WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2021.136475

ARCHIVES OF CIVIL ENGINEERING

Vol. LXVII ISSUE 1 2021

TIME-TO-FAILURE FORECAST FOR CORRODED SHELL OF ABOVE-GROUND STEEL TANK USED TO STORE LIQUID FUELS

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An original simplified procedure to estimate the remaining service time of corroded shell of an on-the-ground steel tank used to store liquid fuels is presented in this paper. Current corrosion progress trend, identified a'posteriori based on the obligatory technical condition monitoring, is extrapolated to the future tank service time under the assumption that the conditions of service would not change and no renovation or modernization works would be undertaken. Failure probability understood as exhaustion of the capability to safely resist the loads applied due to the corrosion progress constitutes the measure of the sought uptime. For comparative purposes several effective inference methods have been proposed for the same input data, based on formally qualitatively different but corresponding description measures. It has been shown, that in the analysis of this type the representative values, usually expressed as quantiles of probability distributions describing random variables in use, need not be specified to verify the safety condition. The proposed algorithm is based on fully probabilistic considerations, and those, according to Authors' opinion, by their nature lead to more reliable, and at the same time, objective estimates.

Keywords: steel tank, corroded shell, failure probability, durability prediction, time-to-failure forecast, remaining service time.

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1. INTRODUCTION

On-the-ground steel tanks used to store the liquid petroleum fuels should be treated as ageing structures in the sense of reliability theory, due to the corrosion weakening of their cylindrical shells progressing in time. The basic source of corrosion risk may be attributed to the internal exposure of sheathing plates to the potential chemical reactions with aggressive media, often contaminated, and exhibiting high level of sulphur content [1-4]. The exposure to external atmospheric conditions seems to be only an additional aggravating factor [5-7]. Monitoring the intensity of corrosion weakening in this type of structures belongs to the basic tasks of service personnel managing the fuel depots and oil refineries. In practice the actions undertaken are usually limited to the periodical evaluation of technical condition, as required by the law [8], and possible consideration of the need to undertake the necessary renovation or modernization works. With such an approach the strategic planning and reasonable management of available resources in both economic as well as purely technical aspects is difficult. In the Authors' opinion, due to the strategic importance of the monitored resources, the traditional evaluation of technical condition should be enriched by the elements of qualitative and quantitative risk analysis, combining the probabilistic procedures with calibration of potential failure consequences. Therefore an algorithm allowing to estimate the so called forecast remaining service time for a steel tank used to store the liquid petroleum products is proposed for practical application. In our interpretation, this is the time counted beginning at the moment of the technical inspection of the considered structure until the anticipated future loss of the capability to safely resist the applied loads, of course subject to the condition, that the service regimen would remain unchanged during the whole period, and no maintenance activities resulting in the possible strengthening of the bearing structure would be undertaken. In this sense this is simply forecast durability, quantified only due to the corrosion weakening progressing in time (all the remaining factors generating additional risks in this domain are disregarded here). The estimated service time will be called by us "time-to-failure (TTF)" in the following analysis. It has to be underlined however, that the traditionally quantified in the relevant bibliography "mean-time-to-failure (MTTF)" remains beyond the scope of our interest. Instead, the appropriate for this random variable, quantile of the probability distribution determined for the maximum acceptable failure probability level is sought. We will limit our considerations to the computational scenario, where the bearing capacity of the corroded tank shell is limited by the ability to resist the hoop tensile force. This happens, when the tank is completely filled with the stored product. The alternative scenario, dealing with local stability loss of empty tank shell will be considered in a separate work.

2. CONVENTIONAL TECHNICAL CONDITION EVALUATION OF A CORRODED TANK SHELL

A survey of the real, observed during inspection, sheathing plates thickness of the corroded tank shell degraded in service is the main task of the expert assessing the evaluated tank. After the inspection the expert has at his disposal the uniform set of N results for each shell section, which is subjected to statistical treatment. In the traditional approach, based on the available data set the expert determines empirical parameters of the random corroded plate thickness probability distribution (the parameters determined on a sample will be denoted by the superscript asterisk in the following considerations), i.e. the mean value m_t^* and standard deviation σ_t^* or alternatively coefficient of variation v_t^*, as estimators of the probabilistic moments for a normal probability distribution $\mathrm{N}(m_t, \sigma_t)$:

(2.1) $$m_t^* = \frac{1}{N}\sum_{i=1}^{N} t_i, \qquad \sigma_t^* = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(t_i - m_t^*\right)^2} \quad \text{and} \quad v_t^* = \frac{\sigma_t^*}{m_t^*}.$$

Based on this, the design value of the random thickness t_d^* representative for the considered shell section is equal:

(2.2) $$t_d^* = m_t^* - 3\sigma_t^* = m_t^*\left(1 - 3v_t^*\right).$$

At the moment of the technical inspection, further denoted as $\tau^* > \tau_0$ (the moment τ_0 denotes in this notation the beginning of the service life), the corroded shell section is capable of safely resisting the load applied to it, provided that the below inequality is satisfied:

(2.3) $$t_d^* = t_d\left(\tau = \tau^*\right) \geq \max\left(t_d^{(e)}, t_d^{(w)}\right).$$

In the above the thickness $t_d^{(e)}$ is due to the service condition:

(2.4)
$$\left(\gamma_{F,p}\rho_p H_{red} + \gamma_{F,E}\, p_E^{(e)}\right)\left(\frac{r}{t_d^{(e)}}\right) \le \frac{f_y}{\gamma_{M,0}},$$

while the thickness $t_d^{(w)}$ is due to the water test condition:

