This paper considers the deformation process of a typical section of a steel trunk pipeline with a defective zone, strengthened with a carbon fiber composite lining, under the influence of stationary internal pressure. Defects in the form of thinning of the pipe thickness and cracks were investigated. The stressed-strained state of the structure at critical pressure was analyzed. The thickness of the composite lining was determined, at which the bandage compensates for the effect of internal pressure on the damaged section of the pipeline. Research was carried out numerically based on finite element modeling in the ANSYS software package.

When studying the stressed-strained state of a pipe with a defect of an arbitrary complex shape under the influence of critical pressure, a compensating value was obtained. The result showed that a carbon fiber lining with a thickness of 17 % of the rated thickness of the pipe could completely compensate for the effects of internal pressure in the defect area. In this case, the stresses in the carbon fiber lining were close to minimal. When studying the stressed-strained state of a pipe with a large crack of arbitrary shape at critical pressure, a compensating value was also obtained.

It has been established that to compensate for the concentration of internal pressure in the crack zone, the thickness of the composite lining should be at the level of 34 % of the rated thickness of the pipe. In this case, the deformation of the steel pipe in the area of the crack occurs in the elastic region. The exception is the crack tips, where plastic deformations are observed, and stresses arise up to 93 % of the ultimate strength of the pipe steel. At the same time, the stresses in the carbon fiber lining remain close to minimal. Thus, it is recommended to use carbon fiber linings with a thickness of 17 % or more of the rated pipe thickness to bandage damage constituting up to 75 % of the thickness of a steel pipe. To bandage cracks, it is recommended to use carbon fiber linings with a thickness of at least 34 % of the rated pipe thickness

Keywords: steel pipeline, pipe reinforcement, carbon fiber reinforced plastic bandage, finite element analysis

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DEFORMATION FEATURES OF TRUNK PIPELINES WITH COMPOSITE LININGS UNDER STATIC LOADS

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1. Introduction

The operation of sections of trunk pipelines that are on the verge of exhausting their design life cycle is associated with a number of problems in ensuring industrial safety. One of the most pressing issues is the occurrence of local defects. The basic material for the manufacture of trunk pipelines is steel. During pipeline operation, local defects occur due to metal corrosion or mechanical damage to the pipe. They are small compared to the main dimensions of the structure, but

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the resulting cracks and dents are stress concentrators [1, 2]. Such concentrators with high internal pressure in the pipeline can lead to destruction of the entire structure. In this case, the situation of destruction is especially critical since it can cause a man-made disaster.

To prolong the service life of damaged sections of trunk pipelines in places where defects are located, banding with composite linings, bandages, is used [3]. It should be noted that in recent years, strengthening of thin-walled steel structures with composite materials has found wide practical application [3, 4]. Fiberglass or carbon fiber reinforced plastic is most often used as a composite material for the bandage [5]. Fiberglass is a cheaper material but under heavy loads it exhibits viscoelastic properties. And carbon fiber is an orthotropic material with elastic properties. The front surfaces made of carbon fiber have great strength even with small thickness [6].

When repairing each section of a pipeline with defects, questions arise about the advisability of banding for various sizes and configurations of defects, as well as about the parameters of the band. A preliminary numerical analysis of the stressed-strained state of the section repaired in this way makes it possible to answer these questions. Numerical modeling allows one to determine the thickness of the linings to compensate for the effect of internal pressure on the damaged section of the pipeline. The proper choice of bandage makes it possible to save financial resources when performing repair work.

Thus, studies aiming at analyzing the stressed-strained state of a typical section of a trunk pipeline with composite linings at stationary internal pressure are relevant. The results of such studies could be of interest to a number of specialized research and design institutes.

2. Literature review and problem statement

Research into methods for assessing simple dents, fatigue dents, and dents with a single notch in pipe structures is widely reported in the literature. Paper [7] reviews these experimental and theoretical studies. It is shown that the depth criterion and the deformation criterion are successfully used for simple dents in pipelines. However, for dents in combination with other defects, assessment methods are not sufficiently developed. Work [8] shows that flat dents cause significant plastic deformation but do not reduce the failure pressure of pipelines. Articles [9, 10] report the results of studies of pipelines with dents during long-term operation. It has been shown that other types of defects, in particular cracks, can form in the area of dents. In works [11, 12], defects associated with corrosion cracking are studied. Various types of cracks and their effect on the bearing capacity of the pipeline are considered. Analysis of the above studies revealed that the presence of dents on the pipeline wall does not significantly affect the load-bearing capacity of the pipeline. Moreover, the presence of cracks in the defective area significantly increases the possibility of structural failure.

The development of finite element analysis methods in combination with ANSYS software makes it possible to study even thin-walled structures based on accurate three-dimensional geometric models. Article [13] provides reasons for the need to use three-dimensional geometric models to assess the destruction of a pipeline with defects. In [4, 14], a thin cylindrical shell of variable thickness is studied as a three-dimensional structure. It is shown that the use of shell models is unacceptable. And in studies [15, 16], using three-dimensional geometric models, the stressed-strained state of cylindrical [15] and conical shells [16] is determined, where linear structures were not considered. In study [17], only the smooth composite round thread winding was taken into account. Articles [18, 19] study the influence of frames on the dynamics of conical and parabolic shells. It is shown that the presence of even three frames changes the longitudinal modes of vibration. Thus, it is advisable to analyze the stressed-strained state of a typical section of a trunk pipeline using three-dimensional geometric models that include elements of fastening supports.

