Innovative Solutions in Repair of Gas and Oil Pipelines

Edited by
Prof. Dr. Sc. Evgeny Barkanov
Prof. Dr. Sc. Mitko Mihovski
Assoc. Prof. Dr. Sc. Vladimir Sergienko

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The present book considers the reasons of decreasing maintainability of the oil and gas pipelines. The mechanisms of generation and the features of local corrosive and mechanical damages of the pipes are analyzed. A variety of known in the art methods of internal and surface diagnostics are reviewed. Application of highly promising techniques of the low frequency range directional waves and the broadband laser-induced ultrasound are discussed. Special attention is paid to the numerical estimation of the reliability, safety and residual life of the pipelines. Recently published papers with the investigation results of new polymers and advanced technologies for the pipe repair are summarized. The composites with improved mechanical strength, adhesion to steel, chemical and corrosive resistance are suggested. The book is recommended for the researchers, service engineers and specialists in this sphere.

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### CHAPTER XXI

**Optimal design of pipeline with volumetric surface defect**

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The pipeline transportation of oil and gas is of great economic significance for both sides of the process — those who export and the countries consuming the hydrocarbon raw materials. Oil and gas transportation by the pipelines was considered for a long time to be a fully safe procedure. Nevertheless, with prolongation of the pipeline service life and raising quality of their diagnostics, the amount of damages of the pipes was found to augment noticeably, especially due to corrosion processes. So, corrosion, to a lesser or greater extent, turns to be the main cause or an accompanying factor of all emergency failures of the pipelines.

This book presents a collection of topically linked articles reflecting the search for the causes that are worsening the performances, and the novel methods intended to ameliorate durability of the oil and gas pipelines. The urgency of investigations in this field for the countries with a highly developed pipeline system of the oil and gas transportation is connected with the necessity to keep the pipelines in a stable operation condition and to eliminate ecological risks caused by emergency situations leading to contamination of the environment.

In conditions of a long-term service, the local damaging of the pipes may go hand in hand with the total impairment of strength and reliability of the pipes. In this connection, the problems of damage diagnostics and serviceability prediction of the damaged pipes, as well as their repair without stoppage are becoming highly actual today. The authors have analyzed the methods of the internal and external diagnostics of the pipe damages. Along with this, the probability of revealing damages of the pipes is discussed depending on the engineering facilities employed and physical principles laid in the base of the diagnostic procedures. Special attention is paid to detection of the volumetric longitudinal surface defects and improvement of monitoring sensitivity.

A modern method for determining volumetric surface defects has gained popularity lately that is based on the use of the low-frequency guide waves. This method makes possible to improve the resolving power of the diagnostic equipment, to raise the efficiency of measurements and to exclude the necessity to remove large portions of the insulation and anticorrosion protective coats. The use of the laser-induced ultrasound and possibilities of its technical realization in diagnostics of the small-size defects of the pipes are discussed.

The damaged areas of the pipelines detected by the diagnostic instruments should be reinforced and repaired. The choice of the repair methods depends on the
condition of the pipeline and must be substantiated by the diagnostic data. It should be noted that the composite materials are the ones that are most intensively used at present for healing local damages on the oil and gas pipelines. The repair using the composite materials has been regulated in a number of international standards. However, there still remain some unsolved problems of the materials science character that are connected, first of all, with improvement of strength of the used composites, reduction of their ageing rate under various outer effects and atmospheric conditions, perfecting adhesion of the composites to the pipe metal, raising resistance to the cycling pulse loads, sign-varying temperatures, and so on.

The book also treats some solutions of above-mentioned problems. In particular, the authors touch upon application of the nanosize additives aimed at improving physicomechanical properties of the composites; elaboration of the new elastic materials for the sublayer able to hamper the sublayer corrosion intensity and having strong adhesion to both ferrous metal and the repair composite; use of the novel reinforcing components for the polymeric matrix, e.g., metal fibers, mesh structures and other. The main accent is put on the composite materials for repair of the external damages of the pipelines.

Elaboration of the efficient methods used to predict reliability, safety and residual life of the pipes presumes the account of degradation of the pipe steel properties during operation; accumulation of irreversible fatigue damages due to a cyclic loading; shape, size and the character of the defects induced by the corrosive and mechanical damaging. It seems improbable to take into account the whole set of named factors in the known methods based on solution of the classical analytic equations of the theory of strength. Therefore, the forecasting problems are solved in the present book proceeding from the numerical means enabling to allow for the nonlinearity of physicomechanical properties of the materials, pipe design, geometry of the defects, variations of stresses in the material induced by different environmental effects, and etc.

The investigation results considered in this book are targeted to the decision of interrelated problems of the diagnostics, repair and forecasting, to promote effective solutions of the tasks concerning improvement of reliability and endurance of the existing pipeline systems.

Academician of the National Academy
of Sciences of Belarus,
Professor

Myshkin N.K.
Piezoelectric transducers for detection of laser-induced ultrasound

Kozhushko¹ V.V., Sergienko¹ V.P., Tuleika¹ A.S., Mirchev² Y.N., Mihovski² M.M.

¹V.A. Belyi Metal Polymer Research Institute of National Academy of Sciences of Belarus, Gomel, BELARUS, kozhushko@laser-ultrasound.com
²Institute of Mechanics, National Academy of Science, Sophia, BULGARIA, nntdd@abv.bg

Summary: The immersion technique and laser-induced ultrasonic pulses of longitudinal waves are suggested for the evaluation of mechanical properties of metals and composites. The laser radiation of 10 ns pulse illuminates the surface of the specimen placed in the water. The beam spot of about 6 mm diameter launches longitudinal pulses, which can be detected by broadband transducers based on 25 μm polymer piezoelectric film. The features of possible preamplifier’s circuits are considered for time-resolved measurements of the primary pulse and the following reverberations.

Keywords: laser ultrasound, coil sensor, piezoelectric film, PVDF, PZT

1.1. INTRODUCTION

The estimation of the elastic constants of composites and metals is important for prediction of their response to the load. In general, elastic properties are frequency dependent and can be evaluated by different techniques as, for instance, dynamical mechanical analysis, which confines the range from 0.01 Hz up 200 Hz by measurement of stress-strain dependencies. The estimation of elastic properties in a mega Hertz range
usually employs conventional ultrasonic pulse-echo methods, which measure velocity and attenuation via time-resolved detection of sequences of the pulses [1]. The small size of the samples and/or strong attenuation of the ultrasound are the main obstacles for direct application of conventional ultrasonic methods, which require mechanical contact for delivering and detection of the probe elastic pulses. The excitation of the pulses with short-time transient profile is a challenge for conventional methods. Laser-induced ultrasound has been developed for numerous applications due to its capacity of non-contact excitation of ultrasonic pulses [2, 3].

The spot of the laser radiation on the absorbing material defines the efficiency of excitation of different elastic modes such as longitudinal, shear and surface acoustic waves. Obviously, the pulses of all these modes take place while the focusing of the laser radiation in line segment increases the efficiency of excitation of the surface acoustic waves which run along the specimen interface [4, 5]. The excitation of longitudinal pulses by wide laser spot in the plate is the simplest case, which can be considered in one-dimensional approach for evaluation of elastic modulus of primary wave. The probe pulse arrives to the opposite side of the plate and can be detected by variety of methods, which demonstrate some advantages and disadvantages [6, 7]. The following echoes of the primary pulse can be detected for the estimation of velocity and attenuation of the longitudinal waves in broadband. The spectra of sequences of the pulses are getting narrower during the propagation these changes contain the information about microstructure and inhomogeneities such as, for instance, length of dislocations, their density and mean values grain size in metals.

The proper detection of the broadband pulses propagating in the specimens is the crucial task for the evaluation and nondestructive testing. Contact free detection is very attractive for industrial applications. All-optical solution allows diagnostics of graphite fiber-reinforced epoxy composite materials by laser-based interferometer, which is sensitive to the displacement of the specimen surface [8].
Despite the essentially broadband spectrum of initially induced ultrasonic pulses, the detection of the high frequencies above 20 MHz is challenge for practical realization. The reasons are strong scattering of mainly high frequency part of the pulse spectrum that occurs at the interfaces between fibers and epoxy matrix in composites due to the large difference of elastic modulus. The scattering also happens at the grain boundaries of randomly oriented anisotropic crystallites in metals, where anisotropy of elastic modulus, a texture and a mean value of the grain size determine the loss of frequencies with distance. The scattering leads to the transfer of the elastic energy of initially longitudinal pulse to the shear and longitudinal waves deviated from the straightforward direction in case of plate [9]. The amplitude of the primary pulse decreases with distance, and The scattered elastic waves spreading in different directions in the bulk disturb the whole medium. Laser-induced longitudinal pulse propagates perpendicular to the surface in the case of the plate. Obviously, the directed forward part of the primary pulse arrives faster while the scattered waves delay because of the deviation [10]. The potential of the optical methods is evident in detection of the broadband pulses. The feature of the optical detection is relatively high sensitivity to the scattered field due to the small area of the detection laser spot in comparison with the piezoelectric sensors, which average the signal induced by conserved part of the probe pulse over at least 1000 times larger area. Thus, the application of the piezoelectric transducers for the measurements of laser-induced pulses is reasonable for the solution of the tasks of elastic properties evaluation in the laboratory. This paper considers two possible modes and corresponding circuits of preamplifiers employed for broadband transducers based on polarized polyvinylidenefluoride (PVDF) film with piezoelectric properties.

1.2. OPTOACOUSTIC CONVERSION

The excitation of the elastic pulse is based on the conversion of the laser radiation to heat sources and fast thermoelastic response of the
absorbing medium. The experimental arrangement considers efficient excitation of longitudinal ultrasonic pulses by wide laser spot illuminating the surface of the specimen that satisfies the conditions of one-dimensional approach. A pumping pulse of neodymium-doped yttrium aluminium garnet (Nd:YAG) laser with \( \sim 10 \) ns duration, 1064 nm wavelength and a pulse energy below 10 mJ illuminates the water-specimen interface. The laser spot diameter is about 6 mm and the maximum of the laser power density is \(<10 \text{ MW/cm}^2\). The absorbed part of laser radiation produces heat sources at the interface. The laser pulse duration \( \tau \) of 10 ns restricts the heat diffusion length to \( \sqrt{\chi \tau} \), where \( \chi \) is thermal diffusivity. The typical heat penetration depth is less than 0.5 \( \mu \text{m} \) into metals, but it is only \( \sim 0.02 \mu \text{m} \) into water [11]. The diffusion of the heat locally increases the temperature of the materials whereas the thermal expansion launches the pressure pulses traveling in the opposite directions. As the coefficient of thermal expansion of water is about one order of the magnitude higher in comparison with metals the contribution of the water is dominating that yields the efficiency of the conversion of about 1 Pa/(W/cm\(^2\)). Thus, water layer increases the efficiency of the conversion and it should be thick enough to delay the reflection of the pulse initially propagating outward the sensor from the water-air interface. The transient form of the induced pressure pulse approximates the envelope of the laser pulse intensity that yields smooth profile and nanosecond duration. The polished metal surfaces reflect significant part of the laser radiation that reduces the efficiency of conversion, while the threshold intensity for laser ablation of metals is about 20 MW/cm\(^2\). To increase the efficiency of the conversion the specimen can be covered by thin layer of black acrylic paint.

The mentioned conversion coefficient and power density allow launching of pulses with the pronounced compression phase of nanosecond duration and the amplitude about 20 MPa. The profile and the spectrum of the pulse change with the distance because of the diffraction,
scattering and attenuation. The scattering and attenuation strongly depend on the microstructure of the metals that can be used for the evaluation of the elastic properties. The decreasing of the mean value of the grain size reduces the scattering [9]. The attenuation of the ultrasound implies conversion of the elastic energy of mechanical motion to the heat that is mainly connected with dislocations in crystallites. The discrimination of the losses is practically very cumbersome task since the mean value of the grain size also influence to the length of dislocations' loop and, therefore, their distribution and arrangement in cells. Moreover, nanosecond disturbance of the metals induce interaction between dislocations. These processes are insufficiently known because of the lack of experimental results and complexity of the modeling.

1.3. DETECTION OF PROBE PULSE

The requirements to the detection system comprises of sensitivity, spatial and temporal resolution, which relates to the bandwidth. The laser based detection methods are usually used to satisfy non-contact approach and the range up to 100 MHz that shows the lateral spatial resolution about 100 µm that is defined by the area of the detection spot. Some schemes, as for instance, with photorefractive crystals are capable measure elastic pulses from the rough metal surface [12]. The finite size of the sensor leads to the situation when the contribution of scattered ultrasonic signal is comparable with the primary pulse signal. The way-out implies increasing the area of the sensor, which magnifies the contribution of primary ultrasonic pulse.

Very promising non-contact technique relates to the electro-magnetic acoustic transducers (EMATs), which can induce acoustic pulses and detect the variable electromagnetic field near the surface of metals biased by permanent magnetic field [13]. The sensitive element of EMATs is a coil with required number of winding that is rather simple and cost-effective solution. EMATs fit for conductive and/or magnetic materials
Chapter I

where the transient electromagnetic field occurs due to the eddy currents and/or forces on the magnetization vector whereas the contribution of magnetostriction is dominant in the case of ferrous materials. The combination with laser-induced ultrasound significantly extends bandwidth. As an example, the frequencies up to 200 MHz were measured in 0.4 mm thick steel by pancake coil of 5 mm diameter [7]. The variety of experimental arrangements and coils allows detection of surface and bulk acoustic pulses. The amplitude of the EMAT's signal decreases with the air gap between coil and sample hence the determination of the absolute value of the pressure pulse amplitude is nearly impossible.

The sensitivity of any transducer correlates with the noise equivalent power (NEP), which defines the minimum of detectable amplitude. NEP increases proportionally to the square root of the frequency bandwidth that includes also the noise of the preamplifier, which depends on the circuit and can be cumbersome task, which is out of the aim of this paper.

The low frequency part of pulse spectrum decreases due to the diffraction. The influence of diffraction can be estimated by the expression:

$$D = \frac{x\lambda}{a^2}$$  \hspace{1cm} (1)

where $x$ is a distance from the source, $\lambda$ is the wavelength of ultrasound, $a$ is the diameter of the laser spot. The influence of diffraction is negligible when $D < 1$. The typical size of the laser spot is 6 mm, the specimen thickness is usually more than 1 mm that provides time-resolved detection of the primary pulse and its following reverberations. The value of the velocity varies from 3 km/s up 6 km/s in plastics and metals, respectively. The diffraction diminishes the low frequency part of the spectrum that changes the transient profile of the pressure pulse, which gets the rare phase after pronounced compression peak. To summarize the detection of the frequencies $< 1$ MHz is challenging for any technique if high spatial and temporal resolution required.
1.4. PIEZOELECTRIC SENSORS

The direct piezoelectric effect implies appearance of electrical polarization due to induced charges on the electrodes of the opposite faces of the sensor. Brothers Curie discovered primarily the effect in 1880 and it is inherent for crystals without centre of symmetry. The direct and inverse piezoelectric effects are employed in numerous applications among them are detection and excitation of acoustic waves. The quartz was the first crystal used in acoustical physics. The relatively low efficiency of electromechanical coupling in quartz encouraged the search and development of synthetic piezoelectric materials such as lead zirconate titanate also known as PZT, which is relatively cheap material with high dielectric permittivity. Nowadays the variety of PZT ceramics is used. Piezoelectric properties of polymer PVDF films were found in the 1970th. As the task of excitation is carried out by optoacoustic conversion only detection has to be solved that certainly simplifies the solution.

The voltage $g_{33}$ and charge $d_{33}$ constants describe piezoelectric properties, they are connected as $g_{33} = d_{33} / \varepsilon$, where $\varepsilon$ is dielectric permittivity, which value depends on the frequency. Ceramics demonstrates large piezoelectric charge constant $d_{33} \approx 1000 \text{ pC/N}$ and lower voltage constant $g_{33} \approx 0.02 \text{ Vm/N}$ while PVDF possesses lower $d_{33} \approx 20 \text{ pC/N}$ and higher $g_{33} \approx 0.2 \text{ Vm/N}$. The ratio of the velocity to the thickness of the sensor defines the resonance frequencies and operational bandwidth of the sensors. The velocity of longitudinal waves is about 3 km/s and 2.4 km/s in PZT and PVDF, respectively. The minimal thickness of PZT ceramics is about 0.2 mm that gives the first thickness resonance at about 6 MHz while commercially available PVDF film is 9 μm thick and it can be used for detection of the frequencies up to 250 MHz Evidently, the laser-induced pulses comprise of the frequencies above the first resonance in the case of PZT sensors that involves a 'ring' of the signal due to the reverberation, which can overlap with the other signals. The acoustical
impedance of the material is very important characteristic for designing of transducers since the use of the backing material decreases the reverberations. The acoustical impedance of PVDF is $2.5 \times 10^6$ Mrayl that is close to the impedance of water $1.5 \times 10^6$ Mrayl. The polymer materials, such as polycarbonate or polymethylacrylate (PMMA), can easily damp PVDF films. The wedge or concave surfaces of backing decrease and delay the reflection that excludes the echo-signal involved by reflection of the probe pulse from the air-backing interface. The damping of PZT ceramics is cumbersome task. Thanks to the flexibility PVDF film can be placed to the cylindrical surface for localization of spatial sensitivity [14]. The combination with the laser-induced ultrasonic pulses simplifies the task of practical application since transducers only detect ultrasound.

The piezoelectric sensors based on 25 µm thick polarized PVDF foil were used for evaluation of metals in our previous publications [15, 16]. A disk of 2 mm diameter of metalized PVDF film was glued on a backing of PMMA and covered by protecting aluminium film. The capacity of the sensor with the area about 3.2 mm$^2$ is 12 pF. In contrast to PZT sensors, which produce enough charge and can be directly connected with low impedance load by short cable without preamplifiers. In the case of film sensors the close integration with preamplifier is very important for successive detection and passing of the whole pulse spectrum to an oscilloscope or analogue to digital converter. It is noteworthy that any piezoelectric sensor can be considered as high impedance source, but in order to provide detection of high frequencies the resistor of low nominal should be placed in parallel. In considered scheme one electrode of the film sensor is connected to the electrical ground, the wire from the second electrode is bound with the non-inverting input of the operational amplifier.

The electrical impedance of the piezoelectric sensor can be written in the following form:
where \( i \) is an imaginary unit, \( \omega = 2\pi f \) is a cyclic frequency, \( R \) is the value of the resistor which is parallel to the sensor with capacity \( C_s \). Thus, the electrical impedance of the sensor has active and reactive parts, which are frequency dependent. The time constant is \( T = 2\pi RC_s \).

There are two established approaches for the sensors the first scheme is 'short circuit' mode, where the low impedance resistor of 50 Ohms is in parallel to the capacitance of the sensor and condition \( R < 1/\omega C_s \) is fulfilled. The 'short circuit' mode allows detection of high frequency part of the induced pulse spectrum while 'voltage' mode is working in the narrower band because of the slower charge flow. The high frequency limit of the operating bandwidth should satisfy the condition \( f < 1/T \) in the 'short circuits'. A calculated time constant of \( \sim 3.8 \) ns allows the detection of the frequencies up to 200 MHz. The voltage drop across the resistor according to the Ohm's law is as:

\[
\frac{dq(t)}{dt} = \frac{U}{R}
\]

(3)

The displaced charge is proportional to the instantaneous mean stress inside the foil that can be written as follows [17]:

\[
q(t) = A d_{33} \int_{0}^{h} p(x, t) dx,
\]

(4)

where \( d_{33} \) is the piezoelectric charge constant, \( A \) is the area of the sensor, \( h \) is the thickness of the foil, \( p(x, t) \) is the pressure field including counter propagating waves reflected by backing material. This pressure field depends on the thickness of the covering protective foil and the acoustical impedances of all materials.
**Fig. 1** Preamplifiers’ circuits, (a) relates to the 'short circuits' and (b) corresponds to 'voltage' detection modes

The calculation of the voltage yields the following expression:

\[
U(t) = R \frac{dq}{dt} = R \frac{d_{33}A h}{h} \int_0^t \frac{d}{dt} P(x, t) \, dx. \tag{5}
\]

The expression shows that the voltage drop signal is proportional to the area of the sensor that is true if the pressure pulse with the plane wavefront covers the larger area of piezoelectric foil then the stronger current flows through the resistor. The proportionality to the value of the resistor increases the sensitivity with the decreasing of the bandwidth. It is noteworthy that measured signal is proportional to the derivative of the pressure field over time that highlights the inefficiency of the 'short circuit' mode for the measurement of the slow variations or the signals composed by low frequencies.

The foil’s thickness defines the sensitivity within the frequency range. The estimation of the spectral sensitivity of the transducer construction can be carried out in the frequency domain by numerical solution of the task of ultrasonic field distribution, which includes counter propagating waves in covering layer of aluminium foil and PVDF film while the thickness of the glue layers is disregarded. The estimated frequency range relates to the thickness resonances of the piezoelectric film. The mean
value of the stress and the sensitivity drop down if the whole number of wavelength equal to the film thickness. The local maximum of the sensitivity is about 50 MHz, which wavelength in piezoelectric foil is equal to its double thickness, while the first local minimum of the sensitivity is about 100 MHz, please, see for details measured spectra [15]. The Fourier transformation for the both parts of eq. (5) turns the expression into frequency domain where a time derivative is a product to $i\omega$.

![Fig. 2 Printed circuit board of the preamplifier](image1.jpg) ![Fig. 3 Picture of the assembled transducer](image2.jpg)

The high-speed operational amplifiers with a gain bandwidth product 1.5 GHz as, for example, LMH6624, allows amplification up to 20 dB in the range 150 MHz. The operational amplifiers in SOIC case and SMD components are on the printed circuit board with the area of 25x20 mm$^2$ that was produced from single side coated copper paper-based laminate, please, see Fig. 2. The circuits should include tantalum capacitors from 4.7 up to 6.8 μF and decoupling SMD ceramic capacitors of 100 nF with short traces to the power supply pins. The noise figures of non-inverting amplifier presented in the Fig. 1a. can be found in the literature.
It was mentioned that the detection of frequencies >15 MHz in composites can be difficult, while the low frequency range is limited by diffraction. The high impedance resistor placed in parallel to the capacitor of the sensor increases the sensitivity in the low frequency range and omits the high frequencies. The simplest and limit case of infinite impedance of sensor leads to the following expression:

\[
U(t) = \frac{q(t)}{C_s} = g_{33} \int_0^h P(x, t) \, dx
\]  \hspace{1cm} (6)

As the charge and capacity are proportional to the area the expression (6) shows that voltage dependence mainly proportional to the integral value of the pressure over the thickness. The time dependence gives also some integrated pressure value in comparison with 'short circuit' mode. The high impedance source needs the circuit of the voltage follower and extra operational amplifier but can be replaced as it is presented on the scheme in the Fig. 1b. The resistor of 50k Ohm is parallel to the capacity of the sensor and the transducer operates in the intermediate 'voltage' mode with a time constant 3.6 µs that is 1000 times slower in comparison with 'short circuit' mode. Obviously, the detection of the frequencies > 15 MHz is problematic due to the strong scattering. The resistor and capacitor with the nominal close to sensor nominal compensate the changes of voltage on the inverting input of the operational amplifier. The amplification of the preamplifier circuit is 40 dB for the frequency band from 0.1 up to 15 MHz. The noise calculation of preamplifier working in 'voltage' mode is more cumbersome.

The sensor and preamplifier are in the aluminum cylindrical case of 28 mm outer diameter and the length of 45 mm, please, see Fig. 3. The necessity of coupling liquid is an intrinsic disadvantage of the immersion method that also influences the detection of high frequencies since the attenuation of the ultrasound in water increases according to the second
power law of the frequency as $\alpha = 2.17 \times 10^{-3} \text{dB} \cdot \text{MHz}^2 / \text{cm}$, but for the relatively thin coupling layers of about 1–2 mm it is negligible.

1.5. CONCLUSION

The features of piezoelectric detection of laser-induced ultrasonic pulses are considered. Sensors measure longitudinal ultrasonic pulses by immersion technique both in the metals and in the polymer composites. There are two types of preamplifiers’ circuits for broadband piezoelectric sensors based on 25 µm thick PVDF film. The detection of the frequencies in the range from 5 to 90 MHz requires low value resistor in parallel to the capacity of the sensor that is called 'short circuit' mode where the measured signal is proportional to the time derivative of the mean pressure field in PVDF film. The 'voltage' mode narrows the bandwidth down to 15 MHz while the absolute sensitivity of the sensor increases.

1.6. REFERENCES


Enhancement of contrast in detection of small defects in pipes using guided waves

Tatarinov¹ A.M., Davydov² E.A., Barkanov¹ E.N.

¹Riga Technical University, Riga, LATVIA, alta2003@apollo.lv
²E.O.Paton Electrical Welding Institute, Kiev, UKRAINE, davydov@paton.kiev.ua

Summary: The reduced-scale model study has demonstrated improved detection of small defects in a tube by LRUT using guided waves. Echo signals were collected from 4 magnetostrictive transducers positioned in steps along the tube. The processing included time-shifting and multiplication of signals in the region-of-analysis thus to exaggerate helpful responses related to the torsional wave and suppress parasite acoustic modes. As the result, considerable enhancement of contrast was achieved.

Keywords: ultrasonic testing, long range guided waves, tubes and pipelines

2.1. INTRODUCTION

Application of guided waves in long range ultrasonic testing (LRUT) of pipelines has at least a two-decade history of research and practice [1–3]. The technology is based on propagation of acoustic waves in a pipe that, due to the wave-guiding nature of the pipe, can propagate along it for a long distance before is fully attenuated. Reflected signals from defects on the way are used for the structural health monitoring. LRUT uses ultrasonic waves in a low kilohertz range from 20 to 100 kHz, having a lower attenuation and propagating for longer distances than high frequency waves typically used in NDT. For emitting powerful pulsed ultrasonic
signals in pipes and receiving relatively weak reflections, complicated acoustic antennas are designed, containing either a number of piezoelectric elements around the pipe or magnetostrictive transducers applied to the pipe’s circumferential perimeter [4]. Commercial LRUT is presented by such systems like Ultrawave LRT (Olympus Co.), Teletest (Plants Integrity Ltd.), MsS (Guided Ultrasonics Ltd.) and others. Despite demonstrated efficacy in detection of such defects in pipes like loss of material due to wall corrosion, cracks and in-cuts [1–5], there are still limitations in the technology performance and a room for further development and perfection, respectively [2, 5]. One of the shortcomings is caused by the objective physical factor — dispersion of reflected ultrasonic waves and propagating back along the pipe in the form of different acoustic modes at different velocities. The best practicability for defects detection was found for the torsional T(0,1) wave. The wave has shear origin and the propagation velocity the same to shear wave. The main advantage of torsional wave is absence of dispersion, i.e. its velocity is not frequency dependent and the pulses remain relatively short without spreading during propagation over long distances. It provides the best resolution of detection. The disadvantage is in the fact that the velocity of shear (torsional) wave is about twice lower than that of the longitudinal wave. Thus, the first running longitudinal wave can mask the arrival of the torsional one. Prevalent generation of torsional waves can be provided by special design of ultrasonic antennas. However, the wave conversion at a target (defect, weld or tube’s cut) results in appearance of all possible wave types in the echo, including longitudinal, torsional and flexural [2]. A possible approach to eliminate influence of this effect is to set additional transducers at some distance from the first one and to apply mathematical processing of the received signals in the array in order to enhance signals propagating with the shear velocity and scatter all others. Purpose of the present work was to test such an approach in model studies in reduced spatial and time scales. Processing of a combination of signals recorded by
an array of transducers along a tube included time offsets and further multiplication of the amplitudes.

2.2. METHODS

To realize the proposed approach, the experimental setup schematically shown in Fig.1 was constructed. Four magnetostictive transducers were stiffly set along a 1 cm diameter tube with a step of 25 mm. The transducers presented thin 7 mm wide Ni strips glued by epoxy around the tube to provide uniformly excited wave upon the perimeter. Inductor coils were wound over the strips with number of turns 40. Torsional T(0,1) was excited according to the effect of Wiedemann, where shear oscillations in Ni strips were generated by alternating current in the inductor coils in the presence of permanent magnetic field with the orthogonal direction of the vector of magnetic induction to the same of alternating field. The permanent magnetic field was created by ferrite magnets placed over the coils.

![Fig.1 Layout of experimental setup](image-url)
**Fig.2** Modeled defects: view of a tube’s fragment with a single defect (left) and location of a single and multiple defects (n=8) in tube’s cross-section

The test-object was a 2.5 m duralumin tube with OD = 10 mm, ID = 8 mm, wall thickness 1 mm. The transducers’ array was placed approximately in the middle. Two defects were considered (Fig.2): 1) small single defect—a 1 mm diameter through hole in the wall (about 3% of the cross-section area) and 2) multiple defects—8 symmetric holes of the same diameter upon the cross-section (about 25% of the area). The distances from the transducer’s array to the defects and the tube’s end cut were 92.5 cm and 105 cm. The end cut was damped by a massive piece of viscous plasticine.

**Fig.3** Example of recorded signals: single signal without shielding (A); the same with shielding (B); with shielding and 256 times averaged (B)
Generation and acquisition of ultrasonic signals were performed by a laboratory data acquisition unit with the following parameters: a) excitation: 2-period sine waveform enveloped by Gauss function, frequency 125 kHz, voltage 140 V peak-to-peak; b) acquisition: 30 MHz sampling, 10-bit, time frame 30 kS or 1 ms. Ultrasonic signals were acquired from all possible combinations of transducers’ pairs switched in turn, where one of the transducers was the emitter and the second one was the receiver. Thus, the total number of pairs and acquired signals was 6.

The technical problems to overcome were, firstly, the low level of signals caused by much weaker ultrasonic outcome of magnetostrictive transducers than of piezoceramic ones and noisiness of acquired signals due to external electromagnetic interferences. The first problem was solved by application of an additional 40 dB preamplifier and electrical matching of the transducers by series connection of capacitors in the excitation and receiving circuits in order to reach resonances in the electrical oscillatory circuits at the applied ultrasonic frequency. To eliminate signals noisiness, the transducers were shielded by grounded foil housings and signals averaging at a degree 256. Although, the latter measures seem routine, importance of it is illustrated in Fig. 3.

![Diagram of signals processing](image)

**Fig. 4** Diagram of signals processing

Further and the main processing of the recorded signals was focused on enhancement of contrast of the helpful T-wave echo signal. The aim was to
reveal the T-wave echo from small defect on the background of parasite signals related to other acoustic modes from the same and other targets propagating at different velocities. The processing algorithm is presented in Fig. 4. After raw signals from 6 possible combinations of transducers (3 pairs, 2 alternating input and output variants for each pair) were recorded in digital form, the mathematical processing began. The first step included offsets or bringing all signals to a common start time accounting delays of T-wave propagation between the pairs. T-wave velocity was experimentally determined in the tube as 3150 m/s that corresponded to shear velocity in duralumin. The differences in distances between pairs were 0, 25 and 50 mm that corresponded to 0, 8 and 16 μs in time domain. Taking that the wave period at 125 kHz was 8 μs, the signal offsets were comparable and larger than the wavelength. After corresponding offsets had been applied, the region-of-interest was determined in time scale in order to avoid residuals of excitation and unwanted components from far zone. Then the amplitudes of 6 portions of time-shifted signals in the region-of-interest were multiplied in each sample point. The resulted signal or the product of multiplication was rectified, enveloped by a linear smoothing and displayed.

2.3. RESULTS AND DISCUSSION

Raw signals presented recorded echograms from individual pairs of transducers in the array. Examples of raw signals for the single and multiple defects are shown in Fig. 5. Since the tested plot of tube was of rather short distance, the echograms are densely saturated by many interfering signals that are difficult to be decomposed into separate components with a clearly understood origin. Obviously, these could be different acoustic modes reflected from tube’s end cuts, edge of damping, defects, and transducers themselves that were travelling back and forth the tube with different velocities. Locations of responses from defect (1), damping edge (2) and tube’s end cut (3) can be predicted by real knowledge of the distances and T-wave velocity. Although in the case of large defect (Fig.5B) the echo response
from the defect is pronounced and can be detected by the threshold exceeding the average amplitude level in the region-of-analysis, it is problematic in the case of small defect, the response from which is within the average level of acoustic noise and is masked (Fig.5A).

During mechanical processing of the tube and insertion of multiple defects in the cross-section, the damping at the end cut was partially broken. In further tests, it manifested in appearance of a pronounced reflection from the end cut (3) seen in Fig. 5B, while it is not notable yet at the well damped condition in Fig. 5A. Instead of it, the edge point of damping (2) produced a larger response. We intentionally left these cases to illustrate boundary effects and sensitivity of guided waves to such changes.

**Fig.5** Raw signals for cases of a small single defect (A) and multiple \((n=8)\) defects across tube’s cross-section (B). Arrows show locations of defect(s) (1), edge point of damping (2) and tube’s end cut (3) in time scale. Region-of-analysis for further processing is shown by rectangular frame
Then the above mentioned complex processing of signals from all transducers pairs in the array was applied, including time-shifting of signals and multiplication procedures. The results are presented in Fig. 6 in the form of A-scans with the amplitudes normalized by the maximum in the region-of-analysis. The processing allowed for exaggeration of signal amplitudes related to T-wave propagation in the direction from the defect towards receivers and chaotization of all other modes. As the result, the T-wave amplitude increased substantially and dominated over all other modes. In the case of small defect (Fig.6A), the weak reflection signals from the single defect (1) and the edge point of damping (2) became the most prominent in the signal background. In the case of large defect (Fig.6B), domination of the responses from the defect (1) and tube’s end cut (3) became absolute with practically complete suppression of parasite signals. A defect area of 3% of the cross-section is usually considered as a cut point of resolution for LRUT systems in its real application. The applied processing approach showed an opportunity to lower the resolution threshold and increase the detection ability.

Fig.6 Processed signals for cases of small single defect (A) and multiple (n=8) defects across the tube’s cross-section (B). Arrows show locations of defect(s) (1), edge of damping (2) and tube’s end cut (3) in time scale
Fig. 7 shows raw and processed signals for both cases as B-scans, where a line corresponds to one signal in the time scale and brightness codes the amplitude. All signals are presented at the same settings of signals conditioning and imaging contrasting. In raw signals, only the large defect ((1) multiple) and the tube’s end cut free from damping (3) can be surely detected, while the response from small defect ((1) single) is masked by parasite signals. As for processed signals, only helpful information remained in the scans that are responses from small and large defects (1) and boundaries— edge of damping (2) and end cut (3). All the rest signals were diminished to extremely low values. For the large defect, the processing narrowed the responses width allowing more precise location.

**Fig. 7** B-scan presentation of raw and processed signals for the cases of single and multiple (n=8) defects. Locations of defect and boundaries 1, 2, 3 are the same as in Fig. 5 and Fig. 6

Summing, the complex processing proved it helpfulness for the contrast enhancement in LRUT, especially valuable in the case of small
defects, responses of which were masked by acoustical noise from parasite modes. Increase of number of transducers in the array can increase the resolution of detection, at one hand, since the more multiplication factors act, the higher is the product, increasing the difference between the desired T-mode and parasite signals. On the other hand, this increase is limited by the damping role of stiffly glued transducers themselves that and act as attenuators of guided waves within the array’s plot. A compromise solution can be obtained experimentally in further technical development of the system.

2.4. CONCLUSION

1. Effectiveness of the proposed complex processing of a plurality of signals obtained along the tested tube for contrast enhancement in detection of small defects in a tube was demonstrated in the reduced-scale model study.

2. The proposed approach can be applicable in LRUT for long and middle ranges, using changeable or permanently fixed arrays of transducers. The technology can be scaled on real technological pipes, inspected distances and other testing conditions.

2.5. REFERENCES


Investigations in cyclic strength of pipeline with volumetric surface defect in the weld zone

Yukhymets¹ P., Gopkalo² A., Zecheru³ G., Mihovski⁴ M.

¹ Paton Welding Institute, Kyiv, UKRAINE, yupeter@ukr.net
² Problem of Strength Institute, Kyiv, UKRAINE, apg@ipp.kiev.ua
³ Petroleum-Gas University, Ploiesti, ROMANIA, gheorghe.zecheru@yahoo.ro
⁴ Institute of Mechanics, Sofia, BULGARIA, nntdd@abv.bg

Summary: The present study investigates the influence of volume surface defect, located near the weld, on the strength and residual life prediction of pipeline. Developed analysis procedure combines the results of an experimental investigation of the stress-strain state and durability of full-scale model with finite element analysis. It was shown that in evaluating of residual life of pipeline it is necessary to take into account the features of relative position of the defect and the weld, as well the features of weld joint material.

Keywords: pipeline, volumetric surface defect, weld, low-cycle fatigue

3.1. INTRODUCTION

A feature of service environment under which main and technological pipelines are operating is characterized by a high loading level and non-stationary stress-strain state (SSS). This creates the prerequisites for low-cycle fatigue failure in the zones of stress concentration, which is, primarily, volumetric surface defect (VSD), in view of its commonness. In Paton Welding Institute, an engineering procedure was developed to assess the low-cycle fatigue strength of pipelines in the presence of volumetric surface defect and its validity was experimentally confirmed [1].
Main principles of the procedure include:
— calculation of maximum deformations on defect surface, proceeding from its geometrical parameters and pressure in the pipeline;
— finding the admissible number of cycles of load variation observed in operation, based on the data on stress-strain state (SSS) in the damage zone and cyclic properties of pipe material;
— determination of residual life of the pipeline by comparison of admissible number of cycles with their number during the prior period of service.

On the other hand, the question of application of this procedure in the case of defect location in the vicinity of the weld was still open, as it was anticipated that the result of calculations without allowing for interaction of such stress raisers as VSD and weld can turn out to be non-conservative.

Investigation of mutual influence of stress raisers in the form of weld and VSD was performed by FEA calculations using the geometrical model of welded straight seam pipe, dimensions of which — D530×8 (outer diameter D<sub>e</sub> = 530 mm and wall thickness h = 8 mm), corresponded to nominal dimensions of full-scale sample (steel 17G1S, the longitudinal seam was made at the factory by 2-sided multihead submerged arc welding using flux AN-60 and welding wire Sv-10G2, see Fig. 1).

