

Investigating the temperature field distribution over transport structures' metal corrugated construction surface under temperature influences

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Abstract: The experimental studies results of temperature distribution over metal corrugated sheet structure surface at positive and negative ambient temperatures are presented. It is established that the temperature is distributed unevenly over the sheet surface along its plane. An analytical method for calculating the temperature field from a fragment of a structure metal sheet in the case of setting the temperature at the sheet area boundaries is presented. The calculation of the temperature field distribution on the metal sheet of the structure with the setting of the temperature along the contour of the sheet is performed. As a result, it is established that at the metal sheet boundaries there is a temperature difference, which can cause the occurrence of temperature stresses and deformations.

Keywords: metal corrugated structure; ambient temperature; temperature field; finite difference method

I. INTRODUCTION

Transport structures made of metal corrugated structures (hereinafter MCS) are related to the most progressive and promising types of transport structures that are built on highways and railway tracks [1-2]. They consist of a multi-dimensional closed loop structure assembled from individual corrugated sheets of a given radius and bolted together [3]. However, during operation, MCS structures are damaged by cracking the corrosion-resistant zinc coating, etc. (**Fig. 1**).

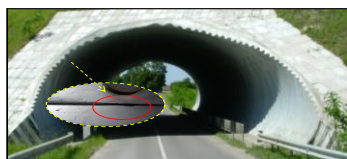


Figure 1. Damage to zinc coating of metal corrugated structure in operation

One of the reasons for this damage is the level of the temperature field at the steel–zinc or steel–zinc–soil borders. The high level of the temperature field,

and therefore of stresses, can be caused by the fact that in the summer the metal structure on the outer part is heated to high temperatures due to the significant thermal fluxes passing through the inner part of the structure. The basis of this calculation is the prediction of the temperature field using mathematical modeling.

In this regard, the problem of studying the temperature field of metal corrugated structures that are under the influence of variable heat fluxes of the environment is relevant. Such studies, along with studying the impact of static and transport loads, are the basis for assessing the load-bearing capacity and reliability of transport structures with MCS when calculating the effect of climatic temperature influences. In work [4] it is indicated that such studies will allow engineers of various organizations at the stage of project work for constructing transport structures with MCS to take into account the influence of temperature changes on the stress-strain state of metal corrugated structures. This will make it possible to make design decisions to reduce this impact on the thermoelastic state of these structures

by selecting materials that can withstand the specified temperature influences under operating conditions.

II. ANALYSIS OF LITERATURE DATA AND PROBLEM STATEMENT

In work [5] it is noted that the general stress state of transport structures depends on both the action of the transport load and the influence of climatic temperature changes in the environment.

To correctly determine the temperature distribution over the structures' surface, a one-dimensional calculation is not enough, it is necessary to use more complex models (two-dimensional or three-dimensional).

However, in practical calculations design engineers take into account simplified calculation methods when studying temperature effects on bridge structures [6, 7] that is insufficient to correctly take into account the temperature distribution over the structures' surfaces.

In works [8, 9], it was established that uneven temperature distribution over the surfaces of transport structures causes the development of structural structures' stresses and deformations. It is recommended that their values should be taken into account at operating transport loads.

In the regulatory document DBN v. 2.3-14 [10], it is indicated that the standard temperature and climatic influences should be taken into account when calculating the limit state of the second group for bridges of all systems. At the design calculation, the operating temperature value should be determined by the maximum temperatures recorded in the area where the structure is in operation.

In the AASHTO standards [11] for different types of bridges, the maximum values of high and low temperatures, which must be taken into account when designing bridge structures, are given. However, the standards [12] recommend taking into account the temperature unevenly in the vertical direction of bridge structures, which most accurately reflects the real influence of ambient temperatures on the stress state of bridge structures.

The standards En -1991-1-5-2009 [12] they require calculating the thermal stress state of bridges under the action of maximum and minimum recorded ambient temperatures.

Studying the temperature distribution in a reinforced concrete superstructure is given in work [13]. And in works [14, 15] it was established that temperature fluctuations cause asphalt subsidence on road bridges.