A large number of publications reports the experimental and theoretical studies of the repair of steel pipelines with composite materials. A review article [20] showed that the use of fiber reinforced polymer liners improves the stiffness, strength, pressure resistance, and durability of pipes. Composites do not exert a negative impact on the environment when combined with other materials. Work [21] reports the results of the successful use of composites for the repair of existing pipelines. At the same time, the bandage is lightweight, corrosion resistant, and able to withstand high pressure. Many researchers have studied the behavior of repaired glass/carbon composite steel pipes under bending loads and combinations of axial and bending loads. Thus, work [22] presents an assessment of the bending response of composite pipes reinforced with hybrid carbon and glass fibers. For repair work on damaged areas, epoxy resin with carbon fibers is often used, as shown in [20]. Paper [23] investigated a damaged steel pipe repaired using carbon fiber and epoxy resin. Tensile pressure tests showed that the load transfer from the pipe material to the wrapped CFRP depends on the length of the defect. It was experimentally found that the use of carbon fiber in pipelines increases the ratio of strength and weight to rupture resistance. Finite element modeling of the burst test of defective pipes with a CFRP shell was carried out using three-dimensional nonlinear models.

Study [24] examined the design solution of a main overhead pipeline with a prestressed winding under static and dynamic loads. It was revealed that an increase in the tension force of the winding wire reduces the hoop stresses in the pipeline wall by 1.3...1.6 times and increases the meridional stresses by 1.2...1.4 times. Analysis of changes in the dynamic characteristics of the models depending on the prestress force showed that the frequencies of free vibrations increase by 1.5÷1.6 times, and the decrement of vibrations decreases by 1.2÷1.25 times. The numerical research technique taking into account the prestress parameters was considered in [25], and experimental studies of the parameters were carried out in [26], however, the study considered only a winding made of steel wire. At the same time, the existing national standards for steel [27] and shell structures [28]. Also, the international standards for dynamic effects on shells [29] provide for traditional, as well as [30] cost-ineffective methods of strengthening steel structures. For steel pipelines [31] of large diameter [32], reinforcements are associated with the choice of only the parameters of the pipe material. In gas pipelines [33] and main gas pipelines [34], reinforcement methods are associated only with various technological solutions, such as the choice of burial depth, the specifics of backfilling, changes in operating mode, etc.

Our review showed [7–34] that, despite a significant number of publications on the issue under study, the stressed-strained state of typical sections of steel trunk pipelines with carbon fiber composite linings at internal pressure has been poorly studied. Additional studies should include a variable analysis of the stressed-strained state of the damaged pipeline section with composite linings of different thicknesses in order to determine the parameters of the linings that make it possible to compensate for the effect of internal pressure on the damaged section of the pipeline. In the future, such studies could be positively used in banding to extend the service life of sections with defects in trunk pipelines.

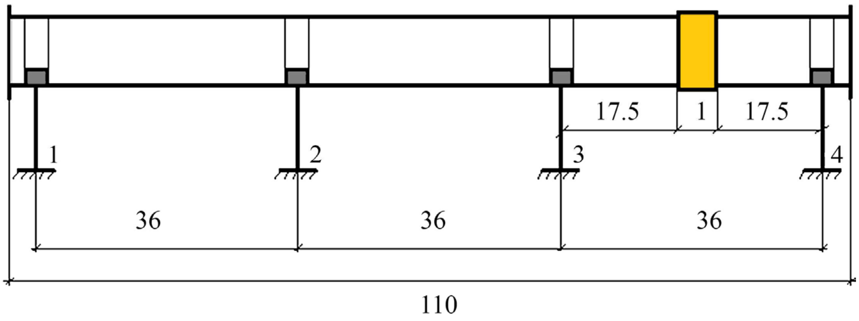


Fig. 1. Diagram of a section of the trunk pipeline strengthened with a composite lining

3. The aim and objectives of the study

The purpose of this study is to determine the characteristics of the deformation process of a typical section of a steel trunk pipeline with damage and cracks, strengthened with carbon fiber composite linings, under the influence of uniformly distributed stationary pressure based on finite element modeling. The devised calculation procedure for determining the stressed-strained state of a damaged section of a pipeline with a composite lining could make it possible in the future to determine the thickness of the bandage to prolong the service life of the pipeline.

To achieve the goal, the following tasks were set:

– to build a computational finite element model of static deformation of a typical section of a trunk pipeline under the influence of internal pressure;

– to investigate the accuracy and reliability of the results of numerical studies obtained using the devised calculation model;

– to assess stress in the damaged section of the pipeline without a lining and with a composite lining at critical pressure.

4. The study materials and methods

The object of our study is the deformation process of a typical section of a steel trunk pipeline with a defective zone, reinforced with a carbon fiber composite lining, under the influence of stationary internal pressure. The possibility of compensating for the effect of internal pressure on a damaged section of a pipeline by bandaging it with a composite lining of a given thickness is analyzed.

The stressed-strained state of a section of a trunk pipeline 110 m long between four supports under the influence of internal uniformly distributed stationary pressure is being investigated (Fig. 1). A working pressure of 7.5 MPa and a critical pressure of 9.8 MPa are considered. The diameter of the pipe is 1.067 m, and the wall thickness is assumed to be minimal and equal to 11.9 mm. The pipe material is X 70 steel, which has elastic-plastic properties. Support 1 implements the conditions for rigid pipe sealing, supports 2 and 3 are freely movable supports, and support 4 is a longitudinally movable support. It is assumed that the defect zone is located between supports 3 and 4 (Fig. 1). This area is reinforced with a carbon fiber composite overlay. In this study, it is assumed that the composite lining is applied along the length of the pipe for 1 m. And its thickness is determined during calculation studies.

