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DURABILITY PREDICTION OF RANDOMLY CORRODED SIDE SURFACE SHEET IN STEEL ON THE GROUND TANK FOR LIQUID FUEL STORAGE

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ABSTRACT

The probability-based durability assessment methodology for corroded side surface steel sheet of cylindrical tank serving as a liquid fuel storage has been proposed and discussed in detail. Random nature of corrosion progress has been considered. Data related to the sheet thickness reduced by corrosion, obtained as a result of tank technical inspections, give the potential expert an opportunity to make the reliable prediction of the tank side surface behaviour in the future. Consequently, the predicted time can be evaluated, during which the examined tank still will be working properly, up to the particular point-in-time, when its decreasing loadbearing capacity becomes insufficient, because of exceeding the acceptable failure probability level.

Keywords: corrosion, steel tank, safety, failure probability, durability

INTRODUCTION

To carry out effective maintenance of steel tank in the future its reliable durability prediction should be made at present. The obtained results will be well justified only if such calculation is based on the generalised probability-based approach. Inevitable progressive corrosion of structural members seems to be the phenomenon being one of the most influential in this field. The input data used for the analysis proposed by the authors are the random values of the considered tank side surface sheet thickness t, reduced by corrosion and measured during technical inspections. Such results allow to estimate the statistic trend describing the intensity of predicted corrosion process as well as to specify its probabilistic parameters. Let the time τ_0 mean the beginning of the tank use, whereas $\tau^* > \tau_0$ be the point-in-time the durability prediction is made for. The aim of the study is to assess time-period $\tau_d - \tau^*$ when the examined steel sheet works properly and the acceptable failure probability level Ω_{ult} is not exceeded.

RANDOM RESISTANCE AND RANDOM ACTION EFFECT

The side surface of the considered steel tank is a thin cylindrical shell with random thickness $t(\tau)$, decreasing in time because of corrosion, and with constant radius r, treated in the presented study as a fully deterministic parameter. No imperfections resulted from the shell shape ovalization are taken into account. In further analysis only the steel sheets not adjoining the tank bottom are examined in detail. Such limitation allows to assume that bending moments being one of the conclusive action effects are small enough and owing to that they can be neglected in the proposed algorithm. As a consequence only the random internal tensile axial force N_φ becomes decisive for the structural analysis. It is induced in the considered sheet when hydrostatic pressure ρ_c and/or internal overpressure ρ_n are applied to the structure (Fig. 1). Its value can be calculated as follows:

$$N_\varphi = (\rho_c z + \rho_n) r \tag{1}$$

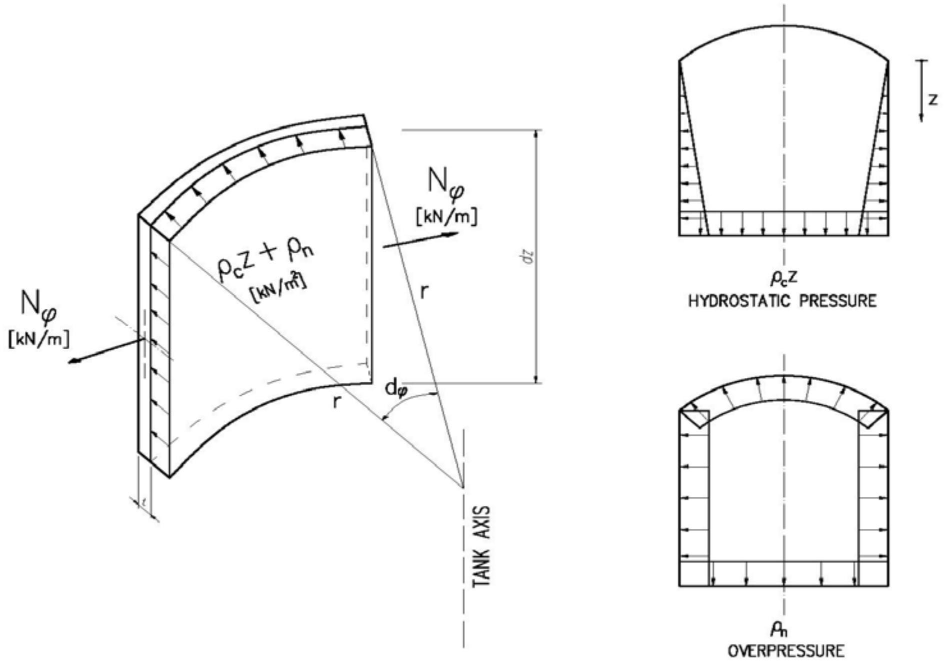

Fig. 1 External and internal forces in a considered steel sheet

On the other hand, random sheet resistance N_R is limited by the resistance of weld joining the neighbouring sheets. Factor $\alpha_\perp$ is then a deterministic coefficient, quantifying the resistance reduction of considered butt weld in relation to the yield point f_y of steel the tank is made of. Consequently:

$$N_R = \alpha_\perp f_y t \tag{2}$$

As one can see the searched resistance is the product of two random variables: the sheet thickness and the steel yield point. Let us assume that they are randomly independent (in reality the steel yield point slightly decreases when the sheet thickness becomes greater). Furthermore, both these variables can be characterised by log-normal probability distribution: $LN(\breve{t}, \upsilon_t)$ and $LN(\breve{f}_y, \upsilon_f)$, respectively. Such formal model gives the conclusive random sheet resistance being also the random variable with adequate log-normal parameters $LN(\breve{N}_R, \upsilon_{NR})$. Finally, for time τ^* occurs:

$$\breve{N}_R^* = \alpha_\perp \breve{f}_y \breve{t}^* \qquad \text{and} \qquad \upsilon_{NR}^* = \sqrt{\upsilon_f^2 + \left(\upsilon_t^*\right)^2} \tag{3}$$

Statistic parameters of considered sheet thickness t are usually estimated taking into account the measured data obtained in situ, during the tank technical inspection:

$$ln\breve{t}^* = \frac{1}{N}\sum_{i=1}^{N} ln t_i^* \rightarrow \breve{t}^* \qquad \text{and} \qquad \upsilon_t^* = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N} ln^2\left(\frac{t_i^*}{\breve{t}^*}\right)} \tag{4}$$

The median value of steel yield point $\breve{f}_y$ can be easily calculated if the suitable characteristic value f_{yk} is known in advance. Such value is in general taken directly from the standards, especially from EN 1993-1-2. Assuming that it is the lower 2%-fractile of log-normal probability distribution occurs:

$$\breve{f}_y = f_{y,k}\, exp\left(2{,}05\sqrt{\upsilon_f^2 + \upsilon_A^2}\right) \tag{5}$$

In this formula υ_A^2 is the variance describing the variability of steel sheet geometrical dimensions. However, such variability is specified in relation to the nominal value of sheet thickness, usually interpreted as the mean value $\bar{t}(\tau_0)$. It is important that always occurs $\upsilon_A(\tau_0) < \upsilon_t^*(\tau^*)$ because the coefficient of variance υ_t^* contains not only the initial variability υ_A but also the additional variability being the inevitable result of the later corrosion process. In Poland it was identified that $\upsilon_f = 0{,}08$ and $\upsilon_A = 0{,}06$, which means that:

$$\upsilon_R = \sqrt{\upsilon_f^2 + \upsilon_A^2} = \sqrt{0{,}08^2 + 0{,}06^2} = 0{,}10 \tag{6}$$

in accordance with numerous statistical estimations. Furthermore, in the presented analysis it is accepted that $\breve{f}_y(\tau_0) = \breve{f}_y^*$ and $\upsilon_f(\tau_0) = \upsilon_f^*$. In fact, the statistic parameters of steel yield point depend on the intensity of corrosion process, because of the influence of both newly generated and amplifying old microdefects in the material structure (Maślak & Siudut, 2008c); however, this effect is not yet reliably quantitatively evaluated and, as a consequence, it cannot be considered in the presented design algorithm.

The random parameters dealing with the loads applied to the tank (i.e. with ρ_c and ρ_n) can be adopted directly from the suitable standard recommendations if only the values of the adequate partial safety factors are known in advance, dependently on the probability distributions assumed for description of particular load cases (Maślak & Siudut, 2007).