In work [16], the temperature distribution in the cross-section of elements of superstructures, taking into account the uneven temperature distribution in the vertical direction of the structure, is studied.

When calculating the stresses of transport structures in work [17], it is established that the

temperature distribution in the structures of such bridges should be taken into account while designing structures with taking into account the most heating side of the bridge superstructure.

In work [18], it was found that the temperature difference between the lower and upper surfaces of the bridge box beam can be up to 24 °C

In work [19, 20], it is noted that the distribution of the temperature field along the bridge beams is influenced by weather and climatic conditions. The calculations of temperature gradients showed that the temperature is unevenly distributed along the guide section in the vertical direction of the beam.

It was found in [21] that to describe the general stress state of metal corrugated structures, it is necessary to take into account the effect of climatic temperature differences on metal corrugated 143 structures.

The study of the influence of ambient temperature on the thermal stress state of repaired reinforced concrete pipes with metal corrugated structures was carried out in [22]. It is obtained that at the contact of concrete and metal shells there is a significant jump in temperature stresses, which can lead to premature failure of structures.

The authors studied in [23] the influence of temperature on the dynamic characteristics of the railway ballast. As a result, it was found that the dynamic characteristics of the ballast in the frozen state dramatically change the dynamic characteristics of the track.

In [24-25], the authors conducted a study of the stability of the seamless track, taking into account temperature effects. It is shown that the stability of the track significantly depends on the action of temperature.

In [24], a study of the temperature effect depending on the distribution of moisture on the surface of the material. It is established that moisture has a significant effect on the temperature distribution of the surface.

In [25] the influence of metal oxide on thermal radiation and heat generation of metal structures was carried out.

The surface coating effect of temperature on structures is demonstrated in [26] for the improvement of structures in terms of thermal properties by applying nanoparticles. A study of changes in the structure of wood at elevated temperatures is produced in [27].

In [28], the influence of the thermal cycle of welding on the structure and properties of the metal of the thermal impact zone for steel C460M was studied. The results of the experimental data relate to the values of static strength, ductility and toughness at the level of the parent metal, as well as structural changes in the weld.

A method for investigation of the ballast material deformations, that could be potentially useful for monitoring of metal corrugated construction is

presented in [29]. The paper [30] presents the Concrete Canvas a promising material for application in many civil engineering fields.

From the research projects' analysis, it was established that studying the temperature distribution on the metal sheets surfaces of transport structures were not carried out. Although the structures made of metal corrugated structures are intensively introduced into the practice of the road industry. And in a short service life, they have damage in the form of peeling off the zinc coating, etc. That can cause premature decommissioning of such structures. The novelty of the present paper is the assessment of the temperature field in the metal corrugated construction surface of soil-filled structures.

III. PURPOSE AND OBJECTIVES

The study's objective is to determine the influence of climatic temperature changes on the distribution of the temperature field over the metal corrugated structures' surfaces of transport structures.

To achieve this object, the following tasks were set:

- to conduct experimental measurements of the temperature distribution on the surfaces of a metal corrugated sheet at positive and negative ambient temperatures;
- to improve the model for estimating the temperature distribution over the surface of the structure metal sheet;
- to study the temperature field distribution by a structure metal sheet when setting the measured temperatures along the contour of a metal corrugated sheet.

IV. STUDIES' RESULTS OF THE TEMPERATURE FIELD DISTRIBUTION OVER THE SURFACE OF A STRUCTURE METAL SHEET

1. Experimental measurements of the temperature distribution on the surfaces of structural sheets

To determine the heat fluxes acting on metal structures of structures in operation, the temperature distribution over metal corrugated structures' surfaces of transport structures was measured. Full-scale experimental measurements of the temperature distribution were measured on a transport structure made of metal corrugated structures, which is shown in Fig. 1. Temperature was measured with a pyrometer. The results of the temperature distribution over the surface of a structure metal sheet fragment are shown in Table. 1.

The diagram of coordinates for measuring the temperature distribution of the surface of the construction sheet is shown in Fig. 2.