![Diagram of weld dimensions](image)

**Fig. 1** Main geometrical parameters of the weld of a design model. Unit: mm

### 3.2. PRELIMINARY INVESTIGATIONS

In case of VSD location in the middle of the longitudinal weld it was established that stresses on defect surface grow with increase of its depth
Investigations in cyclic strength of pipeline with volumetric surface defect in the weld zone

and reduction of its width, remaining smaller than in the defect of the same size located at a distance from the weld. At variation of width in the studied range the ratio of stresses in the defect on the weld to stresses in the defect at a distance from the weld remains approximately constant and equal to

\[ \sigma' = 0.5 - 0.6. \]

At defect removal from the weld, the stresses in it gradually rise, reaching a relative maximum of \( \sigma' = 1.2 \), which remains constant in the range of \( e/2d = 1.25\ldots 2 \) (Fig.2)

![Graph](image)

**Fig. 2** Dependence of stresses in the defect on distance to the weld:

- \( e \) – the distance between defect and weld axis; 2d – defect width

The stressed state in the characteristic zones of transition from weld to base metal in the area adjacent to the defect were also considered. Maximum increase of stresses occurs on the boundary of weld outer surface at coincidence of longitudinal defect axis with it. Stress increase by \(~1.5\) times occurs in the area of crossing of the boundaries of weld and defect. A similar stress growth occurs on the boundary of weld inner surface facing the defect, on the level of defect middle at distance between stress raisers equal to 0.5 of defect width.
3.3. EXPERIMENT AND ANALYSIS

Tensile (Table 1) and low-cycle fatigue tests of the material of full-scale specimen were carried out in air at room temperature in accordance with the requirements of [2, 3, 4]. The cyclic loading of the laboratory samples by axial tension-compression was performed under control of the amplitude of strain that was applied with constant rate of 0.1% /sec and asymmetry of the cycle $R_z = -1$.

Table 1 Mechanical properties of material of individual weld joint zones

<table>
<thead>
<tr>
<th>WJ zone</th>
<th>Sample direction</th>
<th>$\sigma^1$, MPa</th>
<th>$\sigma_{0.2}$, MPa</th>
<th>$\psi^3$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>circumferential</td>
<td>595.1..602.3</td>
<td>408.4</td>
<td>53.1</td>
</tr>
<tr>
<td>WM</td>
<td>axial</td>
<td>596.5..600.6</td>
<td>400.8</td>
<td>56.4</td>
</tr>
<tr>
<td>HAZ</td>
<td>circumferential</td>
<td>614.1..620.0</td>
<td>402.5..430.3</td>
<td>42.9..43.4</td>
</tr>
</tbody>
</table>

1 — material ultimate strength; 2 — material yield limit; 3 — reduction in area

![Diagram](image_url)

**Fig. 3** Diagrams of deformation of samples from various zones of welded joint at amplitude of strain $\varepsilon_a = 0.623\% = \text{const}$
Diagrams of cyclic deformation of metal of various zones differ, mainly, by the magnitude of plastic strain per cycle (Fig. 3). Stress kinetics of samples of various zones is indicative of cyclic stability of material of all the welded joint zones. According to experimental data, metal of heat affected zone (HAZ) has the shortest fatigue life. Weld metal (WM) samples demonstrated the highest cyclic strength and base metal (BM) fatigue life has close values (Fig. 4).

![Graph showing fatigue life of samples from welded joint zones]

**Fig. 4** Fatigue life of samples from welded joint zones

Obtained calculation results were compared with the data of experimental studies of full-scale sample (Fig. 5) SSS by electro-tensometry method under the conditions of elastic loading by inner pressure. Obtained experimental data, on the whole, confirmed the results of FEM calculations.
Fig. 5 Full-scale sample: relative position of defects.
Figures denote defects numbers. Unit: mm

At the first stage of cyclic hydraulic testing the sample was subjected to loading by pulsed inner pressure of 0.2–7.5 MPa of the frequency of 4–5 cycles per minute. After 10 090 cycles maximum cycle pressure was increased up to the level of 9 MPa. After the first failure, as in the subsequent similar cases, the defect was repaired and testing was continued.

As shown by the results of testing the full-scale sample, application of corrected procedure:

– substitution in the equation of fatigue curve the values of mechanical properties of welded joint zone, depending on the defect location;

– introduction of correction factors (Fig. 2) in calculation of maximal strains on defect surface according to [1], only slightly increased the conservatism of assessment of fatigue life of defects adjacent to the weld, while assessment of defects on the weld was essentially improved (Fig. 6).
**3.4. CONCLUSION**

Results of testing the full-scale sample confirmed the rationality of application of the corrected engineering procedure for assessment of residual life of a pipeline with VSD in the weld zone.

It is recommended to perform calculation of pipeline residual life using the equation of fatigue curve allowing for defect location and characteristics of mechanical and fatigue properties of the respective zone of the welded joint. If required fatigue characteristics are not available the design fatigue curve based on mechanical properties of base metal with introduced safety factors on durability \( n_\infty = 10 \) and strain \( n_\varepsilon = 2 \) may be used.

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The research of ultrasonic antenna array for non-destructive testing of extended technological pipelines

Glukhovskyi¹ V.U., Călțaru² M.M., Bădicioiu² M.

¹ The E.O.PATON EWI, Kiev, UKRAINE, glukhovskyy@gmail.com
² PGUP, Ploiesti, ROMANIA

Summary: The article describes the approaches and decisions of non-destructive testing of installation welds of pipelines by ultrasonic testing with phased array sensors. The optimum parameters of ultrasonic inspection for pipe diameters of 255 mm.

Keywords: non-destructive testing, ultrasonic testing, phased array, wavefront, ultrasonic antenna array

4.1. INTRODUCTION

Ultrasonic waves are mechanical vibrations induced in an elastic medium (the test piece) by the piezocrystal probe excited by an electrical voltage. Typical frequencies of ultrasonic waves are in the range of 0.1 MHz to 50 MHz. most industrial applications require frequencies between 0.5 MHz and 15 MHz.

Conventional ultrasonic inspections use monocrystal probes with divergent beams. In some cases, dual-element probes or monocrystals with focused lenses are used to reduce the dead zone and to increase the defect resolution. In all cases ultrasonic field propagates along an acoustic axis with a single refracted angle.
A single-angle scanning defects. Most of the “good practice” standards add supplementary scans with an additional angle, generally 10–15 degrees apart, to increase the component has a complex geometry and a large thickness, and/or the probe carrier has limited scanning access. In order to solve the inspection requirements, a phased array multicrystal probe with focused beam activated by a dedicated piece of hardware might be required (see Figure 1.1).

Assume a monoblock crystal is cut into many identical elements, each with a pitch much smaller than its length \((e < W)\). Each small crystal or element can be considered a line source of cylindrical waves. The wavefronts of the new acoustic block will interfere, generating.

![Figure 1](image)

**Fig. 1** Example of phased array ultrasonic technology on a complex geometry component. *Left:* monocrystal single-angle inspection requires multiangle scans and probe movement; *Right:* linear array probe can sweep the focused beam through the appropriate region of the component without probe movement

An overall wavefront with constructive and destructive interference regions. The small wavefront can be time-delayed and synchronized in phase and amplitude, in such a way as to create a beam. This wavefront is based on constructive interference, and produces an ultrasonic focused beam.
with steering capability. A block-diagram of delayed signals emitted and received from phased array equipment is presented in Figure 1.2.

![Block-diagram of phased array equipment](image)

**Fig. 2** Beam forming and time delay for pulsing and receiving multiple beams (same phase and amplitude)

For the application of ultrasonic testing phased array as a method of diagnosing the state of extended technological pipelines necessary to carry out a number of studies: to analyze the directional properties of ultrasonic antenna array according to the number of array elements and the method of its excitation.

The purpose of this research is to analyze the directional properties of ultrasonic antenna array according to the number of array elements and the method of its excitation.
It should be noted that research of analysing the directional properties of ultrasonic antenna array according to the number of array elements and the method of its excitation was divided into two parts.

The first part of the research involves:

1. To analyze the literature in order to familiarize with the international practice of using ultrasonic testing using phased array sensors.

2. To conduct a simulation of ultrasonic testing with phased array probes of the pipe welds using ESBeam Tool 4 PC software software from the Intelligent equipment for the OCTG dimensional control.

3. To Identify the main types of defects and the propagation of sonic waves in pipe material

The second part of the research will involve:

1. Conducting practical research using OMNISCAN MX portable control unit from the Intelligent equipment for the OCTG dimensional control.

2. Selection of the optimal parameters of ultrasonic testing to the most effective defect identification.

3. Preparation of a general report on the subject of analysing the directional properties of ultrasonic antenna array according to the number of array elements and the method of its excitation.

In order to perform the research work, we have used the OMNISCAN MX portable control unit and the ESBeam Tool PC software from the Intelligent equipment for the OCTG dimensional control (Echipament inteligent pentru controlul dimensional al tubulaturii) OMNISCAN MX PA / ECA - OLYMPUS, acquired by the Petroleum-Gas University of Ploiesti within the Sector Operational Program „The increase in the economic competitiveness”, in the framework of the project POSCCE ID860/cod SMIS – CSNR 14682 „Regional Center to Determine the Performance and Monitoring the Technical Condition of Tubular Material Used in the Petroleum Industry (Centru regional de determinare a performantelor si monitorizare a starii tehnice a materialului tubular utilizat in industria petroliear)”, co-financed by the European Regional Development Fund „Investing in your future”.

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Chapter IV

4.2. COMPUTER SIMULATION OF ULTRASONIC TESTING USING THE ESBEAM TOOL 4 INSTRUMENTS

**Input data**: Pipe material — steel 20 (AISI 1020 Carbon Steel (UNS G10200)); Pipe thickness — 8 mm. Pipe diameter — 255 mm.

The tool of ESBeam Tool 4 has been used. This program allows to simulate the type of the product, choose the ultrasonic phased arrays, set the coordinates of its location, choose the angle of the input signal and an active matrix element, specify the form of the defect.

The figures below show the location of the phased arrays probe (Fig.3–5), the propagation of sound waves and their reflection from defects (Fig. 6).

![Fig. 3 The phased arrays probe (a) and sixteen element matrix (b) with thirteen active elements](image1)

![Fig. 4 The mounting pipe weld](image2)
4.3. THE INVESTIGATION OF ULTRASONIC TESTING OF THE PIPE USING THE CALCULATED DATA (DIRECTIONAL PROPERTIES TO THE NUMBER OF ARRAY ELEMENTS AND THE METHOD OF ITS EXCITATION)

The result of the first stage of the research:
1. Analyzed the literature in order to familiarize with the international practice of using ultrasonic testing using phased array sensors.
2. Conducted a simulation of ultrasonic testing with phased array probes of the pipe welds using ESBeam Tool 4 PC software software from the Intelligent equipment for the OCTG dimensional control.
3. Identified the main types of defects and the propagation of sonic waves in pipe material

After modeling the ultrasonic testing process and selection the optimal testing parameters it was decided to produce a full-scale tests
using *OMNISCAN MX* equipment (*portable control unit*) (Fig. 7) and welding rover (Fig. 8).

**Fig. 7** The portable *OMNISCAN MX* equipment for ultrasonic NDT

**Fig. 8** The welding rover with tow ultrasonic transducers

The experiments were carried out on the industrial pipeline segment with the following parameters: thickness – 8 mm; diameter – 255 mm. The defects were introduced as three holes in weld body with 4 mm diameter (Fig. 9 and Fig. 10).

**Fig. 9** The schematic image of the industrial pipeline segment with defect coordinates
The research of ultrasonic antenna array for non-destructive testing of extended technological pipelines

Fig. 10 The real image of the industrial pipeline segment with three defects in the weld

Rover with two transducers which located at 18 mm from the centre of the weld on either side, passed over the surface of the pipe, describing a full circle (798 mm). During its movement the operator received data from transducers using OMNISCAN equipment. After the field tests completion, the results were processed using TOMOVEW 2.9 software.

The results have shown that the transducers location, predetermined number of the first element and the angle signal input are correct for the aforementioned type of pipe. The following diagrams (Fig. 11—16) display the detected defects and their coordinates that coincide with the coordinates of the artificial defects on the weld.

Fig. 11 The result of ultrasound scanning the defect 1 using the transducer № Probe 9
Fig. 12 The result of ultrasound scanning the defect 1 using the transducer № Probe 7

Fig. 13 The result of ultrasound scanning the defect 2 using the transducer № Probe 9

Fig. 14 The result of ultrasound scanning the defect 2 using the transducer № Probe 7
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Fig. 15 The result of ultrasound scanning the defect 3 using the transducer № Probe 9

Fig. 16 The result of ultrasound scanning the defect 3 using the transducer № Probe 7

Thus, pre-modeled process with the help of ultrasonic testing ESBeam Tool 4 are correct, and the following parameters for ultrasonic transducers are true for pipe diameters of 254 mm and a thickness of 8 mm.

The results (Fig. 11-16) have shown that the predetermined location of the transducers, number of the first element and the angle of the signal water are correct for this type of pipe. The following diagrams display the detected defects and their coordinates that coincide with the coordinates of the artificial defects.
Thus, pre-modeled process with the help of ultrasonic testing Toole is correct, and the following parameters for ultrasonic transducers are correct for pipe diameters of 254 mm and a thickness of 8 mm.

4.5. REFERENCES


CHAPTER

Protective coatings based on thermosetting plastics

Kudina¹ H., Barkanov² E., Negoita³ L., Mirchev⁴ Y., Kryzheuski¹ I.

¹V.A. Belyi Metal-Polymer Research Institute of the National Academy of Sciences of Belarus, Gomel, BELARUS, kudina_mpri@tut.by
²Riga Technical University, Riga, LATVIA, barkanov@latnet.lv
³Petroleum – Gas University of Ploiesti, Ploiesti, ROMANIA, cdusescu@upg-ploiesti.ro
⁴Institute of Mechanics-BAS, Sofia, BULGARIA, AL68@abv.bg

Summary: The paper presents investigation results of the materials designed to protect pipelines against corrosion. The classifications of protective coatings and materials used are given. The factors causing defects on the polymer-based coatings are analyzed, their advantages and drawbacks are formulated along with the requirements needed to achieve most efficient anticorrosion protection and improved durability of the pipelines. The procedures able to refine the properties of the epoxy-based materials by functionalization of the binder and addition of the functionally active hybrid fillers have been investigated. The formation of the coatings based on combined matrices is shown to improve their physico-mechanical properties and strength of adhesion to steel. Introduction of hybrid fillers in the epoxide resin promotes a 3.3% strengthening and till 12% growth of elasticity modulus, as well as a 2.3 times hardening of the material.

Keywords: pipeline, corrosion, materials, polymer, epoxy resin, modification, thermoset, combined binder, filler, properties

5.1. INTRODUCTION

Durability and fail-free operation of the pipelines depends much on the efficiency of their anticorrosion protection. The use of composite materials
in the pipe insulation repair techniques is considered in most countries as showing vistas. Each decade is noted by the appearance of the novel insulation materials in this field and new insulator coating systems.

To make a protective coating function reliably, it should meet a series of demands. Most important among them are mechanical characteristics and adhesion to steel, resistance to cathodic delamination, perfect dielectric parameters, low moisture and oxygen penetrability, resistance to UV and heat ageing, and other. Besides, insulator coatings are to maintain properties within a wide temperature range during construction and usage and protect pipelines against corrosion within a maximum possible service life.

Numerous materials for protecting materials against corrosion have been developed lately. Unfortunately, they are unfit for operation in aggressive media in which the objects and equipment for oil production are installed. Most of the technologies and materials used are insufficiently efficient. The newly applied insulating coatings are quickly loosing their adhesion (especially in the case of poor surface cleaning from corrosion products), thus soil waters may penetrate beneath the coat and corrode the metal. Therefore, safety and reliability of a pipeline operation will be inefficient unless a strong durable adhesive interaction between the coating and the pipe metal is enforced. Although there exists a system of adopted in practice standards and the level reached globally in this sphere gives opportunities to obtain economic and reliable formulas of the materials, there still remain a number of unresolved problems.

5.2. CLASSIFICATION OF PROTECTIVE COATINGS AND MATERIALS

A broad spectrum of protective coatings available for today differed in the way of application and their properties make possible to decide successfully the protective problems of pipeline surfaces.

According to work [1] anticorrosion coatings are subdivided into the following categories:
1. Insulating coatings applied in factory conditions. Most applicable of them are the epoxide ones (fine-film and two-layered), three-layer coatings, hot-applied bands (including thermocontractable cold-pack bands), coal tar pitch and bitumen coatings.

2. Insulator coatings applied in semi-movable conditions. Most applicable are the hot-pack bands, liquid coatings, cold-pack bands, coal tar pitch and bitumen coats.

3. Insulator coatings applied in field conditions. Most applicable are the cold-pack and hot-pack bands.

4. Insulation coatings used to protect crosswise welded joints: cold-pack bands (polyvinyl chloride and polyethylene), liquid coatings based on the raw and modified coal tar pitch as well as on polyurethane or epoxide binders, thermocontractable cuffs (most usable).

5. Insulation coatings for repair and reconditioning pipelines. Most widely applied are the cold-pack bands and liquid coats.

The materials for protective anticorrosion coatings for the pipelines can be classified [2, 3] proceeding from their

- composition of the material (polymeric, mineral, combined, paint and varnish, glass-enamel, paste, metallized);
- type (normal or reinforced);
- application technology (factory, field or basic);
- reinforcement (with/without reinforcement);
- deposition temperature (cold/hot, with thermal treatment or heating);
- deposition method (painting, spraying, extrusion, winding (tapes) pouring (liquid types), by thermal shrinkage);
- state of the initial material (liquid, plastic, solid-plastic, solid, powdery);
- purpose (insulating, structural (reinforcing), wrapping);
- temperature preparation of the pipe metal (with/without preheating);
- chemical resistance (weather-proof, gasoline-proof, waterproof, chemically resistive, thermoresistant, biostable).
5.3. ANALYSIS OF THE PROTECTIVE COATINGS OF PIPELINE MATERIALS

Polymer materials. Polymers are the main and most promising materials for insulation of pipelines. As compared to other materials they show a number of advantages, such as better waterproofness, stronger electric resistance, longer service life, convenience and affordability in use. It is used in the form of polymeric tapes in the basic and route conditions or as polymeric compositions deposited on the pipe surface as powders or liquids in the basic or field conditions. The polymer composite materials can be subdivided into three types: 1 – based on a single-component organic binder; 2 – based on a bicomponent organic (mainly thermosetting) binder; and 3 – tape ones (based on thermoplastics).

Polymer composite materials based on a single-component binder. These materials are manufactured on the base of epoxy resin, polyurethane or polyurea.

Epoxy resin. Epoxy resin does not screen the cathodic protection, shows high water resistance. It ensures reliable protection of the metal within a wide range of the cathodic polarization potential under low current densities via metal surface passivation by the products of cathode reactions [4, 5]. This takes place beneath the delaminated coat as well. Epoxide displays perfect adhesive properties to metal, high thermal resistance and resistance to moisture, as well as low cathode-induced delamination values. However, the epoxide layer is rather brittle, insufficiently elastic and, consequently, has low impact strength and is inclined to cracking [6–8]. The minimal thickness of the epoxy layer is 150–250 µm. Epoxide-based factory 150–400 µm thick coatings have gained popularity in the USA, Canada, GB and a number of other countries thanks to their perfect protective and other service characteristics, and elevated thermal resistance (till 80–100°C). Nevertheless, they possess low impact strength, especially under the negative temperatures.
Most applicable today are the epoxide coatings of grades: Scotchkote 226 "ZM" Co. (USA), Resicoat R-726 LD of "AkzoNobel" (Holland), Eurocote 712 PP produced by "BS Coating France", PEP 0103 of the Yaroslavl factory ZPK (Russia) and PEP-0305 of the NPO "Pigment" (Russia).

**Polyurethane.** Polyurethane is more elastic and tough at impacting, weather resistant, undergoes fast curing [9–11] but its adhesive and thermostable properties cede the epoxide coatings. It requires, as a rule, special equipment and should not be applied under negative temperatures.

Among extensively used at present high-grade polyurethane coatings are "SCOTCHKOTE 352 NT" of "ZM" Co. (USA), "PROTEGOL" of Goldschmidt TIB Gmbh (Germany) (the coatings "PROTEGOL UR-Coating 32-55", obtained by the hot airless spraying and "PROTEGOL UR-Coating 32-55 L" applied by hand, "PUR STOP 2000" produced by Ernesto Stoppani (Italy); "SIGMALINNING 7655" of "Sigma Coating BV" (the Netherlands); "COPON HYCOTE 165" of Co. "E. Wood" (GB), "BIURS" of the "PORSIL" Co (Russia).

**Polyurea.** Polyurea displays film impermeability and high setting rate along with reactionary capacity under negative temperatures and the presence of water. Nevertheless, viscosity of the composition tends to increase in cold conditions leading to reduction of surface wettability and, as a consequence, to poor adhesion. Availability of water on the surface reduces adhesion. Primer application is desirable.

Most frequently used polyurea coatings are "KARBOFLEX" of manufacturer "Polybent" and "Izocor-140" of Co. NPP "Izolin" (Russia), Nukote NT "NUKOTE Coating Systems" (NCS) (USA).

**Polymer composite materials based on bicomponent binders.** Such materials are based mainly on the epoxy resins and polyurethane [11]. A combination of these ingredients reduces brittleness of the former and improves adhesion of the latter. Most known grades of epoxy-polyurethane coatings are: "UP 1000|FRUCS 1000 A" produced by
«Kawakami Paint» (Japan); POLYKEN 980, 1600, 2000 of «Covalence Corrosion Protection Group» (USA).

**Combined materials.** This is rather new class of materials manufactured on the base of different organic and inorganic ingredients thus combining positive properties of two components in one material. For instance, named composites can be obtained as: acrylosilicates or acrylo-polysiloxane [2, 3], epoxy-silicates [12–14], epoxy-polysiloxane [15,16], polyester silicates and other [3,17,18].

When selecting a coating one should take into account the fact that the organic types of coatings (PE, epoxide, urethane and other) are very expensive. Nevertheless, the decisive factor in choosing a coating is their properties. The properties like ageing, narrow temperature range present a barrier to a broadened use of organic coatings. For e.g., PE and epoxide coatings should not be used above 60–80°C. More resistant are the PP (above 150°C) and fluoroplastic coatings (200°C). These properties limit life of named coatings within 10–20 years.

**Glass-enamels.** Silicate (glass-enamel) coatings possess higher technical and performance characteristics as compared to organic coatings [13–15]. This includes higher chemical resistance to acids, alkalis and salt solutions, aqua, organic solvents and so on. They have strong adhesion to metals, their hardness is on a par with steel, they endure higher temperature gradients and may be used under higher operation temperatures (till 300–400°C). The distinguishing feature of the glass-enamel coatings is their specific thermal conductivity and thermal expansion coefficient, which are similar to metal. Therefore, the temperature difference in the pipelines do not damage enamel coatings, which is especially important for the curvilinear portions of the mains. These properties of the glass-enamel coatings serve the base for a prolonged operation of the pipes till 40–50 years. It is also important that the raw materials for inorganic coatings are available and rather cheap.
Protective coatings based on thermosetting plastics

There are the primer-free enamels of grades T, ML, MK-5R, E-1, E-1L (Russia), etc. for obtaining a glass-enamel coating.

**Paint-and-lacquer materials.** Paint-and-lacquer materials are used to protect objects from atmospheric corrosion. They are subdivided into the oil, enamel, powder paints and lacquers. More frequently applied grades are: COPON KSIR 88 of «E.WOOD Ltd.» (GB); TK-2 and 770-33 produced by «Tuboscope Vetco» (USA); Amercoat 391 PC of «PPG Industries Netherlands B.V.» (the Netherlands); Sigmalining SF 23 of «Sigma Coatings» (the Netherlands); Hempadur 87540 of «Hempe» Co. (Denmark); Permacor 128/A and Permacor 2807/HS-A of «Permatex» Co. (Germany); «GAMMA for pipes» and «Eloben-Terma» («GAMMA» (Russia)); TK-236, TK-216 and NN-205 of «Tuboscope Vetco» (USA); Scotchkote XC-6171, XC-6178 of «3M» (USA); PEP-585 (OAP NPF «Pigment» (Russia)).

To protect steel pipes from corrosion most efficient in world practice are considered to be two types of anticorrosion coatings, namely the one-layer and two-layer epoxy coatings (Fusion Bonded Epoxy (FBE) and Dual Fusion Bonded Epoxy (DFBE)) two-layer and three-layer epoxy-polyolefin 3LPE or 3LPP (PE-based or PP-based) [19–20]. Mainly the 3LPE and 3LPP coatings are used in Europe, in the USA and Canada, 99% of steel pipes of any diameter are covered by the systems FBE and DFB. The 2-layered epoxide system is advantageous in the reliable and fast-made protection of the couplings between pipes and compatibility of the coatings with the cathodic protection. In the course of a more than a 50-year experience in operation of the 2-layer epoxide coatings there was not a single case of stress-corrosion cracking under the coatings. Besides, impact resistance of the 2-layer epoxide systems is lower than that of the 3-layer polyolefin ones. Nevertheless, the 2-layer epoxide coatings have not gained popularity so far in Russia. Taking into account technological and economic merits of the technology and wide experience in operation of the 2-layer epoxide coatings in different
countries it seems expedient to use the 2-layer epoxide systems for insulation of till 820 mm in diameter pipes. Like in the case with the 3-layer polyolefin systems, the main protection against corrosion is provided by the epoxide coating.

By the present moment a wide spectrum of materials has been developed for various corrosion-proof pipe coatings. The analysis of operation of restored pipelines has shown high manufacturability of the protective repair coatings based on epoxide and polyurethane binders as well as their combinations with other polymers in different ratios. However, assimilation of the rout insulation by polyurethane and epoxy-polyurethane coatings is restricted by the weather effect. Besides, the existing application technology does not suit the protracted reinsurance of the linear parts of the mains. Polyurethane mastics are good for the oil pipelines in the case there is no possibility to employ the pipes with a factory-made insulation. The materials based on epoxide resins efficiently used today in repairing corrosion-damaged trunk pipelines possess, however, a number of disadvantages (e.g., low resistance to cathodic delamination, low impact strength) that impair their performances. It should be noted, nevertheless, that the developed protective corrosion-proof coats based on epoxy resins are most applicable for the present and efficient. It follows that the problem of creation of still new highly efficient protective formulations for the pipe coats with a wide range of characteristics still remains an urgent task for specialists.

5.4. THE CAUSES OF DEFECT ORIGINATION ON COATINGS

The quality of the coatings on the external surface of underground pipelines defines the efficiency of insulation materials and depends on the composition of the initial material, structure and properties of the formed coating, application technology on the pipe surface, coating structure, operation conditions of the pipeline, and so on.
The appearance of defects on the insulation coatings is induced by the following main reasons [28]:

1. Low-quality application of the primer on the pipeline.
2. Use of poor quality insulation materials.
3. Low adhesion of the coating to metal.
4. Technological peculiarities of application of the insulation layer (e.g., interval between the primer application on the pipe surface and the wrapping tape is insufficient for the total evaporation of the solvent, which leads to swelling under the little permeability film (PE or PP) and reduction of adhesive strength between the layers of the coating).
5. The defects arising at application of polymeric insulation tapes (folding, wrinkles, embossing, that result from using different in thickness tapes, shear of the coils at tape application, insufficient tension of the tapes, insufficiently clean base surface violation of temperature conditions for coating application, and other).
6. The defects occurring in the course of insulation-laying works when covering the pipeline with earth.
7. Soil influence: the mechanical effect leads to shear or tensile stresses in the coating that bring about scuffing, folding or embossing; physico-chemical effects when the surface-active components of the soil environment promote washing of plasticizers out of the insulation coatings; elevated humidity leads to augmented cracking of the coating and reduced service life.
8. Insufficient electrochemical protection of pipelines (potential difference at the pipe/earth interface).
9. Breach of operation conditions of the pipeline due to temperature drop at transportation of the products, elevated temperature norms during pumping, etc.
10. Residual defectiveness of the metal pipes, along with formation and accumulation of defects on the pipe walls.
11. Ageing of the insulation material.
5.5. REQUIREMENTS TO MATERIALS OF INSULATION COATINGS

In spite of a wide spectrum of available today insulation composite materials and systems, no material can be found that meets all requisite requirements. Therefore, when searching for an optimal protective system one should take into account certain operation conditions of the pipeline, technological processes of application of the protective coating and its efficiency in the given conditions, economic benefits from the repair works by the chosen materials on the pipeline in question.

The main criteria that improve reliability of a trunk oil pipeline and define its life span are the following:

- improved quality of insulation system materials;
- perfection of technologies for application of insulation materials during overhaul repair;
- quality of the insulation coating;
- service characteristics of the coating material;
- competitiveness of the coating material towards its cost and technology.

5.6. DEVELOPMENT OF PROTECTIVE COATINGS BASED ON EPOXY RESIN

The analysis of coating compositions intended for efficient anticorrosion protection of pipeline surfaces has shown that the major binder type involved is epoxy resin (ER). The investigations aimed to achieve a composite material with refined characteristics have two main trends:

- functionalization of ER in order to obtain a combined binder;
- modification of the binder using synthesized high-filled compounds.

*Materials and investigation methods*

The ER of grade ED-20 has been used as a binder for the developed composite materials. As a curing agent for the ER-based composite material served polyethylene polyamine (PEPA). Concentration of the hardener in the composition was 10 mass% of the ER amount.
Functionalization of the ER was made using phenol formaldehyde resol resin (PFR), polyvinyl butyral (PVB), ε-caprolactam (CL) and tripolyphosphate.

Highly dispersed nanostructured hybrid products (iron, cobalt, copper epoxy-silicates) have been used as the dispersed fillers for the ER and combined organic matrices. The said products were produced by a sol-gel technology in solutions of the mixtures of aqua alkali-silicate solutions functionalized by epoxydiene and polyvalent metal salts [21]. These synthesized products present hybrid mixed composites consisting of a chemically linked epoxy-silicate matrix in which silica nanoparticles are dispersed [21]. The hybrid matrix is intercalated with the metals like iron, cobalt or copper. The powder dispersion is about 25–50 nm (80%).

Steel plates of grade St.08kp were used as the substrate for coating application. The plates were subjected to sand-blasting and degreasing before coating application. After the composition is applied on the surface the samples were endured in air under 18–20°C for 24 h. Then the samples were thermally treated in 80±5°C temperature during 40 min and then under 180±5°C during 2 h. Thus obtained composites or coatings were endured before testing under 20°C in air.

Physico-mechanical properties of the coatings were tested 7 days after their formation. Their microstructure was investigated on a scanning electron microscope VEGA II LSH. Physico-mechanical properties of the materials and coatings were determined using standard procedures. Such physico-mechanical properties as the instant elasticity modulus, time of relaxation, max penetration were estimated by a measuring instrument for viscoelastic properties of polymeric materials. Strength of the adhesive joint coating/metal was found by the method of the lattice incisions. Hardness of the coating on the metal was found by the Vickers method on a microhardness meter PMT-3M. The strength limit of the glue joint and some physico-mechanical properties (breaking stress at compression, elasticity modulus) were estimated on a testing machine Instron (USA).
The effect of ER functionalization on the material properties

Introduction of PFR or PVB into the ER has lead (see Table 1) to formation of a sufficiently elastic coating from the binary binder having higher adhesion to steel surface as compared to the initial thermoset.

Table 1 The effect of ER functionalization on properties of the coatings

<table>
<thead>
<tr>
<th>Properties</th>
<th>Without modifier</th>
<th>Modifier Phenol formaldehyde resin (C=30%)</th>
<th>Modifier Polyvinyl butyral (C=10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elasticity modulus, GPa</td>
<td>6.70</td>
<td>3.61</td>
<td>4.44</td>
</tr>
<tr>
<td>Adhesion, points</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Coating surface after testing by lattice incision</td>
<td>![Image]</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>

1—after introduction of 10% PEPA of the total ER amount

The coating obtained from the binary binder of ER/PFR composition shows a 1.9 times reduction of the elasticity modulus. Investigations of the binary binder bond strength to steel have shown (Fig. 1) also that introduction of PFR into ER reduces much brittleness of the joint ER/steel.

![Graph a)](image1) ![Graph b)](image2) ![Graph c)](image3) Fig. 1 The effect of material composition on the coating/steel bonding strength: ER (a), ER/PFR (b), PFR/butylene-nitrile rubber (c)
Further functionalization has resulted in achieving three-component binders on which base uniform coatings with even higher elastic properties were formed at curing on the steel surface (Table 2).

**Table 2** The effect of functionalization of the combined binder\(^1\) ER/PFR on properties of the coatings

<table>
<thead>
<tr>
<th>Properties</th>
<th>Without modifier</th>
<th>Modifier</th>
<th>Modifier</th>
<th>Modifier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(\varepsilon)-caprolactam</td>
<td>Polyvinyl butyrat(^2)</td>
<td>Triopolyphosphat</td>
</tr>
<tr>
<td>Elasticity modulus, GPa</td>
<td>2.02</td>
<td>0.02</td>
<td>3.40</td>
<td>0.02</td>
</tr>
<tr>
<td>Adhesion, points</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Coating surface after testing by lattice incision</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) – composition of the binder ER/PFR = 10/90,
\(^2\) – after introduction of 10% PEPA of the total ER amount

Thus formed coatings are also characterized, according to their testing by the method of lattice incision, by a high adhesive strength to the steel surface. The visual estimate of the coatings obtained from the initial optimized binder ER/PFR and the functionalized one has proved that by their appearance, quality and covering capacity the best turned to be the coating containing \(\varepsilon\)-caprolactam (Table 2). It is to be noted that with increasing modifier amount the external appearance of the coating improves, i.e., it becomes more uniform, smooth, incision edges are without burr. This is, probably, because certain physico-chemical processes take place in the mixture during coating formation, which are attributed to polymerization of the ingredients and formation of a grid of interpenetrating organic matrices. These processes are also promoted by the polyamide resin formed after introduction of \(\varepsilon\)-caprolactam into the formulation, where polymerization occurs under heating in the presence of
small amounts of water, alcohol, amines and organic acids. Table 3 lists the properties of the coatings based on a combined three-component binder.

The experimental evidences prove that the max penetration depth of the indenter in the coating samples based on the ER/PFR/CL binder by as much as 2.9–3.3 lower than the binary composition ER/PFR shows. This fact confirms that the coatings based on the combined binder ER/PFR/CL are more resistant to damages from external impacts.

**Table 3** Characteristics of coatings based on ER/PPR/caprolactam binder

<table>
<thead>
<tr>
<th>Concentration of ε-caprolactam, %</th>
<th>Relaxation time, x10⁻⁶ ms</th>
<th>Elasticity modulus, GPa</th>
<th>max penetration, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without modifier</td>
<td>11,10</td>
<td>2,02</td>
<td>88,88</td>
</tr>
<tr>
<td>1</td>
<td>6,74</td>
<td>0,02</td>
<td>27,36</td>
</tr>
<tr>
<td>2</td>
<td>23,7</td>
<td>0,02</td>
<td>27,75</td>
</tr>
<tr>
<td>3</td>
<td>8,29</td>
<td>0,02</td>
<td>30,38</td>
</tr>
<tr>
<td>5</td>
<td>11,34</td>
<td>0,02</td>
<td>20,05</td>
</tr>
</tbody>
</table>

**5.7. THE EFFECT OF ER MODIFICATION BY HYBRID PRODUCTS UPON THE MATERIAL PROPERTIES**

The investigations of physico-mechanical properties of the composites based on epoxide resins have shown that addition of the dispersed fillers in question results in the elasticity modulus increase (Fig. 2) by about 12%. The highest increase is reached when iron and cobalt epoxy-silicates are introduced in the composition.

The modifiers under study ensure strengthening of the initial epoxide binder by as much as 20 to 33%. By their efficiency in raising strength of the composite material the modifiers can be arranged in a series like: iron epoxy-silicate (20%) → copper epoxy-silicate (28%) → cobalt epoxy-silicate. Besides, addition of the fillers in the binder makes possible to transfer from the brittle failure of the ER-based materials to the elastoplastic deformation of the composites.
Formulations: 1 – initial ER; 2 – ER+5% iron epoxy-silicate, 3 – ER+5% cobalt epoxy-silicate, 4 – ER+5% copper epoxy-silicate

**Fig. 2** Young modulus variations in the compositions

<table>
<thead>
<tr>
<th>Composition</th>
<th>Young modulus, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>2</td>
<td>1.85</td>
</tr>
<tr>
<td>3</td>
<td>1.77</td>
</tr>
<tr>
<td>4</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Fig. 3** The effect of the filler kind on breaking stress strength at compression for the composites, and views of the samples before and after breakage

![Images showing samples and their breaking strengths](image)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Breaking Stress Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial ER</td>
<td>σ = 58.7 MPa</td>
</tr>
<tr>
<td>ER+5% iron epoxy-silicate</td>
<td>σ = 71.8 MPa</td>
</tr>
<tr>
<td>ER+5% cobalt epoxy-silicate</td>
<td>σ = 77.4 MPa</td>
</tr>
<tr>
<td>ER+5% copper epoxy-silicate</td>
<td>σ = 75.8 MPa</td>
</tr>
</tbody>
</table>

Improvements in physico-mechanical properties of the composite material are attributed to their chemical composition and functional activity of hybrid fillers towards the thermosetting binder. These processes promote interactions between nanoparticles and the epoxide binder, thus making the material stronger. Named phenomenon agrees with the material strength dependence on the filler concentration (Table 4). Above-
mentioned data show that the filler concentration is most efficient within 1–10% limits. Further elevation of concentration does not bring about any perfection in properties of the material and so is inexpedient.

**Table 4** The effect of filler on properties of the ER-based composite

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Initial matrix</th>
<th>Concentration of iron epoxy-silicate, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Breaking stress at compression, MPa</td>
<td>58.7</td>
<td>73.4</td>
</tr>
<tr>
<td>Deformation, %</td>
<td>6.5</td>
<td>6.6</td>
</tr>
</tbody>
</table>

The properties of the material are affected noticeably by the distribution character of the filler within the organic matrix bulk. The dispersion phase of the functionally active nanoparticles uniformly distributed in the matrix bulk promotes strengthening of the material (Fig. 3).

![Graph](image)

\[ E = 1.81 \text{ GPa} \]

\[ E = 0.75 \text{ GPa} \]

**Fig. 3** Compressive strength of the material ER+5% iron epoxy-silicate versus the procedure of ingredients mixing in a vibromill (1) or by ultrasound (2)

When a modifier is dispersed in the binder volume under the US effect the nanofiller particles tend to agglomerate (iron epoxy-silicate) due to the excess surface energy of the nanoparticles. Agglomeration of the nanoparticles gives rise to the centers of excess stresses together with a 40% strength fall of the material. The method of introduction of iron or cobalt epoxy-silicate does not affect anyhow the stress-strength parameters of the material.
Formation of the coatings from the modified epoxide resins on steel surfaces has shown that all hybrid products under study promote better quality, covering capacity, reduction of brittleness, increased hardness and adhesive strength of the ER-based coating (Table 5).