PREDICTION OF FAILURE PROBABILITY

The additive convention is chosen to illustrate the proposed design methodology, therefore the recalculation is required for all random parameters specified previously into their normal (Gaussian) equivalents. Finally, the following normal distributions are considered in detail: $N\left(\overline{N_\varphi}, v_{N\varphi}\right)$ and $N\left(\overline{N_R(\tau)}, v_{NR}(\tau)\right)$. Let us notice that the loading process is in this model stationary in the whole time of the tank use, which means that $\overline{N_\varphi(\tau)} = \overline{N_\varphi} = const$ and $\sigma_{N\varphi}(\tau) = \sigma_{N\varphi} = const$, then also occurs $v_{N\varphi}(\tau) = v_{N\varphi} = const$ (see Fig. 2). However, it is important to underline the fact that in such approach any local fluctuations of the load level are possible, and only the mean values as well as the variability parametrs are assumed to be constant. Particularly, it occurs (symbol σ means the adequate standard deviation):

$$\overline{N_\varphi} = \left(\overline{\rho_c} z + \overline{\rho_n}\right) r \qquad \sigma_{N\varphi} = r\sqrt{(\sigma_c z)^2 + \sigma_n^2} \qquad v_{N\varphi} = \sqrt{v_c^2 + v_n^2} \tag{7}$$

$$\overline{f_y} = \breve{f}_y \, exp\left(\frac{\upsilon_f^2}{2}\right) \approx \breve{f}_y \quad v_f = \sqrt{exp(\upsilon_f)^2 - 1} \approx \upsilon_f \quad v_t(\tau) = \sqrt{exp[\upsilon_t(\tau)]^2 - 1} \approx \upsilon_t(\tau) \tag{8}$$

On the other hand, basing on Eq. (3) one has:

$$\overline{N_R(\tau)} = \alpha_\perp \overline{f_y}\,\overline{t(\tau)} \qquad \text{and} \qquad v_{NR}(\tau) \approx \sqrt{v_f^2 + (v_t(\tau))^2} \tag{9}$$

Consequently, the random safety margin Δ becomes the function of time τ :

$$\Delta(\tau) = N_R(\tau) - N_\varphi(\tau) \tag{10}$$

hence:

$$\overline{\Delta(\tau)} = \overline{N_R(\tau)} - \overline{N_\varphi} \qquad \text{and} \qquad \sigma_\Delta(\tau) = \sqrt{(\sigma_{NR}(\tau))^2 + \sigma_{N\varphi}^2} \tag{11}$$

where $\sigma_{NR}(\tau) = \overline{N_R(\tau)} v_{NR}(\tau)$ and $\sigma_{N\varphi} = \overline{N_\varphi} v_{N\varphi}$. The next step is the standardization of random variable $\Delta(\tau)$:

$$u(\tau) = \frac{\Delta(\tau) - \overline{\Delta(\tau)}}{\sigma_\Delta(\tau)} \tag{12}$$

In general, failure probability $\Omega(\tau)$ can be evaluate by *cdf* function (cumulative distribution) specified for normal probability distribution. This function will be a well known Laplace's function $\Phi(u(\tau))$, given in detail in numerous statistical tables, provided that it is identified for standardized random variable $u(\tau)$. Let us notice that the symbol $F(\Delta(\tau))$ means also the *cdf* function characterizing the normal probability distribution but in such notation it is specified for other type of random variable (i.e. $\Delta(\tau)$), not necessarily being standardized. Finally, it is true that:

$$\Omega(\tau) = Prob(N_R(\tau) \le N_\varphi(\tau)) = Prob(\Delta(\tau) \le 0) = F(\Delta(\tau)) = \Phi(u(\tau)) \tag{13}$$

Failure occurs for the particular value $u(\tau) = u_0(\tau)$, when the random sheet resistance $N_R(\tau)$ becomes at least equal to (or possibly even lower than) the random action effect $N_\varphi(\tau)$. In such case $\Delta(\tau) = 0 < \overline{\Delta(\tau)}$, then also $u_0(\tau) < 0$. However, the convention is usually accepted that the parameter $u_0(\tau)$ is always positive, hence:

$$\Omega(u_0(\tau) < 0) = 1 - \Omega(u_0(\tau) > 0) = \Omega(-(u_0(\tau) > 0)) \tag{14}$$

