Reliability Analysis of Pipeline Network

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Abstract

The aim of the work presented in this paper is development and application of a common scientific methodology for the assessment of reliability of the pipeline network energy systems. The developed methodology is applicable for district heating, gas and oil supply networks. The reliability of all these systems depends on the degradation mechanisms and structural integrity of pipes. The developed approach for assessment of reliability for pipeline networks is treated as a complex task, which involves the probabilistic mathematical and deterministic-probabilistic structural integrity analyses. As example in this paper this approach was applied for the analysis of Kaunas (Lithuania) district heating system. In the first step of research the statistical analysis was performed and the piping with the highest failure rate was determined. The next step was the integrated deterministic-probabilistic structural integrity analysis. This analysis evaluates the uncertainties associated with loads, material properties, and geometrical parameters. The pipe rupture probability dependence on the defected zone thickness and loading was indentified. Finally, Bayesian method was applied for the integrated assessment of failure probability (and opposite characteristic – reliability) of the district heating network piping. The reliability of pipelines (per 1 km per year) depending on operation time was calculated.

Keywords: Reliability Analysis, Deterministic-Probabilistic Structural Integrity Analyses, District Heating Network Pipeline, Bayesian method.

1. Introduction

In bigger cities of Lithuania and other Baltic countries the district heating (DH) systems were designed and installed more than 30 years ago. Due to the ageing of piping installation of new technologies should help to increase system efficiency. However, main pipelines are usually replaced only when the following reasons occur: the failure (rupture) of pipeline or throughput of the piping is not enough. Therefore, bigger part of pipeline and its components (valves, muffs, connections and etc.) are near the end of their lifetime. Frequent failures of the main piping during hydraulic testing and normal operation also show the end of piping lifetime. For this reason the evaluation of the real district heating piping operation reliability and of the risk factor is important for safety operation. Also, this evaluation helps to identify the weakest system node, take necessary measures to prevent accidents or find an optimal solution in case of an accident.

There are research works devoted for investigation of piping degradation mechanisms [1, 2] or assessment of piping system reliability based on statistical data [3, 4], structural integrity analysis which are performed by using analytical formulas [5, 6] or finite element method [7]. However there are no systematic evaluation methods or single technology related to real district heating piping operation reliability and risk factor evaluation and the weakest system node identification, accident prevention, optimal solution evaluation if there is an accident and other.

Kaunas DH system is one of the most complex system designs in Lithuania. The main heating pipelines are over 160 km long. In order to evaluate ageing mechanisms like corrosion, fatigue, the change of material properties in all DH system it is important to evaluate uncertainties associated with material properties, geometrical parameters, boundaries and other parameters. Therefore, a probability-based approach was applied for the deterministic-probabilistic structural integrity analysis of DH.

The aim of this work was to determine the reliability of selected part of DH network pipeline. For this purpose the most dangerous (with the highest failure rate) part of the network was selected according to statistical analysis results. As usually the pipe failure occurs at movable support section the structural evaluation of previously selected pipeline part was done to find out the most loaded section with movable support. The next step was to define the pipe failure probability due to of various parameters. And finally, Bayesian method was applied for integrated assessment of reliability of the selected part of district heating pipeline network.

2. Statistic analysis of pipe failure cases

For the reliability analysis of district heating network there were collected data: failures (ruptures) of pipelines, pipelines repair times, diameters and types of pipes, groundwater levels, causes of the failures, etc. Collected data consists of AB “Kaunas energy” information about Kaunas district heating system of last three years. Kaunas district heating system is one of the most complicated and the oldest in Lithuania, the data collected on this system well represents the other systems installed in the bigger cities of Lithuanian. Performed initial statistical analysis shows that failure rate (per 1 km per year) depends on piping laying technique and technical properties (diameter) of pipes (Figure 1 and Figure 2).

