Збірник наукових праць. Галузеве машинобудування, будівництво
Academic journal. Industrial Machine Building, Civil Engineering
http://journals.nupp.edu.ua/znp
https://doi.org/10.26906/znp.2021.57.2582

UDC 539.3

Strength of steel pipelines in corrosive sites with repair composite bandage

Vereshchaka Serhii[1*], Mukoseev Volodymyr[2], Rohovyi Stanislav[3], Tsyhanenko Hennadii[4]

[1] Sumy National Agrarian University https://orcid.org/0000-0001-5369-3689
[2] Sumy National Agrarian University https://orcid.org/0000-0002-5781-4721
[3] Sumy National Agrarian University https://orcid.org/0000-0002-9431-5884
[4] Sumy National Agrarian University https://orcid.org/0000-0002-3335-4804
*Correspondence address E-mail: vereshaka.sm@gmail.com

During operation, defects may appear on the surface of local sections of steel pipelines due to corrosion or adhesive wear, reducing their strength, and sometimes, unfortunately, leading to an accident of the entire pipeline. The use of repair bands made of innovative composite materials is one of the promising areas for maintaining the working pressure of steel pipelines. The task of this work is the development of the method for determining the destructive hydrostatic pressure of repair bands made of composite innovative materials. The obtained theoretical results and experimental studies made it possible to choose the strength criterion and determine the values of the ultimate stresses at the junction points of the bands' composite tire and the steel pipe.

Key words: composite materials, local defects, repair bandage, steel pipeline.

Міцність сталевих трубопроводів на кородованих ділянках з ремонтним композитним бандажем

Верещака С.М.[1*], Мукосєєв В.М.[2], Роговий С.І.[3], Циганенко Г.М.[4]

[1, 2, 3, 4] Сумський національний аграрний університет
*Адреса для листування: E-mail: vereshaka.sm@gmail.com

В процесі експлуатації на поверхні локальних ділянок сталевих трубопроводів внаслідок корозії або адгезійного зносу можуть з'являтися дефекти, що знижують їх міцність, а іноді, на жаль, і призводять до аварії всього трубопроводу. Ця проблема дуже актуальна при експлуатації й ремонті трубопроводів. Застосування ремонтних бандажів з композиційних інноваційних матеріалів є одним з перспективних напрямків збереження робочого тиску сталевих трубопроводів у зв'язку з тим, що ремонтні роботи можуть проводитися без зупинки процесу транспортування енергоносіїв. Розробка методики визначення руйнівного гідростатичного тиску ремонтних бандажів з композиційних інноваційних матеріалів складають завдання даної роботи. З причини суттєвої різниці фізико-механічних характеристик матеріалів труби і композиту, потрібно більш глибоке вивчення їх спільної роботи як в пружній, так і в пластичній області деформування. Для отримання числових результатів використовувався метод кінцевих елементів, а також було поставлено й проведено фізичний експеримент. У роботі пропонується експериментально-теоретична методика розрахунку на міцність конструктивної системи − сталева труба і ремонтний бандаж. В результаті проведених експериментальних і теоретичних досліджень, були досягнуті певні результати: розроблена методика визначення руйнівного гідростатичного тиску ремонтних композитних бандажів; встановлено, що усунення дефектів трубопроводу за допомогою композитного бандажа призводить до перерозподілу кільцевого навантаження; особливо важливим фактором є створення надійного зчеплення композитного бандажа з металом труби, що забезпечує їх спільне деформування; представляється перспективним напрямком робота по підвищенню ефективності фізико-механічних характеристик композитних бандажів і створення конструкцій, що забезпечують більшу жорсткість.

Ключові слова: композиційні матеріали, локальні дефекти, ремонтний бандаж, сталевий трубопровід.

Introduction

Transportation of oil and gas in the modern world is carried out using trunk pipelines. The reliability of the linear part of pipeline systems [1] is becoming one of the most important competitive advantages and the main component of energy and environmental state security.

On local sections of pipelines due to corrosion, including stress corrosion, appear defects that reduce their strength and can lead to accidents with a length of destroyed pipeline sections from 10 to 40 m [2, p.9]. In general, corrosion processes account for 15 to 20 percent of all reports of serious accidents [3, p.116].

The consequences of the gas explosion of the Urengoy-Pomary-Uzhgorod pipeline in 2007 are illustrated in the article [4, p.26].

In accordance with the development plan of the Ukraine gas transportation system until 2030, it is planned to overhaul 791 km of gas pipelines [5, p.99].

It should be noted that the repair of corrosive sections of pipelines using welding technologies leads to a halt in the transportation of energy carriers and entails significant losses. The development of effective repair structures in the form of multilayer bands composite tires will make it possible to carry out repairs without interrupting the process of transporting products. This emphasizes task relevance.

As a rule, while the repair is used composite bandages based on glass and carbon fibers, as well as Kevlar-49 fibers (Aramid Kevlar 49) [6-12], a regulatory framework has been created for the repair of pipelines with composite systems [13-17], the range of used composite materials is expanding [11]. For example, the American company ClockSpring [18] has developed a unique technology for repairing of steel pipes defective sections using special ClockSpring cuffs (clock spring). The ClockSpring cuff is special glass fiber, unidirectional composite material with a memory matrix. The authors of this development note that the cuff "takes on" 1/6 of the total load, therefore, the limits of the pipe "primary" elastic deformations zone increases by 18%.

In Ukraine, for local pipelines' repair, the composite bandages of the company «Polypromsintez" are used, made based on fiberglass and polyester resin. It has developed a technology for the manufacture of composite bandages by multilayer winding of fiberglass fabric on a pipe.

In publications [19-20], a brief review of the scientific literature dedicated to the problem of defects detection, monitoring, and restoring of the steel pipelines corroded sections is given. The main directions for the use of repair composite bandages in a world practice are outlined. It is noted that fiber-reinforced composites are an ideal choice of material for steel pipe rebuilding due to their lightness, high strength and stiffness, good corrosion, and fatigue resistance.

