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Corrosion durability estimation for steel shell of a tank used to store liquid fuels

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Abstract

An original approach to forecasting the remaining safe service time of a corroded steel shell of a tank used to store liquid fuels is presented for the case where the reconstruction or repair is not planned. The estimated durability is determined by the forecast corrosion progress described based on the previous trends catalogued during earlier, periodically performed checks of the monitored structure. The analysis is conducted numerically on a three dimensional model of a tank, precisely replicating the real, imperfect geometry. Influence of the degradation due to the corrosion is superimposed over geometrical imperfections specific to the considered tank and identified as a result of geodetic measurements. Interaction of both phenomena results in local stress concentrations determining the durability sought for.

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Keywords: steel tank; corrosion; durability; trend; forecast.

1. Introduction

The reliable estimation of the forecast time to failure for a corroded steel shell of a tank being in service belongs to the basic duties of the personnel serving at the fuel base where the considered tank is located. The time, during which such tank, subjected to the evaluation of its technical condition, will be able to safely resist the loads applied

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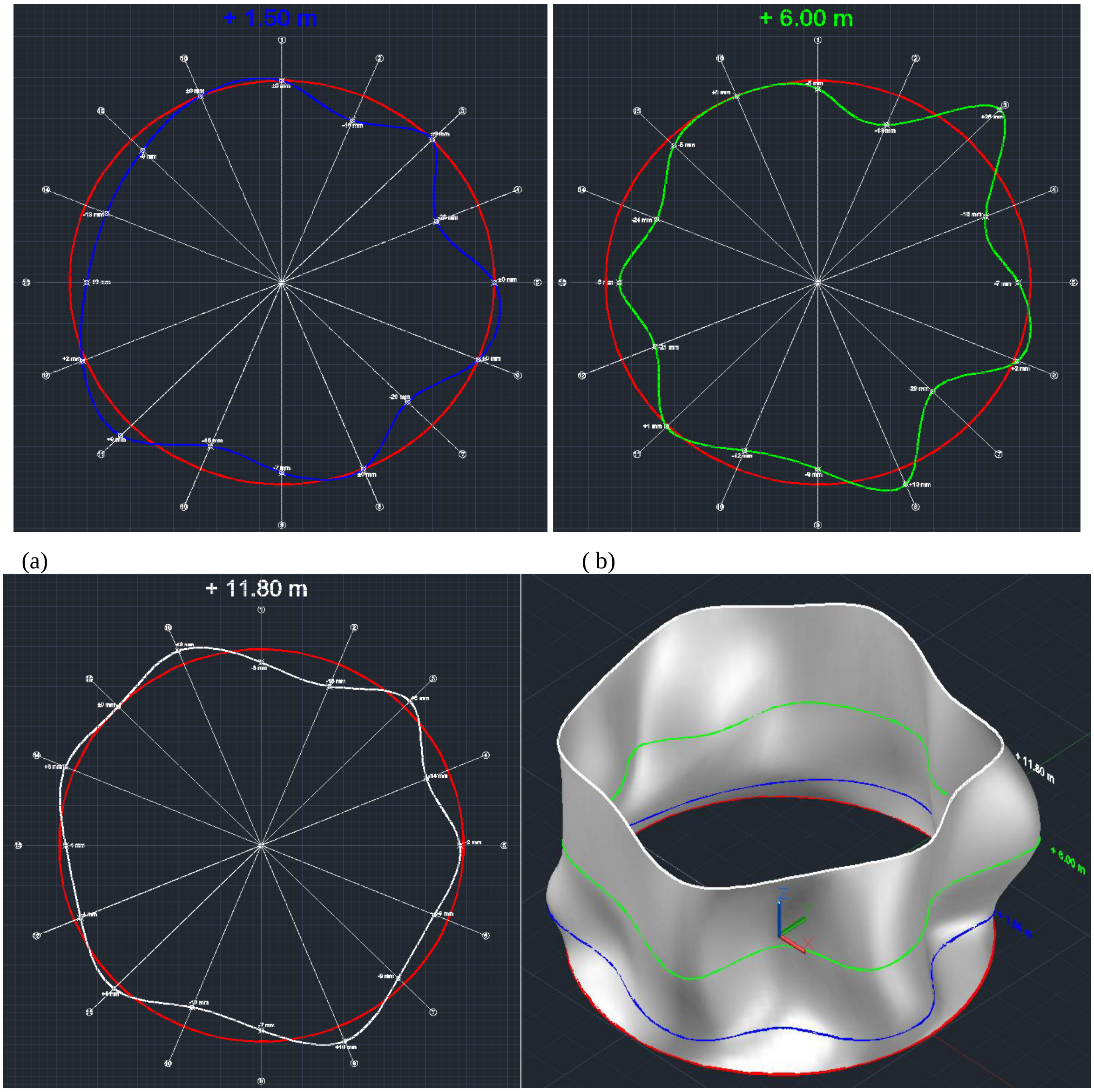
to it in spite of the weakening due to the progressing corrosion degradation, if no corrective actions are planned in the future resulting in partial or even total reconstruction of the shell, including its strengthening, is of interest here. The knowledge of such forecast durability related to all the tanks in the base allows for a rational management of the resources through appropriate planning of all logistic activities, and in particular preparation of the timetable of economically justified modernization works if necessary.

