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ASSESSMENT OF THE STRESSED-STRAINED STATE OF A REINFORCED TRANSPORT PIPE UNDER THE COMBINED EFFECT OF AMBIENT TEMPERATURE AND STATIC LOADS

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The object of this study is a reinforced three-layer transport pipe, which is subjected to the joint action of ambient temperature and static loading of the road subgrade soil.

The analytical model for assessing the stressed-strained state of reinforced three-layer pipes, under the combined action of temperature and static loads, has been improved using the theory of elasticity.

The stressed-strained state of the reinforced pipe was assessed taking into account the values of the joint action of temperature and loads from vehicles, the physical and mechanical parameters of structural materials, and the geometric parameters of the pipe.

As a result of the calculation of the reinforced multilayer pipe, it was found that the maximum movements that occur on the outside of the defective pipe are 0.64 mm, the metal pipe – 0.75 mm, and in the concrete mortar (fine-grained concrete) – 0.69 mm.

It was established that under the combined action of ambient temperature and static loads from the road subgrade soil, ring stresses are maximum. They are 151 MPa. Axial stresses are also high – 141 MPa. At the same time, the maximum radial stresses are the smallest – 37.4 MPa.

It has been established that a small difference in displacements occurs on the contact of structural materials of the reinforced pipe. However, the magnitude of the stresses is high. The maximum difference in ring stresses was 73 MPa, while the difference in radial and axial stresses was up to 1.0 MPa.

It has been established that to restore the bearing capacity of damaged reinforced concrete pipes, it is possible to use the repair technology by the method of "sleeving". It involves pulling a metal pipe into the middle of the layer damaged with concrete mortar remaining between the concrete defective and the new metal pipes

Keywords: concrete defective pipe, temperature, metal pipe, movement, stress, static load

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1. Introduction

Reinforced concrete pipes that are in operation are exposed to a complex of factors. Variable loads from vehicles, aggressive environmental influences, the action of variable climatic temperature changes, the weight of soil backfill, etc. These loads lead to the development of defects and damage to pipes. As a result, the bearing capacity of pipes decreases and there is a threat to safe operation.

To restore the bearing ability of pipes, a variety of repair measures is applied. One of the modern repairs is the use of the method of "sleeving" [1, 2]. The technology involves the installation of a new metal pipe in the existing defective one, followed by filling the layer with high-strength self-expanding concrete mortar (fine-grained concrete). The scheme of the reinforced pipe is shown in Fig. 1.

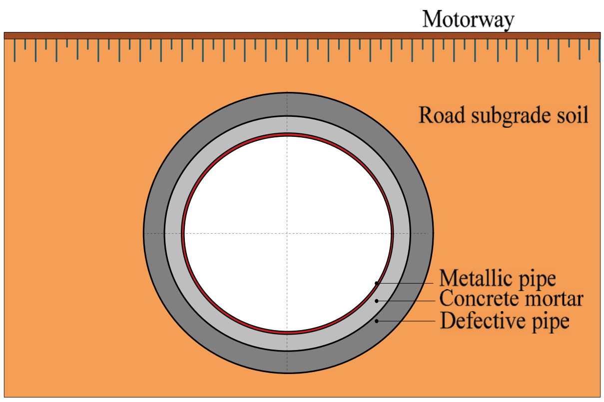

Fig. 1. View of reinforced defective metal pipe

The advantage of this technology is the performance of work without stopping the movement of vehicles. However, in the process of reinforcement, a multilayer structure arises consisting of materials that have different physical and mechanical properties. To assess the stresses and deformations of such structures, it is necessary to apply complex mathematical models. Therefore, the improvement of the theoretical methodology and the assessment of the stressed-strained state of three-layer structures is an urgent task of scientific research. It is necessary to take into account the combined effect of ambient temperature, the mechanical properties of the material, and the values of static loads.

2. Literature review and problem statement

Work [2] states that a large number of reinforced concrete pipes are operated in road construction, which have various damages and defects. The main factors that lead to destruction and damage to pipes under operating conditions are the magnitude of static and dynamic loads from the action of vehicles and fluctuations in ambient temperature [3]. As a result of the action of the force load, cracks develop in the pipes, which further evolve and lead to the loss of the carrying capacity of the pipes. Many scientific works consider the development of cracks in concrete and reinforced concrete structures, under the influence of loads. In [4] it was established that the development of cracks in reinforced concrete structures is influenced by the reinforcement coefficient, and, in works [5, 6], the relationship between the width of crack opening and the load level has been established.

