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Remaining service time prediction for corroded shell of a steel tank used for liquid petroleum fuels storage

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Abstract

A numerical example allowing for effective forecasting of the remaining service time for corroded steel shell of a tank used to store liquid petroleum fuels is presented. This time is interpreted here as a period of time counted from the moment of an obligatory tank shell inspection to the moment of the anticipated shell failure understood as the loss of the capacity to safely resist the loads applied to it. Reaching the limit value of failure probability, i.e. the highest probability of failure acceptable to the tank user, is in this approach a determinant of such failure. The detailed considerations pertain to a typical on-the-ground storage tank equipped with a floating roof, located in one of fuel depots in the south of Poland. The forecast has been prepared based on measurements of the random thickness of tank shell weakened by corrosion and measured after 27 years of service time. In the recommended analysis fully probabilistic computational procedures have been applied. This led to a more credible and less conservative service time assessment than the one usually determined via the traditional standard approach. For comparative purposes qualitatively different but formally corresponding safety measures have been applied to describe the obtained results.

Keywords: steel tank, corrosion, durability prediction, remaining service time, time-to-failure

1 Introduction

A typical cylindrical shell of a steel on-the-ground tank used to store liquid petroleum fuels is usually made of several rings differing in thickness, the thinnest of which are located at the top, while the thickest ones are placed at the bottom near the tank floor. These rings, in terms of the reliability analysis, form a classical serial system, as the weakest ring is authoritative when the bearing capacity of the whole shell is evaluated. However, this is not necessarily the ring exhibiting the lowest bearing capacity, as the ring strained to the highest i.e. usually the thickest one, located at the bottom, is considered the weakest. This ring is affected by the highest hydrostatic pressure exerted

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by the liquid stored inside the tank. In the practically important design cases, due to the stepwise change of the shell thickness between adjacent rings, any of the intermediate rings, located above the bottom one, may also prove to be the highest stressed at a certain moment of tank service time. The Authors' experience seems to indicate, that relatively frequently, after long-term service of the tank shell, the bearing capacity of such shell becomes to be limited by the corresponding capacity of one of its topmost rings, the one permanently bonded to the tank top stiffener. It is at this level, where at relatively low load in nooks and crannies created by many difficult to protect tank details, the potential corrosion seems to find the best conditions for growth.

Due to the inevitable corrosion process, progressing in time, each layer has to be treated as an aging object in the sense of the reliability theory. Depending on the tank service time the loss in bearing capacity of the considered layer is a consequence of not only decreasing thickness, a phenomenon obvious to the designer, but also degrading changes occurring in the steel microstructure and intensified by corrosion [1]. The quantitative evaluation of these changes is so far difficult to ascertain. For this reason, in our opinion, any attempt to reliably model the influence of this type requires at least an access to the expanded database of experimental results.

Taking inventory and monitoring the corrosion process initiated in the shells of steel tanks is counted among the basic duties of fuel depot and refinery personnel managing such entities [2-4]. In the Authors' opinion, to make these actions fully effective, one should consider expanding them by predicting the so-called remaining service time for tanks in service, progressively weakened by corrosion. Only then an effective management of fuel depot resources and rational planning of necessary renovation and maintenance activities is possible.

Undoubtedly, bases of this type should be classified as infrastructure facilities of key, critical importance for the economy of a country.

In this paper an original, novel procedure for obtaining such forecast is presented in detail on the example of a 27 years old steel tank used to store liquid petroleum products, equipped with a floating roof and located in one of typical fuel depots in southern Poland. This procedure is based on fully probabilistic inference. We intend to show not only several statistical processing methods of data obtained during measurements performed at the moment of obligatory technical inspection of the tank in question, but also qualitatively different, though mutually corresponding approaches to describe the obtained results, each of which finally leads to the specification of this tank remaining service time quantified as a representative value of the random time-to-failure. The considered example pertains to the case of a tank completely filled with stored fuel, where the bearing capacity of weakened cylindrical steel shell is determined by the tensile hoop force. The alternative design scenario of a tank technologically empty (i.e. filled to the minimum level), implying the risk of stability loss, is excluded for separate considerations.

2 Alternative formal models describing the progress of corrosion

The primary source of corrosion risk in steel tanks used to store liquid petroleum products may be attributed not only to the exposure to external climate conditions [5-8], but also, even more importantly, to the internal exposure of sheathing plates to potential chemical reactions with aggressive media, often contaminated and characterized by high level of sulfur content [9-12]. The development of corrosion process in structures of this type is therefore peculiar, determined mainly by the service regimen and the type of the stored media [13, 14]. In the simplest computational models it is usually described by a linear function of time, having the form:

$$t_{\tau} = t_{nom} - A\tau \;\; [\mathrm{mm}] \tag{1}$$

where the following denotations hold: $\tau\,[\mathrm{years}]$ - the tank service time counted from the moment τ_0 associated with its commissioning, $t_{\tau}\,[\mathrm{mm}]$ - the representative thickness of the corrosion weakened tank ring, measured or forecasted for the moment τ , $t_{nom}\,[\mathrm{mm}]$ - nominal thickness as specified in the technical design of considered tank, $A\;[\mathrm{mm/year}]$ - service time independent directional coefficient of the trend line. Such an adoption requires an assumption, that at the moment τ_0 the mean value of the random shell thickness was equal to $m_t(\tau_0) = t_{nom}$. This specification seems to be justified, as at the moment of the considered tank technical inspection the real value $m_t(\tau_0)$

obtained on the statistical sample may be hardly available, and besides that, possible deviations from the so interpreted average may be positive or negative with the same probability (though some statistical research on the measurements performed in this field in the previous century seems to indicate, that the measured mill tolerances usually yielded negative deviations). On one side, in many cases the experimental research indicated that the corrosion process development was the most intensive in the initial period of the tank service time. This was so, because with the passage of time a layer of corrosion products developed on the steel surface, and this layer seemed to protect the steel to a significant degree against destructive action. On the other hand, the research conducted by the Authors on fuel tanks located in the south of Poland yielded a different result [15]. The corrosion progress in the sheathing plates, at the beginning relatively slow and fairly even due to the layers of protective coating applied on the inside surfaces of the tank, after extended service time usually exhibited significant increase in speed. Detailed verification of this trend led to the conclusion, that the protective surfaces affected by the long term exposure to the aggressive medium gradually degraded, and locally in many spots even partially delaminated and crumbled.