The progressing in time reduction of the cross section of structural elements constitutes the basic factor taken into consideration during the analyses dealing with estimation of the corrosion weakening of such the elements. This reduction directly affects not only their bearing capacity but also the rigidity. An additional destructive effect of the corrosion is known as well, induced by the weakening of the internal structure of the material, but this phenomenon is too difficult for quantification, as to be reliably accounted for in formal models specified to determine the forecast corrosion durability of the tank shell. Influences of this type have been considered by the Authors of this paper, and their preliminary quantitative estimates were published among others in [1]. It is also worth to cite here the more general works [2] and [3], dealing with the corrosion effects specific to the structures of petrochemical industry. The corrosion weakening effect for the tank shell may be estimated with probabilistic methods as well. An approach proposed in the paper [4] may be treated as an example here, as well as the algorithm prepared by the Authors of this paper, presented among others in [5]. Due to the inherent complexity of the analytical model, in spite of taking into account the random nature of the corrosion process, the estimates will be burdened by the locality constraint, which may result in the incompatibility with the results obtained for the tank treated as a whole. Presentation of a numerical procedure allowing for a reliable prediction of the corrosion progress, as specified for the considered tank, based on the previous trends of the corrosion process intensity catalogued during cyclically performed evaluations of the technical condition of such the tank is the objective of the present paper. The proposed rating takes into account only the influence of the locally variable thinning of the shell during the years passing in service. Nevertheless, in the Authors' opinion, due to the individual approach to the rating as well as application of the three dimensional numerical model replicating the real tank geometry instead of the ideal one with if need be assumed arbitrarily patterned imperfections, this model yields highly reliable results. This fact should make the considered approach highly attractive to the users.

2. Replication of the real tank geometry

In the analysis performed by the Authors it is assumed that the case of the completely filled tank erected in such a manner that the bearing capacity of the vertical welds is at least equivalent to the bearing capacity of the adjacent steel sheets is authoritative for the determination of corrosion durability of a corroded tank shell. This means, that the possible exhaustion of the bearing capacity will occur in the corroded steel sheets subjected to the hoop tension, and not in the welds, which are stronger than the adjacent sheet metal. Let us note, that the case of the empty tank subjected to the combined wind and internal underpressure, leading to tank destruction by the loss of stability through shell denting, is expressly omitted from the analysis, in spite of being undoubtedly interesting from the scientific point of view. It is widely known that the shell bearing capacity is very sensitive to imperfections, especially those of geometrical character, specifying the deviations from the perfect cylindrical shape. This is especially true in the case of compressive meridional and/or latitudinal forces acting in a shell. The tank shell imperfection sensitivity problem has been considered in many papers, for instance in [6], [7], [8] and [9]. In the case analyzed in this paper, where the shell is subjected to the hoop tension, the influence of imperfections is substantially less pronounced. One may even state, that the tensile hoop stresses will to a large extent negate the influence of possible imperfections arising first during the erection and later on during the service of the considered tank. Nevertheless, the influence of such imperfections may be substantially more pronounced, than the sole corrosional weakening of the steel sheets. Besides, both phenomena will superimpose, locally generating the stress concentrations, which may result in exhausting the shell bearing capacity. Because of that, in the Authors' opinion, during the analysis recommended in the current paper one should depart from the arbitrarily assumed imperfection pattern, even such one which seems to be the most adverse with respect to the bearing capacity of the considered tank shell, and replace it with a model representing the real geometry of the filled tank, obtained as a result of geodetic measurements performed during each evaluation of the tank technical condition. Of course this course of action is associated with the assumption that the assumed geometry will not change substantially in the future, during the time period corresponding to the forecast durability. This may not necessarily be true. This assumption, however, does have a certain degree of probability, on admission that the technological regime specific for the considered tank will not change and the service regimen will be kept the same as well. The geometry of the tank analyzed by the Authors of this paper and discussed in [10] is presented in the Fig.1. The measurement results are gathered for the levels of +1.50 m, +6.00 m and +11.80 m counting from the tank bottom, respectively. One may easily observe that the radial variations listed with respect to the perfect circle reach up to 30 mm, thus being equivalent to several times the shell thickness.