Review of the research sources and publications

A significant difference in the physical and mechanical characteristics of the pipe and composite materials requires a deeper study of their joint work in both elastic and plastic deformation regions. Investigation of the pipeline-bandage system, in order to study the mechanical properties of the bandage and create structural and technological schemes for strengthening defective areas during pipeline repair, as well as the methods for calculating them, are given in publications [19, 21-27].

Here it should be noted that the norms for the permissible defects' sizes of the power engineering facilities impose rather strict restrictions on their sizes. The following classification of defects has been adopted:

– non-thorough: corrosive, erosional, and metallurgical type;

– through (holes, fistulas) and linear (cracks).

Table 1 – Basic requirements for permissible defects according to the most common standards

Types of defects	δ_{res} , %	Permissible defect area, mm^2	Notes
through defect	0	< 150	Distance between adjacent defects ≥ 1000 mm $\sum П \leq 0.5м^3$
non-through defect	> 90 80– 90 70 – 80 60 – 70 50 – 60 <50	≤ 300000 ≤ 200000 ≤ 150000 ≤ 100000 ≤ 50000 The repair technology is the same as for the through defect	

Note: $\delta_{res} = (\delta_{act}/\delta)$ 100 – relative pipe wall thickness in the area with a defect, δ_{act}/δ – actual and nominal pipe wall thickness; $\sum П$ is the total area of sites with defects.

In publications [14, 16-17, 19-20], the joint work and strength of a repair band and a pipe with a blind flaw are studied. For example, Showman A. and Taheri F. [21] give the values of the deformation limits of repaired pipelines under combined loading conditions, Keller M. W. and others [22] evaluate the effect of moisture on the thermoelastic properties and creep characteristics of a carbon fiber-reinforced bandage.

The authors [24–25] have carried out experimental and theoretical studies on full-scale fragments of pipes with non-through local defects to determine their joint work with a repair composite bandage. The results of testing pipes with composite-polymer bandages in areas with defects that simulate local corrosion damage are presented. The joint operation of the shroud and the pipe under static and cyclic loads caused by internal pressure was shown.

The reinforcement efficiency of the pipelines' defective sections with composite-polymer bandages is established and the destruction features of the pipe reinforced by the bandage are noted.

Much less theoretical works are devoted to the problem of corroded pipeline sections through defects repair. The ultimate internal pressure of the through-thickness defects pipes with the use of the composite band was determined in publication [24] based on the approaches to solve the fracture mechanics problems of composite materials. Kopple M. W. and others [23] solve the strength issues of the repaired pipelines through defects using analytical and numerical models compiled in accordance with ISO / TS24817.

Definition of unsolved aspects of the problem

Unfortunately, the lack of refined methods for assessing the effect of defects on the structures' strength leads to an unreasonable increase in the volume of repair work to eliminate defective areas without special need. A refined method for assessing the effect of detected defects on the strength of the pipeline-composite bandage system will make it possible to have a more accurate prediction of the feasibility of pipeline corrosive section repairing.

In this regard, special attention should be paid to both theoretical and experimental study of the stress state at the points of the mating surface of the steel pipe and the band. This is necessary for the determination of the most effective strength criteria and assessment with sufficient accuracy of the limiting state of repair systems during their operation.

Problem statement

Purpose of work. Based on the discrete-structural theory of multilayer shells and the finite element method, static stresses and the peculiarities of deformation of the steel pipe material and a repair composite bandage along their mating surfaces were determined in this article. This, in its turn, has made it possible to find the bandage design parameters depending on the damageability of the pipe material and the defects' geometric parameters. The obtained theoretical results, confirmed by the experimental data, have made it possible to find the values limiting stresses, to select the strength criterion, and to determine the value of the breaking internal pressure.

Object of the Study. Fragment of the seamless hot-rolled steel pipe (GOST 8731-74, GOST 8732-78) made of 09G2S steel. The specified non-through and through defects were applied on the outer surface of the pipe.

Subject of the Study. The strength of the steel pipes reinforced with a repair composite bandage on the local areas with the corrosive defects under the action of the internal hydrostatic pressure.

Research methods. To obtain the numerical results, the finite element method was used, which was implemented in the ANSYS software package, as well as the laboratory research program was developed and a physical experiment was carried out.

Research results. It is proposed an experimental-theoretical method for calculating of a structural system strength - a "steel pipe and a repair bandage". The bandage is made of a composite material with one plane of elastic symmetry, which allows to apply the tensor-polynomial strength criterion. This strength criterion makes it possible to take into account the limiting mechanical characteristics of the bandage under the transverse shear deformations and transverse separation or compression at the points of the mating surfaces of the layered structure elements. The comparison of the destructive internal pressure values according to the proposed method with experimental data proves its effectiveness.

Basic material and results

The experiment presented in this article was carried out on the basis of JSC "Fiberglass pipes" in Kharkiv. As it has already been noted, the object of the research was a fragment of a seamless hot-deformed steel pipe (GOST 8731-74, GOST 8732-78) made of 09G2S steel. The main characteristics of the pipe are shown in Table 2. The flanges were welded to a 1-meter long pipe. The artificial defects were applied to the pipe's outer surface using a cutter. The internal working pressure of the pipe is assumed to be 20 MPa.

Table 2 – Geometrical and mechanical parameters of the investigated pipe

Volume, mm^3	Diameter, mm	Wall thickness, mm	Pipe length, mm	Mechanical properties	
				σ_B, MPa	σ_T, MPa
$2{,}243 \cdot 10^7$	169	5,8-6,2	1000	490	340

The pipe in question satisfies the requirements for a long shell. Therefore, the edge effects that occur in the area of flange joints, quickly decay and do not affect the stress state in the area of applied defects.