(2.5)
$$\left(\gamma_{F,w}\rho_w H_{red} + \gamma_{F,E}\, p_E^{(w)}\right)\left(\frac{r}{t_d^{(w)}}\right) \le \frac{f_y}{\gamma_{M,0}},$$

where H_{red} defines the shell depth at which the bearing capacity condition is verified, measured relative to the stored fuel surface at the completely filled tank. The quantities $p_E^{(e)}$ $\left[\mathrm{kN/m^2}\right]$ and $p_E^{(w)}$ $\left[\mathrm{kN/m^2}\right]$ represent the overpressure generated in the gas zone of the tank equipped with permanent roof, or alternatively the dead weight of the floating roof divided by the cross sectional area of the tank equipped with floating roof, while ρ_p $\left[\mathrm{kN/m^3}\right]$ and ρ_w $\left[\mathrm{kN/m^3}\right]$ represent specific gravity of the fuel stored in the tank and water used in the water test (Fig. 1). Additionally $r\left[\mathrm{m}\right]$ denotes the radius of the tank measured with respect to the central axis of the shell while f_y $\left[\mathrm{MPa}\right]$ denotes yield limit of the steel the tank has been made of. Symbols γ_F and γ_M denote partial safety factors typical for the traditional approach to the standard limit states method.

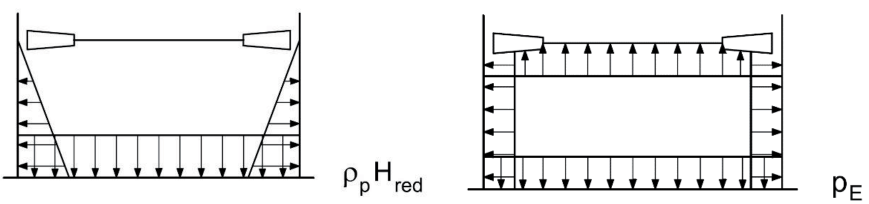

Fig 1. Tank load determining the required shell thickness: at left hydrostatic pressure, at right overpressure.

In the Authors' opinion the quantitative difference between the design value of the strength f_d specified for the steel used to make the tank shell plates at the moment of acceptance for service τ_0 and at the time of testing its technical condition $\tau^* > \tau_0$ after many years in service should be taken into consideration. For the moment τ_0 this strength is usually determined by the following formula:

(2.6) $$f_d\left(\tau_0\right)=\mu_y \exp\left(-3\sqrt{\upsilon_R^2+\upsilon_A^2}\right),$$

where μ_y and υ_R represent the median value and logarithmic coefficient of variation of the steel yield limit, respectively, while υ_A - logarithmic coefficient of variation of the element cross section and influence of imperfections (in the case of tank shell plates this pertains in general to the initial variation in plate thicknesses due to the acceptable mill tolerances). Based on statistical research [9], for structural steels made in Poland $\upsilon_R=0,08$ and $\upsilon_A=0,06$, resulting in $\sqrt{\upsilon_R^2+\upsilon_A^2}=0,10$. The design value of the strength $f_d\left(\tau_0\right)$ estimated with an assumed safety margin for the whole population of plates of this type is by its nature lower than the strength $f_d\left(\tau^*\right)$ related to a specific implementation. The empirical coefficient of variation v_t^* determined according to (2.1) covers the influence of real (and thus smaller than the previously conservatively estimated for quantification according to the standard) initial variability $v_A \approx \upsilon_A\left(\tau_0\right)$. This is superimposed over the variability generated during the service by the random nature of the corrosion process. Thus the design value of bearing capacity of the shell t_d^* thick should be determined based on the adjusted value:

(2.7) $$f_d^*=f_d\left(\tau^*\right)=\mu_y^* \exp\left(-3\upsilon_R^*\right).$$

The median μ_y^* and logarithmic coefficient of variation υ_R^* in this case should be determined based on the real steel yield limit measurements, performed at various locations on the shell simultaneously with the measurements of its random thickness. However, such action on the tanks used to store liquid petroleum products may be undertaken rather infrequently, and in general only after emptying, therefore usually only code values $\mu_y^*=\mu_y$ and $\upsilon_R^*=\upsilon_R$ are applied to evaluate the bearing capacity of the tank during inspection. Replacement of the f_d value by f_d^* implies a modification of the safety condition (2.3). A comparison of bearing capacities $t_d^* f_d^* \geq \max\left(t_d^{(e)}, t_d^{(w)}\right) f_d\left(\tau_0\right)$ yields:

(2.8) $$t_d^* \geq \max\left(t_d^{(e)}, t_d^{(w)}\right)\frac{f_d\left(\tau_0\right)}{f_d^*}.$$

In addition, the experimental research reported in [10-12] indicated, that due to the corrosion progressing in the extended service time of the tank τ^* the median value μ_y^* itself decreases as well. This is a result of intensifying degradation changes of various nature weakening the integrity of ferrite grains in the corroded steel microstructure. Unequivocal quantification of such phenomena is so far difficult to estimate, as it requires much wider experimental basis. A certain modification of the approach presented here has been proposed in [13]. A relative corrosion loss related to the nominal plate thickness t_{nom} is assumed, subject to the assumption, that at the moment τ_0 the equality $t_{nom} = m_t\left(\tau_0\right)$ was satisfied, as due to the mill tolerances the real initial plate thickness could have been higher or lower than the nominal one with equal probability. This is basically an approximation, as the plates rolled in the 1970's and 1980's generally had negative tolerances. A random quotient $c_i = t_i / t_{nom}$ is a measure of the observed loss in this approach. The probability distribution parameters of the variable c are estimated by determining the median μ_c^* for each shell layer and empirical variation $\left(\upsilon_c^*\right)^2$ adjusted for the small sample. This results in:

$$\ln \mu_c^* = \frac{1}{N}\sum_{i=1}^{N} \ln c_i \to \mu_c^* \qquad \text{and} \qquad \upsilon_c^* = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} \ln^2\left(\frac{c_i}{\mu_c^*}\right)}. \tag{2.9}$$

The bearing capacity condition specified for the moment τ^* in this case should be verified for the nominal plate thickness t_{nom}, at the design value of the strength f_d^* reduced according to the formula:

$$f_d^* = \mu_y \mu_c^* \exp\left(-3\sqrt{\upsilon_R^2 + \left(\upsilon_c^*\right)^2}\right). \tag{2.10}$$

The main advantage of the above presented approaches, which may be applied to estimate the bearing capacity of a corroded tank shell lies in their simplicity. However, in each case calculations of this type yield only approximate results. In the following considerations we propose to replace this simplified approach by an alternative one, based on the fully probabilistic inference procedures.

