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Linear and Physically Non-linear Stress State Analysis of Local Shape Defects on Steel Cylindrical Tank Walls by Finite Element Method

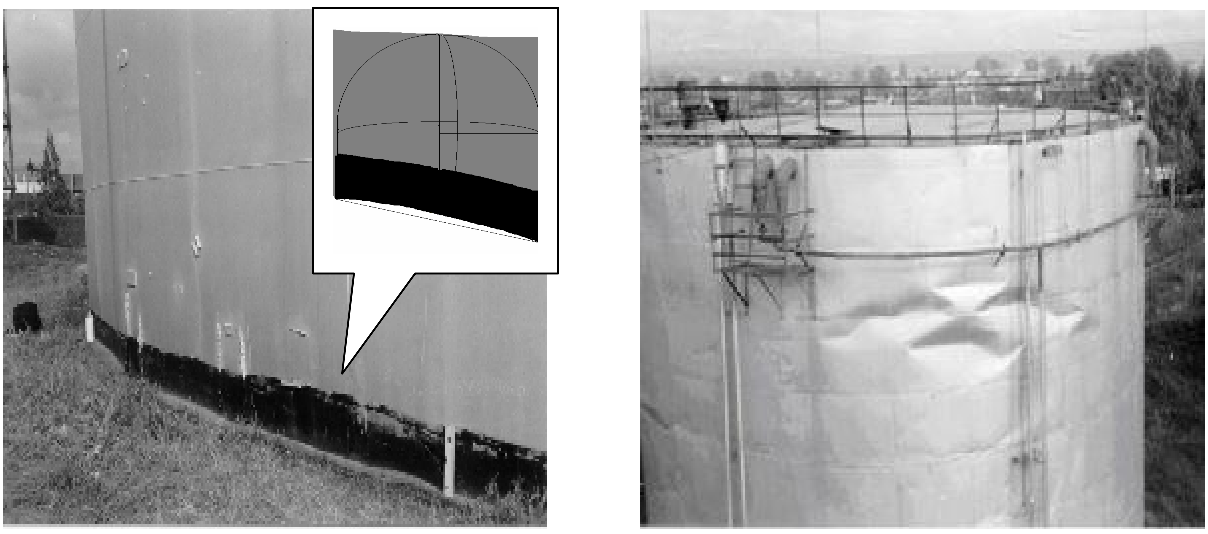
K. Romanenko*, M. Samofalov, A. Šapalas***, L.A. Aliphanov******
**Vilnius Gediminas Technical University, Saulėtekio 11, Vilnius, LT-10223, Lithuania, E-mail: kostia75@hotmail.com*
***Vilnius Gediminas Technical University, Saulėtekio 11, Vilnius, LT-10223, Lithuania, E-mail: ms@fm.vtu.lt*
****Vilnius Gediminas Technical University, Saulėtekio 11, Vilnius, LT-10223, Lithuania, E-mail: Antanas.Shapalas@st.vtu.lt*
*****Institute of Computing Modelling of Siberian Branch of Russian Academy of Sciences, Akademgorodok, Krasnoyarsk, 660036, Russia, E-mail: aliphanov@ayndex.ru*

1. Introduction

Operation of huge volume steel tanks is always connected with a full control of their state and diagnostics. A thin-walled shell of such structures requires a careful maintenance and repair, if necessary. In practice, it is rather difficult to make and use such kind structures avoiding considerable deviations from the design requirements. In time different common damages, local defects and other imperfections are accumulated. They have a tendency to increase due to non-observance of all the requirements and standards during mounting, as a result of the supports shrinkage and insufficient control of the process running. Constant inspection and elimination of such shortcomings is considered to be a common practice during the operation of huge volume structures. To simplify visual inspection, special requirements to the defect values defined by the technical standards [1-3] are provided. By their features local shape, defects of steel cylindrical tanks are close to those of the pipes thus, in practice, local defects of the pipes can be successfully applied with respect to the tanks [4]. Therefore, for the analysis of local shape defects (dents, bulges and so on) a more exact description [5, 6] is required.

In many cases, the local shape defects, according to statistical investigations, are considered as secondary factors of various technical collapses. More important influence of such defects is observed in combination with a poor-quality steel or near welded zones.

Practically, to study the influence of local shape defects on tank thin walls, the descriptions of 84 cylindrical steel tank crashes have been investigated [7]. In general, the most valuable 16 factors have been considered (Fig. 1). This research has proved that the most important errors may be (an additional number points to the number of references in the specialists experts reports) as follows: the defects of welded joints – 47; low temperature – 28; the disturbance in realisation of a corresponding project – 24; poor quality of steel – 25; the differences of temperatures – 21; stress concentration – 16; the differences of pressures – 11; violation of operating conditions – 9; supports shrinkage – 7; the influence of corrosion – 8; non-observance of the initial test conditions – 9. In many cases, the local shape defects may be described as an additional factor. On the other hand, this factor should be taken into account during the analysis of mechanical behaviour of a geometrically non-perfect structure. Besides, the local shape defects are not considered to be uncommon phenomenon. For example, an industrial complex of 78 thin-walled cylindrical tanks has been considered as a case of typical structures, designed for light oil products



a b

Fig. 1 Local shape defects on a wall of steel cylindrical tanks: a dent on the lowest part (a); dents on the upper part (b)

[7]. A great part of local geometric defects has been disclosed on the first (lowest) strip of the tanks. Generally, 286 defects have been detected, 106 of which had highest geometrical parameters in comparison with those limited by the standards: 95 dents and 11 bulges. In particular: 41 dents and 3 bulges have been found on walls of 420 m^3 volume tanks; 24 dents and 6 bulges – on walls of 700-3350 m^3 tanks; 26 dents and 2 bulges – on 5000 m^3 tanks; 4 dents – on the tanks of more than 5000 m^3 volume.