The classic linear model in more advanced formal approaches has been often replaced by at first a bilinear one, later on a tri-linear one and finally a power one [16-20]. In this sense the relative decrease of the considered shell thickness due to the corrosion, related to the moment τ , may be determined via the following formula:

$$\rho(\tau) = \frac{t_{nom} - t_{\tau}}{\tau} = A\tau^{\alpha} \tag{2}$$

where the exponent α is a measure of efficiency of the protective coating layer simulated in the model. Values of α close to zero denote strong retardation of the corrosion processes. When $\alpha \cong 1$ the corrosion progress is constant-in-time. In such case the corrosion products do not protect the considered steel plate in any way. The progress of corrosion processes modelled in this way is depicted in Fig. 1 under assumption that $A = 0.04\ [\mathrm{mm/year}]$ holds.

Calibration of the parameters used in the suitable power models has been performed also based on the probability-based approach [21, 22]. For example Yamamoto [23] treated the corrosion progress as a random variable with probability density function (*pdf*) characterized by Weibull distribution. The following research allowed for development of more extensive multistage (mainly four-stage) power models, described for instance in [24-29], but verified on data sets concerning corrosion of ship plates, generated by the action of salty and contaminated sea water. In the Authors' opinion the formal models of this type may be inappropriate when corrosion progress description is sought for shell plates of tanks located inland, under climate conditions usually typical for urbanized suburban areas. Therefore a simple linear model defined by the Eq. (1) has been effectively applied in the following considerations as an authoritative one. Let us note that in juxtaposition with nonlinear models depicted above in Fig. 1 with continuous lines, the linear model denoted by a dashed line yields always conservative and thus safe estimates of the forecast corrosion development, if only it is performed at the moment τ_i for the future time period $\tau > \tau_i$.

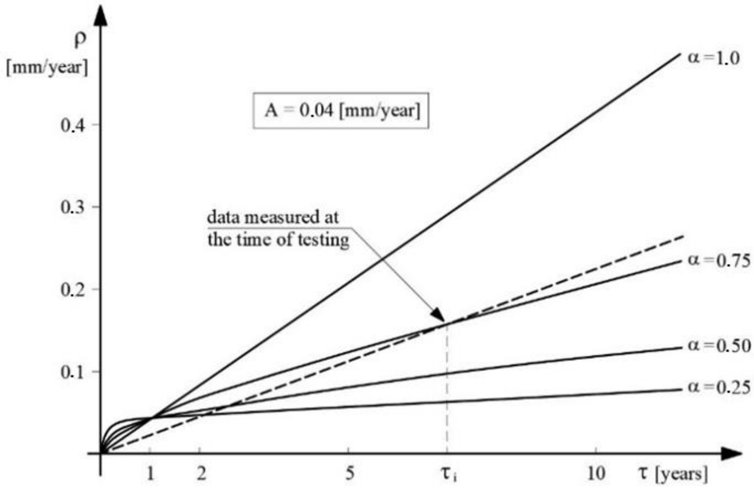

Fig. 1. Development of the corrosion process in a power model described by Eq. (2) under assumption that $A = 0.04\ [\mathrm{mm/year}]$.

The reliable expected durability forecast for the corroded fuel tank shell in question has been undertaken by the Authors in their previous works. For instance, in [30, 31] evaluation of this type has been executed based on the results of numerical simulation, while in [32-34] the basics of reasoning within this domain supported on probabilistic computational procedures have been recommended. The tank considered in the example presented here has been preliminarily analysed in [35]. The results presented below constitute a significant extension and generalization of these developments.

3 The tank considered in the example and the loads applied to it

The example presented here pertains to the existing on-the-ground steel tank equipped with a floating roof and designated to store liquid petroleum products characterized by a high vapour pressure and volumetric weight $\rho_p = 9.0\,\mathrm{kN/m^3}$. The nominal tank capacity is equal to $2000\mathrm{m^3}$ while the service one is assumed as $2011\mathrm{m^3}$, respectively. Its basic geometrical dimensions are as follows:

- height of the bearing cylindrical shell $h = 10.46\mathrm{m}$,
- shell diameter (with respect to the centre axis) $d = 16.70\mathrm{m}$,
- shell radius $r = d/2 = 8.35\mathrm{m}$,
- diameter of the floating roof $d_{roof} = 16.15\mathrm{m}$,
- external diameter of tank floor $d_b = 16.82\mathrm{m}$.

The tank has been made of S235 steel, exhibiting the characteristic yield limit of $f_y = 235\mathrm{MPa}$. The authoritative limit state of the whole corroded tank shell is in current considerations related to the bearing capacity of a single shell ring against its yielding when subjected to the axial tensile hoop force. According to the provisions of EN 1993-4-2 code [36] a partial safety factor $\gamma_M = \gamma_{M0} = 1.00$ has been assumed to specify the design value of steel strength. The static schemes of basic loads applied to the tank shell are depicted in Fig. 2.

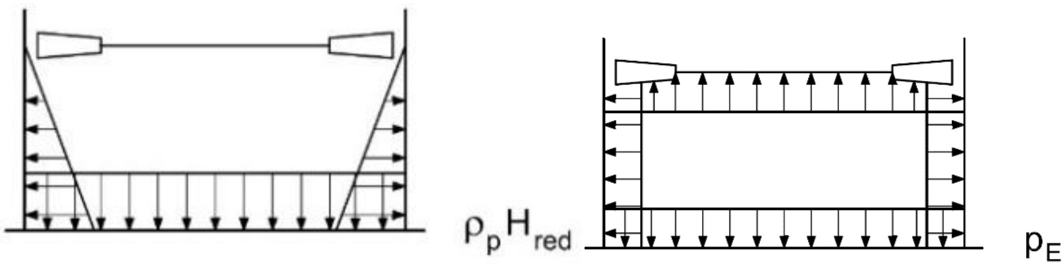

Fig. 2 Tank loads determining the required shell plate thickness: at left - hydrostatic pressure, at right - overpressure.

In order to determine the characteristic value of overpressure p_E existing inside the considered tank two alternative loading cases have been considered separately:

- characteristic snow load on the floating roof: $s = 0.9\,\mathrm{kN/m^2}$,

- characteristic pressure exerted by a 100 mm deep rainwater pool collected on the floating roof: $w = 1.0\,\mathrm{kN/m^2}$.

