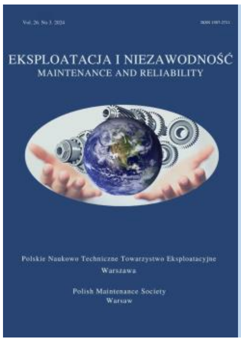

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Numerical model of interaction of a mobile lift chain with a main gas pipeline pipe in the process of repair work

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Highlights

- Technologies for diagnostics and repair of large-diameter gas pipelines were developed.
- The design of a mobile lift for repair of gas pipeline support nodes was developed.
- A model of interaction of the mobile lift chain with the gas pipeline pipe was built.
- The stresses caused by the contact of the rollers of the lifting chain with the pipe were estimated.

Abstract

The paper proposes an original design of a mobile lifting device for diagnosing and repairing support nodes of above-ground segments of gas pipelines without stopping gas transportation. When using such a device, the rollers of the lifting chain interact with the surface of the pipe, which can possibly cause additional stresses in the gas pipeline. At the first stage of studying this problem, a model of a typical gas pipeline overhead crossing for the Carpathian region was built and the maximum operating force that should be developed by the mobile lift during repair operations was determined. At the second stage, a finite-element model of the interaction of the mobile lift chain with the main gas pipeline pipe was built. The additional equivalent stresses arising from the contact of the rollers of the lifting chain with the pipe surface were estimated. Recommendations are given to ensure the safe operation of the gas pipeline when using a mobile lift for local lifting of the pipe above the support of above-ground segments of gas pipelines.

Keywords
main gas pipeline, support, mobile lift, corrosion defect, finite element method, interaction model

1. Introduction

Main gas pipelines are highly loaded engineering structures designed to transport natural gas from the place of its production to consumers or to gas storage facilities. Long-term operation of pipeline systems under pressure is associated with certain risks [23, 28, 39], which causes the need for regular monitoring of their technical condition. Usually, the main part of the main gas pipeline is located under the soil layer, where the pipes are well protected from corrosion and external natural and anthropogenic influences [1, 2, 64]. However, in areas of natural and artificial obstacles, such as rivers, ravines, marshlands, etc., pipeline sections are installed on special supports above the ground and are called above-ground pipeline sections. Beam above-ground segments are the most widely used because they are the cheapest in terms of construction work and are simple and convenient to operate [37, 51]. At the same time, above-ground gas pipeline overpasses are long-term operation facilities that have large dimensions and weight and are under

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high internal pressure of the transported product. At the same time, they are subject to time-varying environmental influences, in particular, corrosive effects of the atmosphere, wind and snow impacts, temperature deformations, etc. [13, 24, 56].

The motivation for this study was a real industrial problem that the authors of the article were involved in solving. In the process of implementing the target program of the National Academy of Sciences of Ukraine on monitoring the technical level of safety of hydrocarbon transportation facilities, diagnostics of long-term operated above-ground overpasses of main gas pipelines constructed in the Carpathian region was carried out. It was found that intensive corrosion processes of the metal surface of the pipes occurred at the points of contact between the gas pipelines and the supporting structures, local defects (cavities, cracks) appeared, and a local decrease in the residual thickness of the pipe wall was observed. The most frequently identified problems concerned the pipe surfaces above the saddles of the supports and under the insulating gaskets of the support clamps, especially on the pipeline sections that run through floodplains and wetlands. Fig. 1 shows a typical above-ground pipeline crossing typical of the region where the surveys were conducted. In order to assess and eliminate the effects of corrosion, it is necessary to raise the pipeline above the base plate to a certain height, fix it, and remove the clips and saddle.

The problem of diagnosing and carrying out restoration work on main gas pipeline support nodes at above-ground overpasses over water obstacles or wetlands is as follows. Moving lifting equipment (truck cranes or pipe-layers) to an above-ground overpass support located in a hard-to-reach place requires costly preparatory work to arrange access roads and additional installation sites. We propose to carry out technological operations of repair of gas pipeline support units without stopping gas transportation using mobile lifting devices of the original design (Fig. 2). Such a device is mounted on a reinforced concrete crossbar of the main gas pipeline support, and two installers are enough to perform all the work. Its advantages are high lifting capacity and small weight and dimensions, as well as the placement of the lift on one side of the support saddle, which provides good access to the repair area.

Fig. 1. A typical above-ground overpass of a long-operated gas pipeline in the Carpathian region.

Fig. 2 Mobile lift for diagnostic and repair and restoration work on above-ground overpasses of main gas pipelines.

When using the proposed device, the rollers of the lifting chain interact with the pipe surface, which may cause additional stresses in the pipe material. To ensure the safety of the gas pipeline when using a mobile lift, this issue requires further study.

Problems on the contact interaction of elastic bodies form a relevant section of mechanics and are of great practical importance for the efficient construction and operation of pipeline transport [11, 47, 67]. There are well-known models for the interaction of a deformable pipe under internal pressure with a rigid bearing surface [31] and for the contact of a seal assembly with a pipeline [19]. Many studies have been devoted to the contact interaction of the pipeline with the ground [14, 50, 66], including modeling the safe length of a gas pipeline subjected to transverse displacement [35, 32], assessing the strength of the pipe in case of sudden damage to the foundation [53], predicting the behavior of gas pipelines during freezing of heaving soils [58], and in other emergency situations [62]. The study of the interaction of the pipe surface with protective coatings [9, 20, 54], surfacing [10, 16], and banding [38] is used for efficient gas pipeline repair. Models of the structural behavior of pipelines during lifting or lowering are considered in [26, 27]. The problems of contact mechanics on the interaction of rods or shells with their surrounding environment are very popular in such areas as the immersion of construction piles [33, 51, 52], the design of layered support columns [14], the construction of deep wells [25, 59, 61], and the elimination of emergency sticking of long drilling tools [34, 41]. Attention should also be drawn to a series of theoretical and experimental works devoted to the frictional contact of a deformable aggregate with a cylindrical shell [7, 8, 42], the interaction of two cylindrical shells with each other [6, 18, 60], and the contact of an open metal pipe with an elastic body [21, 48]. In articles [5, 12] the contact interaction of the roller with the bearing ring was studied and the influence of the roller shape on the service life of the bearing was determined. In work [17] using the Lankarani-Nikravesh contact model, the behavior of a pin connection with a gap was studied. In a series of publications [43–45], the evolution of approaches to the maintenance and repair of technical objects that have been operating for a long time in difficult conditions was studied, and multifactor models were proposed for assessing the efficiency of production processes. Works [65, 36] consider the impact of the contact interaction of pipes with the supporting nodes of overpasses on the safety of pipeline transport.

Corrosion defects are the most common type of defect in actual operating conditions, and thus, they are an essential element for evaluating pipe structural integrity as they are most often connected to accidents [30, 55, 63]. Therefore, for pipelines of long-term operation, it is necessary to periodically monitor the technical condition and, if necessary, carry out repair and restoration work on the supporting units of beam overpasses. There is a known method of lifting a pipeline section above the support using a device consisting of a screw pair and two wedge plates. Such a lifting device is installed on a concrete support directly under the pipeline, which is impossible in the case of narrow reinforced concrete pile foundation. There are also designs of lifting devices that are equipped with pneumatic cushions mounted on additional portable support platforms. Such mobile lifting devices can be used to repair support nodes of pipelines with a diameter of up to 1020 mm. The peculiarity of lifting large-diameter pipelines above the base plate is the significant mass of two adjacent pipeline runs and the high bending stiffness of large-diameter pipes, which ultimately requires a large lifting force [46, 49].

