ISSN 1392 - 1207. MECHANIKA. 2006. Nr.3(59)

Stress and strain state investigation of soft defects on thin steel plate using experimental and numerical methods

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1. Introduction

Technical progress in many fields of engineering as well as the most successful business in the large-scale industry in 20th century (energy, chemical, gas, oil engineering, etc.) provides a quick growth of huge industrial complexes all over the world. So, an actual problem in the nearest future concerning operation, maintenance, redesign, inspection and utilisation periods of such potentially dangerous composed technical systems will be solved by using many requirements and codes. When solving this problem, the accumulated experience, obtained during operation of an individual plant as well as the experiments are very essential and they should be taken into account as the primary factor [1-5]. On the other hand, the accumulation of new data by means of regular exact inspections of large volume thin-walled structures (which will be employed) may be very expensive [6, 7].

One of the above-mentioned industrial vessels may be a steel thin-walled tank of large capacity, which at a real factory has many global and local damages [8-10]. Generally, defects on thin walls of the tank may be not dangerous, but the description of real constraints is very complicated and in engineering practice is done by some mechanical state parameters [11-14]. An engineer could find such kind of information in technical manuals and codes [15-21].

Thin-walled shell of a tank is sensitive to both: single defects of a local type or a series of such defects. Practical observations prove [1, 2, 22] that the accumulation of the defects becomes the main reason of 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 help of the most advanced modern engineering software.

The main difficulty, while estimating the defects danger, lies in 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 an agreement 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 is introduced taking into consideration physical sense and the peculiarities of an individual situation [11-14].

In the classical theory of defects [23-26] estimation of the problem has been presented for the “sharp” (incuts, cracks, etc.) and “soft” (dents, bulges, flaps, etc.) defects. The “sharp” defects are more dangerous because of a higher destruction risk. The “soft” defects are not investigated so widely as the “sharp” ones and their limitation concerns the geometrical parameters only [15-21]. Moreover, the influence of such defects location, their forms, thickness of the tank wall and etc. has not been taken into account. The above-mentioned reasons show that the “soft” defects are not sufficiently investigated and there is a possibility to improve their evaluation methods.

In many cases, 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 [4, 27-29].

One of the ways to investigate local defects is to prepare an experimental model with corresponding geometric parameters of the region around the defect. It is meant that the model may describe only a local strain and stress problem, but for many real thin-walled structures such kind of analysis is exact enough. The small experimental model in comparison with natural dimension huge tank is cheap and shows many possibilities for testing with various geometrical parameters, such as wall thickness, depth and radius of dent etc. Really, the natural test of each tank (by technological water more often) before filling it with product has a more general character of global damages and other imperfections of the whole plant operation system. Theoretically, the above-mentioned usage of limits from technical codes of different countries means the application of many results based on various researches in experimental context.

On the other hand, numerical modelling by various computer software and advanced technologies have opened a possibility to describe general stress and strain state of the whole tank or individual stress and strain state for its specific sector. In numerical modelling the *finite element analysis* (FEA) is the most powerful tool and the popular method in design practice because of its quick and effective results. Therefore, the classical FEA uses typical hypotheses and assumptions in virtual mechanical models. Such methodology is actual for a new designing, but in case of repair or preventive maintenance process, the FEA requires particular approach, which should “read between lines” and be adapted for the simulated given situation. However, in our case the usage of standard point of view in the FEA may provide very complicated results.

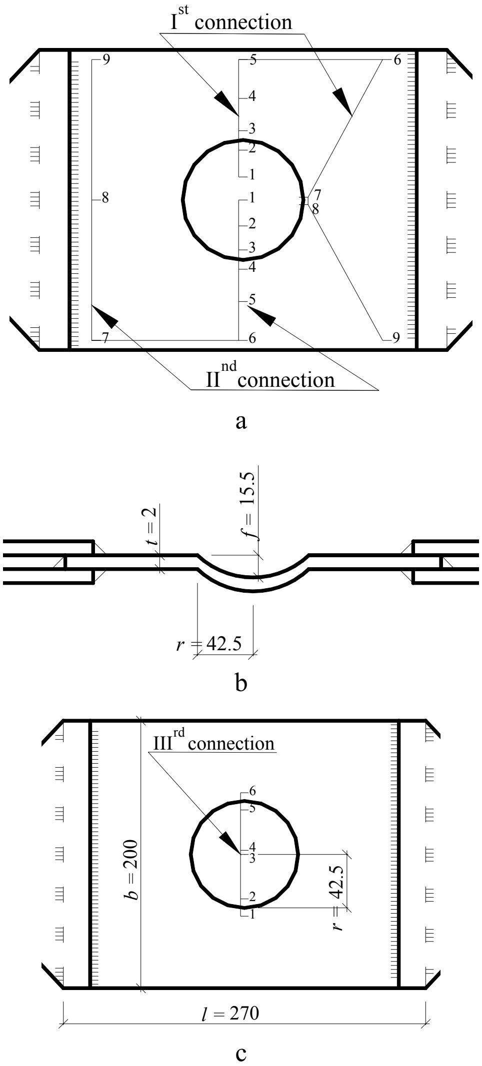


Fig. 1 Distribution of the strain gauge transducers on steel plate with geometrical defect: view from side of the dent (a); section from side of the plate (b); view from side of the bulge (c)

Fig. 2 Experimental model: steel plate with geometrical defect

The analytical methods suggested to solve the problems [3, 5, 12, 30] are based on the assumptions common for engineering practice. One of the most popular assumptions is membrane analogy. Unfortunately, the determination of stress concentration using this model is not quite exact. The standards allowing deflections from geometrical form [16-18] enable to consider a model with the modified geometry taking into account the initial stresses according to the increase in 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.