(a) (b)

(c) (d)

Fig. 1. Tank shell geometry of a filled tank obtained by the geodetic measurements and its representation in the numerical model applied. The radial displacements multiplied 100 times. The levels, respectively: (a) +1.50m above the tank bottom; (b) +6.00 m above the tank bottom; (c) +11.80m above the tank bottom; (d) deformed tank shell modelled in 3D.

3. Replication of the tank shell corrosion at the moment of technical condition evaluation and its extrapolation to the future

Reasonably precise replication of the tank shell corrosion state, performed for the moment of technical condition evaluation, constitutes the next step of the analysis. One has to deal here with the precise inventory of the uneven corrosion zones, usually existing on large areas of shell external surface. Potential detection of the local pitting corrosion node, generating the risk of tank shell leakage, results in the need for immediate corrective action for instance by padding (surfacing by welding). Because of this, the pitting corrosion, repaired immediately during the evaluation of technical condition, does not have the decisive importance in assessing the corrosion durability of the tank shell. Examination of the non-uniform corrosion progress is performed, according to the Polish recommendations [11], in five characteristic spots on each shell plate, namely in the geometrical center and at the four corners. An example of such inventory taken for an on the ground steel tank, equipped with the floating roof, in service for 30 years and located in one of the fuel depots in Poland is presented in the Fig.2. As one may note, due to the multiple interventions by the fuel depot personnel, resulting in the local pad welding of the shell sheets, in many places the thickness of these plates exceeded the nominal thickness specified in the technical design.