One may easily observe, that out of those two cases the latter one proved to be authoritative for the following calculations. As the characteristic weight of the floating roof equals $G_{roof} = 236.0\mathrm{kN}$ and its area:

$$A_{roof} = \frac{\pi d_{roof}^2}{4} = \frac{\pi \cdot 16.15}{4} = 204.85\mathrm{m}^2 \tag{3}$$

thus the characteristic overpressure p_E in the tank equals:

- for verification of the service condition (load exerted by the weight of the roof and the collected rainwater is authoritative):

$$p_E^{(e)} = \left(\frac{G_{roof}}{A_{roof}} + 1.0 \right) = \frac{236.0}{204.85} + 1.0 = 2.15\,\mathrm{kN/m^2} \tag{4}$$

- for verification of the water test condition (load exerted solely by the roof weight is authoritative):

$$p_E^{(w)} = \frac{G_{roof}}{A_{roof}} = \frac{236.0}{204.85} = 1.15\,\mathrm{kN/m^2} \tag{5}$$

Since the random overpressure p_E is treated here as a fully variable load a partial safety factor $\gamma_{F,E} = 1.50$ has been applied to determine its design value. The liquid stored in the tank has been treated as a flammable fuel to determine the hydrostatic pressure. Based on that, according to the provisions of the code [36], the partial safety factor $\gamma_{F,p} = 1.30$ has been assumed. Verification of the bearing capacity limit state has been performed for the most heavily loaded shell ring plate, adjacent to the tank bottom. For this plate the distance from the top surface of the stored fuel is equal:

$$H_{red} = h - 0.30 = 10.46 - 0.30 = 10.16\mathrm{m} \tag{6}$$

The thickness of the considered shell ring required to safely bear the loads applied has been determined by two complementary conditions. The first one is the service condition, for which:

$$\left(\gamma_{F,p} \rho_p H_{red} + \gamma_{F,E}\, p_E^{(e)} \right) \left(\frac{r}{t_d^{(e)}} \right) \le \frac{f_y}{\gamma_{M,0}} \tag{7}$$

yielding in turn:

$$\left(1.30\cdot 9.00\cdot 10.16+1.50\cdot 2.15\right)\cdot 10^{3}\cdot\left(\frac{8.35}{t_d^{(e)}}\right)\leq\frac{235\cdot 10^{6}}{1.00} \tag{8}$$

This is reduced finally to the requirement:

$$t_d^{(e)}\geq 4.34\text{mm} \tag{9}$$

The second one is the water test condition, for which:

$$\left(\gamma_{F,w}\rho_w H_{red}+\gamma_{F,E}\,p_E^{(w)}\right)\left(\frac{r}{t_d^{(w)}}\right)\leq\frac{f_y}{\gamma_{M,0}} \tag{10}$$

In these calculations it has been assumed that $\rho_w = 10.0\,\text{kN/m}^3$. Besides that, based on the provisions taken from [23], the partial safety factor $\gamma_{F,w} = 1.20$. Therefore:

$$\left(1.20\cdot 10.00\cdot 10.16+1.50\cdot 1.15\right)\cdot 10^{3}\cdot\left(\frac{8.35}{t_d^{(w)}}\right)\leq\frac{235\cdot 10^{6}}{1.00} \tag{11}$$

This is an equivalent to the requirement:

$$t_d^{(w)}\geq 4.39\text{mm} \tag{12}$$

In the considered tank a shell ring:

$$t = 7\text{mm} > \max\left(t_d^{(e)}, t_d^{(w)}\right) \tag{13}$$

thick has been used in the bottommost, most heavily loaded zone. As one may see, the real surplus for the corrosion losses foreseen in the future at the moment of the tank commissioning was adopted to be more than 2.6mm.

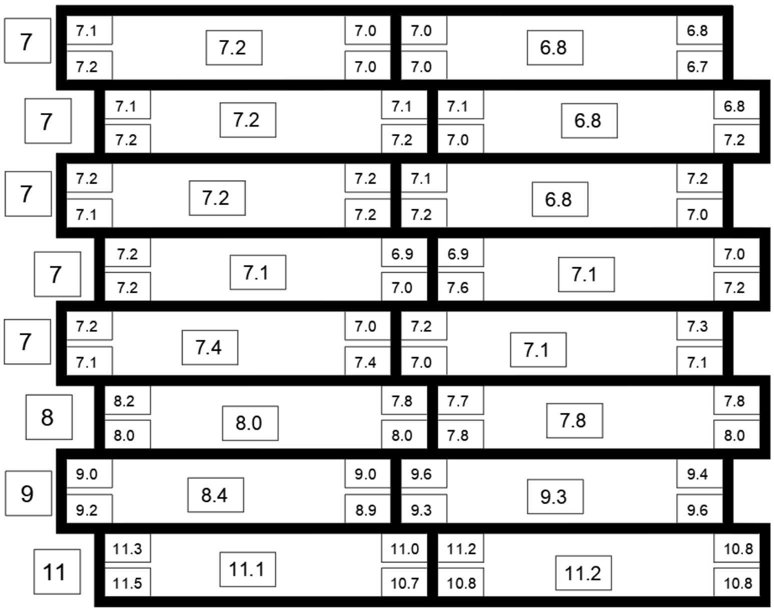

Fig. 3 Standardized location of measurement points used in the typical inventory of the random thickness $t\left(\tau^{*}\right)$ taken on the corroded tank shell (according to recommendation given in [37]). Only a segment of the whole tank shell is presented. At left the nominal thickness $t_{nom}=t\left(\tau_{0}\right)$ of each tested ring is indicated (based on [15]).

4 Evaluation of the safety level performed at the moment of the tank technical inspection

The technical condition of the corroded tank shell selected by the Authors for the durability prediction has been evaluated after $\tau^{*}=27$ years of its service. The plate thickness values, measured along the bottom ring of this shell, authoritative for verification of bearing capacity limit state, are listed in Table 1 in a form of a frequency distribution series. The presented results show only the influence of uniform corrosion. The local weakening zones created by pitting corrosion are neglected in this list. All the measurements have been performed in accordance with the requirements of a representative statistical sample, at a regular and uniformly arranged measurement grid, according to the recommendation given in [37] (Fig. 3). The subscript *i* denotes here the class number, while t_i^{*} stands for the measured plate thickness. The value n_i in this table lists the number of measurements assigned to given class.

Table 1

Measurement results of a random corroded plate thickness related to the bottom ring of the tank shell analysed in the example.

t_i^{*} [mm]	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9
n_i	1	3	6	3	13	7	1	3

As one can see the total number of measurements is equal to:

$$N = \sum_i n_i = 37 \tag{14}$$

This yields the empirical mean value:

$$m_t^* = \frac{1}{N}\sum_i n_i t_i^* = 6.573\text{mm} \tag{15}$$

and the empirical standard deviation:

$$\sigma_t^* = \sqrt{\frac{1}{N}\sum_i n_i \left(t_i^* - m_t^*\right)^2} = 0.169\text{mm} \tag{16}$$

The thickness t^* is thus a random variable having the design value determined at the level of:

$$t_d^* = m_t^* - 3\sigma_t^* = 6.573 - 3 \cdot 0.169 = 6.066\text{mm} \tag{17}$$

with the probability of underestimation equal to 0.00135. Let us note that this thickness is substantially higher than the authoritative design thickness required to safely bear the loads applied to the plate:

$$t_d^* = 6.066\text{mm} > t_d^{(w)} = 4.39\text{mm} \tag{18}$$

The coefficient:

$$\gamma^* = \frac{t_d^*}{\max\left(t_d^{(e)}, t_d^{(w)}\right)} = \frac{6.066}{4.39} = 1.382 \tag{19}$$

may be treated as the measure of a guaranteed safety level in this approach.