However, the developments of accurate analytical models [3, 22, 26, 31-35] are particularly essential for the state investigation of the structures to be used. To date, such solutions are of special concern for practice 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 [3, 28].

From the practical point of view, for more exact conclusions about mechanical state near the defect minimum two duplicated investigation methods should be applied. Of course, imperfection of the experimental equipment as well as assumptions in the FEA methodology should be taken into account. Another also important task of the below presented research is to show some problems of interrelation and comparison between experimental and numerical models.

2. Experimental investigations

The test of steel plates with a soft geometrical defect such as a dent is the most common simple method. It is not so cheap, to investigate the influence of the dent on stresses distribution on the wall surface of a steel tank under the action of pressure of the stored product [4, 26]. The experimental model is described by such parameters: width $b = 200$ mm, length $l = 270$ mm and thickness $t = 2$ mm (Fig. 1). The steel grade of the plate is Ст3пс [3]. The semispherical dent was pressed out on the surface of the steel plate by a semispherical extruding die (Fig. 2). The dent geometrical parameters are: radius $r = 42.5$ mm, depth $f = 15.5$ mm (Fig. 1). The relative radius and depth of the dent are defined correspondingly by the formulas

$$\beta(r,t) = \frac{r}{t} \tag{1}$$

$$\gamma(f,t) = \frac{f}{t} \tag{2}$$

So, relative radius of the dent is $\beta = 21.25$, relative depth of the dent is $\gamma = 7.75$.

During test, one plate with the dent was loaded by a cross-arm. The model was tested till destruction under the load being applied by steps. The load was applied according to the diagram (Fig. 3). Here n is the number of tests and η is load factor, which is equal to the ratio of test and destruction loads respectively during the last test. In the course of the last test, the plate was subjected to test till destruction. The steps in the tests were equal to: 7/1000 for the first four tests, 14/1000 for next three ones, 28/1000 for next three tests and 34/1000 for the last one (Fig. 3). In case of high level of the load nonlinear properties of the material become evident therefore basic tests were executed in case of load factor till 0.2.

Strain gauge transducers were added from both sides on the defect (Fig. 1). Five transducers of the Ist connection and six transducers of the IInd connection 1 - 5, 1 - 6 are placed on the middle part of the plate. The two

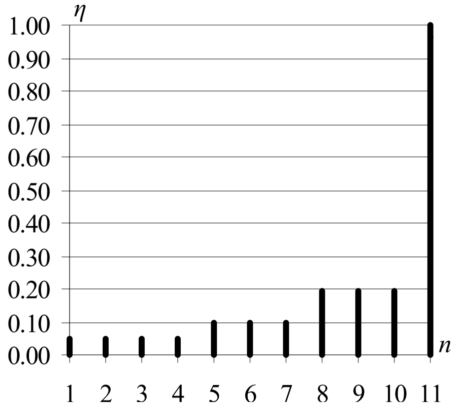


Fig. 3 Plan of loads during experiments

transducers of the Ist connection 7, 8 are situated on the contour of the dent. The three transducers of the IInd connection and two transducers of the Ist connection 7 - 9, 6, 9 are disposed next to the cross-arm. And six transducers of the IIIrd connection were added from the bulge side (Fig. 1). All three connections were switched in to the electric equipment [36] for measuring voltage in every strain gauge transducer during test time. At every load step the difference between voltages in previous load step and next one was defined. The voltage differences were used for the determination of longitudinal stresses σ_z in cross-section of the steel plate by means of the formula

$$\sigma = E \times \frac{4 \times x}{S \times U} \tag{3}$$

here E is modulus of elasticity defined by means of the standard tension test; x is the difference between voltages in previous load step and next one; S is sensitivity factor of the strain gauge transducer; U is constant voltage provided by the electrical equipment [36].

At every step of the load longitudinal stresses σ_z in cross-section of the steel plate were determined. The variation of the stresses defined from indications of the transducers of the Ist connection and transducers of the IInd connection 1 ÷ 5, 1 ÷ 6, from one side of the plate till another one directly through a defect, is presented (Fig. 4). The indications of the transducers were defined when the load factor η was of the order of: 0.07; 0.12; 0.16; 0.20; 0.22. On the vertical axis of the diagram relative longitudinal stresses σ^* due to the load are marked; on the horizontal axis − relative distances ε between transducers. The relative longitudinal stresses σ^* represent the ratio between longitudinal stresses under load η and strength stresses of the plate steel. Relative distance ε is the ratio between the distance from a middle point of the dent till location point of the strain gauge transducer and the dent radius. According to the diagram (Fig. 4) with increasing of the load the concentration of stresses on the contour of the defect is increased too [3, 12, 30]. The diagrams (Fig. 5), which determine the value of stress concentration factor (SCF), show that the concentration factor is changing slightly from $k = 2.5$ when load factor is 0.07 to $k_{max} = 2.7$ when load factor is 0.12 - 0.22 and within the limits from $k = 3.0$ when load factor is 0.07, to $k_{max} = 3{,}3$, when load factor is 0.12 - 0.22. The SCF values were determined by relations between longitudinal stresses on the plate surface with a defect and longitudinal stresses on the plate surface without the defect.