On the other hand, practically a lot of tanks with the defect values exceeding those allowable by the standards [1-3, 5, 6] are used, and this fact, as it follows from the observations, does not cause deterioration of the tanks state [7]. In the presented analysis special attention is given to the computation of the shape defects, such as dents. It should be noted that no sufficient attention is payed to this problem that is why restrictions concerning dimensions, depth, radius and other geometrical parameters of the dents, are as a rule either too high or described not quite exactly.

The main difficulty, while estimating the defects danger, lies in the proper selection of the simulation model as it greatly influences the subsequent determination of mechanical state within the dent area. Besides, it is very important to achieve the correspondence between the shape of a real dent and its computational model. A predetermined value of the stress available in this region is also essential. There is one more problem, which is of great significance – variation of the dent shape during loading of the structure and sometimes-even the change of its location. All the above-mentioned questions are of equal importance. For the investigation of each specific case or a group of such problems a series of simplifying assumptions are introduced taking into consideration a physical sense and the peculiarities of an individual situation [4, 8-13].

A rapid progress in hardware and constant improvement of the software enables to extend the possibilities of the creation of virtual and mathematical models as well as to consider a much higher number of various combinations. However, the developments of accurate analytical models [4, 7-10, 12-14] are particularly essential for the state investigation of the structures to be used. To date, such solutions are of special concern for practicing engineers. As an efficient approach one can consider duplicating of the analytical methods by numerical ones and, vice versa, as such comparisons considerably improve both means of the solution [15]. The proposed investigations are devoted to the solution of all the above-mentioned problems.

2. Assumptions in Analytical Stress State Analysis

The causes of shape local defects, occurring using tanks, can be different: minor deviations from the fabrication process, departures during mounting of structures or the accessory equipment, non-uniform foundation shrinkage etc. If during the structure inspection inadmissible departures from the ideal design shape are stated, it is not enough to find out the reason of their appearance but it is necessary to investigate the influence of these defects on the mechanical state of the structure. The thin-walled shell of the tank is sensitive to both: single defects of a local type or a series of such defects. The practical observations prove [8, 14,] that accumulation of the defects becomes the main reason of a failure if the tank is being used for 20-25 years. The serviceability standards of the structures of that kind provide their safe operation for 25-30 years. In order to use the structure serviceable life completely, one should thoroughly study its strain state at the sites of the defects, which have appeared, but it is not so easy to do it even with the usage of the most advanced modern engineering software.

When analysing the influence of shape local defects on mechanical state of the tanks, the experience and skills acquired during operating the structures, which have been already damaged, are of particular importance. It is also very essential to select properly the appropriate computation method and existing standards. Different design codes and instruction manuals confine the presence of tank defects by their external appearance, e.g. [3]: if the defect diameter does not exceed 1.5 m the dent value must not be over 15 mm; with 1.5 to 3.0 m diameter this value should not exceed 30 mm; in case of 3.0 to 4.5 m diameter the dent allowable sag is not more than 45 mm; the defects of more than 4.5 m diameters are not considered to be local. Analogously, the defect values are standardized by the design and scientific organizations of such famous international companies as British Gas, Shell, American Petroleum Institute and so on [1, 6], e.g.: the dent depth should not exceed ½ inch for a three-foot defect. Such requirements do not take into account many important factors such as: the tank shell thickness; the defect location; causes of its occurrence; loading frequency etc. Of course, the available requirements are formulated too strict as the specific circumstances of a real situation are not described and taken into consideration. Why such a condition takes place is quite clear. While developing the design standards the main attention was payed to more dangerous “sharp” defects (holes, joints and so on) and the problem of “soft” defects (dents, bulges etc.) was not so important at this stage. At the present time, when specifying the design standards and operating rules, it is necessary to describe the influence of local defects on the strain state more precisely [16-19].

The analytical methods suggested to solve the problems [10, 12] are based on assumptions common in engineering practice. One of the most popular assumptions is membrane analogy [13]. Unfortunately, the determination of stress concentration using this model is not quite exact. The standards allowing deflections from geometrical form [3] suggest to consider a model with the modified geometry taking into account the initial stresses according to the increase of *stress concentration factor* (SCF). The shortcomings of such theoretical model, when a part of the factors is being ignored, are not always compensated for a margin of safety. The local shape defects of the tanks are very similar to those of the pipes as far as their physical characteristics are concerned [4].

The main task, when investigating local defects of a geometrical shape in the vertical cylindrical tanks, is to describe the strain state within the defect area and to determine the most dangerous sections expressing it in terms of SCF. It is also important to look into the problem of the development and usage of the proposed methods for a wider spectrum of the computational versions.

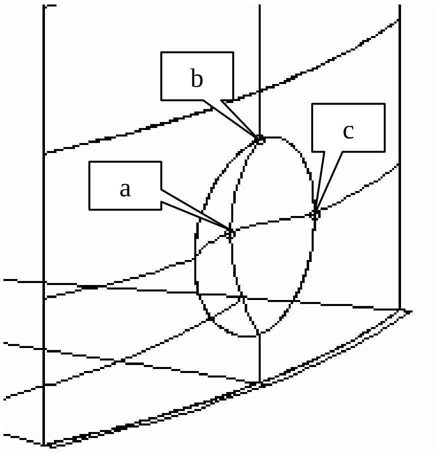


Fig. 2 Location of the analysed points: midpoint (a); contour upper point (b); contour side point (c)

The location of the most dangerous points (Fig. 2) has been selected on the basis of inspection practice for steel cylindrical tanks considering also the features of the task given and the results of the observation and study published in other papers [8-10].

The most dangerous sites of a dent are an area of its centre and its profile portions (Fig. 2).