On the surface of the pipe, there are six segments of 30 mm wide undercuts and an annular 50 mm wide undercut. Residual pipe thickness in the area of the segmented and annular recesses varies from 1.6 to 3.1 mm.

The stress-strain state of the pipe was investigated in order to establish the joint operation of the pipe and the bandage at all stages of loading. To measure the relative deformations, wire strain gauges of the KF4P1-3-200 type with a base of 3mm, 5mm, and 10mm were used. The sockets consisted of two strain gauges. The average value of the tensosensitivity coefficients is $K = 2 \cdot 10^{-6}$. All strain gauges are included in the electrical measuring circuit according to the documentation for the SIIT-3 device. Deformations at the points of the pipe wall and on the surface of the repair bandage were measured in the longitudinal and annular directions. The sensor layout is shown in Fig. 1.

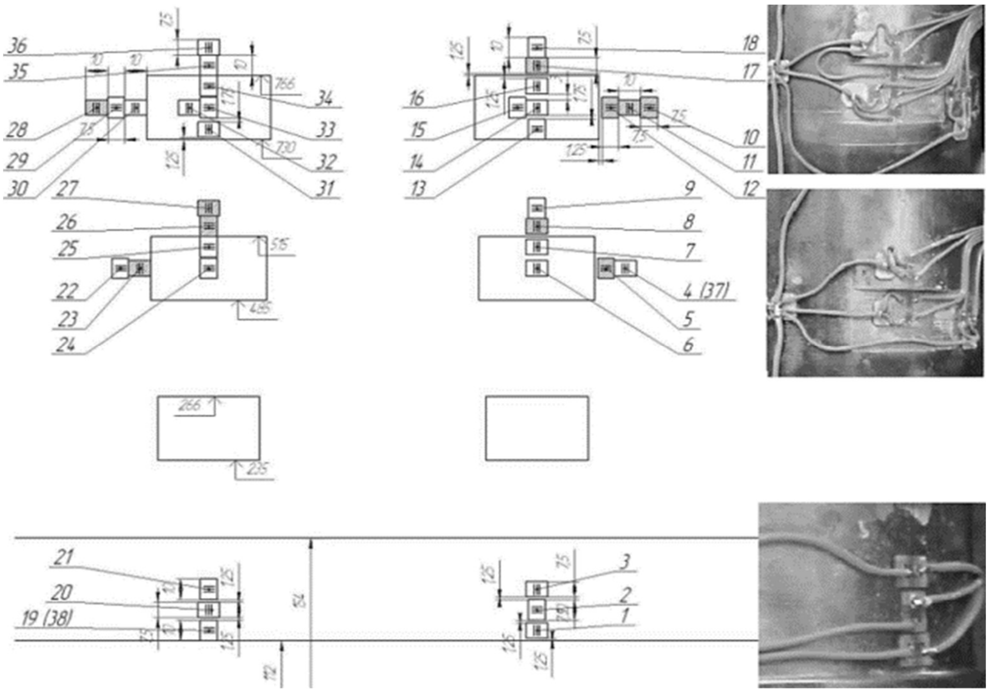

Figure 1– Layout of load cells on a steel pipe

Since the pipe wall is weakened by surface defects, during the experiment the created hydrostatic pressure was lower than the working pressure. Loading parameters were monitored with a high-precision pressure gauge.

The experiment has consisted of three stages. At the first stage, the stress-strain state of the pipe in the zones of applied defects was studied. The step of the hydrostatic pressure increase was 0.2 MPa. At the pressure of 14.6 MPa at point 33, a crack appeared in the longitudinal direction with a length of 3 mm and an opening width of 0.5 mm. With the appearance of the crack, the leak and the drop in hydrostatic pressure began. It should be noted that plastic deformations of steel in point 33 began at a pressure of 4.8 MPa, i.e. long before the onset of the destructive load.

Defective areas reinforcement at the second stage of the experiment was carried out by applying the multilayer bandage. After preparing the pipe surface by sandblasting, as well as manually grinding the surface, a fiberglass bandage was applied.

Fiberglass matrix. In this work, the fiberglass matrix is represented by an epoxy polymer 5-211B with the following elastic parameters: E_m = 3500 MPa, v_m = 0.35.

The ultimate strength of the above composition was:

σ_m^+ = 30 MPa; v_m = 0.35 – for tensile;

σ_m^- = 70 MPa; v_m = 0.35 – for compression.

Reinforcing material. The reinforcing element of the composition is a fabric of satin structure T-10-80. The fabric is obtained by the weaving of the aluminoborosilicate threads БС6-26×1×1 (E glass). The elasticity modulus of aluminoborosilicate threads E_B and Poisson's ratio v_B is: E_B = 72000MPa; v_B = 0.2.

In each reinforced layer, the volume occupied by the threads is v_B = 0.4 of the total volume.

The ultimate strength of the interweaving of aluminum-borosilicate threads BC6-26×1×1 (E - glass) while stretching is assumed to be – σ_B^+ = 1500 MPa.

The ultimate strength of the interweaving of aluminum-borosilicate threads BC6-26×1×1 (E - glass under compression is assumed to be σ_B^- = 600 MPa.

The physical and mechanical properties of the fiberglass bandage were determined according to the method described in the work [26], and are given in Table 3.

Table 3 – Physical and mechanical characteristics of the fiberglass bandage

Reinforcement scheme	E_{ij}, MPa	G_{ij}, MPa	v_{ij}	v_{ji}
$\left[(0^o/90^o)_6\,0\right]_s$	E_z=17900 E_θ=16800 E_r=8700	$G_{\theta z}$=2980 G_{rz}=2689 $G_{r\theta}$=2654	$v_{z\theta}$=0.06 v_{zr}=0.38 $v_{\theta r}$=0.38	$v_{\theta z}$=0.06 v_{rz}=0.19 $v_{r\theta}$=0.2

Note: E_z, E_θ, E_r – elastic modulus of the 1st kind in the longitudinal, circumferential, and radial directions; $G_{\theta z}$, G_{rz}, $G_{r\theta}$ – shift modules;
$v_{z\theta}$=$v_{\theta z}$, v_{zr}=v_{rz} , $v_{\theta r}$=$v_{r\theta}$ – poisson's ratios.