**Table 5** The filler effect on properties of the coating

<table>
<thead>
<tr>
<th>Properties</th>
<th>Without a filler</th>
<th>Filler (concentration 5%)</th>
<th>Iron epoxy-silicate</th>
<th>Cobalt epoxy-silicate</th>
<th>Copper epoxy-silicate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardness, MPa</td>
<td>40</td>
<td>90</td>
<td>91</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>Adhesion, points</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Coating surface after testing by lattice incision</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 — after introduction of 10% PEPA of the total ER amount

Figure 4 visualizes the investigation results concerning the effect of filler composition on adhesive strength of the splice between the coating based on the modified epoxide resin and steel surface.

![Graph](Image)

**Fig. 4** The effect of modifier composition on coating/steel adhesive strength

According to above data, the filler that improves adhesive strength of the coating material to steel most efficiently is the iron epoxy-silicate.
Investigations in the filler composition effect on physico-mechanical properties of the binary binder ER/PFR have proved that the efficiency of the products under study are arranged in the following order: iron epoxy-silicate → copper epoxy-silicate → cobalt epoxy-silicate (Table 6). It was found that introduction of the fillers resulted in the adhesive strength improvement (by up to 20%).

**Table 6** Physico-mechanical properties of the coatings based on RE/PFR

<table>
<thead>
<tr>
<th>Filler</th>
<th>Filler amount, %</th>
<th>Relaxation time, $\times 10^6$ ms</th>
<th>Elasticity modulus, GPa</th>
<th>Max penetration, $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>without filler</td>
<td>0</td>
<td>11.1</td>
<td>2.02</td>
<td>88.9</td>
</tr>
<tr>
<td>iron epoxy-silicate</td>
<td>1</td>
<td>8.0</td>
<td>0.02</td>
<td>30.7</td>
</tr>
<tr>
<td>copper epoxy-silicate</td>
<td>3</td>
<td>8.0</td>
<td>0.02</td>
<td>34.6</td>
</tr>
<tr>
<td>cobalt epoxy-silicate</td>
<td>1</td>
<td>6.6</td>
<td>-</td>
<td>29.2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>4.7</td>
<td>-</td>
<td>28.2</td>
</tr>
</tbody>
</table>

**5.8. CONCLUSION**

The present investigations have led to the conclusions that physico-mechanical properties of the composite materials based on epoxy-diene resin can be improved by using two technological procedures, namely:

— functionalization of the initial binder with production of combined matrices;

— modification of the binder by the functionally active fillers that are chemically affine to epoxydiene resin.

In order to exercise functionalization of the epoxydiene resin it would be most efficient to employ the oligomer of phenol formaldehyde resin and a monomer of $\varepsilon$-caprolactam. The coatings produced on the base of combined binders ER/PFR and ER/PFR/CL display elevated physico-
mechanical characteristics and adhesive strength of the coating material/steel joint. The use of the ER base or the combined binders of the hybrid fillers improves both strength of the coating material adhesion to steel and its performances. Introduction of hybrid fillers in the ER promotes up to 33% strengthening, till 12% elasticity modulus growth and till 2.3% hardening of the material. Addition of the fillers into the combined binder makes base for increasing strength of the adhesive joint by about 20% and its resistance to damaging by external factors. Besides, the fillers are able to ameliorate quality and reduce brittleness of the coating.

5.9. REFERENCES


Heat stability and dynamical mechanical properties of the polymer composites for adhesive layer ("soft adhesive") in the pipelines repair system with wrap

Sergienko¹ V., Bukharov¹ S., Dușescu² C., Alexiev³ A., Sychev⁴ A.

¹V.A. Belyi Metal Polymer Research Institute of National Academy of Sciences of Belarus, Gomel, BELARUS, sbuharov@tut.by
²Petroleum-Gas University of Ploiesti, Ploiesti, ROMANIA, cdusescu@upg-ploiesti.ro
³Institute of Mechanics-BAS, Sofia, BULGARIA, al68@abv.bg
⁴Southern Scientific center, Russian Academy of Science, Rostov-on-Don, RUSSIA, sap@rgups.ru

Summary: Investigation of newly developed polymer composites which can be used as intermediate adhesive layer for pipelines repair in the system “pipe metallic wall — filler — composite material wrap” have been conducted in the work using Simultaneous Thermal Analysis (STA) and Dynamic Mechanical Analysis (DMA). The main advantage of the developed materials is prevention of delamination of composite material wrap in the full range of the thermal and mechanical operating loads due to high elasticity as well as high adhesion to metallic wall of the pipe and material wrap.

Keywords: polymer composites, adhesive, pipelines repair, thermal analysis, heat stability, mechanical properties
6.1. INTRODUCTION

Composite repair systems should ensure operability of the pipelines, including the protection against corrosion-mechanical faults for the entire period of their operation. In the CIS countries normative operation term of pipelines in accordance with the existing amortization is 33 years, although in fact some of them are in operation for about 50 years [1, 2]. The conditions of operation may be changed during this period: it is possible development of erosion soil erosion over oil pipelines, change the properties of the pumped oil, reduces the amount of pumping. In addition, it is possible disconnection or preservation of pipeline section for a long time, sometimes accompanying their emptying or using to pump other liquids, such as water, etc.

The selection and practical application of coatings designed for corrosion protection of oil and gas pipelines are regulated by GOST R 51164 "Steel Pipelines. General requirements for corrosion protection". This standard defines the list, design, the minimum thickness and range of applications of the external coating (pipeline diameter, the maximum permissible operating temperature) and, in addition, it establishes technical requirements for protective coatings of pipelines for route and factory (basic) application.

In connection with the increased technical requirements for anticorrosion coatings of pipelines the use of bituminous mastic, polymer tape and single-layer epoxy anti-corrosion coatings was highly restricted especially for pipes of large diameter (over 820 mm) [3]. In the case of epoxy coatings limitations relate primarily to their low mechanical (impact) strength and inadequate (for steel of the pipe) thermo-mechanical characteristics. For instance the impact strength of the epoxy monolayer (thickness 350–400 microns) do not exceed values of 6.8 J at 20±5°C and decreases to 2.3 J at minus 40°C. Low mechanical properties together with relatively slow thermal deformation of steel of the pipe and fast dynamic loads (pressure gradients and related vibration and
hydroblows) generated by a pressure system operation or triggering of the lock valves are the main factors that lead to exfoliation and damage of the protective coatings. They may also appear occasionally because of erroneous behavior of the staff, the emergency shutoff or response of the local technological protection system or other reasons [4, 5].

Restrictions on the use of bitumen-mastic coating caused by their high water absorption and extremely narrow temperature range of application. At subzero temperatures the construction and operation of pipelines bituminous coatings embrittle and break down at low loads and deformations, and, on the other hand, at temperatures above +40°C bituminous coatings are softened, transformed into a viscous or fluid condition and may gutter under its own weight. In addition to a low impact strength, the propensity to stress cracking and insufficiently high adhesion (1.5 to 2.0 kg/cm) to primed steel are significant disadvantages of the tape polymer coatings. Because of the low adhesion and under the influence of settling ground the corrugation and folds may occur on the side surface of large-diameter pipes. At the same time continuous coating deformation at the upper portions of the forming pipe causes its cracking and destruction.

One of the main directions of improving the reliability of corrosion protection of pipelines is the widespread introduction of technology, equipment and modern protective materials. Among the most effective anti-corrosion coatings can be attributed materials based on extruded polyethylene. Compared with the traditional bitumen mastic tape, the factory polyethylene coating has a high (up to 40–50 J) impact strength, relatively higher adhesion to steel, high resistance to punching and puncture, resistance to abrasive wear. Due to the higher adhesion of the polyethylene coating is resistant to shear stresses produced in soil and sediment in the process of shifting sections of pipelines during operation. Furthermore, extremely low oxygen and moisture permeability makes the polyethylene coatings effective diffusion barrier to the penetration of corrosive substances to the metallic surface of the pipe.
However, as a result of many years of practical experience in the use of polyethylene anticorrosion coating revealed a number of shortcomings including the insufficient water resistance, low adhesion and resistance to the cathode peeling at elevated temperatures so these coatings have not been widely used.

Mastic-polyethylene coatings the design of which is composed of a layer of extruded polyethylene, coated on mastic sublayer (the so-called "soft" adhesive) materials have been developed and put into practice of pipelines construction as an alternative for a single-layer polyethylene coatings. Initially, insulating mastic based on bituminous compositions and the asphalt-resinous compounds used in such laminate coatings as the adhesive underlayer. Technology of outer pipeline protection using mastic-polyethylene coatings in some cases applied so far. The soft adhesive or primer in the tape design of the mastic-polyethylene coatings (for example, tape applied over the primer type NC-50, "Polyken", "Altena", etc.), performs basic insulation function: provides the high adhesion of the main coating to the steel of pipe, coating stability to cathodic disbondment and others. Nevertheless, the use as an adhesive underlayer bituminous materials because of their low heat resistance and extremely narrow temperature range of mechanical properties does not satisfy the operational requirements of modern composite repair systems.

The heat stability and dynamic mechanical characteristics of known materials and newly developed polymer composites which can be used as intermediate "soft" adhesive for pipelines repair in the system “pipe metallic wall – filler – composite material wrap” have been investigated in the present work. New formulations of composites for "soft" adhesive materials based on combined polymer-rubber binders with improved damping characteristics and heat resistance have been proposed. The use of such layers is intended to prevent a delamination of composite material wrap in the full range of the operating loads due to high elasticity as well as high adhesion of the intermediate layer to metallic wall of the pipe and material wrap.
6.2. MATERIALS AND RESEARCH METHODS

Nine experimental formulations of composite materials based on rubber and combined thermosetting polymer binders (powder phenolic resins of resol and novolak types) for "soft" adhesive have been developed in this work in accordance with the table 1. The compositions obtained have been used in manufacture of the samples in the form of plates for dynamical mechanical tests. All these samples for the tests (11 samples total) were divided into three groups: I group – the materials of the base composition without modifying fillers but different temperature and pressure in the pressing on the step of obtain samples; II and III group – materials containing various modifying fillers obtained in medium of MEK (methyl ethyl ketone) and ACE (ethyl acetate), respectively.

Heat resistance and mechanical characteristics of the compositions have been investigated in this work using Simultaneous Thermal Analysis (STA) and Dynamic Mechanical Analysis (DMA). Simultaneous Thermal Analysis (STA) is a simultaneous technique that determines the weight change of a sample (TG) and measures the change in temperature between a sample and the reference as a function of temperature and/or time (DTA). The heat resistance tests were conducted using Simultaneous thermal analyzer STA-6000 (Perkin Elmer, USA). The STA 6000 (Fig. 1) combines the high flexibility of the differential analysis feature (DTA, DSC) with the proven capabilities of the thermogravimetric (TG) measurement technology to provide highly reliable characterization information. Degradation processes of composite materials and components included in their composition, at elevated temperatures was investigated by thermogravimetric (TGA) and differential heat (DTA) analysis at a heating rate of 5°C/min in a neutral (nitrogen) gas medium. When carrying out thermal analysis sample of the test material weighing 10.0±5.0 mg was placed in a pan made of oxide ceramics (Al₂O₃).
<table>
<thead>
<tr>
<th>Sample group</th>
<th>Sample No.</th>
<th>Composition and technological parameters of obtaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>Rubber: Novolac 1:1; high pressure, 180°C</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Rubber: Novolac 1:1; medium pressure, 140°C</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Rubber: Novolac 1:1; small pressure, 140°C</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3 g Rubber; 0.75 g novolac; 0.75 g resol; 0.15 g SnCl₂ in MEK</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3 g Rubber; 0.75 g novolac; 0.75 g resol; 0.15 g SnCl₂; 0.15 g MgO; 0.15 g Stearic acid, in MEK</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>3 g Rubber; 1.5 g resol; 0.15 g SnCl₂ in MEK</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>3 g Rubber; 1.5 g resol; 0.15 g SnCl₂; 15 g MgO; 0.15 g Stearic acid, in MEK</td>
</tr>
<tr>
<td>III</td>
<td>8</td>
<td>3 g Rubber; 1.5 g novolac; 0.15 g SnCl₂ in ACE</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>3 g Rubber; 1.5 g novolac; 0.15 g SnCl₂; 15 g MgO; 0.15 g Stearic acid, in ACE</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3 g Rubber; 0.75 g novolac; 0.75 g resol, in ACE</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>3 g Rubber; 0.75 g novolac; 0.75 g resol; 0.15 g SnCl₂ in ACE</td>
</tr>
</tbody>
</table>

The non-resonance method of determining the dynamic mechanical characteristics of the materials is based on measurements of the phase shift of the signals of the driving force and the resultant deformation $\delta$ during forced harmonic vibrations of the sample at the frequencies by far lower than the resonance one. Method of dynamic mechanical analysis (DMA) is used to study the viscoelastic properties of the material (elastic modulus $E'$, the viscous modulus $E''$, the angle of mechanical loss tangent of the sample) as a function of time, temperature and frequency at various oscillating loads. The method allows to obtain the information about changing mechanical properties ($E'$, $E''$ and $\tan \delta$) under dynamic loads (forces at a certain determined frequency or a set of discrete
frequencies) and controlled temperature. From the temperature
dependence graphs it is possible to define the glass transition temperature
in thermoplastic polymers, melting point and other physical and phase
transitions. It is also possible definition of the enthalpy of transition.

Fig. 1 Simultaneous thermal analyzer STA-6000:
a) general view of the device; b) internal design:
1 – small furnace for accurate temperature control; 2 – SaTurnA sensor for
direct measuring both the sample and reference temperature; 3 – corrosion-
resistant rugged alumina furnace; 4 – furnace cool-down system;
5 – thermal insulated balance housing; 6 – intermediate space for balance
purge gas; 7 – integrated mass flow controller for sample purge gas

Dynamical Mechanical tests were conducted using a dynamic
mechanical analyzer Q 800 (TA Instruments, USA) in order to determine
the dynamic characteristics of the materials as a function of time,
temperature and frequency (Fig. 2). In this work the storage modulus and
mechanical loss tangent of the materials have been studied at two discrete
frequencies of 1 and 10 Hz over a temperature range of 30 ... 180°C under the
tensile test mode (Fig. 3).
Fig. 2 System of the nonresonance thermal analysis of mechanical characteristics of materials DMA Q800 (TA Instruments, USA)

Fig. 3 Test cell of the DMA Q800 for tensile mechanical tests of materials: 1 – sample of material; 2 – clamps for tension film test; 3 – heated chamber
6.3. INVESTIGATION RESULTS AND DISCUSSION

Results of STA tests

As can be seen from the TGA curves presented in Fig. 4 for unmodified materials of group I (Table 1) the thermal degradation in the operating temperature range, actually when heated to 200°C has extremely low intensity, and the loss of material mass does not exceed 1.0%. In the temperature range 350 ... 470°C there is a low-temperature phase of intensive loss of material mass. By the end of this stage, the loss of mass of the sample is 70%. At temperatures of 566 ... 646°C thermal degradation of the intensity is substantially reduced, and the loss of weight of the sample is 75%. At the final stage when a heating temperature above 686°C, more intense thermal decomposition is observed and is accompanied by loss of mass of the sample to 80%.

![Thermogravimetric and Differential Thermal Analysis](image)

**Fig. 4** Thermogravimetric (1) and differential thermal (2) analysis for unmodified compositions of adhesive material (Group I) in medium of nitrogen

As shown in Figure 5, the same way occurs thermal degradation of materials containing various additional components for modifying adhesion and elastic properties. Low-intensity phase of mass loss up to 5% observed when heated to 337°C. When the temperature rises over 330°C the rate of mass loss increases substantially up to a temperature of 470°C. By the end of this stage, the loss of mass of the sample reaches 70%. Further heating up to a tempera-
ture of 800°C sample mass varies similarly to the first stage. The loss of mass of the sample at 800°C is about 80%. DTA curves (Figures 4 and 5) in the first stage of thermal degradation (up to 570°C) for all sample groups under study show an endothermic nature of the thermal degradation of these materials.

The results of TGA in the first stage of thermal degradation range (up to 400°C) for eleven formulations of model polymer adhesion material shown in Figure 6. Additionally, thermal stability of materials on the basis of bitumen, bitumen-rubber and epoxy resin have been studied for comparative analysis. As shown in Fig. 7, the heat resistance of the samples is determined mainly by the chemical type of binder in material composition. New formulations of adhesive materials based on combined polymer-rubber binders have improved heat resistance in comparison with the materials based on bitumen, bitumen-rubber and epoxy binders. It was found that a slight decrease in thermal stability when heating over temperatures of 220°C take place for №5 samples and №8 compared to the unmodified composition of material. A slight increase in thermal stability in the temperature range 250 ... 380°C is observed for composition №10. Thus, technological parameters of obtaining materials as well as introduction the adhesion and viscoelastic modifiers to composition have no significant effect on the thermal resistance of materials studied.

![Graphs showing TGA and DTA curves](image)

**Fig. 5** Thermogravimetric (1) and differential thermal (2) analysis for modified compositions of adhesive material:
- Group II (a) and Group III (b) in medium of nitrogen
Heat stability and dynamical mechanical properties of the polymer composites for adhesive layer ("soft adhesive") in the pipelines repair system with wrap

**Fig. 6** Results of thermogravimetric thermal analysis for 11 samples of adhesive materials (numbering of samples corresponds to Table. 1) in medium of nitrogen

**Fig. 7** Thermogravimetric (a) and differential thermal (b) analysis for adhesive materials based on various binders: 1) epoxy resin; 2) bituminous resin; 3) combined rubber-bitumen; 4) combined phenol-rubber (developed composition №11 according to Table. 1)

Results of the experimental investigations indicate that of the complex physical and chemical processes that determine the level of heat resistance the most important are the processes of thermal degradation of its polymeric binder – phenol-formaldehyde resin and butadiene-nitrile rubber (NBR).

The presence of low-temperature and high-temperature phases of intensive mass loss of the studied model materials in the first place caused
by process of thermal degradation of the polymer binder, and then processes the binder burnout and other components. It was established experimentally that the introduction in composition the modifiers adhesive and viscoelastic characteristics have no significant effect on the thermal stability of the materials. It is found that the proposed adhesive compositions based on rubber-resin binders have higher heat resistance in comparison with conventional materials of similar purpose based on bitumen, rubber- bitumen and epoxy binders.

**Results of DMA tests**

Temperature dependences of the storage modulus and mechanical loss tangent for experimental compositions are presented in Fig. 8 – 10.

![Graphs](image)

**Fig. 8** Temperature dependence of the storage modulus (1) and mechanical loss tangent (2) for Sample group I (table 1): a – Sample 1; b – Sample 2; c – Sample 3; d – curing kinetics of the rubber component of the polymer binder at 110°C (1', 2') and 140°C (1'', 2'')
Fig. 9 Temperature dependence of the storage modulus (1) and mechanical loss tangent (2) for Sample group II (see table 1)

In contrast to the findings obtained based on the simultaneous thermal analysis, results of dynamic mechanical analysis show in a wide temperature range a strong dependence of the mechanical properties of both the composition and processing conditions when obtaining samples of adhesive materials. As shown in Fig. 8 (a–c), for the base composition containing no modifying additives, there is a significant (up to 35%) reduction in tanδ and offset of $T_{gb\text{max}}$ from 20–40°C to temperature region 90–110°C. This is due to intensification of cross-linking of macromolecules of the thermosetting binder with an increase in temperature from 140°C to 180°C during thermocompression treatment of the samples. Thus, in Fig. 8 (d), shows the kinetics of curing the rubber component in isothermal test modes at temperatures of 110°C and 140°C for 140 minutes. A sharp increase in the dynamic modulus with increasing temperature from 110°C to 140°C as observed in Fig. 8 (d) is a result of the increased intensity of the curing process of the binder.
Figures 10 and 11 shows the results of dynamic mechanical analysis for II and III groups of samples of adhesive materials containing various modifying additives obtained in the medium of methyl ethyl ketone (MEK) and ethyl acetate (ACE) respectively. The results shown in Figures 8–10 confirm a substantial effect of modifiers on the viscoelastic properties of adhesive materials, expressed mainly in changing the storage modulus value and position $T_{g\text{max}}$ peak on the temperature scale. For all the studied samples with increasing frequency at 10 Hz is observed 30–40°C $T_{g\text{max}}$ offset to higher temperatures, which is in good agreement with experimental data [4, 5]. Thus, based on the obtained experimental data it is possible to make an appropriate selection of material composition taking into account the climatic operation conditions of the pipeline in a wide temperature range.

**Fig. 10** Temperature dependence of the storage modulus and mechanical loss tangent for Sample group III (see Table 1)
It should be noted that mechanical properties at negative temperatures were not investigated therefore the values of $T_{\text{lgmax}}$ have not been obtained for all studied samples. However, the investigation of mechanical properties of composite materials containing the rubber components is of particular interest since the main peak of the maximum mechanical losses is at negative temperatures, for example as shown in Fig. 11. In the following work is planned to study properties of these materials in a wider temperature range including subzero temperatures down to -50°C and to offer special compositions for low-temperature application.

![Graph showing storage modulus and mechanical loss tangent vs. temperature](image)

**Fig. 11** Dependences of the storage modulus and mechanical loss tangent on temperature including subzero region for composite materials containing the rubber components

### 6.4. CONCLUSION

New formulations of polymer composites which can be used as intermediate adhesive layer (so-called "soft" adhesive materials) for pipelines repair in the system “pipe metallic wall – filler – composite material wrap” have been developed to minimise delamination composite material wrap in the full range of the mechanical and thermal operating loads due to high elasticity and adhesion of the intermediate layer to metallic wall of the pipe and material wrap.
The results of the simultaneous thermal analysis (STA) conducted in this work have shown that the newly developed adhesive materials based on combined polymer-rubber binder have a higher thermal stability in comparison with the conventional materials based on bitumen, bitumen-rubber and epoxy binders. The investigation results indicate that of the complex physical and chemical processes that determine the level of heat resistance, and as a result, the ability to maintain the specified characteristics of the adhesive and mechanical properties of the materials during all operation period the processes of thermal degradation of its polymeric binder (phenol resin and nitrile rubber) are the most important.

The findings of the dynamic mechanical analysis (DMA) shows that a substantial impact due to adding modifiers in the viscoelastic properties of adhesive materials and their temperature dependence, is expressed mainly in changing the position of the maximum of mechanical loss factor on the temperature scale, as well as in the storage modulus value. For all investigated materials the $T_{\text{ghmax}}$ offset to higher temperatures on 30–40°C is observed when increasing frequency at 10 Hz. Based on the obtained experimental data it is possible to make an appropriate selection of material composition taking into account the climatic operation conditions of the pipeline in a wide temperature range.

6.5. REFERENCES

Assessment of mechanically stressed state in pipelines according to Russian standards

Mihovski¹ M.M., Mirchev¹ Y.N., Bukharov² S.N., Kozhushko² V.V.

¹Institute of Mechanics of BAS, Sofia, BULGARIA, nntdd@abv.bg, mirchev@imbm.bas.bg
²V.A. Belyi Metal Polymer Research Institute of National Academy Science of Belarus,
Gomel, BELARUS, sbuharov@tut.by

Summary: In work is presented method for assessment mechanical stress state (MSS) in pipeline materials in accordance with GOST R 52890-2007. The method is based on measurement spreading time of longitudinal and two transverse waves to pipe radius, which must done with enough high accuracy. In work the method is verified as investigated pipe from steel 38XC as used experimental acoustic-elasticity coefficients. Relationships for MSS to axis and circumference direction from pressure are presented in this work.

Keywords: mechanical stress state (MST)

7.1. INTRODUCTION

Serviceability of the materials is determined by the physical and mechanical properties and internal applied or residual stresses in the material. On the basis of a set of data are solves the problem of resource assessment and future process in order to ensure safe working conditions to prevent the destruction of the structure.

There are a significant amount of methods that allow to obtain information data correlated with the values and types of existing or residual stresses. To these methods can be referred the following: X-ray diffraction, neutron diffraction, electromagnetic, magnetostrictive and
based on magnetic effect Barkhauzen, on magnetic memory, thermoelectric, volume and surface ultrasonic, acoustic emission, strain measurement, speckle interferometry, laser optics, mechanical through holes and others. Most often, in practice using magneto noise methods based on the Barkhauzen effect and ultrasonic methods. The main advantages are: high satisfactory accuracy, portability of equipment, ability to realize the method in working condition.

A major influence on the accuracy of these methods have the following factors: microstructure of the material, scale factor and size of the object, residual of plastic deformation, changing temperature conditions during calibration and measurement, inhomogeneity in the distribution of mechanical stresses in the volume and surface of the object, mutual influence of the components under biaxial stress state, macro elastic inhomogeneity and others.

In cases, where the working conditions at the calibration of equipment are not the same, the determination of mechanical stresses in magnitude and type is especially difficult and sometimes unsolvable task.

*The purpose of work is:* analysis of the basic methods for determining the mechanical stress state (MSS) of pipelines using the change in the velocity of propagation elastics waves or time difference of propagation in environments with mechanical stress compared to mechanical unstressed materials.

**7.2. DESCRIPTION OF THE METHOD**

In the system of Russian legislation are presented two standards [1, 2], which regulate the application of ultrasonic methods for evaluation of the MSS.

GOST R 52890-2007 regulates the basic requirements for determining the MSS. Use volume ultrasonic waves that propagate in radius direction on controlled pipes. The standard is applicable to pipes of steel
(welded and seamless) with ratio the wall thickness to the outer diameter 20 times and to pipes with a diameter greater than 325 mm.

The standard was developed based on research developments Nizhgorodski branch of the Institute of Mechanical Engineering "A.A. Blagonravov" a subsidiary of Russian Academy of Sciences, conducted under the direction of Nikitina N.E. [3].

The main task in research MSS on pipes is determination of axially $\sigma_z$ and tangentially (perimeter direction) $\sigma_t$ mechanical stress, which is solved on the basis of existing theoretical relationship between velocity of propagation volume ultrasonic waves in square direction according to direction of mechanical stress. In thin-walled tube radial stresses are relatively small compared with $\sigma_z$ and $\sigma_t$, that warrant MSS of pipes be considered as two-dimensional flat. The determination of the MSS is done by measuring the velocities or times of spread transverse waves, polarized to and across of forming and longitudinal wave that propagates to the radius of the tube. Fig. 1 shows the direction of the existing mechanical stresses and polarized transverse and longitudinal waves in the tensile stresses in the pipe.

![Fig. 1 Direction of the existing mechanical stress $\sigma$ and polarized transverse waves](image)

Measurements are realized with specialized equipment with high accuracy when measuring the velocity and times of volumetric ultrasonic
waves. Emitted and received of the latter is realized with special transducers for transverses polarized waves and normal transducers for longitudinal waves.

In the process of measurement is recorded the initial velocities (time of propagation) in the material in the absence of mechanical stresses, taking into account the acoustic anisotropy of the material, microstructure etc. factors.

Depending on the measurement conditions, the current primary acoustic state of the material is carried on specially prepared samples or on the test pipes.

Coefficients of acoustical-elasticity necessary for the transformation of ultrasound parameters to mechanical stresses are characteristics of materials related to describe the mechanical behavior of materials modules for linear and non-linear elasticity (coefficient of Lame $\lambda$ and $\mu$ and modules Murnaghan l, m and n). Typically, these acoustical-elastic characteristics of the material are obtained by combining of the loaded mechanical forces on samples and measuring the information ultrasonic parameters. Permissible relative error in measuring according to standards is $\pm 10\%$.

Measurements shall be done with certified measuring equipments. Use normal probe for emitted of longitudinal and transverse ultrasonic waves. The measurements are usually in the echo-pulsed type of the test. The surface in the measuring zone mast be a roughness $Ra\approx 2.5\mu m$. As contact medium is used an epoxy resin. Mandatory is monitoring the temperature of the test material. In order to increase the accuracy of the method is used repeatedly reflected signals received in an area of a plane opposing walls in the pipe and in the absence of signals from a discontinuity in the volume of the tube.

**7.3. THEORETICAL APPROACH OF THE METHOD**

Based on the theory of linear acoustical-elasticity in the case of the model shown in Figure 1, loaded with mechanical stresses $\sigma_z$ and $\sigma_t$, (flat stressed state) can enroll the following relations:
Assessment of mechanically stressed state in pipelines according to Russian standards

\[ V_1 = V_{01}(1 + k_1 \sigma_z + k_2 \sigma_t), \]  
\[ V_2 = V_{02}(1 + k_2 \sigma_z + k_1 \sigma_t), \]  
\[ V_3 = V_{03}(1 + k_3 \sigma_z + k_3 \sigma_t), \]  

wherein \( V_1 \) and \( V_2 \) are respectively the propagation velocity of transverse waves with different polarization, \( V_3 \) — propagation velocity of longitudinal wave. All waves propagate in the radius of the tube, \( k_i \) are acoustical-elastic coefficients. \( \sigma_z \) and \( \sigma_t \), are respectively, mechanical stresses to the axial and perimeter direction.

The system of equations for determining the main stress to the axis of symmetry of the pipe, from velocity of propagation ultrasonic waves is present with the follow relationships

\[ k_1 \sigma_z + k_2 \sigma_t = \frac{L}{t_1} \cdot \frac{t_{01}}{L_0} - 1, \]  
\[ k_2 \sigma_z + k_1 \sigma_t = \frac{L}{t_2} \cdot \frac{t_{02}}{L_0} - 1, \]  
\[ k_3 \sigma_z + k_3 \sigma_t = \frac{L}{t_3} \cdot \frac{t_{03}}{L_0} - 1, \]  

wherein \( L_0 \) and \( L \) are respectively the paths of the spreading wave before and after applying the mechanical stresses, \( t_{0i} \) and \( t_i \) — times of propagation waves, respectively, before and after applying the stress \( \sigma_z \) and \( \sigma_t \).

After transformation of dimensionless quantities and the use of values \( L/L_0 \) is reached the new formula for elastic-mechanical material characteristics \( K_1 \) and \( K_2 \), which depend on the dimensionless evaluation of the propagation times of the elastic waves.

Mechanical stress are recorded in the form
\[ \sigma_z = K_1 \Delta_1 - K_2 \Delta_2, \tag{7} \]
\[ \sigma_t = K_1 \Delta_2 - K_2 \Delta_1, \tag{8} \]

where
\[ \Delta_1 = \left( \frac{t_3 - t_{01}}{t_1 t_{03}} - 1 \right), \tag{9} \]
\[ \Delta_2 = \left( \frac{t_3 - t_{02}}{t_2 t_{03}} - 1 \right). \tag{10} \]

\( t_1, t_2 \) and \( t_3 \) indicate, respectively, the times of the distribution of both transverses and longitudinal waves, \( t_{01}, t_{02} \text{ and } t_{03} \) - time distribution in the absence of mechanical stress.

In the case of single axle MSS
\[ \sigma_z = D (\alpha - \alpha_0), \tag{11} \]
where \( D = K_1 + K_2, \, \alpha = (t_2 - t_1)/t_2, \, \alpha_0 = t_{02} - t_{01}/t_{02}. \)

Finally in ГОСТ52890-2007 are recorded the following relation for \( \sigma_z \) and \( \sigma_t \),
\[ \sigma_z = D (\alpha - \alpha_0), \tag{12} \]
\[ \sigma_t = D (\alpha_0 - \alpha). \tag{13} \]

If the material is with strong anisotropy - \( t_{01} \) and \( t_{02} \) differ by \( 1.5 \div 2\% \) then calculations for \( \sigma_z \) and \( \sigma_t \) are realize with relation
\[ \sigma_z = K_1' \left( \frac{t_{01} t_3}{t_1 t_{03}} - 1 \right) - K_2' \left( \frac{t_{02} t_3}{t_2 t_{03}} - 1 \right), \tag{14} \]
\[ \sigma_t = K_1' \left( \frac{t_{02} t_3}{t_2 t_{03}} - 1 \right) - K_2' \left( \frac{t_{01} t_3}{t_1 t_{03}} - 1 \right). \tag{15} \]
where $K_1^\parallel$ and $K_1^\perp$ are acoustical-elastic coefficients, obtained in the case of mechanical stresses which applied on and normal to the perimeter of the tube.

In cases where the difference in temperature before and during the test exceed $10\, ^\circ\mathrm{C}$, the temperature factor is account as the ratio $t_3/t_{02}$ and recorded as $t_3/t_{02}(1+k_i\Delta T)$, wherein $\Delta T$ is the temperature difference, $k_i$ — relative change of timing distribution of transverse (longitudinal) wave for $1\, ^\circ\mathrm{C}$.

### 7.4. INVESTIGATION OF MSS IN PIPELINE

The materials used in technological pipelines are characterized by strong anisotropy, which is associated with structural changes and changes of the MSS, which are comparable in magnitude. Anisotropy of some steels in the form of sheet products used for the manufacture of welded steel tubes with large diameter (800÷1400mm), exceed the mechanical stresses that exist outside of alloying metal. These changes may be within up to 8%, such as steel 10Г2ΦБ20, used for welded steel pipe for the pipeline. Definitely influenced the the velocity change of propagation waves for changes in temperature during the testing [3].

Based on experience [3] give the following advice for the realization of research:

— we believe that the material of the pipe is orthotropic and applied mechanical stress on pipe are strength-pressure;

— anisotropy of the material to be considered only the change of values for the velocity of propagation, and not to assess the stresses of the material;

— providing precise measurements of velocity and times of propagated ultrasonic waves.

**Experimentally obtaining of acoustically-elastic coefficients**

To obtain the coefficients of the acoustical-elastic are prepared comparative samples simple with parallelepiped shape and rectangular cross-section of the material to be tested. When preparing samples of the
test material is taken into account and characteristics—microstructure, preliminary (residual) mechanical stresses and others.

The samples are tensile ore pressure loaded on a test machine with high accuracy. In accordance with the standard is implemented attaching the probes to sample and carry out the necessary determination of the propagation times of transverse and longitudinal waves that propagate in the square direction of the applied load. With the values obtained for the times of the propagated waves are calculated coefficients $K_1$ and $K_2$ with following relation:

$$K_1 = \frac{k'' - k_3}{(k'' - k_3)(k'' - k_3) - (k_2 - k_3)^2},$$

(16)

$$K_1^\perp = \frac{k_1^\perp - k_3}{(k'' - k_3)(k'' - k_3) - (k_2 - k_3)^2},$$

(17)

$$K_2 = \frac{k_2 - k_3}{(k'' - k_3)(k'' - k_3) - (k_2 - k_3)^2},$$

(18)

In [3] is entered data for acoustical-elastic coefficients for some of the traditional tested steels, which are represented by average values and their uncertainty according to their obtaining (Table 1).

<table>
<thead>
<tr>
<th>Steel grade</th>
<th>$K_1.10^{-5}$ MPa</th>
<th>$K_2.10^{-5}$ MPa</th>
<th>$D.10^{-5}$ MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel 20</td>
<td>-1.05±0.12</td>
<td>-0.21±0.1</td>
<td>-1.27±0.11</td>
</tr>
<tr>
<td>38ХС</td>
<td>-1.09±0.05</td>
<td>-0.19±0.07</td>
<td>-1.28±0.04</td>
</tr>
<tr>
<td>17Г1С</td>
<td>-1.07±0.07</td>
<td>-0.15±0.02</td>
<td>-1.21±0.11</td>
</tr>
<tr>
<td>09Г1ФЕ</td>
<td>-1.06±0.03</td>
<td>-0.12±0.04</td>
<td>-1.18±0.03</td>
</tr>
<tr>
<td>09Г1ФЕ</td>
<td>-1.06±0.07</td>
<td>-0.16±0.09</td>
<td>-1.22±0.11</td>
</tr>
<tr>
<td>X70</td>
<td>-0.8</td>
<td>-0.1</td>
<td></td>
</tr>
<tr>
<td>X70</td>
<td>-1.2</td>
<td>-0.14</td>
<td></td>
</tr>
</tbody>
</table>
Based on averages for $K_1$ and $K_2$ for steel 38XC shown received by us values for $\sigma_z$ and $\sigma_t$, in the cases when experimental data are in the range of values for variations to the $K_1$ and $K_2$. The results are presented in Fig. 2 and Fig. 3.

**Fig. 2** Depending of the mechanical stresses $\sigma_t$ obtained by ultrasonic waves with an applied mechanical tensile stress $\sigma$ for steel 38XC

**Fig. 3** Depending of the mechanical stresses $\sigma_z$ obtained by ultrasonic waves with an applied mechanical tensile stress $\sigma$ for steel 38XC

The values represented by the notation 0 refer to calculations obtained average values for acoustical-elastic coefficients [3]. The remaining values refer to the case where we differ from the average of the propagated times of the waves. The maximum variation reaching 10% of the obtained averages.
7.5. CONCLUSION

The article presents a method for determining the MSS on a plane stress state of the material, which corresponds to the load pipeline. The method opens great opportunities for the study of MSS which gives information on both the axial and tangential stresses. Accuracy is practical acceptable and when preparat suitables comparative samples for determining MSS the accuracy can be increased significantly.

7.6. REFERENCES

CHAPTER VIII

Investigation on composite materials used for damaged highway pipelines bandaging by low frequency resonance vibrations method

Alexiev¹ A.R., Masiuchok² O.P., Bukharov³ S.N.

¹ Institute of Mechanics of BAS, Sofia, BULGARIA, alexiev@imbm.bas.bg
² E.O. Paton Electric Welding Institute of NASU, Kiev, UKRAINE, masyuchock@bigmir.net
³ V.A. Belyi Metal Polymer Research Institute of National Academy of Sciences of Belarus, Gomel, BELARUS, suharou@tut.by

Summary: In the work presented in this paper, composite materials are investigated on the basis of epoxy resins with fillers, used for manufacturing of bandages for damaged highway pipelines repairs. The samples produced for this purpose are with or without reinforcement of tissues, on the basis of glass or carbon fibers. Method of low frequency resonance bending vibrations is approbated, thus materials’ mechanical characteristics are derived and particularly, dynamic module of elasticity and coefficient of internal friction.

Keywords: composite materials, bandaging, highway pipelines, low frequency resonance vibrations, dynamic module of elasticity, coefficient of internal friction

8.1. MATERIALS AND SAMPLES

Composite materials are investigated on the basis of epoxy resins with fillers, used for manufacturing of bandages, scheduled for high way
pipelines’ repairs. Samples are produced in V.A. Belyi Metal Polymer Research Institute of NANB and their composition is presented in Table 1.