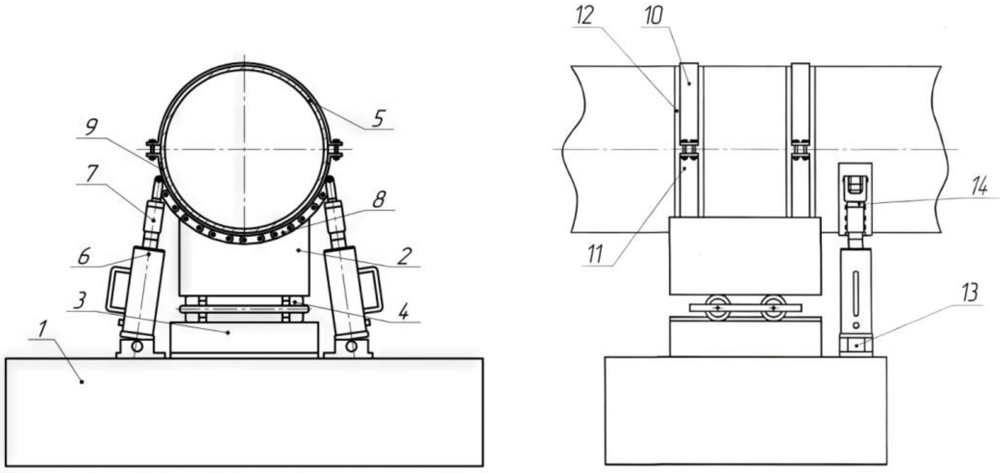
Below, we will consider the problem when, under normal operating conditions of the main gas pipeline (internal pressure and self-weight load), a local lifting of the above-ground overpass above the support is performed in order to replace the insulation in the support node. The lifting is carried out using a mobile lifting device of the original design.

The aim of the study is to substantiate the safety of the main gas pipeline operation when using a mobile lift with a roller chain for local lifting of the pipe above the overpass support. To do this, it is necessary to assess the additional stresses that will arise as a result of the contact interaction of the chain rollers with the pipe surface.

2. Materials and Methods

2.1. Design features of a mobile lift with a load-gripping device in the form of a roller chain

The unloading of the support node and lifting of the pipeline using a mobile lift is carried out as follows. First, on the support of the gas pipeline beam overpass, disconnect the fastening half-clamps 10 and 11 and insulating gaskets 12 (Fig. 3). Hydraulic cylinders 6 are mounted on the reinforced concrete crossbar of the support 1 symmetrically relative to the longitudinal axis of the pipe 5. For better stability, the hydraulic cylinders are tilted towards the pipeline axis at a small angle (3-5°), and their hinged supports 13 are connected to each other by several turns of metal rope (not shown). This rope acts as a tightening device that fixes the distance between the hydraulic cylinder supports. Depending on the diameter of the pipe, extensions 7 (of the required length) are installed on the hydraulic cylinders, on which a load gripping device 8 is mounted (if necessary, a metal lining 9 is installed).



a b

Fig. 3. Diagram of a mobile lifting device mounted on an above-ground support of a main gas pipeline: (a) cross-section of the pipe above the support node, (b) side view of the support node, 1 - reinforced concrete support beam, 2 - support saddle, 3 - base plate, 4 - moving rollers, 5 - gas pipeline, 6 - hydraulic cylinder, 7 - hydraulic cylinder rod extension, 8 - load-gripping element (roller chain), 9 - metal lining for the chain, 10, 11 - half clamps, 12 - insulating gaskets, 13 - hinged supports of hydraulic cylinders, 14 - hinged yoke for chain fastening.

The load gripping element 8 is attached to the hydraulic cylinder rod extensions via the articulation yoke 14. After that, the hydraulic cylinders are supplied with working fluid. The fluid is supplied to the cylinders by a hydraulic pump driven by a compressor or compressed air cylinder. First, a small pressure of 0.5-1 MPa is created in the hydraulic cylinders to select all the gaps and check the symmetry of the installation of the lift elements. Next, the pressure in the hydraulic cylinders is increased and the pipeline 5 is raised to a reasonable safe height determined according to the calculations. Using wooden bars, the raised pipeline is fixed and the half clamps and carriage with the saddle 2 are dismantled. After that, comprehensive visual and instrumental inspections of the pipe surface are performed to check for cracked or corroded defects, determine the residual thickness of the pipe wall, measure metal hardness, etc. If necessary, repair and restoration work is carried out.

We want to note that the design of the mobile lifting device considered in the study is an own development of authors. The authors have a number of patents for invention for the design of a mobile lift and for a method for repairing gas pipeline support units.

The load-gripping element 8 is made of a standard bushing drive chain (national standard of Ukraine DSTU 13568:2006), in which traditional bushings are replaced by rollers whose diameter is 10 mm larger than the width of the chain's plate links (Fig. 4). The interaction of the lifting chain with the pipeline through the rollers significantly reduces the friction force in the chain-pipe pair, which allows for even loading of both hydraulic cylinders and prevents frictional jerks during the pipeline lifting (lowering) process.

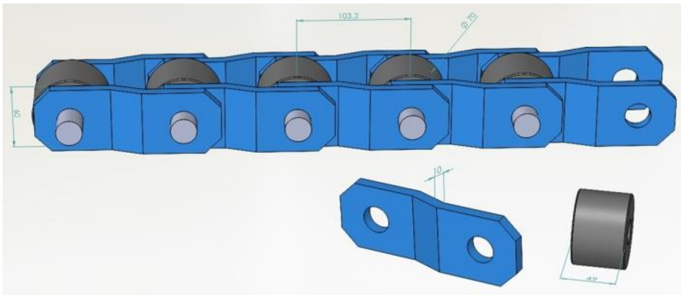


Fig. 4. Drive chain with bent plates (DSTU 13568:2006) with increased bushing diameter.

It should be noted that the design of the presented mobile lift is quickly collapsible, and the weight and dimensions of the individual parts are small. The lift is installed on one side of the saddle of the support node, which makes it possible to move the heavy saddle to the other side directly along the pipeline after lifting to create good access to the repair area. As a potential disadvantage of the proposed lift, we should consider the possibility of additional stresses in the pipeline material due to the contact interaction of the rollers of the lifting chain with the pipe surface. To study this issue, it is first necessary to estimate the maximum lifting force that the mobile lift should develop when working with typical above-ground overpasses in our region.

2.2. Model of an above-ground gas pipeline overpass to determine the maximum operating force that a mobile lift should develop

It should be noted that this paragraph is of an auxiliary nature and is used to estimate the maximum lifting force that a mobile hoist should develop. It is planned that the mobile lift will be used to monitor the technical level of safety and repair hydrocarbon transportation facilities, in particular, long-term operating gas pipeline racks built in the mountainous regions of the Carpathian region. Therefore, for the study, we chose a gas pipeline diagram that is typical for the region under consideration. Of course, the number of spans may vary, but the span length is usually between 25 and 30 m.