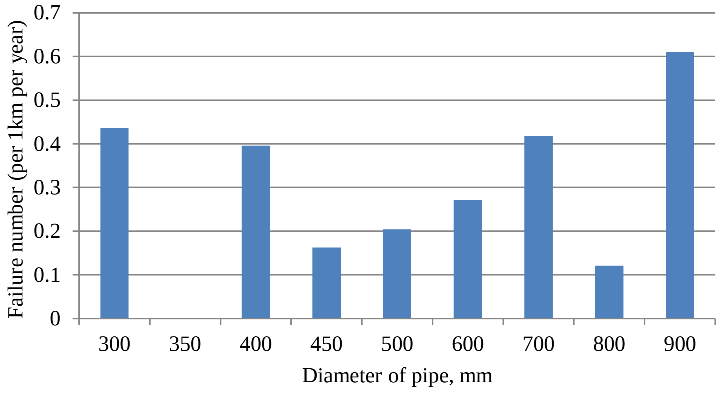

Figure 1. Failure rate (per 1 km per year) dependence on piping technical properties(diameter of pipe, mm).

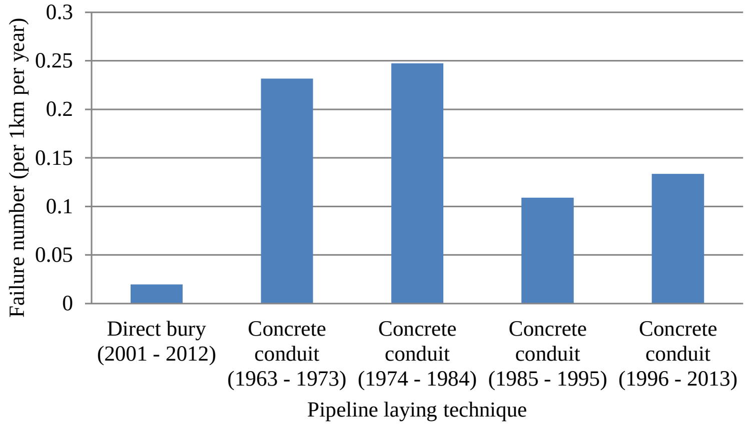

Figure 2. Failure rate (per 1 km per year) dependence on piping laying technique.

The part of district heating network with the highest failure rate was identified with respect to

- calculated failure rates that are presented in Figure 1 and Figure 2;
- information about district heating system (length of piping with analysed diameters and lying techniques).

The selected part of district heating network (diameter of pipe 400 mm, concrete conduit (1974-1984)) is lying in the centre of Kaunas. Not only citizens heat their flats and houses, but also the major public and city objects are located in this district.
This part (with the highest failure rate) was analysed in more details performing deterministic-probabilistic structural integrity analysis.

3. Deterministic-probabilistic structural integrity analysis

3.1 Analysis of failure reason and aging of district heating system

Main mechanisms that have influence to DH systems lifetime are the metal degradation/ageing due to operation and environmental conditions. One of the leading cause which shorten the lifetime of DH pipeline system is the corrosion. Using the collected information about failures of the pipeline the damage cause and ageing processes were analysed. The analysis results show what damaging mechanism dominates and allows determining the actions for elimination of these causes.

DH system pipeline failure data analysis was performed on AB "Kauno energija" stored data base on last three year period. According to collected failure data recorded pipeline failure occurred for the following causes:

- External effect,
- Poor quality of pipeline welding,
- Poor quality of pipeline additional protection (leaking concrete channel, leaking concrete element connection, leaking chamber lid).

Structured information about pipeline failure according to the previously mentioned causes is presented in Figure 3.

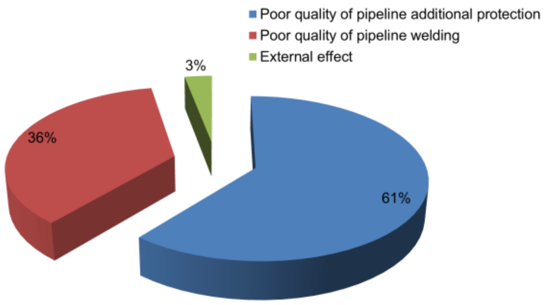

Figure 3. The number of Kaunas city DH pipeline failure according to its causes

According to the presented results it can be seen that only 3% of total number of pipeline failures occurs due to external effect. Initiation of corrosion appears in case of poor quality of pipeline welding or poor quality of pipeline additional protection that results to pipeline failures due to corrosion. Performed failure data analysis shows that failure due to ageing mechanism (corrosion) represents 97% of cases. Other ageing mechanisms that lead to pipeline failure were not registered in failure data base.