### Table 1  Samples’ composition

<table>
<thead>
<tr>
<th>№</th>
<th>Component</th>
<th>Quantity (% per kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Composition № 1 (Sample 1)</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Epoxy resin ED-20</td>
<td>53,0</td>
</tr>
<tr>
<td></td>
<td>Epoxy resin ED-181</td>
<td>37,0</td>
</tr>
<tr>
<td>3</td>
<td>Epoxy-bisphenol resins hardener PEPA</td>
<td>10,0</td>
</tr>
<tr>
<td>1</td>
<td><strong>Composition № 2 (Sample 2)</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Epoxy resin ED-20</td>
<td>48,8</td>
</tr>
<tr>
<td></td>
<td>Epoxy resin ED-181</td>
<td>34,3</td>
</tr>
<tr>
<td>3</td>
<td>Epoxy-bisphenol resins hardener PEPA</td>
<td>16,9</td>
</tr>
<tr>
<td>1</td>
<td><strong>Composition № 3 (Sample 3)</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Epoxy resin ED-20</td>
<td>46,0</td>
</tr>
<tr>
<td></td>
<td>Epoxy resin ED-181</td>
<td>32,3</td>
</tr>
<tr>
<td>3</td>
<td>Epoxy-bisphenol resins hardener PEPA</td>
<td>15,9</td>
</tr>
<tr>
<td>4</td>
<td>Calcium stearate</td>
<td>0,3</td>
</tr>
<tr>
<td>5</td>
<td>Graphite</td>
<td>5,5</td>
</tr>
<tr>
<td>1</td>
<td><strong>Composition № 4 (Sample 4)</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Epoxy resin ED-20</td>
<td>46,0</td>
</tr>
<tr>
<td></td>
<td>Epoxy resin ED-181</td>
<td>32,5</td>
</tr>
<tr>
<td>3</td>
<td>Epoxy-bisphenol resins hardener PEPA</td>
<td>16,0</td>
</tr>
<tr>
<td>4</td>
<td>Epoxy-silicate filler (Fe)</td>
<td>5,5</td>
</tr>
</tbody>
</table>

Samples from composition No. 2 are produced, reinforced by tissues on the basis of glass (Sample 2 + fibreglass tape) and carbon fibres (Sample 2 + graphite tape). Tissue of carbon fibres is unidirectional, of type TU RB 400031289.170-2001, produced in Belarus. At one of the samples, the tissue of carbon fibres is treated by vacuum spraying with Polytetrafluoroethylene
(PTFE) (Sample 2 + graphite tape + PTFE). The aim is investigation on the influence of decreasing of the stage of adhesion between the tissues and the epoxy resin on the mechanical characteristics. Samples are manufactured in the form of rods with a rectangular cross section, in order to carry on the up to date experiments. Steel ferromagnetic rod is stuck at one of the rod walls, thus a composed of two materials rod is configured — investigated and possessing well known characteristics. The samples length is 120 mm, 9 and 10 mm width, 7.5 — 10 mm thickness, 1.38 mm thickness of the steel rod. Their appearance is shown in Fig. 1.

![Samples — External appearance](image)

**Fig. 1** Samples — External appearance

### 8.2. MEASURING METHOD AND APPARATUS

Low frequency resonance method is used at the experiments. Mechanical bending vibrations are excited by electromagnetic transformer in the appropriately handled samples. Resonance vibrations are formed in the sample by means of excitation frequency variation by the sound generator, which are registered according to the maximal amplitude of the accepted electrical signal by analogical electromagnetic transformer. Registration of this signal is performed by voltmeter and oscilloscope.

The first (the lowest) resonance frequency of the investigated sample is registered in the measurement process and the width of the resonance curve on level 3dB, at which the vibration power decreases twice, that
means frequencies at which the amplitude of the registered vibrations are equal to 0.7 of the maximal value of the measured at resonance amplitude.

Mechanical stand for sample fixing is designed in such a way, that sample is fixed in vibration nods in resonance mode. Nods are located at 0.22 from both sample ends, for the used rod samples with a rectangular cross section. Apparatus block scheme is shown in Fig. 2.

![Apparatus block scheme](image)

**Fig. 2** Apparatus block scheme

Apparatus block scheme includes the following elements and devices: FM — Frequency meter, SG — Signal generator, EC1, EC2 — Electromagnetic converter, V — Voltmeter, O — Oscilloscope, Stand for sample fixing, Sample. Measuring set up general view for measuring frequencies of low frequency resonance bending vibrations is shown in Fig. 3.

![Measuring set up general view](image)

**Fig. 3** Measuring set up general view for measuring frequencies of low frequency resonance vibration
8.3. TESTED SAMPLES MODULE OF ELASTICITY AND COEFFICIENT OF INTERNAL FRICTION DEFINITION

The module of elasticity of material real part of a rod sample with a rectangular cross section and free ends is defines below as follows:

\[ E = 48\pi^2 \rho \left( \frac{L^2}{h \cdot f} \right)^2 \]  

(1)

where: \( L \) and \( h \) are, the length and the thickness of the rod sample, respectively, \( \rho \) – material density, \( f \) – resonance frequency, \( k \) – coefficient, at the first resonance frequency \( k = 22.4 \). Coefficient of external friction \( \eta \) is defined from the value:

\[ \eta = \frac{\Delta f}{f} \]  

(2)

where: \( \Delta f = f''-f' \), \( f'' \) and \( f' \) are frequencies, at which the registered vibrations’ amplitudes are equal to 0.7 of maximal value of the measured at resonance amplitude. Complex module of elasticity is defined from the relation:

\[ E_{\text{comp}} = E (1 + i\eta) \]  

(3)

The investigated material module of elasticity is defined from the equality [1]:

\[ E_2 = E_1 \frac{\left( \frac{D}{D_1} - 1 \right) (1 - q_1 - xq_2) + q_2 (1 - q_1) 3x(q + x)^2}{x \left[ 4 + 6x + 4x^2 - D / D_1 - x^2 (q_1 + xq_2) - 3q_1 (1 + x)^2 \right]} \]  

(4)

where: \( D = \frac{4\pi^2 L^4 f^2 m}{k^2} \) and \( D_1 = \frac{E_1 h_1^3}{12} \) are bending stiffness of the composite and the steel rods, respectively, \( x = h_2 / h_1 \), \( m = \rho_1 h_1 + \rho_2 h_2 \); \( h_1, h_2 \) and \( \rho_1, \rho_2 \) – thickness and density of the metal and the investigated
material, respectively, \( f \) — first resonance frequency of the investigated composite sample, \( q_1 = \frac{\rho_1}{E_1} \omega \sqrt{D/m} \), \( q_2 = \frac{\rho_2}{E_1} \omega \sqrt{D/m} \), \( \omega = 2\pi f \).

Coefficient of the investigated material internal friction is presented by the value [2]:

\[
\eta_2 = \eta \frac{1 + Ax}{Ax} \frac{\frac{1 + Ax}{Ax} \left( \frac{2 + 3x + 2x^2}{3 + 6x + 4x^2 + 2Ax^3 + A^2x^4} \right) + A^2x^2}{3 + 6x + 4x^2 + 2Ax^3 + A^2x^4} \tag{5}
\]

where: \( A = \frac{E_2}{E_1} \), \( \eta \) — coefficient of the composite rod internal friction.

**8.4. DERIVET RESULTS AND ANALYSIS**

Values are derived of the investigated materials dynamic elasticity modules and coefficients of internal friction, as a result of the carried out experiments and analysis and processing of the experimental data. Data are presented in Table 2.

**Table 2** Dynamic elasticity modules and coefficient of internal friction

<table>
<thead>
<tr>
<th>Sample, №</th>
<th>( E ), GPa</th>
<th>( \eta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>5,660</td>
<td>0,082</td>
</tr>
<tr>
<td>3</td>
<td>5,868</td>
<td>0,081</td>
</tr>
<tr>
<td>4</td>
<td>5,893</td>
<td>0,084</td>
</tr>
<tr>
<td>2+graphite tape</td>
<td>10,004</td>
<td>0,102</td>
</tr>
<tr>
<td>2+graphite tape+PTFE</td>
<td>9,076</td>
<td>0,126</td>
</tr>
<tr>
<td>2+fiberglass tape</td>
<td>9,540</td>
<td>0,157</td>
</tr>
</tbody>
</table>

**8.5. CONCLUSION**

In the work presented in this paper, non destructive method is approbated of low frequency resonance bending vibrations for mechanical characteristics derivation of composite materials on the basis of epoxy resins. Data are derived for the dynamic elastic module and the
coefficient of internal friction of the materials under investigation. The material, reinforced with tissue made from carbon fibres, possesses the highest value of dynamic module of elasticity. The treated material with the aim of low adhesion between the resin and the tissue possesses lower value of the module, than the raw one. Results are comparable with ones, derived for the dynamic elastic module at non destructive ultrasound material investigation [3].

8.6. REFERENCES


New composite systems for pipeline coating

Dușescu¹ C.M., Oprescu¹ E.E., Negoiță¹ L.I., Bukharov² S.N.,
Sementouskaya² A.A., Kudina² H.F.

¹Petroleum — Gas University of Ploiesti, Ploiesti, ROMANIA, cdusescu@upg-ploiesti.ro
²V.A. Belyi Metal Polymer Research Institute of National Academy of Sciences of Belarus,
Gomel, BELARUS, kudina_mpri@tut.by

Summary: This study investigate the possibilities to prepare and characterize a new material for reinforcement of pipelines with volumetric surface defects, starting from acrylonitrile rubber, phenolic resins, additives and filler. After preparation and conditioning, the obtained composites were characterized from chemical point of view, in order to evaluate the crosslinking between rubber and resin, and physical point of view, to point out the influence of crosslinking degree over the mechanical properties of the new proposed materials.

Keywords: rubber, phenolic resins, crosslinking, tensile properties, dynamic mechanical analysis

9.1. INTRODUCTION

Even nowadays new technologies using plastic, flexible tubes are implemented on field, in traditional way the networks for petroleum products distribution, as well as the storage systems are made by rigid steel. In time, because of the atmospheric factors, the composition of the transported products or because of other types of incidents, the pipeline can suffer damages. There are several practices in the oil industry for repairing and reinforcement of pipelines, by using composite materials.
Between the materials used for synthesis of pipeline coating are fiber reinforced polymers, polyurethanes, carbon fiber reinforced polymer matrix composite, glass -fiber based composite systems, bitumen, polyolefines, polyimides, rubbers. The polyurethanes have the advantages of low viscosity, excellent bonding with the matrix material without special sizing of the fibers, relatively low price and fast reaction time [1–4]. Generally, the material proposed for pipe coating must take into account the elastic behavior of the steel that pipe is made of, about the soil elasticity in the case of buried pipe, about the pedo – climatic factors that may cause the occurrence of the corrosion phenomena on the pipe surface.

The composites materials based on nitrile rubber (NBR) and phenolic resin have high damping properties and at the same time, may retain high mechanical strength over a wide and useful temperature range, but unfortunately are scarcely studied in the scientific literature as composites for refining the vibration absorption. Viscoelastic materials are able to reduce vibration damping and improve isolation due to a unique combination of low modulus and inherent damping [5]. Rubber products have many uses as engineering materials because of their unique combinations of elastic and viscous properties [6]. However, efficient damping properties of rubbers are limited by the glass transition temperature Tg. Therefore, it is important to prepare some new composite materials with high damping and soundproofing properties modified by physical or chemical methods [5]. Phenolic-resins (PH) has been the most common polymeric binder because contains a high density of hydroxyl groups that are able to interact with numerous other polymers through hydrogen bonding [7]. PH are widely used as coatings, adhesives, composites and stable additives on damping performance due to their excellent flame resistance, heat resistance, insulativity, dimensional stability and chemical resistance [8].

The incorporation of PH into rubber matrix enables the obtaining of a polymeric binder with balanced properties of flexible rubber and the
thermosetting resin [9]. The most established and commercially exploited rubber from rubber-PH systems is nitrile rubber because its solubility parameter is the closest to phenolic resin and the interactions between nitrile rubber and phenolic resin at the interfacial zone have a dominant effect on the mechanical properties of the blend by absorbing energy [10].

The aim of this paper was to synthesis pipe repairing composite materials based on nitrile rubber and two phenolic resins using dissolution technique. It was analyzed also the influence of the solvent type on the properties of the prepared materials. In this regard were evaluated the crosslinking degree between rubber and resins and the mechanical properties of the composite materials.

9.2. MATERIALS AND METHODS

For the formulation of the composite materials were used as starting material nitrile rubber with a content of 29 % acetonitrile groups (NBR) provided by Krasnoyarsk synthetic rubber plant. As crosslinking agents two types of phenolic resins: Novolac (NOV) and Resol (RES) provided by Hexion were used. The phenolic curing system was choose because the common vulcanizing agents used such as sulfur, peroxide and mixed sulphur–peroxide have some the disadvantage i.e. sulfur curing agent always give an unpleasant strong odor during the fabrication process, meanwhile the peroxide curing system induce a blooming effect, decompose into smelly byproducts and in addition, undesired side reactions, such as disproportionation and chain scission, also occur during the mixing process [11]. To accelerate the crosslinking reaction, MgO and stearic acid were selected as accelerate agents, while SnCl₂ was added as Lewis acid activator for the crosslinking reaction of phenol resin. The catalyst and the accelerators used are reactive grade from Sigma – Aldrich.
Table 1 Legend for samples prepared by solvent method

<table>
<thead>
<tr>
<th>Sample</th>
<th>Solvent</th>
<th>Resin</th>
<th>Catalyst</th>
<th>Accelerator, (MgO+Stearic Ac.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ACE</td>
<td>ACE</td>
<td>50%NOV</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2 ACE</td>
<td>ACE</td>
<td>50%NOV</td>
<td>5%</td>
<td>-</td>
</tr>
<tr>
<td>3 ACE</td>
<td>ACE</td>
<td>50%NOV</td>
<td>5%</td>
<td>5%MgO, 5% Stearic Acid</td>
</tr>
<tr>
<td>4 MEK</td>
<td>MEK</td>
<td>50%NOV</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5 MEK</td>
<td>MEK</td>
<td>50%NOV</td>
<td>5%</td>
<td>-</td>
</tr>
<tr>
<td>6 MEK</td>
<td>MEK</td>
<td>50%NOV</td>
<td>5%</td>
<td>5%MgO, 5% Stearic Acid</td>
</tr>
<tr>
<td>7 ACE</td>
<td>ACE</td>
<td>50% RES</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8 ACE</td>
<td>ACE</td>
<td>50% RES</td>
<td>5%</td>
<td>-</td>
</tr>
<tr>
<td>9 ACE</td>
<td>ACE</td>
<td>50% RES</td>
<td>5%</td>
<td>05%MgO, 5% Stearic Acid</td>
</tr>
<tr>
<td>10 MEK</td>
<td>MEK</td>
<td>50% RES</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11 MEK</td>
<td>MEK</td>
<td>50% RES</td>
<td>5%</td>
<td>-</td>
</tr>
<tr>
<td>12 MEK</td>
<td>MEK</td>
<td>50% RES</td>
<td>5%</td>
<td>5%MgO, 5% Stearic Acid</td>
</tr>
</tbody>
</table>

The selected method for making the composite blends was co-solvent blending. The process of preparing samples by co-solvent blending consists in 3 stages. In the first step, rubber was dissolved into solvent (methyl ethyl ketone (MEK) or ethyl acetate (ACE)). After rubber swelling, all components dissolved separately in solvent were blended and sonicated for 30 minutes at 50°C to ensure a homogeneous composition and finally, the solvent was removed progressive until the temperature reach 140°C. In order to study the possibility to increase the crosslinking degree and to ameliorate the mechanical properties of the composite materials, there were prepared samples with different composition, including only the rubber and phenolic resins, or the two components in the presence of catalyst, or the catalyst and the accelerators in the same time. The different compositions prepared are presented in Table 1. ATR–FTIR spectroscopy was used to study the crosslinking reactions of
the blends. The Fourier transform infrared (FTIR) spectra were recorded on a Alpha FTIR spectrometer in the range 4000–650 cm\(^{-1}\).

9.3. RESULTS AND DISCUSSION

The structure and the chemical changes of the samples based on NBR-Novolac system using ethyl acetate (ACE) and methyl ethyl ketone (MEK) as solvents are presented in figure 1. Figure 1a, exhibit the characteristic peaks for NBR at 2923 and 2851 cm\(^{-1}\) (aliphatic C-H stretching), 2236 cm\(^{-1}\) (\(-\text{C}=\text{N}\) stretching), 1663 cm\(^{-1}\) (\(\text{C}=\text{C}\) stretching), 965 cm\(^{-1}\) (\(-\text{C}=\text{C}\) stretching of BD) and 815 cm\(^{-1}\) (\(\text{=C}-\text{H}\) deformation), meanwhile Novolac shows vibration bands 3382 cm\(^{-1}\) (hydrogen bonding of phenol), 1640 (\(-\text{C}=\text{C}-\) stretching of aromatic rings of phenol), and 1237 cm\(^{-1}\) (\(-\text{C}=\text{O}-\) stretching of aromatic rings of phenol) [11].

Figure 1b presents the FT-IR spectra in a range of 1100–600 cm\(^{-1}\) for samples obtained by solvent method using ethyl acetate. By comparing the spectra may be observed a diminishing absorption intensity of the peaks at 968 and 917 cm\(^{-1}\) attributed to stretching vibration of \(-\text{C}=\text{C}\) from butadiene group and out-of-plane vibration of the methylene hydrogen atom of the vinyl group, respectively, possible due to the crosslinking phenomenon which occurred at the double bonds of butadiene part from NBR. The shifting and weakening of the peaks at 757 and 820 cm\(^{-1}\), which corresponds to the out-of-plane deformation vibration of C-H at the ortho and para position of phenolic hydroxyl group [10], indicates the fact that the hydrogen atoms at ortho position of PF were subject to substitution of some active functional group on NBR.

The same behavior was observed for the samples obtained using MEK solvent (Figure 1c). The best results were obtained for samples 2 ACE, respectively 5 MEK, where only SnCl\(_2\) was used as catalyst.
Fig. 1 FT-IR spectra for NBR-Novolac system for solvent method:
a) nitril butadiene rubber (NBR), phenolic resin NOVOLAC, and their blends with different crosslinking agents;
b) FTIR spectra in range 1100-600 cm\(^{-1}\) for NBR, NOV, samples 1-3 ACE;
c) FTIR spectra in range 1100-600 cm\(^{-1}\) for NBR, NOV, samples 4-6 MEK

Another vulcanization agent tested having phenolic resin structure was RESOL (RES). The FT-IR spectra of the samples based on NBR-Resol system using ethyl acetate (ACE) and methyl ethyl ketone (MEK) as solvents are presented in figure 2. Figure 2a, presents the peaks for Resol. The stretching vibration of phenolic hydroxyl group shows a broad peak at 3299 cm\(^{-1}\). The absorptions vibration at 1653 and 1227 cm\(^{-1}\) (-C=O- stretching of aromatic rings of phenol and -C-O- stretching of aromatic rings of phenol, respectively [15]. Figures 2b and 2c, compares the representative FT-IR spectra in the wavenumber range of 1100–600 cm\(^{-1}\) for the samples 7–9 ACE and 10-12 MEK (Table 1). As can be seen in figures 2b and 2c, after the reaction, the peaks 968 and 917 cm\(^{-1}\) decreases in intensity indicating a low saturation in butadiene group.
Therefore, the crosslinking mostly took place in the butadiene group of NBR. This affirmation is sustained by the vibration reduction of the hydrogen atoms at ortho or para position (peaks at 818 and 756 cm\(^{-1}\)) of phenolic hydroxyl group which are very active and can be subject to substitution of some active functional groups.

![FT-IR spectra for NBR-Resol system for solvent method](image)

**Fig. 2** FT-IR spectra for NBR-Resol system for solvent method:

a) nitril butadiene rubber (NBR), phenolic resin RESOL (RES), and their blends with different crosslinking agents;

b) FTIR spectra in range 1100-600 cm\(^{-1}\) for NBR, RES, samples 7-9 ACE;

c) FTIR spectra in range 1100-600 cm\(^{-1}\) for NBR, RES, samples 10-12MEK

All samples were subjected to the DMA and STA tests. Regarding Dynamic Mechanical Thermal Analysis (DMTA), the effect of the mixing processing on the dynamic mechanical properties was also evaluated, in terms of storage modulus and tan delta versus temperature. All samples displayed higher storage modulus below glass transition temperature and higher glass temperature than those found
for samples 3ACE and 12 MEK, indicating reinforcing action of the catalyst and additives.

The storage modulus reflects the recoverable (elastic, solid like) energy in a deformed specimen while loss modulus represents the (liquid like) energy lost by dissipation. The storage modulus (E) and dynamic loss factor (tan\(\delta\)) were measured as a function of temperature with a dynamic mechanical thermal analyser under the tension mode at a frequency of 1 Hz and 10 Hz. The strain amplitude in the temperature range of 25 to 175°C was 0.15%. The heating rate was 5°C/min.

In figure 3 shows the storage modulus of our samples at the frequency of 1.0 Hz and 10 Hz and the variation of tan\(\delta\) with temperature.

The DMA investigation reveals that the variations for the storage modulus and tan\(\delta\) are similar for the different solvent, this fact proves that mixing does not depends on solvent.

Ignoring the solvent, it was obtained the same variations for the storage modulus and tan\(\delta\) (TAN) for samples 2ACE and 11MEK where the components are rubber, resin and catalyst SnCl\(_2\). The same thing happened with samples 3ACE and 12 MEK where the components are rubber, resin, catalyst and additives. For the samples 2ACE and 11MEK are used only catalyst in mixture with rubber and resin (novolac or resol). In figure 3 shows that the high peak tan\(\delta\) (TAN) are at highest temperature for 10 Hz frequency. This temperature varies between 110–130°C. For the samples 3ACE and 12 are used catalyst and additives together with rubber and resin. Figure 3 shows that the peak tan\(\delta\) are at highest temperature for 10 Hz frequency. This temperature varies between 150–170°C. For all the samples at a lower frequency, 1 Hz respectively, the max tan\(\delta\) correspond to a lower temperature.
Fig. 3 Variation of the storage modulus and the damping with temperature

Thermal analysis (STA) measures the properties of materials qualitatively and quantitatively as a function of temperature and time. As shown in figure 4 it is very clearly that for all the samples prepared with solvent and subjected STA investigation the variations weight and delta T endo down with temperature are similar. For STA investigation are used a temperature range of 50 to 400°C, but for the sample 12 MEK bis subjected on STA the investigation temperature range was 50 to 800°C. The heat was made from 50 to 400°C or 800°C at 5°C/min. The experiments were done in switch gas to nitrogen at 20 ml/min.
Fig. 4 Variation of weight and delta T endo down with temperature by STA investigation

The STA investigation from 50 to 800°C is relevant to show the initial decomposition temperature. The initial decomposition temperature at weight loss is 400°C it can be observed in all diagrams from figure 4.
9.4. CONCLUSION

The experimental data for the analysed systems shows that the best results regarding to crosslinking reaction for the new formulations of NBR-NOV and NBR-RES system were obtained when only SnCl₂ was used as reaction catalyst. Using the data obtained by FT-IR analysis it can be propose a reaction mechanism in which during reaction, phenolic resin interacts with butadiene group of NBR yielding a methylene bridge structure.

The dynamic mechanical properties such as storage modulus (G’), loss modulus (G'’), and damping behaviour (tan δ) of NBR with resin (Novolac or Resol) have been studied as a function of temperature, different mass ratios of resin, catalyst and additives at two frequency (1 Hz, 10 Hz).

The storage modulus was found to be increased with increment in resin whereas it decreased with temperature, while increased with the increase of frequency.

The damping characteristics (tanδ) were observed to be decreased with the increase of frequency, while increased with the increase of temperature.

The combination of high onset temperature and high final char residue of the degradation process is a good reference of the thermal stability of the composite material.

9.5. REFERENCES


Experimental and numerical testing of small scale models of gas pipeline subjected to excavator elements interference

Baranowski¹ P., Neacsu² A., Dinita² A., Naim² R.,
Malachowski¹ J., Sybilski¹ K.

¹Faculty of Mechanical Engineering, Military University of Technology,
2 Gen. S. Kaliskiego Street, 00-908 Warsaw, POLAND,
pawel.baranowski@wat.edu.pl, jerzy.malachowski@wat.edu.pl, kamil.sybilski@wat.edu.pl

²Faculty of Mechanical Engineering, Petroleum-Gas University from Ploiești,
Blvd. Bucharest, no. 39, 100680, Ploiești, Prahova, ROMANIA,
adnea@mail.upg-ploiesti.ro, alindinita@yahoo.com, ing_ramadan@yahoo.com

Summary: The main aim of the paper is to investigate the behavior of a small-scale model (SSM) of pipeline in the conditions of three part intervention. A discrete model of a tested pipe was developed and validated with the actual one. The results obtained from the analyses were compared with the experimental tests and showed good accuracy in terms of force characteristics obtained in all simulated cases. Moreover, stress distribution in every case was also compared and discussed.

Keywords: FE analysis, hyperelastic material, copper, SSM
10.1. INTRODUCTION

The experimental testing plays a major role in developing and investigating pipelines used for natural gas transport. However, typical experimental tests are usually expensive due to large dimensions of tested parts of the pipeline and they require machines that can develop very large compressive forces. To be able to reduce the costs it is significant to optimize such tests using small-scale models (SSM). The results obtained can be transferred to actual-scale models with larger dimensions using principles of similarity theory.

One can find numerous papers [1-4] focused on the assessment of the material behavior both in the macroscopic and microscopic scale. Alternative to experimental testing is numerical modelling using the Finite Element Method (FEM), which enables estimation of deformation and stress states in the pipe structure in different loading conditions and configurations, which is impossible or very hard to be done by experimental means and, if necessary, to perform necessary design modifications, even before the production stage. The ultimate goal of investigations is usually to develop a numerical methodology, which allow for simulating the typical problems relating to pipelines, i.e. blast loading [5], bending testing [6,7] or pressure inflow inside pipe structure [8].

In the presented paper, besides experimental testing, SSM developing of the pipe and its simulating concept was presented. Actual tests were repeated using numerical simulations using Finite Element Method (FEM), more particularly LS-Dyna implicit code using full Newton-Raphson algorithm [9]. With the pipe proper material data, constitutive modeling as well as initial-boundary conditions it was possible to estimate a level of the stresses occurring within the area of the pipe which is directly in contact with the indenter (stamp). Additionally, different boundary conditions resulting from v-shaped and cylindrical mount were analysed. In the latter a hyperelastic material needed to be adopted which is based on the Mooney-Rivlin’s constitutive theory [10]. The results obtained from
the analyses were compared with the experimental ones in terms of force characteristics obtained in all simulated cases. Moreover, stress and plastic strain distribution in every case was also compared and discussed.

10.2. OBJECT OF INVESTIGATIONS

The behavior of the SSM pipe structure made of copper in the conditions similar to the excavator bucket teeth damage was investigated (Fig. 1). In order to carry out the experiments four different indenters were chosen with the same angle between the cutting surfaces of 45°. Also, two different mount surface were used: v-shaped mount and cylindrical mount with rubber-like insert. Therefore, eight tests can be distinguished with four different indenter widths (20 mm – test 1, 15 mm – test 2, 10 mm – test 3 and 5 mm – test 4).

![Experimental testing set-up with A) SSM copper pipe](image)

**Fig. 1** Experimental testing set-up with A) SSM copper pipe

10.3. FE ANALYSES

During FE simulations geometry of the pipe corresponded the actual SSM of pipe which was tested experimentally. As mentioned
before, eight different cases were taken into consideration, with their schematics presented in Figure 2.

In all simulated cases the pipe and the indenter were modelled using Belytschko-Tsay (BT) shell elements [9]. Such choice was dictated by the fact that these shell elements have five integration points through the thickness which requires only 725 mathematical operations compared to 4050 under integrated Hughes-Liu element (35 350 in selectively reduced) [9]. Rubber insert was modelled using brick elements with one integration point were adopted (constant stress solid elements) which are recommended for large deformation analyses [9]. Such solid formulation is default in LS-Dyna software and is efficient and accurate, however hourglass control needs to be used in almost every case.

Due to the small dimensions of the pipe there was no need for remeshing the area of pipe within a direct interaction with indenter and the fine mesh was used in whole model of the pipe. Moreover, indenter was simulated as a non-deformable part with steel properties, also, with a very fine mesh (where the part is a rigid one, the characteristic length of its element does not influence the timestep [9]).

![Diagram of investigated cases](image)

**Fig. 2** Schematic of investigated cases
The pipe—rigid indenter and pipe—mount (also with rubber insert) interaction was simulated using penalty based method. In the pipe and rigid indenter case, stiffness was calculated based only on the pipe material [9]. The principal feature of this method in FE code is placing normal interface springs between all nodes that penetrate the contact surface [9, 11]. At this point it should be noted that defining the contact stiffness should be carried out very carefully (its parameters) as it can change results drastically, even for the same initial-boundary conditions.

In order to simplify the model and reduce the computational time a symmetry of the problem was assumed and quarter of the model in all cases was taken into consideration (Fig. 3, Fig. 4).

**Fig. 3** FE model of pipe with initial-boundary conditions (cases with v-shaped mount)
Experimental and numerical testing of small scale models of gas pipeline subjected to excavator elements interference

Fig. 4 FE model of the pipe with the initial-boundary conditions (cases with cylindrical mount)

In all FE models the same material with copper properties was adopted for the pipe [12]. The behaviour of the material was described using piecewise linear plasticity constitutive model [9].

The behaviour of the insert was described using the Mooney-Rivlin (MR) [10] constitutive model which is a modified version of the Mooney model. Its parameters were taken from the literature [13]. The model is widely used and was one of the firsts in which the rubber response is linear under simple shear loading conditions. This model has been used until now for modelling rubber which deformation are lower than 200%. Mechanical parameters of both materials are listed in Table 1 and Table 2.

Table 1 Material data for copper material [12]

<table>
<thead>
<tr>
<th>ρ [kg/m³]</th>
<th>E [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Failure strain [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>8960</td>
<td>1.30E+5</td>
<td>395</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Table 2  Material data for MR material [13]

<table>
<thead>
<tr>
<th>$\square$ [kg/m³]</th>
<th>E [MPa]</th>
<th>Poisson’s ratio [-]</th>
<th>$C_1$ [MPa]</th>
<th>$C_1$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1173.00</td>
<td>14.00</td>
<td>0.45</td>
<td>0.81</td>
<td>1.81</td>
</tr>
</tbody>
</table>

10.4. RESULTS

From the carried out analyses the overall response of the pipe was obtained. Due to similar results in all cases only test 4 was selected and is discussed in the following section. In Fig. 5 the Huber–Mises–Hencky (HMH) equivalent stress distribution is presented, both with v-shaped and cylindrical mount. Different contact surface area (due to width of the knife) resulted in some discrepancies between maximum HMH stress values in the pipe area where the interaction with the indenter takes place. The narrower indenter was, the higher HMH stress values were obtained. Therefore, for the 5 mm indenter the highest values of HMH stress were observed ($267 \text{ MPa} – \text{test 4a}, 334 \text{ MPa} – \text{test 4b}$). In analyses with the cylindrical mount with rubber, the maximum HMH stress value was approximately 15% higher than in v-shaped cases. The main reason of such effect was the larger contact area between pipe and rubber insert and higher value of the coefficient of friction between those surfaces.

All simulations proved that the most deformed area is near the smaller edge of the indenter. Deformation characteristic is presented in Fig. 6 showing the plastic strain distribution in the area directly beneath indenter. The same relation between width of the indenter and maximum values can be noticed. Also, in simulations with the cylindrical mount with rubber insert approximately two times higher maximum plastic strains were obtained, which is also the result of different boundary conditions (discussed earlier).

As for the rubber insert the HMH stress distribution for test 4b is shown in Fig. 7. The higher values of the stresses are in the side part of the rubber
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insert, where, due to radial-like deformation of the pipe, the largest pressure on the insert occurs. With increasing a distance lengthwise towards the end of the pipe, the maximum value of HMH stress decreases with simultaneous change of its distribution characteristics. The highest HMH stress values were obtained for the 5 mm width indenter: 15.8 MPa. By increasing its width the values decreased: 10 mm – 13.3 MPa, 15 mm – 12.3 MPa and 20 mm – 8.8 MPa.

Different width of the indenters influenced deformation characteristic, and consequently stress and strain distribution. The opposite relationship is observed in the force vs. displacement graphs presented in Fig. 8 – Fig. 15 for the v-shaped and cylindrical mounts. During FE analyses force characteristics were taken from the contact force between the indenter and the pipe surface. One can see that the wider indenter was, the higher force value was obtained. However, between test 1b and test 2b discrepancies are negligible. Moreover, different boundary conditions also affected the results: in rubber insert simulations the amplitude of the force was higher in all four cases (test 1b – test 4b). It can be clearly noticed that the discrete model behaves close to the actual one: the force history curves obtained from the experiments and FEA are relatively coincident. Nevertheless, some differences are observed, which were caused by the factors that could not be foreseen and prevented during the experimental and the numerical testing, i.e. errors during force measuring, initial-boundary conditions reflection in FE analyses, discrete representation of the pipe (considered as perfectly symmetrical, without any irregularities) or numerical problems regarding contact stiffness or constitutive modelling. In fact, as mentioned before, for the rubber insert and copper pipe a literature data was used, which also could affect the result.
**Fig. 5** HMH stress distribution [MPa] in pipe with 5 mm width indenter: a) v-shaped mount (test 4a), b) cylindrical mount with rubber insert (test 4b)

**Fig. 6** Plastic strain distribution [-] in pipe with 5mm width indenter: a) v-shaped mount (test 4a), b) cylindrical mount with rubber insert (test 4b)

**Fig. 7** HMH stress distribution in rubber insert (test 4b)
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Fig. 8 Force vs. displacement curves from FEA and experiment (test 1a)

Fig. 9 Force vs. displacement curves from FEA and experiment (test 1b)

Fig. 10 Force vs. displacement curves from FEA and experiment (test 2a)
**Fig. 11** Force vs. displacement curves from FEA and experiment (test 2b)

**Fig. 12** Force vs. displacement curves from FEA and experiment (test 3a)

**Fig. 13** Force vs. displacement curves from FEA and experiment (test 3b)
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**Fig. 14** Force vs. displacement curves from FEA and experiment (test 4a)

**Fig. 15** Force vs. displacement curves from FEA and experiment (test 4b)

The comparison between maximum values of all discussed quantities obtained is all simulations is listed in Table 3. The maximum force value was taken for 10\textit{mm} displacement of the indenter in all cases, besides test 4b where max. 8\textit{mm} displacement was measured.
Table 3 Comparison of results obtained in all simulated cases

<table>
<thead>
<tr>
<th>Test no.</th>
<th>HMH Stress [MPa]</th>
<th>Plastic strain [%]</th>
<th>Force [kN]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>254</td>
<td>9.5</td>
<td>~650</td>
</tr>
<tr>
<td>1B</td>
<td>295</td>
<td>16.5</td>
<td>~980</td>
</tr>
<tr>
<td>2A</td>
<td>260</td>
<td>10.0</td>
<td>~620</td>
</tr>
<tr>
<td>2B</td>
<td>296</td>
<td>18.8</td>
<td>~980</td>
</tr>
<tr>
<td>3A</td>
<td>261</td>
<td>10.8</td>
<td>~560</td>
</tr>
<tr>
<td>3B</td>
<td>304</td>
<td>19.3</td>
<td>~970</td>
</tr>
<tr>
<td>4A</td>
<td>267</td>
<td>12.0</td>
<td>~510</td>
</tr>
<tr>
<td>4B</td>
<td>334</td>
<td>21.3</td>
<td>~620*</td>
</tr>
</tbody>
</table>

* value taken from 8 mm indenter displacement

10.5. CONCLUSION

The paper presents the investigations of SSM pipe experimental testing case of three part intervention with FE validation. One of the authors’ main intentions was also to present a possibility of numerical modelling of the pipe using Finite Element Method (FEM). Obtained results (more particularly force characteristics) allow to withdraw the general conclusion that the applied contact algorithm based on the penalty function works properly. It should be stressed out, though, that effectiveness of the contact was strongly dependent on mesh quality and the value of a contact stiffness. Final, validated model can be used for simulating other problems related to pipelines investigations. Results obtained using such model can be then considered as proper and much more reliable ones.

10.6. REFERENCES


The optimization method of composite repair system for large area surface defects

Małachowski¹ J., Sybilski² K., Baranowski³ P.

¹ Military University of Technology, Warsaw, POLAND, jerzy.malachowski@wat.edu.pl
² Military University of Technology, Warsaw, POLAND, kamil.sybilski@wat.edu.pl
³ Military University of Technology, Warsaw, POLAND, pawel.baranowski@wat.edu.pl

Summary: The aim of this paper is to develop fast and accurate optimization method of composite repair system for large area surface defects. In the paper results of several numerical analyses were presented. Based on these results, the key factors of composite repair systems geometry and properties were designated. It allowed to elaborate optimization algorithm based on numerical analysis, which takes into account: dimensions of the defect and pipeline, pipeline parameters (like operating pressure) and material data.

Keywords: FE analysis, pipeline, composite repair, defect, optimization

11.1. INTRODUCTION

Proper operation and good technical condition of the pipeline is of key importance to economy and security of many countries. Therefore, pipelines should be constantly monitored and checked for the occurrence of various types of defects, the development of which can damage it. In the case of a defect, it is important to take corrective action to remove or minimize the negative effect of the defect. One method of repairing pipelines are bandages composite, which are wrapped the damaged section. Such bandage must be of sufficient dimensions and stiffness.
Therefore, the algorithm of selection of these parameters to the specific defect and operating parameters of the pipeline was developed.

11.2. NUMERICAL MODEL

In order to develop the optimization method for the composite repair system the numerical model of the pipe with the volume surface defect (VSD) was developed. Geometry of the pipe corresponded to the actual pipes, which are used in pipelines industry and they are presented in Fig. 1.