We use carbon fiber plastic, which is an orthotropic material with the following engineering mechanical characteristics: Young's moduli E_{xx}=35 GPa, $E_{\varphi\varphi}$=35 GPa, E_{zz}=8 GPa; shear moduli $G_{x\varphi}$=6 GPa, $G_{\varphi z}$=30 GPa, G_{xz}=30 GPa; Poisson's ratios $\upsilon_{x\varphi}$=0.01, $\upsilon_{\varphi z}$=0.09, υ_{xz}=0.09; density ρ=1477 kg/m^3. These values were obtained experimentally in [35]. The composite overlay satisfies Hooke's law in the following form:

$$\begin{bmatrix}\sigma_{xx}\\ \sigma_{\varphi\varphi}\end{bmatrix}=\begin{bmatrix}\bar{C}_{11}\bar{C}_{12}\\ \bar{C}_{12}\bar{C}_{22}\end{bmatrix}\begin{bmatrix}\varepsilon_{xx}\\ \varepsilon_{\varphi\varphi}\end{bmatrix},$$

$$\sigma_{x\varphi}=2\bar{C}_{66}\varepsilon_{x\varphi},\quad \sigma_{xz}=2\bar{C}_{55}\varepsilon_{xz},\quad \sigma_{\varphi z}^{(j)}=2\bar{C}_{44}\varepsilon_{\varphi z}\ , \tag{1}$$

where σ_{xx}, $\sigma_{\varphi\varphi}$, $\sigma_{x\varphi}$, σ_{xz}, $\sigma_{\varphi z}$, ε_{xx}, $\varepsilon_{\varphi\varphi}$, $\varepsilon_{x\varphi}$, ε_{xz}, $\varepsilon_{\varphi z}$ are the elements of the stress and strain tensors.

The conditions for applying a repair bandage to a pipeline can be as follows:

– the lining is mounted without tension on a pipeline that is not loaded with internal pressure;

– the lining is mounted without tension on the pipeline, which is loaded with internal pressure, i.e., there is an initial stressed-strained state;

– the lining is mounted with a tension on the pipeline, which is not loaded with internal pressure;

– the lining is mounted with a tension on the pipeline, which is loaded with internal pressure.

It is obvious that only in the first case of applying a repair bandage in the absence of internal pressure in the pipe, the stressed-strained state of the structure will be zero. Therefore, this particular technique of applying a repair bandage to the defect zone was modeled.

The problem is solved by the finite element method, which is implemented in the ANSYS software package. The finite element statement of the problem is as follows [36].

The equilibrium equations for the case of dynamic behavior of an absolutely elastic medium with internal friction take the form:

$$\sigma_{\alpha\beta,\beta}-\mu\dot{u}_{\alpha}-p\ddot{u}_{\alpha}+Q_{\alpha}=0^{\circ}, \tag{2}$$

where $\sigma_{\alpha\beta}$ are the components of the stress tensor (tensor of the second rank), depending on spatial coordinates;

u_{α} – components of the displacement vector depending on spatial coordinates;

μ – coefficient of internal friction, independent of time;

ρ – material density;

Q_{α} – components of the vector of distributed loads.

Here, summation is performed using silent indices, sorting of equations is performed using free ones, differentiation along the corresponding coordinate is indicated by an index after the decimal point, and differentiation with respect to time is indicated by a dot.

Strain compatibility equation:

$$\varepsilon_{\alpha\beta} = \frac{1}{2}\left(u_{\alpha,\beta} + u_{\beta,\alpha}\right), \qquad (3)$$

where $\varepsilon_{\alpha\beta}$ are the components of the strain tensor (tensor of the second rank).

Physical relationships determined by Hooke's law:

$$\sigma_{\alpha\beta} = C_{\alpha\beta\gamma\delta}\varepsilon_{\gamma\delta}, \qquad (4)$$

where $C_{\alpha\beta\gamma\delta}$ are the coefficients of the material stiffness tensor (fourth-rank tensor).

Using the finite element method, the complete system of elasticity theory equations (2) to (4) is represented in the form of a matrix equation for nodal displacements:

$$[M]\{\ddot{w}\} + [D]\{\dot{w}\} + [K]\{w\} = \{F\}, \qquad (5)$$

where $[M]$ is the mass matrix of the structure;

$[D]$ – structure damping matrix;

[K] – structure stiffness matrix;

$\{w\}$ – vector of nodal displacements of the structure;

$\{F\}$ is the vector of nodal loads.

For the case of static and quasi-static problems, equation (5) is simplified and takes the form:

$$[K]\{w\} = \{F\}. \qquad (6)$$

The elastic-plastic deformation of X 70 steel is modeled on the basis of a bilinear relationship within the framework of the "Bilinear Isotropic Hardening" material model. This model is used to solve equation (6).

5. Results of investigating the stressed-strained state of trunk pipelines with composite linings under static loads

5. 1. Construction of a finite element model of static deformation of a typical section of a trunk pipeline

The developed computational model of static deformation of a typical section of the trunk pipeline under the influence of internal pressure is shown in Fig. 2.

The calculation model includes a pipe with a diameter of 1.067 m and a thickness of 11.9 mm. A uniformly distributed stationary pressure of 9.8 MPa acts on the inner surface of the pipe. Since the ratio of the pipe length to its thickness in the original design exceeds nine thousand, for the model problem the pipe length was reduced by a factor of thirty. At the same time, a part of the structure of real length between two supports was additionally modeled. The pipe is attached to four supports with four frames. The lower ends of the supports are rigidly fixed. The fastening of the upper ends of the supports to the frames is modeled with permanent "Bonded" connections. The frame at the support, which implements the conditions for rigid sealing of the pipe, is rigidly fixed. Its contact with the pipe is modeled as "Bonded". The contact between the pipe and the two central free-moving supports is modeled as "Frictionless". The frame at the longitudinally movable support is fixed so that movements in the direction normal to the pipe surface are impossible. The model takes into account the weight of the structure.

