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FRACTURE ASSESSMENT AND RELIABILITY ANALYSIS OF CAST IRON WATER PIPES

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ABSTRACT

In this paper, Monte Carlo simulation method is used for fracture assessment and reliability analysis of cast iron pipes. Fracture failure is considered as a limit state for corrosion affected cast iron pipes. It will be shown how this failure mode affects the probability of pipe failure.

Sensitivity analysis also is carried out in the paper to show the effect of changing basic parameters on the reliability and life time of the pipe. It can be concluded that the applied methodology can consider different random variables for estimating life time of the pipe and it can also provide scientific guidance for rehabilitation and maintenance plans. In addition, the results of the fracture assessment and reliability analysis in this study can be useful for the design of more reliable new pipeline systems.

Keywords: fracture assessment, reliability analysis, life time prediction, cast iron pipes, water mains, corrosion, Monte Carlo simulation

INTRODUCTION

Cast iron has been widely used as a construction material in general and as pipe material in water industry, in particular before the 1960s. In the United Kingdom, although cast iron pipes are being phased out of the water pipeline network, a significant portion of current networks are comprised of cast iron pipes and some of them can be up to 150 years old (Mohebbi and Li 2011). There are about 335,000 km of water mains in the UK and more than 60% is estimated to be cast iron pipes (Water UK 2007). Pipes used in trunk mains networks, which take water from reservoirs to major settlements, are of large diameter, usually greater than 300 mm (12 inches), whilst pipes used in distribution mains networks are typically of a diameter between 75 to 300 mm (3 to 12 inches).

Same as other infrastructure, age is one of predominant causes of pipe failure. Thus, it is predictable for infrastructure managers that the number of incidents in urban water supply systems is likely to be increasing in the future as systems grow older.

To have an optimum strategy for maintenance and rehabilitation plans in water supply management systems, accurate prediction of service life is essential. Predictive models can be classified into deterministic and probabilistic. Deterministic models do not consider variation in deriving break patterns, but are based on pipe age and breakage history. Probabilistic models consider some or all parameters as random variables that affect the system. A comprehensive review of models for service life prediction of water mains (deterministic and probabilistic) can be found in Rajani and Kleiner (2001).

In the case of failure assessment of cast iron water pipes, the uncertain nature of the problem necessitates infrastructure managers to use probabilistic approaches rather than deterministic ones.

It has been found (Rajani and Kleiner 2001, Mohebbi and Li 2011) that material corrosion is the most common form of pipeline deterioration and is a matter of concern for both the safety and serviceability of the pipes.

Corrosion affects strength of the pipe and it is of practical importance to know how to incorporate the effect of corrosion in the structural analysis of a pipeline. There are several parameters which may affect corrosion rate and hence the reliability of pipelines. In conventional methods for service life prediction of pipelines, these parameters are considered to be deterministic. However, in reality there are uncertainties associated to these parameters. In a time-dependent reliability problem all or some of uncertain (random) variables are modeled as stochastic processes. The evaluation of the contributions of these uncertain parameters is carried out by using sensitivity analysis techniques.

Various research has been undertaken on assessment and service life prediction of buried pipes, using both deterministic and probabilistic methods. Ahammed and Melchers (1997) proposed a reliability method to predict the probability of failure of underground pipes. In their study models for both the residual capacity and stresses in the pipe were proposed. A nonlinear corrosion model was used to represent the loss of pipe wall thickness over time. The probability of failure of the pipes was calculated by first order second moment method. Camarinopoulos et al. (1999) presented a method to assess the reliability of water pipes, considering both the corrosion pit depth and the load that was likely to cause failure. A power law model was developed for corrosion pits which leads to the loss of wall thickness. Monte-Carlo simulation technique was employed for reliability calculation of the pipes. Yves and Patrick (2000) also presented a method to calculate the reliability of the buried water mains, using the maintenance records and the Weibull distribution for underlying variables. The method appears to rely entirely on the historical data, which in most cases is unknown.