In 2007 UAB "EKOTERMIJOS" service has carried out applied research work [8] which purpose was to determine the condition of heating water and heating system components. For this purpose survey of DH systems which produce over 5 GWh heat energy per year was carried out. The results were obtained of 76 DH systems. One of surveys result has revealed that metal corrosion rate in the heating water vary from

0.05 to 0.2 mm/year. However not only internal corrosion but also external corrosion is potentially dangerous for the pipeline. As DH pipelines are built in underground channels they are exposed to corrosive environments and need constant supervision. Thus, the operation of heat pipes built in underground channels in poor waterproofing, leads to constant flooding of rain, snowmelt, groundwater and often other water pipes close to the DH pipeline, which further accelerates the corrosion process. Old hydro and thermo insulation (mineral wool covered with sheet metal, asbestos-cement on the metal net or fiberglass) eventually breaks down and becomes ineffective. Loss of hydro protection contributes to the accumulation of moisture on the surface of the metal pipe and eventually reinforces the processes of corrosion-erosive wear of the material. Corrosion processes of outer surface of the pipes are also accelerated by the presence of corrosive gases in water (oxygen, carbon monoxide), temperature and stray currents. Such unfavourable conditions can cause extremely high corrosion rates (above 1 mm/year) [9]. These types of defects will be detected during hydraulic testing. Usually corrosion rates are 0.1 - 0.15 mm/year [10]. According to classification of DH pipe corrosion rates [8] the rate over 0.2 mm/year is called an emergency rate. Therefore, in this analysis due to conservativity corrosion rate of 0.2 mm/year was used.

Some examples of external corrosion accidence in DH pipeline are shown in Figure 4 [11] and in Kaunas DH pipeline are shown in Figure 5.

Figure 4. DH pipeline accidents in case of external corrosion [11]

Figure 5. Kaunas DH pipeline accidents in case of external corrosion

3.2 Analysis of material properties of district heating piping steel

In order to examine the influence of degradation on mechanical properties of the steel St3 the standard tensile test has been carried out. The testing was performed on 10 kN capacity low-cycle tension-compression testing machine UME-10TM with the stress rate of 20 MPa/s and loading rate of 1 mm/min [12].

Yield stress $R_{p0,2}$, ultimate tensile strength σ_u and elongation A_5 of the specimens after break was determined for each specimen separately and then averaged. Averaged mechanical properties of the steel St3 is presented in (Table 1).

The engineering curve (Figure 6) were developed dividing applied force by actual cross-section of the specimen. This curve was recalculated to true stress-strain curve (Figure 6) and was used in strength analysis of piping. The tested specimen at temperature 120 ^{0}C after break is presented in Figure 7.

Table 1: Mechanical properties of piping steel St3 at temperature 120 ^{0}C.

Specimen No	Yield limit $R_{p0,2}$, MPa	Ultimate strength $R_{m,}$, MPa	Elongation A_5, %
3	256	401	30.5
4	249	398	28.4
Averaged values	253	399	29.5

