ANALYSIS OF GEOMETRICAL SHAPE DEFECTS OF A STEEL CYLINDRICAL TANK WALL BY NUMERICAL AND ANALYTICAL METHODS

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Abstract. Steel storage tanks and other structures of such a 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. In general, a local curve of a perfect geometrical shape influences on the mechanical state of the whole tank during its operation. The concentrators, which are expressed by stress concentration factors, may be "sharp" (holes, joints etc.) or "soft" (dents, bulges and so on). Researches of the sharp defects are popular and well known, whereas the soft defects of a geometrically perfect shape are not exactly described by design standards of many countries. 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 the analytical approach of their investigation by using existing design standards is rather complicated. On the other hand, the strain state analysis of a cylindrical thin shell depends on the geometric shape.

The main objective of the presented investigations is development of an easy engineering algorithm for solution of the soft stress concentrator. It is interesting for the engineer-inspector, who can use short analytical expressions for computation of a dent defect value as well as strain state of the whole structure. 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 the finite element method.

Review of the analytical solution algorithms for such kind of problems, checking of the results by means of a standard finite element code, conclusions and recommendations for the inspection service and design codes are proposed in this paper.

Keywords: steel storage tank, dent, numerical modelling, finite element, stress concentration factor, strain state

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 main tenancy and repair, if necessary. In practice, it is rather difficult to make and use such kinds of the structures avoiding considerable deviations from the design requirements. On the course of time different common damages, local defects and other imperfections are being accumulated. They have got 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. A constant inspection and elimination of such shortcomings is considered to be a common practice during operations of the huge volume structures. To simplify a visual inspection, special requirements to the defect values defined by the technical standards [1, 2, 3] are provided. By their features the local shape, defects of the steel cylindrical tanks are close to those of the pipes thus, in practice, the local defects of the pipes can be successfully applied with respect to the tanks [4].

On the other hand, practically one uses a lot of the tanks with the defect values exceeding those allowable by the standards [1-3, 5, 6], and this fact, as it follows from the observations, does not cause deterioration of the tanks state [7]. In the presented analysis the 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 either too high as a rule or described not quite exactly.

The main difficulty, while estimating the defects danger, lies on the proper selection of the simulation model as it greatly influences the subsequent determination of the mechanical state within the dent area. Besides, it is very important to achieve 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 the structure and sometimes-even change of its location. All the above-mentioned questions are of equal importance. For investigation of each specific case or a group of such problems one introduces a series of simplifying assumptions taking into consideration physical sense and peculiarities of the individual situation [4, 8-13].

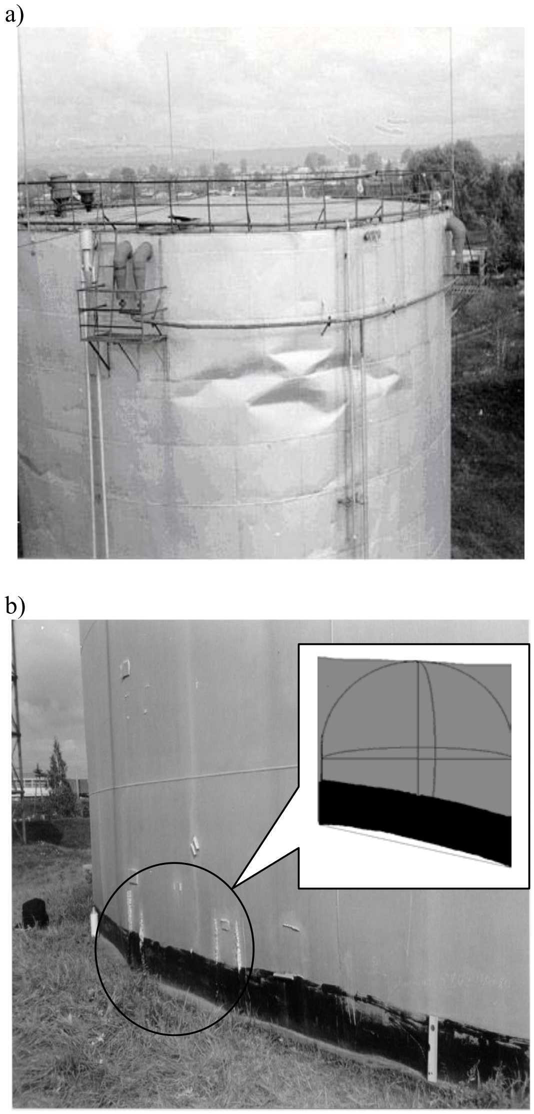

Fig 1. Examples of damages of a shell of the steel cylindrical tank: dents on the upper part (a); a dent on the lowest part (b)

A rapid progress in hardware and constant improvement of the software enable to extend the possibilities of creation of virtual and mathematical models as well as to consider a much larger number of various combinations. However, developments of accurate analytical models [4, 7-10, 12-14] are particularly essential for investigating state of the structures to be used. To date, such solutions are of special concern for the 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 tools of the solution [15]. The proposed investigations are devoted to solution of all the above-mentioned problems.