Let's consider a typical scheme of a four-span above-ground gas pipeline crossing in the Carpathian region (Fig. 5, a). The crossing consists of an above-ground section *BC* and adjacent underground sections *AB* and *CD*, which are laid on the bottom of the trench. The underground sections of the gas pipeline are covered with backfill soil, and their length significantly exceeds the length of the above-ground part of the gas pipeline.

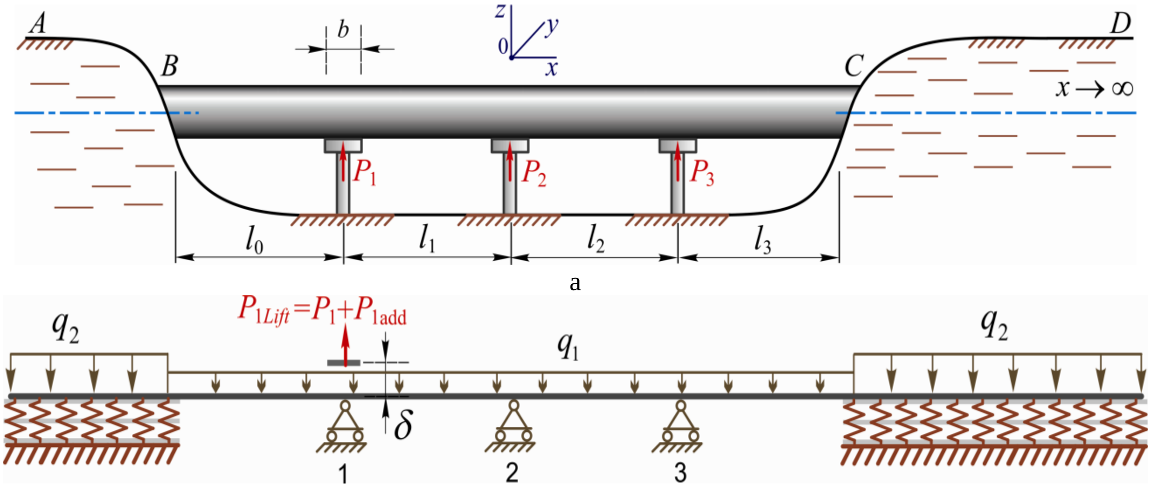


Fig. 5. Diagram of a typical gas pipeline above-ground overpass: a - general view of an above-ground overpass located in the mountainous areas of the Carpathian region; b - design scheme of the overpass.

Beams supported by elastic foundations one of the complex soil-structure interaction problems and analysis carried out using the concept of “beam on elastic foundation” approach. The structural foundation and the soil continuum must act together to support the loads [22, 28]. In sections AB and CD, where the gas pipeline is located in the soil massif, its stress-strain state will be modeled by a semi-infinite rod with an annular cross-section that interacts with an elastic Pasternak foundation (Fig. 5, b). Such an elastic foundation can be represented as a set of springs that are interconnected by additional shear ties. This is a two-parameter soil model with two bedding coefficients: coefficient C_1 characterizing the compressive stiffness of the soil; coefficient C_2 characterizing the shear stiffness of the soil. When the pipe interacts with such an elastic base, a distributed reaction occurs, which is proportional to the deflection of the gas pipeline and depends on the physical and mechanical characteristics of the soil.

Stresses and deformations of the above-ground part of the gas pipeline, which is laid on supports, will be modeled by transverse bending of a tubular rod of finite length. The force effect on the structure of the gas pipeline's own weight and the weight of the backfill soil in the underground sections is modeled by uniformly distributed loads with intensities q_1 and q_2.

2.2.1 Operation of the gas pipeline above-ground overpass in normal mode

During normal operation of the gas pipeline, the reactions P_1, P_2, P_3 will occur in the support nodes of the overpass (Fig. 5, a). Let us estimate their significance for a specific case (typical for the region under study). The 120-meter-long *BC* gas pipeline aboveground section is laid on three supports (each span is 30 meters long). Geometric parameters of the pipes: pipe diameter – $1220mm$, pipe wall thickness – $14mm$. Pipeline material – pipe steel: Young's modulus – $2.1 \cdot 10^5 MPa$, shear modulus – $8 \cdot 10^4 MPa$, Poisson's ratio – 0.3, yield strength – $480MPa$. The depth of trenches for laying underground sections *AB* and *CD* is 1,8m. The soil base on which the pipes are laid is loam with crushed stone, for which the bedding coefficients are $C_1 = 10MN/m^3$, $C_2 = 39MN/m$, and the specific gravity of the backfill soil – $21kN/m^3$. Pipelines transport natural gas under pressure $4MPa$, we consider the temperature drop to be absent.

The intensities of the distributed loads for the computational model (Fig. 5, b) were as follows: aboveground section $q_1 = 4.16KN/m$; underground sections $q_2 = 19.1KN/m$. The Lira-Sapr software package [3, 4] was used to estimate internal forces in the pipeline and reactions in the support nodes. Fig. 6 illustrates the distribution along the length of the pipeline of transverse forces (Fig. 6, a), bending moments (Fig. 6, b), and reactions (Fig. 6, c) that occur in the support nodes of the aboveground section (concentrated reactions) and in the soil base of the underground sections (distributed reactions). Note that the magnitude of the reaction of each support node ($P_1 = P_3 = 131.4\ kN$, $P_2 = 120.8\ kN$) is equal to the magnitude of the corresponding jump on the transverse force graph (Fig. 6, a). Analysis of the graph shown in Fig. 6, b shows that the largest modulus bending moments occur in the first and third support nodes of the gas pipeline above-ground overpass. Using the methodology described in [19], it is easy to estimate that the maximum axial stresses in the outermost fibers of the gas pipeline caused by transverse bending are $22.3MPa$, at the same time, hoop stresses in the pipe walls from the normal internal pressure – $174.3MPa$.

