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THE STUDY OF STRENGTH OF CORRUGATED METAL STRUCTURES OF RAILROAD TRACKS

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Наведено основні дефекти металевих гофрованих водопропускних труб, які виникають внаслідок експлуатації, та висвітлено проблеми забезпечення їх довговічності та міцності. Проаналізовано проблеми адаптації закордонних нормативних документів щодо проектування металевих гофрованих конструкцій на залізничних та автомобільних дорогах України. Наведено результати експериментальних та теоретичних розрахунків несучої здатності металевих гофрованих конструкцій

Ключові слова: залишкові деформації, проектування, пластичний шарнір, рухомий склад залізниць, щільність грунтової засипки

Приведены основные дефекты металлических гофрированных водопропускных труб, возникающие вследствие эксплуатации, и освещены проблемы обеспечения их долговечности. Проанализированы проблемы адаптации иностранных нормативных документов по проектированию металлических гофрированных конструкций на железных и автомобильных дорогах Украины. Приведены результаты экспериментальных и теоретических расчетов несущей способности металлических гофрированных конструкций

Ключевые слова: остаточные деформации, проектирование, пластический шарнир, подвижной состав железных дорог, плотность грунтовой засыпки

1. Introduction

Metal corrugated structures (MCS) have been known since the end of the XIX century [1, 2]. In Russia, the first mention of the MCS constructions were found as early as in 1875, when about 1300 linear meters of pipes were laid on the Transcaspian railway. From 1887 to 1914, another 64000 linear meters were laid, which comprised five thousand constructions. These days, corrugated metal pipes are recommended to be used during construction and reconstruction of roads and railways by the order of the Ministry of Transport of the Russian Federation [3].

In the United States, MCS first appeared in 1896 [2]. Originally, pipes with small openings (up to two meters) were constructed, and later, with manufacturing more powerful metal profile, large structures like bridges (arch-type), overpasses, tunnels, powerful fences started to be constructed. Having examined durability, corrosion resistance and reliability of galvanized MCS, the Americans have recognized them suitable both for severe conditions of Canada and Alaska and for the tropics of Africa, Asia and South America.

In other countries, the corrugated pipes became widely used only in the last 50 years. Now Canadian firm ARMTEC (corrugations of 152×51 and 400×150 mm at thickness of 3–7 mm), Italian FRACASSO (152×51, thickness of 3–7 mm), Norwegian-Swedish-Finnish firm VIACON (150×50, thickness of 3–7 mm). They provide the needs for metal corrugated structures in the countries of Europe, America, Africa and Australia.

Special attention to the research into MCS is paid in such countries as Poland, Sweden, Italy, the United States, moreover, the MCS application is increasingly developing.

In Ukraine, the MCS construction started developing mostly since the mid-90s of the 20th century [4]. Such structures were used in the construction of traffic junctions and bypasses in the Crimea on automobile road Kyiv-Odesa, Kharkiv-Simferopol [4], at railway, MCS were constructed on section Vadul-Siret – the State border [5].

Observations of behavior of a metal corrugated pipe in the process of operation [5, 6] revealed its non-attenuated character. Thus, the analysis of intensity of accumulation of residual deformation by a metal corrugated pipe within a year of service showed that relative deformations of the pipe do not increase, but rather gradually decrease.

The conducted studies, aimed at establishing the causes of emergence of such defects, are necessary and relevant at present. Appropriate monitoring will make it possible to make timely engineering decisions for increasing the bearing capacity of MCS.

2. Literature review and problem statement

In papers [2, 3], it was indicated that for the optimum design of MCS, it is necessary to consider the influence of thickness of a corrugated metal sheet on the strength and stability of the whole structure. As a result of the conducted research into strength of the arch-type MCS depending on the thickness of a metal corrugated sheet, it was established that thickness of a metal sheet mostly influences the stressed state of the structure and vertical deformation of MCS. As the object of study, we chose the structure of the horizontal ellipse type (Fig. 1).

With a view to selecting effective solutions to prevent further destruction and reinforcement of pipe structures, it is necessary to identify the main factors of this destruction.

In paper [7], it was indicated that the possible factors that influence the pipes destruction might include: loading and deformations due to permanent and dynamic loading; destruction of pipe walls because of frost.

From the analysis of scientific-research work [8], it follows that factor influence on the pipe destruction is also the formation of corrosion of a pipe metal, as a result of water stagnation near the corrugation waves. Corrosive processes that extend around the pipe surface may have a negative impact on the operation stability of corrugated metal culverts, as well as influence effectiveness of the hydraulic system. In addition, the conducted research highlight the effect of deterioration in the material of culverts, operated in soil.