2. Mechanical state analysis problem

The causes of the shape local defects, occurred in the tanks usage, 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 inspection of the structure 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 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 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 analyzing influence of the shape local defects on the mechanical state of the tanks, 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 civil engineering standards. Different design codes and instruction manuals of the tanks confine presence of the 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; 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. [6]: the dent depth should not exceed ½ inch for a three-foot defect. Such requirements do not take into account many important factors 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 main attention was payed to the more dangerous “sharp” defects and the problem of “soft” defects 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 the local defects on the strain state more precisely.

The analytical methods suggested to solve the problems under investigation [10, 12] are based on assumptions common in engineering practice. One of the most popular assumptions is membrane analogy [13]. Unfortunately, determination of the stress concentration using this model is not quite exact. The standards allowing for deflections from a geometrical form [3] suggest to consider a model with the modified geometry taking into account the initial stresses according to the increase of the *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 shape defects of the tanks are very similar to those of the pipes as far as their physical characteristics are considered [4].

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

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

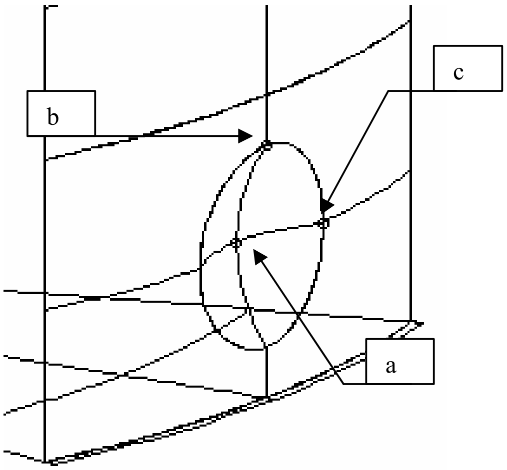

Fig 2. Location of the analyzing points: midpoint (a); contour upper point (b); contour side point (c)

The most dangerous sites of a dent are an area of its centre and its profile portions (see figure 2). A value of the SCF in the middle of the defect is calculated by the formula:

$$k_a\left(q_i,\beta,\gamma\right)=\frac{P_1\left(q_i,\beta,\gamma\right)}{P_2\left(q_i,\beta,\gamma\right)}, \qquad (1)$$

where semiempirical coefficient q are adopted on the basis of natural observations and theoretical investigations, they slightly correct the results of analytical solutions: $q_1=56{,}07$; $q_2=27{,}382$; $q_3=0{,}821$; $q_4=0{,}286$; $q_5=0{,}057$; $q_6=0{,}034$; $q_7=0{,}028$; $q_8=0{,}16$; $q_9=0{,}15$; $q_{10}=59{,}54$; $q_{11}=9{,}71$; $q_{12}=1{,}79$; $q_{13}=0{,}378$; $q_{14}=0{,}174$;. Coefficient β expresses a conventional dimension of an across of the tank shell:

$$\beta(r,R,t)=\frac{r}{\sqrt{R\times t}}, \qquad (2)$$

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

$$\gamma(f,t)=\frac{f}{t}, \qquad (3)$$

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

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

$$P_1\left(q_i,\beta,\gamma\right)=q_1-q_2\,\beta-q_3\,\beta^2+q_4\,\beta^3+q_5\,\beta\gamma-$$
$$-q_6\,\beta^2\gamma-q_7\,\beta^3\gamma+q_8\,\beta\gamma^2-q_9\,\gamma^2; \qquad (4a)$$

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

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 the SCF expressed in a form:

$$k_b\left(s_i,\beta,\gamma\right)=A\left(s_i,\gamma\right)\times\beta^{m}\left(s_i,\beta,\gamma\right), \qquad (5)$$

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

$$A\left(s_i,\gamma\right)=s_1+s_2\,\gamma-s_3\,\gamma^2+s_4\,\gamma^3-s_5\,\gamma^4 \qquad (6a)$$

where $s_1 = 2{,}57$, $s_2 = 0{,}5$, $s_3 = 0{,}0688$, $s_4 = 0{,}00376$, $s_5 = 0{,}000075$.

