ISSN 2413-6212 (Online), ISSN 2227-1252 (Print)
Bridges and tunnels: theory, research, practice, 2025, № 28

BRIDGES AND TUNNELS: THEORY, RESEARCH, PRACTICE

UDC 624.21.095:625.85-027.45

R. S. LISNEVSKYI

Department of Bridges, Tunnels and Hydraulic structures, National Transport University,
Mykhaila Omelianovycha-Pavlenka St., 1, Ukraine, Kyiv, 01010, tel. +38 (050) 447 70 09,
e-mail 4477009@ukr.net, ORCID 0000-0003-1128-913X

METHODOLOGY FOR CALCULATING PAVEMENT STRENGTH BASED ON THE SHEAR RESISTANCE OF THE ASPHALT CONCRETE SURFACING ON THE ORTHOTROPIC DECK SLAB OF HIGHWAY BRIDGES

Purpose. The purpose of the study is to develop a method for calculating the bond strength of waterproofing between asphalt concrete and an orthotropic slab under shear under the condition of shear resistance on the carriageway of road bridges, in particular bridges over watercourses, overpasses, overpasses, etc. **Methodology.** The methodology encompasses the main methods and approaches for evaluating the shear resistance of asphalt concrete laid on the waterproofing and the orthotropic deck slab, under the action of static, short-term, and dynamic loads that arise during the operation of transport structures. **Findings.** To ensure a uniform distribution of forces among the beams of the bridge superstructure, the stiffness of the carriageway slab is conditionally assumed to satisfy the conditions of strength and deformability according to the limit states. Given this, only the asphalt concrete layers of the pavement are taken into account. The proposed calculation model does not consider the possibility of reaching any limit state, and the calculation is performed under the condition of normal operation of the structure. This calculation approach is aimed at simplifying the engineer's work and reducing labor costs when making design decisions. **Originality**. The scientific novelty of the research lies in the determination of the stress-strain state of the "asphalt concrete – waterproofing – orthotropic deck slab" system. This determination, achieved through numerical modeling using the Finite Element Method (FEM) and/or by utilizing analytical solutions of the theory of elasticity, makes it possible to verify the accuracy of the performed calculations for the maximum permissible shear stresses for local roads/highways. **Practical value.** This calculation methodology is intended for use in the design of highway bridges by specialists from organizations regardless of ownership, and can be applied by design engineers, specialists in technical maintenance and monitoring of transport structures, as well as experts in the field of road construction and infrastructure.

Keywords: pavement; asphalt concrete surfacing; shear resistance; highway bridge; shear stresses; orthotropic deck slab; traffic load

Introduction

One of the main problems that leads to the reduction of the durability of the asphalt concrete pavement on the orthotropic deck of a road bridge is the premature failure of the asphalt concrete. In particular, one of the most common defects that occur in the asphalt concrete pavement and reduce its service life is the appearance of shear rutting/shoves. The insufficient shear resistance of the asphalt concrete pavement on the orthotropic deck of a road bridge to shear rutting/shoves reduces both the structural strength of the asphalt concrete pavement and, critically, the level of traffic safety by creating a hydroplaning effect in areas of water stagnation and winter slipperiness. This also leads to frequent repairs and the formation of traffic jams on bridges, reduces traffic capacity, increases the cost of transportation, and results in significant economic losses. The shear resistance of asphalt concrete is one of the important factors in the quality of the asphalt concrete pavement on the orthotropic deck of road bridges.

The improvement of the shear resistance of the asphalt concrete pavement on the orthotropic deck of a road bridge has, until recently, been mainly achieved through the use of multi- and medium-sized stone asphalt concretes (granulometric types A and B). However, the effect of increasing shear resistance provided by the mineral skeleton of the asphalt concrete proved to be insufficient to solve the problem of the accumulation of unacceptable shear deformations in the asphalt concrete pavement. An alternative solution for increasing the

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shear resistance of asphalt concrete is the modification of bitumen with polymers, which are capable of simultaneously increasing deformability at low temperatures and increasing cohesive strength at high temperatures, thereby contributing to the increase in the asphalt concrete's shear resistance. However, this issue of ensuring the shear resistance of asphalt concrete pavement on the orthotropic deck of road bridges has been insufficiently studied. Furthermore, the shear resistance of the asphalt concrete pavement also significantly depends on the bond strength between the pavement, the waterproofing layer, and the metal orthotropic deck of the road bridge, as well as its stability over time.