Knowledge of the design value t_d^* allows to determine the design bearing capacity N_{Rd}^* specified for an authoritative plate in the ring considered in the example. In the traditional computational approach, when any additional estimates of the random steel yield limit parameters, modelled usually with log-normal probability distribution, especially the median value μ_y^* and the corresponding logarithmic coefficient of variation υ_R^*, are not conducted, one gets:

$$N_{Rd}^* = t_d^* \frac{f_y}{\gamma_{M0}} = 6.066 \cdot 10^{-3} \frac{235 \cdot 10^3}{1.0} = 1425.51\text{kN/m} \tag{20}$$

As the statistical estimate of the value t_d^* already accounts for the variability of plate thickness in the considered ring at the moment τ^*, in the following analysis the influence of this type of variability is disregarded. This results in the code value:

$$f_d = \frac{f_y}{\gamma_{M0}} = \frac{235}{1.0} = \mu_y \exp\left(-3\sqrt{\upsilon_R^2 + \upsilon_A^2}\right) = 235\text{MPa} \tag{21}$$

being replaced by a corrected one derived from the formula:

$$f_d^* = \mu_y^* \exp\left(-3\upsilon_R^*\right) \tag{22}$$

The variation $\upsilon_R^2 = \left(\upsilon_R^2\right)^*$ is a measure of a variability in the yield limit, while the variation $\upsilon_A^2 = \upsilon_A^2\left(\tau\right)$ accounts for changing-in-time variability of the plate thickness intensified during shell service by the progressing corrosion. The statistical research on structural steels manufactured in the last years of the previous century indicates, that the logarithmic coefficients of variation are equal to $\upsilon_R = 0.08$ and $\upsilon_A\left(\tau_0\right) = 0.6$, respectively, and therefore:

$$\sqrt{\upsilon_R^2 + \upsilon_A^2\left(\tau_0\right)} = 0.10 \tag{23}$$

Since:

$$f_d = \mu_y \exp\left(-3\cdot 0.10\right) = 235\text{MPa} \rightarrow \mu_y = 317.22\text{MPa} = \mu_y^* \tag{24}$$

then:

$$f_d^* = 317.22 \exp\left(-3\cdot 0.08\right) = 249.53\text{MPa} \tag{25}$$

Based on this:

$$N_{Rd}^* = 6.066\cdot 10^{-3}\,\frac{249.53\cdot 10^3}{1.0} = 1513.65\,\text{kN/m} \tag{26}$$

The estimate of the design bearing capacity for a corroded shell plate analysed in the example does not require any specification of the design value of its random thickness, as one has:

$$m_{NR}^* \approx \mu_{NR}^* = \mu_y^* \mu_t^* = 317.22\cdot 10^3 \cdot 6.573\cdot 10^{-3} = 2085.09\,\text{kN/m} \tag{27}$$

and also:

$$\nu_t^* = \frac{\sigma_t^*}{m_t^*} = \frac{0.169}{6.573} = 0.026 \tag{28}$$

This leads to the specification that:

$$\nu_{NR}^* = \sqrt{\nu_R^2 + \left(\nu_t^*\right)^2} = \sqrt{0.08^2 + 0.026^2} = 0.084 \tag{29}$$

yielding in turn the estimate:

$$N_{Rd}^* = 2085.09\left(1 - 3 \cdot 0.084\right) = 1559.65\,\mathrm{kN/m} \tag{30}$$

Comparison of the results obtained after application of the formulae (20), (26) and (30) shows, that the quantitative differences in the specification of design value of random bearing capacity N_{Rd}^* of the bottommost tank shell ring after application of several computational models may exceed $130\,\mathrm{kN/m}$. It is crucial, however, that the estimate obtained using the probabilistic inference is by its very nature the most reliable and at the same time the least conservative one.

In the next calculation step the design value of a random bearing capacity N_{Rd}^* is compared against the design value of a random hoop load $N_{\varphi d}^* = N_{\varphi d}$ tensioning the ring. Such representative value of this random load is adopted to be constant-in-time during the whole tank life in service and is equal to, respectively:

- at the service condition:

$$N_{\varphi d}^{(e)} = \left(1.30 \cdot 9.00 \cdot 10.16 + 1.50 \cdot 2.15\right) \cdot 8.35 = 1019.51\,\mathrm{kN/m} \tag{31}$$

- at the water test condition:

$$N_{\varphi d}^{(w)} = \left(1.20 \cdot 10.00 \cdot 10.16 + 1.50 \cdot 1.15\right) \cdot 8.35 = 1032.44\,\mathrm{kN/m} \tag{32}$$

Based on the above, the following has been obtained:

$$\gamma^* = \frac{N_{Rd}^*}{\max\left(N_{\varphi d}^{(e)}, N_{\varphi d}^{(w)}\right)} = \frac{1559.65}{1032.44} = 1.511 \tag{33}$$

As one may easily compare, this value is substantially higher than the analogous value yielded previously by the formula (19).

5 Evaluation measures used in the probability analysis

The partial safety factors $\gamma_{F,p} = 1.30$ and $\gamma_{F,E} = 1.50$, used in the analysis presented so far, in the recommended probabilistic approach have been replaced by corresponding standard deviations when random loads applied to the analysed shell ring are considered. Due to their specificity, both these loads, i.e. the hydrostatic pressure and overpressure, have been modelled in the current example with normal probability distribution, such that the appropriate characteristic value corresponds to the corresponding mean value. Thus the following occurs:

$$\rho_p = 9.00\,\mathrm{kN/m^3} = m_p \quad \text{and} \quad \rho_w = 10.00\,\mathrm{kN/m^3} = m_w \tag{34}$$

$$p_E^{(e)} = 2.15\,\mathrm{kN/m^3} = m_E^{(e)} \quad \text{and} \quad p_E^{(w)} = 1.15\,\mathrm{kN/m^3} = m_E^{(w)} \tag{35}$$

yielding in turn:

$$9.00 \cdot 1.30 = 9.00\left(1 + 3\sigma_p\right) \Rightarrow \sigma_p = 0.100\,\mathrm{kN/m^3} \quad \text{and} \quad \nu_p = \frac{0.100}{9.00} = 0.011 \tag{36}$$

and also:

$$10.00 \cdot 1.20 = 10.00\left(1 + 3\sigma_w\right) \Rightarrow \sigma_w = 0.067\,\mathrm{kN/m^3} \quad \text{and} \quad \nu_w = \frac{0.067}{10.00} = 0.007 \tag{37}$$