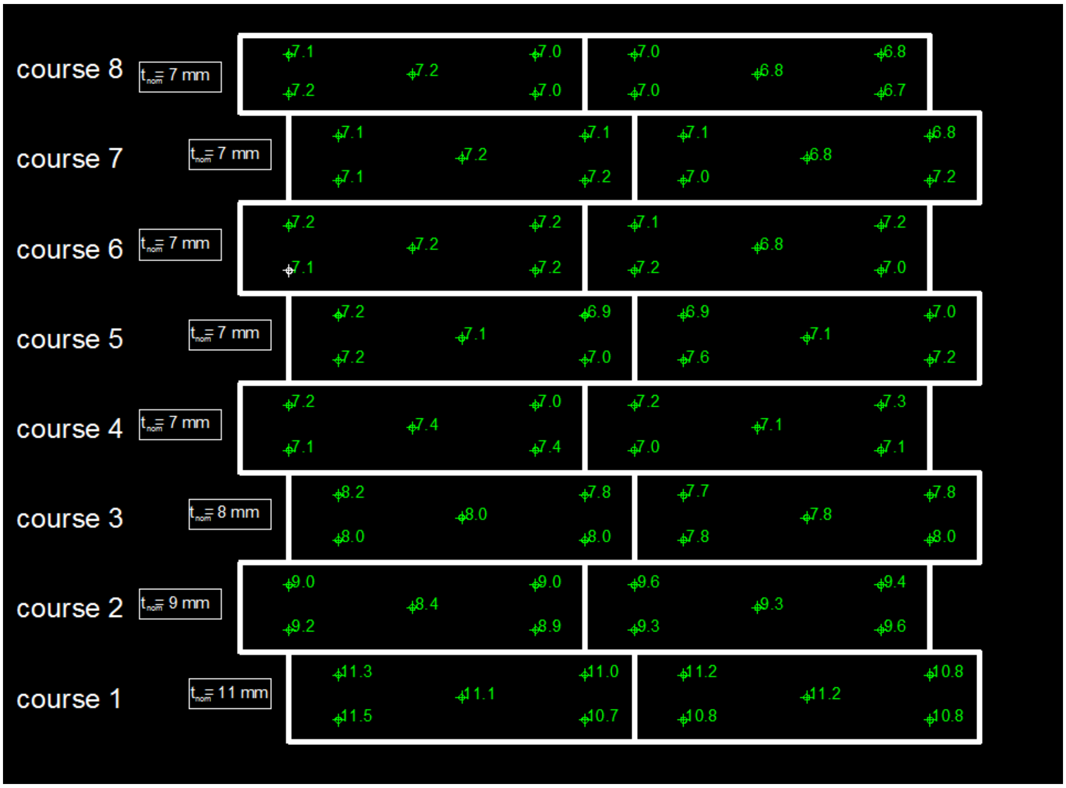


Fig. 2. Fragment of the considered tank shell with measured corroded plate thicknesses superimposed. Nominal plate thicknesses at left.

According to Polish regulations [11] all on the ground steel tanks are to be subjected to the detailed evaluation of the technical condition at least every 10 years. However, if such tanks are in the service for more than 30 years, the maximum allowed time span between inspections is shortened to six years. Cyclically repeated inventories of the corrosion progress taken on the same steel sheets, and on more or less the same locations on these sheets, yield the possibility to gather homogenous population of the statistical data monitoring the changes of random steel plate thicknesses. This will allow to determine the statistical trend describing the hitherto corrosion process and extrapolate this trend to the future for each considered spot. One shall assume only, that the usage pattern of the tank and the conditions determining the environmental aggressiveness in the near vicinity of the considered structure will not change. The observations and measurements taken by the Authors seem to indicate, that the assumption of a linear trend yields sufficient accuracy, though there are no formal obstacles to applying more complex nonlinear trends, especially the exponential trend very popular in the professional literature.

The plate thickness measurements related to the moment of inspection have to be interpolated in order to get adjusted to the applied element mesh in the numerical model. This interpolation, as performed by the Authors, is presented in Fig.3.

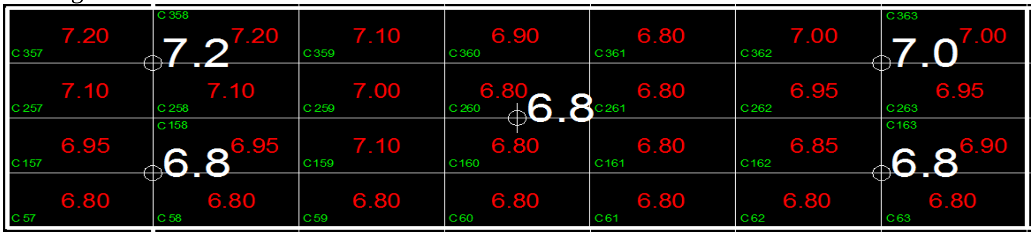


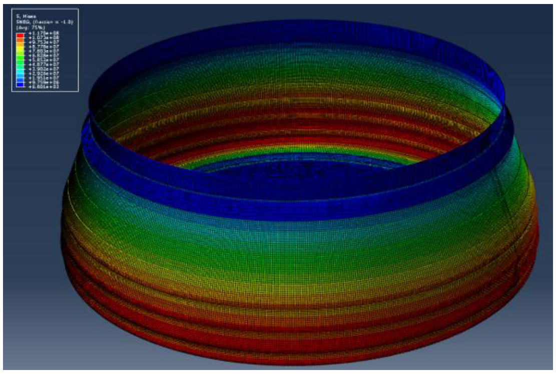
Fig. 3. Interpolation of the measured corroded steel plate thickness assumed by the Authors in order to adjust the obtained results to the element mesh of the applied numerical model (compare to Fig. 2).