Rajani et al. (2000) proposed a method to estimate the remaining service life of grey cast iron mains by considering that the corrosion pits reduce the structural capacity of the pipes. The residual capacity of the pipes was calculated by a reiterative model based on corrosion pit measurement and the anticipated corrosion rate, which may not always be available due mainly to operational conditions. To consider the uncertainties involved in all factors contributing to the corrosion and subsequent failures, various research on probabilistic assessment of cast iron pipes has been undertaken. Sadiq et al. (2004) developed a probabilistic method to predict the remaining service life of in-service pipes based on Monte Carlo simulation. A model of residual capacity of the pipes was proposed based on corrosion induced deterioration of the pipe. The failure of pipes was determined when the factor of safety of an individual pipe segment falls below a minimum acceptable value set by the utility owner.

Lee et al (2010) also used FORM (first order reliability method) to evaluate time-dependent reliability index for a fully deteriorated piping component rehabilitated with FRP considering the demand of internal fluid pressure, external soil pressure and traffic loading. Mahmoodian and Li (2011a) developed an analytical time dependent reliability method to predict the probability of failure for concrete buried pipes. The analytical results, obtained from first passage theory, then are verified by Monte Carlo simulation method. Mahmoodian and Li (2011b) also used a numerical method (Monte Carlo simulation) for system reliability analysis of cast iron pipes. They considered two limit state functions as failure modes of cast iron pipes and by using system reliability analysis they predicted service life of corrosion affected cast iron mains.

An inspection of failures of trunk mains in service reveals that most cast iron water mains failures are of fracture type, i.e., the failure is caused by the growth of a crack induced stress concentration and subsequent collapse of the pipe (Marshall 2001). Cast iron pipes can fail as a result of loss of toughness due to the stress concentration at the tips of cracks or in general defects in the pipes. A review of the research literature (see reference) shows that the time effect of the deterioration process of cast iron pipes has not been explicitly considered in the assessment of pipe collapse. It is well known that both the deterioration of pipes and the external actions on the pipes are not only time-variant but also highly uncertain. As such, a method that cand consider these features of time-variant uncertainty is more appropriate in assessing the pipe collapse and its remaining service life.

In this paper, Monte Carlo simulation method is used for fracture assessment and reliability analysis of a cast iron pipe during its service life. Sensitivity analysis also is carried out to show the effect of each basic variable on the reliability and service life of the pipe system.

CORROSION MODEL

The predominant deterioration mechanism on the exterior of cast iron pipes is electro-chemical corrosion with the damage occurring in the form of corrosion pits. The damage to cast iron is often identified by the presence of graphitisation, a result of iron being leached away by corrosion. Each form of metal loss represents a corrosion pit that grows with time and reduces the thickness and mechanical resistance of the pipe wall. This process eventually leads to the breakage of the pipe.

Corrosion pits have a variety of shapes with characteristic depths, diameters (or widths), and lengths. They can develop randomly along any segment of water pipe and tend to grow with time at a rate that depends on environmental conditions in the immediate vicinity of the water main (Rajani & Makar 2000). Models for estimation of the depth of corrosion pit are usually presented the form of the following equation:

$$a = kt^n \tag{1}$$

where t is exposure time and K and n are empirical constants largely determined from experiments and/or field data.

Rajani et al. (2000) proposed a two-phase corrosion model to accommodate this self-inhibiting process.

$$a = \alpha t + \beta\left(1 - e^{-\lambda t}\right) \tag{2}$$

where α, β and λ are constant parameters.

In the first phase of the above equation there is a rapid exponential pit growth and in the second phase there is a slow linear growth. This model was developed based on the data set that lacked sufficient points in the early exposure times. Therefore prediction of pit depth in the first 15-20 years of pipe life should be considered highly uncertain when equation (2) is used.

Formulation of Fracture Assessment and Reliability Analysis

Failure can be defined in relation to different possible mechanisms and can be described by a limit state. In the theory of structural reliability these criteria can be expressed in the form of limit state functions as follows:

$$G(S,R,t) = S(t) - R(t) \tag{3}$$

where G( ) is termed the limit state function, S(t) is the action (load effect) at time t and L(t) is the critical limit (resistance) for the action or its effect.