![Dimensions of the pipe with volume surface defect](image)

**Fig. 1** Dimensions of the pipe with volume surface defect  
(top view and cross section)

The pipe originally was made from X42 steel. To describe the behavior of this material an elastic-plastic model was implemented. Here, deviatoric stresses are determined so that they satisfy the yield function as follows [1]:

\[
\phi = \frac{1}{2} s_{ij} s_{ij} - \frac{\sigma_y^2}{3} \leq 0
\]

(1)

where

\[
\sigma_y = \beta \left[ \sigma_0 + f_h \left( \varepsilon_{\text{eff}}^p \right) \right] \text{ or } \sigma_y = \beta \left[ \sigma_0 + E_p \left( \varepsilon_{\text{eff}}^p \right) \right]
\]

(2)

where: \(\sigma_y\) – yield stress; \(\beta\) – hardening parameter (for isotropic hardening \(\beta = 1\)); \(f_h(\varepsilon_{\text{eff}}^p)\) – hardening function; \(E_p(\varepsilon_{\text{eff}}^p)\) – tangent modulus (linear hardening).
For X42 steel the plastic area was described using hardening function, which consisted of eight points presented in Fig. 2 [2].

The same constitutive material model was used to describe a behavior of the filler, but in this case tangent modulus was used to describe plastic area. Material mechanical data for the pipe and the filler are listed in Table 1.

![Graph of plastic range of steel]

**Fig. 2 Plastic range of steel**

**Table 1 Material data for pipe and filler material**

<table>
<thead>
<tr>
<th></th>
<th>( \rho ) [kg/m(^3)]</th>
<th>( E ) [GPa]</th>
<th>( \nu ) [-]</th>
<th>Yield stress [MPa]</th>
<th>( E_p(\varepsilon_{\text{eff}}) ) [MPa]</th>
<th>Plastic strain to failure [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe</td>
<td>7850</td>
<td>205</td>
<td>0.3</td>
<td>290</td>
<td>-</td>
<td>0.268</td>
</tr>
<tr>
<td>Filler</td>
<td>1600</td>
<td>30</td>
<td>0.3</td>
<td>60</td>
<td>100</td>
<td>0.3</td>
</tr>
</tbody>
</table>

The repair system used in the investigations is made of a composite bandage, in which the reinforcement component consists of layers of carbon fabricant and the matrix in the polymeric material used to impregnate the fabric. To describe the composite elements behavior the orthotropic material model with several failure mechanisms was applied. The various types of failure criteria were specified in the model [1, 3]:
For the tensile fiber mode:
\[ e_1^2 = \left( \frac{\sigma_{11}}{R_i^f} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases} \] (3)

\[ E_1 = E_2 = G_{12} = \nu_{21} = \nu_{12} = 0 \] (4)

for the compressive fiber mode:
\[ e_2^2 = \left( \frac{\sigma_{11}}{R_i^c} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases} \] (5)

\[ E_1 = \nu_{21} = \nu_{12} = 0 \] (6)

for the tensile matrix mode:
\[ e_3^2 = \left( \frac{\sigma_{22}}{R_i^f} \right)^2 + \left( \frac{\sigma_{12}}{S_{12}} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases} \] (7)

\[ E_1 = E_2 = G_{12} = \nu_{21} = 0 \] (8)

for the compressive matrix mode:
\[ e_4^2 = \left( \frac{\sigma_{22}}{2S_{12}} \right)^2 + \left( \frac{R_i^c}{2S_{12}} \right)^2 - 1 \begin{cases} \geq 0 & \text{failed} \\ < 0 & \text{elastic} \end{cases} \] (9)

\[ E_2 = G_{12} = \nu_{21} = \nu_{12} = 0 \] (10)

where: \( R_i^f, R_i^c, R_{\bar{f}}, R_{\bar{c}} \) – tensile (\( t \)) and compressive (\( c \)) strength in direction 1 and 2, \( S_{12} \) – shear strength.

If the criterion is reached the corresponding values of parameters (pointed above) are reduced to zero. In the material model erosion can also occur, when:
- the tensile fiber strain is greater than \( \varepsilon_{\text{max}}^+ \) (maximum strain for fiber tension) or smaller than \( \varepsilon_{\text{max}}^- \) (maximum strain for fiber compression),
- the effective strain is greater than \( \varepsilon_{fs} \) (effective failure strain).
When the failure occurs in all of the composite layers (through-thickness integration points), the element is deleted (its stiffness and stress is reset to zero). Material data for composite is shown in Table 2 [4].

<table>
<thead>
<tr>
<th>$E_1 = E_2$ [GPa]</th>
<th>$E_3$ [GPa]</th>
<th>$v_{12}$ [-]</th>
<th>$v_{31} = v_{32}$ [-]</th>
<th>$G_{12}$ [GPa]</th>
<th>$G_{23} = G_{31}$ [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>31.9</td>
<td>10</td>
<td>0.09</td>
<td>0.15</td>
<td>2.370</td>
<td>0.781</td>
</tr>
<tr>
<td>$R_1^c = R_2^c$ [MPa]</td>
<td>$R_1^c = R_2^c$ [MPa]</td>
<td>SC [MPa]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>332</td>
<td>474</td>
<td>41.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In order to minimalize computation time required to achieve results, only ¼ of the pipe was modeled. To include stiffness of the whole pipe, the symmetry boundary conditions were added. Location of symmetry planes are shown in Figure 3.

**Fig. 3** Location of symmetry planes in the model

The pipe during numerical computations were loaded by pressure acting on internal side of the pipe. The pressure was changing linearly from 0 MPa to 13 MPa.
11.3. PRINCIPLE OF OPERATION

In the first stage of the numerical research the pipe without the composite repair system was analyzed. It was performed to obtain reference case required to assess effectiveness of the repair system.

The VSD shown in Figures 1 results in certain behavior of the pipeline during loading with internal pressure. Figure 4 shows an example of the stress state (von Mises) for the pipeline. It can be noticed that the highest reduced stresses occur along the edges of the defect extending along the axis of the pipeline. It is the effect of reduced stiffness of the geometry, which together with its large area of the VSD causes the occurrence of bending moments along the edge of the defect. It can be observed by analyzing the deformation of the pipeline, which is shown in Figure 4.

![Image](image.png)

**Fig. 4** Location of symmetry planes in the model and pipeline deformation (pressure $p = 7$ MPa)

11.4. INFLUENCE OF COMPOSITE MATERIAL PROPERTIES ON ITS EFFECTIVENESS

In the second stage an influence of composite material properties on its effectiveness as the repair system was checked. During the numerical computations the longitudinal, axial and radial stiffness were taken into consideration. Hence, three cases were considered:
- I — the circumferential stiffness (EA) is about three times higher than in other directions (EA = 3190 MPa, EB = EC = 1000 MPa);
- II — the circumferential (EA) and longitudinal stiffness (EB) is three times higher than in radial direction (EA = EB = 3190 MPa, EC = 1000 MPa);
- III — the composite repair is isotropic material (EA = EB = EC = 3190 MPa).

Each of the model were obtained by modification of the composite material model. As a result of the numerical simulations the comparison of the von Mises stress in VSD presented in Figure 5 was obtained. Value of the stress was taken from element 34970 (Fig. 5), in which the highest value was observed. Von Mises stress for each model are almost the same. Differences are very small and do not exceed 2%.

![Image](image1.png)

**Fig. 5** von Mises stress in VSD and von Mises stress in the pipe
(pressure $\rho = 8$ MPa)

The largest influence on von Mises stress has x (circumferential) component of stress. Longitudinal stress (z - component) is three times lower, whereas radial (y - component) stress is four times lower than circumferential (Fig. 6) one.

In Figures 6 comparison of circumferential (x - component), radial (y - component) and longitudinal (z - component) stress is presented. The highest difference can be observed on radial stress, which value is
relatively small (in relation to other component), so it does not have a significant impact on maximal von Mises stress in the pipe.

**Fig. 6** Comparison of X, Y and Z – component of stress in element 34970

The main conclusion is that for large area VSD the biggest influence on von Mises stress has circumferential stress. The longitudinal and radial component of stress do not have significant impact on von Mises stress and also do not depend on stiffness of the composite repair in these directions.

### 11.5. COMPARISON OF COMPOSITE RESERVE

The main aim of third stage of presented investigations was to verify if the longitudinal reserve (Fig 7) of the composite repair has an influence on the value of maximal von Mises stress in VSD. Several numerical analyses were performed. During simulations the width of composite reserve varied from 0 mm to 50 mm.

For comparison Von Mises stress values were measured from two elements with IDs: 34970 and 35851 (Fig. 8). First element was taken, due to the highest stress level. Second element was chosen because of the biggest difference in stress value, depending on longitudinal reserve of composite repair.
Comparison of the von Mises stress for element 34970 is presented in Figure 9. It can be observed that stress level in the center of VSD does not depend on composite repair reserve.

Comparison of the von Mises stress for element 35871 is presented in Figure 10. Close to the edge of VSD stress level is lower for a larger
composite repair reserve, but this influence is not significant (maximal difference is less than 5%)

Based on the obtained results, the main conclusion is that stress level in big area VSD is almost independent on reserve of the composite repair.

11.6. COMPOSITE THICKNESS IMPACT ON MAXIMAL VON MISES STRESS

In the last stage an influence of composite repair thickness on maximum value of von Mises stress in VSD was analyzed. The simulations were performed for composite thickness from 25 mm to 175 mm. It was assumed that each of composite layer has a thickness of 0.5 mm. As a result of numerical analysis the maximum values of von Mises stress in VSD were obtained and investigated (Figure 11). Thickness equals 0 defines the pipe is without any filler or repair system.

![Graph showing the relationship between maximal von Mises stress and composite thickness](image)

**Fig. 11** Maximal von Mises stress in VSD depend on thickness of composite repair

The main conclusion is that for the big area VSD maximum stress level is linearly dependent on composite thickness.
11.7. OPTIMIZATION METHOD

Considering above conclusions and obtained results the authors developed a scheme of composite repair optimization shown in Figure 12. The bolded type mark tasks to complete, while italics products obtained after the completion of tasks.

![Diagram of composite repair optimization process]

**Fig. 12** Optimization of composite repair scheme

The first step of optimization are pipeline and VSD measurements. An exemplary set of dimensions is shown in Figure 13.
The optimization method of composite repair system for large area surface defects

The next step is the FE model preparation, which requires a definition of material properties of the pipe and the composite (besides geometry parameters). Such data should be obtained from experimental tests or available material library. To develop the complete FE model operating parameters of the pipeline have to be provided, especially internal pressure $p$ acting on the structure and allowable stress level $\sigma_{op}$, which guarantees the required level of fatigue.

The developed numerical model is used in the next step to determine the level of stress in the VSD for a first thickness $t_1$ of the composite. If the stress level $\sigma_{vms}$ is equal to the $\sigma_{op}$, proceed to estimation of repair system costs. If it is larger or smaller, increase or decrease the thickness of the composite and repeat the calculations for the new thickness $t_2$. If $\sigma_{vms}$ (for $t_2$) = $\sigma_{op}$ proceed to estimation of repair system costs. In other case, on the basis of previous results for $t_1$ and $t_2$ interpolate or extrapolate the new value of the thickness of the composite and repeat the calculation. Calculations is running until obtain the required level of stress, and in each subsequent cycle for interpolation or extrapolation there is an increasing number of results.

After determining the optimum thickness of the composite proceed to estimate the cost of repair system. If cost is the lowest (or ensure different criteria), prepare documentation needed to implement the developed composite repair. Otherwise, proceed to change the material, perform material tests and go to numerical modeling.
11.8. CONCLUSION

In the paper results of several numerical analyses were presented. Performed simulations were aimed at determination of the impact of key factors of composite repair system on its effective work. During investigations the stiffness in each direction, composite reserve in reference to volumetric surface defect and composite thickness were checked. Taking into account all analyzed aspects, it can be concluded, that the biggest impact on proper operation of composite repair system has circumferential stiffness of the bandage. Based on obtained results the algorithm of selection of geometry and material of repair system for the specific dimensions of defects and operating conditions in pipe was developed.

11.9. REFERENCES


CHAPTER

Numerical model for focusing technique of fundamental torsional mode in pipes

Mirchev¹ Y.N., Kudina² H.F., Sergienko² V.P., Lvov³ I.G.

¹Institute of Mechanics of BAS, Sofia, BULGARIA, mirchev@imbm.bas.bg
²V.A. Belyi Metal Polymer Research Institute of National Academy of Sciences of Belarus, Gomel, BELARUS, kudina_mpri@tut.by, sergienko vp@mail.ru
³Kharkiv Polytechnic Institute, Kharkiv, UKRAINE

Summary: The paper considers the excitation and the propagation of ultrasonic waves in the pipe. The calculations of the emitted ultrasonic waves into pipe by transducer's array as well as the signals received by the same array after reflection from the edge of the pipe are presented. The calculations are performed using numerical method based on the principle of Huygens and Fermat that presents ultrasonic field as the interference of the waves emitted from the separate transducer in the array. The synthetic focusing technique is employed for calculations of the matrix elements where the columns and the rows corresponds to the location. The sensitivity of the array has been investigated in the experiments of propagation of low-frequency torsional mode \( T(0,1) \) using focusing technique. The sensitivity is specified for reflection of ultrasound from the edge of the pipe. The sensitivity depends on the number of elements, their nominal frequency and the set of the time delays of the emitted waves that allows to focus the ultrasonic beam to the required area in the investigated object.

Keywords: synthetic Focusing Technique (SFT), Total Focusing Technique (TFT), dynamic distance focusing technique (DDFT), low frequency guided waves testing, electronically time delay, phased antenna array, axial and circumferential ultrasonic beam
12.1. INTRODUCTION

The opportunities to using focusing technique for guided waves testing of pipeline is one possibility to improving sensitivity for detection and evaluation of investigated discontinuity.

Practical application of focusing technique can be done successful when is known the character and values of spread focused ultrasonic beam in dependence of characteristics of antenna array and testing object (pipeline).

The main goal is to determine influence of the characteristics for the phased array antenna and the electronic delay of the emitted ultrasonic waves on the sensitivity of the reflected signal from the pipe end.

12.2. NUMERICAL METHOD AND INITIAL DATA

The numerical model is presented in [1] for convention phased array probe in immersion mode and developed in this work for the case of pipeline ultrasonic testing with guided wave. The development is based on investigation in [2].

The case when the pipe has a radius much larger than the thickness of the wall is investigated. Then for distributed waves, the cylindrical contour of the pipe is neglected and can be replaced with a plate, having dimensions equal to the circumference and the length of the tube [3].

Schematically in Fig.1 is shown by an active group of antenna array probe with a length $l_a$ formed by $N_a$ number of elements having pitch $p=l_a/N_a$, arranged in a linear array attached to the circumference of the outer surface of the pipe with diameter $D$ and a thickness $h$.

Virtual active group with length $l_a$ presents one of all possible virtual aperture of ultrasonic beam emitted by the antenna array in the pipe. The sequence (delay time) of the emitted wave from the individual elements in the phased array antenna is given by the interference of emitted signals by the elements, as a base is the signal emitted by the element $m(n)=1$ at a distance $H_{m(n)}$, for $r=0$.

In the shown scheme on Fig.1 are specified additional requirement to boundary conditions in the Z-axis of the pipe marked with the letters A-A
and \( \Lambda' - \Lambda \). The requirement is that the calculation of the ultrasonic beam at the boundary of the pipe \( \Lambda - \Lambda \) and \( \Lambda' - \Lambda' \) match. Compliance with this requirement mean that no interruptions in the calculation of the ultrasound beam for the analogue plate in Fig. 1, which is represented studied pipe.

![Diagram](image)

**Fig. 1** Geometry of unrolled pipe and position of antenna array

Below are the basic zero and two additional extra path of the pipe, denoted by \( r=-1 \) and \( r=1 \). This approach removes the restriction of
distributed waves in the pipe of the contour with a black solid line. To calculate all possible extra path of distributed mode in the pipe is necessary to include in the calculations sufficient number of r of the pipe.

With a solid line in Fig.1 is shown emitted focused on the point S ultrasonic beam from active group la, with dotted lines— unfocused ultrasonic beam reflected from the end of a pipe with length H and received by the antenna arrays.

Ultrasonic beam emitted from virtual active group as part of antenna array \( I_{PA}^{Na} \) is written in next form:

\[
I_{PA}^{Na}(Z, \theta) = \max \left[ \frac{\sum A(Z, \theta)}{\sum A(F,0)} \right] \tag{1}
\]

Where

\[
\sum A(Z, \theta, t) = A_0 \cdot \sum_{r=-\infty}^{\infty} \sum_{n=1}^{Na/2} \left[ R_{n,r} \cdot T_{n,r} \cdot A_{n,r} \left( Z, \theta, \Delta t_{n,r} \right) \right] \tag{2}
\]

\[
| R_{m(n),r} | = A(Z,t) - \frac{Z}{\sqrt{Z^2 + \frac{la^2}{2}}} \cdot A \left( \sqrt{Z^2 + \frac{la^2}{2}} \cdot t \right) \cdot \sin \left( \frac{la \cdot k \cdot \sin(\theta)}{2} \right) \tag{3}
\]

\[
T_{m(n),r} = \frac{H}{H_{m(n),r}^2(Z, \theta)} \tag{4}
\]

\[
\Delta t_{m(n),r}(Z, \theta) = \frac{\left[ H_{m(n),r}(Z, \theta) - H_{m(n),r}(Z,0) \right]}{C} - \frac{\left[ H_{m(n),r}(F, \theta) - H_{m(n),r}(F,0) \right]}{C} \tag{5}
\]
\[
H_{m,r}(Z, \theta) = \sqrt{Z^2 + [p(m-0.5) + r \cdot la]^2} \\
- [p(2m-1) + r \cdot la]Z \cdot \sin(\theta)
\]  
(6)

\[
H_{n,r}(Z, \theta) = \sqrt{Z^2 + [p(n-0.5) + r \cdot la]^2} \\
+ [p(2n-1) + r \cdot la]Z \cdot \sin(\theta)
\]  
(7)

\( \Sigma A(Z, \theta, t) \) is the amplitude of the signal in every point of spatial plane OYZ, represented by the interfering pulses of all the individual elements Na. \( R_{m(n),r} \) is the reflectance of the surface of the reflector, for the element m(n) and the number of extra path of the wave around the circumference of the pipe r. The reflection from the pipe end can be studied as from infinity plane. With coefficient s in equation (3) is describes the form and size of the reflector (e.g. rectangular reflector with respect to the sides 0.5, s=1.01) [4]. \( T_{m(n),r} \) is coefficient considering decrease amplitude due to change to the front of propagated ultrasonic beam for probe element m(n) and number of extra path r (not consider change of ultrasonic beam due to absorption and scattering in the medium). \( \Delta t_{m(n),r}(Z, \theta) \) is the delay from the beginning of the coordinate axis Z from point \( O_{z=0} \) depending on the lateral spread ultrasonic beam \( \theta_{m(n)} \) of the distance \( H_{m(n),r} \) propagated by the waves reflected from the pipe end and received back into antenna array. \( F \) — focal length of focused phased antenna array probe.

The first part in equation (5) give the electronically time delay between each elements and second one is real delay time depend of position of each elements m(n) in spatial plane OYZ, depending on the number of extra path r. If emitted ultrasonic beam is unfocused, for focus low with \( F \approx \infty \), then first part from equation (5) is equal to zero and all elements emitted simultaneously without electronically time delay.

The results obtained by the numerical model are presented in two-dimensional matrix in image of unrolled pipe (Fig. 1). For displaying the pipe is used SFT algorithm. All calculations in this work is carried out with mode T(0,1) having a constant phase velocity \( C=3260 \text{m/sec} \), which wave
number is a linear function of frequency. The calculations are done with
RF impulse for pulse-echo method with bell impulse in the form of sine
wave, whereby the sequence (time delays) emitted from the individual
elements in the arrays are represented by the following relationship:

\[ A(H_{m(n),r}, \Delta t) = A_0 \cdot \exp \left( i \left( (\alpha_0(t-\tau_0)) - \varphi \right) - (\beta^2 \cdot ((\alpha_0(t-\tau_0)) - \varphi)^2) \right) \]

(8)

Where

\[ \varphi_i = (H_{m(n),r} - H) k_i \]

(9)

\( A_0 \) is the maximum amplitude of the transmitted pulse (in any case the
submitted work in this theoretical model the maximum values of the amplitude
of the transmitted pulse signal from the probe conditional accepted for one
\( A_0 = 1 \), \( j \) – imaginary unit, \( \alpha_0 = 2 \pi f_0 \) – circular resonance frequency, \( f_0 \) – linear
resonance frequency, \( t \) – time of spread impulse, \( \varphi_i \) – phase shift between two
waves, spread in one medium, \( H_{m(n),r} \) and \( H \) – distance which propagated
impulses on first and second waves in medium, from their emitted to received,
\( k_i \) – wave number of ultrasonic wave, \( \tau_0 = H/C \) – time of impulse received for
reference wave, corresponding to maximum amplitude, \( C \) – values of
propagated ultrasonic wave in medium, \( \beta = \sqrt{\ln(2)} / \pi n_0 \) – coefficient of impulse
shape, \( n_0 \) – number of impulse oscillations at amplitude level \( A = 0.5 A_0 \).
Calculations in this work are conducted with two (\( n_0 = 2 \)) oscillations at level
half of the maximum amplitude.

The geometrical characteristics of investigated pipe are: outside diameter
\( D = 323.9 \text{mm} \), thickness \( h = 9.5 \text{mm} \) and length \( H = 2.2 \text{m} \). Antenna array
placed on outer diameter of the pipe is equal circumference of pipe \( l_a = \pi D \),
consists of \( N_a \) number of elements with distance between the centers of the
elements (pitch) \( p = l_a / N_a \), while respecting the requirement \( p < \lambda / 2 \).

12.3. RESULTS AND DISCUSSION

On Fig. 2 is represented two-dimensional image of reflected signal from
the end of the test pipe with position of the unfocused phased array
antenna in the other end of the pipe, which have Na=24 number elements and nominal frequency f=30KHz. The image in Fig. 2 is represented by a matrix of interference of all elements in the antenna array for researched area of interest in the direction of propagation of ultrasonic waves (to pipe axis) H from 896 mm to 3070 mm with element size ΔH=2.17 mm (Δt=0.67 μs) and the direction of the circumference of the pipe h from -508.8 mm to +508.8 mm with an element size Δh=2.12 mm. The thickness of the pipe is investigated as an element with size Δw=w=9.5 mm. With gray scale is represented the amplitude of the reflected signal relative to the amplitude of the signal reflected from the end (edge) of the pipe at a distance H=2.2 m from the phased antenna array.

![Image of 2-D pipe image for reflected from pipe end ultrasonic beam shown by matrix with interference amplitude of all elements in unfocused antenna array](image)

**Fig. 2** 2-D pipe image for reflected from pipe end ultrasonic beam shown by matrix with interference amplitude of all elements in unfocused antenna array

By using this technique for presenting the image of the testing object is obtained primary information to detect deviations from object form.

On Fig. 3 is shown the characteristic of the field in the circumferential position of the pipe at the position of axial distance on the end of the pipe.
from the image given in Fig.2. It is used to determine the width of the half maximum amplitude, give us information about the circumference size of the reflector on the circumference distance in the pipe.

![Graph showing normalised amplitude vs. circumferential position](image)

**Fig. 3** Reflected signal amplitude from pipe end in circumference position to pipe axis for results shown on Fig.2

On Fig. 4 is an A-scan of signal, along the axis of the pipe. With A-scan is determined the location of the reflecting surface from the center of the phased array antenna, located at the end of the tube.

![Graph showing normalised amplitude vs. axial distance](image)

**Fig. 4** Reflected signal amplitude from pipe end in normal to axial direction of pipe for results shown on Fig.2

On Fig. 5 and Fig.6 are shown the results for the reflection of the end of the pipe for unfocused and focused system with characteristics of antenna array: Na=24, p= 42.4mm, f=30 KHz. The active group is one and consists from all 24 numbers of elements, emitted simultaneously
with and without electronically time delay. The amplitude is normalized to the signal of the focused antenna array with focal length F=2m, reflected from edge, located at the same distance as focal length H=2m from the phased antenna array.

Axis X on Fig.5 is shown the circumferential position of pipe in m.

**Fig. 5** Reflected signal amplitude from pipe end in normal to axial direction of pipe for results shown on Fig.2

On axis X in Fig.6 is shown axial distance from the antenna array to the edge of the pipe in m.

**Fig. 6** Reflected signal amplitude from pipe end in normal to axial direction of pipe for results shown on Fig.2

On Fig. 5 and Fig. 6 can see that gain coefficient of amplitude for focused (F=2 m), according to unfocused antenna array is $K = \frac{I(\text{Focused})}{I(\text{unfocused})} = 1.43$, for back scattering signal from pipe end at axial distance from
antenna array H=2m. It is note that for given initial condition, when working with focusing technique, the testing area in circumferential position is necessary to be not more then 1/8 of pipe perimeter from the maximal amplitude in focusing area (see Fig. 4a). Otherwise the amplitude of reflected signal is decreases more then two time (-6dB) and sensitivity to discontinuity is not enough good for practical application.

The gain coefficient K for focusing technique is investigated according to unfocused techniques with the same characteristics of antenna array and testing pipe used for calculation of 2-D image shown on Fig. 2. The numerical calculation is done for dynamic distance focusing technique (DDFT), as focal lows has focal lengths F from 0.5m to 4m, through step 0.5 m. The same calculation is done for unfocused technique. The amplitudes is normalized to amplitude for focusing technique with focal length F=0.5 m. The results is shown on Fig. 7, on axis X is axial distance of dynamic focusing low in m, on axis Y is shown normalised amplitude.

From results shown on Fig. 7 can make conclusion, that testing with focusing technique with increasing axial distance is decrease gain coefficient K. The gain coefficient K=1.5 at axial distance 4m is decreased with 2 for distance 3.5m and tends to one. When K=1 then have not differences in amplitude of reflected signal from focused and unfocused technique for antenna array in pipeline.

**Fig. 7** Gain coefficient K and maximum reflection amplitude
Ultrasonic back scattering signal has investigated according to focused antenna array with constant focal length $F=2m$ and $F=3.5m$. The characteristics of antenna array and pipeline are the same as calculation shown on Fig.2. Only pipe length $H$ is changed. The reflected signal is calculated for distance of pipe end from antenna array from $H=0.5m$ to $H=4m$, with step 0.5m. Results are shown on Fig.8, on axis $X$ is shown axial distance of pipe end from antenna array in m. Normalised amplitude to reflection from pipe end at $H=2m$ with focusing technique at focal length $F=2m$ is shown on axis $Y$.

![Graph showing back scattering signal](image)

**Fig. 8** Back scattering signal from pipe end for focusing technique

From results shown on Fig.8 is seen that acoustical focal length have less value then geometrical focal length, as it is usually observed in practical application of conventional ultrasonic focusing technique. Using focusing technique for the initial date of calculations has not maximum of amplitude for focal length $F=3.5m$. The best axial distance for using focusing technique is 1.5m, when have maximum of back scattering signal. It is seen that the amplitude for focusing technique is more close to amplitude for unfocused technique with increase the axial distance from antenna array.

**12.4. CONCLUSION**

In the work is developed numerical model based on synthetic focusing technique to submit 2-D image of investigated pipelines from antenna array
working with fundamental torsional mode. The model are used to demonstrated form and values of back scattering signal from pipe end in axial and circumferential position for antenna array with difference focal low.

In the work is set the width of focused ultrasonic beam where amplitude decreased by 6dB for investigated pipe and focal low, which is important for practical application of low-frequency guided waves testing.

The gain coefficient $K$ is calculated for dynamic distance focal technique according to unfocused technique for the same antenna array and pipeline. For practical application of low-frequency guided waves testing is set the greatest axial distance from array for which is suitable to use focused technique, for specified characteristics of antenna array and pipeline in this work. The axial distance is set according to values of the gain coefficient $K$.

### 12.5. REFERENCES


Contact problem of anisotropic viscoelasticity of two cylindrical shells

Lvov G.I., Martynenko V.G.

National Technical University «Kharkov Polytechnic Institute», Dynamic and strength of machines department, Kharkov, UKRAINE, lvovgi@list.ru, martynenko.volodymyr@gmail.com

Summary: The following paper shows an analytical research of the stress-strain state of a section of a steel pipeline connected with a viscoelastic repair bandage for different installation conditions of the bandage and changing internal pressure. The complete system of equations of viscoelasticity theory for an orthotropic material was reduced to integral-differential equations in displacements, and the method of its solution was proposed. The analysis of contact stresses between the pipeline and the bandage accounts the nonstationary internal pressure and an influence of viscoelastic properties of fiberglass.

Keywords: pipeline, repair bandage, tension, viscoelasticity, relaxation kernels, Prony series, integral-differential equation

13.1. INTRODUCTION

The natural gas is one of the most important sources of fuel, which has wide industrial and domestic use. This fact makes the need for transporting it over long distances both within the country and abroad. Steel pipelines are used for this purpose. Considering the great value of the internal pressure they belong to heavy duty structures. In such circumstances, the question as to their strength arises, because the destruction of a pipeline is not only
extremely harmful for economics, but also a life-threatening event. Therefore, under normal circumstances, this type of construction is often designed and operates within the elasticity with a large enough margin of safety [1]. But during the operation of a pipeline local defects (caused by corrosion, erosion, mechanical impact of foreign objects, etc) can appear [2]. In terms of the mechanics such defects are stress concentrators, which can cause rapid local increase of stresses and as a result, even the appearance of a plastic deformation zone, a further increase of the plasticity and a destruction. To prevent the spread of the zone of defects and to reduce tensions in this area engineers use different methods. Among them we can denote the method of applying a repair composite layer (bandage) on a pipeline using specially developed approaches [3]. Often they use fiberglass as a composite material for the manufacture of such preventive approach, which, unlike elastic material, shows viscoelastic properties. In addition, in accordance with the repairing procedure a gas inside a pipeline can be released or not and it is under internal distributed pressure. In this case, the repair bandage remains unstressed until the pressure changes. Otherwise, a repair bandage may be applied to the problem area with tension, resulting in the prestressed state of the composite layer and at the same time stress redistribution in the pipeline. Finally, there are cases, in which the gas is released from the pipeline during the repair and filed down again just after the repair, resulting in a load of the whole construction by an internal pressure. Under such conditions, an engineer deals with a question of adequate modeling and analysis of the stress-strain state of a repaired pipeline section taking into account the effects of viscoelasticity of a composite material and repair procedures and parameters that should be required to determine its effectiveness or appropriateness at all. After all, if the analysis shows that stresses in the repaired pipeline is not reduced to the acceptable level or contact stresses are stretching and exceed the permissible level, leading to the separation of the bandage, the project will need to undergo appropriate changes.
The problem of evaluation of the stress-strain state of cylindrical viscoelastic bodies for different cases found a solution since the second half of the last century. In the book [4] the author carries out the solution of the problem of a loading of a hereditary viscoelastic thick-walled cylinder by a distributed internal pressure. The work [5] considers the case of the functioning of a rocket engine and gives the result of the flat strain state of two coaxial cylinders at that the external one is thin-walled elastic and internal one is thick-walled viscoelastic.

At the same time, sufficient attention is paid to the problem of load of the repaired pipeline. For example, in [6] an experimentally and numerically performed comparative analysis of the stress-strain state of a pipeline accounts various forms of defects in walls and an elastic repair layer. The problem is solved using finite-element analysis, but viscoelastic properties of the composite material are not included in the calculation model. The study [7] conducts the consideration of similar design, but taking into account the effects of a plastic deformation in the area of the defect.

The paper [8] gives a finite-difference analysis of two coaxial cylinders, taking into account the effects of viscoelasticity for a biomedical application, but such a formulation of the problem cannot be extended to cases of an analysis of repaired pipelines. In [9] the authors provide an experimental study of a viscoelastic behavior of plastic pipes and give the results in a tabular form.

The article [10] deals with the detailed analyses of the impact of the tension during the installation process of a bandage on the effectiveness of the repair of a pipeline. In [11] the authors present an analytical study of two cylinders under an internal pressure, where the outer cylinder exhibits viscoelastic properties. The mathematical model takes into account the different effects of these properties on bulk and shear deformations and solving of the model is performed by Laplace transform. In [12] the three-dimensional finite-element analysis of a pipeline, repaired by using viscoelastic bandage, is carried out. Finally, [13] gives an analytical solution for two viscoelastic cylinders loaded with an internal pressure, where the
external one is hereditary viscoelastic, in a flat statement by using the method of solution of integral-differential equations.

This paper shows the analytical model of the viscoelastic pipeline repair layer, which among other properties reflects two important aspects: firstly, the viscoelasticity curve can be approximated by exponential Prony series; secondly, it allows one to reflect different conditions of an installation of the composite layer, such as an internal pressure or tension during repair.

13.2. PROBLEM FORMULATION

Calculations of the stress-strain state of a pipeline with a fiberglass repair layer are conducted analytically in a flat axisymmetrical statement for a simultaneous loading of a long pipe and composite bandage. It is assumed that the pipeline is long enough to allow one considering the strain state as flat. The influence of defects on the overall distribution of the stress-strain state of the construction is neglected because it is local in nature and important when considering the problem in terms of a stress concentration. Figure 1 shows the calculation model of the problem where the pipeline is marked (I) and bandage is marked (II).

![Fig. 1 Calculation model of the problem](image)

The pipeline without the bandage is loaded by distributed internal pressure $P_1$, causing the initial strain state. Radial displacement of its outer surface is labeled $\Delta u$. In such circumstances, the bandage is applied to the loaded
pipeline. After this application the internal pressure changes to the value $P_z$ (for this problem the change occurs instantly but neglecting transient effects).

Steel is considered as homogeneous isotropic elastic material, and fiberglass – as homogeneous viscoelastic orthotropic material. Taking into account simplifications the basic functions of the stress-strain state depend on one spatial variable — radial coordinate $r$, which variable time $t$ is added to, and independent kinematic variable is radial displacement of the pipeline and the bandage $u$. This formulation of the problem, given the nuances of the real construction described, does not introduce a significant error in an assessment of the stress-strain state and thus can simplify the elastic mathematical model to perform the main aim – the development of the model of a behavior of the repair bandage applied to the pipeline and study of the impact of mounting features on the nonstationary stress-strain state.

13.3. THEORY REFERENCE

According to [14] the system of equations of viscoelasticity theory in polar coordinates in case of orthotropic material with proportional matrixes of elastic and viscous properties in a flat axisymmetrical statement takes the following form:

\[
\begin{align*}
\frac{d\sigma_r^{(II)}(r,t)}{dr} + \frac{\sigma_r^{(II)}(r,t) - \sigma_0^{(II)}(r,t)}{r} &= 0 \\
\varepsilon_r^{(II)}(r,t) &= \frac{du^{(II)}(r,t)}{dr} \\
\varepsilon_0^{(II)}(r,t) &= \frac{u^{(II)}(r,t)}{r} \\
\sigma_r^{(II)}(r,t) &= C_{11}[\varepsilon_r^{(II)}(r,t) - \int_0^t K(t-s)\varepsilon_r^{(II)}(r,t)ds] + \\
&\quad + C_{12}[\varepsilon_0^{(II)}(r,t) - \int_0^t K(t-s)\varepsilon_0^{(II)}(r,t)ds] \\
\sigma_0^{(II)}(r,t) &= C_{21}[\varepsilon_r^{(II)}(r,t) - \int_0^t K(t-s)\varepsilon_r^{(II)}(r,t)ds] + \\
&\quad + C_{22}[\varepsilon_0^{(II)}(r,t) - \int_0^t K(t-s)\varepsilon_0^{(II)}(r,t)ds]
\end{align*}
\] (1)
where $r$ is a radial coordinate; $t$ is a time coordinate; $s$ is a past time; $u$ is a radial displacement; $\varepsilon_r$, $\varepsilon_\theta$ are radial and circumferential strains respectively; $\sigma_r$, $\sigma_\theta$ are radial and circumferential stresses respectively; $C_{11}$, $C_{22}$, $C_{12} = C_{21}$ are stiffness coefficients of orthotropic material; $(I)$, $(II)$ are designations for the materials of the pipeline and the bandage respectively; $K(t-s)$ is viscoelastic relaxation kernel that is presented by Prony series:

$$K(t-s) = \sum_{i=1}^{n} a_i \exp(-b_i(t-s))$$  

where $a_i$, $b_i$ are coefficients and exponents of a Prony series respectively; $n$ is a number of terms of a Prony series.

For the case of an isotropic elastic material the system (1) can be simplified:

$$\begin{align*}
\frac{d\sigma_r^{(I)}(r,t)}{dr} + \frac{\sigma_r^{(I)}(r,t) - \sigma_0^{(I)}(r,t)}{r} &= 0 \\
\varepsilon_r^{(I)}(r,t) &= \frac{du^{(I)}(r,t)}{dr} \\
\varepsilon_\theta^{(I)}(r,t) &= \frac{u^{(I)}(r,t)}{r} \\
\sigma_r^{(I)}(r,t) &= B_{11}\varepsilon_r^{(I)}(r,t) + B_{12}\varepsilon_\theta^{(I)}(r,t) \\
\sigma_\theta^{(I)}(r,t) &= B_{21}\varepsilon_r^{(I)}(r,t) + B_{22}\varepsilon_\theta^{(I)}(r,t)
\end{align*}$$

where $B_{11} = B_{22}$, $B_{12} = B_{21}$ are stiffness coefficients of an isotropic material.

Thus the system (3) corresponds to the stress-strain state of a steel inner cylinder (pipeline) and system (1) — to an external fiberglass cylinder (bandage). The system (3) can be reduced to a differential equation in terms of displacements (Lame equation):

$$\frac{d^2 u^{(I)}(r,t)}{dr^2} + \frac{1}{r} \frac{du^{(I)}(r,t)}{dr} - \frac{u^{(I)}(r,t)}{r^2} = 0$$
Its solution is written in the algebraic form:
\[ u^{(I)}(r,t) = A_1(t)r + A_2(t)/r \]  
and the system (1) is represented by an integral-differential equation in terms of displacements analogically:
\[
\left[ \frac{d^2u^{(II)}(r,t)}{dr^2} + \frac{1}{r} \frac{du^{(II)}(r,t)}{dr} - \gamma^2 \frac{u^{(II)}(r,t)}{r^2} \right] - \\
- \int_0^t K(t-s) \left[ \frac{d^2u^{(II)}(r,s)}{dr^2} + \frac{1}{r} \frac{du^{(II)}(r,s)}{dr} - \gamma^2 \frac{u^{(II)}(r,s)}{r^2} \right] ds = 0
\]  
which has the following solution:
\[
\frac{d^2u^{(II)}(r,t)}{dr^2} + \frac{1}{r} \frac{du^{(II)}(r,t)}{dr} - \gamma^2 \frac{u^{(II)}(r,t)}{r^2} = 0
\]  
where \( \gamma^2 = C_{22}/C_{11} \) is an accepted designation.