As it was mentioned above, the fuel depo personnel has available data sets containing the thickness of corroded sheets measured in the past at the same spots, and gathered during the previous technical inspections of the tank condition. Thus one may prepare, for each considered spot, the trend of corrosion changes (which may be nonlinear). The trends of this type are extrapolated in the numerical model prepared by the Authors to the future service time, and this allows for reliable prediction of the tank durability.

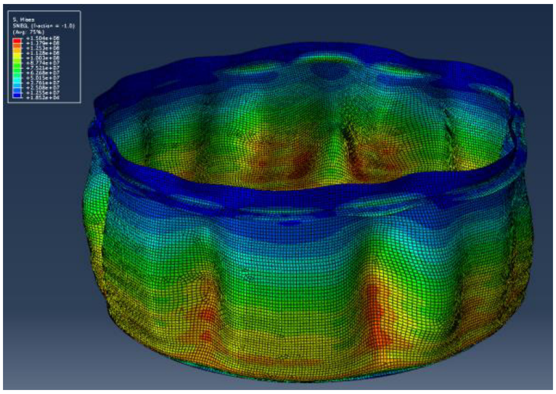
4. Results of statistical analysis conducted for the forecast corroded state of the tank shell

The knowledge of real geometry of the full tank and the corroded state of the tank shell enabled the Authors to develop the numerical model of the considered structure in the Abaqus code. This model was subsequently verified through the analysis of von Mises stresses. The results obtained during geometrically linear and geometrically nonlinear analyses are compared. Stress distributions in the shell of the analyzed tank determined for the case disregarding corrosion are presented in the Fig.4. The solutions obtained for perfect cylindrical shell geometry with geometrically linear analysis (LA), real shell geometry (with measured imperfections) with geometrically linear analysis (LA) and real shell geometry with geometrically nonlinear analysis (GNA) are depicted in Fig4. a), b), c), respectively. As can be seen on these figures, the selected analysis type significantly affects the resultant stress distributions. One may state, that the application of the most accurate formal model based on the geometrically nonlinear analysis (GNA), in the case of hoop tension in the tank shell, results in significant smoothing of all deviations from the perfect cylindrical geometry, introduced in order to consider the actual tank geometry and identified during the geometrically linear analysis (LA). This conclusion is confirmed additionally by the Fig.4 d), in which the differences in von Mises stresses determined using various types of statical analysis in a selected vertical cross section of the deformed tank shell are depicted. This cross section was selected as to yield the highest von Mises stress gradients.

The results of von Mises stress analysis in the tank shell, obtained with the effects of corrosion accounted for, for the state registered during the recent evaluation of the technical condition and for the states forecast for 10 and 20 years of service after this evaluation are depicted in Fig.5. Graphs depicted in Fig.5 a) show the distribution of stresses in the horizontal cross section located 2.00 m above the tank bottom while those depicted in Fig.5 b) the distributions along the selected meridian. Even cursory analysis of the graphs depicted in the Fig.5 a) shows that the distribution of von Mises stresses in the cross section selected for verification and forecast for 20 years in the future leads to the conclusion, that locally those stresses exceed the level of 200 MPa. This indicates a high risk of exceeding the bearing capacity of the considered shell just after that time, as the characteristic yield limit for the steel type of which the considered tank shell was made, specified for the erection time was equal to 235 MPa. Of course, the inference on the forecast corrosion durability of the considered shell would be much more meaningful if one could introduce to the analysis at least the material nonlinearity, substantially affecting the tank steel properties at the high level of stresses.