The reliability of a structure or a component is defined as its probability of survival as follows:

$$\mathrm{Reliability} = \mathrm{P_S} = 1 - \mathrm{P_f} \tag{4}$$

where $\mathrm{P_S}$ is the probability of survival and $\mathrm{P_f}$ is the probability of failure. There are two approaches for calculation of the probability of failure in a time dependent reliability analysis problem: Analytical approaches and numerical approaches. In this study numerical method (Monte Carlo simulation) is used for calculation of the probability of failure.

Considering the safety definition, the structure will fail if its resistance R is less than the stress resultant S action on it. Therefore the probability of failure can be expressed as follows:

$$\mathrm{P_f(t)} = \mathrm{P[R(t) - S(t) \leq 0]} = \mathrm{P[G(R(t), S(t)) \leq 0]} \tag{5}$$

In the presence of corrosion, failure can be defined as when the relevant stress intensity factors exceed fracture toughness. To consider this failure criteria, fracture limit state function is established as follows:

Fracture toughness limit state

Stress Intensity Factor, K, is used in fracture mechanics to more accurately predict the stress state ("stress intensity") near the tip of a crack caused by a remote load or residual stresses. It is a parameter that amplifies the magnitude of the applied stress that includes the geometrical parameter (load type). Laham (1999) presents the formulation for stress intensity factor as the following

$$K_I = \sqrt{\pi a}\sum_{i=0}^{3} \sigma_i f_i\left(\frac{a}{d}, \frac{2c}{a}, \frac{R}{d}\right) \tag{6}$$

where

$\mathrm{K_I}$ = stress intensity factor for crack mode I (more common mode of cracks in pipes)

a = depth of the corrosion pit

σ_i = stress components normal to the prospective crack plane

$\mathrm{f_i}$ = geometry functions, depend on a, c (half-length of crack) and R (internal diameter of pipe)

When a changes with time, the time dependent form of stress intensity factor would be:

$$K_I(t) = \sqrt{\pi a(t)} \sum_{i=0}^{3} \sigma_i f_i(t) \tag{7}$$

If K_{IC} is the critical stress intensity factor, known as fracture toughness, beyond which the pipe cannot sustain the pit crack, Therefore the limit state function would be

$$G(K_{IC}, K_I, t) = K_{IC} - K_I(t) \tag{8}$$

and the failure criterion for the pipe is: $K_{IC} < K_I(t)$ (9)

Stresses in a buried cast iron pipe

Rajani et al. (2000) developed a formulation for total external stresses including all circumferential and axial stresses. σ_θ is hoop or circumferential stress, which is equal to $\sigma_F + \sigma_S + \sigma_L + \sigma_V$, where σ_F is hoop stress due to internal fluid pressure, σ_S is soil pressure, σ_L is frost pressure and σ_V is traffic stress.

Table 1 Stresses on buried pipes considered in this study

Stress Type	Model	Reference
σ_F , hoop stress due to internal fluid pressure	$\frac{pD}{2d}$	Rajani et al. 2000
σ_S , soil pressure	$\frac{3K_m\,\gamma\,B_d^2\,C_d\,E_P\,t\,D}{E_P\,d^3 + 3K_d\,p\,D^3}$	Ahammaed and Melchers 1994
σ_L , frost pressure	$f_{frost} \cdot \sigma_S$	Rajani et al. 2000
σ_V ,Traffic/vehicular stress	$\frac{3\,K_m\,I_c\,C_t\,F\,E_P\,d\,D}{A(E_P\,d^3 + 3K_d\,p\,D^3)}$	Ahammaed and Melchers 1994
σ_{T_e} , Thermal stress	$-E_P\,\alpha_P\,\Delta T_e$	Rajani et al. 2000
$\sigma_{\acute{F}}$, axial stress due to internal fluid pressure	$\frac{p}{2}\left(\frac{D}{d} - 1\right)\nu_p$	Rajani et al. 2000

Similarly axial stress, σ_x , would be equal to $\sigma_{Te} + (\sigma_{\acute{F}} + \sigma_S + \sigma_L + \sigma_V)\,\nu_p$ where σ_{T_e} is stress related to temperature difference, $\sigma_{\acute{F}}$ is axial stress due to internal fluid pressure, ν_p is pipe material Poisson’s ratio and other parameters have already mentioned. Equations and references used for above mentioned stresses have been presented in Table 1.