Besides this:

$$2.25 \cdot 1.50 = 2.25\left(1 + 3\sigma_E^{(e)}\right) \Rightarrow \sigma_E^{(e)} = 0.167\,\mathrm{kN/m^3} \quad \text{and} \quad \nu_E^{(e)} = \frac{0.167}{2.15} = 0.078 \tag{38}$$

and also:

$$1.25 \cdot 1.50 = 1.25\left(1 + 3\sigma_E^{(w)}\right) \Rightarrow \sigma_E^{(w)} = 0.167\,\mathrm{kN/m^3} \quad \text{and} \quad \nu_E^{(w)} = \frac{0.167}{1.15} = 0.145 \tag{39}$$

Tank radius is treated in this approach as a fully deterministic quantity. Therefore parameters of the random tensile hoop force in the considered shell ring are determined as follows:

- at the service condition:

$$m_{N\varphi}^{(e)} = \left(m_p H_{red} + m_E^{(e)}\right) r = \left(9.00 \cdot 10.16 + 2.15\right) \cdot 8.35 = 781.48\,\mathrm{kN/m} \tag{40}$$

$$\nu_{N\varphi}^{(e)} = \sqrt{\nu_p^2 + \left(\nu_E^{(e)}\right)^2} = \sqrt{0.011^2 + 0.078^2} = 0.079 \tag{41}$$

- at the water test condition:

$$m_{N\varphi}^{(w)} = \left(m_w H_{red} + m_E^{(w)}\right) r = \left(10.00 \cdot 10.16 + 1.15\right) \cdot 8.35 = 857.96\,\mathrm{kN/m} \tag{42}$$

$$\nu_{N\varphi}^{(w)} = \sqrt{\nu_w^2 + \left(\nu_E^{(w)}\right)^2} = \sqrt{0.007^2 + 0.145^2} = 0.145 \tag{43}$$

Let $\Delta^* = N_R^* - N_\varphi$ be the random safety margin computed for the considered shell ring at the moment τ^*. After introduction of a standardized random variable:

$$u^* = \frac{\Delta^* - m_\Delta^*}{\sigma_\Delta^*} \tag{44}$$

one obtains a value of the variable $u^* = u_0^*$ related to the shell failure, i.e. such a moment in the tank service life, when the random bearing capacity N_R^*, decreasing in time due to the increasing corrosion losses will get even with the random load N_φ (Fig. 4 - as it was mentioned above the stationarity of the loading process is assumed, meaning that $m_{N\varphi}(\tau) = m_{N\varphi}(\tau_0) = m_{N\varphi}$ and also that $\sigma_{N\varphi}(\tau) = \sigma_{N\varphi}$). In such a situation $\Delta^* = 0$ occurs, and thus for $u^* > 0$ one gets:

$$-u_0^* = \frac{0 - m_\Delta^*}{\sigma_\Delta^*} = \frac{m_{NR}^* - m_{N\varphi}}{\sqrt{\left(\sigma_{NR}^*\right)^2 + \sigma_{N\varphi}^2}} \tag{45}$$

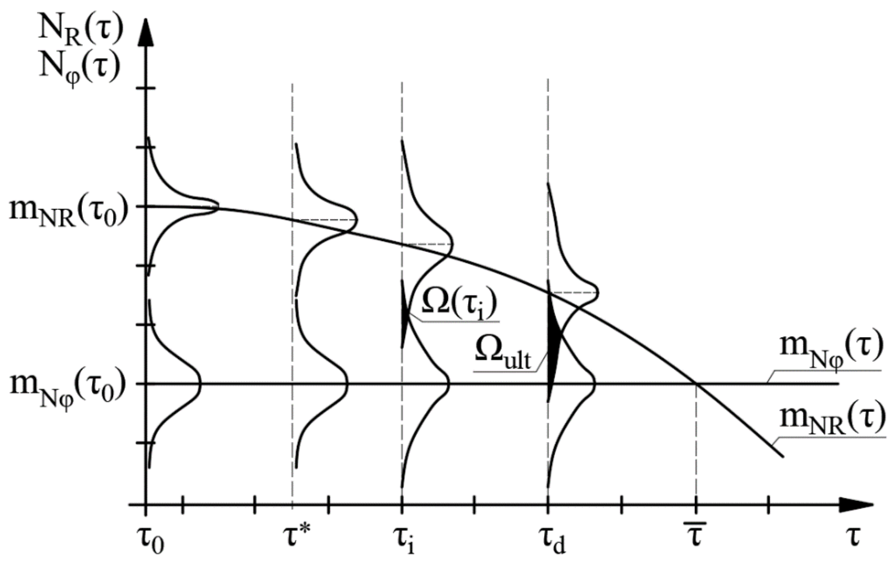

Fig. 4 The increasing-in-time failure probability of the considered corroded tank shell assuming the stationarity of the loading process. The remaining service time $\left(\tau_d - \tau^*\right)$ interpretation is shown here.

The required safety level is assured as long as the failure probability, increasing with progressing corrosion, at the moment τ^* is smaller than the limit probability, the maximum one acceptable to the tank user, i.e. when:

$$\Omega\left(-u_0^*\right) < \Omega_{ult} = \Omega\left(-u_{0,req}\right) \tag{46}$$

The inequality mentioned above is an equivalent to the statement $u_0^* > u_{0,req}$, and also to the relation $\Delta^* = 0 > \Delta_{req}^*$. In the following considerations the condition (46) will be stated applying the central safety factor defined as a quotient:

$$\overline{\gamma^*} = \frac{m_{NR}^*}{m_{N\varphi}} \geq \overline{\gamma_{req}} \tag{47}$$

In such formulation the formula (45) is transformed into the following:

$$u_0^* = \frac{\overline{\gamma^*} - 1}{\sqrt{\left(\overline{\gamma^*} v_{NR}^*\right)^2 + v_{N\varphi}^2}} \tag{48}$$

The required limit value $\overline{\gamma_{req}}$ is obtained directly from (47) by substituting $u_0^* = u_{0,req}$. This leads to the following relation:

$$\overline{\gamma_{req}} = \frac{1 + \sqrt{1 - \left(1 - u_{0,ult}^2 \left(v_{NR}^*\right)^2\right)\left(1 - u_{0,ult}^2 v_{N\varphi}^2\right)}}{1 - u_{0,ult}^2 \left(v_{NR}^*\right)^2} \tag{49}$$