Purpose

The purpose is to calculate the pavement structure for strength based on the shear resistance of the asphalt concrete (considering the combined action of the asphalt concrete layers of the pavement structure and the waterproofing layer) on the orthotropic deck of the carriageway of road bridges. These efforts are aimed at increasing the shear resistance and, consequently, its durability by improving the design of the waterproofing. Such design involves the construction and calculation methodology that takes into account the repeated application of static and short-term dynamic loads.

Methodology

During the design and strength calculation for shear bond of the asphalt concrete layers of the pavement structure with the metal base of the orthotropic deck of a road bridge, it is necessary to comply with all requirements and rules of current building codes and standards, as well as the provisions of these methodological guidelines. The asphalt concrete layers of the pavement structure with increased shear resistance on a road bridge consist of one, two, or three asphalt concrete layers, which are bonded to the waterproofing layer and to the metal base of the orthotropic deck of the road bridge. The calculation of the asphalt concrete layers of the pavement structure is performed using permissible shear bond stresses according to clauses 6.3 - 6.6 between the asphalt concrete layers of the pavement structure, the waterproofing layer, and the metal base of the orthotropic deck of the road bridge.

The main objective of the calculation is to determine the thickness of the pavement layers, taking into account the relevant deformation and strength characteristics of the asphalt concrete (Богомолов, Жданюк, Разніцин, Богомолов, & Цинка, 2017). Recommended designs for asphalt concrete pavement layers are in accordance with AD 2.4-37641918-003. The value of the design wheel print diameter is adopted according to ДБН В.2.3-22:2009 (2010). In the case of load duration of 0.1 s, the dynamic value of the wheel print diameter is used for the calculation, and for load duration of 1.0 s and 10.0 s, the static value of the wheel print diameter according to ДБН В.2.3-22:2009 (2010) must be used.

Numerical modeling is necessitated by the fact that the loading scheme is quite complex and requires a spatial solution to the problem in order to improve the design of the asphalt concrete layers of the pavement structure on the orthotropic deck of the transport structure (Onyshchenko, Ostroverkh, Potapenko, Kovalchuk, Zdolnyk, & Pentsak, 2024). The main goal of three-dimensional modeling is to eliminate the shortcomings of studying the force loading and strength characteristics of the asphalt concrete layers of the pavement structure under the load from pneumatic vehicle tires in a two-dimensional formulation (Гуляєв, & Шлюнь, 2023).

This makes it possible to assess more objectively the effectiveness of the interaction between the pneumatic vehicle tires and the pavement. During the calculation based on the condition of the pavement structure's shear resistance on the orthotropic deck, the orthotropic deck does not change its deformation properties under the action of the load (Onyshchenko, Lisnevskyi, Poliak, Rybchynskyi, & Shyshkin, 2023). The adequacy of the selected model is confirmed by numerical modeling and experimental research.

Climatic data – the geographical boundaries of the road-climatic zones of Ukraine and the road zoning of Ukraine according to the working conditions of asphalt concrete (Onyshchenko, Kovalchuk, Husev, et al., 2025). The average monthly, average maximum, and minimum monthly air temperatures are specified (Onyshchenko, Kovalchuk, Voskoboinick, et al. (2024).

The design features (or structural design specifics) of the asphalt concrete layers of the pavement structure on the orthotropic deck of road bridges

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are presented in the methodology MP B.2.3-37641918-946:2024 (2024).