Worked Example

The proposed Monte Carlo method for system reliability analysis is applied on an worked example. The input data for a cast iron pipeline system is presented in Table 2.

The study presented here included 1000 iterations in each Monte Carlo simulation, to develop relationship between the age of the pipe and the probability of the pipe failure.

The common corrosion model presented in Equation (1) was used in reliability analysis in this study.

Table 2 Values of basic random variables for reliability analysis in the worked example

Symbol	**Parameter**	**Units**	**Min**	**Mean**	**Stdev**	**Max**
S	Toughness exponent	-	0.5	1	0.1	1.2
b_1	Geometric constant for Strength of pipe	-	-0.3	-0.25	0.03	-0.2
P	Internal Pressure	MPa	0.2	0.64	0.17	1.3
D	Internal diameter	mm	240	254	14.28	260
d	Wall thickness	mm	-	16	0.7	-
α	Final pitting rate constant	Mm/yr	0.001	0.009	0.0005	0.015
β	Pitting depth scaling constant	mm	2.5	6.27	1.5	7.5
λ	Corrosion rate inhibition factor	Yr^{-1}	0.01	0.1	0.04	0.18
K_m	Bending moment coefficient	-	-	0.235	0.04	-
C_d	Calculation coefficient	-	-	1.32	0.25	-
B_d	Width of ditch	mm	-	625	125	-
E_P	Modulus of elasticity of pipe	MPa	-	105000	15000	-
K_d	Defection coefficient	-	-	0.108	0.02	-
I_c	Impact factor	-	-	1.5	0.35	-
C_t	Surface load coefficient	-	-	0.12	0.025	-
F	Wheel load of traffic	N	30000	50000	20000	100000
A	Pipe effective length	mm	-	5800	200	-
γ	Unit weight of soil	N/mm^3	-	1 8.5×10^{-6}	18 $.5\times10^{-7}$	-

Results and analysis

A MATLAB code was written to perform Monte Carlo simulation using inverse transform method for random number generation (Melchers 1999). The results in Figure 1 show the probability of failure changing with time. This result provide a realistic information on the prediction of service life to infrastructure.