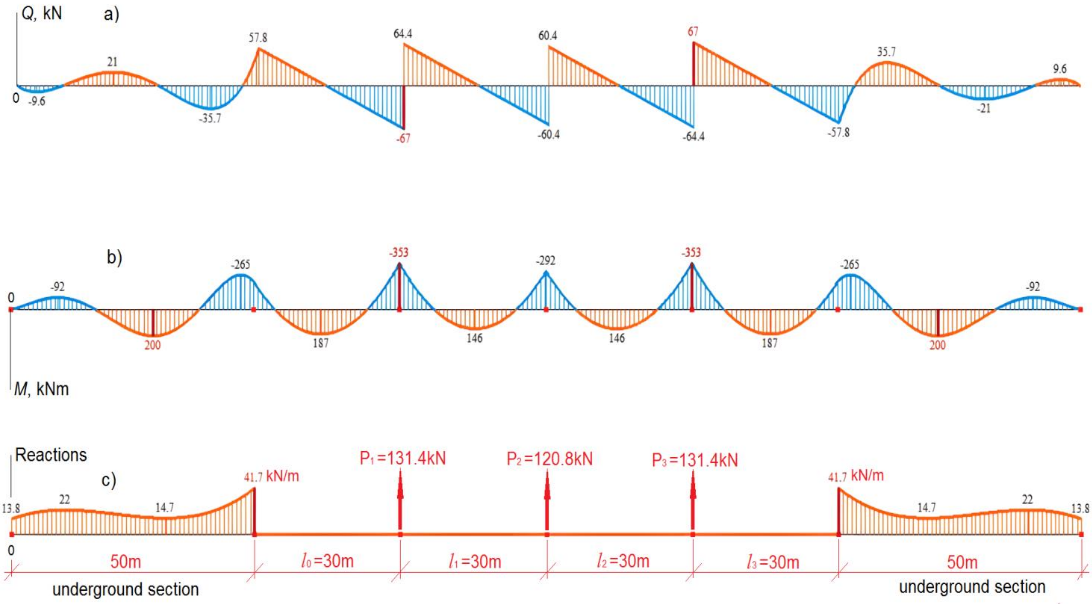


Fig. 6. Force analysis of an above-ground gas pipeline overpass in normal operation: a - distribution of transverse forces along the gas pipeline; b - distribution of bending moments along the gas pipeline (the graph is drawn from the side of the stretched pipe fibers); c - reactions in the support nodes and in the adjacent soil base.

2.2.2 Raising a gas pipeline above-ground overpass above a support

Let's determine the required force P_{Lift}, that a mobile lift must develop to vertically $\delta = 100mm$ lift the pipe above the support. Let's consider lifting a pipe over the first support (Fig. 5, b). Initially, the mobile hoist must unload the support by developing a lifting force of detachment P_1, and then develop an additional force $P_{1\text{add}}$ to elastically deform the pipeline and ensure the required vertical displacement δ. To repair an arbitrary n$^{\text{th}}$ support node of an above-ground gas pipeline overpass, the lift must develop a force $P_{n\ Lift} = P_n + P_{n\text{add}}$. It is necessary to determine the magnitude of such forces for each support node and select the greatest force among them. Using the Lira-Sapr software package, we loaded the gas pipeline above-ground overpass with a vertical kinematic load $\delta = 100mm$. This load was applied to all three support nodes in turn. Fig. 7 shows the graphs of the distribution of transverse forces along the length of the pipeline when the pipe is lifted above the support (50 m of the underground section and three spans are shown). The load value for lifting the pipe above the support is equal to the jump on the graph above the corresponding support node (Fig. 7). Therefore, to lift the pipe above the first or third support, a lifting force $P_{1Lift} = P_{3Lift} = 255kN$ is required, lifting force $P_{2Lift} = 226kN$ is required to lift the pipe above the second support. The maximum axial stresses in the outermost fibers of the gas pipeline caused by transverse bending occur when the pipe is lifted above the first or third support and amount to $87.8MPa$.

For further analysis of the interaction of the gas pipeline pipe with the roller chain of the mobile lift, we assume that the maximum lifting force is $300kN$.

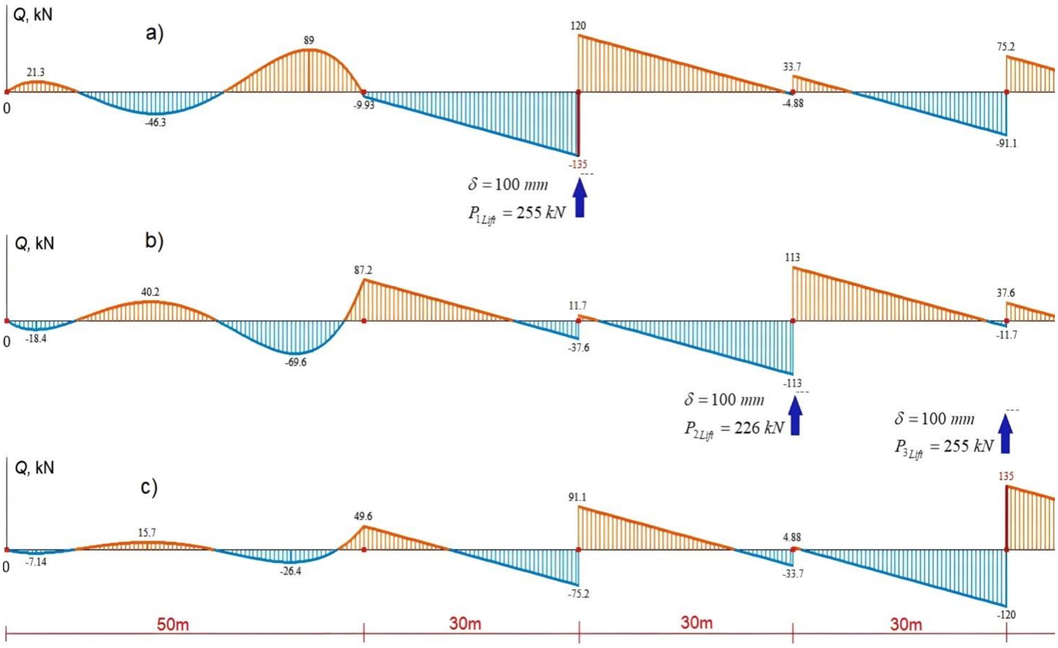


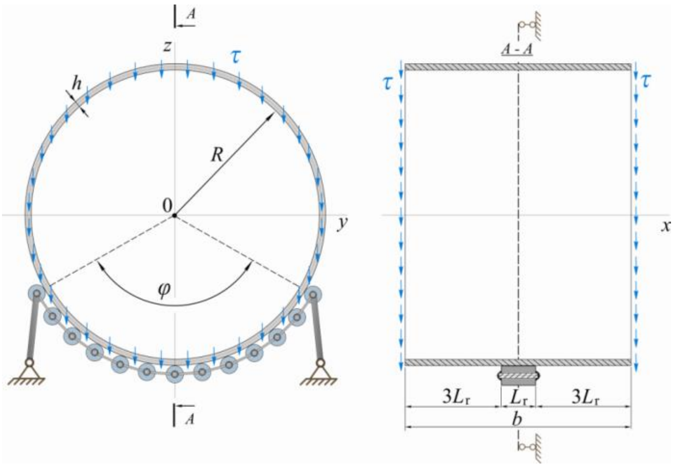
Fig. 7. Distribution of transverse forces along the length of the gas pipeline when lifting the pipe above one of the supports by $\delta = 100mm$: a - lifting the pipe above the first support (it is necessary to apply a lifting force $P_{1Lift} = 255kN$); b - lifting the pipe above the second support (required lifting force $P_{2Lift} = 226kN$); c - lifting the pipe above the third support (the required lifting force $P_{3Lift} = 255kN$).

2.3 A model for analyzing the contact interaction of a gas pipeline pipe with lift chain rollers

We will build a model to estimate the local stresses that will occur in the areas of contact interaction between the rollers of the lifting chain and the pipeline. Contact problems for thin-walled elements (especially shells) have their own specifics, which are associated with an unpredictable contact area, the appearance of irregular contact stresses, additional sticking zones, etc. Analytical solutions to such problems are quite cumbersome and, in order to achieve an analytical result, require a reduction in the dimensionality of the models of elastic bodies in contact to simplify the derivation and solution of equations. Therefore, for our study, we decided to use the finite element method, on the basis of which the engineering software package Ansys Workbench [57] was built.