Work [7] establishes the relationship of the influence of deformations on the development of cracks in reinforced concrete structures. Experimental studies of the bearing capacity of round reinforced concrete pipes [8] showed that in order to assess the rigidity of reinforced concrete under static load, crack exposure should be taken into account.

In [9], it was concluded that metal corrugated structures can be used to increase the bearing capacity of damaged reinforced concrete pipes and small bridges. And in work [10] it is noted that a promising direction for improving transport infrastructure is the use of metal pipes made of prefabricated metal structures. However, no methods for studying the stressed-strained state of pipes under the combined action of loads are given.

There are a number of studies into the stressed-strained state of reinforced defective pipes using corrugated metal structure. However, most of them concern the assessment of temperature fields and stresses from exposure to temperatures. For example, in [1], an assessment of the thermoelastic state of a reinforced concrete pipe reinforced with corrugated metal structures was carried out. However, stresses and deformations are determined only under the influence of variable temperature climatic influences, without taking into account the loads from vehicles. Also, in [11] the results of calculating the distribution of the temperature field on the metal structures of pipes are reported. It is noted that the promising direction of further research is the assessment of stresses and deformations from the combined action of temperature on static loads. In works [12, 13], methods for assessing thermal conductivity in bodies are given. However, there are no analytical models for estimating stresses and deformations.

In work [14], a study of the stressed-strained state of metal pipes was carried out when using them to strengthen a railway track subgrade soil. For this purpose, a model of finite-element analysis was used. However, the calculations were carried out only when the loads from the soil sealing backfill and loads from the rolling stock of railways were set. The model does not take into account the contact between the pipe and the soil backfill, which is relevant in the study of multilayer structures.

In [15], an assessment of stresses and deformations that occur in a reinforced concrete pipe by the method of finite elements is carried out. The stressed-strained state is obtained only when exposed to ambient temperature. In addition, it does not have a practical engineering method for assessing stresses in a multilayer pipe.

Work [16] provides a methodology for assessing the deformed state of pipes under the action of loads from the rolling stock of railways.

It should be noted that polymeric materials with high adhesion rates are also used to restore the carrying capacity of damaged transport structures. Such studies are reported in [17, 18]. Also, work [19] gives the results of experimental tests of the capacity of corrugated polyethylene pipes. It has been established that they are characterized by high rigidity and can be used in transport construction.

In work [20], theoretical studies of three-layer models that have different physical and mechanical parameters in layers are carried out. As a result, it was established that for the practical use of new concrete in the repair of damaged concrete structures, it is necessary to achieve the same modules of elasticity of new and old concrete.

It follows from the review of scientific papers [2–20] that the calculations of pipes are basically carried out by the method of finite-element modeling. In most works, stresses and deformations are determined from the effects of ambient temperature differences, or from rolling stock loads without taking into account the influence of temperature. The tasks of researching the stressed-strained state of reinforced multilayer structures, taking into account the joint action of temperature differences in the environment and static loads remained unresolved.

3. The aim and objectives of the study

The aim of our work is to improve the methodology and assess the stressed-strained state of reinforced concrete pipes reinforced with a metal pipe under the combined action of ambient temperature differences and the action of static loads. This will make it possible to conduct an analytical assessment of stresses and deformations of three-layer reinforced structures.

To accomplish the aim, the following tasks have been set:

– to improve the theoretical model for assessing the stressed-strained state of reinforced concrete pipes, taking into account the effect of temperature differences and static loads;

– to take into account the factors influencing the stressed-strained state under the combined action of temperature differences and the action of static loads.

4. Materials and methods of research

4. 1. Geometric parameters and materials of the studied three-layer pipe

When repairing defective pipes by the method of "sleeving", a multilayer structure is formed, the elements of which differ significantly from each other in physical and mechanical parameters. The stressed-strained state of the pipe reinforced with a metal pipe is monitored with geometric parameters of the multilayer pipe, which is shown in Fig. 2.

