT was calculated as the difference between the thickness obtained by UT, x_m, and that gauged by the micrometer, x_r, by

$$\varepsilon = x_m - x_r \quad (1)$$

where x_r is regarded as the true thickness. In order to characterize the distribution of the measurement error, ε, in overestimation, block method is adopted. This method groups observations into blocks of equal or approximately equal size and takes as data the maxima in each block for EVA. Subsequently, generalized extreme value (GEV) distribution can be used to fit the data through maximum likelihood method. In this study, the 12 measurements obtained at the same position were grouped into one block. As a result, a dataset composed of 126 observations was generated for EVA.

2.3 Bayesian model

To predict the failure probability of carbon steel pipes suffering wall thinning, a model that can evaluate defect growth is demanded. Thus, KWU-KR model[2] is adopted, which can predict corrosion rate, φ_{KWU-KR}, based on given operation and pipe conditions. Accordingly, the wall thickness of pipe, x_c, at time t is calculated by

$$x_c = x_o - \frac{E\varphi_{KWU-KR}t}{\rho} \quad (2)$$

where ρ is material density of pipe, x_o is original wall thickness, E is a factor following lognormal distribution and aims to make up the discrepancy between predicted and practical corrosion growth. It is preferable to adjust E case by case to predict corrosion growth more accurately. Therefore, Bayesian theorem is adopted to update the distribution of E with inspection data. Due to the difficult to deal with E directly, the posterior distribution of x_r, g_r, is inferred instead. The prior and the likelihood are obtained based on KWU-KR model and the fitted GEV distribution, respectively. Finally, the posterior distribution of E, g_E, was deduced numerically using Monte-Carlo method according to Eq. (2) with the samples of g_r. The samples of g_E is subsequently used as input of Eq. (2) to predict future corrosion growth. Based on the distribution of wall thickness at a future time t_p, the failure probability can be determined by

$$p_f(t_p) = \int_{x_s}^{x_o} g_{r|t_p}(x)dx \quad (3)$$

where x_s is safety criterion.

3. Results and Discussion

The distribution of the data extracted by block method is shown in Fig.2 along with the fitted GEV distribution. It is indicated GEV distribution is able to fit the data reasonably.

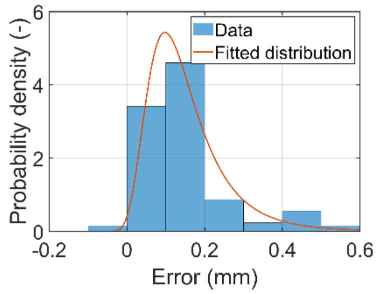

Fig.2 Fitted GEV distribution of measurement error

It is assumed that an inspection is performed after 1 year operation and the measured pipe thickness is 8.4 mm. Accordingly, the distribution of E was updated using the inspection result and the pipe thickness was predicted till 40 years. The failure probability was calculated in terms of Eq.(3) by defining the safety criterion as 0.6 times x_o as shown in Fig.3. By comparison, the predicted failure probability based on GEV distribution is more conservative, which can be used as an index in decision making for maintenance. More details of this study will be presented at the meeting.

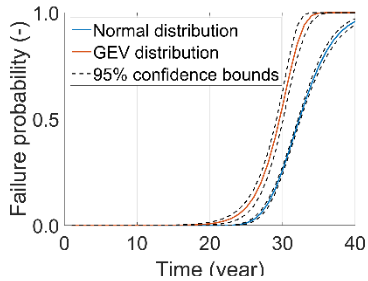

Fig.3 Predicted failure probability with confidence bounds

Reference

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