Asphalt concrete pavements of bridges under thermal stress

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Abstract. The goal of our research is to develop an optimal model of asphalt concrete pavements of bridges under thermal stress. The development of the model was stimulated by the demand to assess the effect of temperature stresses on the destruction of asphalt concrete pavement of bridges while keeping spending to the minimum, which led to the need to choose, if possible, the simplest model. The search was carried out according to the criterion of compliance with the results of numerical modeling in an elastic setting.

As a result of the study, we have made the following conclusions:
- maximum tensile stresses occur in the upper layers of asphalt concrete;
- the increase in stresses caused by the uneven distribution of temperature over the thickness of asphalt concrete does not exceed 7% in the elastic setting, and taking into account stress relaxation this can be ignored;
- an increase in the rigidity of the base under the asphalt concrete layer by a factor of 1000 leads to an increase in stresses of not more than 10% in the elastic setting, which gives reason to use the considered model for both metal and reinforced concrete bridges.

Keywords: bridge deck, thermal stress, asphalt concrete pavements, thermal cracking, thermal expansion, asphalt creep.

1 Introduction

Many studies have noted that one of the main types of defects in asphalt pavements laid on a rigid foundation is the formation of cracks. This problem is typical for bridges [1-7] and for roads [8-12]. One of the reasons for the formation of cracks is the temperature stresses caused by changes in the ambient temperature and the difference in the coefficients of thermal expansion of asphalt concrete and the base material, which for bridges is concrete or metal.

Given the frequency and duration of exposure to temperature load, it becomes necessary to take into account the creep deformations of asphalt concrete and the possible accumulation of damage during its loading and unloading, as shown in [13–17]. We have previously developed a creep model of asphalt concrete at different temperatures, using the technical theory of hardening [18].

There are various approaches to solving this problem [19-21]. One of them is to develop a calculation model of the thermally stressed state of a multilayered plate and apply the creep theory described in [18] and one of theories of damage accumulation to this model. In [22], we proposed three calculation models that allow us to estimate the temperature stresses in a multilayer plate, described by the following equations:

- A model using the hypothesis of uniform in height complete deformations, with stresses determined by the following equation (uniform deformation hypothesis):

\[ \sigma_i(y) = E_i \cdot c - E_i \cdot \alpha_i \cdot \Delta T_i(y) \]  

(1)

- A model using the hypothesis of deformations varying linearly through the height of the entire multilayer plate, with stresses determined by the following equation (inclined line hypothesis):

\[ \sigma_i(y) = E_i \cdot (a \cdot x + b) - E_i \cdot \alpha_i \cdot \Delta T_i(y) \]  

(2)
- A model using the hypothesis of deformations varying linearly for each layer (hypothesis of a broken line):

\[
\sigma_{zz}^{(i)}(y) = E_i \cdot \varepsilon_{zz}^{(i)}(z,y) - E_i \cdot \alpha_i \cdot \Delta T_i(y)
\]

(3)

\[
\varepsilon_{zz}^{(i)}(z,y) = \frac{\partial u^{(i)}(y,z)}{\partial z} = U_i(z) \cdot \left( -y + y_{i+1} \right) / h_i + U_{i+1}(z) \cdot \left( y - y_i \right) / h_i
\]

(4)

To choose a calculation model that uses one or another hypothesis, we can compare the maximum temperature stresses predicted by them in asphalt concrete with the results obtained using the finite element method (FEM). We will make a comparison using the ANSYS software package below.

To determine the influence of the temperature factor using Eq. (1), (2), (3) and (4) and modeling in ANSYS, we considered a section of an orthotropic plate with a protective-bonding layer and a layer of asphalt concrete laid on it, in accordance with Figure 1.