It is accepted that the defective concrete pipe has an outer diameter of 725 mm; internal – 585 mm. The wall thickness of the pipe is 140 mm. The class of concrete from which the pipe is made is C25/30.

The metal pipe installed in the middle of the defective reinforced concrete pipe is made of St3 steel. The inner diameter of the pipe is 500 mm, the metal thickness of the pipe is 2 mm.

To fill the space between the defective concrete pipe and the new metal one, a self-compacting concrete mortar (fine-grained concrete) of class C32/40 was used.

To assess the stresses and deformations, the following geometrical parameters of the pipe are given: a=500 mm; r_1=502 mm; r_2=585 mm; b=725 mm.

Physical and mechanical parameters of structural layers of reinforced concrete pipe: metal pipe made of steel St3: $E_1=2.1\cdot10^5$ MPa; $\nu_1=0.3$; $\alpha_1=1.25\cdot10^{-5}$ 1/°C, $\kappa_1=45$ W/(m·°C); concrete mortar between the metal pipe and the reinforced one (concrete C32/40): $E_2=3.6\cdot10^4$ MPa; $\nu_2=0.25$; $\alpha_2=1.0\cdot10^{-5}$ 1/°C, $\kappa_2=1.51$ W/(m·°C); defective concrete pipe (concrete C25/30): $E_3=3.9\cdot10^4$ MPa; $\nu_3=0.25$; $\alpha_3=1.0\cdot10^{-5}$ 1/°C, $\kappa_3=1.69$ W/(m·°C).

The calculation of the stressed-strained state of the three-layer structure was carried out taking into account the magnitude of the temperature difference between the outer and inner surfaces of the reinforced pipe with a value of Δt=10 °C. The calculations take into account the combined effect of temperature differences and static loads. Therefore, before the temperature drop, the load is also set at a height of soil backfill over a pipe of 1.0 m with a value of 19.4 kPa. These loads are calculated according to the procedure given in work [21].

5. Results of the calculation of the stressed-strained state of the reinforced three-layer pipe

5. 1. Improved mathematical model for estimating the stressed-strained state of a reinforced three-layer pipe

In works [22, 23] it is noted that to assess the stress state in massive structural elements, it is advisable to use the equations of the theory of thermoelasticity or elasticity, and, to calculate the thin-walled elements of structures – the equations of shell theory.

To assess the stressed-strained state of a three-layer pipe, a geometric model is adopted, which is shown in Fig. 2. The base is the model given in [1], according to which the assessment of the stressed-strained state of the reinforced pipe is carried out, only under the influence of an ambient temperature drop. The model has been improved by taking into account the magnitude of the pressure force to the action of ambient temperature. To do this, a piecewise-homogeneous three-layer cylindrical shell is adopted. It can be assumed that the shell in question is within the region

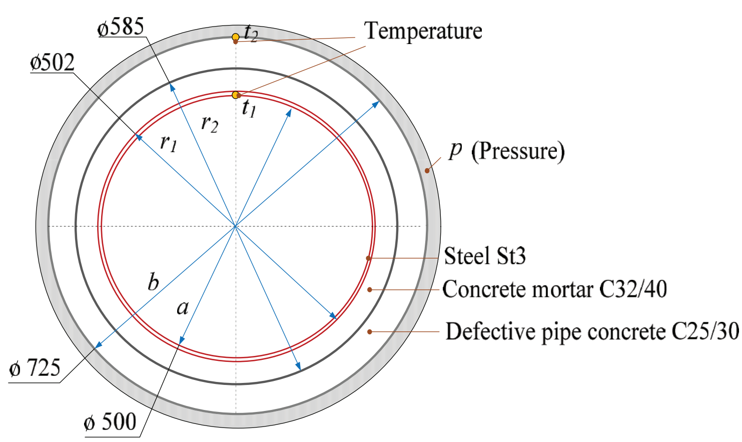

Fig. 2. Geometric model of reinforced multilayer pipe

$$(V)=\{(r,\varphi,z): a\le r\le b, 0\le\varphi<2\pi, 0\le z\le l\},$$

where r, φ, z is the cylindrical coordinate system.