Thus, fiberglass is a transversely isotropic material and consists of 25 unidirectionally reinforced layers of 0.25 mm thick. The composite bandage was fitted along the entire length of the pipe and the bandage thickness was approximately 6 mm.

After polymerization of the bandage, strain gauges were glued to the outer surface of the band at the locations of pipe defects.

At the second stage, the stress-strain state of the pipe in the zones of the applied defects was investigated. The step of the hydrostatic pressure increasing was 0.2 MPa. The device of the repair bandage has allowed increasing the hydrostatic pressure to the working value, i.e. up to 20 MPa. The stress-strain state of the sample was investigated in order to establish the joint operation of the pipe and the bandage at all loading stages corresponding to the operation of the pipeline. The data obtained by the tensometric method indicate that the deformation of the bandage occurs together with the pipe.

The subject of the third stage of the experiment was a through the defect in a round tube with a diameter of 30 mm. The defect area was 730 mm^2. A repair bandage of 10 mm thick and 400 mm wide was applied to the section of the pipe with the defect. After polymerization of the band with a step load of 0.2 MPa, the strength of the pipeline - composite band system was studied in the presence of a through the defect. Already at a hydrostatic pressure of 3.5 MPa, water appeared in the contact zone of the composite bandage and the pipe and the hydrostatic pressure began to drop.

For a hydrostatic pressure of 3 MPa using the ANSYS software package for the model in Fig. 2, the isofields of the stressed state of the "pipeline - composite bandage" system were obtained.

a) b)

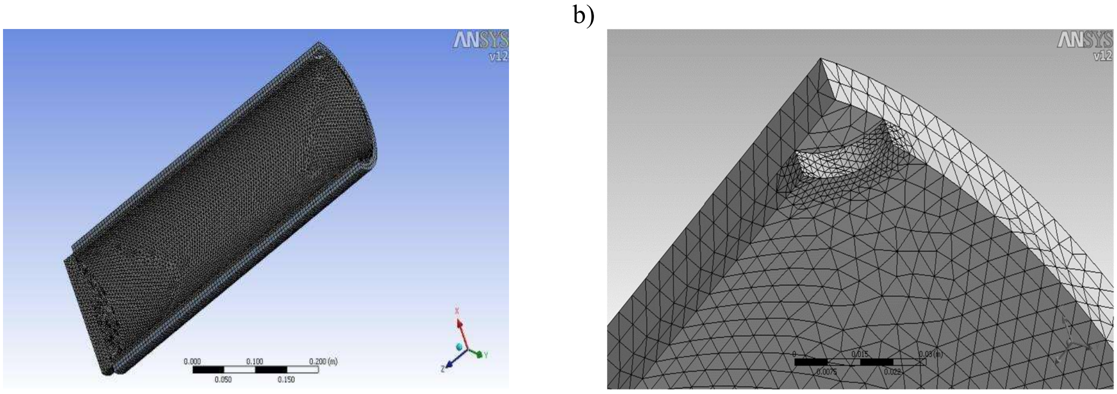

Figure 2 – Numerical model of the sample;
a - general view; b - a fragment with a defect and a repair bandage

a) b)

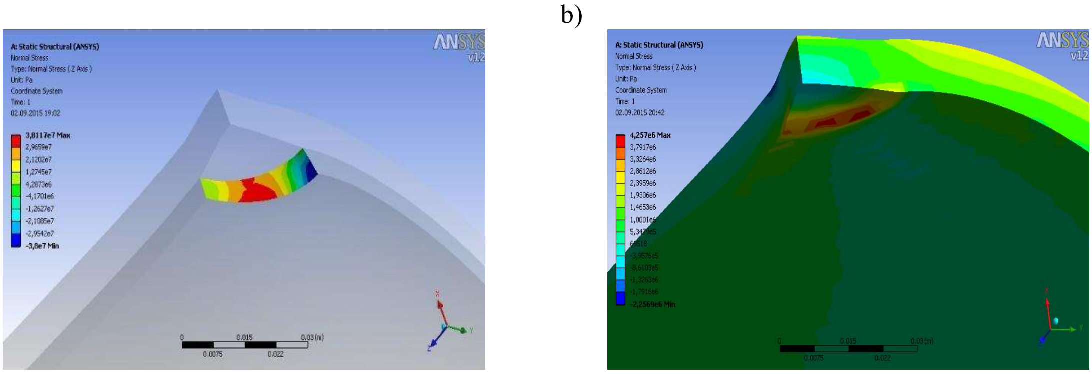

Figure 3 – Distribution of normal axial stresses σ_z:
a - on the surface of the pipe defect; b - in a bandage near the defect

a) b)

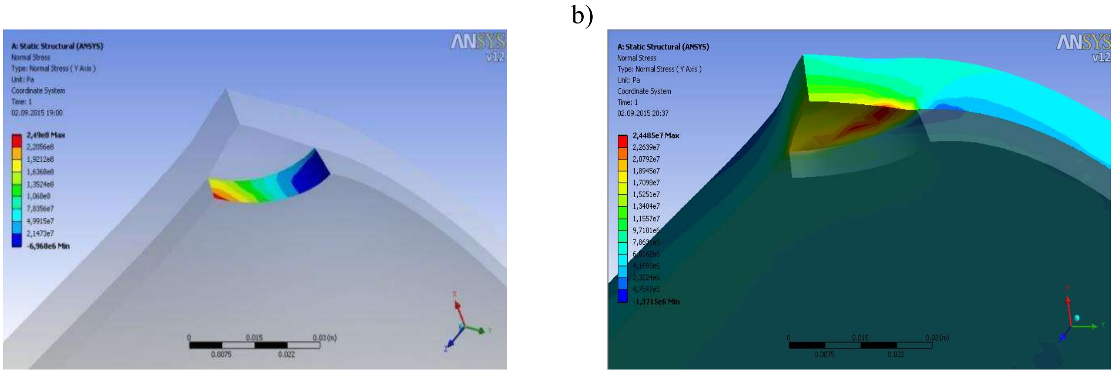

Figure 4 – Distribution of normal circumferential stresses σ_Θ:
a - on the surface of the pipe defect; b - in a bandage near the defect

a) b)