The solution of the differential equation (7) can be written as:
\[ u^{(II)}(r,t) = A_3(t)r^\gamma + A_4(t)r^{-\gamma} \]  

Coefficients \( A_1(t), A_2(t), A_3(t), A_4(t) \), contained in the expressions for displacements (5) and (8), are independent functions of time, appearing in the integration of the relevant differential equations. They can be found on the construction boundary conditions and terms of conjugacy, which, in turn, define a shape and features of its loading and installation:
\[
\begin{align*}
\sigma_r^{(I)}(R_1,t) &= -P_2 \\
u^{(I)}(R_2,t) - \Delta u &= u^{(II)}(R_2,t) \\
\sigma_r^{(I)}(R_2,t) &= \sigma_r^{(II)}(R_2,t) \\
\sigma_r^{(II)}(R_3,t) &= 0
\end{align*}
\]  

It should be noted that the displacement conjugacy condition corresponds to the presence of the assembly design features. As shown in
the problem statement, the absolute difference between the displacement of the outer surface of a pipeline and inner surface of a bandage $\Delta u$ is determined analytically by the stress-strain state of the pipeline without the bandage under the initial internal pressure $P_i$, ie as a solution of such a boundary problem:

\[
\frac{d^2 u_{init}^{(I)}(r,t)}{dr^2} + \frac{1}{r} \frac{du_{init}^{(I)}(r,t)}{dr} - \frac{u_{init}^{(I)}(r,t)}{r^2} = 0
\]  

(10)

\[
\begin{cases}
\sigma_{rinit}^{(I)}(R_1) = -P_i \\
\sigma_{rinit}^{(I)}(R_2) = 0
\end{cases}
\]  

(11)

Therefore $\Delta u = u^{0\ init}(R_2)$.

Thus, after solving the boundary value problem (10)-(11) the boundary conditions (9) are fully defined, which allows, taking into account dependencies for the radial displacement (1) and (3), to apply them to the system of solutions, composed of expressions (5) and (8). The result is a mixed system of algebraic and integral equations with the unknown time-dependent functions $A_i(t)$, $A_3(t)$, $A_3(t)$, $A_4(t)$. During a solving of this system it is necessary to find a solution of an inhomogeneous second-type Volterra integral equation [15]:

\[
A_3(t) = \tilde{\delta} + \tilde{a} \int_0^t K(t - s) A_3(s) ds
\]  

(12)

The possibility of analytical solution of this equation manually using adifferentiation method was demonstrated in [13].

Therefore, after finding the unknown constants of integration of differential equations we gain a fully defined analytical form of radial displacements (5) and (8), that in conjunction with systems (1) and (3) gives all the information about the flat axisymmetric stress-strain state of the considered construction.
13.4. RESULTS AND DISCUSSION

Consider a situation when a viscoelastic bandage is applied to a pipeline loaded by an internal pressure \( P = P_1 \) without tension. In this case, while maintaining the operating pressure the bandage remains unloaded. If the gas is released from the pipeline and the internal pressure \( P = P_2 \) lowers to zero, it will lead to a redistribution of stresses and strains in the repaired area. Therefore, even in absence of the internal pressure in the pipeline the stress-strain state of the general construction is not zero, but the main attention should be paid to the contact stresses between the pipeline and the bandage. They can exceed an adhesive strength of the adhesive layer. Consequently, the band will separate from the pipeline and the repair will be all in vain.

Physical, geometrical and load characteristics are shown in the table 1. In this viscoelastic properties of fiberglass are modeled by a curve represented using one-term Prony series containing coefficients \( a \) and \( b \), that were used in [13].

**Table 1** Initial data

<table>
<thead>
<tr>
<th>Designation</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 )</td>
<td>0.510</td>
<td>[m]</td>
</tr>
<tr>
<td>( R_2 )</td>
<td>0.522</td>
<td>[m]</td>
</tr>
<tr>
<td>( R_3 )</td>
<td>0.572</td>
<td>[m]</td>
</tr>
<tr>
<td>( B_{11}, B_{22} )</td>
<td>23,08*10^{10}</td>
<td>[Pa]</td>
</tr>
<tr>
<td>( B_{12}, B_{21} )</td>
<td>6.92*10^{10}</td>
<td>[Pa]</td>
</tr>
<tr>
<td>( C_{11} )</td>
<td>87.57*10^{8}</td>
<td>[Pa]</td>
</tr>
<tr>
<td>( C_{22} )</td>
<td>131.35*10^{8}</td>
<td>[Pa]</td>
</tr>
<tr>
<td>( C_{12}, C_{21} )</td>
<td>31.52*10^{8}</td>
<td>[Pa]</td>
</tr>
<tr>
<td>( P_1 )</td>
<td>5*10^{6}</td>
<td>[Pa]</td>
</tr>
<tr>
<td>( P_2 )</td>
<td>0</td>
<td>[Pa]</td>
</tr>
<tr>
<td>( a )</td>
<td>0.002</td>
<td>[-]</td>
</tr>
<tr>
<td>( b )</td>
<td>0.003</td>
<td>[-]</td>
</tr>
</tbody>
</table>
Figure 2 shows the dependence of the main characteristics of the stress-strain state of the construction on a radial coordinate for the initial time (solid lines) and for the relaxation time (dotted line) after a full descent of the gas in the pipeline. Curves representing pipeline characteristics, are plotted on graphs within \([R_1, R_2]\), and bandage — within \([R_2, R_3]\). As one can see from figure 2b, the level of contact stresses for the initial time is 0.87 MPa.

![Graphs](image)

**Fig. 2** Dependence of radial displacement (a), radial (b) and circumferential (c) stresses on radial coordinate for the initial time and relaxation time for internal pressure \(P = P_2 = 0\) [Pa]

It is possible to trace a relaxation of this stress at time under the influence of viscoelastic properties of fiberglass in figure 3. As can be seen from the graph, the stress relaxation time is about 2000 hours, which coincides with the corresponding value obtained in [13], and the level of contact stress in this point is approximately 0.33 MPa, that is 62% less than the corresponding result for an elastic solution.
**Fig. 3** Dependence of contact pressure on time for internal pressure $P = P_2 = 0$ [Pa]

Therefore, it is possible to evaluate strength of the pipeline, the bandage and their connection. The results of this assessment can be adjusted by considering these variables over time in terms of durability under the influence of viscoelasticity.

It should be noted that the described analytical model takes into account not only an applying the bandage to a loaded pipeline but also its installation with a tension, if the $\Delta u$ take a negative value. Besides, it is possible to combine these effects.

In addition, this model can be extended for the case, when a matrix of viscous properties is not proportional to the matrix of elastic properties, using the method based on a numerical-analytical solution of integral-differential equations described in [16].

**13.5. CONCLUSION**

The mathematical model of the stress-strain state of a long section of a steel pipeline with a composite bandage loaded by an internal pressure takes into account the impact of orthotropic viscoelastic properties, installation of the bandage on a loaded pipe and with tension. It should be noted that solving the problem numerically using finite-element computer systems and taking into account the above
installation conditions is a complex and resource consuming procedure that, in addition, also has a certain error. The analytical model, contained in a several mathematical expression provides opportunities of the stress-strain state assessment with regard to these features, which undoubtedly gives it a great advantage over the use of a finite-element approach in conducting rapid tests for the pipeline repairs. The curves of change of the basic stress-strain state parameters in a radius and a time, including the graph of contact stresses versus time under influence of viscoelastic properties illustrate the above capabilities of the developed approach.

13.6. REFERENCES


Weight optimisation of composite bandage used for repair of pipe with volumetric surface defect

Akishin¹ P., Barkanov² E.

¹ Riga Technical University, Riga, LATVIA, pavelas.akisins@rtu.lv
² Riga Technical University, Riga, LATVIA, barkanov@latnet.lv

Summary: Optimisation methodology based on the method of experimental design and response surface method has been successfully applied for weight optimisation of composite bandage used for repair of gas transmission pipe with volumetric surface defect. It is achieved that stress intensity in the damaged zone of repaired pipe is less than in the undamaged pipe.

Keywords: optimisation, pipe, defect, repair, bandage

14.1. INTRODUCTION

Pipelines are structures of significant importance, so provision of its continuous and accidents-free operation also is important. One of the most widely used method of volumetric surface defects repair, which does not require a stop of the pipeline operation, is a charging the volume of the defect by a filler and an installation of a composite bandage on the damaged zone. The main objective of this repair is to bring an efficiency of damaged section up to the level of undamaged pipeline. Also an important condition for the repair is saving and rational use of expensive composite materials. Solution of these problems is impossible without
weight optimisation of bandage parameters taking into account stress state of damaged pipe.

14.2. OPTIMISATION METHODOLOGY

An optimisation methodology used in the research is based on the method of experimental design and response surface method. The design methodology is presented in Figure 1.

The basic idea of this approach is that simple mathematical models (response surface) are determined only using the finite element solutions in the reference points of the experimental design. The significant reduction in calculations is achieved in this case in comparison with the conventional optimisation method.

Optimisation methodology is divided into following 5 stages:

— Choice of variable parameters and establishment of the domain of search.

— Elaboration of plan of experiments for the chosen number of reference points.

— Execution of the experiments (numerical simulation).

— Determination of simple mathematical models (response surface) from the experimental data.

— Minimisation of the selected objective function and obtaining of optimal values of variable parameters.

14.3. EXPERIMENT DESIGN

The choice of the design experiments have a large influence on the accuracy of the approximation. In the numerical experiment, there a given input will always yield the same output (there is no random errors and noise as in the physical experiment), the design of experiments need be space filling [1]. The space filling design is graphically illustrated in Figure 2.
Numerous space filling experimental designs were developed in an effort to provide more efficient and effective means for sampling deterministic computer experiments based on Latin hypercube. The initial information for development of the plan is the number of variables $n$ and the number of experiments $p$. The number of levels or factors is equal to the number of experiments and for each level there is only one experiment.

The points of experiments in the domain of factors are distributed as regular as possible. For this reason, the following criterion is used:

$$
\Phi = \sum_{i=1}^{p} \sum_{j=i+1}^{p} \frac{1}{l_{ij}^2} \rightarrow \min
$$

where $l_{ij}$ is a distance between points having numbers $i$ and $j$. 
The problem to minimize the criterion (Equation 1) together with the first principle leads to the solving of a non-linear programming problem. Solving the non-linear programming problem, the plans of experiments were determined for different number of the design variables \( n \) and number of the experiments \( p \).

In this research the EdaOpt software [2] was used for the generation of the experiment design.

### 14.4. RESPONSE SURFACE APPROXIMATION

Low-order polynomials are the most widely used for approximation of experimental data. First, second and third-order polynomials are expressed as follows:

\[
\hat{F}(x) = b_0 + \sum_{i=1}^{m} b_i x_i \tag{2}
\]

\[
\hat{F}(x) = b_0 + \sum_{i=1}^{m} b_i x_i + \sum_{i=1}^{m} \sum_{j=i}^{m} b_{ij} x_i x_j \tag{3}
\]

\[
\hat{F}(x) = b_0 + \sum_{i=1}^{m} b_i x_i + \sum_{i=1}^{m} \sum_{j=i}^{m} b_{ij} x_i x_j + \sum_{i=1}^{m} \sum_{j=i}^{m} \sum_{k=j}^{m} b_{ijk} x_i x_j x_k \tag{4}
\]

where \( m \) total amount of variables, \( b_0, b_i, b_{ij}, b_{ijk} \) are unknown coefficients of regression functions.

As stated in [3], there is a considerable practical experience indicating that second-order models work well in solving real response surface problems. In general it is thought that third and higher order polynomials can over-fit data, consequently avoiding construction of global behavior of the parameters. On the contrary, first order—polynomials are too simple and give prediction errors too high for use in science and engineering.

The second-order full polynomials are used for approximation of results of numerical experiments in this research.
14.5. OPTIMAL DESIGN OF BANDAGE

Research object

The object of the present research is the gas transmission pipe made of Steel type 20 with diameter 220 mm and wall thickness 6 mm. The pipe with 2 internal pressures — 3.34 MPa and 8.99 MPa — has been investigated.

The pipe has a volumetric surface defect with dimensions $102 \times 130 \times 3.3$ mm. During the repair the volume of the defect has been charged by the filler and covered by the composite bandage (Figure 3).

![Diagram of repaired pipe with bandage](image)

**Fig. 3** Symmetry cut of the repaired pipe

Formulation of the optimisation problem

Current work considers the problem of weight optimisation of the bandage and optimal choice of the geometric parameters of the bandage. Width of the bandage $I$ can vary continuously, but thickness $h$ — discretely because of the layered structure of the composite. Bandage thickness variation step is equal to the thickness of 1 layer of bandage material: $h_i = 0.39$ mm. Thus, thickness of the bandage is equal to
\[ h = k \times h_i \]  \hspace{1cm} (5)

where \( k \) is number of layers.

Upper and lower bounds (domain of interest) for the variable parameters of the bandage are listed in Table 1.

**Table 1** Domain of interest for optimisation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandage length</td>
<td>( l )</td>
<td>[mm]</td>
<td>( 140 \leq l \leq 400 )</td>
</tr>
<tr>
<td>Number of layers ( k )</td>
<td>( k )</td>
<td>[psc]</td>
<td>( 15 \leq k \leq 34 )</td>
</tr>
</tbody>
</table>

The plan of experiments created for the optimisation procedure is presented in Figure 4.

**Fig. 4** Plan of experiments

Numeric calculations using the software ANSYS have been created for all points of the plan of experiments. In addition, calculations for undamaged pipe without repair have been created to obtain stress-strain state of the pipe. Calculation results published in [4] are presented in Table 2.
Results obtained in [4] have been approximated using the second-order polynomials to obtain the response surfaces, which are shown in Figures 5–8. Expressions (6)–(9) are corresponding regression equations.

**Fig. 5** Stress in the mid-point of defect. Pressure 3.34 MPa

**Fig. 6** Stress in the edge point of defect. Pressure 3.34 MPa

\[
\sigma_{\text{mid}} = 99.826 - 1.720h + 0.026l + 0.0022h^2 - 0.000465hl - 0.000032l^2
\]

(6)

\[
\sigma_{\text{edge}} = 123.61 - 2.357h + 0.00604l + 0.0033h^2 - 0.000408hl - 0.0000133l^2
\]

(7)
### Table 2: Stress intensities in the defect of the pipe [4]

<table>
<thead>
<tr>
<th>Number of layers, ( k )</th>
<th>Bandage width ( l ), mm</th>
<th>Pressure 3.34 MPa</th>
<th>Pressure 8.99 MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Stress in mid-point, MPa</td>
<td>Stress in edge point, MPa</td>
</tr>
<tr>
<td>15</td>
<td>180.0</td>
<td>76.34</td>
<td>85.51</td>
</tr>
<tr>
<td>16</td>
<td>260.0</td>
<td>74.40</td>
<td>83.87</td>
</tr>
<tr>
<td>17</td>
<td>380.0</td>
<td>72.16</td>
<td>81.33</td>
</tr>
<tr>
<td>18</td>
<td>320.0</td>
<td>70.84</td>
<td>81.01</td>
</tr>
<tr>
<td>19</td>
<td>160.0</td>
<td>70.11</td>
<td>80.28</td>
</tr>
<tr>
<td>20</td>
<td>220.0</td>
<td>69.75</td>
<td>78.92</td>
</tr>
<tr>
<td>21</td>
<td>390.0</td>
<td>68.92</td>
<td>75.05</td>
</tr>
<tr>
<td>22</td>
<td>310.0</td>
<td>68.56</td>
<td>74.69</td>
</tr>
<tr>
<td>23</td>
<td>140.0</td>
<td>64.39</td>
<td>73.52</td>
</tr>
<tr>
<td>24</td>
<td>210.0</td>
<td>62.58</td>
<td>68.71</td>
</tr>
<tr>
<td>25</td>
<td>350.0</td>
<td>59.44</td>
<td>65.57</td>
</tr>
<tr>
<td>26</td>
<td>270.0</td>
<td>57.40</td>
<td>60.57</td>
</tr>
<tr>
<td>27</td>
<td>170.0</td>
<td>53.09</td>
<td>59.26</td>
</tr>
<tr>
<td>28</td>
<td>400.0</td>
<td>51.05</td>
<td>54.31</td>
</tr>
<tr>
<td>29</td>
<td>340.0</td>
<td>50.45</td>
<td>53.71</td>
</tr>
<tr>
<td>30</td>
<td>230.0</td>
<td>49.17</td>
<td>52.43</td>
</tr>
<tr>
<td>31</td>
<td>150.0</td>
<td>50.08</td>
<td>53.34</td>
</tr>
<tr>
<td>32</td>
<td>300.0</td>
<td>48.14</td>
<td>51.40</td>
</tr>
<tr>
<td>33</td>
<td>370.0</td>
<td>46.93</td>
<td>50.19</td>
</tr>
<tr>
<td>34</td>
<td>190.0</td>
<td>46.13</td>
<td>49.39</td>
</tr>
<tr>
<td>Pipe without defect</td>
<td></td>
<td>61.20</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 7 Stress in the mid-point of defect. Pressure 8.99 MPa

\[
\sigma_{\text{mid}} = 268.658 - 4.630h + 0.0704l + 0.00636h^2 - 0.00125hl - 0.0000866l^2
\]

Fig. 8 Stress in the edge point of defect. Pressure 8.99 MPa

\[
\sigma_{\text{edge}} = 325.50 - 6.3432h + 0.0163l + 0.0171h^2 - 0.001098hl - 0.0000358l^2
\]

Optimisation criteria is the minimum of the bandage volume. The main constrains of the optimisation procedure are values of the stress intensity in damaged zone of the pipe. These values in the repaired pipe must be less or equal to the in corresponding values in the pipe without defect: 61.2 MPa for the pipe with inner pressure 3.34 MPa and 168.8 MPa for the pipe with inner pressure 8.99 MPa.

Inner radius of the bandage is equal to the outer radius of the pipe – 110 mm. Outer radius of the bandage is equal to 100 + h. Area of the bandage cross-section is equal to:

\[
S = \pi \left( 220h + h^2 \right)
\]
Volume of bandage is equal to:

\[ V = \pi \left( 220h + h^2 \right) \times l \]  \hspace{1cm} (11)

Equation (11) rewritten using number of layers \( k \) instead of bandage thickness \( h \) is the objective function of the optimization problem:

\[ V = \pi \left( 220 \times 0.39k + (0.39k)^2 \right) \times l = \pi kl \left( 85.8 + 0.152k \right) \rightarrow \text{min} \]  \hspace{1cm} (12)

**Results of the optimisation**

Non-linear optimisation problem has been executed by the random search method realized in EdaOpt software [2] using the obtained response surfaces and introducing to the solution formulated objective function and constraints. Optimal length of the bandage \( l \) and number of layers \( k \) have been obtained as the main result of the optimisation procedure:

\[ l_{optimal} = 140 \text{ mm}; \]
\[ k_{optimal} = 28 \text{ layers}. \]

These geometric parameters of the bandage give the minimal volume of the bandage \( V_{min} = 1109080 \text{ mm}^3 \). Values of stress intensity in damaged zone of the pipe repaired by the optimal bandage are given in Table 2. As it is seen from the Table 2 stress intensities in the repaired pipe do not exceed corresponding values of undamaged pipe for both applied inner pressures.

<table>
<thead>
<tr>
<th></th>
<th>Stress in the edge point of damage obtained from approximation, MPa</th>
<th>Stress in the mid-point of damage obtained from approximation, MPa</th>
<th>Stress in pipe without damage obtained by FEM, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure 3.34 MPa</td>
<td>60.4</td>
<td>54.6</td>
<td>61.2</td>
</tr>
<tr>
<td>Pressure 8.99 MPa</td>
<td>155.4</td>
<td>147.0</td>
<td>164.8</td>
</tr>
</tbody>
</table>
14.6. CONCLUSION

Optimisation methodology based on the method of experimental design and response surface method has been successfully applied for weight optimisation of composite bandage used for repair of pipe with volumetric surface defect. Obtained optimal width of bandage (140 mm) and number of layers (28 layers) give stress intensity in damaged zone less than in undamaged zone for both considered inner pressures (3.34 and 8.99 MPa) and at the same time the minimal volume of bandage. It is important to note that obtained optimal value of bandage width is equal to the lower bound of considered domain. But reduction of the bandage width is not desirable because of technological reasons.

14.7. REFERENCES


4. Lvov I., Barkanov E. Optimal design of pipeline with volumetric surface defect.
Investigation of the mutual influence of two machined volumetric surface defects of transmission pipeline

Lambrescu¹ I., Chebakov² M., Chebanenko² V., Gusakov² D., Morunova² A.

¹ Petroleum-Gas University of Ploiești, ROMANIA, ionutlambrescu@gmail.com
² Southern Federal University, Rostov-on-Don, RUSSIA, gusakov.dv@yandex.ru

Summary: In this paper, a static problem for the damaged pipeline segment with one or two volumetric surface defects under inner pressure is considered. This problem was solved with the help of finite element modeling in ANSYS and Siemens NX packages. In order to investigate relations between maximum stress values and the defects distance and geometry, a series of computational experiments and comparative analysis of the solutions obtained were performed. To estimate maximum stress in the damaged pipeline, a special similarity criterion was obtained.

Keywords: pipeline, defect, corrosion, finite element, in service repair, ANSYS, Siemens NX

15.1. INTRODUCTION

During the operation and servicing of oil-and-gas pipelines, a plenty of engineering problems arise. One of them is the repair of various defects in the pipeline, for example, defects occurring in welds, damage caused by some external mechanical impact, cracks and surface corrosion [1–4]. The most common method of repair for today is a complete replacement of the damaged segment of a pipeline, or an employment of techniques involving
welding. Both of these approaches require stoppage the pipeline’s product resulting in significant financial losses. In this context, nowadays the objective of the development of pipe repair techniques without the need to suspend its operation [5–8] is highly relevant. Besides, in order to assess if the repair of the da aged pipeline is required and to define the most suitable repair method, it is necessary to provide the analysis of defects in a pipe wall and the evaluation of stresses and strains generated by their presence.

In the current study, we consider several problems for the damaged pipeline with one or two volumetric surface defects (VSD) under internal pressure. In all the cases, it is considered that the defects were caused by the surface corrosion and were subsequently exposed to a mechanical treatment in order to eliminate the sources of stress concentration. At the corrosion occurrence site, a rectangular “pocket” was machined with rounded corners.

15.2. SIMILARITY ANALYSIS

In the first part of the research, a sensitivity analysis was performed in order to find a set of dimensionless parameters and to obtain some similarity criteria allowing to estimate the maximum levels of stress distribution by extrapolating the results for other pipes without the need for additional calculations.

First step was to define set of dimensionless parameters based on some “known” pipe with geometrical parameters equal to those in Table 1.

Table 1 Geometrical parameters of the pipe

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe diameter ($D$)</td>
<td>323.9 mm</td>
</tr>
<tr>
<td>Wall thickness ($s$)</td>
<td>8 mm</td>
</tr>
<tr>
<td>Defect length ($L$)</td>
<td>203.2 mm</td>
</tr>
<tr>
<td>Defect depth ($d$)</td>
<td>6 mm</td>
</tr>
<tr>
<td>Defect width ($l$)</td>
<td>152.4 mm</td>
</tr>
</tbody>
</table>
For this pipe, the set of dimensionless parameters was following:

\[ C_1 = \frac{L}{\sqrt{(Ds)}} = 3.992 \quad C_2 = \frac{l}{\sqrt{(Ds)}} = 2.994 \quad C_3 = \frac{d}{s} = 0.75 \]  \hspace{1cm} (1)

Sets of different values of thickness \((s)\) and diameter \((D)\) were also considered. Defect dimensions were calculated for each pair \((D, s)\) using the dimensionless parameters \((1)\). The inner pressure for each case was constant: 1.6 MPa. Results of calculations are shown below.

**Fig. 1** Results of similarity analysis for different diameters of the pipe: dependence of maximum Von-Mises stresses on the thickness of the wall.

As a result of the analysis of the data from Fig.1, the additional dimensionless parameter \(C_4 = D/s\) was introduced. It was assumed that in the case when values of these parameters are fixed and then pipe dimensions for different diameters are calculated from relations \((1)\), the maximum stresses should be the same. A series of computational experiments was performed to investigate if the similarity presents for different values of the dimensionless parameters. In one of the experiments we have calculated maximum stress values for six different pipe diameters and three values of \(C_4\) (see Fig. 2).
Results from Fig. 2 confirmed our assumptions about similarity of maximum stresses in case of using the dimensionless parameters. Hence, the similarity criteria is: If two damaged pipes have the same values of the parameters $C_{l-a}$, then maximum stress values for these pipes are also the same. These approaches can be used for further extrapolation of the results, thus simplifying the analysis process.

![Graph showing the relation between maximum Von-Mises stress and pipe diameter for different values of $C_4$.]

**Fig. 2** Relation between maximum Von-Mises stress in the defect zone and the pipe diameter for different values of $C_4$

### 15.3. INTERACTION BETWEEN TWO VSD

Another important problem is the investigation of the mutual influence of two volumetric surface defects. We have considered two types of the relative defect location: symmetrical longitudinal and symmetrical circumferential.

For the case of longitudinal defect location, two identical defects were placed symmetrically with distance $F$ between them. To assess if it is necessary to machine two separated defects or a single defect but with length equal to $2L+F$, a “Double defect” with such length was also examined.
Investigation of the mutual influence of two machined volumetric surface defects of transmission pipeline

**Fig. 3** Relation between maximum Von-Mises stress in defect zone and longitudinal distance between two VSD

Fig. 3 shows that for small distance between the defects (from 1 to 30% of defect length), maximum stress values are less than in case of a single defect. For the Double defect the reverse trend appears. Nevertheless, from the distance about 150% of defect length maximum stress values become constant. Consequently, we can claim that to eliminate additional stresses, it is better to cut out two defects with moderate space between them rather than to cut a large one in case of longitudinal defect location.

**Fig. 4** Defect subsurfaces

In the second case, two defects placed symmetrically in circumferential direction with the angle \( \theta \) between their borders were
considered. Taking into account non-symmetrical stress distribution in the defect zone for such a location, the defect surface was separated into two subsurfaces (see Fig. 4). “Double angle defect” with angular width equal to $2\alpha+A$ was also examined.

**Fig. 5** Relation between maximum Von-Mises stress in defect zone and angle between the borders of two VSD

The results at Fig. 5 show that for the angle between defects less than 70 deg., maximum stress values concentrate on the distant edges and appear to be a bit higher than in the single defect case. However, on the nearer edges, stress values are much lower than in the single defect case. For the Double defect, the stress values are the same as in case of a single defect for all the angle values. Therefore, we can affirm that there is no practical use in mechanical processing of two smaller defects rather than large one in case of circumferential location of the defects.

### 15.4. LENGTH AND WIDTH VARIATION

The developed parametrical FE models can be used for a large number of calculating purposes. One of them is investigation of the relation between maximum stress values in the defect zone and
geometrical parameters of the defect itself. When the results for the depth variation appear to be rather simple, relation between defect length or width and maximum stresses is of considerable interest.

![Graph showing the relation between maximum Von-Mises stress and Total Deformation in defect zone and length of VSD.](image)

**Fig. 6** Relation between maximum Von-Mises stress and Total Deformation in defect zone and length of VSD

Relations from Fig. 6 show that maxim stress values increase rapidly with the growth of the defect length. Then maximum appears, and after short decreasing zone, stresses become constant. This fact allows assuming that there is range of values of the defect length that should be avoided during the machining of the corrosion zone. These values should be determined individually for specific pipe geometry. Another approach is to determine dimensionless parameters corresponding to the maximum point. Defect length to width ratio ($L/l$) can be used as an additional parameter to those described in first section of the paper.

In case of width variation reverse trends appear. Maximum stress observed for the thin defect (situation when the defect is close to the crack) and with the increase of the width, stress values decrease and become constant at some point. According to the Fig. 7, we can claim that angular width of the defect should be over 25 degrees to avoid unnecessary stress concentrations.
15.5. CONCLUSION

FE analysis of the damaged pipeline was performed in frames of several static problems. On the basis of this analysis, asimilarity criteria was obtained in order to estimate the maximum stress values in the pipeline with VDS. The usage of dimensionless parameters from the similarity criterion can reduce the amount of time needed for the strength analysis of the damaged pipe. The results of investigation of the mutual influence between two defects provide information on the most efficient relative defect location in terms of maximum stresses. Relations obtained for the defect length/width and stress in defect zone reveal general tendencies in stress distribution. Also, a range of defect parameters values corresponding to the highest stress concentrations was obtained.

15.6. REFERENCES


Experimental observations of orthotropic elastic and viscoelastic characteristics of the elastomeric textile reinforced composites

Barkanov E.N., Larin O.O., Petrova Ju.A.

Riga Technical University, Riga, LATVIA
National Technical University “Kharkiv Polytechnic Institute”, Kharkiv, UKRAINE,
barkanov@latnet.lv, alexeya.larin@gmail.com, usuanushka@gmail.com

Summary: The paper deals with investigation elastic and viscoelastic properties of elastomeric composites by experimental tests. The composites has a textile unidirectional reinforcement. The experiments have been carried out in different directions of cyclic loading with different amplitudes. It allows us to evaluate a hysteresis loss as well as the initial modules of elasticity in the stabilize state of material. The loss modulus is evaluated depending on strain amplitude in different loading directions.

Keywords: elastomeric composites, elastic and viscoelastic properties, experimental study

16.1. INTRODUCTION

In modern engineering practice an elastomeric composites are widely used for repairing of damaged pipelines. Such composites are used as a bandage that apply on the damaged area of the pipeline [1]. Mentioned above repairing technology allow to renew the pipeline strength in the damaged zone even during the operation of the pipeline as it does not need
Experimental observations of orthotropic elastic and viscoelastic characteristics of the elastomeric textile reinforced composites

...to use a welding or other heating techniques [2]. Repaired pipe should be considered as a conjugated system of metal pipe and composite shroud. The composite shroud in this case becomes a principal element whose strength and durability will form the pipeline reliability.

A lot of reinforced elastomers are composed of a rubber matrix with reinforced textile fibers. The presence of reinforcement leads to multidirectionality of mechanical properties. In addition, there are exists an internal localization of the stress-strain state in the corresponding elements that makes it difficult to assess the operational durability [3–8]. However, the theoretical modeling reliability, functionality and durability of engineering structures with the reinforced plies of composite materials can’t be considered in an explicit form of their internal structure. So simplified models are used. It implies that composite layers are considered homogeneous with averaged properties, so some specific peculiarity of the internal structure are neglected.

Thus, characteristic of viscoelastic behavior of elastomeric composites defines a reliability and functionality of design. Thus, the definition of mechanical characteristics of the material is an actual scientific and practical problem. The elastic and viscoelastic properties as well as a strength should be considered as orthotropic. Defining constants of orthotropic materials of reinforcement composites can be carried out theoretically using the phenomenological models (eg Halpin-Tsay rule of mixture) [9–10] or they can be found by computer simulations conducted with a representative cell of composites model which explicitly takes into account cords elements [11]. Another way to determine the appropriate characteristics of the composite are experimental tests. Unfortunately, it is rather difficult to determine all orthotropic material constants by experiments. However, the key characteristics (three main directions) accurately can be determined from experimental tests along of reinforcement and across it.
The main goal of paper is carrying out an experimental study to determine elastic and strength characteristics of the composite which is consist of a rubber matrix and has a textile unidirectional reinforcement. Tests have been carried out in three principal directions: tensile test along reinforcement textile cord, tensile test across the reinforcement, and the test on compression of a plate in the direction perpendicular to the plane of the composite reinforcement.

16.2. METHODOLOGY OF EXPERIMENTAL RESEARCH

The study of static strength and determination of the deformation curve was carried out using specialized measuring complex Zwick / Roell Z100. The specimen samples of geometry corresponds to standards for mechanical tests of rubber-like materials and rubber-cord composites ISO 527-2 1A.

The specimens had the following geometric parameters: actual thickness: 10±0.1 mm; width: 10 mm; the length of the working part: 80 mm; overall length: 150 mm. The thickness of the samples has 1% variation due to technological tolerances which exists in the manufacture of composite sheets. The remaining parameters have accurate values because all specimens were obtained by cutting them using the same stamp with standard size. Fig. 1 shows a schematic drawing of the geometry of specimens and its photo.

Fig. 1 The geometry of specimens for testing
Specimens were rigidly fixed by mechanical clamps as shown in Fig. 2. A displacement control load were posed ie fixed values of strains were set for specimen. Thus we measured the effort that had been occurring in the lower clamps by standard sensor (using this machine with maximum effort 10 kN ± 0,01 N).

Quasi-static loading was applied to specimen with the speed of deformation 100% / min. The results are automatically recorded, for each test in real time and have been recorded each 0.1 seconds. The experiments have been carried out in two different variants. The first experiments carry out to determine the static strength. During those tests specimens were loaded up to failure. A second variant of experiments were cyclic tests with fixed strain levels that allows to determine elastic properties of such materials in stabilized condition. Each experiment was performed at least 3 times to check the repeatability of the results. The test results have been obtained in three main directions.

Fig. 2 Fixation of specimen in experimental equipment
16.3. ANALYSIS OF COMPOSITE STATIC STRENGTH

During the gradual static loading of specimens directly along reinforcement linear response of system observed within 15% strain after which fiber cord damage took place (Fig. 3,a.) Subsequent loading of specimens accompanied by a series of damages of fibers and their detachment from the rubber matrix. Then, it was observed the deformation of the rubber matrix that remained up to its total destruction Fig. 3 b. It should be noted, that the final break is observed for strain levels considerably lower than the ultimate strain of pure rubber specimens (250–300% compared to 570–630%). Perhaps this situation is caused most likely by the presence of high concentrations of internal stresses and strains in the areas around the fibers.

Subsequent experiments were static strength tests on the same material, but specimens have been cut down in cross-direction to reinforcement. Figure 3,b presents the deformation curves up to failure. The behavior of the composite in the direction orthogonal to the reinforcement qualitatively repeats the behavior of pure rubber material.

Note that the final specimen break is also observed for strain levels considerably lower than the limit deformation of pure rubber samples (200–250% compared to 570–630%) and is even less than the ultimate strain level, leading to the final break in this composite under loading coincident to the direction of reinforcement. Similar conclusions can be drawn about limit the stress on the break, which also are less for composite with its loads in the direction orthogonal to the reinforcement compared to pure rubber material. This situation is also due to the presence of high concentrations of internal stresses and strains in areas where there is a cord. That leads to violation of the uniformity of the material structure.
16.4. IDENTIFICATION OF THE COMPOSITE ELASTIC PARAMETERS

In addition to strength characteristics the quasi-static cyclic test has been provided giving an opportunity to assess the elastic properties of the stabilized materials. The samples were subjected to cyclic deformation with a fixed amplitudes of strains. It was carried out 50 cycles. The experiments were conducted with strain sweep 2% and 5%. Engineering evaluation for the average initial modulus for this material of 140 MPa (calculated on the strains of 5%).

Characteristic curves of deformation that were obtained in these tests are shown in Fig. 4. The results indicate almost linear of behavior of the composite. It should be noted that a little Malin effect took place. At the same time we have to emphasize that in this study this effect is not under current study and all the properties are determined for materials in stabilized state.
Fig. 4 Deformation curves of elastomeric composite specimen in a direction of reinforcement on different amplitudes (stabilized state)

Just as in the previous case, we investigated characteristics of elasticity of the composite in the direction orthogonal to the reinforcement. The experiments were carried out with strain sweep 5% and 10%. Engineering evaluation for the average initial modulus for this material of 11.5 MPa material (calculated on the deformation of 5%). Characteristic curves of deformation, which was obtained in these tests are shown in Fig. 5.

Fig. 5 Deformation curves of elastomeric composite specimen in across direction to reinforcement on different amplitudes (stabilized state)
Using measuring complex Zwick in a modified configuration allows to study materials on compression. In this work was carried out a series of experiments allowed to determine the elastic properties of the composite in the direction perpendicular to the direction of reinforcement. We used a square flat plate composite 50×50 mm with a thickness of 10 mm to conduct these measurements. This sample was clamped between two metal plates, which surface has been previously greased with special graphite paste that provides free sliding on the surface of the sample. And thus it provides no restrictions on the deformation of the sample in a plane perpendicular to the loading.

Elastic properties of specimens under compression in the direction perpendicular to the reinforcement plane, have been defined from a series of tests under cyclic deformation with a fixed level of strain. 50 cycles were carried out. The experiments were conducted with strain sweep of 3%, 5%, 10% and 15%. Engineering evaluation of initial average elastic modulus of the material in the direction perpendicular to the reinforcement plane 15 MPa (calculated on the strain of 5%). Characteristic curves of deformation, which were obtained during these tests, are shown in Fig. 6.

![Graph](image)

**Fig. 6** Deformation curves of elastomeric composite specimen under compression load in the plane orthogonal to reinforcement on different amplitudes (stabilized state)
16.5. IDENTIFICATION OF THE COMPOSITE VISCOS PARAMETERS

The results were obtained during the cyclic loading experiments allow to estimate the viscous component of the deformation of rubber-cord composite. Loss modulus is determined from hysteresis losses (Fig.7) for quasi–harmonic loading (Fig. 8).

\[ \tilde{E} = \frac{\Delta W^*}{\pi (\varepsilon_1^*)^2} \]  

(1)

\( \Delta W^* \) — hysteresis loop area is defined in the experiment, \( \varepsilon_1^* \) — strain amplitude which is applied to the specimens.

![Fig. 7 Hysteresis loss curves in different direction](image)

The available experimental data allow us to determine the area of the hysteresis loop by numerical integration for cycles with different amplitudes of loading in different directions.
Experimental observations of orthotropic elastic and viscoelastic characteristics of the elastomeric textile reinforced composites

![Graph showing loss modulus curves with different strain amplitudes in different directions.](image)

**Fig. 8** Loss modulus curves depending on different strain amplitudes in different direction

Generalization of experimental tests complex are presented in Table 1.