3. RANDOM BEARING CAPACITY AND RANDOM LOADS OF TANK SHELL

The tank shell is a thin cylindrical shell of random thickness $t(\tau)$ and non-random radius r (the potential geometrical imperfections are not being considered here). In current analysis it is assumed, that the bending moments acting on the shell are negligibly small and may be disregarded. In such case the hoop tensile force N_φ is authoritative for safety estimates. This force is induced in the shell plates by the simultaneous action of the hydrostatic pressure ρ_p and overpressure p_E. Its value may be expressed as:

$$N_\varphi = \left(\rho_p H_{red} + p_E\right) r \,, \tag{3.1}$$

In the random implementation it may not exceed the bearing capacity:

$$N_R = f_y t \,. \tag{3.2}$$

In the following considerations it is assumed that N_φ and N_R are mutually independent random variables (in reality the steel yield limit is inversely related to the plate thickness). Under the assumption that both thickness and yield strength are described by the log-normal probability distributions having the parameters $N(\mu_t, \upsilon_t)$ and $N(\mu_y, \upsilon_R)$, respectively, the stability properties of the distributions of this type with respect to multiplication imply that the variable N_R as well is characterized by the log-normal probability distribution having the parameters $N(\mu_{NR}, \upsilon_{NR})$. At $\tau = \tau^*$ occurs:

$$\mu_{NR}^* = \mu_y^* \mu_t^* \qquad \text{and} \qquad \upsilon_{NR}^* = \sqrt{\upsilon_R^2 + \left(\upsilon_t^*\right)^2} \,, \tag{3.3}$$

where:

(3.4) $$\ln \mu_t^* = \frac{1}{N}\sum_{i=1}^{N} \ln t_i^* \rightarrow \mu_t^* \quad \text{and} \quad \upsilon_t^* = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} \ln^2\left(\frac{t_i^*}{\mu_t^*}\right)}.$$

The probability distribution parameters of random force N_φ are determined based on the values of partial safety factors available in the design codes, subject to the assumption that the mean values of these loads correspond to their characteristic values. Thus when the random loads ρ_p, ρ_w and p_E are described by normal probability distributions the following holds:

(3.5) $$\rho_{p,k} = m_p \quad \text{and} \quad \rho_{p,d} = \rho_{p,k}\gamma_{F,p} = m_p\left(1+3\nu_p\right) \rightarrow \nu_p = \frac{\gamma_{F,p}-1}{3},$$

(3.6) $$\rho_{w,k} = m_w \quad \text{and} \quad \rho_{w,d} = \rho_{w,k}\gamma_{F,w} = m_w\left(1+3\nu_w\right) \rightarrow \nu_w = \frac{\gamma_{F,w}-1}{3},$$

(3.7) $$p_{E,k} = m_E \quad \text{and} \quad p_{E,d} = p_{E,k}\gamma_{F,E} = m_E\left(1+3\nu_E\right) \rightarrow \nu_E = \frac{\gamma_{F,E}-1}{3}.$$

Since random loads ρ_p, ρ_w and p_E are characterized by normal probability distribution and the random force N_φ is a linear combination of these, its distribution $\mathrm{N}\left(m_{N\varphi}, \nu_{N\phi}\right)$ is normal as well, and therefore:

(3.8) $$m_{N\varphi}^{(e)} = \left(m_p z + m_E\right) r, \quad \sigma_{N\varphi}^{(e)} = r\sqrt{\left(\sigma_p H_{red}\right)^2 + \sigma_E^2} \quad \text{and} \quad \nu_{N\varphi}^{(e)} = \sqrt{\nu_p^2 + \nu_E^2},$$

(3.9) $$m_{N\varphi}^{(w)} = \left(m_w z + m_E\right) r, \quad \sigma_{N\varphi}^{(w)} = r\sqrt{\left(\sigma_w H_{red}\right)^2 + \sigma_E^2} \quad \text{and} \quad \nu_{N\varphi}^{(w)} = \sqrt{\nu_w^2 + \nu_E^2}.$$

The representative design value of bearing capacity $N_{R,d}^*$ is defined in paper [14] subject to the assumed value of material coefficient γ_m as:

(3.10) $$N_{R,d}^* = \frac{m_{NR}^*}{\gamma_m}\left(1 - 1{,}645\nu_{NR}^*\right).$$

When the log-normal probability distribution is applied to model the random bearing capacity of a plate the formula (3.10) is reduced to the following:

$$N_{R,d}^{*} = \frac{\mu_{NR}^{*}}{\gamma_m} \exp\left(-1,645\upsilon_{NR}^{*}\right). \tag{3.11}$$

Definition of the design value $N_{R,d}^{*}$ is reasonable only when it is accompanied by the definition of the random load design value $N_{\varphi,d}$ against which it could be compared. Should one assume, that the parameters of the random load are time independent, one may also assume that $m_{N\varphi}^{*} = m_{N\varphi}$ and $\nu_{N\varphi}^{*} = \nu_{N\varphi}$. For the quantities determined according to (3.8) and (3.9) the following holds:

$$N_{\varphi,d}^{(e)} = m_{N\varphi}^{(e)}\left(1+3\nu_{N\varphi}^{(e)}\right) \qquad \text{and} \qquad N_{\varphi,d}^{(w)} = m_{N\varphi}^{(w)}\left(1+3\nu_{N\varphi}^{(w)}\right). \tag{3.12}$$

The safe service condition requires that $N_{\varphi,d} < N_{R,d}$. Therefore the global factor defined below may be treated as the measure of safety.

$$\gamma^{*} = \frac{N_{R,d}^{*}}{\max(N_{\varphi,d}^{(e)}, N_{\varphi,d}^{(w)})} \geq 1. \tag{3.13}$$

An application of the representative values $N_{R,d}^{*}$ and $N_{\varphi,d} = \max\left(N_{\varphi,d}^{(e)}, N_{\varphi,d}^{(w)}\right)$ in the analysis in our opinion constitutes an unnecessary simplification of the computational model.