(a)



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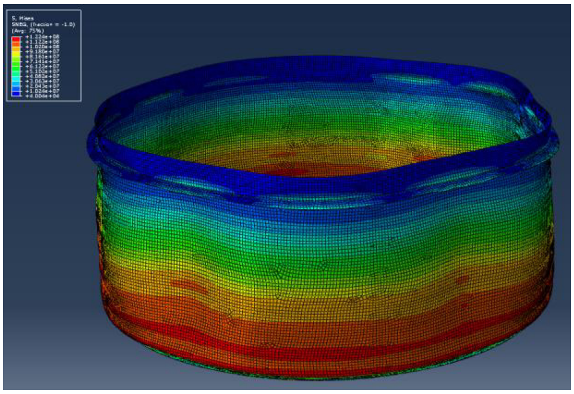
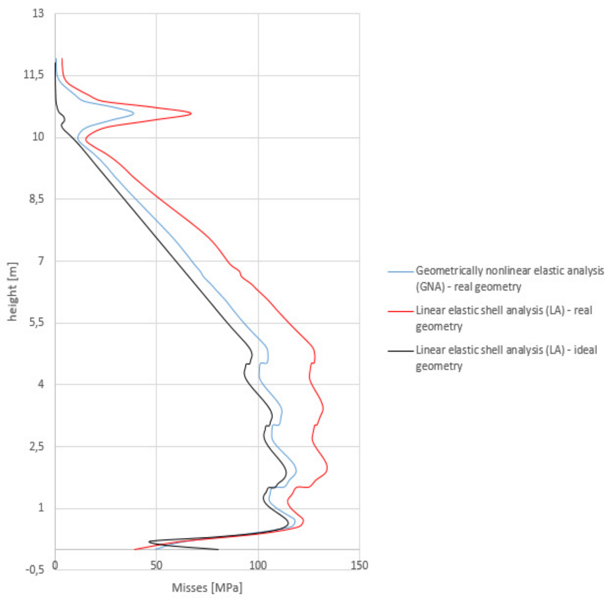
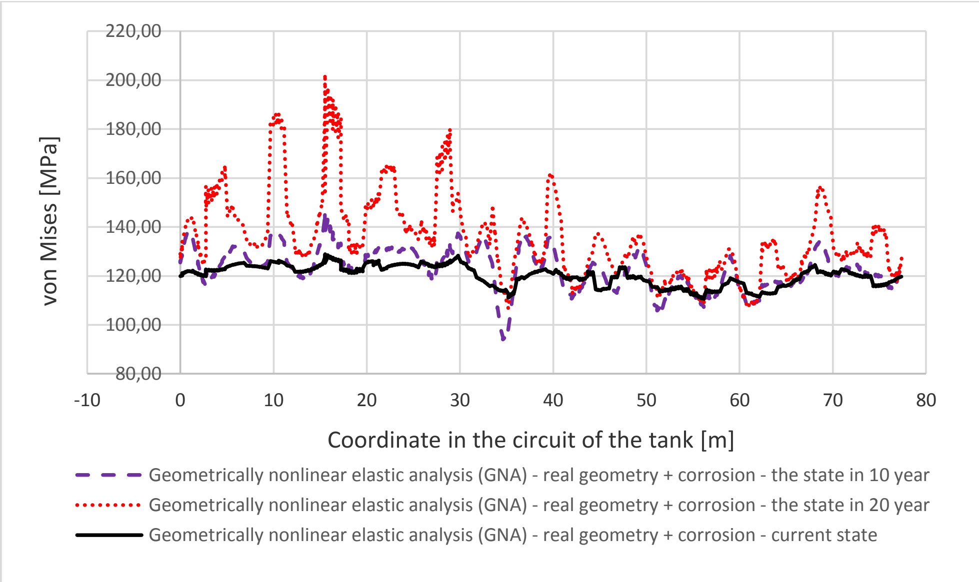


(c)