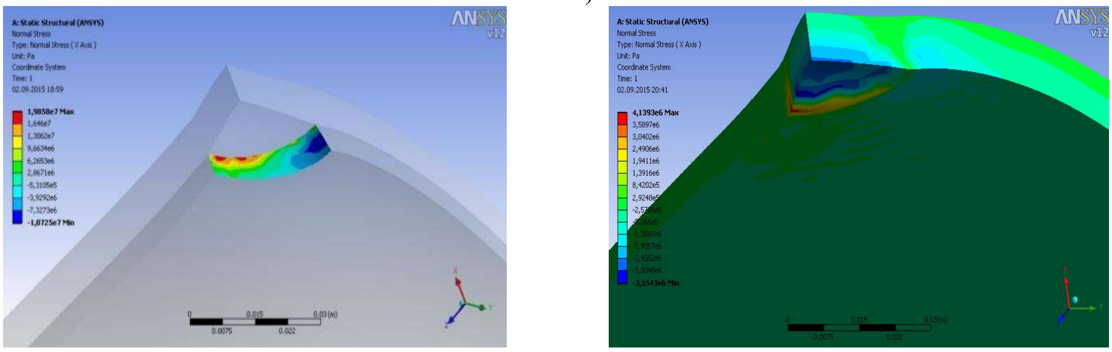

Figure 5 – Distribution of normal radial stresses σ_r:
a - on the surface of the pipe defect; b - in a bandage near the defect

a) b)

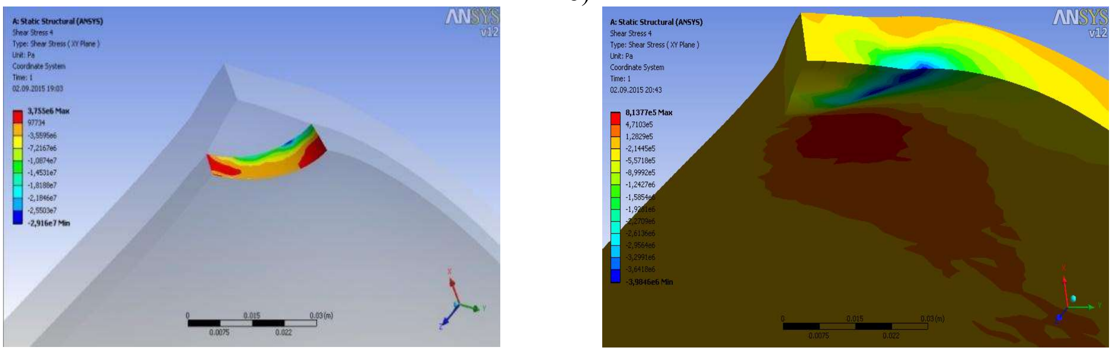

Figure 6 – Distribution of shear stresses $\tau_{r(}$:
a - over the surface of the pipe defect; b - in a bandage near the defect

a) b)

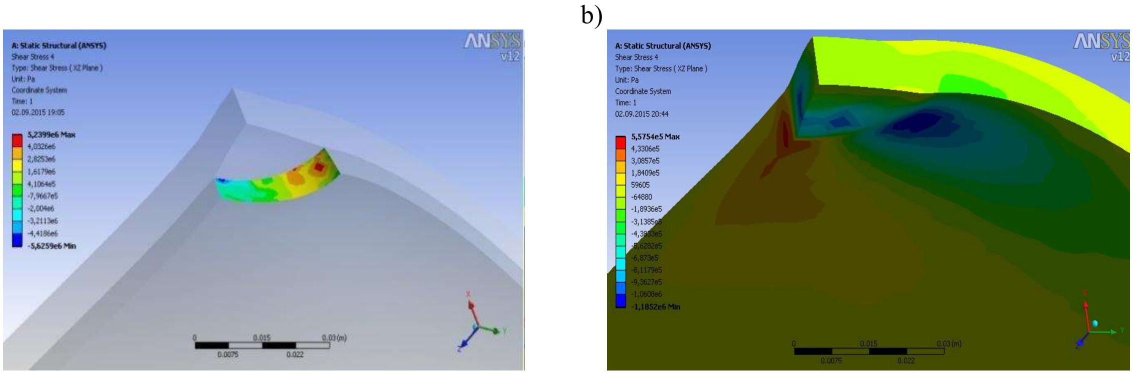

Figure 7 – Distribution of shear stresses τ_{rz}:
a - over the surface of the pipe defect; b - in a bandage near the defect

a) b)