Taking into account the numerical results derived via the formulae (27), (40) and (42) leads to the specifications:

$$\overline{\gamma^{*(e)}} = \frac{m_{NR}^*}{m_{N\varphi}^{(e)}} = \frac{2085.09}{781.48} = 2.668 \tag{50}$$

$$\overline{\gamma^{*(w)}} = \frac{m_{NR}^*}{m_{N\varphi}^{(w)}} = \frac{2085.09}{857.96} = 2.430 \tag{51}$$

6 Forecast of the safety state for the future tank service

Verification of the guaranteed safety level, performed at the moment $\tau = \tau^*$, constitutes a starting point for an attempt at forecasting the degree of reduction of this level in the future. The purpose of this analysis may be stated as: determine the service time of the considered structure after which the monotonously increasing failure probability Ω will reach the limiting acceptable value Ω_{ult}. Since after 27 years from commissioning the mean plate thickness in the considered ring decreased from the nominal value of $t_{nom} = m_t(\tau_0) = 7\text{mm}$ to the measured value $m_t^* = m_t(\tau^*) = 6.573\text{mm}$, then under assumption of the continuous-in-time corrosion progress described by the formula:

$$m_t(\tau) = m_t(\tau_0) - \overline{A}\tau \tag{52}$$

the directional coefficient of such a progress, averaged over measurements, may be determined as:

$$\overline{A} = \frac{t_{nom} - m_t^*}{\tau^*} = \frac{7 - 6.573}{27} = 0.0158\,\text{mm/year} \tag{53}$$

After entering (53) into (52) for the future tank service time $\tau > \tau^*$ one obtains:

$$m_t(\tau) = m_t^* \frac{\tau}{\tau^*} + t_{nom}\left(1 - \frac{\tau}{\tau^*}\right) \quad \text{and} \quad \sigma_t(\tau) \approx \sigma_t^*\left(\frac{\tau}{\tau^*}\right) \tag{54}$$

and thus:

$$\nu_t(\tau) = \frac{\sigma_t(\tau)}{m_t(\tau)} = \frac{\nu_t^*}{1 + \frac{t_{nom}}{m_t^*}\left(\frac{\tau^*}{\tau} - 1\right)} \tag{55}$$

Taking into account the measurement data gathered in the Table 1, and also parameters of the random shell plate thickness in the considered ring determined previously based on the measurements performed at the moment $\tau = \tau^*$, the forecasted parameters of this thickness specified after the time $\tau > \tau^*$ equaling 40, 60, 70 and 80 years, respectively, counting from the moment of tank commissioning τ_0, have been determined. These results are listed in detail in the Table 2.

Table 2

Forecast of the future changes in the corroded shell ring plate thickness of the tank analysed in the example.

τ [years]	27	40	60	70	80
$m_t(\tau)$ [mm]	6.573	6.368	6.052	5.893	5.735
$\nu_t(\tau)$	0.026	0.039	0.101	0.110	0.119

This data allowed for calculation, by application of the formulae (27) and (29), of the forecast mean value of random cross-section bearing capacity m_{NR} $[\mathrm{kN/m}]$ specified for the analysed shell ring as well as the coefficient of variation of this capacity v_{NR}, and subsequently, based on these results via the formula (47) the values of the central safety factors $\overline{\gamma}$, i.e. $\overline{\gamma^{(e)}}$ - pertaining to the service condition and $\overline{\gamma^{(w)}}$ - pertaining to the water test, respectively. For comparative purposes these values have been juxtaposed with the forecast values of the parameters $u_0^{(e)}$ and $u_0^{(w)}$ determined by application of the formula (45). The obtained results are presented in detail in the Table 3.

Table 3

Values of the authoritative safety parameters in the durability forecast of the corroded tank shell ring considered in the example.

τ [years]	27	40	60	70	80
m_{NR} $[\mathrm{kN/m}]$	2085.09	2020.06	1919.82	1869.38	1819.26
v_{NR}	0.084	0.089	0.101	0.110	0.119
$\overline{\gamma^{(e)}}$	2.668	2.585	2.457	2.392	2.328
$u_0^{(e)}$	7.019	6.516	5.595	5.067	4.610
$\overline{\gamma^{(w)}}$	2.430	2.354	2.238	2.179	2.120
$u_0^{(w)}$	5.711	5.314	4.610	4.209	3.849

Should the limit failure probability acceptable to the user be set at the level of Ω_{ult}, then this value corresponds to the limit value of the parameter $u_0 = u_{0,req}$, which in turn with certain simplification may be determined as [38]:

$$u_{0,req} = 2\left[\left(-\frac{\ln \Omega_{ult}}{0.693}\right)^{\frac{1}{2.46}} - 1\right] \tag{56}$$

Values of this parameter related to selected levels of probability Ω_{ult} are listed in the Table 4. When $u_0(\tau) > u_{0,req}$ the considered shell ring satisfies stated requirements and is capable of safely transferring the loads applied to it.

Table 4

Relation between the limit value of the parameter $u_{0,req}$ and the maximum failure probability Ω_{ult} acceptable to the tank user.

Ω_{ult}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
$u_{0,req}$	2.319	3.093	3.725	4.268	4.751

Detailed analysis of the results presented in the Tables 2, 3 and 4 indicates that the corroded tank shell ring, inspected after 27 years of service, at the moment of technical inspection fully satisfies the requirements of bearing capacity, even at the assumed very low acceptable failure probability, set at the level of $\Omega_{ult} = 10^{-6}$. Should the forecast uniform corrosion process progress on the considered tank shell ring with the intensity identical to the one observed prior to the technical inspection, these requirements would be satisfied after different service times, depending on the acceptable failure probability level. Of course, the considered tank may be taken out of service much sooner. The failure risk may be induced by causes other than uniform corrosion. Possible creation and development of pitting corrosion centres seems to be especially dangerous in this field. Analogous conclusions may be drawn by comparing the central safety factors $\overline{\gamma^{(e)}}$ and $\overline{\gamma^{(w)}}$ specified for the considered shell ring and listed in the Table 3 with their limit values $\overline{\gamma^{(e)}_{req}}$ and $\overline{\gamma^{(w)}_{req}}$ identified for the same ring and listed in the Tables 5 and 6, respectively. These values are determined via the formula (49), by substituting the corresponding value ν_{NR} related to the selected moment-in-time $\tau > \tau^*$ and taken directly from the Table 3 for ν^*_{NR}. Let us note, that with such verification the required limit value $\overline{\gamma_{req}}$ increases with the extending service time of the structure. This is different from the case when the safety level is determined based on the time independent parameter $u_{0,req}$.

Table 5

Limit required values of the factor $\overline{\gamma^{(e)}}$ resulting from the service condition of the tank shell ring analysed in the example.