**Table 1** Elastic characteristics and strength properties of rubber-cord composite

<table>
<thead>
<tr>
<th>Direction of the measurement</th>
<th>Initial elasticity modulus $E$, MPa</th>
<th>Ultimate strains $\varepsilon$, %</th>
<th>Ultimate stresses $\sigma_\text{u}$, MPa</th>
<th>Residual ultimate strains $\varepsilon$, %</th>
<th>Residual ultimate stresses $\sigma_\text{r}$, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>in reinforcement</td>
<td>140</td>
<td>15,5</td>
<td>15,2</td>
<td>252</td>
<td>12</td>
</tr>
<tr>
<td>across reinforcement</td>
<td>11,5</td>
<td>223</td>
<td>7,8</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>perpendicular to the reinforce-</td>
<td>15</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>cement plane</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Here is summarizes the results of average evaluation of strength and elasticity in different directions for composite under investigation. The statistical dispersion coefficient of variation is within 10% for all experiments (the exception is only boundary residual deformation).

16.6. CONCLUSION

The paper deals with the study of determination the elastic and strength characteristics of the rubber-cord composite in three main direction: tensile test along textile cord tensile reinforcement, tensile test cross-direction to textile cord and the compression test plate which is reinforced in its plane.

The results showed that the presence of internal reinforcement leads to high internal stress and strain concentrations in places where there is a cord.

As a results a samples break occurs at levels of strain, much lower than the ultimate strain of pure rubber samples.

Averaged estimate the strength and elasticity in different directions for composite elastomers were obtained based on the research results

16.7. REFERENCES


Assessment of the probability characteristics of the stress state of the pipeline damaged by pitting corrosion

Vodka O.

National Technical University “Kharkiv Polytechnic Institute”, department “Dynamics and strength of machines”, Kharkiv, Ukraine, alexey.vodka@gmail.com

**Summary:** Pitting corrosion is one of the most frequently occurring kinds of pipeline systems damage. Under pitting corrosion the pipe wall is thinning. It is causing to stress increasing. This work is devoted to research of probabilistic characteristics of the stress state, which occurs at different stages of pitting corrosion. For this purpose, the finite-element model of pipeline with multiple spherical defects is built. Probabilistic characteristics of the stress state are investigated by Monte-Carlo method. The conditional density probability of stress concentration factor at various defect radii has been obtained.

**Keywords:** stress concentration factor, pitting corrosion, extreme value statistic, stress-strain state, pipeline

17.1. INTRODUCTION

Pitting corrosion is one of the most common mechanisms of damage to different kind of pipelines [1]. A distinctive feature of pitting corrosion lay in its local character. As a result of the corrosion relative small to the size of the pipe complex shape cavities are occurred. These cavities grow under the influence of the environment and it may lead over time to perforation of the pipe walls.

Research development of pitting corrosion [2]—[6] show that the point of origin of the initial corrosion damage are random and depend on
the microstructure of the material, processing surface, the presence of surface defects, and other environmental factors. Despite the complexity of the process of the evolution of pitting corrosion, it should be noted that the researchers’ highlights standard defect types [7]: shallow, elliptical, deep, undercut, and subsurface. However, in the process of modeling a defect types variety replaced by an even more simple shapes: an ellipsoid or a parallelepiped with rounded corners (box defects) [8], [9].

In spite of the large number of papers in the direction of developing probabilistic models of evolution of the size of defects [2]–[4], [6], [10], [11], investigation of the stress-strain state of structural elements with pitting defects paid much less attention [12].

**17.2. PROBLEM STATEMENT**

The work is necessary to study the probabilistic characteristics of the stress-strain state of pipeline part with pitting corrosion and to determine the characteristics of its reliability.

**17.3. SIMULATION PIPELINE PART WITH PITTING CORROSION**

In this work fragment of main pipeline was modeled with respect to GOST 31447–2012, which corresponds to the API Spec.5L, DIN 17120, EN 10208–2, BS 4515: 1992. The parametric model of pipe part with pitting corrosion defects has been build (Fig. 1). The defect position describes in cylindrical coordinates \((\rho, \varphi, z)\), where \(z\)-axis coincides with the axis of the pipe. The defect position is determined by two coordinates \(\varphi, z\) and the third one is determined from the condition that the center of the defect laid on the pipe outer surface. It is also assumed the defects in \(\varphi\) and \(z\) direction are uniformly distributed. The parameters of model are presented in Table 1. The pipeline part is loaded with internal pressure \(P = 2.5\) MPa. The mechanical properties of the material were taken from the recommendations of these standards (Table 2).
Table 1 Parameters of pipeline geometry

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(R_1), mm</th>
<th>(R_2), mm</th>
<th>(t), mm</th>
<th>(l_1), mm</th>
<th>(l_2), mm</th>
<th>(l_3), mm</th>
<th>(Rd), mm</th>
<th>(Rd / t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>245</td>
<td>235</td>
<td>10</td>
<td>300</td>
<td>100</td>
<td>300</td>
<td>2.5..8.75</td>
<td>0.25..0.875</td>
</tr>
</tbody>
</table>

Fig. 1 Parameterized sketch of pipeline with defects

Table 2 Material properties

<table>
<thead>
<tr>
<th>(E), N/m²</th>
<th>(\nu)</th>
<th>(\sigma_y), N/m²</th>
<th>(\sigma_u), N/m²</th>
<th>(\delta), %</th>
<th>(E_\text{t}), N/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's modulus</td>
<td>Poisson ratio</td>
<td>Yield stress</td>
<td>Ultimate stress</td>
<td>Elongation before fracture</td>
<td>Tangent (plastic) modulus</td>
</tr>
<tr>
<td>2.1×10¹¹</td>
<td>0.3</td>
<td>235×10⁶</td>
<td>375×10⁶</td>
<td>22</td>
<td>63.6×10⁶</td>
</tr>
</tbody>
</table>

To determine the parameters of the stress-strain state of the pipeline part the finite elements method have been used. The pipeline part geometric model bases on a parametric model have been created (Fig. 2a) and the finite element model bases on geometry model have been created too (Fig. 2b). The boundary conditions are shown in Fig. 1. Such boundary conditions ensure that on the one hand no edge effects at the ends of the pipeline part and this pipeline is loaded only by internal pressure on the other hand. In the simulation of defects may be
significant surge in relation to the stresses away from the stress concentrator, so it is necessary to take into account the plastic deformation. To do this, a bilinear elastic-plastic material model in FE model is used. Parameters of that model are given in Table. 2. Typical stress distribution for various defect radii is shown on Fig. 3.

**Fig. 2** Models of pipe with defects: a – geometric; b – finite element

**Fig. 3** Distribution of equivalent von Mises stress (Pa) for different defect radii
For assessing the influence of the pitting corrosion on the stress-strain state of the pipeline is convenient to use the stress concentration factor (SCF), which can be defined as follow:

\[ K_\sigma = \frac{\sigma_{(i)}}{\sigma_{nom}} \]  

(1)

17.4. ANALYSIS OF RESULTS

The maximum SCF have been defined for iteration of Mont-Carlo algorithm. Thus, we obtain a set of values consisting of a maximum SCF for each realization \( K_\Sigma^i = \max(K_{\sigma}^i), \ i = 1..n, \ j = 1..m \), where \( n \) – number of nodes of the finite element model, \( m \) – the number of realizations. Thus, \( K_\Sigma \) is maximum of sequence of independent and identically distributed variables, so it subject to the conditions of the Fisher-Tippett-Gnedenko theorem, and its PDF obeys the generalized extreme value (GEV) distribution law [13]. Generalized extreme law probability distribution is a three-parameter PDF and can be written as follow:

\[ f(x) = \begin{cases} 
\frac{1}{s} \exp\left(-\left(1+k\zeta\right)^{-\kappa}\right)\left(1+k\zeta\right)^{-1-\kappa} & k \neq 0 \\
\frac{1}{s} \exp(-\zeta) & k = 0 
\end{cases} \]  

(2)

\[ \zeta = \frac{x-\mu}{s} \]  

(3)

To identify the parameters of GEV PDF the histograms of the obtained SCF statistical data have been built. These histograms have been approximated with the GEV PDF using maximum likelihood method (Fig. 5). PDF parameters (\( \mu, s, k \)) here depend on the defect radius and for each of the latter they have been aggregated in Table. 3. The generalized extreme law with obtained parameters satisfies the
Assessment of the probability characteristics of the stress state of the pipeline damaged by pitting corrosion

Kolmogorov-Smirnov test with the significance level of 0.05 for all the defects radii.

**Fig. 4** Histogram of SCF approximated by generalized extreme distribution for various defects radii
Table 3 The parameters of generalized extreme distribution for various defects radii

<table>
<thead>
<tr>
<th>Rd</th>
<th>k</th>
<th>s</th>
<th>μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.50</td>
<td>-0.71601</td>
<td>0.60615</td>
<td>3.4766</td>
</tr>
<tr>
<td>3.75</td>
<td>-0.48911</td>
<td>0.25497</td>
<td>3.8654</td>
</tr>
<tr>
<td>5.00</td>
<td>-0.34859</td>
<td>0.16378</td>
<td>4.0544</td>
</tr>
<tr>
<td>6.25</td>
<td>-0.22184</td>
<td>0.11329</td>
<td>4.1160</td>
</tr>
<tr>
<td>7.50</td>
<td>-0.16408</td>
<td>0.07851</td>
<td>4.1669</td>
</tr>
<tr>
<td>8.75</td>
<td>-0.06967</td>
<td>0.08530</td>
<td>4.2011</td>
</tr>
</tbody>
</table>

On the next step the dependence of defects radius of parameters of generalized extreme distribution (μ, s, k) have been approximated using least-squares method. The quality of obtained approximation curves confirmed by the value of the correlation coefficient $R^2>0.98$. Approximation result is shown in Table 4.

Table 4 Approximation coefficients distribution parameters (μ, s, k)

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k(Rd)$</td>
<td>-0.9636</td>
<td>0.4257</td>
<td>-0.7098</td>
<td>$k(Rd) = A + B \log(C + Rd)$</td>
</tr>
<tr>
<td>$s(Rd)$</td>
<td>0.0833</td>
<td>4.2045</td>
<td>-0.8353</td>
<td>$S(Rd) = A + B \exp(CRd)$</td>
</tr>
<tr>
<td>$μ(Rd)$</td>
<td>4.2070</td>
<td>3.3016</td>
<td>-0.6039</td>
<td>$μ(Rd) = A + B \exp(CRd)$</td>
</tr>
</tbody>
</table>

Substituting obtained functions, we can obtain the conditional PDF of the SCF by the radius of the defect (Fig. 5). The mean and mode of SCF is shown on Fig. 6. The coefficient of variation is shown on Fig. 7.
Assessment of the probability characteristics of the stress state of the pipeline damaged by pitting corrosion

Fig. 5 The conditional PDF of the SCF depending on the defect radius

Fig. 6 Mean and mode depends on the radius of defects divided by wall thickness of the pipe

Fig. 7 Coefficient of variation depends on the radius of defects divided by wall thickness of the pipe
17.5. CONCLUSION

In this paper the probability characteristics of the stress-strain state and SCF of pipeline part with defects arising as a result of pitting corrosion has been studied. For work the following conclusions:

The PDF of the SCF obeys a generalized extreme distribution, but the parameters of the distribution are largely dependent on the radius of the defect:

– with increasing defect radius mean of SCF is growing. It indicates a significant change in shape and position of the PDF;
– the skewness of PDF for Rd/t < 0.562 is less than zero. It indicates the shift of the PDF to the right and for Rd/t > 0.562 — to the left. In range of 0.5 ≤ Rd / t ≤ 0.625 it is a substantially symmetrical distribution;
– defect radius increasing lead to the decreases SCF spread. It is associated with the growth of the plastic deformation and overlap areas of corrosion.

17.6. REFERENCES


An estimation of the residual reliability of the pipeline elbow with VSD

Potopalska¹ K.E., Larin² O.O.

¹NTU “KhPI”, Kharkiv, UKRAINE, ks.potopalskaya@gmail.com
²NTU “KhPI”, Kharkiv, UKRAINE, alexya.larin@gmail.com

Summary: This paper deals with the predictions of the residual reliability of pipeline elbow section with the corrosion defect under a high-cycle fatigue failures. The lifetime of pipeline in this case is determined by the non-localized damage accumulation process that is accompanied the cycling of stresses that exists due to the operational pressure oscillation. The investigation has been done based on 3D FE models of the main pipeline elbow with a corrosion box-shape defect.

Keywords: pipeline, corrosion, reliability, corrosion box-shape defect, lifetime

18.1. INTRODUCTION

Pipelines are used as one of the most practical and low cost methods for transmission of different liquid petroleum products and gases. The pipelines network is generally used during a long-term. For example, European pipeline network in situation, when over 20% of large-diameter pipelines are with an exhausted lifetime. Hence, an important task at the present time becomes an ensuring of reliability for this transport system.

Damage to the pipeline is capable to appears during operation due to the accumulation of fatigue and arising of corrosion. That can lead to cracks in pipes and to depressurization of system. Late identification of damage can be
a reason of dangerous emergency situations leads to ecological disasters, pollution, substantial consumer losses and to be a threat of human life. Therefore, development of methods prediction of pipelines durability and reliability in operation is important and actual practical problem.

In spite of numerous papers focusing on the analysis of the strength of corroded pipes, there are still a lot of non-investigated issues. The most known research in the literature is focused on for solving the problems of assessing residual strength of pipelines with corrosion defects in it straight sections [1–4]. But although, the works [5, 6] analyzes the stress state of a pipe elbow with volume defects. It is shown that corrosion damage on such curvilinear geometry leads to a bigger stress concentration. It should also be mentioned that most papers deal with analysis of the residual strength [7] but not with estimation of reliability (durability) of corroded pipes. However, prediction of their residual life-time and estimation of the probability of non-failure operation are of great practical use as they provide information for planning of repair works and risk assessment.

This work deals with exploration of the reliability characteristics and lifetime of a toroidal pipelines section with corrosion damage. The investigation was done based on 3D FE models. The simulations for analysis of stress concentration values for different load have been carried out. The work proposes a method for estimation of reliability of a corroded pipe in operation based on the FE simulations of probability characteristics of the stress state in the pipe with box shape defect.

18.2. PROBLEM STATEMENT

This paper deals with the predictions of the residual reliability of pipeline elbow section with the corrosion defect under a high-cycle fatigue failures. The lifetime of pipeline in this case is determined by the non-localized damage accumulation process that is accompanied the cycling of stresses that exists due to the operational pressure oscillation. The presence of the defect may leads to the stress concentration in the
region of corrosion that reduced the pipeline reliability. So, the maximum amplitudes of stress cycles in the defected pipe are important parameter that we precisely define based on 3D FE models.

18.3. MODELING OF A CORRODED PIPELINE ELBOW

A fragment of the main pipeline elbow is modeled with geometry, material properties and loads, which correspond to API Spec 5L / ISO 3183:2007. The model has been composed of toroidal and cylindrical parts. The following values of the structure dimensions were used for calculation: outside radius of the pipeline \( R = 245 \) mm; wall thickness \( h = 10 \) mm; length of the studied pipeline part \( L = 1.5 \) m. Those correspond to the X42 pipe grade. The length of the straight part of the pipe section is chosen a posteriori after a number of preliminary tests when edge effects in the model do not influence the deformed state in the investigated section of the pipe. The section of the pipe is loaded by the internal pressure \( q \) and fixed on its edges. The nominal level of internal pressure for the investigated type of pipes is \( q_0 = 2.5 \) MPa and at the start/stop regimes it can be increased up to the value \( q_{\text{max}} = 6 \) MPa.

The finite element model is shown in Figure 1.

![Finite element model of quarter part pipeline elbow](image)

**Fig. 1** The finite element model of quarter part pipeline elbow
Preliminary linear analysis depicted that the stresses in the damaged area of the pipe exceeded the yield stress $\sigma_y = 235$ MPa of the material and there was a necessity of a non-linear analysis. The stress-strain curve was approximated by a bilinear isotropic hardening model using the von Mises plasticity. The material properties are shown in Table 1.

The described model allows obtaining of the pipe burst pressure which equals $q_{cr} = 9.3$ MPa as well as to find the level of internal pressure that corresponds to the yielding point in the pipe $q_{cr} = 9$ MPa. The zone with plastic strains is occurred in the bottom part of the pipe elbow where the highest curviness exists.

**Table 1** Material properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Young’s modulus, MPa</th>
<th>Poisson ratio</th>
<th>Yield stress, MPa</th>
<th>Ultimate stress, MPa</th>
<th>Endurance stresses, MPa</th>
<th>Tangent modulus, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>$2.1 \cdot 10^5$</td>
<td>0.3</td>
<td>235</td>
<td>375</td>
<td>171.9</td>
<td>63.3</td>
</tr>
</tbody>
</table>

A volumetric surface defect (VSD) is modeled in the center of outer surface of the curved section of the pipes elbow. VSD has a box shape with the following parameters: width set to 1.1 mm (0.11·h); length set to 2.4 mm (0.24·h); and the depth was set to half of the pipe thickness $h_d = 0.5 \cdot h$. Box defect is modeled at the surface of the pipe bend, so sketch was projected in a local toroidal coordinate system, which depends on the radius of pipeline elbow.

Analysis of the static stress state of the damaged pipe elbow shown that maximum of stresses is appeared near the damage and not exceeds yield stress in the nominal operational pressure. The stress exceeds yield point in at the load of 5.4 MPa (Fig. 3) that’s less on the 40% comparing to the non-defected pipe.

In the study was determined that at the bottom of the pipe curving plastic deformation may also occur. It’s happened if internal pressure is more than 9 MPa (Fig. 4). The appeared plastic strain equal 0.189.
Analysis of the static stress state of the damaged pipe elbow shown that maximum of stresses is appeared near the damage and not exceeds yield stress in the nominal operational pressure. The stress exceeds yield point only at the load of 5.4 MPa (Fig. 3) that’s less on the 40% comparing to the non-defected pipe. In the study, it was determined that at the bottom curving part of the pipe some plastic strains are also occurred. It’s happened if internal pressure is more than 9 MPa (Fig. 4). It should be mentioned that internal pressure overcomes the level of 9 MPa the plastic zone is raising in the bottom part of the pipes elbow like in the non-defected pipe and the burst pressure has the same value.

So, the corrosion defect on the outer upper surface of the pipeline elbow caused a magnification of the stresses at the small level of the internal pressure but does not reduced pipe general strength.

Fig. 2 Von Mises stresses at internal pressure 2.5 MPa

It should be claimed that even a small level of cycling stresses leads to an accumulation of the fatigue and the concentration of stresses in the defected part of pipeline at operational regimes is reduced the reliability of the system.
The cycling of the stresses is caused by the oscillation of internal pressure that is known from the literature is a random narrow-band process. Within the operation, a different standard variation of the internal pressure fluctuations can be observed. Here we assume that they coefficient of variation can be starting from the 20% and up to 30% of nominal level of pressure.

Fig. 3 Von Mises a) stresses and b) strain at internal pressure 5.4 MPa

Fig. 4 Von Mises a) stresses and b) strain at internal pressure 9 MPa
18.4. ANALYSIS OF THE RESIDUAL RELIABILITY OF THE PIPE ELBOW WITH THE VSD

Models of the fatigue damage accumulation are represented in numerous surveys [8]. The approach of continuum damage mechanics [9] is used in this paper. So, we assume that cyclic loading leads to accumulation of damage \( D \) which is introduced within the framework of Rabotnov-Kachanov theory [9]. We use a hypothesis of the damage isotropy, which is associated with the decrease in the cross-section effective area in the vicinity of the point of the body, and the fatigue damage is set by a scalar function of time \( (t) \), stress amplitudes \( \sigma_a \) and some material parameters. The presented definition limits the damage parameter within \( 0 \leq D \leq 1 \).

The process of damage accumulation is described by the kinetic equation:

\[
\frac{d}{dt} D = B \left( \frac{\sigma_a}{1 - D} \right)^c
\]

(1)

where \( B \) and \( c \) is constants of kinetic equation that should be determined experimentally and can be expressed through characteristics Wöhler curve.

\[
B = \frac{\omega_e}{\sigma_{-1}^m N_0(m + 1)}
\]

(2)

where \( \sigma_{-1} \) — an endurance stresses, \( N_0 \), \( m \) — parameters of Wöhler curve, \( \omega_e \) — effective frequency of cycles.

Presented kinetic equation describes the process of fatigue accumulation in the weak point of the design (defected pipe). It should be noted that this equation is a stochastic as the stress amplitudes are the random process due to the operational conditions.

There is no way to accurately determine and predict the residual fatigue lifetime of defected pipe elbow due to the uncertainty of the load. So, the probability approach should be used here. The key point of the approach is to define the probability of a non-failure operation of the
mechanical system as a function of time or to define the probability distribution of the fatigue lifetime.

Identification of the non-failure operation probability (often called the reliability function) can be defined as a probability of double inequality relatively to the damage parameter, i.e. as a probability, which has a damage parameter as positive and less than unity [10]

\[ P(t) = \Pr[D(t) \in [0;1]] \]  

(3)

where \( P(t) \) is the probability of non-failure system operation (reliability function). \( \Pr[...] \) is an operator of event probability.

Such a probability will be a function of time due to the dependence of the damage parameter on time, so it can be calculated via the probability density function (PDF) of the damage [10] in the following way

\[ P(t) = \int_0^1 f_D(D,t) dD \]  

(4)

So, the solution of the fatigue lifetime estimation of the defected pipe elbow, which has uncertainty in the load reduced to a problem of identification the PDF of the fatigue damage, which is a process described by the kinetic equation (1). Due to the nonlinearity of the equation (1) a definition of PDF of the fatigue damage accumulation process in each moment of time is a difficult mathematic problem. However, it is possible to linearize the equation (1) by introducing the change of a variable

\[ z(t) = 1 - (1 - D)^{m+1} \]  

(5)

\[ \frac{dz}{dt} z(t) = (m + 1)(1 - D)^{m+1} \frac{d}{dt} (1 - D) \]  

(6)

Expressing of derivative at \( D \) through a new variable:

\[ \frac{dD}{dt} = \frac{dz}{dt} \left( \frac{1}{(m + 1)(1 - D)^m} \right) \]  

(7)
\[ z = \int_{0}^{t} B \sigma_{a}^{m}(\tau) d\tau \]  \hspace{1cm} (8)

The mean value of the function \( z(t) \) is easily found by the averaging procedure. In current paper it is assumed that the process of stress fluctuations is stationary Gaussian random process. So, the stress amplitude is under the Rayleigh law.

\[
\langle z \rangle = \left\langle \int_{0}^{t} B \sigma_{a}^{m}(\tau) d\tau \right\rangle = B \langle \sigma_{a}^{m} \rangle t = k_{1} t
\]  \hspace{1cm} (9)

\[
\langle \sigma_{a}^{m} \rangle = \int_{0}^{\infty} \frac{\sigma_{a}^{m+1}}{\sigma_{a}^{2}} \exp\left( -\frac{\sigma_{a}^{2}}{2\sigma_{a}^{2}} \right) d\sigma_{a}
\]  \hspace{1cm} (9a)

Variance can be found from the correlation function of \( z(t) \) at the point of equal times \( t_{1} = t, t_{2} = t \).

\[
\sigma_{z}^{2} = K_{z}(t_{1} = t, t_{2} = t)
\]  \hspace{1cm} (10)

Let’s express \( K_{z} \) through the second initial statistical moment by the definition:

\[
K_{z} = \langle z(t_{1}) \cdot z(t_{2}) \rangle - \langle z(t_{1}) \rangle \cdot \langle z(t_{2}) \rangle = \langle z(t_{1}) \cdot z(t_{2}) \rangle - k_{1} t_{1} t_{2}
\]  \hspace{1cm} (11)

Taking into account (11) on will obtains:

\[
\langle z(t_{1}) \cdot z(t_{2}) \rangle = B \int_{0}^{t_{1} t_{2}} \int_{0}^{t_{1} t_{2}} \langle \sigma_{a}^{m}(\tau_{1}) \cdot \sigma_{a}^{m}(\tau_{2}) \rangle d\tau_{1} d\tau_{2}
\]  \hspace{1cm} (12)

Integrand expression of (12), which is a correlation between stress amplitude in a power \( m \), according to the definition of correlation moment has the following form:
An estimation of the residual reliability of the pipeline elbow with VSD

\[
\left\langle \sigma^m_a(\tau_1) \cdot \sigma^m_a(\tau_2) \right\rangle = \\
\int_0^\infty \int_0^\infty \sigma^m_{a_1} \cdot \sigma^m_{a_2} \cdot f_{\sigma_a}(\sigma_{a_1} \cdot \sigma_{a_2}, \tau) d\sigma_{a_1} d\sigma_{a_2}
\]

where, \( \tau = \tau_1 - \tau_2 \), and \( f_{\sigma_a}(\sigma_{a_1} \cdot \sigma_{a_2}, \tau) \) this two-dimensional probability density function of stress amplitudes as a stationary random process. For the Rayleigh probability distribution with known correlation function we can assume that:

\[
f_{\sigma_a} = f(x_1)f(x_2) \left[ 1 + R(\tau) \cdot \left( 1 - \frac{x_1^2}{2\sigma^2} \right) \left( 1 - \frac{x_2^2}{2\sigma^2} \right) \right]
\]

where for simplicity \( \sigma_a(\tau_1) = x_1 \) and \( \sigma_a(\tau_2) = x_2 \) are introduced \( R(\tau) \) a correlation function of random stress, which is exponential amplitudes:

\[
R(\tau) = e^{-\alpha \tau}
\]

where \( \alpha \) - a damping coefficient of correlation functions.

Taking into account (14) we can rewrite expression (13):

\[
\left\langle \sigma^m_a(\tau_1) \cdot \sigma^m_a(\tau_2) \right\rangle = \int_0^\infty \int_0^\infty x_1^m \cdot x_2^m \cdot f(x_1)f(x_2) d\tau_1 d\tau_2 + \\
+ x_1^m \cdot x_2^m R(\tau) \cdot \left( 1 - \frac{x_1^2}{2\sigma^2} \right) \left( 1 - \frac{x_2^2}{2\sigma^2} \right) dx_1 dx_2 = \\
+ \left( \frac{\int x_1^2 - x_2^2}{2\sigma^2} \right) R(\tau) = I_1^2 + I_2^2 R(\tau),
\]

where \( I_1 \) and \( I_2 \) are constants that can be expressed using Euler gamma-function in following way:
\[ I_1 = \int_0^\infty \sigma^m_{a_1} \cdot f(\sigma^m_{a_1})d\sigma_{a_1} = \sigma^m_{\sigma} 2^{\frac{m}{2}} \Gamma(\frac{m}{2} + 1) \] (17)

\[ I_2 = \int_0^\infty \sigma^m_{a_1} \cdot f(\sigma^m_{a_1}) \left(1 - \frac{\sigma^m_{a_1}}{2\sigma^2_{\sigma}}\right)d\sigma_{a_1} = \sigma^m_{\sigma} 2^{\frac{m}{2}} \Gamma(\frac{m}{2} + 1) \] (18)

where gamma-function is \( \Gamma(x) = \int_0^\infty y^{x-1}e^{-y}dy \).

After substituting (15) and (16) to (14):

\[ \left\langle \sigma^m_{a}(\tau_1) \cdot \sigma^m_{a}(\tau_2) \right\rangle = k_2 + k_3 R(\tau) \] (19)

where \( k_2 \) and \( k_3 \) are constants, that equals to:

\[ -k_2 = \sigma^2_{m} 2^m \Gamma^2(\frac{m}{2} + 1) \] (20)

\[ k_3 = \sigma^2_{m} 2^m \left[ \Gamma(\frac{m}{2} + 1) - \Gamma(\frac{m}{2} + 2) \right]^2 \] (21)

These results shown that the coefficients \( k_2 \) and \( k_3 \) can be expressed from \( k_1 \):

\[ k_2 = \frac{k_1^2}{\psi^2} \quad k_3 = \frac{m^2}{4} k_1^2 \] (22)

The next step is to determine the correlation function of \( z \) process (12) subject to (19) – (21):

\[ \left\langle z^m(t_1) \cdot z^m(t_2) \right\rangle = B \omega_e \int_0^{t_1} \int_0^{t_2} (k_2 + k_3 R(\tau))d\tau_1 d\tau_2 \] (23)

Denote the integral of the correlation function as \( A \):

\[ A = \int_0^{t_1} \int_0^{t_2} R(\tau)d\tau_1 d\tau_2 = \int_0^{t_1} \int_0^{t_2} e^{-\alpha|\tau_2 - \tau_1|}d\tau_1 d\tau_2, \] (24)
Since the for further calculations we needs variance of $z$ process, it can be calculated from correlation function respect to $t_1 = t_2 = t$:

$$A|_{t_1=t_2=t} = \frac{2(-1+e^{-\alpha t} + \alpha t)}{\alpha^2}$$ (25)

Expression (25) can be simplified taking into account the fact time $t$ presents a pipeline life-time, which is measured in years (and in the formula (25) is given in seconds). This allow to neglected terms $e^{-\alpha t}$ and 1 the time $t$. Thus, the expression (25) will be as follows:

$$A|_{t_1=t_2=t} = \frac{2t}{\alpha}$$ (26)

So, variance of $z(t)$ function, according to (21) with (26) and (22) can now be found as follows:

$$\sigma_z^2 = K_z(t_1 = t, t_2 = t) = \psi^2 k_3 A|_{t_1=t_2=t} =$$

$$= \psi^2 k_3 \frac{2t}{\alpha} = \frac{k_1^2 m^2}{2a} t,$$

where $\psi$ - constant, which is expressed through the parameters of the Wöhler curve. Using the relationship between the process $z(t)$ and damage ($D$) its probability density function can be found as:

$$f_D(D,t) = f_u(z(t),t) \left| \frac{dz}{dt} \right|$$ (28)

$$f_D = \frac{(m+1)(1-D)^m}{\sqrt{2\pi \sigma_z^2(t)}} \exp \left( -\frac{(1-(1-D)^{m+1} - \langle z(t) \rangle)^2}{2\sigma_z^2(t)} \right)$$ (29)

Therefore, the probabilistic characteristic of accumulation of fatigue damage in service has been obtained. These results can be used to estimate the probability characteristics of time to failure as a random variable.
Fig. 5 Reliabilities of pipeline depend on stress coefficient of variation

The probability of failure-free operation of the pipeline depending on the stress coefficient of variation has been obtained on nominal operating pressure (2.5 MPa). The graph shows that an increase in the stress coefficient of variation of 10% lifetime rapidly reduced. The lifetime is change from 30 years to 7 years.

18.5. CONCLUSION

In this paper, the analysis of stress-strain state of a pipe elbow for different load has been obtained. It is determined that plastic strain was appeared near defect at a load 5.4 MPa. The lifetime of pipeline elbow has been found. According to the results of reliability analysis, concluded that lifetime decreases depending on stress coefficient of variation. The lifetime of pipeline elbow is depended of stress coefficient of variation in such way: for 0.2 is equal 31 years, for 0.25 – 15 years and for 0.3 – 7 years.

The developed algorithm allows varying the size of the defect, which allows finding the maximum equivalent stresses in the pipe with a defect,
depending on the change in its geometrical parameters, such as width, length and depth.

18.6. REFERENCES


On a method of reduction of stress concentrators in damaged transmission pipelines

Chebakov¹ M., Dumitrescu² A., Lambescu² I., Nedin¹ R.

¹ Southern Federal University, Rostov-on-Don, RUSSIA, chebakov@math.rsu.ru, rdn90@bk.ru
² Petroleum-Gas University of Ploiești, ROMANIA, andrei.upg@gmail.com, ionutlambescu@gmail.com

Summary: In the present study, we have considered several issues for a damaged pipeline with one or two volumetric surface defects, subjected to internal pressure loading. The problem of an optimal repair system for a pipe based on its wrapping via laminate composite is considered. The analysis of the most efficient repair wrap properties was performed; some practical recommendations are provided.

Keywords: transmission pipeline, volumetric surface defect, laminate composite repair, stress concentrator

19.1. INTRODUCTION

The maintenance of safety and reliability of transmission pipelines is vital in the petroleum industry. Such pipelines often suffer from various defects especially weld defects, cracks, defects due to corrosion and erosion. The common repair methods presently used are based on the usage of the techniques involving welding. In conditions of the necessity of applying the pipe repair techniques without suspending its operation (in order to avoid significant financial losses), special measures need to be taken when welding directly on an in-service pipeline. One of the possible ways to avoid them is
to develop alternative in-service repair techniques that do not require welding, like the use of composite materials repair systems. Therefore, the mechanical engineering problems of proper modeling and development of such repair systems for transmission pipelines are of great importance [1–3].

**Fig. 1** (a) A defect on a pipe surface due to corrosion. (b) The machined pocket in the defect area. (c) Cross-sectional view of the pocket. Here \( a \) is the longitudinal size of the defect, \( D \) is the exterior pipe diameter, \( \varphi \) is the half opening defect angle, \( d \) is the defect depth

**19.2. FINITE ELEMENT MODEL**

Both stated problems require a series of computational experiments. One of the best ways to optimize the numerical solutions of a large number of similar problems is to use the automation of calculations. To carry out the finite element (FE) analysis of the considered pipeline segments, we used the package Siemens NX. For the described pipe with defects, we built a general FE-model depending parametrically on the initial data and on all the problem parameters including pipe geometry and material, operating pressure, sizes and locations of the defects, wrap and fillers properties. With its help, it was possible to achieve the automatic execution of the main stages of the finite element simulation like editing model geometry and materials properties, creating/refreshing a finite element mesh,
and (re)calculating the solution. An efficient algorithm of automatic generation of the most optimal FE mesh is developed based on the initial geometrical data (See Fig. 2).

![Fig. 2](image)

**Fig. 2** (a) Sectioning of the pipe body for further FE meshing. (b) FE meshes refinement at the pipe exterior and inner surfaces by large (1), middle (2) and small FE (3) depending on the zone.

![Fig. 3](image)

**Fig. 3** FE meshing of the fillers (a) and the composite wrap (b)

To solve the problems stated, we have performed linear elastic analysis; the nonlinear analysis is not needed here as far as in such a pipe only stresses lower than yield stress are allowed. The pipe itself and the fillers were meshed by 3D 10-node FE based on the general 3D elasticity theory, while the wrap was meshed by 2D 4-node FE based on the classical laminate theory in order to obtain the most adequate solution (see Fig. 3).
19.3. COMPUTATIONAL EXPERIMENTS

As testing specimens, we have examined pipe segments made of API X52 steel with various geometry and defects parameters. The results are shown below for the standard pipe with exterior diameter $D = 323.9$ mm and wall thickness $t = 8$ mm. The operating inner pressure was $7$ MPa. As a composite material for the wrap, a fiberglass was chosen with fibers in the circumferential direction.

In the problem for the unwrapped pipe with one defect, a sensitivity analysis was performed in order to find a set of dimensionless parameters and to obtain some similarity criteria allowing us to estimate the maximum levels of stress distribution by extrapolating the results for other pipes without the need for additional calculations. In the problem with two defects, we investigated the dependence of the relative position of the two defects on the non-uniform distribution of stresses, and we have proposed a set of dimensionless parameters uniquely characterizing the way the two defects influence one another. In every considered case, we have assessed the inhomogeneous stress distribution in the defects area and revealed the most dangerous zones from the viewpoint of the analysis of stress concentrators.

The conducted series of computational experiments for the unwrapped pipe allowed us to select the most hazardous geometrical parameters and relative locations of the defects and to reveal the optimal conditions of processing defect zones including cutting shape of a pocket and parameters of edge blending inside it for a number of specific cases. At the same time we revealed a range of allowable defect parameters for which it is not necessary to replace the pipe segment during repairs.

In case we vary the longitudinal distance between two machined defects of the same rectangular shape (with the same fixed circumferential location), stress distribution in each of them does not change significantly for any chosen distance. In case the defects are located in the same cross-section circumference, there is a significant
interaction between them (change in the stress distributions) only if the
distance does not exceed the defect circumferential size; at the closest
defects edges, stresses always reduce up to 2 times (see Fig. 4).

![Graphs of Von Mises stresses on the middle cross-sectioning path of the
defect area in the circumferential direction.]

Fig. 4 Graphs of Von Mises stresses on the middle cross-sectioning path of the
defect area in the circumferential direction.
Here, the cases of small (a) and large (b) circumferential distance between two
defects are depicted. The sizes of each defect are $a = 76.2$ mm, $\rho = 26.96$ deg,
$d = 6$ mm, $r = 19$ mm (blending curvature radius)

Secondly, we considered a problem for the same damaged pipe which
was then repaired by filling the cut pockets and setting the composite
wrap. As an example of FE calculations for such a pipe with an arbitrary
defects location and shapes, see Fig. 5.

On the basis of the numerical experiments conducted for the repaired
pipes, several conclusions were drawn. Regarding the effect of total wrap
thickness on stress-strain state, we have revealed that depending on a wrap
thickness, max stress and strain may reduce up to 4 times. For the particular
case considered for the standard pipe ($D = 323.9$ mm, $s = 8$ mm), the range
of the efficient homogeneous wrap thicknesses is about
$7 \div 20$ mm (see Fig. 6). Concerning the wrap structure, there is almost
no difference between laminate and homogeneous structure from the
viewpoint of stress-strain state (see Fig. 7) in all the cases considered.
Investigation of the mutual influence of two machined volumetric surface defects of transmission pipeline

**Fig. 5** Comparison of the displacement (a) and von Mises stress (b) fields for the unwrapped (to the left) and wrapped (to the right) pipe in case of arbitrary shapes and location of the initial defects. The 3 mm wrap consists of four 0.5 mm fiberglass layers bonded by 0.25 mm adhesive layers.

**Fig. 6** Max Von Mises stresses graphs for the pipe itself (a), the fillers and the wrap composite part (b) for different wrap thicknesses. The green zone corresponds to the most efficient range of the wrap thicknesses.
19.4. CONCLUSION

Several problems for the damaged pipeline subjected to internal pressure loading and containing one or two volumetric surface defects have been solved. The defects were caused by surface corrosion and subsequently exposed to a mechanical treatment in order to eliminate the stress concentration effects. The problem of an optimal repair system for a pipe based on its wrapping via laminate composite has been considered. The proposed approach on the alternative in-service repair method leads to significant cost reduction of repairs of damaged transmission pipelines.

19.5. REFERENCES


CHAPTER

Wave propagation in a cylindrical waveguide with periodic structures

Chebakov¹ M.I., Barkanov² E.N.

¹Southern Federal University, Rostov-on-Don, RUSSIA, chebakov@math.sfuedu.ru
²Riga Technical University, LATVIA, barkanov@latnet.lv

Summary: The results obtained in the study of the excitation and wave propagation in a cylindrical waveguide with periodically varying mechanical properties along the longitudinal coordinates are presented. The considering part of waveguide corresponding to the minimal period of changing in the mechanical properties can be of any number of homogeneous regions (finite cylinders) of different length and with different elastic characteristics.