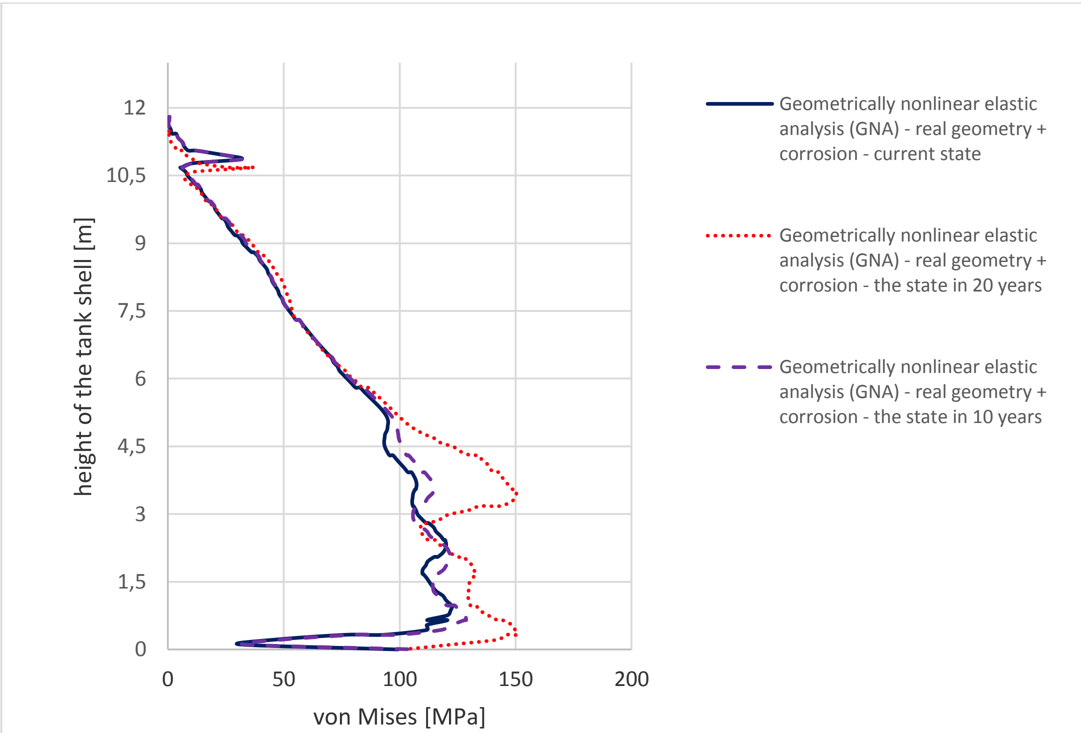


(d)

Fig. 4. Distribution of the von Mises stresses and deformations in the shell of the completely filled tank obtained for: (a) perfect shell geometry and geometrically linear analysis; (b) real shell geometry and geometrically linear analysis; (c) real shell geometry and geometrically nonlinear analysis; (d) von Mises stresses in the selected vertical cross sesction of the tank shell (the jump in the stress distribution at the top of the tank is due to the influence of the stiffening ring).



(a)



(b)

Fig. 5. Distributions of the von Mises stresses obtained during the numerical analysis for the deformed configuration of the considered tank and the non-uniform corrosion development: as observed during the most recent technical state evaluation and forecast for 10 and 20 years of continued service: (a) determined in a selected horizontal cross section of the shell located 2.00 m above the tank bottom; (b) calculated at the selected vertical cross section of the analyzed shell.

5. Concluding remarks

According to the Authors' opinion, the procedure presented in this paper yields an opportunity for a reasonably reliable estimate of an corrosion durability for a steel tank remaining in service. This optimistic ascertainment seems to be justified by the fact, that the real tank geometry is introduced into the analysis, instead of the clearly misleading analysis of the cylindrical shell with perfect geometry or the analysis of a perfect shell with arbitrarily introduced imperfection pattern.

The influence of the progressing in time degradation due to the corrosion is superimposed over local stress concentrations due to the deviations from the perfect geometry in the cross section of the shell. One may easily note, that in the global quantitative balance determining the bearing capacity of the considered shell, the influence of the locally existing deformations is usually significantly more pronounced than the sole influence of the corrosion weakening added to it. Besides, the estimated durability strongly depends on the analysis type. One may easily prove, that replacement of the geometrically nonlinear analysis (GNA) applied in this paper, by the geometrically linear one (LA) would lead to much more restrictive estimates than those obtained by the Authors (see Fig.4 d)). The difference between the compared estimates would be in many cases significantly more pronounced, than the quantitative effect introduced by the addition of the corrosion influence into the analysis. From this point of view it seems, that the corrosion durability determined based on the forecasting method recommended in this paper should rather be interpreted as a fluctuation of durability determined independently during analysis of the same shell having imperfect geometry, but excluding the influence of corrosion. Undoubtedly this fluctuation will tend to increase its intensity in time, and this may make the presented analysis useful for the potential operator of the fuel depot.

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