Ω_{ult}	$\overline{\gamma^{(e)}_{req}}$				
	27	40	60	70	80
10^{-2}	1.315	1.330	1.370	1.402	1.437
10^{-3}	1.449	1.464	1.539	1.595	1.657
10^{-4}	1.574	1.609	1.706	1.790	1.887
10^{-5}	1.695	1.743	1.876	1.996	2.136
10^{-6}	1.816	1.879	2.055	2.219	2.417

Table 6

Limit required values of the factor $\overline{\gamma^{(w)}}$ resulting from the water test condition of the tank shell ring analysed in the example.

Ω_{ult}	$\overline{\gamma^{(w)}_{req}}$				
	27	40	60	70	80
10^{-2}	1.438	1.450	1.484	1.512	1.543
10^{-3}	1.614	1.627	1.694	1.744	1.800
10^{-4}	1.775	1.806	1.894	1.972	2.061

10^{-5}	1.928	1.972	2.095	2.207	2.340
10^{-6}	2.078	2.136	2.302	2.457	2.648

The process of decreasing guaranteed safety level, following the increasing corrosion loss of the sheet thickness, forecast for the considered shell ring of the tank analyzed in the example is depicted in Figures 5 and 6. Each of these pictures may be applied in the engineering practice to evaluate the representative value of the random time-to-failure (TTF) for this tank, i.e. the time during which in the future, with sufficiently high probability value and subject to the unchanged service conditions, the tank will be capable of safely resisting the loads applied to it. As one can see, it is estimated that the corroded shell of the considered tank will lose the so interpreted capacity to withstand the loads applied to it after approximately 56 years in service, should one take into account the water test condition. However, should one take into account the service condition, then based on the results of performed calculations, the tank in question will be able to safely remain in the service until 77 years have passed since its commissioning.

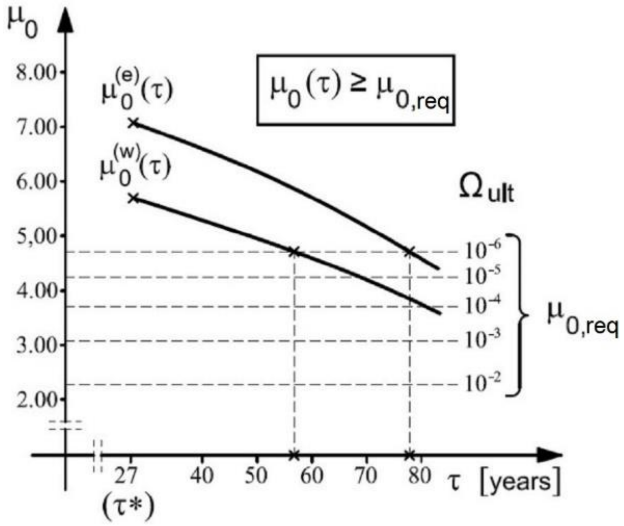

Fig. 5 The method of estimating the representative value of random time-to-failure for the tank considered in the example based on the condition $u_0(\tau) \geq u_{0,req}$.

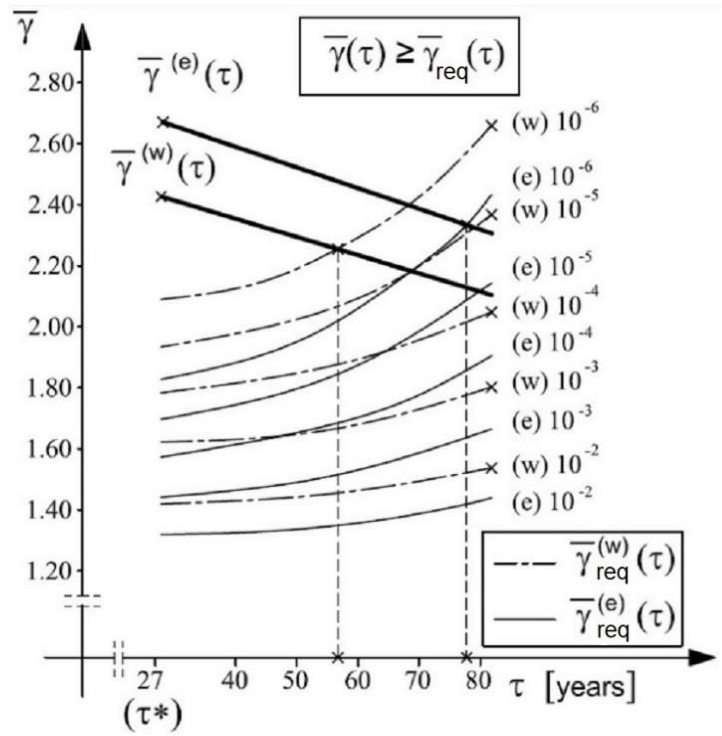

Fig. 6 The method of estimating the representative value of random time to failure for the tank considered in the example based on the condition $\overline{\gamma} \geq \overline{\gamma_{req}}$.

7 The relation between the remaining service time and the mean time-to-failure identified for the same corroded tank shell

The remaining service time interpreted in this article as a representative value of a random time-to-failure, forecast here and calculated for the considered corroded tank shell at the level of $\tau_{1,d} = \tau_d - \tau^* = 56 - 27 = 29$ years counting from the moment when the tank technical condition has been evaluated (or alternatively at the level of $\tau_{1,d} = \tau_d - \tau^* = 77 - 27 = 50$ years if only the service condition is treated as authoritative for calculations), does not directly represent the time after which the failure of such the tank is expected. It has to be interpreted only as a quantile of the random time-to-failure, specified at the assumed maximum acceptable probability level of the failure occurring. Simply speaking, after the time $\tau_{1,d}$, determined by calculations, the failure probability of the corrosion weakened steel tank shell considered in the example will become unacceptably high.

However, should the assessing inspector be interested in the most probable time, after which failure of the analysed shell, caused by corrosion weakening progressing-in-time is expected, then its value $\overline{\tau}$, counted from the moment $\tau = \tau_0$, may be found from the following condition:

$$m_{\Delta}\left(\tau = \overline{\tau}\right) = m_{NR}\left(\tau = \overline{\tau}\right) - m_{N\varphi} = 0 \tag{57}$$

Based on this, after expressing the formula (27) as a function of time, yielding:

$$m_{NR}\left(\tau\right) = m_y m_t\left(\tau\right) \tag{58}$$

and taking into account the rule (54), one gets:

$$\bar{\tau} = \frac{\left(\dfrac{m_{N\varphi}}{m_y} - t_{nom} \right) \tau^*}{m_t^* - t_{nom}} \tag{59}$$

In the case of the tank analysed in the example, after entering numerical data into the formulae mentioned above, the following has been obtained:

- for the service condition:

$$\overline{\tau^{(e)}} = \frac{\left(\dfrac{781.48}{317.22 \cdot 10^3} - 7 \cdot 10^{-3} \right) \cdot 27}{\left(6.573 - 7\right) \cdot 10^{-3}} = 286.85 \text{ years} \tag{60}$$