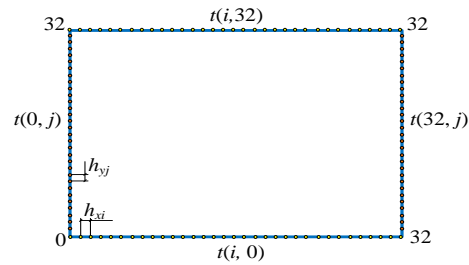


Figure 2. Coordinate diagram of measuring the temperature distribution on the surface of the metal sheet of the structure

From the experimental studies, the maximum positive value of the surface temperature of the structure metal corrugated sheet was recorded at +38.7 °C, and the minimum negative value was –27.5 °C.

It is established that the temperature is distributed unevenly over the surface of the corrugated structure sheet. There is a fluctuation in temperature in the vertical direction. The difference in the distribution of positive temperatures along the vertical of the sheet is 2.3 °C, and the negative values of temperatures –3.7 °C.

The experimental measurements of the surface temperature of the structure metal sheet showed that the temperature changes slightly in the longitudinal direction and over time (over a short period).

2. The mathematical model for estimating the thermal conductivity process of metal corrugated sheets

Let's assume that the cross-section of the structure sheet occupies the area

$$(P) = \{(x, y) : 0 \leq x \leq a, 0 \leq y \leq b\}, \quad (1)$$

where x, y are the coordinates of a rectangular Cartesian system.

In the model let's assume that the temperature field distribution does not depend on time. Then the equation of thermal conductivity in the two-dimensional case will be [20]. The coordinates of the points where the temperature was measured are shown in Fig. 2.

$$\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} = 0 \quad (2)$$

here t – the temperature value is measured at a specific point in the contour of the sheet.

Table 1. The results of experimental measurements of the temperature distribution over the surface of the structure sheet

i	$t_{i,0}, ^\circ\text{C}$		$t_{i,32}, ^\circ\text{C}$		j	$t_{0,j}, ^\circ\text{C}$		$t_{32,j}, ^\circ\text{C}$	
	Positive temperatures	Negative temperatures	Positive temperatures	Negative temperatures		Positive temperatures	Negative temperatures	Positive temperatures	Negative temperatures
0	31.8	-27.8	35.4	-20.5	0	32.7	-27.1	31.7	-27.5
1	32.4	-27.4	36.2	-20.2	1	32.8	-27.4	33.1	-27.2
2	32.8	-26.5	35.2	-20.4	2	32.0	-26.4	34.5	-27.1
3	32.3	-26.3	37.3	-20.5	3	33.2	-26.8	34.5	-26.2
4	31.3	-27.4	38.5	-21.7	4	33.4	-26.8	35.2	-26.0
5	31.5	-27.4	38.0	-20.4	5	33.7	-26.5	35.5	-26.1
6	31.0	-26.5	38.4	-21.5	6	33.7	-24.2	35.4	-26.5
7	32.2	-26.5	35.2	-21.4	7	33.5	-25.5	35.5	-25.4
8	32.1	-26.4	34.2	-21.9	8	34.2	-25.7	35.8	-25.3
9	32.2	-26.4	35.5	-20.5	9	35.8	-25.9	36.5	-25.7
10	32.3	-25.1	36.4	-21.7	10	34.8	-25.4	36.4	-25.1
11	32.5	-26.4	37.2	-21.5	11	34.4	-24.6	36.2	-25.2
12	33.4	-26.4	36.8	-20.2	12	35.8	-24.4	36.5	-25.1
13	33.7	-26.1	38.2	-20.1	13	36.8	-24.5	36.2	-24.1
14	33.7	-26.8	37.4	-20.1	14	35.8	-23.5	36.0	-23.7
15	33.8	-26.4	37.4	-20.2	15	35.8	-23.5	36.7	-23.6
16	33.2	-26.8	37.2	-21.4	16	36.7	-23.7	36.9	-22.5
17	32.5	-27.1	37.4	-20.1	17	36.3	-23.4	37.4	-22.4
18	32.2	-26.2	37.1	-21.1	18	36.4	-23.4	37.8	-22.4
19	32.6	-27.1	37.1	-21.0	19	36.4	-21.4	37.9	-22.8
20	31.2	-26.8	37.7	-21.7	20	36.9	-22.5	38.5	-22.5
21	31.2	-26.1	38.8	-21.8	21	37.9	-21.9	38.1	-22.4
22	31.5	-26.4	38.7	-20.7	22	37.9	-22.3	37.8	-21.2
23	31.6	-26.4	38.4	-20.4	23	37.5	-21.4	38.1	-20.4
24	32.5	-25.4	38.1	-20.2	24	37.2	-21.3	38.0	-21.5
25	32.0	-25.4	38.5	-21.5	25	38.5	-20.7	37.9	-21.9
26	32.0	-25.6	38.4	-21.4	26	37.9	-20.5	38.1	-21.8
27	31.2	-25.4	37.5	-20.7	27	38.4	-20.4	37.2	-20.7
28	31.5	-24.1	37.8	-20.8	28	37.4	-20.1	37.4	-20.4
29	31.5	-24.4	38.5	-20.4	29	38.1	-20.4	37.5	-20.5
30	32.0	-24.7	37.5	-21.2	30	38.4	-20.3	37.2	-19.5
31	32.3	-24.5	36.5	-21.2	31	38.4	-20.4	37.2	-19.3
32	32.4	-24.4	37.4	-21.2	32	38.5	-21.0	38.4	-20.2