The distribution of the temperature field in a three-layer reinforced pipe is sought by the equations given in [1]. They take the form:

$$t=\begin{cases} C_1\ln r+C_2 \text{ if } a\le r\le r_1,\\ C_3\ln r+C_4 \text{ if } r_1<r\le r_2,\\ C_5\ln r+C_6 \text{ if } r_2<r\le b.\end{cases} \quad (1)$$

Formulas for determining integration constants $C_1...C_6$ are given in [1].

In the improved model, it is accepted that on surfaces $r=a$ and $r=b$ there is a load p. The modulus of elasticity, the Poisson coefficient, and the coefficient of linear thermal expansion of the shell will be determined, accordingly, from formulas:

$$E=\begin{cases} E_1 \text{ if } a\le r\le r_1,\\ E_2 \text{ if } r_1<r\le r_2,\\ E_3 \text{ if } r_2<r\le b,\end{cases}$$

$$v=\begin{cases} v_1 \text{ if } a\le r\le r_1,\\ v_2 \text{ if } r_1<r\le r_2,\\ v_3 \text{ if } r_2<r\le b,\end{cases}$$

$$\alpha=\begin{cases} \alpha_1 \text{ if } a\le r\le r_1,\\ \alpha_2 \text{ if } r_1<r\le r_2,\\ \alpha_3 \text{ if } r_2<r\le b.\end{cases}$$

Evaluation of the stressed-strained state of a three-layer pipe is carried out according to the equations and ratios of the theory of elasticity. It is accepted that the movements u_φ, u_z are zero, then the components $e_{r\varphi}$, e_{rz}, $e_{\varphi z}$, e_{zz} of the strain tensor and the components $\sigma_{r\varphi}$, σ_{rz}, $\sigma_{\varphi z}$ of the tensor of the stresses will also be zero. Thus, the equilibrium equation is:

$$\frac{d\sigma_{rr}}{dr}+\frac{1}{r}\left(\sigma_{rr}-\sigma_{\varphi\varphi}\right)=0, \quad (2)$$

where σ_{rr}, $\sigma_{\varphi\varphi}$ are the components of the stress tensor.

The Duhamel-Neumann ratio linking the stresses σ_{rr}, $\sigma_{\varphi\varphi}$, σ_{zz} and the deformations e_{rr}, $e_{\varphi\varphi}$, e_{zz} are:

$$\sigma_{rr}=2\mu e_{rr}+\lambda e-\beta t,$$

$$\sigma_{\varphi\varphi}=2\mu e_{\varphi\varphi}+\lambda e-\beta t,$$

$$\sigma_{zz}=2\mu e_{zz}+\lambda e-\beta t, \quad (3)$$

where

$$e=e_{rr}+e_{\varphi\varphi},$$

$$\lambda=\frac{E\nu}{(1+\nu)(1-2\nu)},$$

$$\mu=\frac{E}{2(1+\nu)},$$

$$\beta=\alpha(3\lambda+2\mu).$$

There is a relationship between the deformations e_{rr}, $e_{\varphi\varphi}$ and the movement u_r:

$$e_{rr}=\frac{du_r}{dr},\quad e_{\varphi\varphi}=\frac{u_r}{r}. \quad (4)$$

At $r=a$ and $r=b$ and setting loads p, we received:

$$\sigma_{rr}\big|_{r=a}=0,\quad \sigma_{rr}\big|_{r=b}=-p. \quad (5)$$

In the case of $r=r_1$ and $r=r_2$, the conditions of ideal mechanical contact are met

$$u_r\big|_{r=r_1-0}=u_r\big|_{r=r_1+0},\ \sigma_{rr}\big|_{r=r_1-0}=\sigma_{rr}\big|_{r=r_1+0}, \quad (6)$$

$$u_r\big|_{r=r_2-0}=u_r\big|_{r=r_2+0},\ \sigma_{rr}\big|_{r=r_2-0}=\sigma_{rr}\big|_{r=r_2+0}.$$

From the system of equations (2) to (4), we obtained:

$$\frac{d^2u_r}{dr^2}+\frac{1}{r}\frac{du_r}{dr}-\frac{u_r}{r^2}=\frac{\beta}{2\mu+\lambda}\frac{dt}{dr}. \quad (7)$$