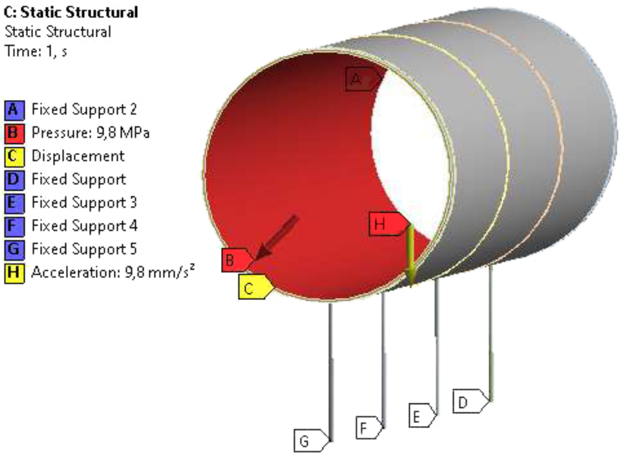


Fig. 2. Computational model of static deformation of a typical section of the trunk pipeline

5. 2. Investigating the accuracy and reliability of results of numerical studies obtained using the developed calculation model

The convergence of the numerical solution to the problem was studied. The research was carried out using the standard method of condensing a finite element mesh. The value of the "element size" parameter was determined, which is equal to the maximum size of the final element. This parameter is not the same for pipes and frames. For a pipe, it is 12 mm, and for frames – 3 mm. Based on the results of this study, a finite element model of the problem was constructed, a fragment of which is shown in Fig. 3.

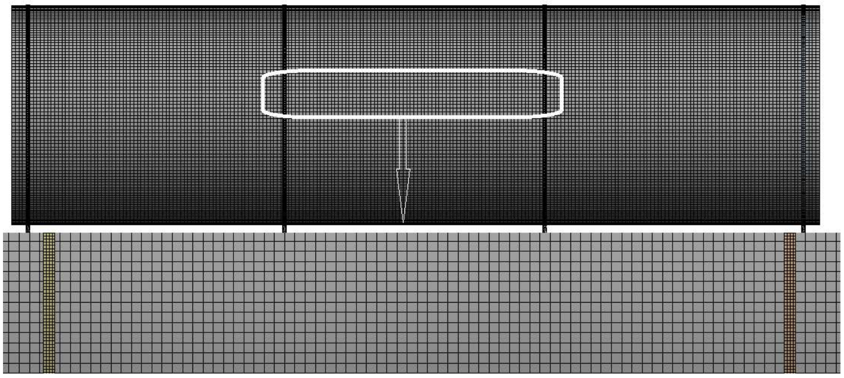


Fig. 3. Fragment of the finite element model

5. 3. Assessing stresses in a damaged section of a pipeline without a lining and with a composite lining at critical pressure

Displacements in a typical section of a trunk pipeline at critical pressure were obtained (Fig. 4). They do not exceed 2 mm in two areas between the frames at the rigidly fixed edge and 3 mm at the longitudinally movable support. The movements are not symmetrical relative to the pipe axis.

The research results at a working pressure of 7.5 MPa are of a similar qualitative nature. In this case, the maximum movements of the longitudinally movable support do not exceed 2 mm.

The von Mises equivalent stresses in a typical section of a trunk pipeline at critical pressure were obtained. For the calculation model with a reduced pipe length, they are shown in Fig. 5, and for the area between the frames at the rigidly fixed edge – in Fig. 6.

Note that the equivalent stresses in the pipe between the supports, obtained from two different geometric models, coincide and are equal to 430 MPa. Stress concentration in the structure is observed only in the areas where the support posts are attached to the pipe.

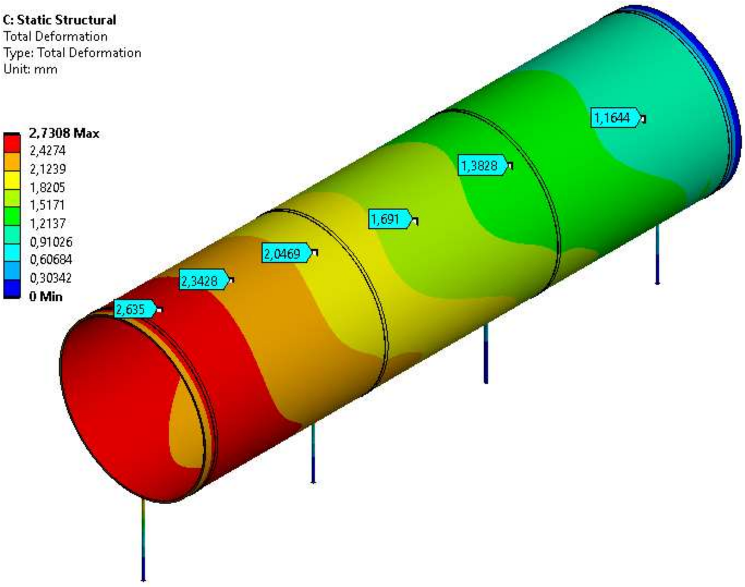


Fig. 4. Distribution of displacements in a typical section of the trunk pipeline at critical pressure

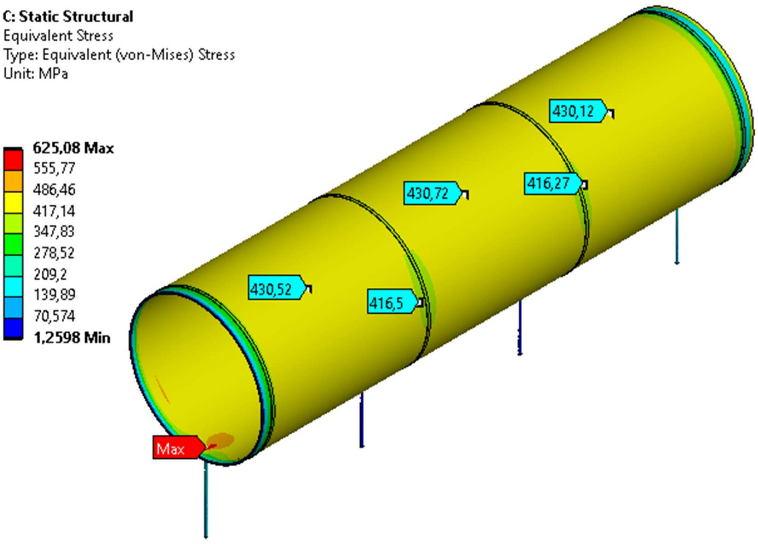


Fig. 5. Distribution of equivalent stresses in a typical section of the trunk pipeline at critical pressure