Let's find a solution of the differential equation (3.32) that would satisfy the boundary conditions

$$t|_{x=0}=t_1(y), t|_{x=a}=t_2(y), t|_{y=0}=t_3(x), t|_{y=b}=t_4(x). \quad (3)$$

Here $t_1(y)$, $t_2(y)$, $t_3(x)$, $t_4(x)$ are the temperature values at the boundaries of the region (P), which were obtained in the experimental studies (**Table 1**) and measured at a specific time of day.

To solve the boundary problem (2), (3) the method of finite differences are used. To do this, let's apply the uniform grid with steps (P) to the area

$$h_x = \frac{a}{m} \quad (4)$$

$$h_y = \frac{b}{m} \quad (5)$$

$$x_i = \frac{ai}{m} \quad (i = 0, 1, 2, \dots, m), \quad (6)$$

$$y_j = \frac{bj}{m} \quad (j = 0, 1, 2, \dots, m). \quad (7)$$

Function value $t(x, y)$ at the nodal point of the grid ($x_i; y_j$) will be denoted $t_{i,j}$. The other derivatives of the function t will be approximated by finite differences [25]. Let's assume that

$$\left(\frac{\partial^2 t}{\partial x^2}\right)_{i,j} = \frac{t_{i+1,j} - 2t_{i,j} + t_{i-1,j}}{(h_x)^2}, \quad (8)$$

$$\left(\frac{\partial^2 t}{\partial y^2}\right)_{i,j} = \frac{t_{i,j+1} - 2t_{i,j} + t_{i,j-1}}{(h_y)^2}. \quad (9)$$

Taking into account the expressions (8) and (9), for each internal node point $(x_i; y_i)$ the Differential Equation (1) is replaced by the finite difference equation

$$t_{i+1,j} - 2t_{i,j} + t_{i-1,j} + \left(\frac{a}{b}\right)^2 (t_{i,j+1} - 2t_{i,j} + t_{i,j-1}) = 0. \quad (10)$$

At the boundary nodal points, the temperature has the value

$$t_{0,j} = t_1(y_j), \quad t_{m,j} = t_2(y_j), \quad t_{i,0} = t_3(x_i), \quad t_{i,m} = t_4(x_i) \quad (11)$$

Thus, using equation (10), let's determine the temperature distribution over the surface of a structure metal sheet fragment.

