Fatigue cracking in road pavement

P Mackiewicz
Wroclaw University of Technology, Faculty of Civil Engineering, Wybrzeże Wyspiańskiego 27, 50-370 Wroclaw, Poland
piotr.mackiewicz@pwr.edu.pl

Abstract. The article presents the problem of modelling fatigue phenomena occurring in the road pavement. The example of two selected pavements shows the changes occurring under the influence of the load in different places of the pavement layers. Attention is paid to various values of longitudinal and transverse strains generated at the moment of passing the wheel on the pavement. It was found that the key element in the crack propagation analysis is the method of transferring the load to the pavement by the tire and the strain distribution in the pavement. During the passage of the wheel in the lower layers of the pavement, a complex stress state arises. Then vertical, horizontal and tangent stresses with various values appear. The numerical analyses carried out with the use of finite element methods allowed to assess the strain and stress changes occurring in the process of cracking road pavement. It has been shown that low-thickness pavements are susceptible to fatigue cracks arising "bottom to top", while pavements thicker are susceptible to "top to bottom" cracks. The analysis of the type of stress allowed to determine the cracking mechanism.

1. Introduction
The issue of fatigue and cracking of asphalt concrete (AC) is a broad topic because it involves both material technology and fracture mechanics.

Depending on the thickness of the pavement, its upper layers undergo varying degrees of fatigue and bending [1], [2]. The asphalt base is more prone to fatigue damage than permanent deformations. The binder course is already exposed to permanent deformation, but it can also be subjected to low-temperature damage, while the initiation of fatigue cracks in this layer is likely when there is no adequate interlayer bonding of asphalt layers [3], [4], [5], [6] with base or propagation of the crack occurs in the base. The surface course is exposed to damage from the bottom in the case of loss of adhesion or initiation of propagation from the lower layers. It is also obviously vulnerable to "top to bottom" cracks due to its upper position.

Fig. 1 shows the scheme of cracks formation in asphalt layers. A crack can occur anywhere where a tensile strain is present. Three such areas can be distinguished: in the lower part of the asphalt layers under the load, on the surface on the edges of the load zone and on the surface in the contact area of the tire tread. The key area is also the edge of the tire and the surface in where shear occurs.

"Bottom-up" cracks are termed as classical fatigue cracks. These cracks start easily on the underside of thin asphalt layers and propagate upwards. Their direct cause is the concentration of repetitive tensile stresses at the bottom of the layers and low tensile strength at the bottom of the layers [7]. Another type of cracking occurs on the surface, mainly on the edges of the load zone. Field tests show that the range of cracks "from top to bottom" covers a small area deep into the surface. They usually reach a limited depth of 50-75 mm. This type of cracks was "discovered" only at the end of the
twentieth century [8], [9], [10], [11]. Despite many studies and analyses [12], [13], [14] the problem still raises many discrepancies in their direct cause. It was also found that the aging and hardening of asphalt intensify these cracks. Low-temperature cracks can also be initiated, which will create "convenient" stress centres for their creation and subsequent development.

Figure 1. Scheme of crack formation in asphalt layers.

The problem of fatigue cracks in the pavement is complex. The calculation of deformations in the lower part of asphalt layers does not cause any problems, as they can be calculated unequivocally using multilayer systems. However, the designation of crack initiation sites in the upper part is not unambiguous. It is important to analyse the distribution of forces depending on the type of tire and tread. Therefore, it is not surprising that most researchers using pavement models still focus on deformations in the lower asphalt layers. This article attempts to analyse the problem of fatigue cracks, including "top-down" cracks.

2. Mechanism of formation of a complex deformation state in pavement

When the vehicle wheel passes on the pavement, the distribution of stresses in the ground changes [15], [16]. Then, a complex state of stress and strain arises. There are vertical, horizontal and tangential stresses causing mainly compression and stretching in varying degrees.

In order to accurately describe the impact of the wheel on the pavement, two cases should be analysed in two cross-sections of the pavement. The first cross-section refers to the case when the pavement is observed in the longitudinal direction of movement, in the second section, it is viewed in the transverse direction. When the wheel passes in the longitudinal direction and is in front of or behind the analysed point, i.e. it approaches a given section or passed it (Fig. 2), there are slight compressive phenomena in the lower points of the asphalt layers, while on the surface course, stretching occurs. In the transverse view, the initiation of stress and tensile strain at the bottom of the layers is observed. On the surface, however, an inhomogeneous distribution of stress and strain begins to appear, which depends on the type of tire and tread. At the moment when the wheel is over the point under consideration (Fig. 3), in the longitudinal view in the lower places of the surface layers, the direction of the interaction changes and the stretching appears at the bottom and the compression at the surface. In the cross-section view, the horizontal values of tensile stresses in the lower point of the asphalt layers increase, while stretching in the surface and shearing at the edges of the tire tracks intensify.