Consequently, Eq. (13) should be corrected to the following form:

$$\Omega(-u_0(\tau)) = \Phi(-u_0(\tau)) = \Phi(-\beta_\Delta(\tau)) \tag{15}$$

As one can see, parameter $u_0(\tau)$ is interpreted as the global reliability index $\beta_\Delta(\tau)$. Its value can be evaluated directly from Eq. (12):

$$-u_0(\tau)=\frac{0-\overline{\Delta(\tau)}}{\sigma_\Delta(\tau)}=-\frac{\overline{N_R(\tau)}-\overline{N_\varphi}}{\sqrt{(\sigma_{NR}(\tau))^2+\sigma_{N\varphi}^2}} \tag{16}$$

The probability $\Phi(-u_0(\tau))$ is commonly taken from the ordinary statistical tables. In the presented article the authors recommend to apply an alternative approach basing on the use of the following formula given by M. Warszyński (Warszyński, 1988):

$$\Omega(-u_0(\tau))=\Phi(-u_0(\tau))\approx 0{,}5^{\left[\left(\frac{u_0(\tau)}{2}\right)+1\right]^{2{,}46}} \tag{17}$$

THE LIMIT STATE CONDITION

The considered steel sheet will be able to carry all the external loads applied to the structure if the predicted failure probability is acceptable. This means that its value cannot exceed the admissible level, specified arbitrarily, most frequently by the adequate rules given in suitable standards. Let us notice that usually the following limitation is accepted, being accurate for 50-years reference period and being adopted in accordance with the standard EN 1990 recommendations for the ordinary safety requirements (for the reliability class RC2):

$$\Omega_{ult}=\Omega\left(-\beta_{\Delta,req}=-\beta_{50,req}=-3{,}8\right)\approx 7{,}2\cdot 10^{-5} \tag{18}$$

Consequently, the considered randomly corroded steel member will be working properly in the future up to the point-in-time of its use when the following inequality becomes unsatisfied:

$$\Omega(-u_0(\tau))\le\Omega_{ult} \tag{19}$$

Specification of the ultimate acceptable level of failure probability $\Omega_{ult}=\Omega(-u_0(\tau)=-u_{ult})$ gives the opportunity to define the minimum admissible value $u_{ult}=\beta_{\Delta,ult}>0$, and also the minimum acceptable safety margin $\Delta_{ult}(\tau)>0$ (symbol $inv\Phi$ is the notation of the inverse Laplace's function):

$$\Omega_{ult}=\Phi(-u_{ult})\rightarrow u_{ult}=-inv\Phi(\Omega_{ult}) \tag{20}$$

$$-u_{ult}=\frac{\Delta_{ult}(\tau)-\overline{\Delta(\tau)}}{\sigma_\Delta(\tau)}\rightarrow \Delta_{ult}(\tau)=\overline{\Delta(\tau)}-u_{ult}\sigma_\Delta(\tau) \tag{21}$$

Formulae presented above lead to the identification of the ultimate values u_{ult} or Δ_{ult} if only the maximum admissible probability is accepted by the tank user. To do this in general the ordinary statistical tables are applied; however, the alternative formula can be used in this field, basing on the rearrangement of Eq. (17) when $u_0(\tau)=u_{ult}$:

$$u_{ult}=2\left[\left(-\frac{ln\,\Omega_{ult}}{0{,}693}\right)^{\frac{1}{2{,}46}}-1\right] \tag{22}$$

Finally, the limit state condition, being the equivalent of Eq. (19), has the form:

$$u_0(\tau)=\beta_\Delta(\tau)>u_{ult}=\beta_{\Delta,req} \quad \text{or alternatively} \quad \Delta(\tau)>\Delta_{ult}(\tau) \tag{23}$$

The authors recommend to replace such conditions by another one which seems to be more illustrative for interpretation and easier for application. Let the symbol $\overline{\gamma(\tau)}$ denote the mean global safety factor, defined as follows:

$$\overline{\gamma(\tau)} = \frac{\overline{N_R(\tau)}}{\overline{N_\varphi}} \tag{24}$$