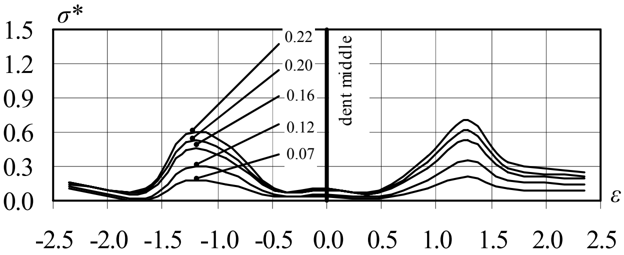


Fig. 4 Variation of the stresses on the surface of the steel plate with a defect across the middle cut of the plate

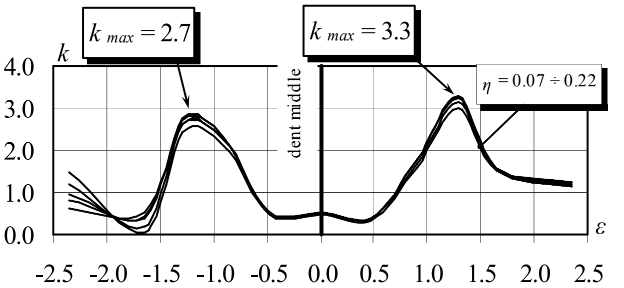


Fig. 5 Variation of SCF on the surface of steel plate with a defect across the middle cut of the plate

Further, according to the experimental and numerical results (Fig. 6) with increasing of the load plastic properties of the material become evident. The material of the plate becomes plastic on the defect contour, therefore further determination of stresses by transducers gets more complicated. With further increasing of the load to 0.62 the transducers show that deformations of the middle and contour parts of the defect are equal. Further load increasing increases the deformation of the middle part of the defect to a more degree than the contour part. Under 145 kN load ($\eta = 1$) a steel plate with the defect has been destructed from its contour part of the defect along the lines of the plate edge (Fig. 7).

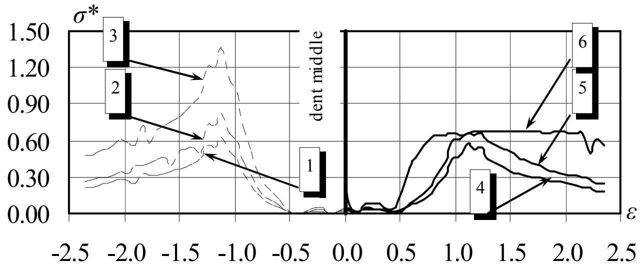


Fig. 6 Variation of stresses on the surface of steel plate with the defect across the middle cut of the plate, when load factor is 0.22 (curves *1*, *4*); 0.29 (curves *2*, *5*); 0.48 (curves *3*, *6*); linear calculations results (curves *1-3*); nonlinear calculations results (curves *4-6*)

Moreover, the same plate without the defect was tested in order to control indication of the transducers and to verify the influence of the cross-arm on stress distribution (Fig. 8). The variation of relative stresses defined by means of the indications of strain gauge transducers and theoretical values of longitudinal normal relative stresses in the cross-section of the plate are shown on the diagram (Fig. 9).