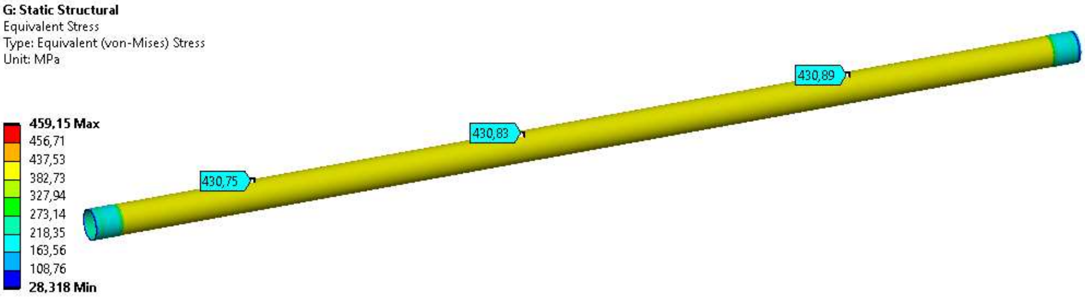
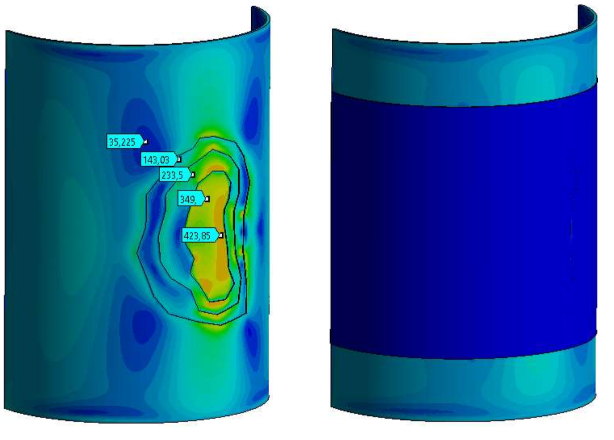


Fig. 6. Distribution of equivalent stresses in the pipeline between two supports at critical pressure

Since the stressed state of an undamaged pipe between the supports does not change, to study the stressed-strained state of trunk pipelines with composite linings under static loads, it is sufficient to consider a limited part of the pipe with a defect zone. This study considers a 1.5 m long section of pipe. Defects are modeled in the central zone at a distance of 0.35 m from the edges. The composite overlay is modeled as a cylindrical shell 1 m long with thicknesses of 2 mm, 3 m, and 4 mm. The inner surface of the composite lining is inextricably connected to the outer surface of the steel pipe.

The appearance of defects and cracks in a pipeline can occur for a number of reasons and randomly. In this case, the shape of the defect (Fig. 7) and crack (Fig. 8) can be of the most arbitrary configuration.

A defect in a part of the outer surface of a pipe of arbitrary configuration, shown in Fig. 7, was investigated. Zones 1, 2, and 3 have different thicknesses – 3 mm, 6 m, and 9 mm, respectively. The crack was also modeled with an arbitrary configuration, as shown in Fig. 8, *a*. In both cases, the overlay was placed so as to completely cover the defect area (Fig. 8, *b*).



a *b*

Fig. 9. Distribution of equivalent stresses in a pipe with a defect covered with a 2 mm thick composite lining at critical pressure: *a* — view without the lining; *b* — view with the lining

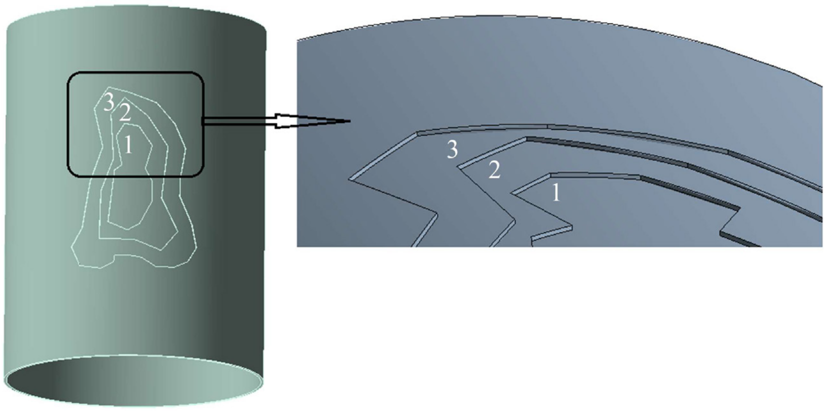
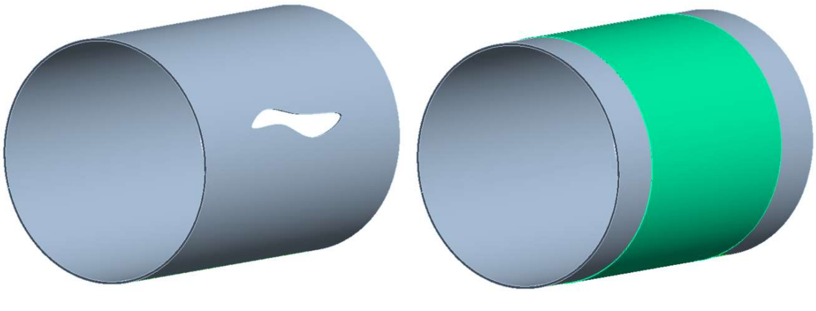