Strength calculation based on the condition of shear resistance of the asphalt concrete pavement on the orthotropic deck of the carriageway of road bridges (Онищенко, Лантух-Лященко, Мішутін, Твардовський, & Здольнік, 2024). The shear bond strength at the contact between the asphalt concrete layers of the pavement structure and the carriageway deck is evaluated by the magnitude of the shear stresses resulting from the action of vertical and horizontal forces at summer temperatures at the boundary of the asphalt concrete layers of the pavement structure and the carriageway deck, according to M 42.1-37641918-767:2017 (2017), M 02071168-708:2012 (2012), and MP B.2.3-37641918-946:2024 (2024). The condition of asphalt concrete shear resistance between the asphalt concrete layers and the waterproofing layer is satisfied in accordance with SOU 45.2-00018112-046. The methodology for assessing the bond between the asphalt concrete layers is intended for checking the quality of the placement of the asphalt concrete layers and the waterproofing. To ensure the specified reliability and the required safety factor of the designed asphalt concrete type based on the shear resistance condition, it must not be lower than the requirements of MP B.2.3-37641918-946:2024 (2024).

The maximum daytime temperature of the asphalt concrete layers of the pavement structure is determined using the dependence:

$$t_{покр}^{\max} = t_{пов}^{\max} + \frac{\rho \cdot I_{ср.доб}}{a_m} K_1 \cdot K_2 \cdot K_n,$$

where: $t_{пов}^{\max}$ is the air temperature on the hottest day, °C; ρ is the absorption coefficient (for asphalt concrete, it is 0.9); $I_{ср.доб}$ is the average daily intensity of solar radiation, kcal/m^2·год·°C; a_m is the heat transfer coefficient (for asphalt concrete, it is 16 kcal/m^2·год·град; K_1 is the coefficient that accounts for the weakening of solar radiation at any hour of the day; K_2 is the transition coefficient from the average daily intensity of solar radiation to the intensity at 12:00 hour; K_n is the dusting (pollution) coefficient (reduction of solar radiation intensity due to dust formation, $K_n = (0{,}7 \ldots 0{,}9)$).

The design temperature between the asphalt concrete layers of the pavement structure and the bridge span structure is determined by the formula:

$$t_{аб}^{h} = t_{пов}^{\max} \exp\left(\left(-h_{аб}\sqrt{\frac{\omega}{2a_{аб}}}\right)\cos\left(\omega T - h_{аб}\sqrt{\frac{\omega}{2a_{аб}}}\right)\right),$$

where: $t_{аб}^{h}$ is the temperature at depth h, °C; $t_{пов}^{\max}$ is the air temperature on the hottest day according to DSTU-N B V.1.1-27, °C; $a_{аб}$ is the thermal diffusivity coefficient of asphalt concrete; $h_{аб}$ is the thickness of the asphalt concrete layers, cm; ω is the angular frequency of temperature oscillation; τ is the time moment from the start of the oscillation period, $\tau = 12h$.

If, according to the calculation, the temperature between the asphalt concrete layers of the pavement structure and the carriageway deck is found to be lower than 40 °C, then a temperature of 40 °C is adopted for the calculation. The elastic modulus of the asphalt concrete and the waterproofing layer is determined according to M 42.1-37641918-767:2017 (2017) and MP B.2.3-37641918-946:2024 (2024), based on the design temperature in the lower part of the pavement structure. The elastic modulus of the pavement structure with several asphalt concrete layers (including the waterproofing) is reduced to a two-layer design model.

The limiting value of shear stresses $\tau_{лаб}$ is determined taking into account the determined temperature ($t_{аб}^{h}$) between the asphalt concrete layers of the pavement structure and the carriageway deck, and the corresponding type of waterproofing:

$$T_{лаб} = A \cdot t_{аб}^{h} + B,$$

where: A, B are the design parameters which are selected depending on the type of waterproofing; $t_{аб}^{h}$ is the design temperature between the asphalt concrete layers of the pavement structure and the carriageway deck.

The frost resistance coefficient of the waterproofing layer is assigned based on the shear bond strength index according to the methodology MP B.2.3-37641918-946:2024 (2024). The coefficient of variation for the shear bond strength index is determined in accordance with the assigned type, using the methodology MR V.2.3-37641918-946. Using the data from the methodology MP B.2.3-37641918-946:2024 (2024), the limiting shear stress $T_{3C}^{0.3}$ is assigned. This stress arises between the asphalt concrete layers of the pavement struc-

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ture and the carriageway deck for local roads (in this case, the horizontal load constitutes 0.3 of the vertical load). The obtained value must be multiplied by the coefficient $k_г$, which accounts for the influence of the waterproofing type on the shear forces. Using the data from the methodology MP B.2.3-37641918-946:2024 (2024), the maximum shear stress $T_{ЗС}^{0.7}$ is assigned. This stress arises between the asphalt concrete layers of the pavement structure and the carriageway deck for state roads (or national roads) (in this case, the horizontal load constitutes 0.7 of the vertical load). The obtained value must be multiplied by the coefficient $k_г$, which accounts for the influence of the waterproofing type on the shear stresses. The vertical loads acting on the asphalt concrete layers are assigned according to DBN V.2.3-4.