While designing MCS, designers faced several problems. Thus, comparison of foreign [3, 9] and Ukrainian [10] design standards revealed significant differences in bound heights of the landfill over the metal corrugated pipe (MCP) at equal thickness of the wall of corrugation. As it turned out, the pipes of foreign design can withstand the weight of the much higher landfills. This fact gave rise to the problem of development of new MCS forms.

Initially, it was assumed that the difference in bearing capacity of MCS was predetermined by the discrepancies in physical-mechanical properties of a metal pipe. However, the study of foreign standards showed that Ukrainian steel brands, used in the construction of MCS, are stronger than those used abroad. The real reason was in the basic discrepancies between the rules of MCS calculation. In Ukraine, the calculation of the culverts with diameter of up to 3 m is performed according to standards [10]. According to them, the first bound condition is determined by the boundary static interaction balance of the "structure-soil" system, based on which the bearing capacity of a pipe may be found. The recommended formula contains a number of empirical coefficients and does not include direct strength characteristics of a metal pipe. However, this condition in most cases is limiting.

Abroad [9, 11], the strength and stability of the wall of corrugation is tested under the influence on the pipe arch of soil column weight and the pressure from the temporary load at the pipe top level. The joint operation of MCS with soil at sufficient height of the backfill above the arch is considered by the introduction of reducing coefficient to the total of temporary and constant loads, which depends on the compaction degree of the soil prism around the structure. Similar testing of the pipe wall strength and stability is the norm in Russia, however, it is almost never limiting [3]. Thus, the pipe calculation by the bound static balance of interaction of the "structure-soil" system is the problem that limits the application range of structures.

In the process of operation, a number of defects occur in metal corrugated pipes. The most common among them is the destruction of additional protective coating of the inner surface of pipes and trays, excess deformations of vertical and horizontal diameters of pipes (Fig. 1), metal crumbling near bolt connections (Fig. 2), corrosion of metal pipes (Fig. 3) and loss of stability of corrugation [6].

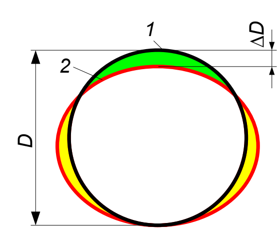

Fig. 1. Schematic of deformation of the cross-sectional cut of a metal corrugated pipe: D – design cross-sectional diameter of a pipe; ΔD – magnitude of deformation; 1 – design position; 2 – deformed state

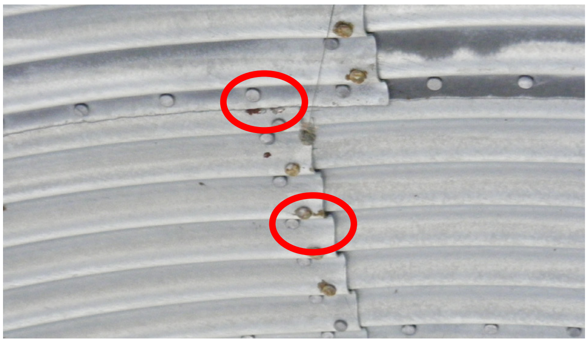

Fig. 2. Crumbling of metal in the bolt junction area

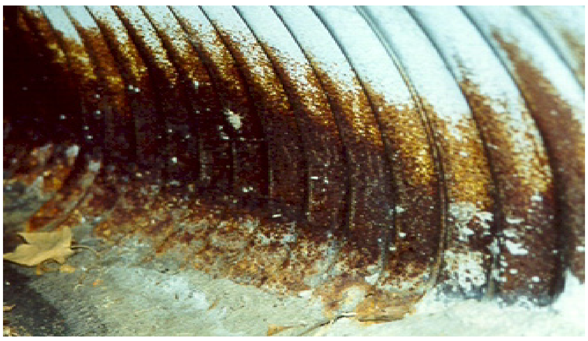

Fig. 3. Corrosion of metal corrugated culverts

The pressure from temporary loading is determined in different ways. At the same height of backfill over a the pipe, the portion of temporary loading in the total pressure on the arch of a pipe, as a rule, will be higher by the Ukrainian [10] standards, although foreign standards [3, 9, 11] take into account dynamics, and at minimal backfills, the intensity of foreign standard loading is larger than that of the similar Ukrainian loading.

Therefore, the assessment of bearing capacity of metal corrugated structures was conducted only for pipes of a small diameter of up to 6 m. The stressed-strained state of pipes of large diameters at bound loading from the rolling stock of railways was not examined. In addition, the given papers do not contain any analysis of bearing capacity of metal corrugated pipes depending on the corrugation type, characteristics of soil and the soil compaction degree during construction and operation of pipes.

3. The aim and tasks of the study

The aim of present work is to carry out experimental and theoretical research into the strength of metal corrugated structures of a railway track, which in the process of operation have residual deformations of vertical and horizontal diameters.