Solving equation (7) taking into account (1), we found:

$$u_r=\begin{cases} A_1r+\dfrac{A_2}{r}+\dfrac{\beta_1C_1}{2(2\mu_1+\lambda_1)}r\ln r \text{ if } a\le r\le r_1,\\ A_3r+\dfrac{A_4}{r}+\dfrac{\beta_2C_3}{2(2\mu_2+\lambda_2)}r\ln r \text{ if } r_1<r\le r_2,\\ A_5r+\dfrac{A_6}{r}+\dfrac{\beta_3C_5}{2(2\mu_3+\lambda_3)}r\ln r \text{ if } r_2<r\le b,\end{cases} \quad (8)$$

where

$$\lambda_i=\frac{E_i\nu_i}{(1+\nu_i)(1-2\nu_i)};$$

$$\mu_i=\frac{E_i}{2(1+\nu_i)};$$

$$\beta_i=\alpha_i(3\lambda_i+2\mu_i)\ (i=1, 2, 3);$$

A_1, A_2, ..., A_6 – integration constants.

From ratios (3), (4), we obtained formulas for calculating stresses in three cylindrical coordinates, taking into account the temperature difference and loads from pressure p:

$$\sigma_{rr}=(2\mu+\lambda)\frac{du_r}{dr}+\lambda\frac{u_r}{r}-\beta t=-p, \quad (9)$$

$$\sigma_{\varphi\varphi}=\sigma_{rr}-2\mu\left(\frac{du_r}{dr}-\frac{u_r}{r}\right),$$

$$\sigma_{zz}=\lambda\left(\frac{du_r}{dr}+\frac{u_r}{r}\right)-\beta t.$$

At the same time, the integration constants A_1, A_2, ..., A_6 were determined from conditions (5), (6), which are reduced to matrix equality:

$$\begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \end{pmatrix} = \begin{pmatrix} 2(\mu_1+\lambda_1) & -\frac{2\mu_1}{a^2} & 0 & 0 & 0 & 0 \\ r_1 & \frac{1}{r_1} & -r_1 & -\frac{1}{r_1} & 0 & 0 \\ 2(\mu_1+\lambda_1) & -\frac{2\mu_1}{r_1^2} & -2(\mu_2+\lambda_2) & \frac{2\mu_2}{r_1^2} & 0 & 0 \\ 0 & 0 & r_2 & \frac{1}{r_2} & -r_2 & -\frac{1}{r_2} \\ 0 & 0 & 2(\mu_2+\lambda_2) & -\frac{2\mu_2}{r_2^2} & -2(\mu_3+\lambda_3) & \frac{2\mu_3}{r_2^2} \\ 0 & 0 & 0 & 0 & 2(\mu_3+\lambda_3) & -\frac{2\mu_3}{b^2} \end{pmatrix}^{-1} \times$$

$$\times \begin{pmatrix} \beta_1\left(\frac{\mu_1 C_1}{2\mu_1+\lambda_1}\ln a + C_2 - \frac{C_1}{2}\right) \\ \frac{1}{2}\left(\frac{\beta_2 C_3}{2\mu_2+\lambda_2} - \frac{\beta_1 C_1}{2\mu_1+\lambda_1}\right) r_1 \ln r_1 \\ \beta_1\left(\frac{\mu_1 C_1}{2\mu_1+\lambda_1}\ln r_1 + C_2 - \frac{C_1}{2}\right) - \beta_2\left(\frac{\mu_2 C_3}{2\mu_2+\lambda_2}\ln r_1 + C_4 - \frac{C_3}{2}\right) \\ \frac{1}{2}\left(\frac{\beta_3 C_5}{2\mu_3+\lambda_3} - \frac{\beta_2 C_3}{2\mu_2+\lambda_2}\right) r_2 \ln r_2 \\ \beta_2\left(\frac{\mu_2 C_3}{2\mu_2+\lambda_2}\ln r_2 + C_4 - \frac{C_3}{2}\right) - \beta_3\left(\frac{\mu_3 C_5}{2\mu_3+\lambda_3}\ln r_2 + C_6 - \frac{C_5}{2}\right) \\ \beta_3\left(\frac{\mu_3 C_5}{2\mu_3+\lambda_3}\ln b + C_6 - \frac{C_5}{2}\right) - \end{pmatrix}. \quad (10)$$

5. 2. To take into account the factors influencing the stressed-strained state under the combined action of temperature changes and the action of static loads

The results of calculating the displacements that occur in the direction of the radial coordinate r with a temperature difference between the outer and inner surfaces of a three-layer pipe of 10 °C and the action of a pressure of 19.4 kPa are shown in Fig. 3.