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

$$\beta^{m}\left(s_i,\beta,\gamma\right)=\left[\beta\right]^{s_6\ln(\gamma)+s_7} \qquad (6c)$$

where undimenless coefficients are expressed as $s_6 = 0{,}169$ and $s_7 = 0{,}153$.

When calculating the 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 calculations of an individual problem by the approximate numerical methods.

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

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

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

Values of the SCF on the contour and at the dent centre will be equivalent $k_a = k_b$ with $\beta = 2$, $\gamma = 4$.

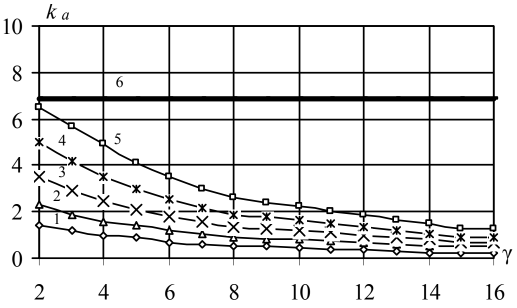

Fig 3. The stress concentration factor at the dent centre on the tank external surface

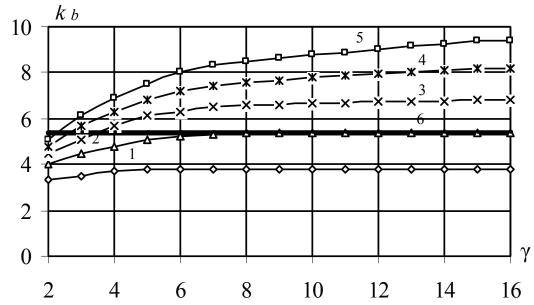

Fig 4. The stress concentration factor at the dent profile on the tank external surface

3. Numerical modelling by finite elements

3.1. Numerical Model

In order to check whether formulas (1) – (6) are correct, modelling of different kinds of the defects for a real structure [15] has been performed. In this case the main solutions are made by using a standard finite elements program (a standard FEM code) COSMOS/M [16], and computation of one of the versions was additionally doubled by ANSYS [17], where somewhat other principles have been applied.

For solution of the problem by COSMOS/M software (see figure 5a), 1/12 portion of the cylindrical tank was taken, considering conditions of geometrical 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 shell 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. Dimensions of the finite elements do not exceed 1/128 of the segment length. In order to simulate the real situation the ground pressure on the tank bottom was considered via conventional rigidities of 10,0 MPa. The model created in COSMOS/M reflects the natural location of a dent on the entire tank and real conditions of its operation.

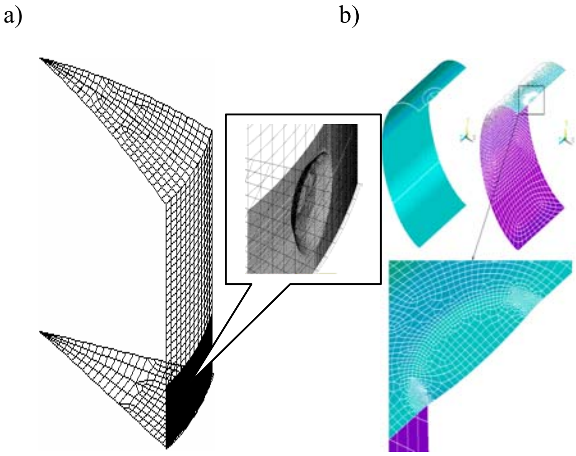

Fig 5. Discretion by the FEM: using COSMOS/M (a); using ANSYS (b)

A segment of the tank was loaded by self-weight and by the product pressure which was linearly applied. Three kinds of a dent were simulated: semi-sphere, cone and truncated cone (see figure 6). The selection of the defects shapes was based upon observation of real structures [14].

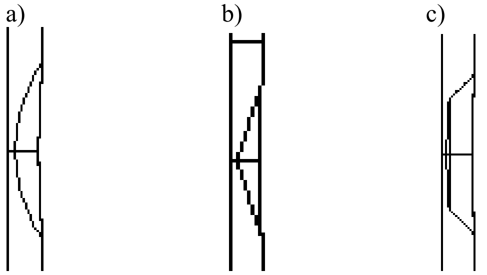

Fig 6. Shape of the simulated: semi-sphere (a); cone (b); truncated cone (c)

While directly containing the defect solution by ANSYS was simulated (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 (see figure 5b). This model was acted only with a load produced by the product pressure.