4. FAILURE PROBABILITY ESTIMATED FOR THE MOMENT OF TECHNICAL INSPECTION

The method proposed by the Authors to infer on the safety level of the corroded tank shell at the moment of technical inspection is based on the estimated failure probability of this shell, understood as the loss of the capacity to safely resist the loads applied to it. Let the $\Delta^{*} = N_{R}^{*} - N_{\varphi}$ be the random safety margin related to the moment τ^{*}. The value $\Delta^{*} > 0$ is equivalent to safe service condition, while $\Delta^{*} \leq 0$ denotes failure. The difference Δ^{*} in this formulation represents a new random variable being a linear combination of two variables N_R^* and N_φ characterized by normal probability distributions. Therefore it is described by a normal probability distribution $\mathrm{N}\left(m_\Delta^*, v_\Delta^*\right)$ as well. In this convention the failure probability is determined by the formula:

$$\Omega = \mathrm{P}\left(N_R^* \le N_\varphi\right) = \mathrm{P}\left(\Delta^* \le 0\right) = F\left(\Delta^*\right), \tag{4.1}$$

where $F\left(\Delta^*\right)$ is a cumulative distribution function of the random variable Δ^*, while the probability of fail-safe service of the shell is its complement:

$$\mathrm{R} = 1 - \Omega = \mathrm{P}\left(N_R^* > N_\varphi\right) = \mathrm{P}\left(\Delta^* > 0\right) = 1 - F\left(\Delta^*\right). \tag{4.2}$$

Since the random safety margin Δ^* is described by the normal probability distribution:

$$\mathrm{R}\left(\Delta^*\right) = \mathrm{P}\left(\Delta^* > 0\right) = \int_0^\infty \frac{1}{\sqrt{2\pi}\sigma_\Delta^*} \exp\left[-\frac{1}{2}\left(\frac{\Delta^* - m_\Delta^*}{\sigma_\Delta^*}\right)^2\right] d\Delta^*. \tag{4.3}$$

After introduction of the standardized random variable $u^* = \dfrac{\Delta^* - m_\Delta^*}{\sigma_\Delta^*}$ one obtains:

$$\mathrm{R}\left(u^*\right) = \frac{1}{\sqrt{2\pi}} \int_{u^*}^\infty \exp\left(-\frac{\left(u^*\right)^2}{2}\right) du^* = 1 - \Phi\left(u^*\right). \tag{4.4}$$

So at the same time:

$$\Omega\left(u^*\right) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{u^*} \exp\left(-\frac{\left(u^*\right)^2}{2}\right) du^* = \Phi\left(u^*\right). \tag{4.5}$$

Function $\Phi\left(u^*\right)$ is the cumulative distribution function of the normal probability distribution of a standardized random variable u^*, i.e. the Laplace function available in statistical tables. The failure probability $\Omega\left(u^{*}\right)$ estimated by the evaluator should not exceed the admissible level Ω_{ult}, i.e. the highest level acceptable by the tank user. This level corresponds to the quantile of the variable u^{*} set at the level of $u^{*}=u_{req}$, meaning that $\Omega_{ult}=\Omega\left(u^{*}=u_{req}\right)$. Then, by definition $u_{req}<0$. In the following considerations u_{req} is treated as a positive parameter by assumption. For such a convention the following holds:

$$\Omega_{ult}=\Omega\left(u_{req}<0\right)=1-\Omega\left(u_{req}>0\right)=\Omega\left(-\left(u_{req}>0\right)\right). \tag{4.6}$$

When the probability value Ω_{ult} is known, one may determine the required limit value $u_{req}>0$, or alternatively Δ^{*}_{req} (the symbol $inv\Phi$ denotes the inverse Laplace function here).

$$\Omega_{ult}=\Phi\left(-u_{req}\right)\rightarrow u_{req}=-inv\Phi\left(\Omega_{ult}\right), \tag{4.7}$$

$$-u_{req}=\frac{\Delta^{*}_{req}-m^{*}_{\Delta}}{\sigma^{*}_{\Delta}}\rightarrow \Delta^{*}_{req}=m^{*}_{\Delta}-u_{req}\sigma^{*}_{\Delta}. \tag{4.8}$$

The failure will occur when the random bearing capacity N^{*}_{R}, decreasing with progressing corrosion, will get equal to the random load N_{φ}. Then $\Delta^{*}=0$, thus for $u^{*}>0$:

$$-u^{*}=-u^{*}_{0}=\frac{0-m^{*}_{\Delta}}{\sigma^{*}_{\Delta}}=-\frac{m^{*}_{NR}-m_{N\varphi}}{\sqrt{\left(\sigma^{*}_{NR}\right)^{2}+\sigma^{2}_{N\varphi}}}. \tag{4.9}$$

The value u^{*}_{0} determined in such manner may be interpreted as the global safety index β_{Δ} combining the partial safety indices $\beta_{R}=\beta_{NR}$ and $\beta_{S}=\beta_{N\varphi}$. Should one keep in force the convention, that both u^{*} and u_{ult} are positive, the safety condition would take the following form:

$$\Omega^{*}=\Omega\left(-u^{*}_{0}\right)<\Omega_{ult}=\Omega\left(-u_{req}\right), \tag{4.10}$$

which is equivalent to the formulation:

$$u_0^* > u_{req} \quad \text{and} \quad \Delta^* = 0 > \Delta_{req}^* . \tag{4.11}$$