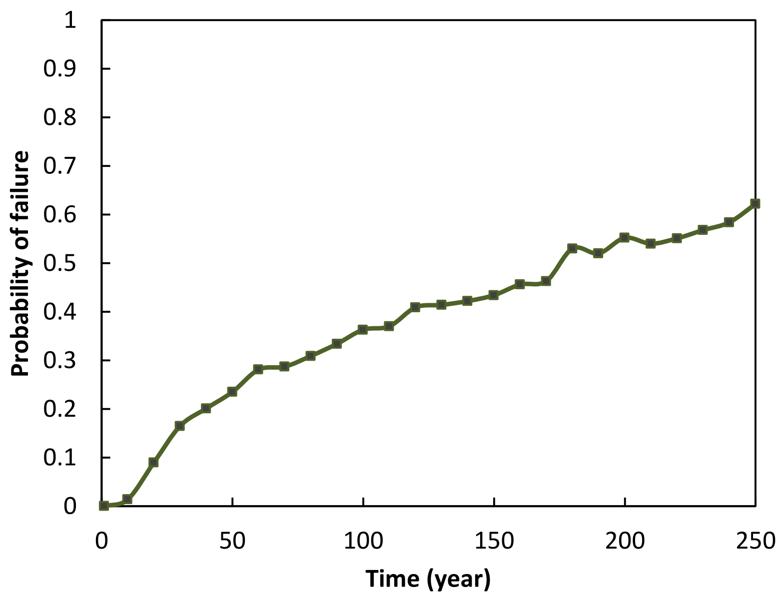

Figure 1- Failure probability of fracture limit state

For repair and rehabilitation planning analysis of the system, the time of the fracture of pipe, i.e.,T_c , can be determined for a given acceptable risk P_a. For example, using the graph in Figure 1, it can be obtained that T_c = 40 years for P_a= 0.2. If there is no intervention during the service period of (0, 40) years for the structure of concern, such as maintenance and repairs, T_c represents the time for the failure of the pipe, based on the reliability analysis. The information of T_c (i.e., time for intervention) is of practical importance to structural engineers and infrastructure mangers with regard to planning for repairs and/or rehabilitation of the pipeline. An optimum funding allocation for the pipeline can be concluded by doing cost analysis for the repair and replacement of corroded pipes with higher risk of failure.

Sensitivity Analysis

To analyze the effect of variables on the reliability of the pipeline, a parametric study was carried out. The effect of changing in pipe wall thickness on the probability of failure has been shown in Figure 2. The graphs show that the thicker the pipe wall, the longer the service life of the pipe. Although this correlation can be obvious without any calculations, the amount of increase in service life is of practical interest for design engineers in design of new pipeline systems. The designer can analyze how using a thicker pipe can improve the service life of the system. A cost benefit analysis can clearly show either more capital investment for having a long life pipeline system (thicker pipe wall) is economical or not. For instance, assuming $P_a = 0.2$ as acceptable risk, the result presented in Figure 2 shows that by increasing the wall thickness from 14mm to 16mm the service life of the system increases from 15 years to 40 years. Interestingly, changing the wall thickness from 14mm to 18mm will dramatically increase the service life of the system from 15 years to 150 years. This considerable difference in service life may encourage the asset managers for more capital investment to have thicker pipes with significant longer service life.

The effect of changing of pipe diameter on probability of failure was also examined by using different typical sizes of cast iron water mains. The results for three various diameters are presented in Figure 3. In this analysis, except the wall thickness (which was increased for greater diameters correspondingly), all other variables were kept the same. As the diameter increases, the difference between service lives of pipes increases for higher degree of risk.

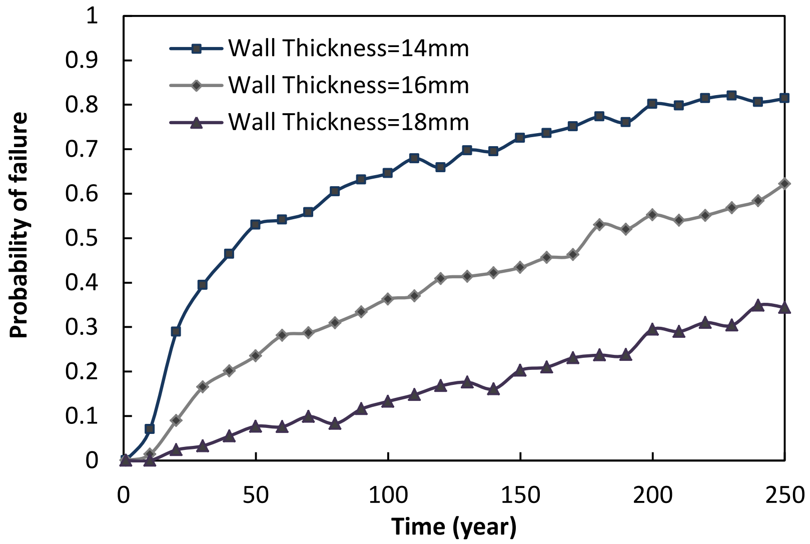

Figure 2- Effect of wall thickness on probability of failure

The graphs in Figure 3 show that, for an acceptable risk of 20 percent ($P_a = 0.2$), a pipe with diameter of 203mm will have less than 18 years service life, while at the same condition, a pipe with diameter of 305mm will have a service life more than 28 years.