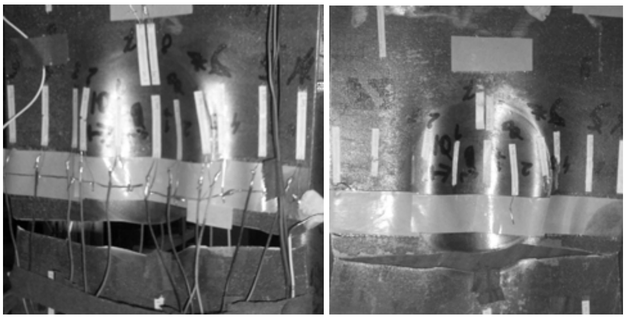


Fig. 7 Destructed steel plate with the geometrical defect

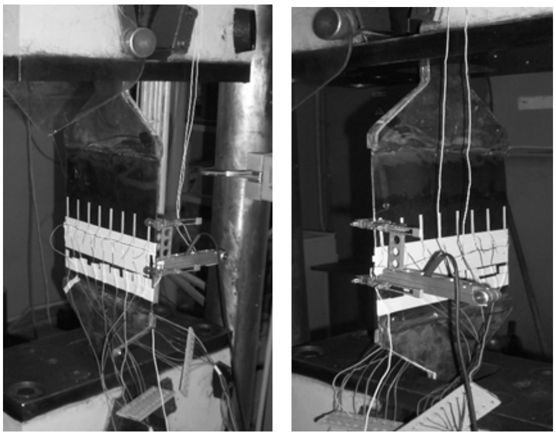


Fig. 8 Experimental model: steel plate without the geometrical defect

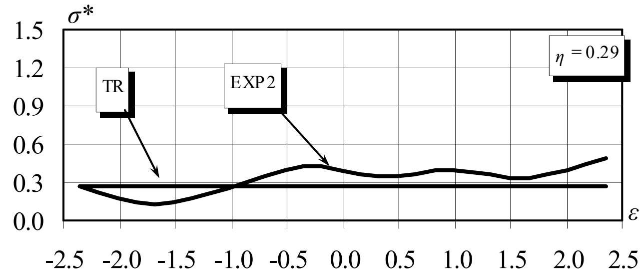


Fig. 9 Variation of relative stresses on the surface of steel plate without the defect across middle cut of the plate, when load is 0.29: curve EXP2 − experimental results; curve TR − analytical results

3. Numerical models

In this investigation additionally, the distribution of normal longitudinal stresses in the cross-section of thin steel plate with a geometrical defect was analysed by the finite element method (FEM). The calculations have been executed by using standard FEM program COSMOS/M [37].

The experimental model of the plate with deviation from the ideal form was done completely by program COSMOS/M (Fig. 10). The geometrical dimensions of the numerical model of the plate were taken as in the natural experiment: width $b = 200$ mm, length $l = 270$ mm and thickness $t = 2$ mm. The dent geometrical parameters are: relative radius $\beta = 21.25$ and relative depth $\gamma = 7.75$ (Fig. 1).

Shell finite elements (FE) with 3 nodes and 18 degrees of freedom (DOF) and volume FE with 4 nodes and 24 DOF were employed during this simulation. The FE mesh was of enough density. Dimension of the FE does not exceed 1 mm. The numerical model has been subjected to distribute load, as in the case of natural experiment, using the cross-arm.

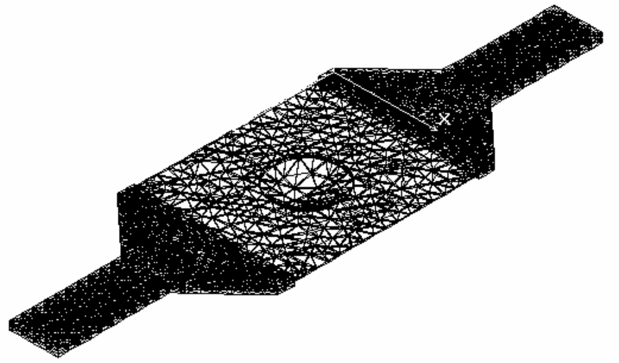
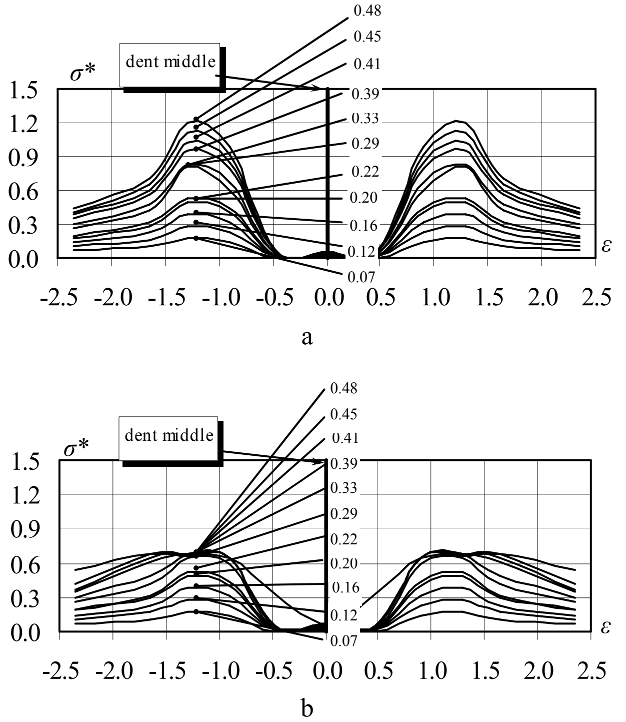