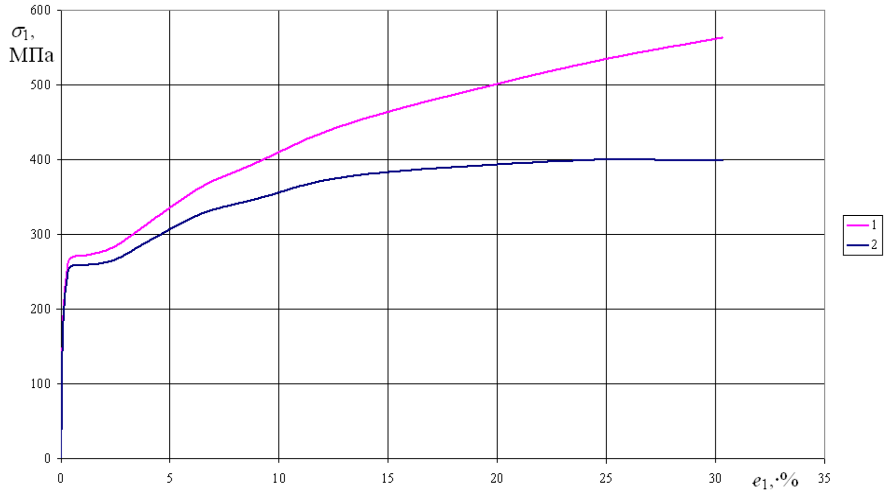

Figure 6. Averaged engineering (2) and true (1) stress-strain curves for piping steel

Figure 7. Picture of specimen after break at temperature 120° C

3.3 Deterministic-probabilistic structural integrity analysis of district heating system

Deterministic-probabilistic evaluation of structural integrity of Kaunas district heating piping was performed by following analyses: 1) general structural integrity evaluation of chosen part of Kaunas district heating main piping; 2) probabilistic analysis of failure of the selected piping part. FE code ADLPIPE was used for general structural integrity evaluation of chosen piping section. The hydraulic test pressure 2.0 MPa was evaluated in strength analysis. During in-service inspection in movable support sections were detected corrosion defects. Therefore the stress analysis were concentrated in these supports. Stresses in movable support (node 95) due to dead weight, pressure and temperature are presented in Figure 8.

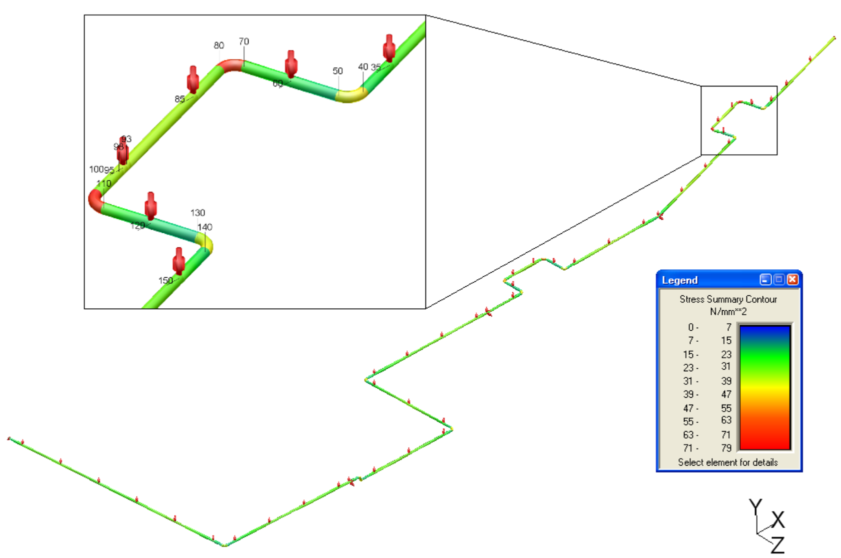

Figure 8. Stress distribution in selected part of piping.

The failure dependence from load and wall thickness of defected zone of the movable support was defined in probabilistic analysis of the structural integrity. FE computer code NEPTUNE [13, 14] was used for deterministic analysis of structure and computer code ProFES [15] was used for probabilistic analysis. In order to perform a probabilistic analysis of structures failure due to loading, the NEPTUNE and ProFES software were coupled by special translator ProFES/NEPTUNE (pn_glue code) [16].
Structural reliability analysis was done using probabilistic methods. Using these methods the influence of uncertainty of material properties, geometric parameters and loads was estimated for the strength of the relevant structures, with their reliability and effectiveness. During operation due to unpredictable reasons the pressure can fluctuate. Also the material properties in different piping places can be different.

Therefore failure probability analysis of pipelines was done using loads, material properties and defected zone thickness as random variable.
The FE model prepared for failure is shown in Figure 9. The pipe section and movable support was modeled using shell elements. The model is divided in the fallowing parts - pipe without defects (wall thickness 7 mm); defected pipe zone and movable support.