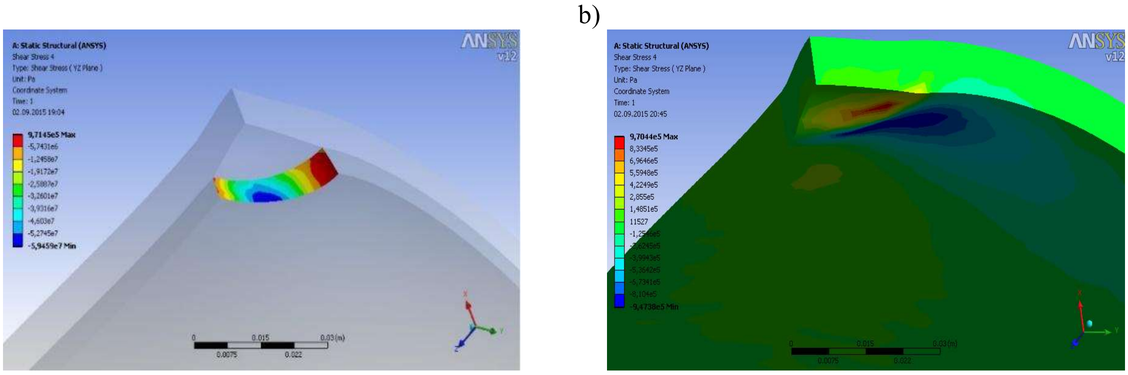

Figure 8 – Distribution of shear stresses $\tau_{z(}$:
a - over the surface of the pipe defect; b - in a bandage near the defect

The results analysis (Fig. 3-8) of the numerical experiment have shown that the maximum stresses in the composite band arise at the points of the glass-reinforced plastic-metal contact surface (adhesive layer) at the border of the through defect:

$\sigma_z = 22.0$ MPa, $\sigma_\Theta = 75.0$ MPa, $\sigma_r = 10.0$ MPa,

$\tau_{rz} = -1.0$ MPa, $\tau_{\Theta z} = -12.0$ MPa, $\tau_{rz} = -9.0$ MPa.

To assess the bearing capacity of the fiberglass shell under consideration, a modified strength criterion can be used [27], that includes transverse stresses and takes into account the effect of weakened interphase contact of layers:

$$\begin{aligned} & R_{11}\sigma_{11} + R_{22}\sigma_{22} + R_{33}\sigma_{33} + R_{1111}\sigma_{11}^2 + \\ & + R_{2222}\sigma_{22}^2 + R_{3333}\sigma_{33}^2 + 4R_{1212}\sigma_{12}^2 + \\ & + 4R_{1313}\sigma_{13}^2 + 4R_{2323}\sigma_{23}^2 + 2R_{1122}\sigma_{11}\sigma_{22} + \\ & + 2R_{1133}\sigma_{11}\sigma_{33} + 2R_{2233}\sigma_{22}\sigma_{33} = 1. \end{aligned} \tag{1}$$

The coefficients of equation (1) are determined using the established ultimate strength characteristics σ_{ij}^+, σ_{ij}^- ($i, j = 1{,}2$). Index "+" means ultimate stretching stress, index "–" in compression. For the components of tensors of the strength surface (1), in the publication [21] the following relations were proposed:

$$R_{11} = \frac{\sigma_{11}^- - \sigma_{11}^+}{\sigma_{11}^-\sigma_{11}^+}; \; R_{22} = \frac{\sigma_{22}^- - \sigma_{22}^+}{\sigma_{22}^-\sigma_{22}^+};$$

$$R_{33} = \frac{\sigma_{33}^- - \sigma_{33}^+}{\sigma_{33}^-\sigma_{33}^+}; \; R_{12} = \frac{\sigma_{12}^- - \sigma_{12}^+}{\sigma_{12}^-\sigma_{12}^+};$$

$$R_{1111} = \frac{1}{\sigma_{11}^-\sigma_{11}^+}; \; R_{2222} = \frac{1}{\sigma_{22}^-\sigma_{22}^+};$$

$$4R_{2323} = \frac{1}{\sigma_{23}^-\sigma_{23}^+}; \; R_{3333} = \frac{1}{\sigma_{33}^-\sigma_{33}^+};$$

$$4R_{1212} = \frac{1}{\sigma_{12}^-\sigma_{12}^+}; \; 4R_{1313} = \frac{1}{\sigma_{13}^-\sigma_{13}^+};$$

$$2R_{2233} = \frac{R_{22} - R_{33}}{\sigma_{23}^-} + R_{2222} + R_{3333} + \frac{1}{\left(\sigma_{23}^-\right)^2};$$

$$2R_{1122} = \frac{R_{11} - R_{22}}{\sigma_{12}^-} + R_{1111} + R_{2222} + \frac{1}{\left(\sigma_{12}^-\right)^2};$$

$$2R_{1133} = \frac{R_{11} - R_{33}}{\sigma_{13}^-} + R_{1111} + R_{3333} + \frac{1}{\left(\sigma_{13}^-\right)^2}.$$

The theoretical values of the ultimate strength of the repair band are determined on the basis of the method proposed in the work [28]. The obtained results are given in the table. 4.

Table 4 - Theoretical values of the tensile strength of the repair band

Reinforcement code	σ_i^+, MPa	τ_{ij}^+, MPa	σ_j^-, MPa	τ_{ij}^-, MPa
$\left[(0^o/90^o)_6 0\right]_S$	$\sigma_z^+ = 347\sigma_\theta^+ = 325\sigma_r^+ = 75$	$\tau_{\Theta z}^+ = 25\tau_{rz}^+ = 23\tau_{r\theta}^+ = 23$	$\sigma_z^- = 209\sigma_\theta^- = 202\sigma_r^- = 135$	$\tau_{\Theta z}^- = 60\tau_{rz}^- = 54\tau_{r\theta}^- = 53$

It should be noted that while passing to a cylindrical coordinate system, the following identities are fulfilled

$\sigma_{11} = \sigma_z$; $\sigma_{22} = \sigma_\theta$; $\sigma_{33} = \sigma_r$;

$\tau_{11} = \tau_{rz}$; $\tau_{21} = \tau_{\theta z}$; $\tau_{32} = \tau_{r\theta}$.

For a hydrostatic pressure of 3 MPa, the strength criterion (1) takes the form

$$KR = 0.931 < 1 .$$

Thus, the theoretical results indicate that the breaking hydrostatic pressure may be even lower than the experimentally obtained result $q_E^* = 3.5$ MPa.