When a gas pipeline is lifted above the support by a fixed value $\boldsymbol{\delta}$, in the section in contact with the roller chain, the lifting force P_{Lift} balances all the effects of volumetric forces, operational loads and elasticity forces caused by the pipeline bending. Let us select a pipe element of length b above the support and consider in more detail the interaction of the selected element with the mobile lift chain Fig. 8.

Taking into account the Saint-Venant's Principle, when selecting the pipe element, we retreated from the ends of the roller by a distance equal to three roller lengths. All loads that are balanced by the lifting force P_{Lift} were represented by an average integral equivalent $\boldsymbol{\tau}$. This load $\boldsymbol{\tau}$ was assumed to be vertical and distributed over the area of the two extreme cross-sections of the selected pipe element. Since the cross-sectional area of the pipe is $\mathbf{530.4}\boldsymbol{cen}^{\mathbf{2}}$, and the maximum lifting force is $\mathbf{300}\boldsymbol{kN}$, we have $\boldsymbol{\tau} = \mathbf{0.5(300/530.4)10^7} = \mathbf{2.83}\boldsymbol{MPa}$.



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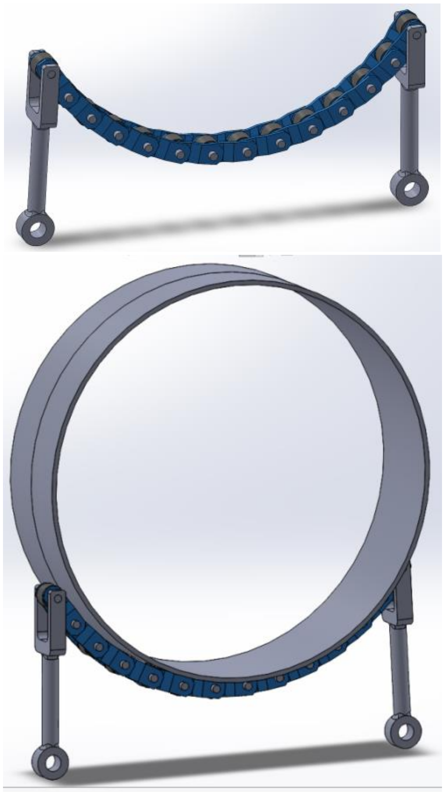


b

Fig. 8. Diagram of the interaction of the gas pipeline with the rollers of the lifting chain (a), 3D model of the lift (b).

Note that the selected pipeline element is nominally stationary in the direction of the axis x, thus, the plane of symmetry can be selected in the design diagram and the structure under study can be fixed in the axial direction in a circle.

Let's discretize the contact bodies into a finite element mesh. Often, in problems solved by the finite element method, the pipeline is considered as a shell (in the sense of the membrane theory of shell calculation). In this case, the pipeline is divided into a surface finite element mesh. However, in our case, when the pipeline is loaded with essentially local bending moments (interaction with the rollers of the lifting chain), its stress-strain state is characterized by local compression on the outer and tension on the inner surfaces of the pipe, and the concepts of outer and inner surfaces are absent in the membrane theory of shells. Therefore, we must use the general theory of shells, which in the understanding of the ANSYS software product means that the shell we are considering is a solid deformable body that is divided into three-dimensional finite elements. It is important to choose the optimal element size. Practice shows that adequate calculation results can be obtained by dividing the object of calculation into such a number of elements that the characteristic parameter of the object contains at least 4 elements of high quality (with an intermediate node). For contact problems, this characteristic parameter is the minimum size of the contact area. Therefore, the area of direct contact in the pipe element - roller chain pair must be divided into very small finite elements.

Fig. 9 shows the result of finite element discretization of the pipeline and mobile lift fragments. Before the final discretization of the model, a mesh independence study was performed using standard ansys recommendations [57]. The calculation mesh for the gas pipeline pipe was generated using the Tetrahedrons method. For the selected pipe element, a three-dimensional mesh with elements shaped like tetrahedrons (with an average edge length of 10 mm) was obtained. For the generation process, we used the "Patch Independent" method, the main idea of which is to overlay the mesh on the design area and then cut off all fragments that go beyond the geometric area. The chain rollers were divided into finite elements using the "Hex Dominant" method, and a mesh based on hexahedron elements with an average element edge length of 4 mm was obtained. Triangulation of the chain plates and hoist supports was performed using similar methods. When describing the contact interaction of the lifting chain rollers with the pipe surface, we used: contact type – “Frictional” with a friction coefficient of 0.1; contact formulation – “Augmented Lagrange method”; 0.0015 penetration tolerance; normal stiffness factor – program controlled.

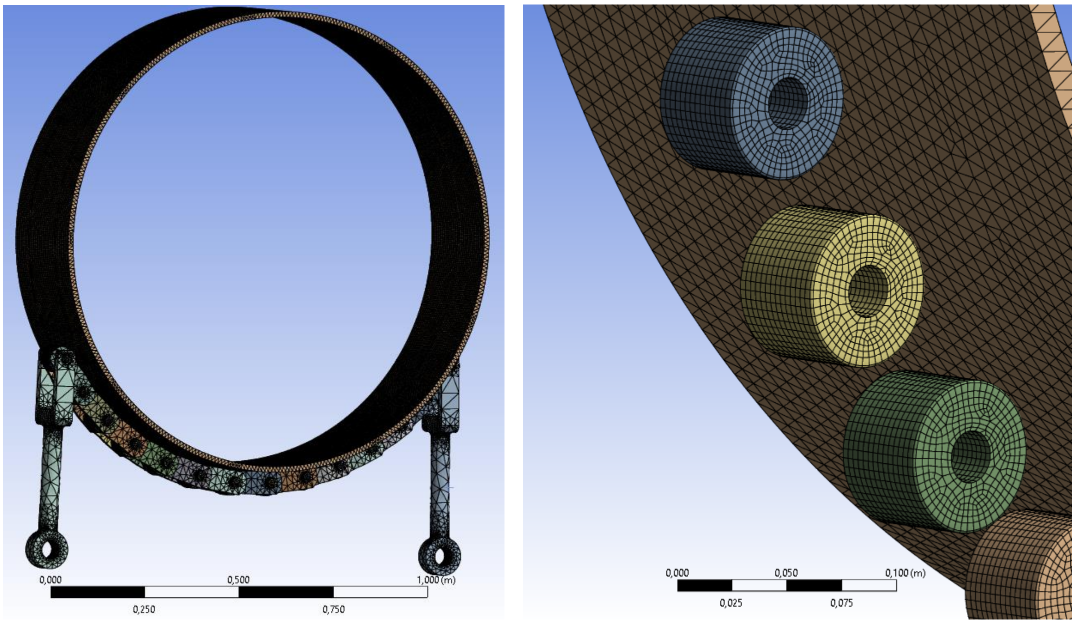


Fig. 9. Finite-element model of interaction of a mobile lift chain with a main gas pipeline pipe.