3.2. Stress concentration factor analysis

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

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

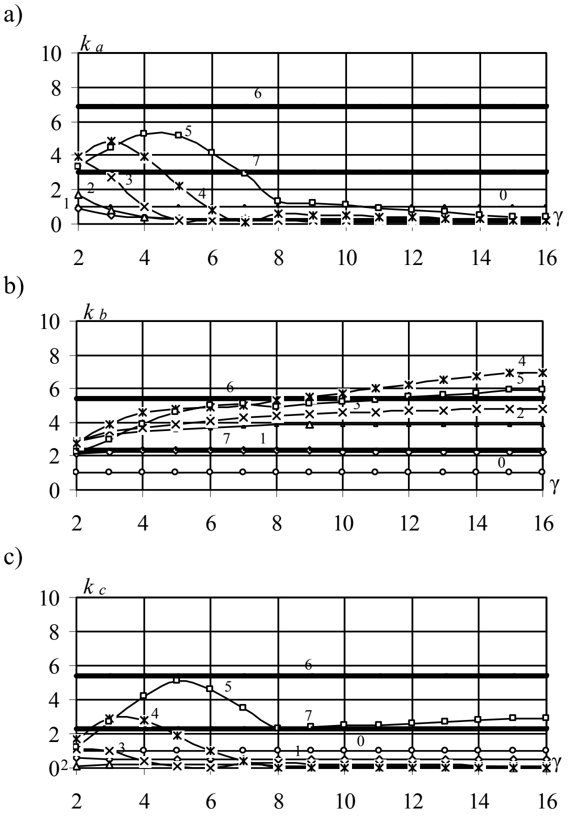

Fig 7. Variation of the stress concentration factor at the points of semi-sphere dent: midpoint (a); upper point (b); side point (c)

In this case the most dangerous value $k_b = 7{,}0$ of SCF within the dent upper is observed $\beta = 4$ and $\gamma = 16$ (see figure 7b). For dent end-points the way of SCF variation as a function of such factors as β and γ 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 $\gamma \geq 9$, it means that the phenomenon as itself is not described exactly line 6 by the analytical formula (5) and that it is possible to make these formulas more precise on the basis of the solution of the FEM. For the centre point of the defect the largest value $k_a = 5{,}2$ is with $\beta = 5$ and $\gamma = 4$ (see figure 7a) while for the side one $k_c = 5{,}1$ at the $\beta = 5$ and $\gamma = 5$ (see figure 7c). It is interesting to note that there is a point at all three points, where the curves with values $\beta = 5$ and $\gamma = 5$ are intersected. The plots show $k = 1$ as SCF values, when influence of the concentrators is left out of account. It means that the influence of the defect radius r and depth f cannot be ignored during investigation.

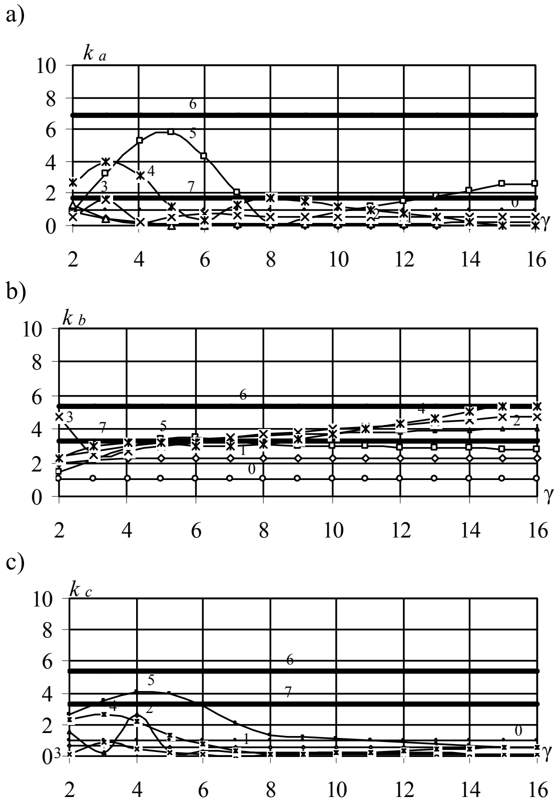

Fig 8. Variation of the stress concentration factor in the points of cone dent: midpoint (a); upper point (b); side point (c)