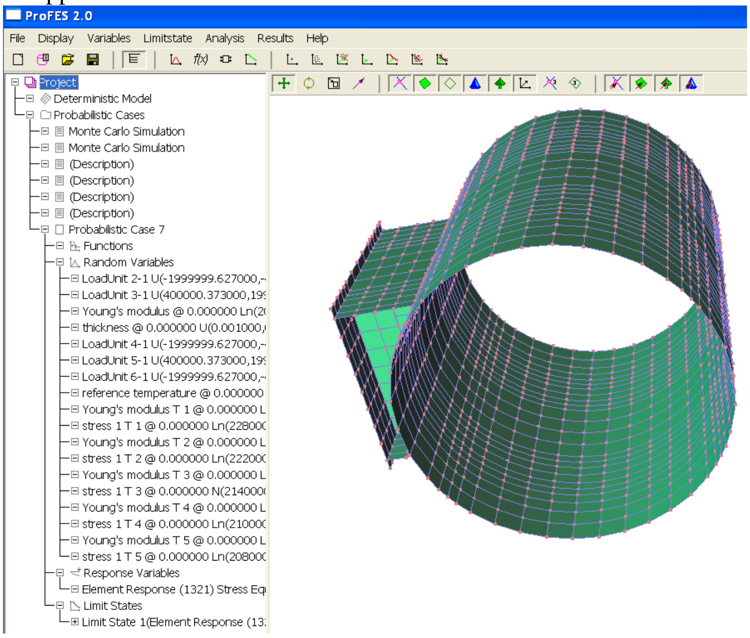

Figure 9. FE model of movable support and piping section for probabilistic analysis.

In this analysis the failure probability dependence of load and defected zone thickness was performed. In this analysis the allowable stresses (114.3 MPa) was accepted as limit state. If the pipe element of the movable support reaches the allowable stresses and a failure of the pipe can occurs.
Firstly using FE model of movable support and piping section and applying "Response Surface / Monte-Carlo simulation" method the load and defected zone thickness - probability function was calculated.

$$y = 7e^{7} - 9.4\,P - 10.3\,P_a + 0.00023\,E_1 - 2{,}25e^{9}\,b + 21.5\,P_b - 13.7\,P_c - \; - 37.5\,P_d - 18672\,t - 1.3e^{-5}\,E_1 - 0.044\;\sigma_{y1} - 2.4e^{-5}\,E_2 - 0.009\;\sigma_{y2} - - 6.4e^{-5}\,E_3 - 0.04\,\sigma_{y3} + 3.7e^{-5}\,E_4 - 0.02\,\sigma_{y4} + 8.2e^{-6}\,E_5 - 0.02\,\sigma_{y5} \qquad (1)$$

here the response variable y is used in limit state, y >114.3 MPa; P, P_a, P_b, P_c and P_d is pressure inside the pipe, Pa; b is defected zone thickness, mm; t is temperature inside the pipe, °C; E_1, E_2, E_3, E_4 and E_5 are elastic modulus of steel St3 at temperatures 20, 50, 100, 120 and 150 °C, Pa; σ_{y1}, σ_{y2}, σ_{y3}, σ_{y4} ir σ_{y5} is yield strength of steel St3 at temperatures 20, 50, 100, 120 and 150°C, Pa.

Secondly this function was used as inner response function calculating failure probabilities using "Monte-Carlo simulations" methods. 1 000 000 Monte-Carlo simulations were done. Nominal material properties and geometry data and normal load distribution (20%) were used in this analysis. Using Eq. (1) the pipe failure probability at movable support section dependence of pressure and defected zone thickness were defined.

Described analysis was done for one selected movable support. However 1 km DH pipeline has around 95 movable supports. Conservatively it was assumed that failure of pipe can occur at any movable support. Therefore ProFES analysis results (pipe failure probability) determined for one pipe section of movable support was recalculated to pipe failure probability per 1 km per year. The analysis results are presented in Figure 10. It was defined that failure probability is $1.9 \cdot 10^{-2}$ when pressure is 5 bars and when defected zone thickness is 1 mm.