The condition (4.10) may be transformed [15] by introducing the average (central) safety factor into the analysis, such that:

$$\overline{\gamma^*} = \frac{m_{NR}^*}{m_{N\varphi}} \ge \overline{\gamma_{req}} . \tag{4.12}$$

Then, by (4.9) it follows, that:

$$u_0^* = \frac{\overline{\gamma^*} - 1}{\sqrt{\left(\overline{\gamma^*} v_{NR}^*\right)^2 + v_{N\varphi}^2}} . \tag{4.13}$$

The necessary value of $\overline{\gamma^*} = \overline{\gamma_{req}}$ is determined directly from (4.13), by taking $u_0^* = u_{req}$, which in turn leads to:

$$\overline{\gamma_{req}} = \frac{1 + \sqrt{1 - \left(1 - u_{req}^2 \left(v_{NR}^*\right)^2\right)\left(1 - u_{req}^2 v_{N\varphi}^2\right)}}{1 - u_{req}^2 \left(v_{NR}^*\right)^2} . \tag{4.14}$$

5. CORROSION PROCESS PROGRESS FORECAST

The basic requirement for forecasting future changes in the safety condition of the corroded shell of the tank is the most reliable extrapolation of the trend describing the corrosion progress to date for the duration of the facility's further service. It is also assumed, that the service mode and other parameters such as climate conditions, air pollution etc., however with random instantaneous values, in the longer period of time would not change (may be described by a narrowband, stationary random process). In current considerations it is assumed, that the decrease in average shell plate thickness due to corrosion losses may be described by the following linear function with a sufficiently high precision:

$$m_t(\tau) = m_t(\tau_0) - \overline{A}\tau, \tag{5.1}$$

where $m_t(\tau)$ is the mean thickness of the analyzed plate forecast for the time τ, $m_t(\tau_0)$ - the mean thickness of the plate observed (hypothetically) at the moment of tank entering service, $\overline{A}$ - directional coefficient of the trend line modelling corrosion progress, averaged over measurements. There are no formal obstacles to assuming various nonlinear trends [16-18] in a more detailed analysis. So, would the parameters in the formula (5.1) be calibrated to obtain for the moment in time τ^* the corrosion state observed at the moment of measurements, one could unequivocally determine the value of the directional coefficient $\overline{A}$. In the corrosion progress model assumed here this value remains constant for the whole tank service time. It is assumed that at the moment of tank entering service $m_t(\tau_0) = t_{nom}$, and this in turn means, that $m_t^* = t_{nom} - \overline{A}\tau^*$. Based on the preceding:

$$\overline{A} = \frac{t_{nom} - m_t^*}{\tau^*}. \tag{5.2}$$

After entering (5.2) into (5.1) for $\tau > \tau^*$ one obtains:

$$m_t(\tau) = m_t^* \frac{\tau}{\tau^*} + t_{nom}\left(1 - \frac{\tau}{\tau^*}\right), \quad \sigma_t(\tau) \approx \sigma_t^* \left(\frac{\tau}{\tau^*}\right) \quad \text{and} \quad v_t(\tau) = \frac{\sigma_t(\tau)}{m_t(\tau)} = \frac{v_t^*}{1 + \frac{t_{nom}}{m_t^*}\left(\frac{\tau^*}{\tau} - 1\right)}. \tag{5.3}$$

The formula for $\sigma_t(\tau)$ applied here is simplified, as the influence of the initial variability of plate shell thickness $t(\tau_0)$ on $\sigma_t(\tau > \tau^*)$ has been disregarded. The component σ_t^* takes this influence into account for $\tau \le \tau^*$. The exact formula would also require the knowledge of the coefficient of variance $v_t(\tau_0)$, which is usually unknown and difficult to obtain at the moment τ^*, as well as taking into account the mutual relationship between t^* and $t(\tau_0)$.

6. FORECAST OF FUTURE CHANGES IN FAILURE PROBABILITY

Knowledge of the formulae (5.1) and (5.3) allows for determination of the random bearing capacity parameters forecast for the assumed time $\tau > \tau^*$. Should one opt for disregarding an insignificant difference between the median value μ_y^* and the mean value m_y^*, then based on (3.3):

(6.1) $$m_{NR}(\tau) = m_y m_t(\tau) \quad \text{and} \quad v_{NR}(\tau) \approx \sqrt{v_R^2 + \left(v_t(\tau)\right)^2}\ .$$

Random bearing capacity safety margin Δ then becomes a function of time τ:

(6.2) $$\Delta(\tau) = N_R(\tau) - N_\varphi(\tau).$$

This pertains to its mean value and standard deviation as well (based on the assumption, on the loading process stationarity $m_{N\varphi}(\tau) = m_{N\varphi}(\tau_0) = m_{N\varphi}$ and $\sigma_{N\varphi}(\tau) = \sigma_{N\varphi}$):

(6.3) $$m_\Delta(\tau) = m_{NR}(\tau) - m_{N\varphi} \quad \text{and} \quad \sigma_\Delta(\tau) = \sqrt{\left(\sigma_{NR}(\tau)\right)^2 + \sigma_{N\varphi}^2}\ ,$$

where $\sigma_{NR}(\tau) = m_{NR}(\tau) v_{NR}(\tau)$ and $\sigma_{N\varphi} = m_{N\varphi} v_{N\varphi}$. Thus, after standardization of the random variable $\Delta(\tau)$:

(6.4) $$u(\tau) = \frac{\Delta(\tau) - m_\Delta(\tau)}{\sigma_\Delta(\tau)}\ .$$

The probability $\Omega(\tau > \tau^*)$ is determined as the cumulative distribution function of the normal probability distribution of the variable $u(\tau > \tau^*)$, i.e. the so called Laplace function ($F(\Delta(\tau))$ is the cumulative distribution function of the normal probability distribution of the variable $\Delta(\tau)$):