Its application in Eq. (16) gives:

$$u_0(\tau) = \frac{\overline{\gamma(\tau)} - 1}{\sqrt{\left(\overline{\gamma(\tau)}\right)^2 \left(v_{NR}(\tau)\right)^2 + v_{N\varphi}^2}} \tag{25}$$

As a consequence the limit state condition is rearranged to the form:

$$\overline{\gamma(\tau)} > \overline{\gamma_{ult}(\tau)} \tag{26}$$

The minimum acceptable value $\overline{\gamma_{ult}(\tau)}$ can be obtained directly from Eq. (25) by substituting $u_0(\tau) = u_{ult}$, which gives:

$$\overline{\gamma_{ult}(\tau)} = \frac{1 + \sqrt{1 - \left(1 - u_{ult}^2 \left(v_{NR}(\tau)\right)^2\right)\left(1 - u_{ult}^2 v_{N\varphi}^2\right)}}{1 - u_{ult}^2 \left(v_{NR}(\tau)\right)^2} \tag{27}$$

The point-in-time of considered tank use for which the limit state condition is reached, defined by Eq. (26) or equivalently by Eq. (23), is proposed to be marked by the symbol τ_d. Then value $\tau_d - \tau^*$ is the objective safety measure being simultaneously the measure of the predicted durability of randomly corroded steel sheet. However, such formal approach can be accurate for its reliable evaluation if only the potential corrosion process intensity is previously estimated for the future. The methodology proposed by the authors for the assessment of searched sheet durability is illustrated in detail in Fig. 2.

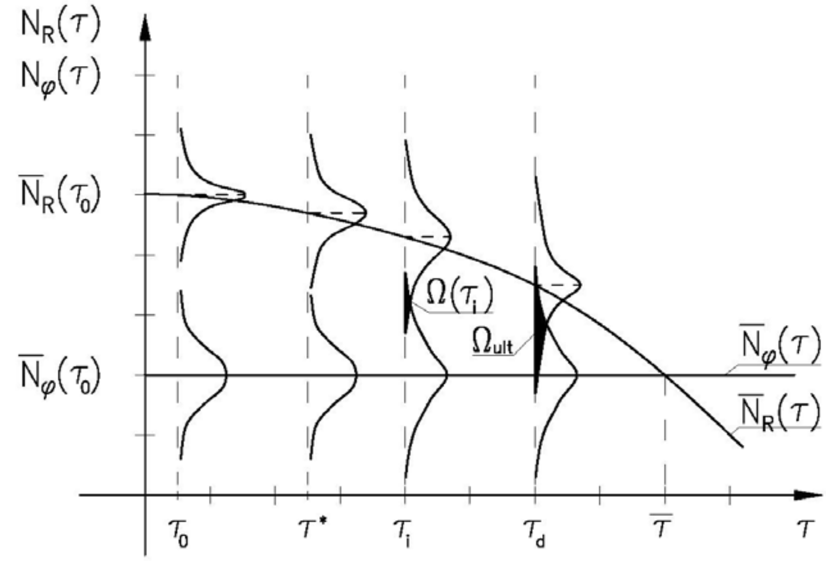

Fig. 2 Interpretation of the ultimate limit state for considered steel sheet

MODELLING OF POTENTIAL CORROSION PROCESS INTENSITY

The detailed measurements performed by the authors in situ, in one of the large tank base localised in Poland, lead to the conclusion that the model being linear-in-time is sufficient to effectively describe the process of the accumulation of corrosion wastages in tank side surface steel sheets. As a consequence the following formula is accepted for the predicted evaluations (Maślak & Siudut, 2008b):

$$\overline{t(\tau)} = \overline{t(\tau_0)} - \overline{A}\tau \tag{28}$$

If an expert knows the mean value of sheet thickness t^* reduced in relation to t_{nom} by corrosion process occured before the considered tank inspection, which is performed exactly in time τ^*, then the direction coefficient $\overline{A}$ can be calculated as follows:

$$\overline{A(\tau^*)} = \overline{A} = \frac{t_{nom} - \overline{t^*}}{\tau^* - \tau_0} \tag{29}$$

where the assumption is accepted that $\overline{t(\tau_0)} = t_{nom}$, giving:

$$\overline{t(\tau^*)} = \overline{t^*} = t_{nom} - \overline{A}(\tau^* - \tau_0) \tag{30}$$