In general, the value of SCF in the middle of the defect is calculated by the formula:

$$k_a\left(q_i, b, g\right)=\frac{P_1\left(q_i, b, g\right)}{P_2\left(q_i, b, g\right)} \tag{1}$$

where coefficient b expresses a conventional dimension of the wall dent:

$$b\left(r, R, t\right)=\frac{r}{\sqrt{R\,t}} \tag{2}$$

where r is dent radius, R is the radius of the whole tank, t is the tank wall thickness at a site of defect. Coefficient g describes relative sag of the thin shell:

$$g\left(f,t\right)=\frac{f}{t} \tag{3}$$

where f is absolute value of the sag, i. e. the greatest deviation from perfect form at the defect location.

The upper side of the equation (1) reflects an increase in stresses across the dent central point, whereas the lower side describes the total (rated) distribution of stresses within the defect area:

$$P_1\left(q_i, b, g\right) = q_1 - q_2 b - q_3 b^2 + q_4 b^3 + q_5 b\,g - q_6 b^2 g - q_7 b^3 g + q_8 b\,g^2 - q_9 g^2 \tag{4a}$$

$$P_2\left(q_i, b, g\right) = q_{10} - q_{11} b + q_{12} b^2 - q_{13} b\,g - q_{14} b^2 g + g^2 \tag{4b}$$

where semi-empirical coefficients q are adopted on the basis of natural observations and theoretical investigations, they slightly correct the results of analytical solutions: $q_1 = 56.1$; $q_2 = 27.4$; $q_3 = 0.821$; $q_4 = 0.286$; $q_5 = 0.057$; $q_6 = 0.034$; $q_7 = 0.028$; $q_8 = 0.161$; $q_9 = 0.150$; $q_{10} = 59.5$; $q_{11} = 9.71$; $q_{12} = 1.79$; $q_{13} = 0.378$; $q_{14} = 0.174$.

The increase in stresses across the dent edge is described by the more obviously pronounced difference, therefore, for the end-points of the dent area SCF is expressed in the following form:

$$k_b\left(s_i, b, g\right)= A\left(s_i, g\right)\cdot b^{\,m}\left(s_i, b, g\right) \tag{5}$$

where the first factor reflects an influence of the dent depth on the SCF:

$$A\left(s_i, g\right)= s_1 + s_2\,g - s_3\,g^2 + s_4\,g^3 - s_5\,g^4 \tag{6a}$$

where algebraic coefficients are $s_1 = 2.57$, $s_2 = 0.51$, $s_3 = 0.0688$, $s_4 = 0.376\cdot10^{-2}$, $s_5 = 0.75\cdot10^{-4}$.

The second factor (multiplier) represents a power function and it takes into account the influence of the dent dimension, as well as the depth and radius:

$$b^{\,m}\left(s_i, b, g\right)=\left[\,b\,\right]^{\left(s_6 \ln(g) + s_7\right)} \tag{6b}$$

where dimensionless coefficients are expressed as $s_6 = 0.169$ and $s_7 = 0.153$.

When calculating SCF of a real structure, it should be kept in mind, that the profile points of the dent are usually placed under different conditions and thus are strained differently. The above equations (5)-(6) do not reflect the position of a point on the profile and specific conditions at this point as well as the defect location on the tank. This deficiency is compensated for easiness and convenience of their usage and also for some exceeding the values in comparison with the real ones. Further, we shall consider accuracy of the given assumptions as compared with the results obtained from the calculations of an individual problem by approximate numerical methods.

To illustrate general dependence of SCF on the dent geometrical parameters, we consider versions of coefficient variation $g = 2, \ldots, 16$ with values $b = 1, 2, 3, 4, 5$ being fixed and coefficients q и s being previously drawn. In the given solution the relationship $k(g)$ between SCF and the relative dent depth is considered. The obtained results have illustrated (Fig. 3), that stresses at the central point are increased if the defect depth f is reduced, when its radius r is being increased. In physical sense it means gradual transition from a soft defect to the sharp one. As compared with the values, allowable by the standards (line *6* is given by formula (1) on Fig. 3), SCF exceeded values do not exist.

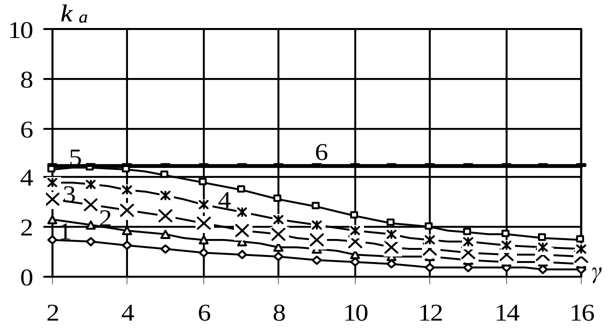


Fig. 3 SCF at the dent centre on the tank external surface

When investigating stresses at the defect contour points the opposite effect is being observed – with the increase in relative depth g , the increase in stresses takes place (Fig. 4). Only in some specific cases, if the values allowed by standards are exceeded with $b \geq 3$ and $g \geq 3$ by line *6*, we can state that there are the most dangerous points on the defect contour.

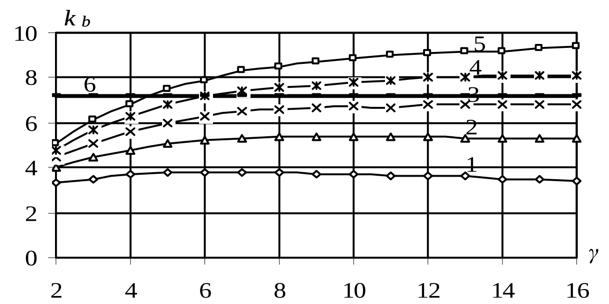


Fig. 4 SCF at the dent contour on the tank external surface

SCF values on the contour and at the dent centre will be equivalent $k_a = k_b$ with $b = 2$ and $g = 4$.

In the presented solution properties of homogeneous elastic steel have been defined by Young's and shear modulus $E/G = 2.6$. The proposed analytical expressions describe stress state depending on geometric factors of the dent as well as on the defect radius, sag and wall thickness. Such analysis does not consider the influence of plasticity and initial stress. More over, there is no investigation of geometric non-linearity problem, which should not be neglected. However, these factors are important in many cases of local shape defects.