The solution results obtained for the model with a cone-shaped defect (see figure 8) have shown that the general character of SCF variation as a function of β and γ values is actually almost the same as for the model with a defect in the form of a semi-sphere. The maximum values of SCF are as follows: $k_a = 5{,}8$ with $\beta = 5$ and $\gamma = 5$; $k_b = 5{,}3$ with $\beta = 4$ and $\gamma = 16$; $k_c = 4{,}1$ with $\beta = 5$ and $\gamma = 4$. However, differences between adjacent values depending on $k_a(\beta,\gamma)$ и $k_c(\beta,\gamma)$ manifest themselves more apparently, and the significant changes have taken place not within the area of the defect "sharpening" but, alternatively, within the area of its reduction, γ 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 explained by the difference in form on the external contour line of the dent.

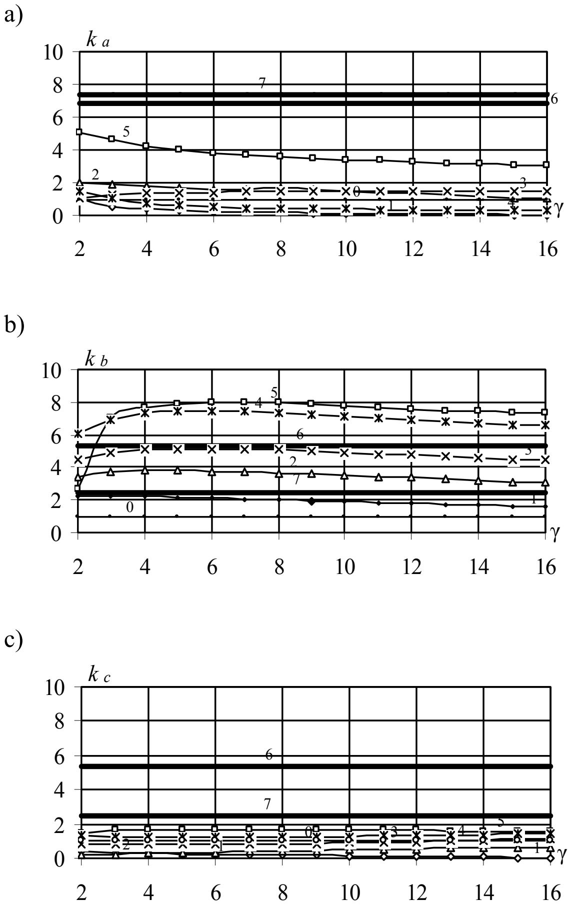

Fig 9. Variation of the SCF in the points of truncated cone dent: midpoint (a); upper point (b); side point (c)

When analyzing the solution results (see figure 9) for the defect of a truncated cone shape with an accepted side angle 45^0, the following maximum values have been received: $k_a = 5{,}1$ with $\beta = 5$ and $\gamma = 2$; $k_b = 8{,}0$ with $\beta = 5$ and $\gamma = 6$; $k_c = 1{,}7$ with $\beta = 5$ and $\gamma = 4$. It is very important that the general trend of ratios $k(\gamma)$, in this case, is constant enough, though SCF values are underrated only for a point *c*. Such a 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.

If to compare SCF of lines 1-5 (see figure 7-9) with allowable SCF, results of the line 6 calculated by analytical formula (1)-(6), will see, that in the midpoint and side point SCF are not exceeding allowable SCF in any case of dent. In the upper point is another situation. The computed SCF are exceeding standard SCF. In the case of semi-sphere dent the exceeded values of the SCF are derived with $\beta \geq 4$ and $\gamma \geq 9$. In the case of truncated cone dent the exceeded values of the SCF are derived with $\beta \geq 4$ and $\gamma \geq 2$. In the case of cone dent the exceeded values of the SCF are not exist.

Further to compare SCF with allowable SCF, results of the line 7 calculated by the FEM observing are exceeding allowable SCF. In the midpoint semi-sphere and cone dent the exceeded values of the SCF are derived with $\beta \geq 3$ and $2 \leq \gamma \leq 7$. In the midpoint truncated dent the exceeded values of the SCF are not exist. In the upper point in every dent the exceeded values of the SCF are derived with $\beta \geq 3$ and $\gamma \geq 2$. In the side point semi-sphere dent the exceeded values of the SCF are derived with $\beta \geq 4$ and $3 \leq \gamma \leq 8$, in case cone dent – $\beta \geq 5$ and $3 \leq \gamma \leq 6$, in case truncated cone the exceeded values of the SCF are not exist.