To achieve the set goal, the following tasks had to be solved:

– to analyze the main defects and damages to MCS in the period of operation and to present the results of experimental measurements of residual deformation of vertical and horizontal diameters of a metal corrugated pipe;

– to perform experimental research into the stressed-strained state of MCS at static and dynamic loading from the rolling stock of railways;

– to assess MCS strength using the finite element method, and compare the obtained values with experimental measurements.

4. Experimental research into the stressed-strained state of a metal corrugated structure

When observing the deformation of vertical and horizontal diameters of a metal corrugated pipe during the operation, we found that they have a non-attenuated character. Thus, the analysis of intensity of accumulation of residual deformation within one year of MCS service showed that relative deformations of a pipe do not increase, but gradually decrease. The chart of residual vertical and horizontal deformations with mapping of the bound (permissible) magnitude of this value is shown in Fig. 4.

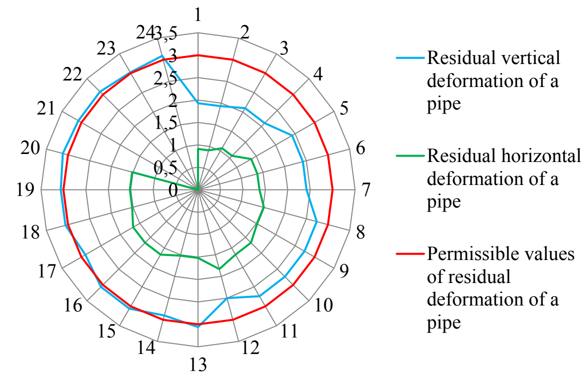

Fig. 4. Intensity of accumulation of residual deformations of MCS

The study of MCS of the Multiplate MP 150 type of horizontal-ellipse-type with the following parameters was conducted: inner vertical diameter of 6.20 m, inner horizontal diameter of 6.57 m, wave length of 150 mm, wave height of 50 mm, metal sheet thickness of 6 mm. In the longitudinal direction, the pipe body is composed of 14 rings. Each ring is made up of 10 sheets, which are connected with bolts. Pipe heads are made using the gabions of the Terramesh system. The modules are arranged in horizontal tiers. The base for the heads is the gabionic mattresses Renault 3:2:0.23, laid out on geotextile and net "Secugrid".

The height of the upper and lower heads is 7.5 m. The length of the reinforcement of left and right slopes of the ground section is respectively 12 m and 28 m.

To determine the actual stressed state of elements (MCP) in order to assess its carrying capacity, static and dynamic tests were conducted. During the tests, fiber stress in corrugated walls of a pipe, vertical and horizontal displacements inside the MCP were measured. Steam locomotive ChME 3 was used as test loading in static testing.

4. 1. Static testing

In static testing, the following schemes of the MCS loading with the railway rolling stock were used (Fig. 5).

Scheme 1 – the first axis of the locomotive was placed above the axis of the pipe.

Scheme 2 – the second axis of the locomotive was placed above the axis of the pipe to create the maximum bending moment.

Scheme 3 – the third axis of the locomotive was places above the top of the pipe.

The scheme of location of strain gauges and sensors for determining displacements on MCS is shown in Fig. 6, 7.

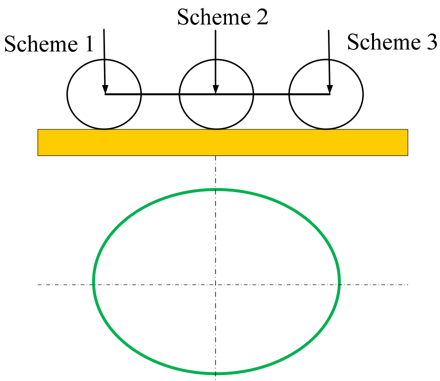

Fig. 5. Schemes of loading of a metal corrugated pipe

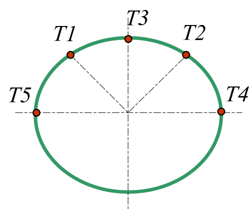

Fig. 6. Scheme of location of strain gauges on the metal corrugated pipe

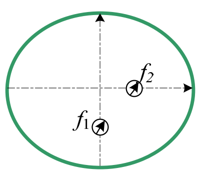

Fig. 7. Scheme of location of sensors for determining displacements on the metal corrugated pipe

The results of experimental research into fiber stresses of a metal corrugated pipe to static loading are shown in Fig. 8.