- for the water test condition:

$$\overline{\tau^{(w)}} = \frac{\left(\dfrac{857.96}{317.22 \cdot 10^3} - 7 \cdot 10^{-3} \right) \cdot 27}{\left(6.573 - 7\right) \cdot 10^{-3}} = 271.60 \text{ years} \tag{61}$$

So high values obtained due to the application of these formulae should not be surprising, as one should be aware that after so long time the shell failure probability will reach the level of 50% (meaning that $\Omega = 0.5$). So, in such situation, in the whole population of hypothetically investigated corroded shell plates of this type every other one will fail. Juxtaposition of the representative value of a random time-to-failure τ_d determined for the shell analysed in the example with its mean time:

$$\bar{\tau} = \min\left(\overline{\tau^{(e)}}, \overline{\tau^{(w)}} \right) \tag{62}$$

specified for the same shell indicates high statistical variability of this random variable. In the Authors' opinion the time τ_d determined as a quantile of this variable has a significant practical meaning for the managing personnel of the fuel depot while the mean time $\bar{\tau}$ known in the professional bibliography as the so-called MTTF (mean time-to-failure) seems to have only cognitive meaning.

8 Concluding remarks

In the Authors' opinion, the computational procedure presented in detail in this article seems to be useful for rational evaluation of the forecast durability for a corrosion degraded shell of a steel on-the-ground tank used to store liquid petroleum products. Data obtained during random plate thickness t^* measurements on a shell ring authoritative for the bearing capacity verification of the whole shell, and determined at the moment τ^* of tank technical inspection constitute a base for those calculations. Determination of the time $\tau_{1,d} = \tau_d - \tau^*$ understood as the representative value of a random time-to-failure, specified at the assumed and maximum acceptable to the user failure probability Ω_{ult}, constitutes the objective of this forecast. The safety condition $u_0\left(\tau > \tau^*\right) > u_{req}$ (or alternatively $\Delta_{req}\left(\tau\right) < 0$) may be replaced by the formula $\overline{\gamma}\left(\tau\right) > \overline{\gamma_{req}}\left(\tau\right)$, which seems to be more convenient in application.

The proposed forecast is based on the assumption of stationary narrow-banded loading process. This means, that during the whole tank service time both the mean value of a random tensile hoop force in the shell plates $m_{N\varphi}$ and its statistical variability quantified by corresponding coefficient of variation $v_{N\varphi}$ remain constant. However, random fluctuations of the force N_φ are not excluded, but these fluctuations do not decide over the final result of performed calculations. The corrosion weakening of the tank shell bearing capacity, progressing in its service time, is described here by the mean value of such random capacity $m_{NR}\left(\tau\right)$, monotonously decreasing-in-time $\tau > \tau^*$. This weakening is correlated with the decreasing shell thickness $t = t\left(\tau\right)$. The changes of this type in the random bearing capacity induce growth of the value of a coefficient of variation $v_{NR} = v_{NR}\left(\tau\right)$.

Progressing-in-time degradation of the considered shell ring may be measured by, for instance, decreasing values of the factor $\overline{\gamma}\left(\tau\right)$ (or by the corresponding parameter $u_0\left(\tau\right)$). These values are compared against the required limit values $\overline{\gamma_{req}}\left(\tau\right)$ or $u_{req}\left(\tau\right)$ respectively, specified for the maximum failure probability Ω_{ult} acceptable to the tank user. A constant requirement of a safety level is postulated for the whole in service period, leading to the condition that $\Omega_{ult} = const$. This means as well, that:

$$u_{req}\left(\tau\right) = \underset{\tau}{const} \tag{63}$$

Such statement, however, is not true for the factor $\overline{\gamma_{req}}\left(\tau\right)$, as in order to keep the probability Ω_{ult} constant-in-time it must increase, following the progressing degradation of the corroded steel plate.

Representative value of the random time-to-failure τ_d for the considered shell ring is derived from the equality $\overline{\gamma}\left(\tau = \tau_d\right) = \overline{\gamma_{req}}\left(\tau = \tau_d\right)$, which in turn is equivalent to $u_0\left(\tau = \tau_d\right) = u_{req}$. Durability of the weakest (in the sense of the most stressed) shell ring determined by the methods described above will be authoritative for the random durability of the whole tank shell (thus one deals here with a serial system in the sense of the reliability theory).

The quantity $u_0\left(\tau > \tau^*\right)$ in the traditional probabilistic approach is interpreted as a global safety index β_Δ. Thus the index $\beta_{\Delta,req}$ should be attributed to the required value u_{req}. This leads to the global safety condition formulated as $\beta_\Delta \geq \beta_{\Delta,req}$. Usually, for ordinary safety requirements, it is postulated to assume the uniform value of $\beta_{\Delta,req} = 3.8$, corresponding to the maximum ultimate value of failure probability set at the level $\Omega_{ult} = \Omega\left(-3.8\right) = 7.237 \cdot 10^{-5}$ if only the corroded shell bearing capacity limit state is verified for persistent design scenario. The calculated values $\Omega = \Omega\left(-u_0\left(\tau\right)\right)$ have to be smaller than that. Specification of the constant value $\beta_{\Delta,req}$ results in the time dependence of partial indices pertaining to the loads $\beta_{N\varphi} = \beta_S$ and to the tank shell bearing capacity $\beta_{NR} = \beta_R$. Should one accept the division rule as authoritative for considerations, where the so-called sensitivity coefficients $\alpha_{SR}\left(\tau\right)$ and $\alpha_{RS}\left(\tau\right)$ of the form:

$$\alpha_{SR}(\tau)=\frac{\nu_{N\varphi}}{\sqrt{\nu_{N\varphi}^2+\nu_{NR}^2(\tau)}} \quad \text{and} \quad \alpha_{RS}(\tau)=\frac{\nu_{NR}(\tau)}{\sqrt{\nu_{N\varphi}^2+\nu_{NR}^2(\tau)}} \tag{64}$$

are the proportionality coefficients, then the following holds:

$$\beta_{\Delta,req}=\alpha_{SR}(\tau)\beta_S+\alpha_{RS}(\tau)\beta_R \tag{65}$$

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

Two qualitatively different, however mutually corresponding, description measures have been applied in the presented considerations, leading to the specification of the authoritative safety conditions. A comparison of the results depicted in Fig. 5 with analogous results shown in detail in Fig. 6 indicates that each of these measures led the evaluator to the same final assessment. Thus these measures are formally equivalent, a fact not surprising, as the formulation of both is based on the transformation of the same initial safety condition stated as $\Omega(\tau)<\Omega_{ult}$.

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