(6.5) $$\Omega(\tau) = \mathrm{P}\left(N_R(\tau) \le N_\varphi(\tau)\right) = \mathrm{P}\left(\Delta(\tau) \le 0\right) = F\left(\Delta(\tau)\right) = \Phi\left(u(\tau)\right).$$

The bearing capacity of the corroded shell is exhausted for $u(\tau) = u_0(\tau)$, as then the random bearing capacity $N_R(\tau)$ gets equal to the random load $N_\varphi(\tau)$. This in turn means that $\Delta(\tau) = 0 < m_\Delta(\tau)$, and thus at the same time $u_0(\tau) < 0$. Should one assume the convention, that the parameter $u_0(\tau)$ is by default positive, then:

(6.6) $$\Omega\left(u_0(\tau)\right) = \Omega\left(u_0(\tau) < 0\right) = 1 - \Omega\left(u_0(\tau) > 0\right) = \Omega\left(-\left(u_0(\tau) > 0\right)\right),$$

and the equality (6.5) should be modified to the following:

(6.7) $$\Omega\left(-u_0(\tau)\right) = \Phi\left(-u_0(\tau)\right).$$

Parameter $u_0(\tau)$ is determined based on (6.4):

(6.8) $$-u_0(\tau) = \frac{0 - m_\Delta(\tau)}{\sigma_\Delta(\tau)} = -\frac{m_{NR}(\tau) - m_{N\varphi}}{\sqrt{\left(\sigma_{NR}(\tau)\right)^2 + \sigma_{N\varphi}^2}}.$$

The safe service condition of the corroded tank shell may be expressed as satisfaction of the inequality [19-22]:

(6.9) $$\Omega\left(u_0(\tau)\right) \le \Omega_{ult}.$$

Specification of the highest failure probability acceptable to the tank user $\Omega_{ult} = \Omega\left(-u_0(\tau) = -u_{ult}\right)$ allows for the determination of the required limit value $u_{req} > 0$, and subsequently $\Delta_{req}(\tau)$ ($inv\Phi$ stands for the inverse Laplace function here):

(6.10) $$\Omega_{ult} = \Phi\left(-u_{req}\right) \to u_{req} = -inv\Phi\left(\Omega_{ult}\right),$$

(6.11) $$-u_{req} = \frac{\Delta_{req}(\tau) - m_{\Delta}(\tau)}{\sigma_{\Delta}(\tau)} \rightarrow \Delta_{req}(\tau) = m_{\Delta}(\tau) - u_{req}\sigma_{\Delta}(\tau).$$

The limit condition (6.9) is thus equivalent to:

(6.12) $$u_0(\tau) > u_{req} \quad \text{and} \quad \Delta(\tau) = 0 > \Delta_{req}(\tau).$$

Should one denote by $\bar{\gamma}(\tau)$ the average (central) safety factor, such as:

(6.13) $$\bar{\gamma}(\tau) = \frac{m_{NR}(\tau)}{m_{N\varphi}} > \overline{\gamma_{req}}(\tau),$$

then the formula (6.8) would take the form:

(6.14) $$u_0(\tau) = \frac{\bar{\gamma}(\tau) - 1}{\sqrt{\left(\bar{\gamma}(\tau)\right)^2 \left(v_{NR}(\tau)\right)^2 + v_{N\varphi}^2}}$$

The required value $\overline{\gamma_{req}}(\tau)$ is obtained by entering $u_0(\tau) = u_{req}$ into the formula (6.14), this yields:

(6.15) $$\overline{\gamma_{req}}(\tau) = \frac{1 + \sqrt{1 - \left(1 - u_{req}^2 \left(v_{NR}(\tau)\right)^2\right)\left(1 - u_{req}^2 v_{N\varphi}^2\right)}}{1 - u_{req}^2 \left(v_{NR}(\tau)\right)^2}.$$

The computational procedure presented by the Authors in this paper has been numerically verified on the example of a forecast prepared for an existing steel tank for fuel storage equipped with floating roof, located in one of fuel depots in the south of Poland. Detailed results of this analysis have been published at first in the limited scope in [23] and subsequently, after updating and adaptation to current guidelines and design standards in [24].