From the presented results of the numerical simulation it is obvious that for a central area of the dent a factor $k_a \leq 1$, the conventional radius β values being 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 it the relative radius β gets larger these values are increased almost in all the cases. It is interesting to note that for this point with $\beta = 4$ and $\gamma \geq 8$ the SCF values almost always are higher than in case when $\beta = 5$, but for areas with $\gamma \leq 8$, the situation when $\beta = 5$ becomes the most dangerous one.

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

4. Comparison of the results

Comparison of the analytical and numerical results shows, that the general trend of analytical formulas (1) - (6) is different in some cases from the numerical relations. Sometimes, the analytical formulas ignore a part of possible combinations of various factors. For a factor k_a with $\beta = 5$ and $\gamma = 4,...,6$ its value gets into an interval not exactly defined in cases when the defect has a shape of a semi-sphere or a cone and in the case of the defect of the third shape with $\beta = 5$ and $\gamma \geq 6$ (see figure 10). Analytical relationships define k_b rather precisely but there is also some dangerous exceeding it the defect is of the third shape with $\beta = 5$ and $\gamma = 3,...,6$ (see figure 11). For the side point the analytical values at the factor are exceeded (see figure 12). 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.

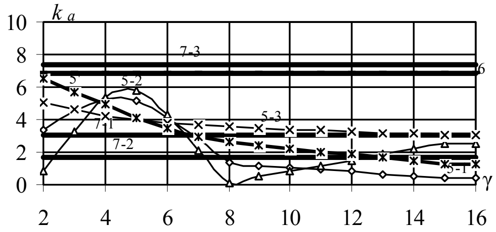

Fig 10. Variation of the stress concentration factor in the midpoint: 5-1,2,3 – semi-sphere, cone, truncated cone dent (FEM); 5' – semi-sphere dent by formula (1); 6 - normative by formula (1); 7-1,2,3 – normative (FEM) where: 7-1 – semi-sphere, cone, truncated cone dent

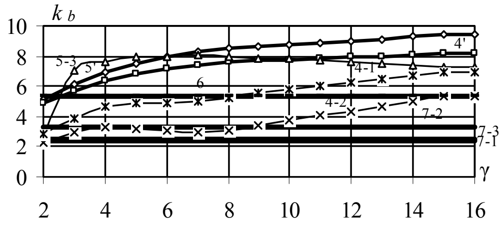

Fig 11. Variation of the stress concentration factor in the upper point: 4-1,2,3 – semi-sphere, cone, truncated cone dent (FEM); 4',5' – semi-sphere dent by formula (1); 6 - normative by formula (1); 7-1,2,3 – normative (FEM) where: 7-1,2,3 – semi-sphere, cone, truncated cone dent

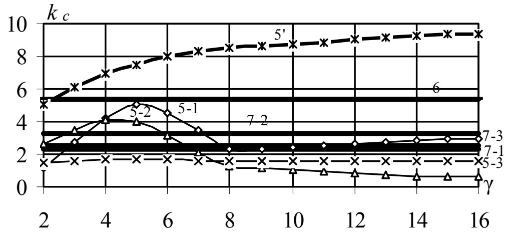

Fig 12. Variation of the stress concentration factor in the side point: 5-1,2,3 – semi-sphere, cone, truncated cone dent (FEM); 5' – semi-sphere dent by formula (1); 6 - normative by formula (1); 7-1,2,3 – normative (FEM) where: 7-1,2,3 – semi-sphere, cone, truncated cone dent

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 danger on the defect contour line than at the centre with relative depth $\gamma > 5$ and $\gamma < 5$ and less with $\gamma = 5$. Near $\gamma = 5$ the SCF is equally dangerous for the dent central area and its contour.
2. Numerical modelling by the FEM has indicated that maximum SCF, thus $k_b = 8$, is obtained for the dent of a truncated-cone shape, in this case a relationship between SCF and relative depth γ of the dent is the most constant and thus simplify predicted.

3. When comparing analytical and numerical SCF results, insignificant discrepancies have been derived for some versions of the computation, however, the suggested solutions estimate more exactly the mechanical state of the tank than those used in the standards.
4. The analytical formulas should be subjected to some refinement on the basis of the results obtained by the FEM, this provides the possibility to improve the way of prediction of the strain state within the dent area. Such formulas can be successfully employed when developing standards of practice in this field.

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