The following physical and mechanical parameters of the materials were assumed:
- Asphalt concrete. Elastic modulus: \( E_{ac} = 14.5 \cdot 10^2 \) MPa. Poisson coefficient: \( \mu_{ac} = 0.07 \). Coefficient of thermal expansion: \( \alpha_{ac} = 3.5 \cdot 10^{-5} \) 1/°C.
- Protective-adhesive layer (adopted characteristics of bitumen as one of the main components of the rolled material). Elastic modulus: \( E_{pl} = 50.1 \) MPa. Poisson coefficient: \( \mu_{pl} = 0.07 \). Coefficient of thermal expansion: \( \alpha_{pl} = 2 \cdot 10^{-4} \) 1/°C.
- Metal of the orthotropic plate. Elastic modulus: \( E_{me} = 2.06 \cdot 10^5 \) MPa. Poisson coefficient: \( \mu_{me} = 0.3 \). Coefficient of thermal expansion: \( \alpha_{me} = 1 \cdot 10^{-5} \) 1/°C.

**Figure 1.** Geometric parameters of a section of an orthotropic plate.

2 Materials and methods

In order to determine the influence of these parameters, we have used the 8-node element QUAD 8 NODE modeling in the ANSYS software package. The average size of the side of an element was 0.01 m. We have considered three cases of loading as follows:

1. With a uniform temperature drop in all the nodes equal to -60 °C.
2. The temperature difference between the nodes of the orthotropic plate and the protective-bonding layer is -60 °C, and the difference in the thickness of the asphalt concrete is set according to the parabolic dependence as seen in the diagram in Figure 2.
3. With a uniform temperature drop in all the nodes equal to -60 °C, and the elastic modulus of the material of the orthotropic plate increased by 1000 times.
Additionally, we have varied geometric parameters of the orthotropic plate:

A. Set of parameters: \(a=1.8\) m; \(b=12\) m; \(l_1=0.3\) m; \(t_1=0.3\) m; \(H_1=0.13\) m.

B. Set of parameters: \(a=5\) m; \(b=11\) m; \(l_1=0.4\) m; \(t_1=0.012\) m; \(H_1=0.15\) m.

C. Set of parameters: \(a=5\) m; \(b=20\) m; \(l_1=0.4\) m; \(t_1=0.012\) m; \(H_1=0.15\) m.

Tables 1, 2 and 3 below show the calculation results in ANSYS with the geometric parameters A, B, C, respectively, for the middle of the orthotropic plate. Moreover, the number presented without brackets is corresponding to the case 1, in curly brackets \{\} – to the case 2, in parentheses ( ) – to the case 3.

### Table 1. Stresses for geometric parameters A.

| Point # | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Normal stresses, MPa | 2.1  | 2.1  | 2.1 | 2.13| 2.13| 2.1 | 1.39| 1.39| 1.39|
|         | (2.32)| (2.29)| (2.17)| (2.32)| (2.29)| (2.19)| (1.46)| (1.45)| (1.48)|
|         | {2.15}| {2.15}| {2.15}| {1.62}| {1.62}| {1.59}| {1.41}| {1.41}| {1.41}|  

### Table 2. Stresses for geometric parameters B.

| Point # | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Normal stresses, MPa | 2.24 | 2.24| 2.14| 2.25| 2.25| 2.13| 1.4 | 1.43| 1.44|
|         | (2.32)| (2.29)| (2.17)| (2.32)| (2.29)| (2.19)| (1.46)| (1.45)| (1.48)|
|         | {2.34}| {2.34}| {2.20}| {1.81}| {1.81}| {1.71}| {1.32}| {1.32}| {1.33}|  

### Table 3. Stresses for geometric parameters C.

| Point # | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Normal stresses, MPa | 2.27| 2.26| 2.14| 2.26| 2.26| 2.14| 1.44| 1.44| 1.44|
|         | (2.42)| (2.32)| (2.32)| (2.32)| (1.77)| (1.47)| (2.37)| {2.36}| {2.26}|  

The column numbers in the tables correspond to the points where stresses were assessed (Figure 3).

**Figure 3.** Numbering the points of stress assessment.

Based on the results of the numerical simulation with the FEM, we can make the following conclusions:
1) Since we are interested in maximum stresses, to compare the calculation models with the results of the FEM calculation, we will consider only the maximum predicted stresses. We assume that the maximum stresses along the length of the plate arise in its center.