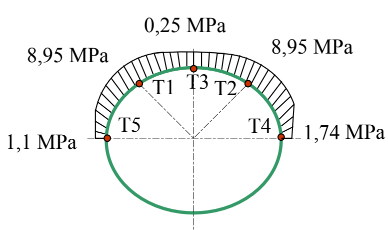

Fig. 8. Diagram of stresses on the metal corrugated pipe from the influence of static loading at the passing of steam locomotive ChME-3

In static tests of the pipe, it was registered that vertical relative deformation (sagging) in the middle of the pipe is 2.05 mm at loading by scheme 2. The maximum fiber stresses at the top points were 8.95 MPa, which does not exceed permissible stresses. Thus, metal of the pipe works in the elastic state without transition to the plastic state.

4. 2. Dynamic testing

During dynamic tests, scheduled trains with the steam locomotive 2M62 with freight wagons and passenger carriages were used, which cruised at the speed of 25 km/h.

The results of experimental research into fiber stresses of the metal corrugated pipe at dynamic loading are shown in Fig. 9.

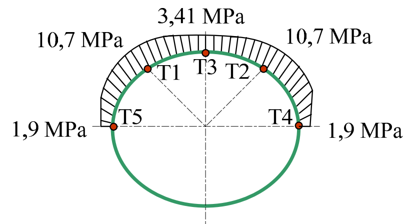

Fig. 9. Diagram of stresses on the metal corrugated pipe from the influence of dynamic loading at the passing of steam locomotive 2M62

During dynamic tests, the following results were registered:

– the maximum vertical relative deformation of the pipe was recorded at passing of a freight train and was 2.74 mm. In this case, residual deformation was 0.21 mm;

– horizontal relative deformation at passing of a freight train reached 0.77 mm. In this case, residual deformation was 0.038 mm.

The maximum fiber stresses from the influence of dynamic loading at the top of the pipe at certain points were 10.7 MPa.

5. Finite-element calculation of the stressed-strained state of metal corrugated structures

The methodology based on theory of the method of finite elements (MFE) forms the base of theoretical study of operation of MCP railway track with a detailed assessment of stressed state in the elements of metal sheets from the influence of the railway rolling stock. Fig. 10 shows schematic of the mathematical model for examining and detailed assessment of operation of the entire MCS in order to obtain reliable results of the stressed state of elements from the external action of forces, transmitted from the wheels of rolling stock.

Given the large spread of the railway and carriages characteristics, the accuracy of measurement of the specified magnitudes during modeling is within permissible error at the level E=10 %. The measure of changes in this magnitude is set by the variation coefficient "ν", the value of which was accepted as ν=10 %. In mathematical modeling, during the discretization of the structure, the number of steps (levels) of the region partition into finite elements (hereinafter FE) was defined based on the difference in the results, which did not exceed 5 %.

Based on the studies conducted in advance, the following algorithm was further developed [12, 13]:

$$R = f_{MKE}(\Omega, F, P, n \,|\, \Delta = 5\,\%), \tag{1}$$

where

$$\Omega = \{\{\omega_1, \omega_2, \omega_i ...\}, \{S_1, S_2, S_i ...\}\}, \tag{2}$$

$$\omega_i = \{\{g_{i1}, g_{i2}, g_{ij} ...\}, \{\varphi_{i1}, \varphi_{i2}, \varphi_{ij} ...\}\}, \tag{3}$$

Hence

$$R = \{\{\sigma_{11}, \sigma_{12}, \sigma_{1k} ... \sigma_{ik} ...\}, \{y_{11}, y_{12}, y_{1k} ... y_{ik} ...\}\}, \tag{4}$$

where Ω is the set of track elements; ω_i is the solid-body i-th element (object) of the totality of track elements (ballast layer, soil backfill, MCS, sleepers, rails); g_{ij}, φ_{ij} are, respectively, the j-th element of the totality of geometrical parameters and the set of physical-mechanical properties of the object ω_i; $S=\{S_1,S_2,S_i...\}$ is the set (totality) of relations between the objects; F is the totality of loading and anchorages; n is the number of cycles of calculation; Δ – % for the similarity of related results; σ_{ik}, y_{ik} are the k-th element of stresses and deformations of object ω_i; R is the state of the model in accordance with calculations of MFE.

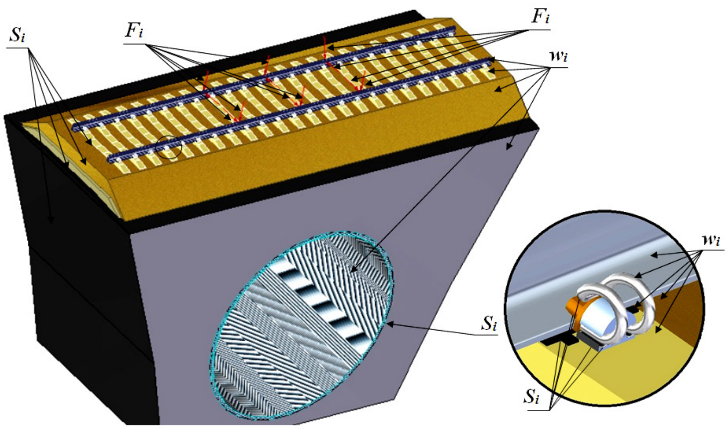

Fig. 10. Schematic of a spatial mathematical model of the MCP railway track structure: W_i – the solid-body i-th element (object) of totality of elements of a track; F – totality of loads; S_i – set (totality) of relationships between objects