Fig. 10 Numerical model of the steel plate with the dent

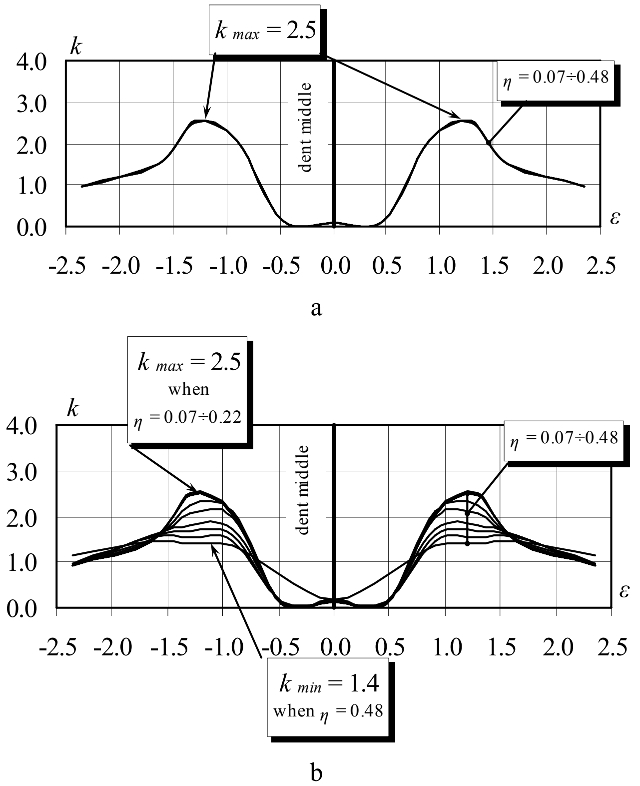
The linear, geometrically and physically nonlinear calculations of the plate with the defect were executed. For physical nonlinear calculation an idealised diagram of the elastic-plastic material with strengthening in the plastic part has been used. The yield stresses were equal to 245 MPa, relative deformation was 1.1×10^{-3} respectively. The strength stresses were equal to 370 MPa, relative deformation was 1,0 respectively. In the first place, the numerical model simulated by volume FE was used for the investigation. Studying the presented diagrams (Fig. 11) of the distribution of longitudinal normal stresses in the cross-section of the plate with the dent, we see the evident stresses concentration on the contour of the dent and their significant decreasing across the middle part of the dent [3, 8, 11, 23]. According to the diagrams of the linear calculations (Fig. 11, a), concentration of the stresses increases on the contour of the defect and a constantly low level of the stresses is observed on the middle part of the dent [5]. In addition to this, SCF as follows from the diagrams, (Fig. 12, a) is constant and is equal to $k = 2.5$ at load of 0.07-0.48. Further, investigating geometrical nonlinearity of deformation of the plate with the defect and physical nonlinearity of the material one observes the agreement of stress and strain state with results of linear calculation at the load of 0.07 - 0.22 (Fig. 11, a, b). In case of the load 0.07 - 0.22 stresses do not exceed yield stresses of the material in the most dangerous place of the defect, that is on the contour of the dent (Fig. 11, b). The stresses values (Fig. 11, a, b) and values of SCF (Fig. 12, a, b) are similar to the results of the linear calculations. Further increase in the load produces geometrical nonlinearity of the model and physical nonlinearity of the plate material. Stresses within the concentration area of the dent do not increase, they are more uniformly distributed across the plate cross-section [28]. The results of linear calculations with the increase in load differ from those of nonlinear calculations (Fig. 6). In case of the load 0.45 stresses across the middle cut of the plate cross-section from its edges to the defect are equal to the yield stresses. In case of the load 0.48 stresses in the middle part of the dent increase too (Fig. 6, 14, e). At the same time SCF decreases from the value $k = 2.5$ when the load is $0.07 \div 0.22$ to $k = 1.4$ when the load is 0.48 (Fig. 12, b).



a

b

Fig. 11 Variation of stresses on the surface of steel plate with a defect across the middle cut of the plate: a - linear calculations; b - nonlinear calculations



a

b

Fig. 12 Variation of the SCF on the surface of steel plate with a defect across the middle cut of the plate: a - linear calculations; b - nonlinear calculations

Further, numerical modelling of the plate with a defect was performed by a triangular shell FE. The calculations similar to those performed using the volume FE model were made as well. In accordance with results of the calculations and natural experiment (Fig. 13) the numerical two-dimensional model provides a higher concentration of stresses than the numerical three-dimensional model and natural experiment. At the same time, results of the calculations of the volume model are equal to those of the natural experiment (Fig. 13).

On the basis of calculations and natural experiment of the steel plate with a "soft" defect, dent, further investigation of the stresses distribution should be carried out by volume numerical model describing stress and strain state on the defect surface more precisely. Also the calculation results of the model nonlinearity have to be taken into account when stresses are equal or higher than yield stresses of the material.

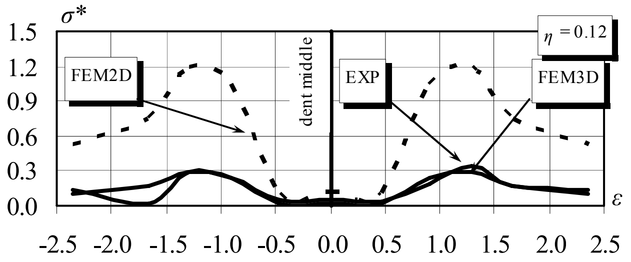


Fig. 13 Variation of stresses on the surface of steel plate with a defect across the middle cut of the plate, when load is 0.12. Curve EXP – experimental results; curve FEM2D – numerical results (nonlinear calculations) when numerical model 2D; curve FEM3D – numerical results (nonlinear calculations) when numerical model 3D