Keywords: wave propagation, periodic waveguide, transition operator

20.1. INTRODUCTION

To study the problem there has developed an effective method based on construction of special transition operator, which allows, using the values of displacement vector and stress tensor for one waveguide cross section, to find values on another cross section spaced from the first by a distance equal to the value of the minimum period of changing in mechanical properties. It is demonstrated that for such waveguides in the whole infinite frequency interval there exist alternating finite intervals, when the oscillations in the waveguide decay or spread, respectively. In addition, for decay intervals the oscillation amplitude of heavy stamp can increases limitless, i.e., may exist V-resonance.
Chapter XX

20.2. PROBLEM STATEMENT

Let consider the problem for cylinder \( R_0 \leq r \leq R, \ |z|<\infty \). The cylindrical space \( |z| \leq z_0 \) has a shear modulus \( G \), density \( \rho \) and for space \( z_n + kL < |z| < z_{n+1} + kL \ (n = 0, 1, 2, ..., m - 1; k = 0, 1, 2, ..., \infty) \) shear modulus \( G_n \) and density \( \rho_n \) respectively. Denote \( z_{n+1} - z_n = l_n, \ z_m - z_0 = L \), where \( L \) is a period in changing of cylinder characteristics along the \( z \) coordinate to the left and to the right from points \( z = -z_0 \) and \( z = z_0 \) respectively. Let on the cylinder surface \( |z| \leq a, r = R \) there is bandage, which vibrates by angular coordinate around \( z \) axe under the action of moment \( M_0 = Me^{-i\omega t} \). The cylindrical surface away from stamp is free (Fig. 1).

![Image](image.png)

**Fig. 1** To the statement of the problem for periodic waveguide

Solution steps:
1. Construction of special transition operator, allowing by using displacement vector value for \( z = z_0 \) to find same value for \( z = z_m \).
2. Analysis of eigen values and eigen functions for transition operator.
3. Satisfaction of the conditions at infinity.
4. Construction and solving the integral equation for dynamic contact problem.
5. The study of V-resonances.
20.3. CONSTRUCTION OF TRANSITION OPERATOR

To avoid consideration of Lame equations with variable coefficients [5], we built first the transition operator within a homogeneous area \( z_n \leq z \leq z_{n+1} \ (0 \leq n \leq m-1) \). Using homogeneous solutions for a cylinder, we obtain

\[
\bar{b}^{n+1}(r) = 2 \sum_{k=0}^{\infty} \frac{F_k(r)}{F_{kk}} \bar{A}_k^n \int_0^R (t) \bar{b}^n(t) dt
\]

(1)

where \( \bar{b}^n(r) \) and \( \bar{A}_k^n \) – respectively vector and matrix

\[
\bar{b}^n(r) = \begin{pmatrix} V_n(r) \\ \tau_n(r) \end{pmatrix}, \quad \bar{A}_k^n = \begin{pmatrix} \cos \alpha_k^n l_n & (G_n^m \alpha_k^n)^{-1} \sin \alpha_k^n l_n \\ -G_n^m \alpha_k^n \sin \alpha_k^n l_n & \cos \alpha_k^n l_n \end{pmatrix}
\]

(2)

\[
F_k(r) = -r / R \int_{R_0}^R F_k(r) F_n(r) rdr = 0 \ (k \neq n); \quad F_{kk} (k = n),
\]

(3)

\[
\alpha_k^n = \sqrt{\alpha_n^2 - \kappa_k^2}, \quad a_n^2 = G_n^0 \rho_n \omega^2
\]

where \( \kappa_0 = 0, \ \kappa_k \ (k \geq 1) \) – positive roots of equation \( \Delta(\kappa_k) = 0 \), где

\[
\Delta(\alpha) = J_2 \left( R_0 \sqrt{a_n^2 - \alpha^2} \right) Y_2 \left( R_0 \sqrt{a_n^2 - \alpha^2} \right) - J_2 \left( R_0 \sqrt{a_n^2 - \kappa_k^2} \right) Y_2 \left( R_0 \sqrt{a_n^2 - \kappa_k^2} \right),
\]

\( J_k(r), Y_k(r) \) – Bessel functions, \( V_n(r) e^{-i\alpha} \) and \( \tau_n(r) e^{-i\alpha} \) – displacements and stresses for \( z = z_n \). Using (1), (2), we can simply get \( \bar{b}^m(r) \) through \( \bar{b}^0(r) \). Thus, we can obtain transition operator \( \Phi \):

\[
\bar{b}^m(r) = \Phi \bar{b}^0(r), \quad \Phi(\ldots) = 2 \sum_{k=0}^{\infty} \frac{j_k(r)}{W_k} \bar{\Phi}_k \int_0^R j_k(\tau) (\ldots) \tau d\tau, \quad \bar{\Phi}_k = \prod_{n=m-1}^0 \bar{A}_k^n
\]

(4)
20.4. STUDYING OF EIGENVALUES

The condition for finding the eigenvalues for $\Phi$ operator is the is equality to zero of the determinant for a block-diagonal matrix or a diagonal matrix of the second order

$$|\tilde{\Phi}_k - \lambda I| = 0 \text{ or } \lambda^2_k - 2p_k \lambda_k + 1 = 0, \quad 2p_k = a_{11}^k + a_{22}^k \quad (k = 0, 1, 2, \ldots),$$

(5)

where $a_{11}^k$ and $a_{22}^k$ - components of matrix $\tilde{\Phi}_k = \{a_{ij}^k\}$, $p_k = p_k(\omega)$ - real numbers.

While receiving (5) is taken into account that the determinants for matrices $\tilde{A}_n^k$, and respectively $\tilde{\Phi}_k$ equal to 1. Let denote with $\lambda_1^k$ and $\lambda_2^k$ the pairs of roots for equation (5) for each $k$, at the same time $\lambda_1^k \lambda_2^k = 1$.

Eigenvalues depending on frequency $\omega$ and number $k$ could be divided on two groups: 1) $\text{Im}(\lambda_k^n) = 0$, $\lambda_k^n \neq \pm 1$, 2) $\text{Im}(\lambda^2_k) \neq 0$ and $\lambda_k^n = \pm 1$.

Wherein, all complex eigenvalues are on the unit circle. We assume that in the first group $\lambda_1^k < 1$ and $\lambda_2^k > 1$.

We made detailed analytical and numerical analysis of the numbers $\lambda_k^n$ depending on frequency $\omega$, number $k$ and number $m$ of homogeneous parts with different properties on period, established the existence of the intervals $\Omega_{Rn}$ of $\omega$ frequency change where all $|\lambda_k^n| \neq 1$ and existence of the intervals $\Omega_{On}$, where at least one $|\lambda_k^n| = 1$. If we assume that wave field could be represented as series of eigenfunctions for transition operator $\Phi$, then for intervals $\Omega_{Rn}$ fluctuations in the waveguide by removing infinity will be damped (waveguide locked), but for intervals $\Omega_{On}$ will be present undamped modes (waveguide open). Since $\Omega_{Rn}$ and $\Omega_{On}$ alternate then locking bands and transmission waveguide will alternate. Thus we have "banding" of bandwidth, which has been noted previously for half-layered areas such as in [1, 4], and others. There are not less than two non-overlapping intervals $\Omega_{Rn}$, if the entire waveguide is not uniform.
We introduce the dimensionless frequency \( \Omega = R \omega \sqrt{\rho_0 / G_0} \), and easy for graphic interpretation of results function \( f(\Omega) = \{1, \omega \in \Omega_{Rn}; -1, \omega \in \Omega_{Cn}\} \). When \( f(\Omega) = -1 \) the waveguide is open. We calculate the eigenvalues of the operator (3), (4) and plot function \( f(\Omega) \) \( (\Omega \leq 5) \) for some values of dimensionless waveguide parameters \( G_j^* = G_j / G_0 \), \( \rho_j^* = \rho_j / \rho_0 \), \( t_j^* = l_j / l_0 \) \( (j = 0,1,...,m-1) \). Further, we demonstrate two variants on Fig. 2 \( (m=6,\ G_1^*=1.0,\ G_2^*=1.1,\ G_3^*=1.2,\ G_4^*=1.3,\ G_5^*=1.4,\ G_6^*=1.5) \) and Fig 3. \( (m=6,\ G_1^*=1,\ G_2^*=2,\ G_3^*=3,\ G_4^*=4,\ G_5^*=5,\ G_6^*=6) \). Other parameters are equals to 1.

The analysis for calculated results have demonstrated:

1. For piecewise homogeneous cylindrical waveguide there always exist alternating intervals \( \Omega_{Rn} \) (waveguide locked) and \( \Omega_{Cn} \) (waveguide open), \( n \geq 2 \) (in the case of a uniform cylinder the waveguide is always open, and for homogeneous strip the waveguide is open for \( \omega \geq \omega_{kp} \neq 0 \)).

2. The nature of the wave propagation in the waveguide is qualitatively similar, if one of the parameters \( G \) or \( \rho \) does not change and other one changes by the same law.

3. The higher the jump for \( G \) or \( \rho \) in their neighbour-homogeneous parts of the waveguide, the longer the intervals \( \Omega_{Rn} \) appear.

4. With the increasing of length of a harder and more dense homogeneous part of the waveguide the intervals \( \Omega_{Rn} \) start to appear at a lower frequency.

5. With the increasing of frequency, the number of slots \( \Omega_{Rn} \) and their length decreases.
Fig. 2 \( G_1^* = 1.0, G_2^* = 1.1, G_3^* = 1.2, \ G_4^* = 1.3, \ G_5^* = 1.4, \ G_6^* = 1.5 \)

Fig. 3 \( G_1^* = 1, G_2^* = 2, G_3^* = 3, \ G_4^* = 4, \ G_5^* = 5, G_6^* = 6 \)

Thus, on the basis of conducted numerical experiments and made above conclusions one can select waveguide with predetermined properties.

20.5. THE CONDITION AT INFINITY

Using the representation of displacements and stresses by eigenfunctions of the transition operator to perform physically justified conditions at infinity in a group of their own functions corresponding \(|\lambda_k^n| \neq 1\), it is necessary to exclude those which give increasing amplitude, i.e. appropriate to \(\lambda_k^2\).

For the selection of eigenfunctions corresponding to \(|\lambda_k^n| = 1\) we use principle of fictitious absorption: we introduce into the system the low internal friction \(\varepsilon \to 0\). Eigenvalues get a small perturbation of \(\lambda_k^n = \lambda_k^n(\varepsilon)\). It is shown that

\[
\lambda_k^n(\varepsilon) \approx \lambda_k^n \left(1 \pm \frac{\varepsilon}{2} \frac{q_k}{\sqrt{1-p_k^2}}\right), \quad q_k = \frac{dp_k}{d\omega} \tag{6}
\]

(\(p_k\) and \(q_k\) are real and \(|p_k| < 1\)). For \(\lambda_k^n = 1\)

\[
\lambda_k^n(\varepsilon) \approx 1 \pm \sqrt{\varepsilon q_k} (1-i) \quad (q_k > 0), \quad \lambda_k^n(\varepsilon) \approx 1 \pm \sqrt{-\varepsilon q_k} (1+i) \quad (q_k < 0) \tag{7}
\]
For $\lambda_k = -1$ equations (7) will have same representation.

In (6) – (7), the sign $\pm$ is chosen so that $|\lambda^1_k(\varepsilon)| < 1$, and $|\lambda^2_k(\varepsilon)| > 1$. The upper index for the eigenvalues whose modulus is equal to 1 for $\varepsilon = 0$ we select according to the limiting transition $\lambda^\pm_k = \lim \lambda^n_k(\varepsilon) \ (\varepsilon \to 0, \ n = 1, 2)$.

Therefore, when you meet the conditions at infinity, eigenfunctions appropriate to $\lambda^2_k$ should be excluded from the consideration.

20.6. CONSTRUCTION OF THE INTEGRAL EQUATION OF THE CONTACT PROBLEM

Assume that for periodic structure in the cylinder $|z| \geq z_0$ the displacements $V$ and stresses $\tau$ could be represented as series for eigenfunctions of transition operator. Satisfying the conditions at infinity and according to tip. 3, we obtain for $z = z_0 + 0$

$$V(r, z_0) = \sum_{k=0}^{\infty} D_k F_k(r) \beta_k, \quad \tau(r, z_0) = \sum_{k=0}^{\infty} D_k F_k(r), \quad \beta_k = \frac{\lambda^1_k - a_{22}^k}{a_{21}^k},$$

($D_k$ – unknown constants).

Considering the known shear stresses $\tau_{r\phi}(R, z) = q(r)$ on the cylinder surface $|z| \leq a$ and for part of cylinder $|z| \leq z_0$ we construct the solution as a sum of solutions for infinite cylinder with parameters $G$ and $\rho$, when the surface $|z| \leq a$ is loaded by tangential stresses $q(z)$, and other surface free of stresses, and superposition of corresponding homogeneous solutions for this cylinder. As a result, we get:

$$V(r, z) = V_0(r, z) + V_H(r, z), \quad V_0(r, z) = \sum_{k=0}^{\infty} C_k F_k(r) \cos \alpha_k z$$

$$V_H(r, z) = -\frac{1}{2\pi G} \int_{-a}^{a} q(y) dy \int K(\alpha) e^{-i\alpha(z-y)} d\alpha$$
\[ K(\alpha) = \frac{J_1\left(R\sqrt{a_0^2 - \alpha^2}\right)Y_2\left(R_0\sqrt{a_0^2 - \alpha^2}\right) - Y_1\left(R\sqrt{a_0^2 - \alpha^2}\right)J_2\left(R_0\sqrt{a_0^2 - \alpha^2}\right)}{\sqrt{a_0^2 - \alpha^2}} \]

Here \( \sigma \) – integration contour, which equals to real axe almost everywhere, avoiding real positive poles of the integrand from below, and negative – from the top.

From condition of equality of stresses and displacements on the left and the right from \( z = z_0 \) we can calculate the constants \( C_k \) and \( D_k \). By substituting \( C_k \) in (8) and satisfying the contact condition for \( |z| \leq a \), \( r = R \) we obtain integral equation for unknown contact stresses.

\[ \int_{-a}^{a} q(x)k(y-x)dx = \pi G\delta \quad (|y| \leq a) \quad (9) \]

\[ k(t) = k_1(t) + k_2(t), \quad k_2(t) = \sum_{k=0}^{\infty} b_k \cos \alpha_k t, \quad k_1(t) = \int K(\alpha) \cos \alpha t dt, \]

where \( \delta \) – amplitude of bandage rotation angle, \( \sigma_+ \) – part of contour \( \sigma \), based in right half-plane,

\[ b_k = \pi \frac{\Delta_k^* - i\Delta_k}{R\alpha_k \Delta_k} (k \geq 1), \quad b_0 = 2\pi \frac{\Delta_0^* - i\Delta_0}{R\alpha_0 \Delta_0} \quad (10) \]

\[ \Delta_k^* = \sin \alpha_k z_0 - \beta_k \alpha_k G \cos \alpha_k z_0, \quad \Delta_k = \cos \alpha_k z_0 + \beta_k \alpha_k G \sin \alpha_k z_0. \]

It could be showed that:

\[ b_k = O\left((1/k)\exp(-2\pi k z_0 / R)\right) \quad (k \to \infty) \quad (11) \]

The kernel of the integral equation (9) consists of two components: \( k_1(t) \) corresponds to the kernel of the integral equation of the contact problem for a homogeneous cylinder with parameters \( G, \rho, \) and \( k_2(t) \) contains information about the properties of the periodic waveguide \( (b_k) \) and is a smooth function.
Taking into account (11), the solution of the integral equation (9) can be obtained with using of known analytical methods (see [10–11] and others).

20.7. REFERENCES


CHAPTER

Optimal design of pipeline with volumetric surface defect

Lvov¹ I.G., Barkanov² E.N.

¹ NTU “Kharkiv Polytechnical Institute”, Kharkiv, UKRAINE, vano_lvov@ukr.net
² Riga Technical University, Riga, LATVIA, barkanov@latnet.lv

Summary: The current work focuses on the development of methodology for the optimal parameters selection of composite bandages, which are installed on the damaged sections of pipelines. The inner diameter of the bandage is equal to the outer diameter of the pipeline and varying parameters are the thickness and length of the bandage. The aim of the optimal design is to provide equiresistant structure, so that repaired area’s maximum stress intensity would not be different from the intensity of the stresses on the undamaged sections of the pipeline. The calculation of the objective function at any point of the feasible set of variable parameters requires structural analysis using finite element method to be performed. A method of optimization was used that require only the objective function calculations. Because of the high complexity of calculating the objective function and the large number of elements of the feasible set of variable parameters, a statistical method for finding the minimum of the objective function is applied. In the first stage of optimization, a Monte Carlo method is used with the Latin hypercube generation of the sample numbers. To perform analysis of the stress state of the pipeline-bandage system the finite element method implemented in software ANSYS is used.

Keywords: pipeline, damage, bandage, optimization, analysis
21.1. INTRODUCTION

Structural optimization of composites stands as a very active topic in different areas of industry. Thanks to the exponential increase of computing resources, the development of numerical tools oriented to structural optimization has been outstanding, reaching now a practical use widespread in industry. Setting the optimization tasks for composite structures can have significant variety. There are several types of methods:

Parametric optimization. The shape of construction is described a priori using a limited number of parameters. Such control variables can be for example the thickness distribution of the structure or the size of structural members. This type of optimization is widely used in industrial applications [1].

Shape optimization. The optimization variable is the boundary of the structure itself. This boundary is not a priori limited to a certain family of curves, but rather completely free. It can be numerically represented, but even though the domain has the freedom to vary according to the boundary, topology changes cannot take place [2].

Topology optimization. This category of shape optimization is the most interesting and allows to explore a larger set of shapes, increasing the possibility to obtain optimal solutions [3].

The methods of statistical tests has been used successfully in solving various problems of optimization of composite structures. Such methods are suitable in cases where the determination of the value of the objective function requires the creation of new geometric patterns and solving complicated boundary value problems of mechanics of composites.

Pipelines are structures of significant importance, so the demands for strength of the repair supplements is high. Methodologies of analysis of such pipeline–bandage systems are receiving considerable attention. The most common approach to the analysis of the pipeline with the installation of composite bandages is the use of the finite element method. Using commercial software packages enables the possibility to
analyze the stress state, taking into account the geometry features of real defects and mechanical properties of composite materials and pipes.

21.2. ELASTOPLASTIC DEFORMATION OF PIPELINE

Considering pipeline deformation to its rupture, it becomes necessary to take into account effects that are a result of geometrical nonlinearities. In engineering practice, it is common to use logarithmic strain tensor introduced by Hencky [4] to describe finite deformations. Constitutive models that bound logarithmic strain tensor with Cauchy stress tensor are included in material model’s library of program software package ANSYS [5]. This allows performing numerical research of plastic deformation of complex constructional elements for finite deformations. Logarithmic strain tensor for isotropic material can be conveniently interpreted with 3 diads:

\[
H = \ln(1 + \varepsilon_1) n_1 \otimes n_1 + \ln(1 + \varepsilon_2) n_2 \otimes n_2 + \ln(1 + \varepsilon_3) n_3 \otimes n_3, \tag{1}
\]

where \(n_i\) - unit vectors of principle directions for strain tensor, \(\varepsilon_i\) - linear relative elongations in principle directions.

Logarithmic strain tensor components in random coordinate system with orthogonal basis \(i_k\) - are defined by its eigenvalues.

\[
\varepsilon_{ij} = i_i \cdot H \cdot i_j = \\
= \ln(1 + \varepsilon_1) \alpha_{i1} \alpha_{j1} + \ln(1 + \varepsilon_2) \alpha_{i2} \alpha_{j2} + \ln(1 + \varepsilon_3) \alpha_{i3} \alpha_{j3} \tag{2}
\]

\[
\alpha_{st} = i_s \otimes n_t
\]

Using the logarithmic strains associative flow rule of Prandtl-Reuss written as follows:

\[
d\varepsilon_{ij} = \frac{3}{2} \frac{d\varepsilon_0}{\sigma_0} S_{ij} 
\tag{3}
\]

where \(d\varepsilon_{ij}\) - increments of plastic strains, \(S_{ij}\) - stress deviator, \(\sigma_0\) - stress intensity, \(d\varepsilon_0\) - intensity of increment of plastic strain.
\begin{equation}
\sigma_0 = \sqrt{\frac{3}{2} S_{ij} S_{ij}}, \quad d \varepsilon_0 = \sqrt{\frac{2}{3} d \varepsilon_{ij} d \varepsilon_{ij}}
\end{equation}

According to hypothesis of unified flow curve for different stress states and deformation history the following relation is implied:

\begin{equation}
\sigma_0 = f (q); \quad q = \int d \varepsilon_0,
\end{equation}

where integral is taken along the full loading path, starting from occurrence of plastic strains.

With unchanged principle directions, strain tensor and plastic strain tensor component’s increments are proportional to one multiplier, Odqvist parameter can be interpreted through finite values of logarithmic strains:

\begin{equation}
q = \sqrt{\frac{2}{3} e_{ij} e_{ij}}
\end{equation}

Flow curve \(\sigma_0 = f(q)\) can be plotted based on the results of uniaxial tension experiments.

If the initial sample with length \(l_0\), is stretched by force \(P\) to the length \(l\), logarithmic strain measure is defined as:

\begin{equation}
e = \ln \frac{l}{l_0}
\end{equation}

True stresses are calculated with respect to changes of initial crosscut area \(F_0\). For incompressible material true stresses:

\begin{equation}
\sigma = \frac{P}{F_0} \frac{l}{l_0}
\end{equation}

Tensile tests experimental results in form of dependency between nominal stress \(\sigma = P/F_0\) and relative elongations \(e = (l-l_0)/l_0\) are necessary to reformulate in a dependence of \(\sigma = f(q)\) kind. Since for uniaxial tension:
\[ \sigma_0 = \sigma; \quad q = e, \]  

(9)

this dependence defines function, required for associative flow rule (3).

21.3. RESEARCH OBJECT

The object of presented research was the gas transmission pipe made of Steel type 20. The pipe diameter was 220 mm, length is 953 mm, thickness 6 mm. Additionally pipe was ramped from both sides with a cap and had a feature of a volumetric surface defect in the middle (Fig. 1-2).

![Design of the pipeline with volumetric surface defect](image)

**Fig. 1** Design of the pipeline with volumetric surface defect
Fig. 2 Design of the pipeline with volumetric surface defect with applied bandage

The defect was subjected to a repair, so that the volume of the damage gap was charged with the filler, and covered with composite bandage so that the pipe could sustain mechanical loading during further operation. Repaired pipe model was subjected to inner pressure. Material properties used in the analysis are shown in the Table 1–5.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_s$, MPa</th>
<th>$\sigma_{02}$, MPa</th>
<th>$\delta_s$, %</th>
<th>$E_s$, MPa</th>
<th>$\nu$</th>
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<tbody>
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<td>Annular</td>
<td>474,76</td>
<td>461,40</td>
<td>305</td>
<td>314</td>
<td>33,13</td>
</tr>
</tbody>
</table>
where \( \sigma_b \) – tensile strength, \( \sigma_y \) – yield strength, \( \delta_s \) – relative extension, 
\( E \) – Elastic modulus (Young modulus), \( \nu \) – Poisson coefficient.

**Table 2** Data of stretching samples of steel 20

<table>
<thead>
<tr>
<th>№</th>
<th>Strain</th>
<th>Stress, MPa</th>
</tr>
</thead>
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<td>1</td>
<td>0.001148</td>
<td>203,2736</td>
</tr>
<tr>
<td>2</td>
<td>0.001511</td>
<td>241,9004</td>
</tr>
<tr>
<td>3</td>
<td>0.002198</td>
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<td>4</td>
<td>0.002889</td>
<td>304,1862</td>
</tr>
<tr>
<td>5</td>
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</tr>
<tr>
<td>6</td>
<td>0.015542</td>
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</tr>
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</table>
Table 3 Mechanical properties of composite used for bandage

<table>
<thead>
<tr>
<th>Experiment</th>
<th>E, MPa</th>
<th>σB, MPa</th>
<th>ν</th>
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<tr>
<td></td>
<td>837,91</td>
<td>75</td>
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</table>

Table 4 Mechanical properties of filler

<table>
<thead>
<tr>
<th>E, MPa</th>
<th>σB, MPa</th>
<th>ρ, g/cm³</th>
<th>ν</th>
</tr>
</thead>
<tbody>
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<td>4500</td>
<td>80</td>
<td>1,2</td>
<td>0,5</td>
</tr>
</tbody>
</table>

Geometrical model of the research object was created in CAE system ANSYS and presented on Fig. 3–4.

**Fig. 3** Model of a pipe with volumetric surface defect (symmetry surface cut)

**Fig. 4** Model of a pipe with surface defect repaired by bandage

Element type SOLID185 Structured Solid was used to mesh the pipeline, filler material and the bandage. Material models for pipe and the filler material were assumed isotropic, while to model the composite bandage the orthotropic material model was used. Material properties were taken from Table 1–4 accordingly.
Fig. 5 Finite element model (zoomed into damaged area)

Mesh dependence was studied, and the element edge size of 2 mm (Fig. 5) was chosen for analysis as the best option to fulfill two criteria — mesh convergence (Fig. 6) and multiplicity to the bandage width discrete values.

Fig. 6 Mesh convergence

21.4. OPTIMAL DESIGN OF BANDAGE

Current work considers the problem of optimal choice of the geometric parameters of the bandage — where width \( l \) can be varied continuously and thickness \( h \) varies discretely because of the layered...
structure of the composite. The objective function $Q(h,l)$ is selected in order to provide the same strength of the repaired part and undamaged area of the pipeline:

$$Q = \left( \frac{\sigma_{i,\max} - \sigma_{i,\text{nom}}}{\sigma_{i,\text{nom}}} \right)^2,$$

(10)

where $\sigma_{i,\text{nom}}$ — stress intensity of undamaged area, and $\sigma_{i,\max}$ is the maximum stress intensity in the damaged zone.

A statistical methodology for finding the minimum of the objective function is applied. In the first stage of optimization, a Monte Carlo [6] method is used with the Latin hypercube generation [7] of the sample numbers. Range of varying for bandage width is 140–400 mm, and range for number of layers is 15–34. Resulting sample numbers are shown in graphical representation on Fig. 7.

![Graph showing sample numbers in the field of all possible values in the given interval](image)

**Fig. 7** Sample numbers in the field of all possible values in the given interval
21.5. NUMERICAL EXPERIMENTS AND RESULTS

Objective function values were obtained for every sample number and for two inner pressure values $P_1=3.34 \text{ MPa}$ and $P_2=8.99 \text{ MPa}$ and the objective function was approximated with second order polynomial, and plotted as a 3D surface graph.

Table 5 Stress intensity and Objective function values for model subjected to inner pressure of 3.34 $\text{MPa}$

<table>
<thead>
<tr>
<th>Number of Layers</th>
<th>Bandage width, mm</th>
<th>Stress intensity in mid-point, MPa</th>
<th>Stress intensity in edge point, MPa</th>
<th>Objective function value in mid-point</th>
<th>Objective function value in edge point</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>180.0</td>
<td>76.34</td>
<td>85.51</td>
<td>0.06119965</td>
<td>0.15778549</td>
</tr>
<tr>
<td>16</td>
<td>260.0</td>
<td>74.7</td>
<td>83.87</td>
<td>0.04865917</td>
<td>0.13721456</td>
</tr>
<tr>
<td>17</td>
<td>380.0</td>
<td>72.16</td>
<td>81.33</td>
<td>0.03207143</td>
<td>0.1081894</td>
</tr>
<tr>
<td>18</td>
<td>320.0</td>
<td>70.84</td>
<td>81.01</td>
<td>0.0248114</td>
<td>0.10477704</td>
</tr>
<tr>
<td>19</td>
<td>160.0</td>
<td>70.11</td>
<td>80.28</td>
<td>0.02119593</td>
<td>0.09719723</td>
</tr>
<tr>
<td>20</td>
<td>220.0</td>
<td>69.75</td>
<td>78.92</td>
<td>0.01951773</td>
<td>0.08383485</td>
</tr>
<tr>
<td>21</td>
<td>390.0</td>
<td>68.92</td>
<td>75.05</td>
<td>0.01591226</td>
<td>0.05121494</td>
</tr>
<tr>
<td>22</td>
<td>310.0</td>
<td>68.56</td>
<td>74.69</td>
<td>0.01446281</td>
<td>0.04858711</td>
</tr>
<tr>
<td>23</td>
<td>140.0</td>
<td>64.39</td>
<td>73.52</td>
<td>0.00271693</td>
<td>0.04052458</td>
</tr>
<tr>
<td>24</td>
<td>210.0</td>
<td>62.58</td>
<td>68.71</td>
<td>0.00050846</td>
<td>0.01505834</td>
</tr>
<tr>
<td>25</td>
<td>350.0</td>
<td>59.44</td>
<td>65.57</td>
<td>0.00082703</td>
<td>0.00509871</td>
</tr>
<tr>
<td>26</td>
<td>270.0</td>
<td>57.4</td>
<td>60.57</td>
<td>0.00385535</td>
<td>0.00010597</td>
</tr>
<tr>
<td>27</td>
<td>170.0</td>
<td>53.09</td>
<td>59.26</td>
<td>0.01756058</td>
<td>0.00100485</td>
</tr>
<tr>
<td>28</td>
<td>400.0</td>
<td>51.05</td>
<td>54.31</td>
<td>0.02750611</td>
<td>0.01267464</td>
</tr>
<tr>
<td>29</td>
<td>340.0</td>
<td>50.45</td>
<td>53.71</td>
<td>0.03085419</td>
<td>0.01497824</td>
</tr>
<tr>
<td>30</td>
<td>230.0</td>
<td>49.17</td>
<td>52.43</td>
<td>0.03863923</td>
<td>0.02053508</td>
</tr>
<tr>
<td>31</td>
<td>150.0</td>
<td>50.08</td>
<td>53.34</td>
<td>0.03301465</td>
<td>0.01649462</td>
</tr>
<tr>
<td>32</td>
<td>300.0</td>
<td>48.14</td>
<td>51.4</td>
<td>0.045539</td>
<td>0.02564185</td>
</tr>
<tr>
<td>33</td>
<td>370.0</td>
<td>46.93</td>
<td>50.19</td>
<td>0.05436822</td>
<td>0.03236472</td>
</tr>
<tr>
<td>34</td>
<td>190.0</td>
<td>46.13</td>
<td>49.39</td>
<td>0.06063504</td>
<td>0.03723891</td>
</tr>
</tbody>
</table>
Using the second order polynomial for fitting the objective function:
\[ a + b \cdot h^2 + c \cdot l^2 + d \cdot h \cdot l + e \cdot h + m \cdot l, \]  

(11)

Fitting coefficients were determined with math software Maple and the 3D plot of the objective function one can see on Fig. 8 for the applied pressure of 3.34 MPa and on Fig. 9 for applied pressure of 8.99 MPa.

**Fig. 8** 3D Plot of the objective function for inner pressure of 3.34 MPa

**Fig. 9** 3D Plot of the objective function for inner pressure of 8.99 MPa

Stress intensity in pipe was considered in two feature points, one called mid-point corresponds to the inner pipe surface point under the middle of the defect, and one called edge point corresponds to the same inner pipe surface point under the corner edge of the defect.

On Tables 5–6 one can see the stress intensity values and corresponding optimal function values for both points under 3.34 MPa and 8.99 MPa.
Table 6 Stress intensity and Objective function values for model subjected to inner pressure of 8.99 MPa

<table>
<thead>
<tr>
<th>Number of Layers</th>
<th>Bandage width, mm</th>
<th>Stress intensity in mid-point, MPa</th>
<th>Stress intensity in edge point, MPa</th>
<th>Optimal function value in mid-point</th>
<th>Optimal function value in edge point</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>180,0</td>
<td>205,43094</td>
<td>222,96741</td>
<td>0,06078541</td>
<td>0,12457906</td>
</tr>
<tr>
<td>16</td>
<td>260,0</td>
<td>201,0177</td>
<td>218,55417</td>
<td>0,0482978</td>
<td>0,10639223</td>
</tr>
<tr>
<td>17</td>
<td>380,0</td>
<td>194,18256</td>
<td>211,71903</td>
<td>0,03178812</td>
<td>0,08105571</td>
</tr>
<tr>
<td>18</td>
<td>320,0</td>
<td>190,63044</td>
<td>210,85791</td>
<td>0,02456683</td>
<td>0,07810773</td>
</tr>
<tr>
<td>19</td>
<td>160,0</td>
<td>188,66601</td>
<td>208,89348</td>
<td>0,02097226</td>
<td>0,07158703</td>
</tr>
<tr>
<td>20</td>
<td>220,0</td>
<td>187,69725</td>
<td>205,23372</td>
<td>0,01930422</td>
<td>0,06019674</td>
</tr>
<tr>
<td>21</td>
<td>390,0</td>
<td>185,46372</td>
<td>194,81955</td>
<td>0,01572181</td>
<td>0,03318134</td>
</tr>
<tr>
<td>22</td>
<td>310,0</td>
<td>184,49496</td>
<td>193,85079</td>
<td>0,01428222</td>
<td>0,03107431</td>
</tr>
<tr>
<td>23</td>
<td>140,0</td>
<td>173,27349</td>
<td>190,70232</td>
<td>0,00264369</td>
<td>0,02470375</td>
</tr>
<tr>
<td>24</td>
<td>210,0</td>
<td>168,40278</td>
<td>177,75861</td>
<td>0,00047793</td>
<td>0,00618305</td>
</tr>
<tr>
<td>25</td>
<td>350,0</td>
<td>159,95304</td>
<td>169,30887</td>
<td>0,00086502</td>
<td>0,00074855</td>
</tr>
<tr>
<td>26</td>
<td>270,0</td>
<td>154,4634</td>
<td>155,85387</td>
<td>0,00393406</td>
<td>0,00294684</td>
</tr>
<tr>
<td>27</td>
<td>170,0</td>
<td>142,86519</td>
<td>152,32866</td>
<td>0,0177155</td>
<td>0,0057268</td>
</tr>
<tr>
<td>28</td>
<td>400,0</td>
<td>137,37555</td>
<td>139,00821</td>
<td>0,02769245</td>
<td>0,02449337</td>
</tr>
<tr>
<td>29</td>
<td>340,0</td>
<td>135,76095</td>
<td>137,39361</td>
<td>0,0310492</td>
<td>0,02765599</td>
</tr>
<tr>
<td>30</td>
<td>230,0</td>
<td>132,31647</td>
<td>133,94913</td>
<td>0,03885188</td>
<td>0,03504454</td>
</tr>
<tr>
<td>31</td>
<td>150,0</td>
<td>134,76528</td>
<td>136,39794</td>
<td>0,0321489</td>
<td>0,02970197</td>
</tr>
<tr>
<td>32</td>
<td>300,0</td>
<td>129,54474</td>
<td>131,1774</td>
<td>0,045765</td>
<td>0,04162442</td>
</tr>
<tr>
<td>33</td>
<td>370,0</td>
<td>126,28863</td>
<td>127,92129</td>
<td>0,05460891</td>
<td>0,05007685</td>
</tr>
<tr>
<td>34</td>
<td>190,0</td>
<td>124,13583</td>
<td>125,76849</td>
<td>0,06088487</td>
<td>0,05609398</td>
</tr>
</tbody>
</table>
Obtained results showed that bandage length parameter did not have significant effect on the stress intensity values. To overcome the one-parameter gradient descent situation, a new set of sample numbers was selected in the vicinity of minimum value of objective function. As with the general set of parameter values, for new set in the vicinity of minimum value of objective function approximation of this function is performed by a second order polynomial and the minimum value for two-parametric function was found (Table 7).

**Table 7** Objective function values for model subjected to inner pressure of 3.34 MPa in the vicinity of minimum value of the objective function

<table>
<thead>
<tr>
<th>Number of layers</th>
<th>Bandage width, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>260</td>
</tr>
<tr>
<td>25</td>
<td>0.0061</td>
</tr>
<tr>
<td>26</td>
<td>1.67E-05</td>
</tr>
<tr>
<td>27</td>
<td>0.001474</td>
</tr>
</tbody>
</table>

**Fig.10** 3D Plot of the objective function for inner pressure of 3.34 MPa in the vicinity of minimum value of the objective function
As one can see from the Table 7 and 3D plot (Fig. 10), the gradient descent situation still was the case, however one can presume that the minimum value of the objective function lies within sample values range of bandage widths lower than 260 mm for the 26 layers. In order to determine the minimum value of the objective function, an additional set of sample values was taken with lower values of bandage width (Table 8).

**Table 8** Objective function values for model subjected to inner pressure of 3.34 MPa in the vicinity of minimum value of the objective function

<table>
<thead>
<tr>
<th>Bandage width, mm</th>
<th>Number of Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
</tr>
<tr>
<td>220</td>
<td>0.006917</td>
</tr>
<tr>
<td>230</td>
<td>0.006594926</td>
</tr>
<tr>
<td>260</td>
<td>0.0061</td>
</tr>
<tr>
<td>270</td>
<td>0.00565</td>
</tr>
<tr>
<td>280</td>
<td>0.004983</td>
</tr>
<tr>
<td>290</td>
<td>0.004401</td>
</tr>
<tr>
<td>300</td>
<td>0.003937</td>
</tr>
</tbody>
</table>

Even though the approximation of the objective function still catches the gradient descent, the table values of the objective function show that the minimum value was found for the discrete values of the bandage thickness of 26 layers and width of 230 mm. An approximation procedure was performed for the set of objective function values that correspond to 26 layers and on Fig. 11 one can see the curve of the approximation function. A minimum value of that function was found for the bandage width of 245 mm. As a result, the optimal parameters for the considered repaired construction are 26 layers and 245 width of composite bandage.
**Fig. 11** 2D Plot of the objective function for inner pressure of 3.34 MPa in the closer range of the minimum value of the objective function

### 21.6. CONCLUSION

Pipeline with volumetric surface defect that was subjected to repair using the composite bandage was investigated. A method for determining optimal geometrical parameters of bandage for was introduced. Objective function was defined so that the stress intensity level in the damage area being equal to undamaged part of the pipe were found. A statistical Monte Carlo method was used to define minimum values of the objective function with sample numbers generated using Latin hypercube. To perform analysis of the stress state of the pipeline-bandage system the finite element method implemented in software ANSYS is used. The values of bandage width and thickness that correspond to this state are obtained.
21.7. REFERENCES