Stresses, associated with deformations, are described by the ratio:

$$\{\sigma\}=[D]\{\varepsilon^{el}\}, \tag{5}$$

where $\{\sigma\}$ is the stress vector; [D] is the stiffness matrix; $\{\varepsilon^{el}\}$ is the elastic deformation vector.

Stress vector is determined from expression:

$$\{\sigma\}=\left[\sigma_x,\sigma_y,\sigma_z,\sigma_{xy},\sigma_{yz},\sigma_{xz}\right]^T. \tag{6}$$

The source array, expressed by elastic deformation vector, is described by expression:

$$\{\varepsilon\}=\{\varepsilon^{th}\}+\left|D^{-1}\right|\{\sigma\}, \tag{7}$$

where $\{\varepsilon\}$ is the full deformation vector; $\{\varepsilon^{th}\}$ is the temperature deformation vector.

Hence:

$$\{\varepsilon\}=\{\varepsilon_x,\varepsilon_y,\varepsilon_z,\varepsilon_{xy},\varepsilon_{yz},\varepsilon_{xz}\}. \tag{8}$$

Temperature deformation vector is determined from expression:

$$\{\varepsilon^{th}\}=\Delta T\left[\Delta_x,\Delta_y,\Delta_z,0,0,0\right]^T,\ \Delta T=T-T_{REF}, \tag{9}$$

where Δ_x, Δ_y, Δ_z are the temper coefficients x, y, z; T is the current temperature at a certain point; T_{REF} is the temperature, at which there is no deformation.

Deformation vectors (ε) at certain points x, y, z, xy, yz, xz are described by the following equations:

$$\varepsilon_x=\Delta_x\Delta T+\sigma_x/E_x-\nu_{xy}\sigma_y/E_y-\nu_{xy}\sigma_z/E_z,$$

$$\varepsilon_y=\Delta_y\Delta T+\sigma_y/E_y-\nu_{xy}\sigma_x/E_y-\nu_{zy}\sigma_z/E_z,$$

$$\varepsilon_z=\Delta_z\Delta T+\sigma_z/E_z-\nu_{xz}\sigma_z/E_z-\nu_{zy}\sigma_y/E_z, \tag{10}$$

$$\varepsilon_{xy}=\frac{\sigma_{xy}}{G_{xy}},\quad \varepsilon_{zy}=\frac{\sigma_{zy}}{G_{zy}},\quad \varepsilon_{zx}=\frac{\sigma_{zx}}{G_{zx}},$$

where ε_x, ε_y, ε_z are the magnitudes of an element deformations in the direction of axes x, y, z; ε_{xy}, ε_{zy}, ε_{zx} are the shear deformations of FE points in planes xy, yz, xz; σ_x, σ_y, σ_z are the stresses in elements along axis x, y, z; σ_{xy}, σ_{zy}, σ_{zx} are the shear stresses in planes xy, yz, xz.

According to (5), the inverse matrix is described by the following expression:

$$\left[D^{-1}\right]=$$

$$=\begin{vmatrix} 1/E_x & -\nu_{yx}/E_y & -\nu_{zx}/E_z & 0 & 0 & 0 \\ -\nu_{yx}/E_x & 1/E_y & -\nu_{zy}/E_z & 0 & 0 & 0 \\ -\nu_{zx}/E_z & -\nu_{zy}/E_y & 1/E_z & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_x & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_y & 1/G_z \\ 0 & 0 & 0 & 0 & 0 & 0 \end{vmatrix}, \tag{11}$$

where E is the Young modulus along axes x, y, z; ν is the Poisson ratio; G is the shear stress modulus in planes xy, yz, xz.