The value of such direction coefficient is predicted to be constant during the whole time of the tank use. Its better justified assessment can be obtained by the application of the measurements performed for the same steel sheet during the technical inspections made at least at two different points-in-time, for example τ^* and τ^{**}. In reality such complete data sets are difficult to collect because the repeated technical inspection is planned relatively rarely, especially for the same steel tank still being unrenoved. Substituting the value taken from Eq. (29) to Eq. (28), and considering time $\tau > \tau^*$, leads to the formulae:

$$\overline{t(\tau)} = \overline{t^*}\frac{\tau}{\tau^* - \tau_0} + t_{nom}\left(1 - \frac{\tau}{\tau^* - \tau_0}\right) \quad \text{and} \quad \sigma_t(\tau) \approx \sigma_t^*\left(\frac{\tau}{\tau^* - \tau_0}\right) \tag{31}$$

hence:

$$v_t(\tau) = \frac{\sigma_t(\tau)}{\overline{t(\tau)}} = \frac{v_t^*}{1 + \frac{t_{nom}}{\overline{t^*}}\left(\frac{\tau^* - \tau_0}{\tau} - 1\right)} \tag{32}$$

Let us notice that the value $\sigma_t(\tau)$ is in such approach calculated in a simplified way because the influence of the variability of initial thickness $t(\tau_0)$ on the conclusive value $\sigma_t(\tau > \tau^*)$, resulted from the inevitable hot-rolling tolerances, is neglected. However, such influence is fully accounted for the parameter σ_t^*, but only for $\tau \le \tau^*$. In more accurate analysis the coefficient of variation $v_{t0} = v_t(\tau = 0)$ should be estimated as well as the precise relation between t^* and $t_0 = t(\tau_0)$. Such data are unknown in practice, particularly at time τ^* of tank technical inspection.

CONCLUDING REMARKS

The methodology presented by the authors, based on the application of the generalised fully probability design approach, seems to be helpful in the reliable evaluation of predicted tank side surface sheet durability. Such assessment is made at the time of tank technical inspection; however, it gives the opportunity to effectively estimate the potential tank behaviour in the future. Owing to that the necessary activities dealing with the tank maintenance can be planned more rationally and they can be even optimised by minimizing the potential costs.

The measure of the predicted durability is time $\tau_d - \tau^*$. To calculate the value τ_d the statistic parameters of randomly corroded sheet thickness $t(\tau)$ should be firstly estimated for selected points-in-time $\tau > \tau^*$, and, in the next step, one from the limit state conditions proposed above should be checked for those input data adopted previously. Reaching such ultimate limit state does not mean the immediate tank collapse but only the circumstances when the failure probability, specified for its loadbearing structure, becomes too large to be acceptable.

The deterioration of the considered steel sheet due to corrosion is in general the continuous process with the intensity being constant, or sometimes even being monotonically incresing, during the tank use. The ratio of such deterioration can be expressed by the suitable reliability index $\beta_{\Delta}(\tau)$, or by the adequate safety margin $\Delta(\tau)$. Alternatively, the partial safety factor $\overline{\gamma(\tau)}$ can be applied in this field. All of those measures are quantitatively decreasing when the corrosion is developing. However, an important difference between their ultimate acceptable values must be underlined. Regarding the required reliability index $\beta_{\Delta,req} = u_{ult}$, its value is constant during the whole time of the tank use. Such conclusion is contrary to the other one, dealing with the values of minimum admissible safety margin $\Delta_{req}(\tau)$ as well as of the ultimate partial safety factor $\overline{\gamma_{ult}(\tau)}$. Both of those values are changing during the tank use; however, the first of them is decreasing when the steel corrosion is expanding, whereas the second has to be increasing under such circumstances, to keep the constant level of the acceptable failure probability Ω_{ult}.

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