Findings

The design value of shear stresses at the contact between the asphalt concrete layers of the pavement structure and the carriageway deck is determined as follows:

$$T_{роз} = T_{лаб} \cdot k_{тр} \left(1 - u_T \cdot t\right)$$

where: $\tau_{лаб}$ is the shear stress that arises between the asphalt concrete layers of the pavement structure, the waterproofing layer, and the carriageway deck, determined experimentally according to the methodology, MPa; $k_{тр}$ is the coefficient that accounts for the influence of water-frost factors on the waterproofing; v_τ is the coefficient of variation of the shear bond strength; t is the coefficient of normalized deviation.

The limiting permissible shear stresses for local roads are determined by the formula:

$$T_{ЗС}^{H} = T_{ЗС}^{0.3} \cdot p \cdot K_б,$$

where: $T_{ЗС}^{0.3}$ is the maximum shear stress that arises between the asphalt concrete layers of the pavement structure and the carriageway deck; P is the design specific pressure from the wheel on the asphalt concrete layers of the pavement structure, which is assigned according to ДБН В.2.3-22:2009 (2010); $K_б$ is the coefficient that accounts for the peculiarities of the stress state of the asphalt concrete layers of the pavement structure under the vehicle wheel (for a wheel with twin tires, $K_б$=0,85; for a wheel with a single tire, $K_б$=1,0).

The limiting permissible value of shear stresses for state roads (or national roads) is determined by the formula:

$$T_{ЗС}^{H} = T_{ЗС}^{0.7} \cdot p \cdot K_б,$$

where: $T_{ЗС}^{0.7}$ is the maximum shear stress that arises between the asphalt concrete layers of the pavement structure and the carriageway deck, MPa.

The shear bond strength at the contact between the asphalt concrete layers of the pavement structure and the carriageway deck is checked for all roads as follows:

$$K_{МЦ}^{T} < \frac{T_{роз}}{T_{ЗС}^{H}},$$

where: $T_{ЗС}^{0.3}$ $K_{МЦ}^{T}$ is the minimum required strength coefficient taking into account the standard safety factor. If this condition is met, the structure is considered to meet the strength requirements under the action of shear stresses. Otherwise, the thickness of the asphalt concrete layers of the pavement structure must be adjusted; $T_{роз}$ is the design value of shear stresses at the contact between the asphalt concrete layers of the pavement structure and the carriageway deck, MPa; $T_{ЗС}^{H}$ is the limiting permissible value of shear stresses, MPa.

In case the shear bond strength condition is not met, it is necessary to replace the material of the asphalt concrete layers of the pavement structure or the waterproofing layer and repeat the calculation following the sequence provided. An example of the strength calculation of the pavement structure based on the shear resistance condition of asphalt concrete on the orthotropic deck of the carriageway of road bridges is provided in the methodology MP B.2.3-37641918-946:2024 (2024).

Originality and practical value

The originality of the study lies in the results obtained during the strength calculation of the shear bond of the waterproofing layer between the asphalt concrete and the orthotropic deck, based on the shear resistance condition of the asphalt concrete pavement on the orthotropic deck of the carriageway of road bridges. This makes it possible to design a pavement structure with increased shear

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resistance and, consequently, durability. The practical value lies in obtaining the results of the pavement structure strength calculation based on the shear resistance condition, which allows for the determination of the bond strength between the orthotropic deck, waterproofing layer, and asphalt concrete pavement on road bridges, and the reasonable selection of pavement structure options with increased shear resistance and a specified reliability.