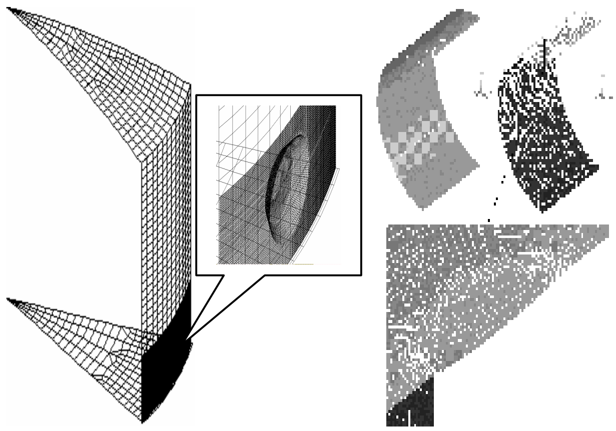
The given formulas (1)-(6) were derived providing the dent shape is a semi-sphere and they are not sensitive to the defects of another form. The presented calculations illustrate an increase in SCF at the centre with relatively small dimensions of the defect and growth of the above-mentioned factor on the contour, when the defect dimension gets larger.

3. Finite Element Modelling

3.1. Concepts of Numerical Model

In order to check whether formulas (1)-(6) are correct, modelling of different kinds of defects for a real structure [7, 15] has been performed. In this case the main solutions are made using standard finite element code COSMOS/M [20], and computation of one of the versions was additionally doubled by ANSYS [21], where other principles have been applied.

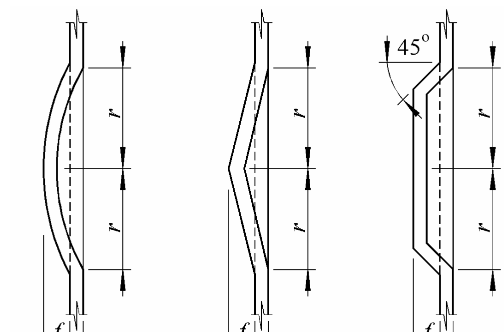
For the solution of the problem by COSMOS/M software, 1/12 portion of the cylindrical tank was taken (Fig. 5a), considering conditions of geometric shape symmetry and loading by the liquid pressure from within. The tank parameters were as follows: $R = 11.5$ m, $H = 12.0$ m, the wall thickness at a site of the defect $t = 7$ mm. Tetragonal *finite elements* (FE) of "SHELL" type having 4 nodes and described by 24 *degrees of freedom* (DOF) were employed during this calculation (three linear displacements and three rotational displacements at each of the node of FE mesh). Dimensions of the FE do not exceed 1/128 of the segment length. In order to simulate the real situation ground pressure on the tank bottom was considered via conventional rigidities of 10.0 MPa. The model created in COSMOS/M reflects natural location of a dent on the entire tank and real conditions of its operation.



a b

Fig. 5 Discretion of the tank by using two standard FEM codes: COSMOS/M (a) and ANSYS (b)

A segment of the tank has been subjected to self-weight and the product pressure, which have been linearly applied. Three kinds of a dent were simulated: semi-sphere (or mathematically hemi-sphere), cone and truncated cone (Fig. 6). The selection of the defects shapes was based upon the observation of real structures [14].



a b c

Fig. 6 Shape of the simulated local defect: semi-sphere (a); cone (b); truncated cone (c)

When the lower strip directly contains the defect, the solution was simulated by ANSYS (that is a half of the tank rim). In this case, the boundary conditions both for defect and for the whole model were taken as symmetric ones (Fig. 5b). This model was acted only with the load produced by the product pressure as the most valuable one.

3.2. Linear Stress State Analysis

Unlike the above-presented investigation concerning stress distribution within the defect area by means of analytical expressions (1) and (5), this part of the paper considers the problem simulation using *finite element method* (FEM). The results, obtained in three typical points a, b and c, have demonstrated that SCF is being changed differently within the centre and over the dent contour depending on the variation of its radius and thickness. The given curves (Fig. 7-9) point to the SCF variation with different values of the defect relative thickness $g = 2, \ldots, 16$ and relative radius $b = 1, \ldots, 5$. In this case, geometrical parameters R and t as well as mechanical characteristics of steel have been considered as constant ones.

The simplest way for abstraction and the most popular [6] one for the shape dent calculation is modelling of the strained-deformed state of semi-sphere (Fig. 6a).

In this case the most dangerous value $k_b = 7.0$ of the SCF within the dent upper point is observed at $b = 4$ and $g = 16$ (Fig. 7b). For dent end-points the way of SCF variation as a function of such factors as b and g is apparently different (Fig. 7b, c). This obvious difference is accounted for by the strained state of the profile various points. This difference is particularly evident with $g \geq 9$, it means that the phenomenon as itself is not described exactly, (line *6* given by formula (5) on Fig. 7) and that it is possible to make these formulas more precise on the basis of the solution by FEM. For the centre point of the defect the largest value $k_a = 5.2$ is with $b = 5$ and $g = 4$ (Fig. 7a), while for the side one $k_c = 5.1$ with $b = 5$ and $g = 5$ (Fig. 7c). It is interesting to note, that there is a point at all three dent characteristic points, where the curves with values $b = 5$ and $g = 5$ are intersected. The plots show $k = 1$ as SCF values, when the influence of the concentrators is left out of account. It means that the influence of the