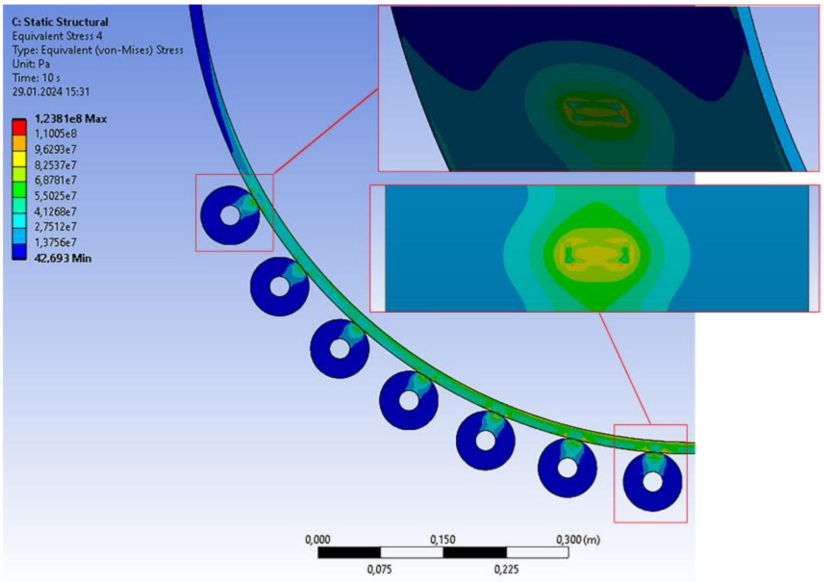
3. Results and Analysis

In solving this problem, we encountered traditional features that are generally characteristic of contact problems. The area and shape of the contact zone of the bodies is unknown a priori. Depending on the boundary conditions, external, physical and geometric factors, the surface of the pipe and the surfaces of the rollers of the lift chain can come into contact and partially out of contact in an unpredictable manner. We carefully monitored the behavior of the contact pairs during the virtual experiments. For a better presentation of the calculation results, we will exclude less important parts of the system under consideration (Fig. 9) from the visualization, i.e., they are present in the calculations, but invisible to the observer.

The highest equivalent stresses occurred in the areas where the bottom rollers of the lifting chain came into contact with the pipe surface. In fact, in these areas, the contact interaction of the rollers with the pipe posed the greatest danger to the strength of the gas pipeline. In the direction from the lower rollers to the upper ones, the equivalent stresses gradually decrease, and in the area of the uppermost roller there is a slight surge in stress. This is obviously caused by the peculiarities of the kinematic scheme of the lifting device and the appearance of a kind of radial thrust on the hinged forks for attaching the chain. We started virtual experiments for the case when the angle of the pipe grip by the lifting chain was $\boldsymbol{\phi} = \mathbf{120}^{\circ}$ (See the diagram in Fig. 8, a). At the same time, the maximum values of equivalent stresses occurred on the outer surface of the pipe and amounted to 124 MPa (Fig. 10 a). The stress were measured with the "probe" tool directly on the contact patch. Such a value of additional equivalent stresses can cause the occurrence of a limit state of the gas pipeline.

Gradual increase in the grip angle $\boldsymbol{\phi}$ was accompanied by a decrease in the maximum equivalent stresses. In particular, when $\boldsymbol{\phi} = \mathbf{180}^{\circ}$ the largest equivalent stresses were equal to 92 MPa (Fig. 10 b), which allows to ensure that the pipe strength condition is met with a sufficient safety factor.

To estimate contact stresses, local coordinate systems corresponding to each individual roller were used. In the area of the contact patch between each roller and the pipe, the maximum normal stresses were measured in the direction perpendicular to the contact surface. In Fig. 11 shows a diagram of the values of normal contact stresses between the rollers of the lifting chain and the surface of the pipe. Number 1 is assigned to the lowest roller, and the diagram is drawn for half the system.



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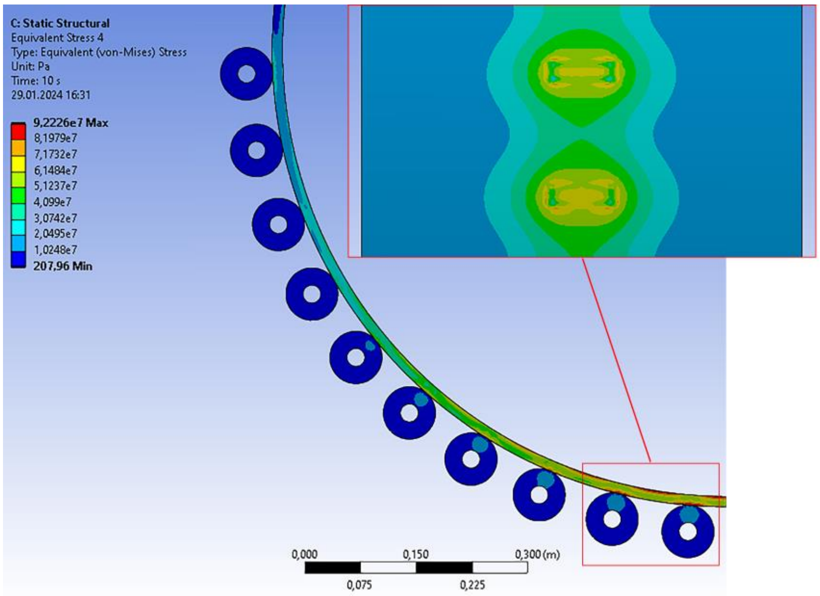


b

Fig. 10. Chromogram of additional equivalent stresses determined according to the Huber-von Mises theory of strength caused by the contact of the lift chain rollers with the pipe: a – grip angle $\boldsymbol{\phi = 120}$° ; b – grip angle $\boldsymbol{\phi = 180}$°.

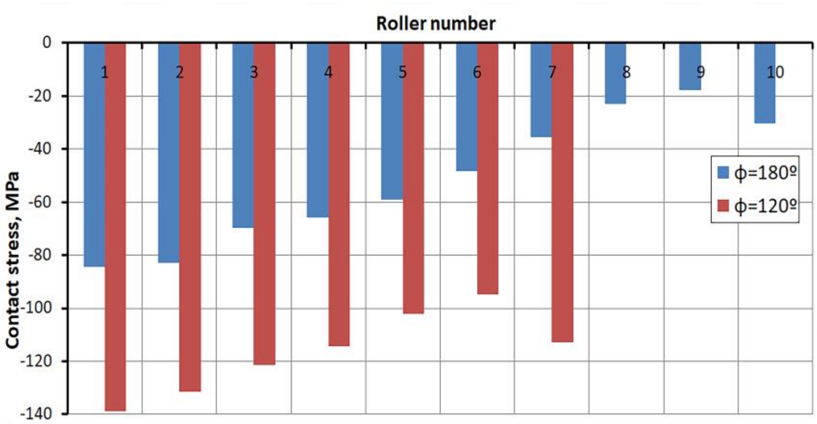


Fig. 11. Normal contact stresses between the roller and the pipe surface: a – grip angle $\boldsymbol{\phi = 120}$° ; b – grip angle $\boldsymbol{\phi = 180}$°.