Conclusions

Thus, as a result of the experimental and theoretical studies, the following results were obtained:

– the method for determining the destructive hydrostatic pressure of repair composite tires, created by the multilayer winding of fiberglass onto a pipe with its simultaneous impregnation at the site of the defect has been developed;

– it was determined that the elimination of pipeline defects using a composite band leads to a redistribution of the annular (circumferential) load between the pipe and the composite bandage under the further loading of the pipeline with the internal pressure;

– a particularly important factor for ensuring the possibility of loads redistribution between the pipe and the composite bandage when the pipeline is loaded with internal pressure is the creation of the reliable adhesion of the composite bandage to the pipe metal and thereby ensuring their joint deformation due to the adhesive properties of the adhesive layer;

– it seems to be a promising direction to work on the efficiency improvement of the physical and mechanical characteristics of composite bandages by using new materials and creating structures that provide greater rigidity;

– due to the effective implementation of composite bandages, the determination of real physical and mechanical characteristics, it is possible to achieve partial or complete restoration of the bearing capacity of the corrosive section of the pipeline, and, although the steel is still subjected to plastic deformation, its degree is limited by an external bandage made of composite material, which ensures the safety of the pipeline at the maximum permissible operating pressure.

References

1. Пічугін С.Ф., Пашинський В.А., Зима О.Є., Винников П.Ю., Біла Ж.Ю. (2018). *Надійність лінійних частин магістральних трубопроводів*. Полтава: Астрая

2. Поляков С.Г., Рибаков А.О. (2009). Основні закономірності стрес-корозійного розтріскування магістральних газопроводів. *Проблемы прочности*, 5, 7-17

3. Вовк О.О., Зайченко С.В., Чвертко Є.П., Шевченко М.В., Пірумов А.Є., Радецька О.Й. (2017). Аналіз аварій на магістральних трубопроводах за період 2005-2015 рр. *Енергетика: економіка, технології, екологія*, 4, 113-118

4. Побережний Л.Я., Яворський А.В., Цих В.С., Станецький А.І., Гриданчук А.В. (2017). Підвищення рівня екологічної безпеки трубопровідних мереж нафтогазового комплексу України. *Техногенно-екологічна безпека*, 1, 24-31

5. План розвитку ТОВ "Оператор ГТС України" 2021-2030 [Електронний ресурс]. Режим доступу: https://tsoua.com

6. Freire J.L.F., Vieira R.D., Diniz J.L.C., Meniconi L.C. (2007). Effectiveness of composite repairs applied to damaged pipeline. *Exp. Tech. Soc. Exp. Mech.*, 31, 59-66

7. Mattos H., Reis J., Sampaio R., Perrut V. (2009). An alternative methodology to repair localized corrosion damage in metallic pipelines with epoxy resins. *Mater. Des*, 30, 3581-3591

8. Leong A., Leong K., Tan Y., Liew P., Wood C., Tian W., et al. (2011). Overwrap composite repairs of offshore risers at topside and splash zone. *Proc. Int. Comm. on Composite Materials (ICCM-18)*. Jeju Island, Korea Int. Comm. on Composite Materials

9. Duell J.M., Wilson J.M., Kessler M.R. (2008). Analysis of a carbon composite overwrap pipeline repair system. *Int. J. Pressure Vessels and Piping*, 85., 782-788

10. Нуржанов Т.Б. (2018). Ремонт трубопроводов и резервуаров с применением композитных материалов. *Инженерная практика*, 5, 36-39

11. Alexander C., Francini B. (2006). State of the art assessment of composite systems used to repair transmission pipe lines. *6th Intern. Pipeline Conf. (IPC-2006)*. Calgary, Alberta, Canada

12. Бандажная система RES-Q Composite Wrap. Режим доступу: http://www.tdwilliamson.com

13. ASME B 31.4, ASME B 31.8. Classes of ASME Boiler and Pressure vessel Code

14. ASME PCC-2-2006. The American Society of Mechanical Engineers. Repair of Pressure Equipment and Piping

15. ASTM D2992-2006. (2006). Standard practice for obtaining hydrostatic orpressure design basis for «fiberglass» (glass-fibre-reinforced thermosettingresin) pipe and fittings

16. ISO/TS 24817 (2006). Petroleum, petrochemical and natural gas industries – composite repairsof pipework – qualification and design, installation, testing and inspection

17. *The Clock Spring Company* (2011). Режим доступу: http://www.clockspring.com

18. Беккер М.В., Бут В.С., Говдяк Р. М. та ін. (2008). *Ремонт магістральних трубопроводів під тиском*. Київ: Кий

19. Shamsuddoha M., Mainul Islam, Aravinthan T., Manalo Allan, Lau Kin-tak (2013). Effectiveness of using fibre-reinforced polymer composites for underwater steel pipeline repairs. *Composite Structures*, 100, 40-54

20. Showman A., Taheri F. (2011). Compressive strain limits of composite repaired pipelines under combined loading states. *Composite Structures*, 93, 1538-1548

1. Pichugin S.F., Pashinsky V.A., Zyma O.E., Vinnikov P.Yu., Bila J.Yu. (2018). *Requirement of the line parts of the main pipelines.* Poltava: Astraya

2. Polyakov S.G., Ribakov A.O. (2009). Basic laws of stress-corrosion development of main gas pipelines. *Problems of Strength*, 5, 7-17

3. Vovk O.O., Zaichenko S.V., Chvertko E.P., Shevchenko M.V., Pirumov A.Ye., Radetska O.J. (2017). Analysis of accidents on main pipelines for the period 2005-2015. *Energy: economy, technology, ecology*, 4, 113-118

4. Poberezhny L.Ya., Yavorskiy A.V., Tsikh V.S., Stanetsky A.I., Gritsanchuk A.V.(2017). Development of the level of ecological safety of pipelines for the oil and gas complex of Ukraine. *Technogenic and ecological safety*, 1, 24-31