2) We can see that tensile stresses in case 1 reach a maximum in the upper half of the asphalt concrete layer. As the stiffness of the base increases, the stresses in the upper fiber gradually begin to exceed the stresses in the center of the layer. Therefore, to make it possible to apply the results obtained for a wider class of structures with different base stiffness, we propose to assume that stresses generally reach their maximum in the upper fiber of asphalt concrete.

3) Stresses increase from the edge to the center of the plate, as shown in Figure 4.

4) Stresses in the upper fiber arising from the uneven temperature distribution along the height of the asphalt concrete layer differ from ones in the underlying layers by no more than 7%. Given stress relaxation, this percentage will greatly decrease. For this reason, we will not take into account this factor in the future.

5) An increase in the rigidity of the base by a factor of 1000 leads to an increase in stress in the upper fiber of asphalt concrete by no more than 10%.

![Figure 4. The change in stress along the length of the orthotropic plate.](image)

### 3 Results

Table 4 below shows the differences between the results obtained using the broken line hypothesis and the inclined line hypothesis from the results obtained using the FEM.

Table 5 presents a similar comparison of the inclined line hypothesis with the uniform deformation hypothesis.

**Table 4. Differences between the results obtained using the broken line hypothesis and the inclined line hypothesis.**

| Description                                                      | The difference between the broken line hypothesis and the FEM | The difference between the inclined line hypothesis and the FEM |
|------------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|
| The difference in maximum stresses at various geometric parameters of an orthotropic plate | 8.4%                                                          | 12%                                                          |
| The difference in maximum stresses with an increase in the elastic modulus of a metal of an orthotropic plate by 1000 times | 10%                                                          | 10%                                                          |
| The difference in maximum stresses with an increase in the elastic modulus of asphalt concrete | 1.5%                                                          | 2.5%                                                          |
The difference in maximum stresses with a decrease in the elastic modulus of asphalt concrete by 10 times

| Parameter Description | Difference between the inclined line hypothesis and the FEM | Difference between the inclined line hypothesis and the uniform deformation hypothesis |
|-----------------------|-----------------------------------------------------------|--------------------------------------------------------------------------------------|
| By 10 times           | 4 % has 4 %                                               | 4 %                                                                                   |
| By 0.05 m             | 2 % has 7 %                                               | 2 %                                                                                   |
| By 0.03 m             | 6 % has 6 %                                               | 6 %                                                                                   |

Table 5. Differences between the results obtained using the inclined line hypothesis and the uniform deformation hypothesis.

4 Discussions

Based on the above analysis, we will choose a calculation model based on a comparison of the stresses occurring in the upper fiber of asphalt concrete, i.e., maximum stresses. This is explained by the fact that our next goal will be an attempt to predict the beginning of the fracture process, which occurs exactly in the place where the maximum stresses appear.

We can see from Table 4 that the broken line hypothesis describes the thermally stressed state in the elastic setting better, but by no more than 4 % for the described parameters.

We can see from Table 5 that the hypothesis of uniform deformations better describes the thermally stressed state of asphalt concrete while being much simpler to implement. Therefore, in the future we propose to use it as the main calculation model.

5 Conclusions

Thus, we can conclude that the maximum temperature stresses in asphalt concrete appear at the level of the center of the span and in the upper fiber of the asphalt concrete layer. To assess the onset of the fracture process, we have selected a computational model using the uniform deformations hypothesis by comparing the maximum stresses obtained using this hypothesis and using the FEM. This model makes possible to assume various stiffness of the span plate and change the number of layers and their rigidity characteristics. We need to note that this is true only for temperature stresses, since when bending deformations appear, the picture will change completely, therefore, for such cases it is necessary to develop a separate model. In the future, we can apply the developed asphalt concrete creep model to this calculation model and predict the magnitude of the temperature stresses appearing then. Applying to these stresses the theory of damage accumulation, which, sadly, is still incomplete.
for asphalt concrete, it is possible to predict the appearance of the first cracks caused by the temperature factor specifically. However, the dynamic influence of the wheel will be superimposed on these results, therefore, the developed model is not applicable separately from models that take into account these dynamic effects and, probably, the effects of aging of asphalt concrete.

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