The highest absolute values of contact stresses were observed in the area of the lower rollers. As you move from the lower roller to the upper roller, the absolute values of the contact stresses gradually decrease. In the area of the uppermost roller, which is connected to the support rod, a slight increase in stress is observed.

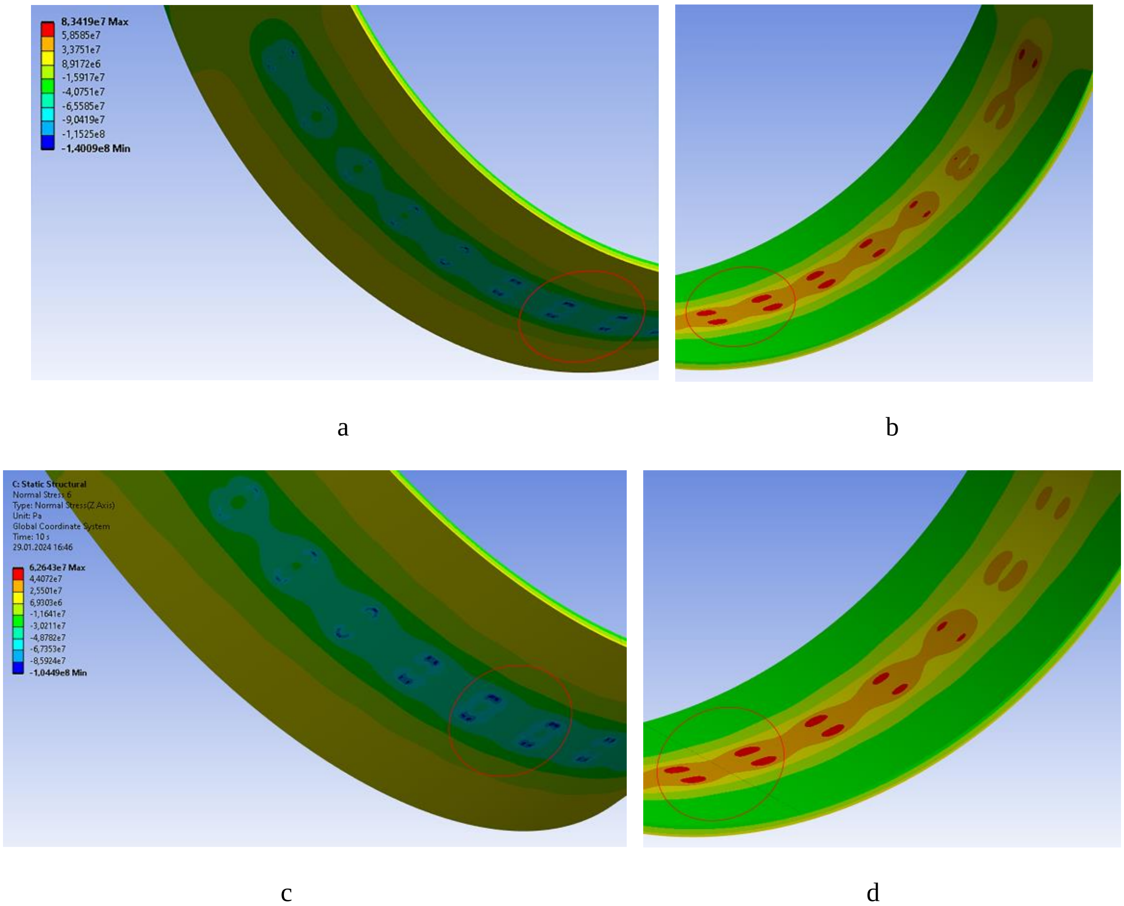
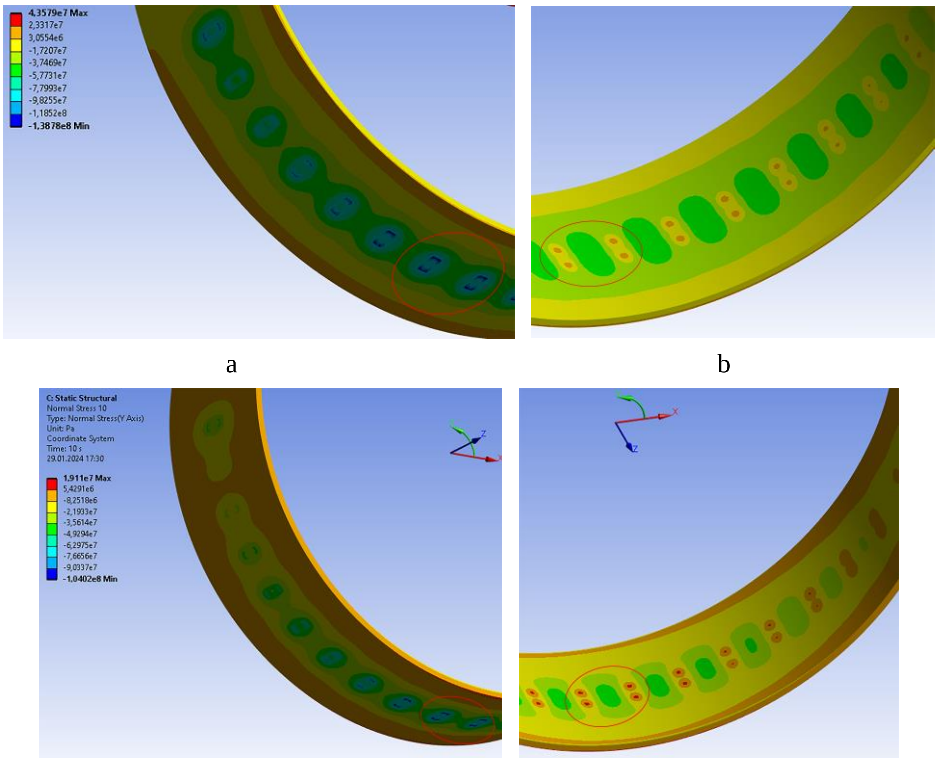


Fig. 12. Chromogram of additional axial stresses that occur in the gas pipeline during contact interaction with the rollers of the lifting chain: a, b – grip angle $\boldsymbol{\phi} = \mathbf{120}°$; c, d – grip angle $\phi = 180°$; a, c – on the outer surface of the pipe; b, d – on the inner surface of the pipe.

Fig. 12 shows a chromogram of additional axial stresses that arise in the gas pipeline as a result of contact interaction with the rollers of the lifting chain. As can be seen from the figure, the gas pipeline fragment is essentially subjected to local bending. The outer surface of the pipeline at the point of its interaction with the roller is mainly compressed, while the inner surface is stretched. Such a stressed state of the pipe is localized (it occurs only in the vicinity of the contact interaction zones). The maximum modulus axial stresses occurred on the outer surface of the pipe: in particular, when $\boldsymbol{\phi} = \mathbf{120}°$ they reached 140.1 MPa, and when $\phi = 180°$they decreased to 104.5 MPa.