Conclusions

The article proposes a methodology for the strength calculation of the pavement structure based on the shear resistance condition of the asphalt concrete pavement on the orthotropic deck of the carriageway of road bridges. It also discusses the operational features of asphalt concrete pavement on metal bridge decks, particularly stress concentration and significant horizontal shear deformations. This occurs because the elastic modulus of the asphalt concrete is substantially reduced at high temperatures, while the elastic modulus of the orthotropic deck remains unchanged. Therefore, to ensure a uniform distribution of forces between the bridge span beams, the stiffness of the carriageway deck is conventionally assumed to satisfy the strength and deformability conditions according to the limit states. With this in mind, only the asphalt concrete layers of the pavement structure are taken into account in the calculation. The proposed calculation model does not account for the possibility of reaching any limit state, and the calculation is performed under the condition of normal operation of the structure. This calculation approach is aimed at simplifying the work of the engineer and reducing labor costs when making design decisions. The use of the proposed methodology will allow for the selection of the most shear-resistant pavement material with the appropriate design characteristics at the design stage of the asphalt concrete pavement on the orthotropic deck of the carriageway of road bridges, which will help reduce operational costs during its maintenance.

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Р. С. ЛІСНЕВСЬКИЙ

[*]Кафедра мостів, тунелів та гідротехнічних споруд, Національний транспортний університет,
вул. Михайла Омеляновича-Павленка, 1, Київ, Україна, 01010, тел. +38 (050) 447 70 09,
ел. пошта 4477009@ukr.net, ORCID 0000-0003-1128-913X

МЕТОДИКА РОЗРАХУНКУ ДОРОЖНЬОГО ОДЯГУ НА МІЦНІСТЬ ЗА УМОВОЮ ЗСУВОСТІЙКОСТІ АСФАЛЬТОБЕТОННОГО ПОКРИВУ НА ОРТОТРОПНІЙ ПЛИТІ ПРОЇЗНОЇ ЧАСТИНИ АВТОДОРОЖНІХ МОСТІВ

Мета. Метою дослідження є розробка методики розрахунку на міцність зчеплення гідроізоляції між асфальтобетоном та ортотропною плитою за зсуву за умовою зсувостійкості на проїзній частині автодорожніх мостів, зокрема мостів через водотоки, естакад, шляхопроводів тощо. **Методика**. Охоплює основні методи та підходи для оцінювання зсувостійкості асфальтобетону, укладеного на гідроізоляцію і ортотропну плиту, під дією статичних, короткочасних та динамічних навантаг, які виникають у процесі експлуатування транспортних споруд. **Результати.** Для забезпечення рівномірного розподілення зусиль між балками прогонової будови мосту умовно приймається жорсткість плити проїзної частини, яка забезпечує виконання умов міцності та деформативності за граничними станами. Зважаючи на це, до уваги прийнято лише асфальтобетонні шари дорожнього одягу. В моделі розрахунку, що пропонується, не враховується можливість досягнення будь-якого граничного стану, а розрахунку виконуються за умови нормальної експлуатації споруди. Такий підхід розрахунку направлений на спрощення роботи інженера та зменшення трудовитрат під час прийняття проєктних рішень. **Наукова новизна.** Науковою новизною досліджень є визначення напружено-деформованого стану системи «асфальтобетон – гідроізоляція – ортотропна плита», що дозволяє розрахунок за допомогою числового моделювання з використанням методу скінчених елементів та/або з використанням аналітичних рішень теорії пружності, що дає можливість визначити вірність виконаних розрахунків гранично допустимих зсувних дотичних напружень для доріг місцевого значення. **Практичне значення** Дана методика розрахунку призначена для використання під час проєктування автодорожніх мостів фахівцями організацій незалежно від форм власності та може застосовуватись інженерами-проєктувальниками, фахівцями з технічного обслуговування та моніторингу стану транспортних споруд, а також експертами у сфері дорожнього будування та інфраструктури

Ключові слова: дорожній одяг; асфальтобетонний покрив; зсувостійкість; автодорожній міст; дотичні напруження; ортотропна плита; транспортне навантаження

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Надійшла до редколегії 01.10.2025.
Прийнята до друку 02.12.2025.

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