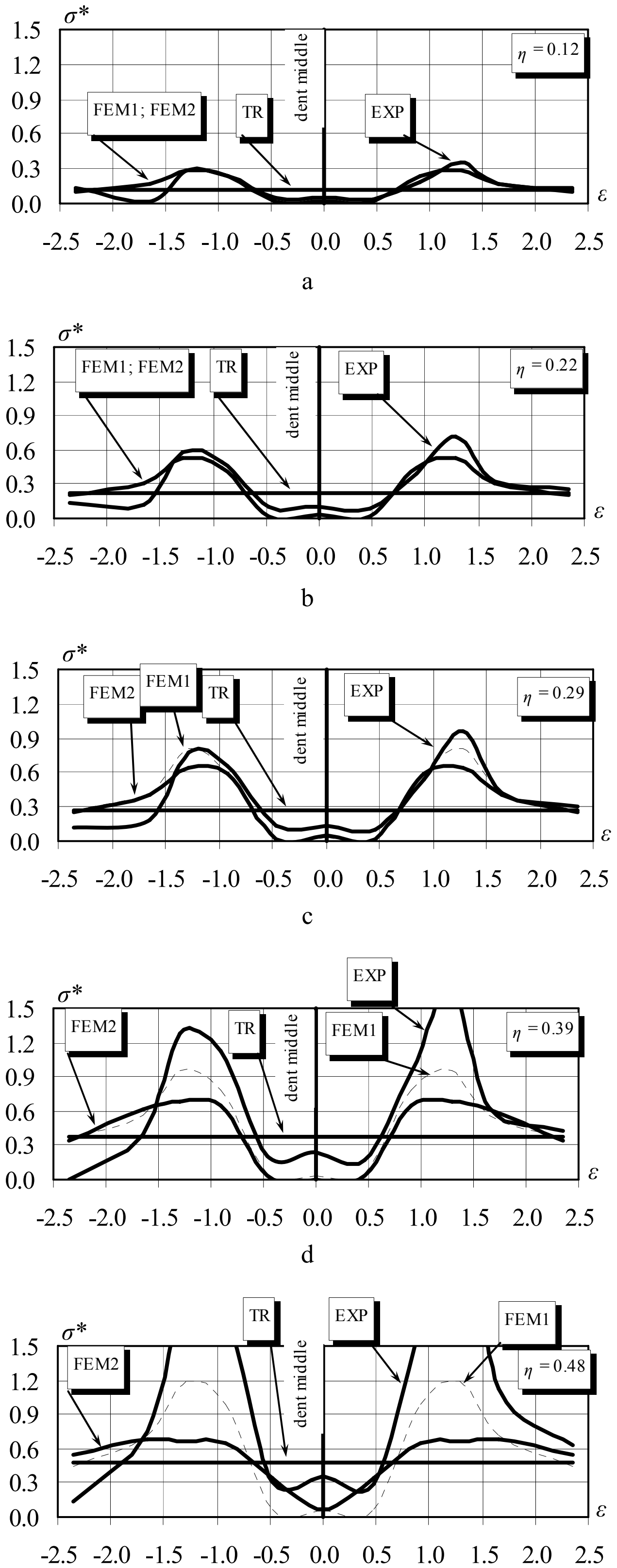
4. Comparison between experimental and finite element method results

To make final conclusion about what kind of numerical models is to be used for modelling of the thin steel plate with geometrical defect, let us compare the natural and numerical experiment results at every stage of the loading (Fig. 14). Moreover, the maximum SCF on the surface of the defect and the most dangerous area of the dent should be defined at separate stages of calculations.

In this part of the investigation together with conclusions of the third part of the article the results of numerical calculations, when volume finite elements were used for modelling, are considered.

On the diagrams (Fig. 14) variations of relative normal stresses across the middle cross-section of the plate with a defect at load of 0.12; 0.22; 0.29; 0.39; 0.48 were defined.

The curves EXP, FEM2, dotted line FEM1, TR, on the diagrams (Fig. 14), describe respectively the results: of the natural experiment, numerical calculations taking into account nonlinearity of the model, numerical linear calculations and theoretical calculations when the plate is without a defect. In the natural and numerical experiments for both modelling versions the defined variations of relative stresses across the middle cut cross-section of the plate with the defect at the load of 0.22 are equal. The stresses on the plate do not exceed yield stresses. Stress and strain state of the material of the plate is elastic. At the load of 0.12 the results of maximum stresses of the natural experiment and numerical calculations on the left point of the dent profile are equal (Fig. 14, a). At the same load on the right point of the contour stresses differ by 13 % (Fig. 14, a). When comparing the results only of numerical