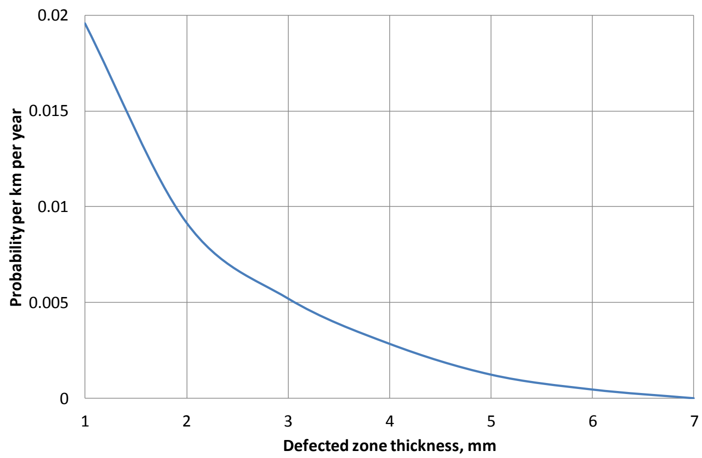

Figure 10. Pipe rupture probability (per 1 km per year) dependence on defected zone thickness at pressure of 5 bar

4. Reliability of the pipeline of district heating network

The result of deterministic-probabilistic structural integrity analysis is the pipe rupture probability dependence on defected zone thickness. In case of known corrosion rate r (mm/years) defected zone thickness b (mm) and operating time t (years) are related

$$b = 7 - rt, \tag{2}$$

where t – pipe operating time (years), new pipe are of 7 mm thickness.

For the calculations corrosion rate r of 0.2 mm/year was used. Thus, pipe rupture probability dependence on the defected zone thickness can be expressed as a function $Q(t)$ of operating time t. Reliability function $R(t) = 1 - Q(t)$, t – time, are known as well. Reliability function with regard to pipe rupture probability dependence on the defected zone thickness (Figure 10) is presented in Figure 11 (dot line).

In general reliability function $R(t) = R(t, \theta_1, ..., \theta_s)$ have s parameters and the estimates of parameters $\theta_1, ..., \theta_s$ are known. The estimates of parameters $\theta_1, ..., \theta_s$ of considered reliability function can be updated by applying Bayesian method [17] (BM) with regard to the statistical data about registered ruptures of operating pipelines, i.e. t_j, $j = 1, 2, ..., n$, t_j – pipeline operation time till rupture (years) at 5 Bar pressure (operation condition).

With respect to available failure data the posterior (updated) probability density function of parameters $\theta_1, ..., \theta_s$ is calculated by applying Bayesian formula

$$\varphi(x_1,...,x_s \mid t_1,...,t_n) = \frac{\prod_{l=1}^{s} p_l(x_l) \cdot L(t_1,..,t_n, x_1,...,x_s)}{\int_{R_1}...\int_{R_s} \prod_{l=1}^{s} p_l(u_l) \cdot L(t_1,..,t_n, u_1,...,u_s) \mathrm{d}u_1 ... \mathrm{d}u_s}, \tag{3}$$

t_j – piping operation time till rupture (years), $j = 1, 2, ..., n$, $L(\cdot)$ – likelihood function with respect of operation time till rupture T distribution, R_l – range (set of all possible values) of parameter θ_l, $l = 1, \ldots, s$.

Bayesian point estimate of parameter θ_l, $l = 1, 2, ..., s$, is expected values of θ_l, $l = 1, 2, ..., s$, calculated using posterior probability density function.