Stresses (σ) that occur in elements in the direction of axes x, y, z, and shear stresses in planes xy, yz, xz are described by the following expressions:

$$\sigma_x=E_x/h\left[1-\left(\nu_{yx}^2\right)E_y/E_z\right]\left(\varepsilon_x-\Delta_x\Delta T\right)+$$
$$+E_x/h\left[\nu_{yx}+\nu_{zx}\nu_{yz}E_y/E_z\right]\times$$
$$\times\left(\varepsilon_y-\Delta_y\Delta T\right)+E_x/h\left[\nu_{zx}+\nu_{yz}\nu_{zx}\right]\times\left(\varepsilon_z-\Delta_z\Delta T\right), \tag{12}$$

$$\sigma_y=E_y/h\left[1-\left(\nu_{zx}^2\right)E_x/E_z\right]\left(\varepsilon_y-\Delta_y\Delta T\right)+$$
$$+E_x/h\left[\nu_{yx}+\nu_{zx}\nu_{yz}E_y/E_z\right]\times$$
$$\times\left(\varepsilon_x-\Delta_x\Delta T\right)+E_y/h\left[\nu_{yx}+\nu_{xz}\nu_{yx}E_x/E_z\right]\times$$
$$\times\left(\varepsilon_z-\Delta_z\Delta T\right), \tag{13}$$

$$\sigma_z=E_z/h\left[1-\left(\nu_{yx}^2\right)E_x/E_z\right]\left(\varepsilon_z-\Delta_z\Delta T\right)+$$
$$+E_x/h\left[\nu_{zx}+\nu_{zy}\nu_{yx}\right]\times$$
$$\times\left(\varepsilon_x-\Delta_x\Delta T\right)+E_y/h\left[\nu_{yz}+\nu_{xz}\nu_{yx}E_x/E_y\right]\times$$
$$\times\left(\varepsilon_y-\Delta_y\Delta T\right), \tag{14}$$

$$\sigma_{zy}=G_{zy}\varepsilon_{zy}, \tag{15}$$

$$\sigma_{zx}=G_{zx}\varepsilon_{zx}, \tag{16}$$

where

$$h=1-\left(\nu_{xy}^2\right)E_x/E_y-\left(\nu_{zy}^2\right)E_y/E_z-$$
$$-\left(\nu_{xz}^2\right)E_x/E_z-2\nu_{xy}\nu_{zy}\nu_{xz}E_x/E_z. \tag{17}$$

Shear modulus in planes xy, yz, xz is described by the following expressions:

$$G_{xy}=\left(E_x E_y\right)/\left(E_x+E_y+2\nu_{yx}E_x\right), \tag{18}$$

$$G_{zy}=\left(E_y E_z\right)/\left(E_y+E_z+2\nu_{yz}E_y\right), \tag{19}$$

$$G_{xz}=\left(E_x E_z\right)/\left(E_x+E_z+2\nu_{zx}E_z\right). \tag{20}$$

The numerical calculation of the stressed-strained state of MCS is obtained using the licensed software complex FEMAP MSC NASTRAN. When performing these calculations, we assumed that thickness of zinc coating of MCS is 85 micron (567 g/m^2), specific weight of the soil backfill is γ=20 kN/m^3; deformation modulus of soil backfill is E_0=33 MPa; the distance from the sole of rails to the top of the pipe arch is h=1.88 m; steel elasticity modulus is E=2.1·10 E_0 MPa; the Poisson ratio of the material of the structure is ν=0.25; specific weight of MCS material is γ_{sh}=145,4 kN/m^2; the area of cross section of one corrugation wave is ℵ=0,757·15=11,355 cm^2; design resistance of steel beyond the yield point is R_y=235 MPa; coefficient of operating conditions is m=0.9. The distribution of loadings on the sleepers along the track was obtained through the calculations of track strength [10].

Loading of the soil backfill weight and loading of the locomotive 2M62 were accepted as the load. The results of equivalent forces, arising from the locomotive 2M62 at passing asperities of the railway track, are shown in Fig. 11.

Modeling of the stressed-strained state of MCS is performed in accordance with the guidelines on conducting finite-element modeling when using the NX NASTRAN software, which are given in [11–19].

In case of plastic deformations in a metal pipe, during the calculations we assign the von Mises criterion. In this case, the value of the yield point of pipe metal σ_j is added to parameters E, ν, ρ.

Results of finite-element calculation of the stressed-strained state of MCS are given in Table 1.

In the course of conducted research, it was found that at overloading the MCS by 2.5 times, the pipe metal is at the bound of transition to the plastic state. As a result, stresses in the pipe walls reach the value of 235 MPa, which may pose a threat of formation of irreversible vertical deformations of the pipe.

A direct cause of the occurrence of residual deformations of a metal corrugated pipe is an increase in the stresses in metal sheets of a pipe. The condition of emergence of a plastic hinge, which takes place in the MCS arch, is satisfied only under condition of adverse simultaneous influence of two factors (causes). The first cause is letting the inequality develop beyond permissible values without taking measures for its elimination. The second cause is a decrease in the degree of backfill soil compaction below 90 %. In the absence of one of the causes, the emergence of plastic hinge may not happen. In the joint effect of both causes, the first cause, the impact of which is 42 %, dominates, whereas the impact share of the second cause is 22 %.