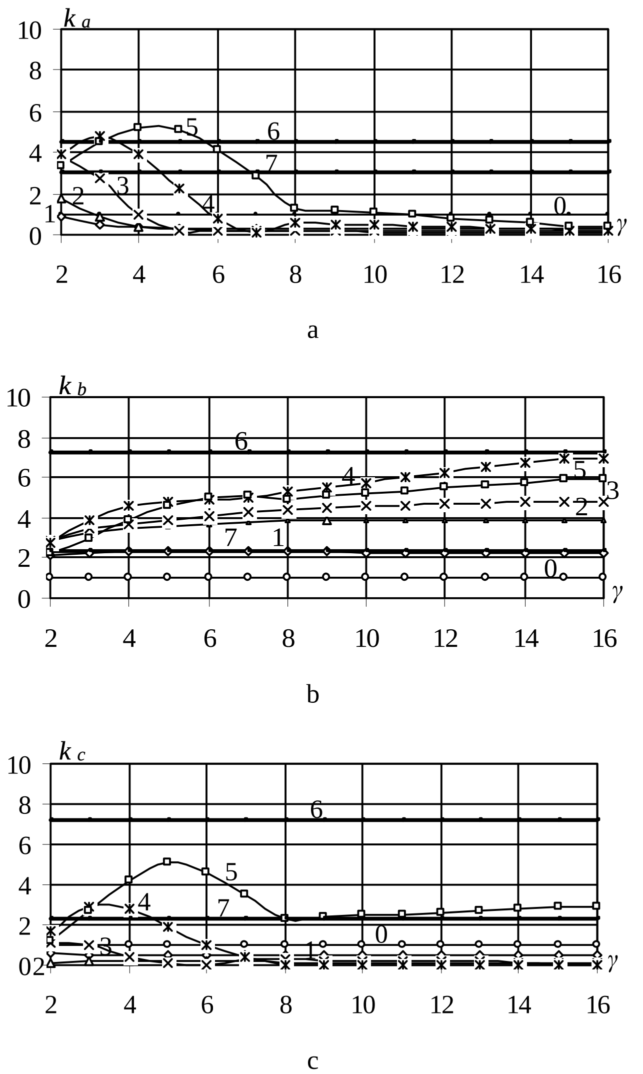


Fig. 7 Variation of SCF at the points of semi-sphere dent: midpoint (a); upper point (b); side point (c)

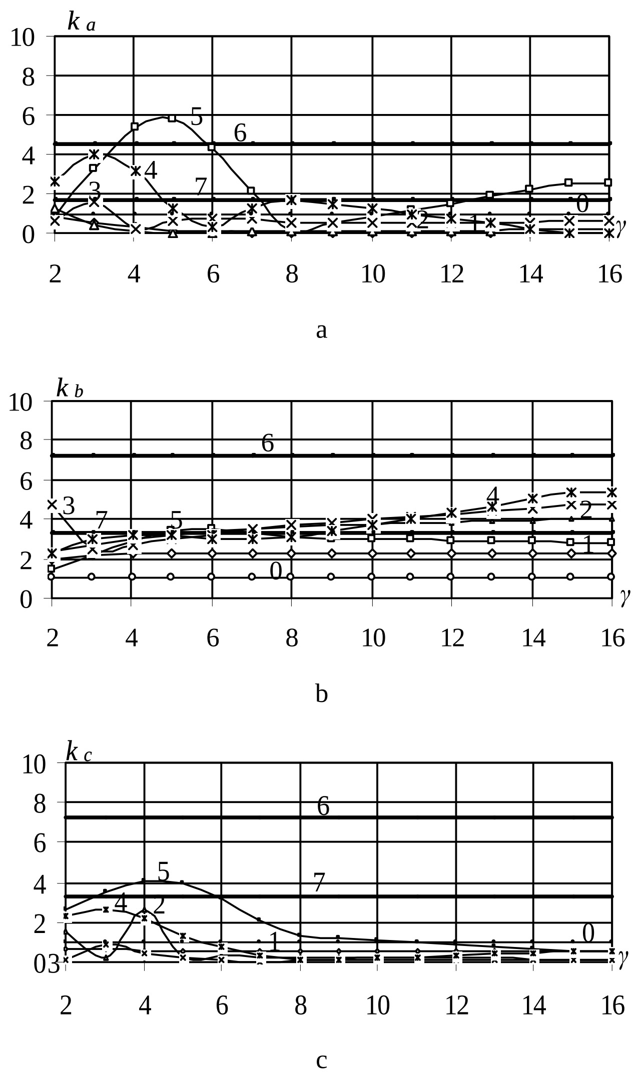
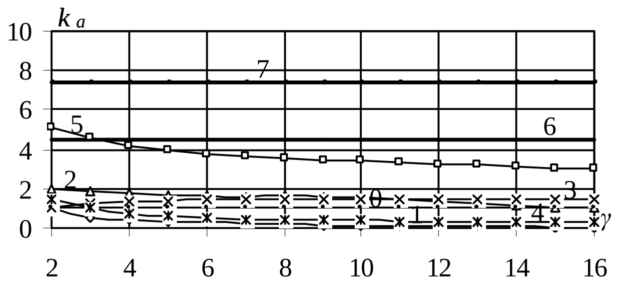


Fig. 8 Variation of SCF at the points of cone dent: midpoint (a); upper point (b); side point (c)

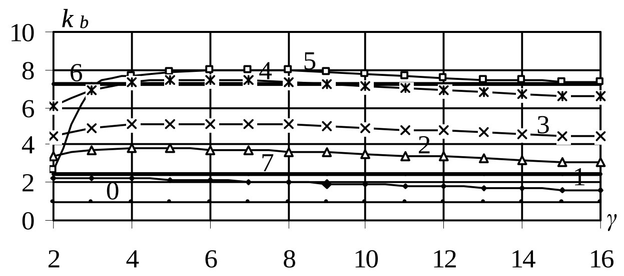
defect radius r and depth f cannot be ignored during the investigation.