3. Results of calculating the temperature field over the surface of a structure metal sheet

Numerical studies of the temperature field are performed based on the of the parameters' values $a=2000$ mm; $b=280$ mm; $m=32$ and temperature values obtained during experimental measurements of the temperature distribution and given in **Table 1**. It should be noted that in our studies we use only the maximum and minimum temperature values obtained in the experiment. It should be noted that the magnitude of stresses that occur at maximum and minimum temperature values is not always the highest. High tension spikes can cause significant temperature differences at adjacent points on the surface of the metal structure.

The results of calculating the temperature field by the finite difference method in the Mathcad 14 software package at positive ambient temperatures are shown in **Fig. 3**, and for negative values – in **Fig. 4**.

From the studies of the temperature distribution over the structure metal sheet surface, it was found that at positive values of sheet temperatures (**Fig. 2**) on the lower surface of the sheet, the temperature varies from $+32.1$ °C to $+33.7$ °C. On the upper edge, the temperature ranges from $+35.5$ °C to $+38.7$ °C.

At negative sheet temperatures (**Fig. 3**) on the lower sheet surface the temperature varies from -27.5 °C to -25.4 °C. On the upper edge, the temperature ranges from -21.2 °C to -20.0 °C.

It is established that in the vertical direction of the sheet, the temperature changes unevenly. In the bottom-up direction, the temperature of the metal sheet changes to values from $+32.1$ °C to $+38.7$ °C at added temperatures, and from -27.5 °C to -20.0 °C at negative temperature values.

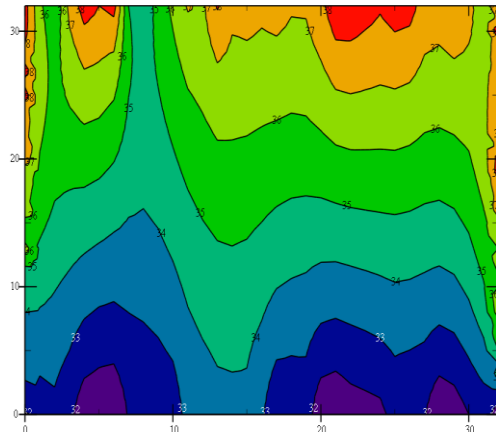


Figure 3. The results of calculating the temperature field by the finite difference method at positive values of metal sheet surface temperatures

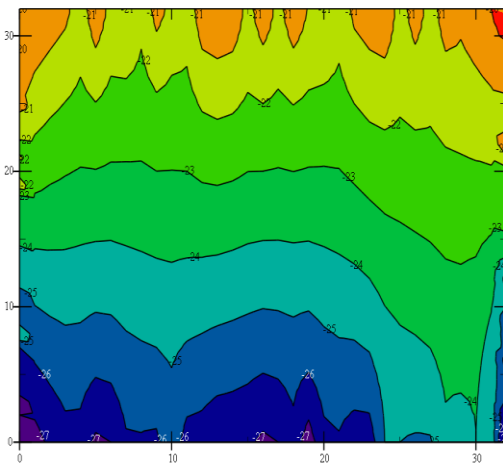


Figure 4. The results of calculating the temperature field by the finite difference method at negative values of metal sheet surface temperatures

It should be noted that the assessment of the temperature field is the first step in solving the temperature problem. In the following research works, studies of the thermostressed state of metal structures will be carried out, taking into account the uneven temperature distribution of the sheet surface.

CONCLUSIONS

1. From the experimental measurements of the temperature distribution over the surface of the metal sheet fragment of a transport structure, it is established that the temperature is distributed unevenly over the surface of the corrugated structure sheet. In addition, the temperature changes slightly in the longitudinal direction and over time (over a short period). The maximum positive temperature value recorded on the surface of the metal corrugated structure sheet was $+38.7$ °C, and the minimum negative value was -27.5 °C.

2. It is established that in the vertical direction of the corrugated metal structure sheet, the temperature changes unevenly. In the bottom-up direction, the temperature of the metal sheet at the added temperatures changes to values from +32.1 °C to +38.7 °C, and from - 27.5 °C to -20.0 °C at negative temperatures.

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