Fig. 13 shows a chromogram of additional hoop stresses that arise in the gas pipeline in contact with the rollers of the lifting chain. Although it is well known that the strength of a pipeline is assessed by three components of principal stresses (Huber-von Mises criterion), in the case of gas pipeline repairs without stopping gas transportation, it is the additional hoop stresses that will be decisive in ensuring the safety of the repair work. After all, the normal tensile hoop stresses due to gas pressure will be added to the hoop stresses that occur on the inner surface of the pipe due to the local interaction of the pipeline with the chain rollers. For the most loaded roller, in fig. 14 we depicted the distribution of additional hoop stresses in the pipe along the length of the contact zone between the roller and the gas pipeline. Here, the abscissa axis is aligned with the contact line, and the origin of coordinates is in the middle of this line (remember that the roller width is 49 mm). When $\boldsymbol{\phi} = \mathbf{180}°$on the inner surface of the pipe the maximum value of such additional hoop stresses is 19.1 MPa (tensile hoop stresses of 104 MPa are observed on the outer surface of the pipe). Recall that when transporting gas, the pipeline is under the influence of the standard internal pressure of 4 MPa, which causes tensile hoop stresses of 174 MPa in the pipe material. As a result, the total hoop stresses on the outer surface of the pipeline will decrease to $\boldsymbol{-70 MPa}$, and on the inner surface – they will increase to 193.1 MPa. It should be noted that the planned reduction of gas pressure in the pipeline during such repairs leads to a decrease in hoop stresses on the inner surface of the pipeline and an increase on the outer surface.



a b

c d

Fig. 13. Chromogram of additional hoop stresses arising in the gas pipeline during contact φinteraction with the rollers of the lifting chain: a, b – grip angle $\boldsymbol{\phi = 120}°$; c, d – grip angle $\phi = 180°$; a, c – on the outer surface of the pipe; b, d – on the inner surface of the pipe.

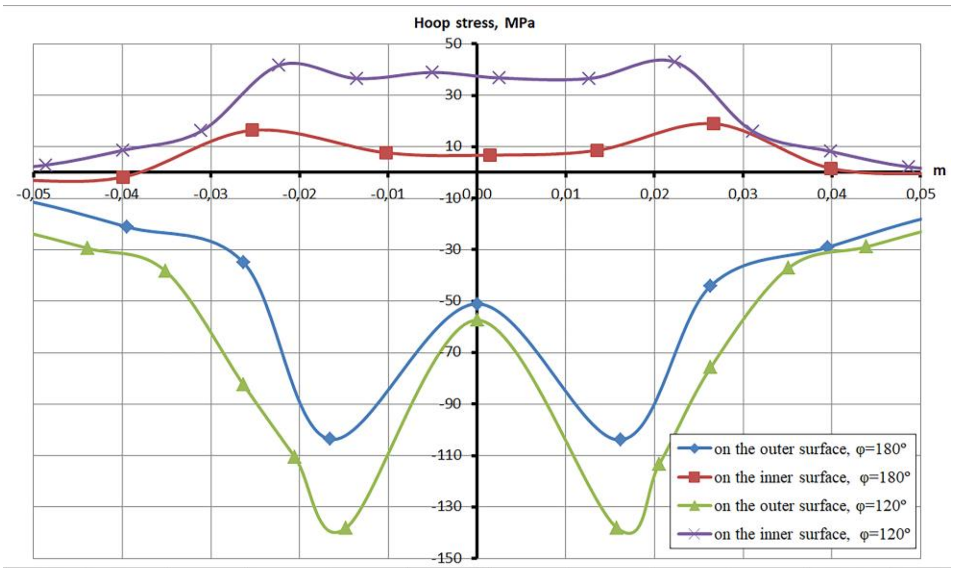
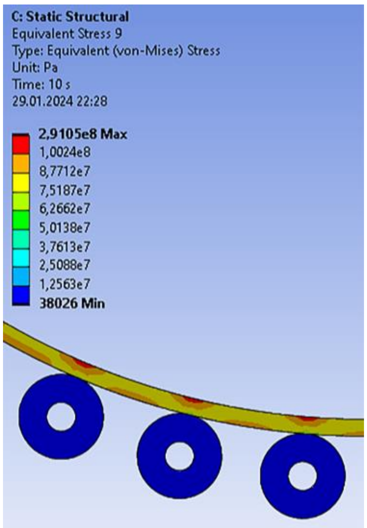
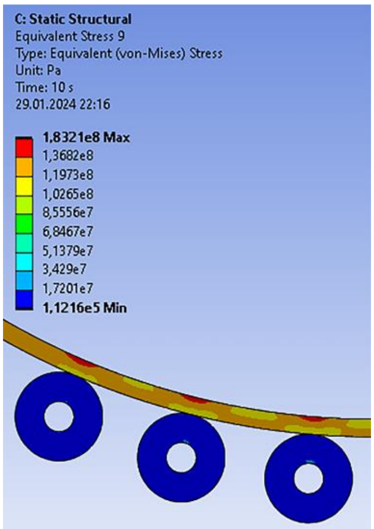


Fig. 14. Distribution of additional hoop stresses in the pipe along the length of the contact zone between the roller and the gas pipeline.

In Fig. 15 presents an assessment of the maximum equivalent stresses in a gas pipeline pipe taking into account the standard load (operational internal pressure in the gas pipeline). The chromogram shows the contact zone of the pipe with the three lower rollers of the lifting chain.



a



b

Fig. 15. Equivalent stresses in the contact zone of the pipe with the lower rollers, taking into account the internal pressure in the gas pipeline: a – grip angle $\boldsymbol{\phi = 120°}$; b – grip angle $\phi = 180°$.

It is in this zone in the pipe that the greatest additional stresses arise from the contact interaction of the gas pipeline with the lifting mechanism. Comparing the highest equivalent stresses (291 MPa) with the yield limit for the pipe material (480 MPa), we can conclude that the boundary state of the gas pipeline has not been reached and strength is ensured. To ensure a greater safety factor, it is recommended to use a mobile lift design with a grip angle of 180°.

It should be noted that a promising way to improve pipeline safety when lifting above the support is to use a metal gasket between the rollers of the lifting chain and the pipe surface. We declare that the use of such a gasket with a thickness of more than 4 mm significantly reduces the uneven distribution of contact pressure between the rollers and the pipe. A quantitative assessment of this phenomenon will be the subject of our next study.

4. Conclusions

A mobile lift has been developed to reduce the time and cost of diagnostic or repair and restoration work on the support nodes of above-ground sections of main gas pipelines. To work with typical above-ground overpasses constructed in the Carpathian region, the maximum lifting capacity of the proposed device is 30 tons. When the rollers of the lifting chain come into contact with the surface of the gas pipeline, local stresses arise in the pipe material, which quickly decay with distance from the contact zones. These stresses are of a bending nature, i.e., local compressive stresses are mainly observed on the outer surface of the pipe, and tensile stresses on the inner surface of the pipe. Among the components of the local stress state, the most influential are the hoop stresses, since on the inner surface of the gas pipeline they are added to the normal hoop stresses due to the action of gas pressure in the pipeline. The maximum equivalent stresses are observed in the areas of contact between the outer rollers of the lifting chain and the pipe surface, and their numerical values at a small angle of grip of the pipe by the lifting chain can approach the limit values. An increase in the grip angle is accompanied by a decrease in the maximum equivalent stresses, which allows to guarantee the safety of repair operations at maximum lifting force.

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