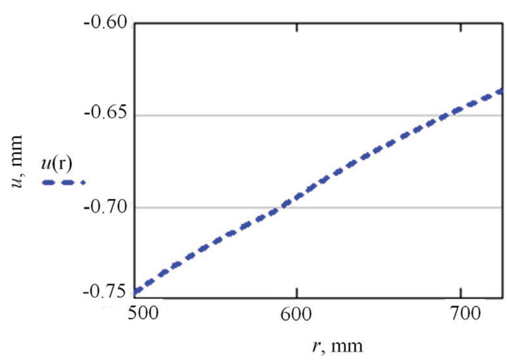

Fig. 3. Distribution of displacements of points of a three-layer pipe

Fig. 3 shows that the maximum movements of the points of the three-layer pipe are 0.75 mm and they occur in the metal pipe. On the outside of the defective pipe, the movements were 0.64 mm, and in concrete mortar 0.69 mm. At the boundary of concrete mortar and the existing defective concrete pipe, a small difference in displacement is observed.

The results of the assessment of stresses that occur under the combined action of ambient temperature and pressure from the road subgrade soil are shown in Fig. 4–6. Fig. 4 shows the distribution of radial stresses σ_{rr}, Fig. 5 – the distribution of axial stresses σ_{zz}, and Fig. 6 – distribution of ring stresses $\sigma_{\varphi\varphi}$.

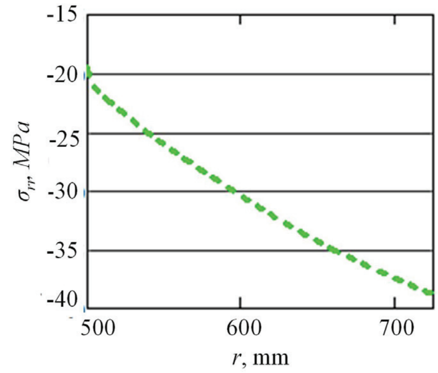

Fig. 4. Distribution plot of radial stresses σ_{rr}

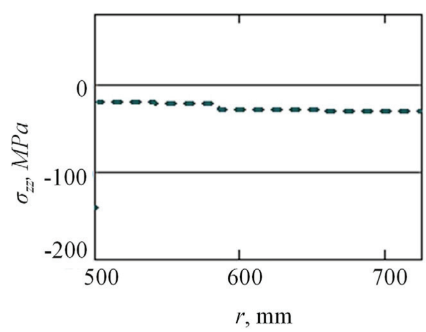

Fig. 5. Distribution plot of axial stresses σ_{zz}

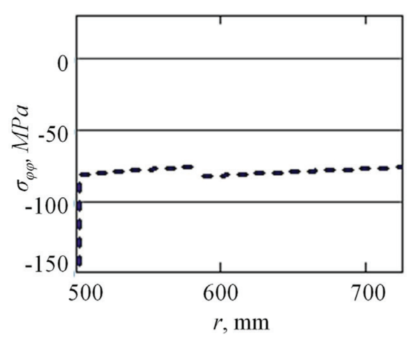

Fig. 6. Distribution plot of ring stresses $\sigma_{\varphi\varphi}$

From the results of the calculation of the stress distribution in a three-layer pipe (Fig. 4–6), it can be seen that a stress jump occurs on the border of structural materials "metal-concrete mortar-concrete". The maximum magnitude of the stress difference between the metal pipe and the concrete mortar is registered when calculating the ring stresses; they are 73 MPa. At the same time, the difference in radial and axial stresses is insignificant – up to 1 MPa.

The maximum radial stresses on the outer surface of the defective pipe σ_{rr} are 37.4 MPa, the axial stresses σ_{zz} are 30.24 MPa, and the ring stresses are 77.34 MPa. At the same time, the radial stresses that occur in the metal pipe are 20.92 MPa, axial – 141 MPa, and ring – 151 MPa.