7. CONCLUDING REMARKS

In the Authors' opinion the proposed algorithm may be applied to effectively estimate the forecast durability of a corrosion degraded shell of a steel tank used to store liquid petroleum products. These calculations are based on the data obtained during random plate thickness measurements t^*, performed on the shell section authoritative for the evaluation of bearing capacity of the whole shell at the moment associated with the obligatory inspection of the tank condition. Determination of the future failure-free service time $\tau_d - \tau^*$ under assumed, user accepted, allowable failure probability Ω_{ult} is the purpose of this analysis. The safety condition $u_0\left(\tau > \tau^*\right) > u_{req}$ (or alternatively $\Delta_{req}\left(\tau\right) < 0$) may be replaced by the condition $\bar{\gamma}\left(\tau\right) > \overline{\gamma_{req}}\left(\tau\right)$ [15], which is not necessarily more convenient to use. The proposed approach is based on the assumption on the stationarity of the loading process. This means, that both the mean value of the longitudinal tensile force in the shell $m_{N\varphi}$ and its statistical variability $v_{N\varphi}$ remain constant during the whole service time. However, random fluctuations of the momentary values of N_φ are not excluded. The progressing in time corrosive weakening of the shell bearing capacity is described by the mean bearing capacity monotonously decreasing in time $\tau > \tau^*$, and associated with decreasing thickness $t = t\left(\tau\right)$. In this approach random fluctuations of the bearing capacity are not authoritative for the evaluation of durability. The changes in the random bearing capacity induce simultaneous increase in the coefficient of variation $v_{NR} = v_{NR}\left(\tau\right)$. The decreasing in time values of the factor $\bar{\gamma}\left(\tau\right)$ or corresponding parameter $u_0\left(\tau\right)$ may constitute a measure of the progressing degradation of the shell section. These values are compared against required limit values $\overline{\gamma_{req}}\left(\tau\right)$ or $u_{req}\left(\tau\right)$, respectively. The latter are specified for the failure probability Ω_{ult} acceptable to the tank user. A constant required level of safety during the whole tank service time is postulated, this comes to the requirement that $\Omega_{ult} = const$. Simultaneously this means, that the coefficient $u_{req}\left(\tau\right) = \underset{\tau}{const}$ is time independent. This statement, however, is not reuse in the case of the factor $\overline{\gamma_{req}}\left(\tau\right)$, which in order to keep the probability Ω_{ult} constant has to grow with the progressing degradation of the corroded tank shell. The forecast corrosive durability of the shell is determined by the difference of times $\tau_{1,d} = \tau_d - \tau^*$. The time τ_d follows from inequality $\bar{\gamma}\left(\tau = \tau_d\right) = \overline{\gamma_{req}}\left(\tau = \tau_d\right)$, which is equivalent to the condition $u_0\left(\tau = \tau_d\right) = u_{req}$. The durability of the weakest tank shell section determined by the method described above will be authoritative for the whole tank shell (thus one deals here with a serial system in the sense of the reliability theory). The value $u_0\left(\tau > \tau^*\right)$ in the traditional approach is interpreted as the global safety index β_Δ . Thus a value of $\beta_{\Delta,req}$, such that $\beta_\Delta \geq \beta_{\Delta,req}$, should be assigned to the required value of u_{req} . It is usually postulated to assume a uniform value of $\beta_{\Delta,req} = 3.8$, corresponding to the value of $\Omega_{ult} = \Omega(-3.8) = 7.237 \cdot 10^{-5}$. The safe values $\Omega = \Omega\left(-u_0\left(\tau\right)\right)$ have to be smaller than that. The specification of constant value $\beta_{\Delta,req}$ results in time dependence of partial safety indices related to the load $\beta_{N\varphi} = \beta_S$ and bearing capacity $\beta_{NR} = \beta_R$. This is because should one accept the division rule, where the so called sensitivity coefficients $\alpha_{SR}\left(\tau\right)$ and $\alpha_{RS}\left(\tau\right)$ such as:

(7.1)
$$\alpha_{SR}\left(\tau\right) = \frac{v_{N\varphi}}{\sqrt{v_{N\varphi}^2 + v_{NR}^2\left(\tau\right)}} \quad \text{and} \quad \alpha_{RS}\left(\tau\right) = \frac{v_{NR}\left(\tau\right)}{\sqrt{v_{N\varphi}^2 + v_{NR}^2\left(\tau\right)}} ,$$

are the coefficients of proportionality, as authoritative for further considerations, then the following holds:

(7.2)
$$\beta_{\Delta,req} = \alpha_{SR}\left(\tau\right)\beta_S + \alpha_{RS}\left(\tau\right)\beta_R .$$

With the progressing corrosion degradation the influence of the index β_R increases at the expense of β_S . Thence the conclusion, that the assignment in the conventional, code based approach to the forecast, based on the specification of the representative design values of bearing capacity $N_{R,d}$ and load $N_{\varphi,d}$, of uniform and service time τ independent values $\beta_R = \beta_S = 3$ seems to be not entirely justified.

REFERENCES

1. L. Garverick, "Corrosion in the petrochemical industry", American Society for Metals, 1994.
2. A. Rim-Rukeh, P.A. Okokoyo, "Underside corrosion of above ground storage tanks (ASTs)", Journal of Applied Sciences and Environmental Management 9 (1): 161-163, 2005.
3. J. Harston, F. Ropital, "Corrosion in refineries", CRC Press Inc., 2007.
4. A. Groysman, "Corrosion problems and solutions in oil, gas, refining and petrochemical industry", Koroze a Ochrana Materiálu 61 (3): 100-117, 2017.