a

b

c

d

e

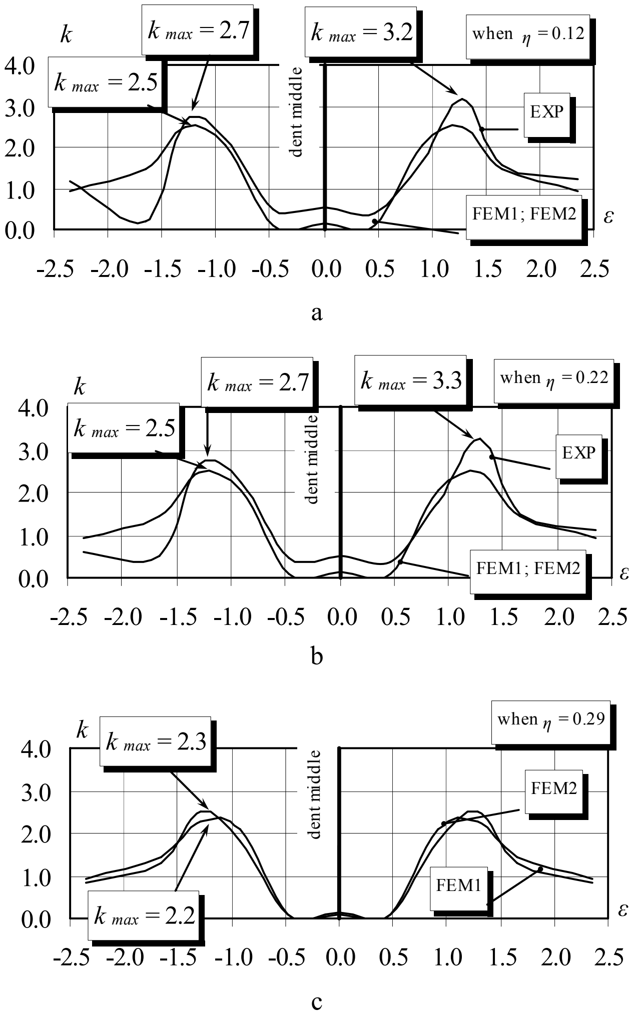
Fig. 14 Variation of normal stresses on the surface of the plate sheet across the middle cut of the plate

linear and nonlinear calculations, we see full coincidence between both results of calculations (Fig. 14, a, b). With increase in load the difference between results of the natural experiment and numerical nonlinear calculation increases too (Fig. 14, a, b). It is especially obvious at the load of 0.29 (Fig. 14, c). Stress and strain state of the plate material on the dent contour is elastic-plastic. At the same time, the difference between results of the numerical linear calculations and those of the natural experiment is not so great at the load of 0.29 (Fig. 14, c). But with load increasing the difference between the results increases as well. Therefore, the determination of stresses by means of the strain gauge transducers is not reasonable. The diagrams of theoretical values of the stresses across the middle cut cross-section of the plate without a defect divide stresses variation across the middle cut cross-section of the plate with a dent into two areas: the stress concentration area and the unloaded one (Fig. 14).

Analysing further results of the linear and nonlinear calculations of the stresses variation across the middle cut cross-section of the plate with the dent with load increasing we see the continuously increasing stresses on the defect contour according to the results of linear calculations and constant stresses on the dent contour according to the results of nonlinear calculations, in this case the stresses are distributed more uniformly [14]. Stress and strain state of the plate is material elastic-plastic. According to the results of numerical linear calculations at the load of 0.39 ÷ 0.48 the plate with a dent must have started its destruction from the dent contour. But this contradicts to the results of the natural experiment and numerical nonlinear calculations. Under 145 kN ($\eta = 1$) load in natural experiment the steel plate with the defect was destructed from a lower point of the contour of the defect along the lines of the plate edge (Fig. 7). As follows from the results of the natural experiment and numerical calculations with the increase in load from 0.39 the variation of stresses becomes more uniform between the dent contour and the plate edge. Beginning from the load of 0.48 stresses become similar on the defect contour, on its middle part and on the surface of the plate without a defect.

At the load of 0.62 stresses on the surface of the defect, on contour and the middle part of the dent are equal to the stresses on the surface of the plate without the defect (Fig. 14). Further with the increase in load stresses on the middle part of the dent increase too. Stresses on another part of the plate remain constant. Under 145 kN load ($\eta = 1$) the steel plate was destructed from a lower point of the contour of the defect along the lines of the plate edge (Fig. 7).

Further, variation of the SCF obtained from the ratio of stresses across the middle cut cross-section of the plate with the defect and theoretical stresses at the same place if the defect is not available, will be analysed. At the load of 0.22 SCF is constant: $k_{max} = 2.7$-3.3 − in case of the natural experiment, $k_{max} = 2.5$ − in both cases of the numerical calculations (Fig. 15, a, b). Stress and strain state of the plate material is elastic. With increasing of the load SCF remains constant in case the numerical linear calculations (Fig. 15, 16). In case of numerical nonlinear calculations SCF decreases till $k_{max} = 1.4$ at load of 0.48 (Fig. 15, 16) and presumably remains constant till destruction. From the performed comparisons it follows that SCF is constant, $k_{max} = 3.3$, when stress and strain state of the plate material is elastic. And SCF does not depend on the version of calculations at this stage. So, in case of the calculation of thin steel structures with a geometrical defect in elastic state numerical linear model can be used. With increasing of the load SCF decreases till $k_{min} = 1.4$ due to the elastic-plastic stress and strain state of the plate material