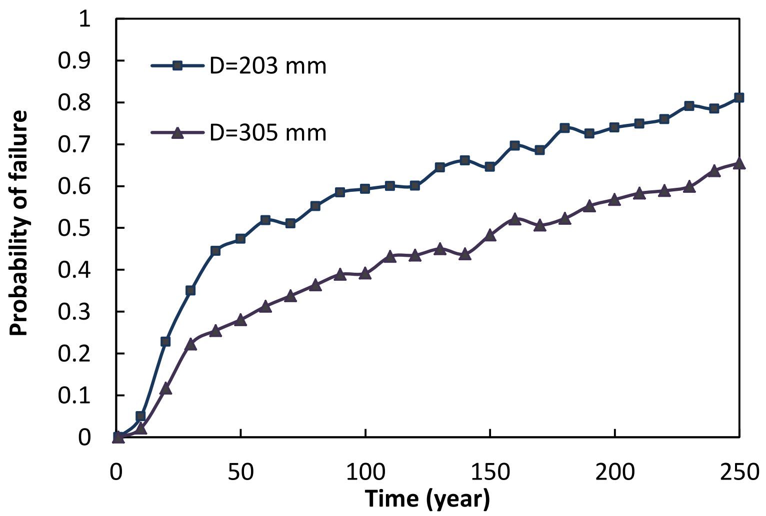

Figure 3- Effect of pipe diameter on probability of failure

Fracture toughness of iron base material can be changed by changing the amount of Carbon used in the production process. To study how change in properties of pipe material can change the reliability of the pipe, different fracture toughness were examined. Figure 4 shows the effect of fracture toughness of pipe material on probability of failure. As it can be concluded from illustrated results, by increasing ductility of pipe material (e.g. increase in fracture toughness) service life of the pipe increases.

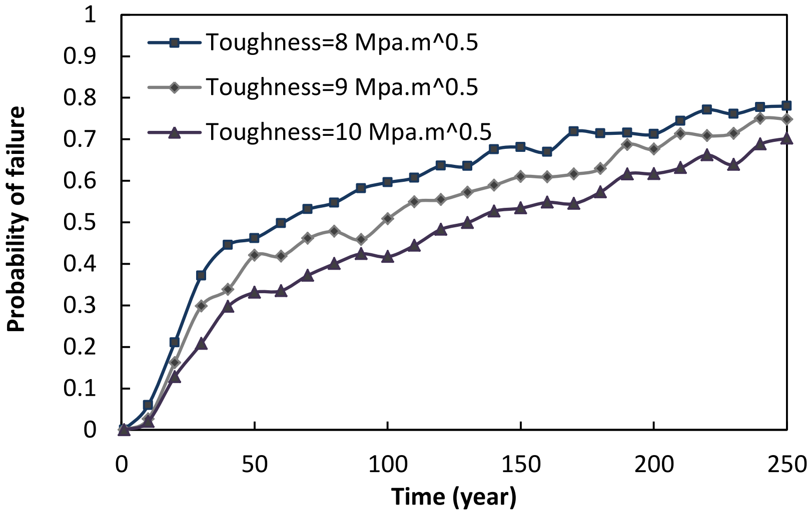

Figure 4- Effect of fracture toughness (K_c) of pipe material on probability of failure

CONCLUSIONS

Fracture assessment of corrosion affected cast iron pipes has been carried out in this paper using reliability analysis method. The service life of the pipeline is predicted based on fracture criteria. A parametric study has also been undertaken to identify factors that affect the probability of pipe failure due to corrosion. The results show how changes in the pipeline material property and pipeline geometry affect the service life of the pipe. It has been found that the thicker the pipe wall, the longer the service life. These results can be used by design engineers for designing of more economical new pipeline and it can help infrastructure managers to develop a risk-informed and cost-effective strategy in the management of corrosion affected pipelines. It can be concluded that reliability methods are rational tools for comprehensive fracture assessment of corrosion affected pipelines. Accurate prediction of the service life of existing pipes has the potential to achieve risk-cost optimization management of the system.

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