Fig. 7. A model of a pipe with a defect of arbitrary configuration



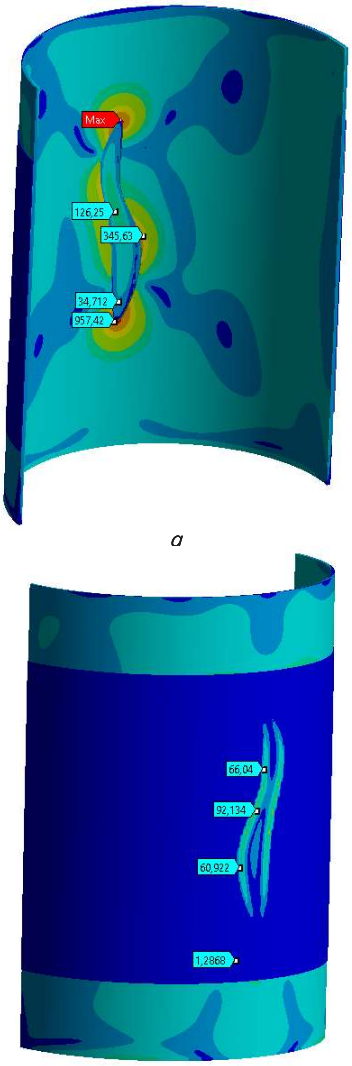
a *b*

Fig. 8. Model of a pipe with a crack: *a* — without lining; *b* — with lining

The results of modeling equivalent stresses in a pipe with a defect covered with a 2 mm thick composite cover are shown in Fig. 9.

The results of the simulation of equivalent stresses in a pipe with a crack closed by a composite lining with a thickness of 4 mm are shown in Fig. 10.

The reported results are obtained for critical pressure. For working pressure, the nature of the deformation process is similar.



a

b

Fig. 10. Distribution of equivalent stresses in a pipe with a crack, closed with a 4 mm thick composite lining, at critical pressure: *a* — view inside the pipe; *b* — view from the outside of the pipe

6. Discussion of results of the analysis of the stressed-strained state of trunk pipelines with composite linings

This study examined a typical section of a trunk pipeline between four supports under the influence of internal uniformly distributed stationary pressure. The results of these studies are shown in Fig. 4–6. An analysis of the distribution of displacements in the pipe between the supports revealed that their greatest value is achieved between the freely movable and longitudinally movable supports. The smallest movements were observed at the support with rigid embedding. In this case, the difference in values did not exceed 1.5 mm for the case of critical pressure. It should be noted that the resulting movements are not symmetrical relative to the pipe axis, which is explained by the influence of the supports on the deformation process of the pipe. Analysis of the distribution of equivalent stresses in the pipe showed that they are evenly distributed along the pipe between the supports. The presence of freely movable supports does not significantly affect the stressed state of the pipe. Stress concentration is observed in local zones near the support posts. In this case, the maximum stress value does not exceed 75 % of the steel yield strength.

The stressed-strained state of a pipe with a defect closed by a composite lining made of carbon fiber was studied at critical pressure. An arbitrary complex defect shape with a piecewise linear contour and variable thickness was considered (Fig. 7). The minimum thickness of the pipe in the defect zone was 25 % of the rated thickness. A variable calculation was carried out for composite linings with a thickness of 2 mm and 3 mm. It showed that in both cases, the carbon fiber lining can completely compensate for the effect of internal pressure in the defect zone (Fig. 9). In this case, the maximum stresses in the pipe in the thinnest defect zone are 51 % of the yield strength of the steel. The stresses in the carbon fiber lining are close to minimal.

The stressed-strained state of a pipe with a large crack of arbitrary shape, closed with a composite lining made of carbon fiber, was studied at critical pressure (Fig. 8). A variable calculation was carried out for composite linings with thicknesses of 2 mm, 3 mm and 4 mm. It was found that to compensate for the effects of internal pressure in the crack zone, the thickness of the composite lining should be 4 mm (Fig. 10). In this case, the deformation of the steel pipe in the area of the crack occurs in the elastic region. The exception is the crack tips, where plastic deformations are observed and stresses up to 93 % of the steel's ultimate strength occur. And the stresses in the carbon fiber lining remain close to minimal.

Our results of the analysis of the stressed-strained state of trunk pipelines with composite linings showed that to bandage pipeline damage amounting to up to 75 % of the pipe thickness, it is advisable to use carbon fiber linings with a thickness of 17 % of the rated pipe thickness. And for bandaging cracks, it is advisable to use carbon fiber linings with a thickness of 34 % of the rated pipe thickness. It should be noted that the results obtained can be used both for new pipelines being designed and for strengthening existing pipelines.

As a drawback of the study, it can be noted that the calculations did not take into account the friction between the pipeline body and the bandage. However, this assumption does not significantly affect the result, and friction can be taken into account in additional calculations.

The main qualitative features of the deformation process were studied on a straight section of the pipeline, which is a limitation of the study. However, this made it possible to test a scientific idea, substantiate some assumptions, and select structural solutions. Given the above, it is necessary to expand the field of study of banded pipelines towards studying curved sections of the pipeline, as well as towards using prestress as a vibration damper for the pipeline during operation.

7. Conclusions

1. A calculation model of static deformation of a typical section of a trunk pipeline under the influence of internal pressure has been built. The developed calculation model includes a pipe with a diameter of 1.067 m and a thickness of 11.9 mm. A uniformly distributed stationary pressure of 9.8 MPa acts on the inner surface of the pipe.

2. A study was carried out into the accuracy and reliability of the results of numerical studies obtained using our calculation model. The study was carried out using the standard method of condensing a finite element mesh. The value of the "element size" parameter was determined, which is equal to the maximum size of the final element. For a pipe, this parameter is 12 mm, and for frames – 3 mm. Based on the results of this study, a finite element model of the problem was constructed.

3. The process of deformation of a typical section of a steel trunk pipeline with a defective zone, strengthened with a composite lining made of carbon fiber, under the influence of uniformly distributed stationary internal pressure was considered. Variable studies on the stressed-strained state of a damaged pipe with banded linings of 2 mm, 3 mm, and 4 mm thickness were carried out. The studies were carried out numerically using the ANSYS software package.

When studying the stressed-strained state of a pipe with a defect of an arbitrary complex shape under the influence of critical pressure, it was found that a 17 % thick carbon fiber lining can completely compensate for the effect of internal pressure in the defect zone. In this case, the maximum stresses in the pipe in the defect zone are 51 % of the yield strength of the steel. The stresses in the carbon fiber lining are close to minimal.