The solution results obtained for the model with a cone-shaped dent (Fig. 8) have shown that general character of SCF variation as a function of b and g is actually almost the same as for the model with a dent in the form of semi-sphere. The maximum values of SCF are as follows: $k_a = 5.8$ with $b = 5$ and $g = 5$; $k_b = 5.3$ with $b = 4$ and $g = 16$; $k_c = 4.1$ with $b = 5$ and $g = 4$. However, differences between adjacent values depending on $k_a(b, g)$ and $k_c(b, g)$ manifest themselves more apparently, and the significant changes have taken place not within the area of the dent "sharpening" but, alternatively, within the area of its reduction, g being from 3 to 8.

When comparing the cone-shaped defect with that one in the form of a semi-sphere, one can notice, that the first defect is more dangerous for a point across the defect edge while the second one – for its central region. This is explained by the difference in the form on external contour line of the dent.



a



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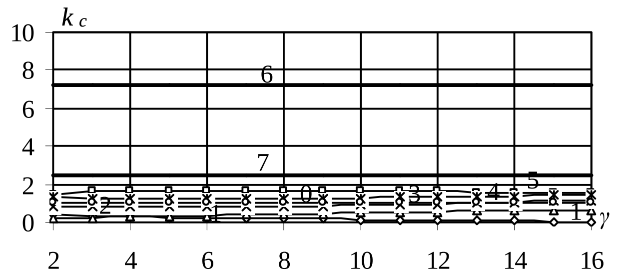

c

Fig. 9 Variation of SCF in the points of truncated cone dent: midpoint (a); upper point (b); side point (c)

When analysing the solution results for the defect of a truncated cone shape (Fig. 9) with an accepted side angle of 45^0, the following maximum values have been received: $k_a = 5.1$ with $b = 5$ and $g = 2$; $k_b = 8.0$ with $b = 5$ and $g = 6$; $k_c = 1.7$ with $b = 5$ and $g = 4$. It is very important that general trend of ratios $k(g)$, in this case, is constant enough, though SCF values are underrated only for the side point. Such shape of the defect is considered to be the most favourable for defining the stress increase in practical situations when it is possible only to measure the defect value but not to perform its modelling.

SCF of the presented FE solution in comparison (Fig. 7-9, lines *1-5*) with the allowable SCF (line *7*) and analytical results (line *6*), given by formulas (1)-(6), have shown that in the side point SCF values do not exceed the allowable ones in any case of dents. Another situation has been observed for the midpoint and upper point, where the computed SCF exceeds the allowable value. In case of a semi-sphere dent, in midpoint the values exceeding SCF are derived with $b \geq 4$ and $3 \leq g \leq 5.75$. In case of cone dent, in midpoint the values exceeding SCF are derived with $b = 5$ and $3.7 \leq g \leq 6.0$. In case of a truncated cone dent, in midpoint the exceeding values are derived with $b = 5$ and $g \leq 3.0$, i.e. in case of a more "sharp" defect. The SCF has exceeded the allowable SCF in the upper point in case of the truncated cone dent, when $b \geq 4$ and $g \geq 3.2$.

From further comparison of SCF value with the allowable one it follows that in case of the results calculated by FEM exceeding of the allowable values (line *7*) is observed. In the midpoint of semi-sphere and cone dent the exceeded values of the SCF are derived with $b \geq 3$ and $2 \leq g \leq 7$. In midpoint of the truncated dent the values exceeding SCF do not exist. In the upper point of every dent the values exceeding SCF are derived with $b \geq 3$ and $g \geq 2$. In the side point of semi-sphere dent the values exceeding SCF are derived with $b \geq 4$ and $3 \leq g \leq 8$, in case of the cone dent – $b \geq 5$ and $3 \leq g \leq 6$, in case of the truncated cone dent the exceeding values of the SCF are not available.

From the presented results of numerical simulation it is obvious that for the central area of the dent when the factor $k_a \leq 1$, relative radius values are small. It means that at a relatively small value of the defect, stresses at this point are of no danger. For the upper point of the defect edge SCF values are $k_b \geq 5$ and if the relative radius gets larger these values are increased almost in all cases. It is interesting to note, that for this point with $b = 4$ and $g \geq 8$ SCF values almost always are higher than in the case when $b = 5$, but for the areas with $g \leq 8$, the situation when $b = 5$ becomes the most dangerous one.

Check solutions using ANSYS [7, 14] have confirmed correctness of the results obtained. Besides they have proved that there is a slight influence of self-weight and other factors if the whole structures are being modelled. The maximum difference in the results as compared with those calculated in COSMOS/M is of the order of 2 % and is not much for engineering computations.

3.3. Physically Non-linear Stress State Analysis

For the sake of comparison, SCF has been additionally calculated by using plasticity properties of the material. In our case, the stress-strain function has been idealistically defined as a two-stage linear dependence. At the first stage, the physically linear function has been described by such stress/strain values as $s = 345$ MPa and $e = 1.6 \cdot 10^{-3}$, and it indicates elastic deformation of the steel. At the second stage, the physically non-linear function has been considered as an elastic/plastic deformation phenomenon and is defined by theoretical values $s = 480$ MPa and $e = 3.0$.

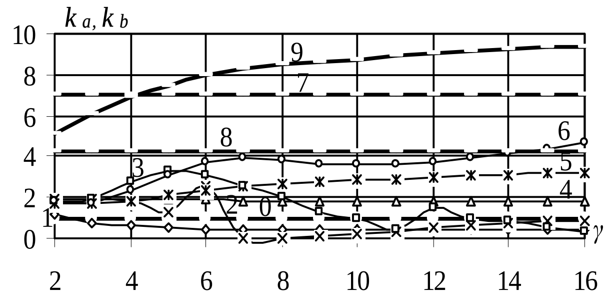

Fig. 10 Variation of SCF for the semi-sphere dent, in case of elastic/plastic deformation: *1*, *2*, *3* – midpoint; *4*, *5*, *6* – upper point; *7*, *8* – allowable values for midpoint and centre; *9* – analytical solution

The given SCF dependences on a relative sag under $b = 1$ (Fig. 10, curves *4*, *5* and *6*) have shown that the biggest SCF value $k_b = 4.7$ is observed near the upper point of the dent (analogically as in case of elastic deformation), when $b = 5$ and $g = 16$. SCF at the central zone (Fig. 10, curves *1*, *2* and *3*) is described by the value $k_a = 3.3$, when $b = 5$ and $g = 5$.