The results of comparison of theoretical calculations of the stressed state of MCP with the experimental data, obtained at the design state of the track and design compaction of backfill soil are shown in Fig. 11. Presented results indicate that the maximum stresses are 10.7 MPa (Table 1). Therefore, the metal of the structure due to temporary loading works in the elastic stage, and, in the absence of critical deformations, it has sufficient safety margin at permissible stresses. However, determining the stressed state of the structure in general, in which already there are deformations exceeding the boundary magnitudes, requires further research.

According to Fig. 12, comparative characteristic of the obtained experimental stresses with theoretical ones proves reliability of the results obtained by mathematical modeling. Fiber stresses in the corrugation of a pipe from the steam locomotive 2M62, determined experimentally (during testing), are in the range of 5–10 % of those calculated theoretically. That is, the design factor is K<1.0, which indicates correctness of the preconditions, accepted in computation. Therefore, this technique is recommended for further practical application in order to assess the bearing capacity of MCS of large diameter.

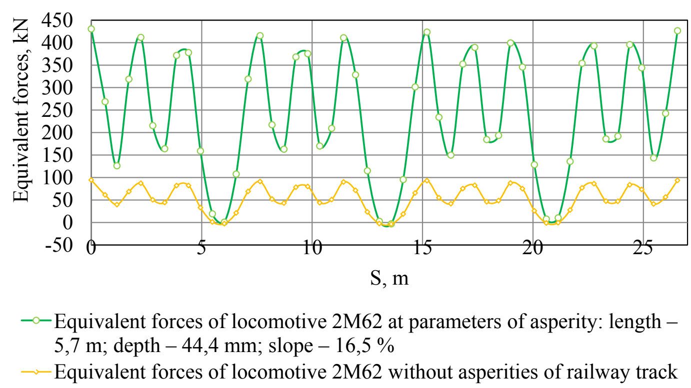

Fig. 11. Equivalent forces of locomotive 2M62 at the value of elasticity modulus of sub-rail base of 92.1 MPa

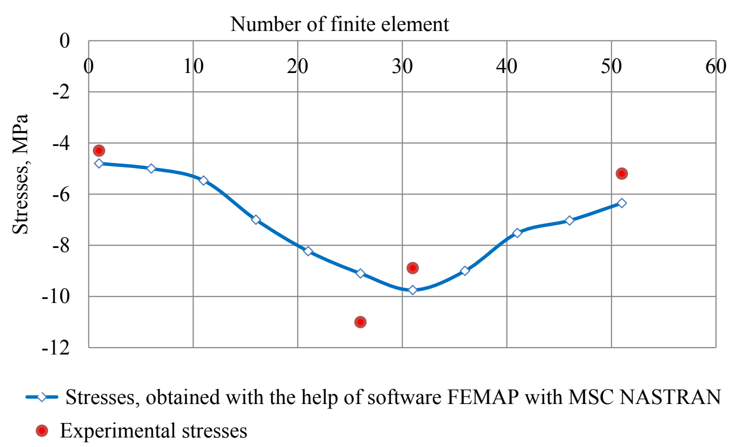

Fig. 12. Comparative chart of the stress magnitudes, obtained experimentally and by computation

Table 1

The stressed-strained state of MCS

No. of entry	Track state	RP, %	Points of determining the equivalent stresses										
			1	2	3	4	5	6	7	8	9	10	11
1	Design state of track without load from the rolling stock	85	1.2	2.5	8.2	17.2	19.4	12.6	7.2	5.6	5.4	4.1	0.9
		90	1.2	3.2	7.3	10.9	11.8	9.1	5.9	5.7	5.4	4.5	1.1
		95	2.5	4.3	6.9	9.2	9.7	8.1	6.1	5.8	5.9	4.5	1.2
		97	3.0	4.6	6.8	8.7	9.1	7.8	6.2	5.7	5.6	4.5	3.2
2	Design state of track and load from the locomotive 2M62	85	17.5	12.2	38.7	52.6	43.8	20.5	5.7	8.1	14.2	7.1	1.5
		90	9.1	19.2	30.2	34.3	28.5	16.9	9.4	9.4	11.1	7.1	4.2
		95	14.4	20.7	27.2	28.8	24.1	16.1	10.6	9.7	10.0	7.9	5.6
		97	15.6	20.9	26.3	27.3	22.9	15.9	10.9	9.7	9.6	7.8	5.8
3	The inequality which is not limited by normative document: l=3m; h=10 mm; i=3.3 ‰ and load from the locomotive 2M62	85	29.8	20.6	65.2	88.2	73.4	34.3	9.4	13.7	23.8	11.9	2.4
		90	15.2	32.2	50.7	57.6	47.7	28.3	15.8	15.8	18.7	13.2	6.9
		95	24.1	34.8	45.7	48.3	40.4	26.9	17.7	16.3	16.7	13.7	9.3
		97	26.2	35.2	44.0	45.8	38.5	26.6	18.2	16.3	16.1	13.1	9.7
4	The inequality which formed in the operation: l=5.7 m; h=44.7 mm; i=16.5 ‰ and load from the locomotive 2M62	85	79.8	155	176.2	235.1	198.1	92.6	64.3	36.8	34	32.4	8.5
		90	54.1	96.9	136.9	185	128.9	76.4	49.8	45.0	45.0	35.3	24
		95	65.2	91.8	123.3	130.5	109.2	72.7	47.9	43.0	45.1	35.0	25.0
		97	70.7	94.8	119.1	123.6	103.9	71.7	49.1	43.9	43.7	35.1	26.3