5. S. Fellu, A. Morcillo, S. Fellu Jr., "The prediction of atmospheric corrosion from meteorological and pollution parameters – 1", Corrosion Science 34: 403-422, 1993.
6. W. How, C. Liang, "Atmospheric corrosion prediction of steels", Corrosion 60: 313-322, 2004.
7. A.O. Umeozokwere, I.U. Mbabuike, B.U. Oreko, D.T. Ezemuo, "Corrosion rates and its impact on mild steel in some selected environments", Journal of Scientific and Engineering Research 3(1): 34-43, 2016.
8. Dz. U. nr 113 poz. 1211 Rozporządzenie Ministra Gospodarki z dnia 18 września 2001 r. w sprawie warunków technicznych dozoru technicznego, jakim powinny odpowiadać zbiorniki bezciśnieniowe i niskociśnieniowe przeznaczone do magazynowania materiałów ciekłych zapalnych.
9. J. Murzewski, A. Sowa, T. Domański, „Prognoza wytrzymałości polskich stali konstrukcyjnych", Inżynieria i Budownictwo 1-4: 32-34, 1982.
10. M. Maślak, J. Siudut, M. Stankiewicz, „Wpływ korozji na własności mechaniczne stali węglowej stosowanej w konstrukcjach nośnych zbiorników na paliwa płynne", Ochrona przed Korozją 5s/A: 366-374, 2004.
11. M. Maślak, J. Siudut, M. Stankiewicz, „Degradacja własności stali w skorodowanych blachach płaszczy naziemnych zbiorników na paliwa płynne", Inżynieria i Budownictwo 3: 153-158, 2007.
12. M. Maślak, J. Siudut, "Deterioration of steel properties in corroded sheets applied to side surface of tanks for liquid fuels", Journal of Civil Engineering and Management 14(3): 169-176, 2008.
13. M. Gwóźdź, „Ocena wpływu uszkodzeń korozyjnych na stan bezpieczeństwa konstrukcji stalowych", Materiały XV Ogólnopolskiej Konferencji „Warsztat Pracy Projektanta Konstrukcji", tom 1: Naprawy i wzmocnienia konstrukcji metalowych, Ustroń, 23-26.02.2000, 227-242, 2000.
14. A. Biegus, E. Hotała, „Oszacowanie losowej nośności granicznej uszkodzonych korozyjnie zbiorników stalowych", Materiały XIX Konferencji Naukowo-Technicznej „Awarie Budowlane", Szczecin – Międzyzdroje, 19-22.05.1999, 569-578, 1999.
15. M. Maślak, J. Siudut, „Oszacowanie degradacji nośności losowo skorodowanego pasa płaszcza stalowego zbiornika walcowego o osi pionowej", Ochrona przed Korozją 12: 456-461, 2007.
16. R.E. Melchers, "Corrosion uncertainty modelling for steel structures", Journal of Constructional Steel Research 52: 3-19, 1999.
17. C. Guides – Soares, Y. Garbatov, A. Zayed, G. Wang, "Non-linear corrosion model for immersed steel plates accounting for environmental factors", Transactions of the Society Naval Architects and Marine Engineers (SNAME) 111: 194-211, 2005.
18. R.E. Melchers, "Predicting long-term corrosion of metal alloys in physical infrastructure", Materials Degradation 4: 1-7, 2019.
19. M. Maślak, J. Siudut, „Szacowanie prognozowanej trwałości losowo skorodowanego pasa płaszcza stalowego zbiornika walcowego o osi pionowej", Ochrona przed Korozją 1: 14-17, 2008.
20. M. Maślak, J. Siudut, "Durability prediction of randomly corroded side surface sheet in steel on the ground tank for liquid fuel storage", Proceedings of the 4th International Conference "Recent Advances in Integrity – Reliability – Failure (IRF)", Funchal, Madeira, Portugal, June 23-27, abstract 159-160 + CD 8 p., 2013.
21. M. Maślak, M. Pazdanowski, J. Siudut, K. Tarsa, "Probability-based durability prediction for corroded shell of steel cylindrical tank for liquid fuel storage", Proceedings of the 1st Workshop of COST Action TU1402: "Quantifying the Value of Structural Health Monitoring", DTU Civil Engineering Report: R-336, Lyngby, Denmark, May 4-5, 82-95, 2015.
22. M. Maślak, M. Pazdanowski, J. Siudut, K. Tarsa "Corrosion durability estimation for steel shell of a tank used to store liquid fuels", Proceedings of the 12th International Conference "Modern Building Materials, Structures and Techniques (MBMST)", Vilnius, Lithuania, May 26-27, 2016, Procedia Engineering, 172, 723-730, 2017.
23. M. Maślak., J. Siudut, „Szacowanie degradacji nośności i prognozowanej trwałości losowo skorodowanego pasa płaszcza stalowego zbiornika walcowego o osi pionowej – przykład obliczeniowy", Ochrona przed Korozją 2: 50-54, 2008.
24. M. Maślak, M. Pazdanowski. „Probability-based remaining service time prediction for corroded shell of a steel tank used for liquid fuel storage", Proceedings of the 29th European Safety and Reliability Conference „ESREL 2019", September 22-26, 2019, Hannover, Germany, Research Publishing Services, Singapore, 3232-3239, 2019.

LIST OF FIGURES AND TABLES:

PROGNOZA CZASU DO AWARII SKORODOWANEJ POWŁOKI NAZIEMNEGO ZBIORNIKA STALOWEGO DO MAGAZYNOWANIA PALIW PŁYNNYCH.

Słowa kluczowe*: skorodowana powłoka, zbiornik stalowy, prawdopodobieństwo zawodu, prognoza trwałości, przewidywany czas do awarii, pozostający czas zdatności.*

STRESZCZENIE

Przedstawiono uproszczoną, autorską procedurę szacowania pozostającego czasu zdatności skorodowanej powłoki naziemnego użytkowanego zbiornika stalowego wykorzystywanego do magazynowania paliw płynnych. W proponowanym algorytmie postępowania dotychczasowy trend postępu korozji, identyfikowany a posteriori na podstawie pomiarów dokonywanych w ramach obowiązkowych ocen stanu technicznego, zostaje ekstrapolowany na czas przyszłego użytkowania zbiornika, przy założeniu że sposób jego wykorzystania nie ulegnie zmianie i nie będą prowadzone jakiekolwiek prace remontowe lub modernizacyjne. Miarą oceny poszukiwanego czasu zdatności jest narastające wraz z postępem korozji prawdopodobieństwo awarii rozumianej jako wyczerpanie możliwości bezpiecznego przenoszenia obciążeń. Awaria nie oznacza przy tym natychmiastowego zniszczenia obiektu ale stan, w którym monitorowane prawdopodobieństwo osiągnęło poziom graniczny, niemożliwy do zaakceptowania przez użytkownika. Dla tych samych danych wejściowych, w celach porównawczych, zaproponowano różne sposoby efektywnego wnioskowania, oparte na formalnie jakościowo odmiennych ale odpowiadających sobie miarach opisu. Potwierdzono, że w tego typu analizie do weryfikacji warunku bezpieczeństwa nie ma potrzeby specyfikacji jakichkolwiek wartości reprezentatywnych, wyznaczanych na ogół jako kwantyle rozkładów prawdopodobieństwa opisujących poszczególne zmienne losowe, w szczególności losowe obciążenie i losową nośność rozważanej powłoki. Proponowany algorytm opiera się bowiem na wnioskowaniu w pełni probabilistycznym, a to, zdaniem autorów, ze swej natury pozwala oceniającemu na uzyskanie bardziej wiarygodnych a przy tym obiektywnych oszacowań. Prezentowana procedura została zweryfikowana numerycznie na przykładzie prognozy opracowanej dla istniejącego stalowego zbiornika paliwowego z dachem pływającym, zlokalizowanego w jednej z baz paliwowych Polski południowej.

Received: 07.08.2020, Revised: 08.11.2020