6. Discussion of results of the assessment of the stressed-strained state of the reinforced three-layer pipe

The theoretical methodology for assessing the stressed-strained state of three-layer pipes under the combined action of ambient temperature difference and the action of static load using the theory of elasticity has been improved. The practical significance is in the possibility of use by engineers and researchers in assessing the stresses and deformations of reinforced pipes. The model makes it possible to take into account the physical and mechanical parameters of structural materials, the geometric parameters of pipes, the magnitude of static loads on the pipe, and the action of ambient temperature.

The results of calculations of displacements that occur in the direction of the radial coordinate r at the temperature difference between the outer and inner surfaces of the three-layer shell are shown in Fig. 3. Movements are calculated for the temperature difference of 10 °C and the action of pressure from the road subgrade soil of 19.4 kPa. The maximum amount of displacement was 0.75 mm in the metal pipe; in the reinforced defective concrete pipe, the movements were 0.64 mm.

The results of the calculation of stresses on the outer surface of the existing pipe showed that the maximum radial stresses σ_{rr} (Fig. 4) are 37.4 MPa. In the metal pipe, the radial stresses were 20.92 MPa. The maximum axial stresses σ_{zz} (Fig. 5) were 30.24 MPa and 141 MPa in the metal pipe. At the same time, the maximum ring stresses $\sigma_{\varphi\varphi}$ are 77.34 MPa and 151 MPa, respectively (Fig. 6).

It was established that the distribution of stresses in the reinforced concrete pipe is characterized by uneven distribution over the thickness of the pipe. At the border of the structural materials of the pipe, there is a jump in stresses. The maximum stress difference between the metal shell and concrete mortar was 73 MPa. At the same time, the difference in radial and axial stresses between structural materials is insignificant and amounts to 1 MPa.

It should be noted that the nonlinear distribution of stresses and displacements in the reinforced pipe is due to different physical and mechanical parameters of structural materials.

Consequently, under the combined action of temperature and static loads, it has been established that the stresses that occur in the axial and ring directions are dominant. However, in the case of calculating stresses in three-layer structures under the action of only the ambient temperature, given in works [1, 24], it was established that only axial stresses are maximum. This difference is explained by the impact on the stressed-strained state of three-layer tubular structures of the amount of pressure from the static load.

It was established that the level of stresses caused by the joint action of the ambient temperature difference and static loads is less than the permissible level of stresses for these structural elements of a three-layer pipe.

So, a theoretical assessment of the stressed-strained state of reinforced concrete pipes using metal pipes showed the effectiveness of repairing damaged pipes. Therefore, it is recommended to apply this type of repair in practice.

One of the limitations of the use of an improved model for calculating the stressed-strained state of reinforced pipes is the assessment of the stress state of reinforced pipes, taking into account only the combined effect of temperature differences and static loads.

The disadvantages of the study of the stressed-strained state of three-layer reinforced defective concrete pipes include the failure to take into account the action of loads from vehicles.

Therefore, a further continuation of research is the development of theoretical foundations for assessing the stressed-strained state of reinforced concrete pipes under the combined action of static and dynamic loads from vehicles.

7. Conclusions

1. The analytical model for assessing the stressed-strained state of reinforced defective concrete pipes under the action of static loads and ambient temperature differences has been improved. This allows for an engineering assessment of the effectiveness of the choice of materials for the repair of defective pipes and for analyzing the stressed-strained state of pipes under the action of static loads of the embankment and the temperature difference of the medium.

2. The amount of displacement in a three-layer reinforced pipe arising from the combined action of temperature and static loads in a reinforced defective concrete pipe was 0.64 mm and 0.75 mm in a metal pipe. At the same time, the maximum radial stresses σ_{rr}, respectively, equaled 37.4 MPa in the defective pipe and 20.92 MPa in the metal pipe. The maximum axial stresses σ_{zz} are 30.24 MPa and 141 MPa, respectively, and the maximum ring stresses $\sigma_{\varphi\varphi}$ are 77.34 MPa and 151 MPa.

At the border of the structural materials of the pipe, there is a jump in stresses. The maximum value of the difference in ring stresses between the metal shell and concrete mortar was 73 MPa. It should be noted that the difference in radial and axial stresses between structural materials is insignificant and amounts to 1 MPa.

Conflicts of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript contains data included as additional electronic material.

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