The stressed-strained state of a pipe with a large crack of arbitrary shape at critical pressure was studied. It was found that to compensate for the effects of internal pressure in the crack zone, the thickness of the composite lining should be 34 % of the rated thickness of the pipe. In this case, the deformation of the steel pipe in the area of the crack occurs in the elastic region. The exception is the crack tips, where plastic deformations are observed and stresses up to 93 % of the steel's ultimate strength occur. The stresses in the carbon fiber lining remain close to minimal.

Our research results could be used to select the thickness of the carbon fiber lining for banding a pipeline with a pipe of the appropriate size. It is recommended to use linings with a thickness of 17 % of the rated pipe thickness for banding damage constituting up to 75 % of the pipe thickness. To bandage cracks, it is recommended to use linings with a thickness of 34 % of the rated pipe thickness.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

References

1. Vishnuvardhan, S., Murthy, A. R., Choudhary, A. (2023). A review on pipeline failures, defects in pipelines and their assessment and fatigue life prediction methods. International Journal of Pressure Vessels and Piping, 201, 104853. doi: https://doi.org/10.1016/j.ijpvp.2022.104853
2. Suleimenov, U., Zhangabay, N., Abshenov, K., Utelbayeva, A., Imanaliyev, K., Mussayeva, S. et al. (2022). Estimating the stressed-strained state of the vertical mounting joint of the cylindrical tank wall taking into consideration imperfections. Eastern-European Journal of Enterprise Technologies, 3 (7 (117)), 14–21. doi: https://doi.org/10.15587/1729-4061.2022.258118
3. Muda, M. F., Mohd Hashim, M. H., Kamarudin, M. K., Mohd, M. H., Tafsirojjaman, T., Rahman, M. A., Paik, J. K. (2022). Burst pressure strength of corroded subsea pipelines repaired with composite fiber-reinforced polymer patches. Engineering Failure Analysis, 136, 106204. doi: https://doi.org/10.1016/j.engfailanal.2022.106204
4. Tursunkululy, T., Zhangabay, N., Avramov, K., Chernobryvko, M., Suleimenov, U., Utelbayeva, A. et al. (2022). Strength analysis of prestressed vertical cylindrical steel oil tanks under operational and dynamic loads. Eastern-European Journal of Enterprise Technologies, 2 (7 (116)), 14–21. doi: https://doi.org/10.15587/1729-4061.2022.254218
5. Reis, J. M. L., Menezes, E. M., da Costa Mattos, H. S., Carbas, R. J. C., Marques, E. A., Silva, L. F. M. (2023). Strength of dissimilar adhesively bonded DCB joints and its connection with the failure pressure of composite repair systems. Composite Structures, 304, 116441. doi: https://doi.org/10.1016/j.compstruct.2022.116441
6. Avramov, K. V., Uspensky, B. V., Derevyanko, I. I., Degtyaryov, M. O., Polishchuk, O. F., Chernobryvko, M. V. (2023). Dynamic properties of nanocomposite and three-layer thin-walled aerospace elements manufactured by additive technologies. Kosmìčna Nauka ì Tehnologìâ, 29 (1), 52–64. doi: https://doi.org/10.15407/knit2023.01.052
7. Zhao, J., Lv, Y.-R., Cheng, Y. F. (2022). Standards and methods for dent assessment and failure prediction of pipelines: A critical review. Petroleum Science, 19 (6), 3029–3045. doi: https://doi.org/10.1016/j.petsci.2022.10.003
8. Kec, J., Cerny, I. (2017). Stress-strain assessment of dents in wall of high pressure gas pipeline. Procedia Structural Integrity, 5, 340–346. doi: https://doi.org/10.1016/j.prostr.2017.07.180
9. Zhao, P., Shuai, J., Sun, M., Lv, Z., Xu, K., Wang, Y. (2021). Burst pressure of thin-walled pipes with dent and gouge defects. Thin-Walled Structures, 159, 107213. doi: https://doi.org/10.1016/j.tws.2020.107213
10. He, Z., Zhou, W. (2021). Fatigue reliability analysis of dented pipelines. Journal of Pipeline Science and Engineering, 1 (3), 290–297. doi: https://doi.org/10.1016/j.jpse.2021.08.004
11. Shirazi, H., Eadie, R., Chen, W. (2023). A review on current understanding of pipeline circumferential stress corrosion cracking in near-neutral PH environment. Engineering Failure Analysis, 148, 107215. doi: https://doi.org/10.1016/j.engfailanal.2023.107215
12. Niazi, H., Eadie, R., Chen, W., Zhang, H. (2021). High pH stress corrosion cracking initiation and crack evolution in buried steel pipelines: A review. Engineering Failure Analysis, 120, 105013. doi: https://doi.org/10.1016/j.engfailanal.2020.105013
13. Qin, G., Cheng, Y. F. (2021). A review on defect assessment of pipelines: Principles, numerical solutions, and applications. International Journal of Pressure Vessels and Piping, 191, 104329. doi: https://doi.org/10.1016/j.ijpvp.2021.104329
14. Tursunkululy, T., Zhangabay, N., Avramov, K., Chernobryvko, M., Kambarov, M., Abildabekov, A. et al. (2023). Oscillation frequencies of the reinforced wall of a steel vertical cylindrical tank for petroleum products depending on winding pre-tension. Eastern-European Journal of Enterprise Technologies, 3 (7 (123)), 14–25. doi: https://doi.org/10.15587/1729-4061.2023.279098
15. Altenbach, H., Breslavsky, D., Chernobryvko, M., Senko, A., Tatarinova, O. (2022). Fast Fracture of Conic Shell Under the Action of Belt Explosive Charge. Advances in Mechanical and Power Engineering, 366–376. doi: https://doi.org/10.1007/978-3-031-18487-1_37
16. Tursunkululy, T., Zhangabay, N., Avramov, K., Chernobryvko, M., Suleimenov, U., Utelbayeva, A. (2022). Influence of the parameters of the pre-stressed winding on the oscillations of vertical cylindrical steel oil tanks. Eastern-European Journal of Enterprise Technologies, 5 (7 (119)), 6–13. doi: https://doi.org/10.15587/1729-4061.2022.265107
17. Tursunkululy, T., Zhangabay, N., Suleimenov, U., Abshenov, K., Utelbayeva, A., Moldagaliyev, A. et al. (2023). Analysis of strength and eigenfrequencies of a steel vertical cylindrical tank without liquid, reinforced by a plain composite thread. Case Studies in Construction Materials, 18, e02019. doi: https://doi.org/10.1016/j.cscm.2023.e02019
18. Chernobryvko, M. V., Avramov, K. V., Romanenko, V. N., Batutina, T. J., Suleimenov, U. S. (2015). Dynamic instability of ring-stiffened conical thin-walled rocket fairing in supersonic gas stream. Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 230 (1), 55–68. doi: https://doi.org/10.1177/0954406215592171