On the basis of the proposed investigations, it is concluded that the influence of plasticity reduces SCF depending on relative dent sag g values. On the other hand, the influence of plasticity does not change considerably the value of relative radius b. Usually in many cases, the solution model with an account of plasticity reduces SCF as well as stress distribution values at the dent zone. However, some values at the most dangerous points may be described as un-allowable ones [2, 3, 6].

4. Comparison of the Results

Comparison of analytical and numerical results shows, that general trend of analytical formulas (1)-(6) differs in some cases from the numerical ratio. Sometimes, the analytical formulas ignore a part of possible combinations of various factors. For the factor k_a with $b = 5$ and $g = 4, \dots, 6$ its value gets into an interval, which is not exactly defined in cases, when the defect has a shape of semi-sphere or cone and in the case of the defect of the third shape with $b = 5$ and $g \geq 6$ (Fig. 11).

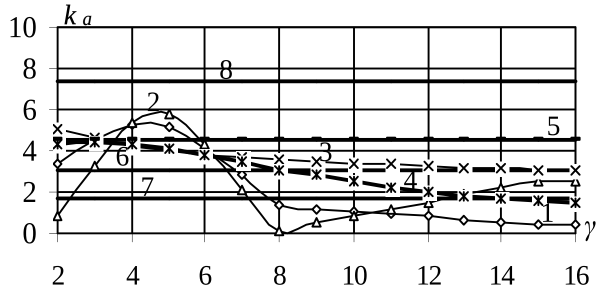

Fig. 11 Variation of SCF at the midpoint: *1*, *2*, *3* – semi-sphere, cone, truncated cone dents; *4* – analytical solution; *5* – allowable values, given analytically; *6*, *7*, *8* – allowable values (FEM)

Analytical relationships define k_b rather precisely, but there is also some dangerous exceeding if the defect is of the third shape with $b = 5$ and $g = 3, \dots, 6$ (Fig. 12).

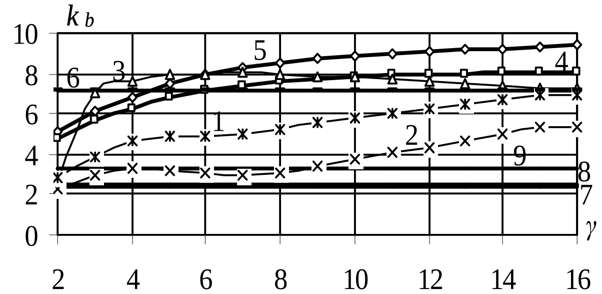

Fig. 12 Variation of SCF at the upper point: *1*, *2*, *3* – semi-sphere, cone, truncated cone dents; *4*, *5* – analytical solution; *6*, *7*, *8* – allowable values (FEM)

For the side point analytical values for the factor are exceeded (Fig. 13). This is due to the fact, that this point is considered to be less dangerous, though in order to have a general concept about the stress distribution within the defect area, it would be convenient to have such an analytical value of SCF.

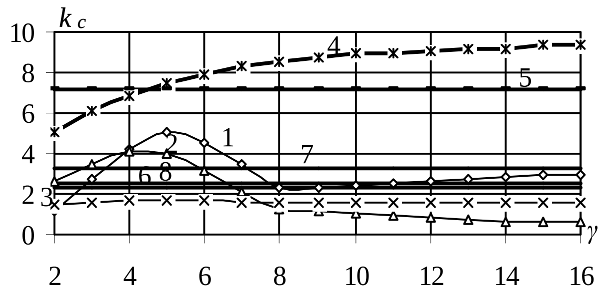

Fig. 13 Variation of SCF at the side point: *1*, *2*, *3* – semi-sphere, cone, truncated cone dent; *4*, *5* – analytical solution; *6*, *7*, *8* – allowable values (FEM)

Comparison of the analytically and numerically given results has shown that the most dangerous zone of the dent defect is near the upper point. Analytically based solution has provided higher values (Fig. 14, curve *1*) than those, solved using FEM elastic (curve *2*) and elastic/plastic (curve *3*) analysis.

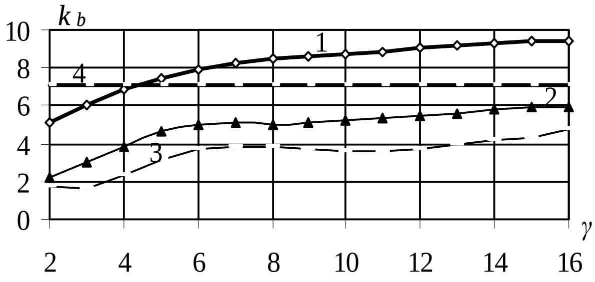

Fig. 14 Variation of SCF in the upper point: *1* – analytical solution; *2* – linear analysis by FEM of the semi-sphere dent; *3* – non-linear analysis by FEM of the semi-sphere dent; *4* – allowable values

Therefore, the proposed analytical expressions are more universal as well as safer and they may be successfully applied for control solution of the primary values. On the other hand, the analytical formulas (1)-(6) cannot describe an individual case, so the proposed numerical modelling is more important for the second more exact control solution of the problem. The valuable factor is that the analytical values exceed the allowable ones in case of relative sag $\gamma > 4$, whereas the numerically obtained values do not exceed them.

SCF on the elastic/plastic stage had the values, which were 20 % less than the elastic ones. On the other hand, strain in case of plasticity is not considered in this paper, but such solution is rather complicated as far as the computer time and memory costs are considered and it will be presented by authors later. It is important to note, that many industrial standards are limited by elastic its formulation in design formulas, but such calculation is valuable in practice in case of mechanical state analysis of the existing structures having defects.