In our analysed case, reliability function obtained using pipe rupture probability dependence (per 1km per year) on the defected zone thickness (Figure 10) is

$$R(t, \theta_1, \theta_2) = \mathrm{e}^{-\left(\frac{t}{\theta_1}\right)^{\theta_2}}, \tag{4}$$

with scale parameter $\hat{\theta}_1 = 73.132$ and shape parameter $\hat{\theta}_2 = 4.366$ (Weibull distribution case [18, 19]). Statistical analysis of the data of operation time till rupture shows that operation time till rupture T as random variable follows Weibull distribution. Failure data t_j, $j = 1, 2, ..., n$. Thus, likelihood function is

$$L(t_1,..,t_n, x_1, x_2) = \prod_{j=1}^{n} \left(\frac{x_2}{x_1}\right)\left(\frac{t_j}{x_1}\right)^{x_2 - 1} \mathrm{e}^{-\left(\frac{t_j}{x_1}\right)^{x_2}}, \tag{5}$$

$p_1(x_1)$ – probability density function of inverse gamma distribution (conjugate prior [17]) with expected value equal to prior estimate $\hat{\theta}_1$ and variance – 10% of estimate value, $p_2(x_2)$ – probability density function of gamma distribution with expected value equal to prior estimate $\hat{\theta}_2$ and variance – 10% of estimate value.

Prior reliability function $R(t)$ (dot line) and updated one (solid line) with Bayesian point estimates of parameters θ_1 and θ_2 (with regard to piping operating data) are presented in Figure 11.

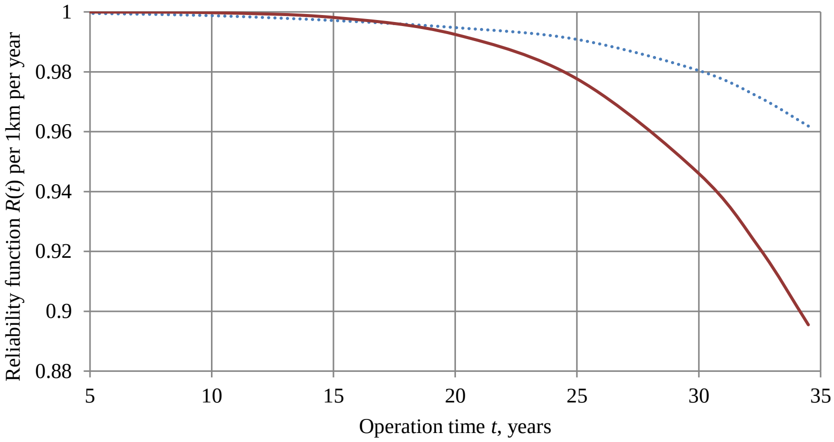

Figure 11. Pipe reliability functions per 1km per year (when pressure is 5 bar): „dot line“ – reliability function obtained in deterministic-probabilistic structural integrity analysis; „solid line“ - reliability function with updated parameter estimates by BM.

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The obtained result shows that lifetime of 1km of pipeline with demand reliability, for instance, 0.9 is 34 years (approximately). For the analysed part of district heating network (pipeline of 8.62km length) this estimate is 22 years (approximately). The behaviour of updated reliability function (Figure 11) shows that reliability of pipelines is significantly decreasing when operation time is over 30 years. The renovation of pipeline is recommended.

The result of analysed case shows (Figure 11) that failures in piping of considered part of district heating main network occur more frequently than it was forecasted with failure probability obtained in deterministic-probabilistic structural integrity analysis, i.e. reliability of pipeline is lower than it is obtained in deterministic-probabilistic structural integrity analysis. More frequent failures in district heating main network can be related to higher corrosion rate, groundwater, inappropriate insulation and/or drainage, external factors (as digging, boring), etc.

5. Conclusions

The reliability analysis of most dangerous part of district heating pipeline network was carried out. This analysis takes into consideration statistical information about Kaunas DH piping failure data, system structure, and pipe failure probability received by deterministic-probabilistic structural integrity analysis.

On the statistical analysis results it was received that DH pipeline part in centre of Kaunas has the highest failure rate.

Analysis of failure reasons revealed that 97% of pipe ruptures are related to corrosion of steel.

Based on probability analysis, which takes into account uncertainty, pipe rupture probability (per 1 km per year) dependence on defected zone thickness at pressure of 5 bar was determined.

Application of Bayesian method allows us to calculate pipeline rupture probability based on mechanical properties, geometry dates, loads and pipeline operation data. Using Bayesian approach the reliability function $R(t)$ was obtained which takes into consideration Kaunas DH piping failure data, system structure, and pipe failure probability received by deterministic-probabilistic structural integrity analysis.

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