6. Discussion of results of the study for the purpose of assessing the state of strength of the MCS elements under conditions of railway tracks operation

Analytical and experimental research into the MCS strength during the interaction with backfill soil were conducted taking into account a complex of factors – degree of backfill soil compaction, magnitude of dynamic loading by the rolling stock, influence of the TTS structures and magnitudes of backfill above the pipe. At the design compaction of backfill soil, which is 95 % by the Proctor method, it was found that at MCS overloading by 2.5 times, the pipe metal is at the bound of transition to the plastic state. As a result of this, stresses in the pipe walls reach the value of 235 MPa, which may pose a threat of formation of irreversible vertical deformation of the pipe. This is due to the fact that the lateral walls of the metal pipe have sufficient resistance against the horizontal deformations. However, at compaction of soil backfill below 90 %, testing of the formation of a plastic hinge of a metal pipe is not provided.

Analysis of the MCS strength by the presented procedure makes it possible to assess the MCS efficiency depending on the pipe diameter and on the physical-mechanical characteristics of the backfill soil. In addition, the use of this technique allows us to define at which geometric, strength and velocity parameters of the rolling stock the loss of bearing capacity of metal corrugated structures is possible.

Therefore, the obtained results prove that when designing the MCS, it is necessary to provide the coefficient of compactness of soil backfill of not less than 95 %. The obtained results of bearing capacity of MCS may be used by engineers of Bridge testing stations of Ukrrailway and Ukravtodor and by designing organizations for the purpose of further development of corrugated metal structures.

The defined stressed-strained state of MCS provides the range of formation of regulations on the reliability of railway transport facilities taking into account a set of source factors that affect their bearing capacity.

One of the shortcomings of the conducted studies is the fact that the design model did not consider deformations that had already been initiated in the course of MCS operation. Therefore, in further research, the assessment of bearing capacity of MCS will be made, taking into account existing deformations. These studies require further work in order to form the assessment criteria of reliability and functional safety of the railway transport facilities.

7. Conclusions

1. Deformations of vertical and horizontal diameters of a metal corrugated pipe in the initial period of operation of a metal pipe have a non-attenuated character. And only in the period of compaction of backfill soil to the standard values, residual deformations decrease to zero. The most common types of the pipe destruction are crumbling of metal near bolt joints, corrosion of metal pipes and loss of corrugation stability.

2. During the static experimental tests of pipe, it was found that relative vertical deformation (sagging) in the middle of the pipe is 2.05 mm. The maximum fibre stresses in the upper points of the pipe were 8.95 MPa, which does not exceed permissible stresses.

3. During dynamic experimental testing, it was found: maximum relative vertical deformation of the pipe was reg-

istered at passing of a freight train and rerached 2.74 mm. In this case, residual deformation was 0.21 mm; relative horizontal deformation at passing of a freight train reached 0.77 mm. In this case, residual deformation amounted to 0.038 mm. The maximum fibre stresses caused by the action of dynamic loading at the top of the pipe in specified points reached 10.7 MPa. Using the theoretical calculation method (finite-element method), it was determined that the strength margin of metal corrugated sheets of pipe ranges from 45 % to 34 % depending on the degree of compaction of the backfill soil. For the irreversible plastic deformation to occur, external loading should be exceeded by more than 2.5 times compared with loading at the design state of the track. The results of comparison of theoretical calculations of the MCS stressed state with the experimental data, obtained at the design state of the track, showed sufficient convergence of the results obtained by the two methods. The fiber stresses in the corrugation of the pipe from the steam locomotive 2M62, determined experimentally (at testing), are in the range of 5–10 % of those calculated theoretically. In other words, the design factor is k<1.0, which indicates correctness of the preconditions, accepted in calculations. Therefore, this technique is recommended for practical application to evaluate bearing capacity of MCP of large diameter. Compiling the recommendations on designing and assessment of bearing capacity of MCS requires a large amount of experimental and theoretical work. But relevant regulations will make it possible to make the best design solutions and increase the quality of work. In turn, this will increase the service life of MCS and make their application on railways and motor roads of Ukraine more expedient and promising.

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