5. Conclusions

On the basis of the proposed investigation the conclusions are made:

1. Analysis of the solution results has shown that SCF is more dangerous on the dent contour line than at the centre with a relative depth $g > 5$. Near $\gamma = 5$ SCF is equally dangerous for the central and contour areas.

2. Numerical modelling by FEM has indicated that the maximum SCF, and namely $k_b = 8$, is obtained for the dent of a truncated cone shape, in this case relationship between SCF and relative depth γ of the dent is the most constant and thus simply predicted.

3. Analytical expressions (1)-(6) more exact by describe the stress state at a dent zone in comparison with the requirements of the existing standards.

4. The proposed analytical formulas may be successfully applied at the first stage of mechanical state analysis of the dents, for a more exact analysis the numerical modelling by FEM may be used.

5. Numerical solution by using FE plasticity model can more exactly describe the stress state near a dent, but plastic deformation is limited by some standards and the strain state should be investigated, additionally.

6. The proposed analytical expressions and numerical results may be effectively used while developing the existing design standards for local shape defects of cylindrical steel tanks.

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K. Romanenko, M. Samofalov, A. Šapalas,
L.A. Aliphanov

PLIENINIŲ CILINDRINIŲ REZERVUARŲ SIENUTĖS TIESINĖ IR FIZIŠKAI NETIESINĖ VIETINIŲ GEOMETRINIŲ DEFEKTŲ ĮTEMPIMŲ BŪVIO ANALIZĖ BAIGTINIŲ ELEMENTŲ METODU

R e z i u m ė

Plieniniai rezervuarai ir tokio tipo inžineriniai statiniai projektuojami atsižvelgiant į jų ilgalaikę eksploataciją. Didelio tūrio statinių remontas arba net profilaktinės apžiūros yra gana brangūs procesai, todėl labai svarbu tirti jų defektus. Analizuojant eksploatacinę būklę ypatingą vaidmenį vaidina įvairūs koncentratoriai, kuriuos įprasta sąlygiškai skirstyti į smailius (įpjovos, technologinės jungtys ir pan.) ir švelnius (įspaudos, įlinkimai, įdubos ir pan.). Minkštų defektų natūriniai stebėjimai (stebėtos talpyklos nuo 1 000 iki 50 000 m^3, sąlyginis defektų skersmuo nuo 0,40 iki 4,50 m, gylis iki 120 mm) parodė, kad esamų projektavimo normų metodikos tokiems defektams vertinti yra netikslios.

Šio darbo tikslas – pasiūlyti nesudėtingą inžinerinį algoritmą minkštiems geometriniams koncentratoriams aprašyti, nes, taikydamas paprastas analitines priklausomybes, inžinierius-praktikas gali apibūdinti defekto įtaką statiniui. Siūlomos išraiškos tikrinamos, gretinant realių objektų skaičiavimo ir natūrinių stebėjimų rezultatus. Taip pat skaitiškai modeliuojamas cilindrinio plieninio rezervuaro mechaninis būvis geometrinių defektų vietose.

K. Romanenko, M. Samofalov, A. Šapalas,
L.A. Aliphanov

LINEAR AND PHYSICALLY NON-LINEAR STRESS STATE ANALYSIS OF LOCAL SHAPE DEFECTS ON STEEL CYLINDRICAL TANK WALLS BY FINITE ELEMENT METHOD

S u m m a r y

Steel storage tanks and other structures of such kind of buildings have been extensively designed following the requirements of continuous cyclic operations. Because of many economically based reasons any engineering inspections of a huge volume are very expensive, so investigations of the local defects are practically important. Natural inspection of tank dents (volumes of tanks were from 1 000 to 50 000 m^3, diameter of dents from 0,40 to 4,50 m, a depth up to 120 mm) has shown that analytical approach of their investigation by using existing design standards is rather complicated.

The main objective of the presented investigations is the development of an easy engineering algorithm for the solution of soft stress concentrator. The results, derived from the proposed formulas, are compared with those of natural inspection of real tanks and also with the results obtained by numerical modelling using finite element method.

К. Романенко, М. Самофалов, А. Шапалас,
Л.А. Алифанов

ЛИНЕЙНЫЙ И ФИЗИЧЕСКИ НЕЛИНЕЙНЫЙ АНАЛИЗ НАПРЯЖЕННОГО СОСТОЯНИЯ МЕТОДОМ КОНЕЧНЫХ ЭЛЕМЕНТОВ В МЕСТАХ ЛОКАЛЬНЫХ ДЕФЕКТОВ ФОРМЫ СТЕНОК СТАЛЬНЫХ ЦИЛИНДРИЧЕСКИХ РЕЗЕРВУАРОВ

Р е з ю м е

Стальные резервуары и другие инженерные сооружения такого типа проектируются учитывая долгосрочность их эксплуатации. Ремонт и даже профилактические осмотры технических сооружений большого объема являются дорогостоящими, поэтому исследование их дефектов очень важно. Особую роль в анализе состояния во время эксплуатации играет влияние различного рода концентраторов, которые условно подразделяются на острые (врезы, отверстия и т. д.) и мягкие (вмятины, выпуклости и т. п.). Натурные наблюдения за такими дефектами (осматривались резервуары объемом от 1 000 до 5 000 м^3, условный диаметр дефекта от 0,40 до 4,50 м, глубина до 120 мм) показали, что методика оценки их состояния при использовании существующих норм проектирования является достаточно неточной.

Основная цель представленной работы – предложить простой инженерный алгоритм для описания мягких геометрических концентраторов, что помогло бы инженеру-практику, используя несложные аналитические зависимости, оценить влияние дефекта на сооружение. Предлагаемые формулы проверяются, сравнивая результаты расчетов с результатами технадзора за реальными объектами и моделируя дефекты методом конечных элементов.

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