5. Development plan of JSC "Operator GTS Ukraine" 2021-2030 [Electronic resource]. Retrieved from: https://tsoua.com

6. Freire J.L.F., Vieira R.D., Diniz J.L.C., Meniconi L.C. (2007). Effectiveness of composite repairs applied to damaged pipeline. *Exp. Tech. Soc. Exp. Mech.*, 31, 59-66

7. Mattos H., Reis J., Sampaio R., Perrut V. (2009). An alternative methodology to repair localized corrosion damage in metallic pipelines with epoxy resins. *Mater. Des*, 30, 3581-3591

8. Leong A., Leong K., Tan Y., Liew P., Wood C., Tian W., et al. (2011). Overwrap composite repairs of offshore risers at topside and splash zone. *Proc. Int. Comm. on Composite Materials (ICCM-18)*. Jeju Island, Korea Int. Comm. on Composite Materials

9. Duell J.M., Wilson J.M., Kessler M.R. (2008). Analysis of a carbon composite overwrap pipeline repair system. *Int. J. Pressure Vessels and Piping*, 85., 782-788

10. Nurzhanov T.B. (2018). Repair of pipelines and tanks using composite materials. *Engineering practice*, 36-39

11. Alexander C., Francini B. (2006). State of the art assessment of composite systems used to repair transmission pipe lines. *6th Intern. Pipeline Conf. (IPC-2006)*. Calgary, Alberta, Canada

12. Bandage system RES-Q Composite Wrap. Retrieved from:

13. ASME B 31.4, ASME B 31.8. Classes of ASME Boiler and Pressure vessel Code

14. ASME PCC-2-2006. The American Society of Mechanical Engineers. Repair of Pressure Equipment and Piping

15. ASTM D2992-2006. (2006). Standard practice for obtaining hydrostatic orpressure design basis for «fiberglass» (glass-fibre-reinforced thermosettingresin) pipe and fittings

16. ISO/TS 24817 (2006). Petroleum, petrochemical and natural gas industries – composite repairsof pipework – qualification and design, installation, testing and inspection

17. *The Clock Spring Company* (2011). Режим доступу: http://www.clockspring.com

18. Becker M.V., Booth V.S., Govdyak R. M. (2008). *Repair of main pipelines in a vice.* Kyiv: Kiy

19. Shamsuddoha M., Mainul Islam, Aravinthan T., Manalo Allan, Lau Kin-tak (2013). Effectiveness of using fibre-reinforced polymer composites for underwater steel pipeline repairs. *Composite Structures*, 100, 40-54

20. Showman A., Taheri F. (2011). Compressive strain limits of composite repaired pipelines under combined loading states. *Composite Structures*, 93, 1538-1548

21. Keller M.W., Jellison B.D., Ellison T. (2013). Moisture effects on the thermal and creep performance of carbon fiber/epoxy composites for structural pipeline repair. *Composites: Part B*, 45(1), 1173-1180

22. Kopple M.F., Lauterbach S., Wagner W. (2013). Composite repair of through-wall defects in pipework – analytical and numerical models with respect to ISO/TS24817. *Composite Structures*, 95, 173-178

23. Гарф Э.Ф., Нетребский М.А. (2000). Оценка прочности и ресурса трубопроводов с эрозионно-коррозионными повреждениями. *Автоматическая сварка*, 9/10, 15-20

24. Гарф Э.Ф., Нехотящий В.А., Дмитриенко Р.И., Банахевич Ю.В., Савенко А.В., Олейник И.Н. (2011). Оценка эффективности композитных бандажей для восстановления дефектных участков трубопроводов. *Автоматическая сварка*, 7, 44-48

25. Vereshchaka S.M., Daniltsev V.V., Deineka A.V. (2016). Stress State of Sealing Ring of Composite Material with the Specified Physical and Mechanical Characteristics. *Strength of Materials*, 48(3), 371-374

26. Верещака С.М. (2009). *Нелинейное деформирование и устойчивость многослойных элементов конструкций с дефектами структуры*. Сумы: Изд-во СумГУ

27. Верещака С.М., Жигилий Д.А., Данильцев В.В. (2019). Определение прочности кольцевых образцов из стеклопластика на основе метода разрезного диска. *Вестник машиностроения*, 12, 25-33

21. Keller M.W., Jellison B.D., Ellison T. (2013). Moisture effects on the thermal and creep performance of carbon fiber/epoxy composites for structural pipeline repair. *Composites: Part B*, 45(1), 1173-1180

22. Kopple M.F., Lauterbach S., Wagner W. (2013). Composite repair of through-wall defects in pipework – analytical and numerical models with respect to ISO/TS24817. *Composite Structures*, 95, 173-178

23. Garf E.F., Netrebskiy M.A. (2000). Estimation of strength and resource of pipelines with erosion-corrosion damage, *Automatic welding*, 9/10, 15-20

24. Garf E.F., Nepomnyaschiy V.A., Dmitrienko R.I., Ba-nakhevich Yu.V., Savenko A.V., Oleinik I.N. (2011). Evaluation of the effectiveness of composite bandages for the restoration of defective sections of pipelines, *Automatic welding*, 7, 44-48

25. Vereshchaka S.M., Daniltsev V.V., Deineka A.V. (2016). Stress State of Sealing Ring of Composite Material with the Specified Physical and Mechanical Characteristics. *Strength of Materials*, 48(3), 371-374

26. Vereshchaka S.M. (2009). *Nonlinear deformation and stability of multilayer structural elements with structural defects*. Sumy: Publishing house of SSU

27. Vereshchaka S.M., Zhigiliy D.A., Daniltsev V.V. (2019). Determination of the Strength of Ring Specimens from Fiberglass Based on the Split Disk Method. *Bulletin of mechanical engineering*, 12, 25-33