19. Chernobryvko, M. V., Avramov, K. V., Romanenko, V. N., Batutina, T. J., Tonkonogenko, A. M. (2014). Free linear vibrations of thin axisymmetric parabolic shells. Meccanica, 49 (12), 2839–2845. doi: https://doi.org/10.1007/s11012-014-0027-6
20. Alabtah, F. G., Mahdi, E., Eliyan, F. F. (2021). The use of fiber reinforced polymeric composites in pipelines: A review. Composite Structures, 276, 114595. doi: https://doi.org/10.1016/j.compstruct.2021.114595
21. Lim, K. S., Azraai, S. N. A., Noor, N. M., Yahaya, N. (2016). An Overview of Corroded Pipe Repair Techniques Using Composite Materials. World Acad. Sci. Eng. Technol. Int. J. Chem. Mol. Nucl. Mater. Metall. Eng., 10 (1), 19–25. doi: https://doi.org/10.5281/zenodo.1110684
22. Dong, C. (2021). Flexural behaviour of carbon and glass reinforced hybrid composite pipes. Composites Part C: Open Access, 4, 100090. doi: https://doi.org/10.1016/j.jcomc.2020.100090
23. Kong, D., Huang, X., Xin, M., Xian, G. (2020). Effects of defect dimensions and putty properties on the burst performances of steel pipes wrapped with CFRP composites. International Journal of Pressure Vessels and Piping, 186, 104139. doi: https://doi.org/10.1016/j.ijpvp.2020.104139
24. Suleimenov, U., Zhangabay, N., Utelbayeva, A., Ibrahim, M. N. M., Moldagaliyev, A., Abshenov, K. et al. (2021). Determining the features of oscillations in prestressed pipelines. Eastern-European Journal of Enterprise Technologies, 6 (7 (114)), 85–92. doi: https://doi.org/10.15587/1729-4061.2021.246751
25. Ibraimova, U., Zhangabay, N., Tursunkululy, T., Rakhimov, M., Dossybekov, S., Kolesnikov, A. et al. (2023). Development of method for calculation of pre-strained steel cylindrical sheaths in view of the winding angle, pitch and thickness. Case Studies in Construction Materials, 19, e02233. doi: https://doi.org/10.1016/j.cscm.2023.e02233
26. Zhangabay, N., Sapargaliyeva, B., Utelbayeva, A., Kolesnikov, A., Aldiyarov, Z., Dossybekov, S. et al. (2022). Experimental Analysis of the Stress State of a Prestressed Cylindrical Shell with Various Structural Parameters. Materials, 15 (14), 4996. doi: https://doi.org/10.3390/ma15144996
27. SP RK EN 1998-4:2006/2012. Proektirovanie seysmostoykikh konstruktsiy. Chast' 4. Bunkery, rezervuary i truboprovody. Available at: https://online.zakon.kz/Document/?doc_id=37105813&doc_id2=37807474#activate_doc=2&pos=1;-0.0999908447265625&pos2=3;-100.09999084472656
28. SP RK EN 1993-4-3:2007/2011. Proektirovanie stal'nykh konstruktsiy. Ch. 4-3. Truboprovody. Available at: https://online.zakon.kz/Document/?doc_id=34586480
29. EN 1998-4 (2006) (English): Eurocode 8: Design of structures for earthquake resistance – Part 4: Silos, tanks and pipelines. Available at: https://www.phd.eng.br/wp-content/uploads/2014/12/en.1998.4.2006.pdf
30. EN 1993-1-8 (2005) (English): Eurocode 3: Design of steel structures - Part 1-8: Design of joints. Available at: https://www.phd.eng.br/wp-content/uploads/2015/12/en.1993.1.8.2005-1.pdf
31. Tekhnicheskie usloviya na truby dlya truboprovodov. API Spec. 5L. Available at: https://buy-pipe.com/home/structure/item_214/955b42b7590d39be6f4d268afcd0a015.pdf
32. SP 284.1325800.2016. Truboprovody promyslovye dlya nefti i gaza. Pravila proektirovaniya i proizvodstvo rabot. Available at: https://files.stroyinf.ru/Data2/1/4293742/4293742910.pdf
33. ASME 831G-1991. Manual for Determining the Remaining Strength of Corroded Pipelines. Available at: https://law.resource.org/pub/us/cfr/ibr/002/asme.b31g.1991.pdf
34. ASME B31.8-2003. Gas Transmission and Distribution, Piping Systems. Available at: https://law.resource.org/pub/us/cfr/ibr/002/asme.b31.8.2003.pdf
35. Derevianko, I., Uspensky, B., Avramov, K., Salenko, A., Maksymenko-Sheiko, K. (2022). Experimental and numerical analysis of mechanical characteristics of fused deposition processed honeycomb fabricated from PLA or ULTEM 9085. Journal of Sandwich Structures & Materials, 25 (2), 264–283. doi: https://doi.org/10.1177/10996362221137292
36. Barbero, E. J. (2013). Finite Element Analysis of Composite Materials Using Ansys. CRC Press, 366. doi: https://doi.org/10.1201/b16295