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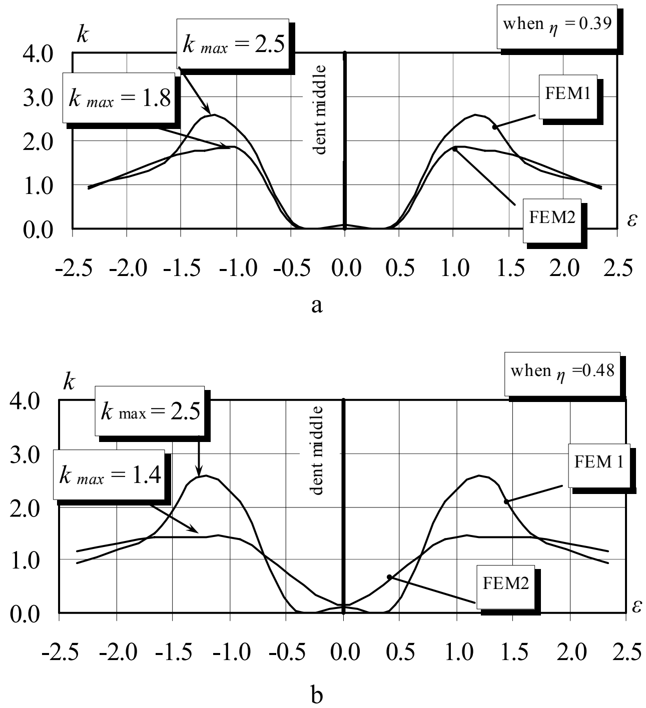
b

c

Fig. 15 Variation of SCF on the surface of steel plate with the defect across the middle cut of the plate



a

b

Fig. 16 Variation of SCF on the surface of steel plate with the defect across the middle cut of the plate

and remains constant till destruction. The most dangerous place of the defect is the dent contour.

5. Conclusions

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

1. Investigation of the variation of stresses on steel plate with a “soft” defect should be carried out by volume numerical model describing the stress and strain state on surface of the defect more precisely.

2. Nonlinearity of the model has to be taken into account when stresses are equal or higher than yield stresses of the material.

3. SCF is constant, $k_{max} = 3.3$, when stress and strain state of the plate materiais is elastic and SCF does not depend on the calculation type at this stage of analysing.

4. For the calculation of thin steel structures with geometrical defect in elastic state linear numerical model can be used.

5. SCF decreases when stress and strain state of the plate material is elastic-plastic and changes from $k_{max} = 3.3$ to $k_{min} = 1.4$ up to destruction.

6. The most dangerous place of the defect is the dent contour.

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MINKŠTOJO DEFEKTO PLONOS PLIENINĖS PLOKŠTELĖS PAVIRŠIUJE ĮTEMPIŲ IR DEFORMACIJŲ BŪVIO ANALIZĖ EKSPERIMENTINIU IR SKAITMENINIU METODAIS

Reziumė

Visose pramonės šakose, ypač energetikoje, plačiai taikomos plonasienės plieninės konstrukcijos. Tokių konstrukcijų pavyzdžiai yra antžeminiai vertikalūs ritinio pavidalo rezervuarai. Kadangi šių potencialiai pavojingų statinių konstrukcijų gamybos ir montavimo darbus sudėtinga atlikti be vietinių ar bendrų nukrypimų nuo idealios geometrinės formos, juos tiksliai nustatyti labai svarbu.

Šių tyrimų pagrindiniai tikslai yra: plonų metalinių plokštelių su defektu eksperimento ir rezultatų aprašymas; įtempių ir deformacijų būvio nustatymas baigtinių elementų metodu; eksperimentinio metodo ir baigtinių elementų metodo rezultatų palyginimas; galutinių išvadų pateikimas.

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STRESS AND STRAIN STATE INVESTIGATION OF SOFT DEFECTS ON THE THIN STEEL PLATE BY USING EXPERIMENTAL AND NUMERICAL METHODS

Summary

In all branches of industry, especially in power-engineering, thin wall steel structures are extensively used. Land vertical cylindrical steel tanks are very popular examples of such structures. Manufacture and assembling of these structures are usually accompanied by the deviations from a perfect cylindrical form. Therefore, exact evaluation of real local imperfections and common deviations from the analytical model of the tank is very important for such potentially dangerous structures.

The main objectives of the presented investigations are: to describe some results of experiments of thin plates with a defect; to identify stress and strain state by using the finite element method; to make the comparison between experimental results and FEM results. The final remarks and conclusions have been presented.

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ИССЛЕДОВАНИЕ НАПРЯЖЕННО-ДЕФОРМИРОВАННОГО СОСТОЯНИЯ МЯГКОГО ДЕФЕКТА НА ПОВЕРХНОСТИ ТОНКОЙ СТАЛЬНОЙ ПЛАСТИНЫ ЭКСПЕРИМЕНТАЛЬНЫМ И ЧИСЛЕННЫМ МЕТОДАМИ

Резюме

Во всех отраслях промышленности, особенно в энергетической отрасли, широко используются тонкостенные стальные конструкции. Наземные вертикальные цилиндрические резервуары являются примером таких конструкций. Изготовление и монтаж таких сооружений невозможен без отклонений от идеальной геометрической формы. Поэтому точная оценка фактических локальных и общих погрешностей от расчетной схемы резервуара очень важна для такого типа потенциально опасных сооружений.

Публикуемые исследования преследуют следующие цели: описание результатов эксперимента тонких металлических пластин с дефектом; определение напряженно-деформированного состояния методом конечных элементов; сравнение результатов экспериментального метода и метода конечных элементов. Представлены окончательные выводы.

Received October 26, 2005