Based on the review of many test results and also numerical simulations [17], [18], [19], [20], [21] it was found that there is no agreement among researchers regarding the value of longitudinal deformations in relation to transverse strains. It is obvious that their relative values depend on the speed, axle load, temperature of the asphalt layers, asphalt mix type and thickness of layers. Differences in deformation depending on the type of tires and axles are also indicated. The steered axle causes greater transverse deformation and the remaining axes cause longitudinal deformations slightly exceeding the transverse values [22]. Based on the literature review, it can be concluded that the ratio of longitudinal to transverse strains can vary from 0.5 to 2.0. In practice, there is a mixed nature of initiation and subsequent development of fatigue cracks. Cracks in the lower layers can first
be initiated from deformations observed longitudinally to the direction of movement and will be laid transversely in the lane. On the pavement, single, short cracks are visible. In contrast, cracks "from top to bottom" that also lay transversally, will be initiated by stretching deformations on the surface course.

Figure 2. A typical distribution of deformations in the pavement when the vehicle approaches the analysed area.

Figure 3. A typical distribution of deformations in the pavement when the vehicle is in the analysed area.

Extensive analyses of the normal and tangential stress distributions were carried out by de Beer [23]. He pointed out that in the case of heavy loads (0.9 MPa, 100 kN), the concentration of normal stresses on the edges of the radial tire footprint reaches 2 MPa, which is over twice as high as the tire air pressure. Contact stresses also concentrate on the edges of the tire. On the other hand, stretching strains alternately with squeezing arise under successive ribs. This was confirmed at work [24].

It is found that different types of tires cause different stress distributions. Therefore, the subject of contact stresses between the tire and the road pavement is still being investigated. At present, no effective analytical methods and models have been developed to predict the initiation of cracks caused by the impact of the tire on the pavement. The tire type is not used in design procedures of crack modelling, either.

3. Characteristics of the road pavement model
In the light of phenomena occurring during loading, the pavement model was developed that also allows for multi-axial conditions in the vicinity of contact between the tire and the pavement. For this purpose, the pavement model was developed in the Cartesian three-dimensional system \(xyz\) using the SOLIDWORKS Simulation, COSMOS/M application [25], [26], [27]. The pavement FEM model with basic geometric parameters is presented in Fig. 4.

The choice of the discretization size for SOLID volume elements was selected based on the analysis of the convergence of vertical displacements and deformation values at the characteristic points of the model. On the side surfaces, a fastening enabling only lateral displacement was used, while on the bottom surface a fastening preventing displacement and rotation was applied. In the lower part of the binding layer and on the edge of the load, geometric discontinuities were used in the form of fracturing slots. GAP contact elements were used in the cracks [28], [29], [30], [31]. They allowed to take into account the appropriate behaviour of the crack when it was closing.

A detailed mapping of the contact effect of the tire on the pavement was also carried out. The model adopted the wheel load with the value of 57.5 kN generating the vertical pressure of 0.705 MPa. Preliminary calculations were made for a radial tire often used in heavy goods vehicles, taking into
account the proper pavement and tread effect. The tire trace of 26 cm × 30 cm was adopted, while the length of the tread ribs was: 5 cm, 4 cm, 4 cm, 4 cm and 5 cm with 1 cm distance between them.

![Pavement model](image)

**Figure 4.** Pavement model.

![Load diagram and distributions of normal and tangential stresses](image)

**Figure 5.** Load diagram and distributions of normal and tangential stresses [Pa] for a radial tire.

Based on research [23], [24], [32], [33], [34], [35], the horizontal load value 0.175 MPa was assumed in the transverse direction, while in the longitudinal direction the load was 0.035 MPa, which corresponded to the rolling wheel with the speed of 72 km/h.
Figure 5 shows the load scheme and distributions of normal and tangential stresses that have been obtained for a radial tire. High values of tangential stresses were found. These observations are consistent with the observations of other researchers who carried out field measurements. To describe the characteristics of the asphalt concrete AC layers, elastic material parameters for temperature +10°C were adopted based on the identification for different mixtures in the fatigue four bending test. This topic will be the subject of a separate publication. Two pavements significantly differing in their layer thicknesses were analysed. The characteristics of the materials in the pavement model and the pavement variants are presented in Table 1. The analyses assumed full interlayer bonding.

| Layer                        | Parameters E = [...], ν = [..] | Pavement I Thickness [m] | Pavement II Thickness [m] |
|------------------------------|---------------------------------|--------------------------|---------------------------|
| Surface course AC 11 S 50/70 |                                 | 0.04                     | 0.04                       |
| Binder course AC 16 W 35/50  |                                 | 0.08                     | 0.08                       |
| Base course AC 22 P 35/50    |                                 | –                        | 0.16                       |
| Sub-Base course (aggregate)  | E = 400 MPa, ν = 0.30           | 0.22                     | 0.22                       |
| Subgrade                     | E = 100 MPa, ν = 0.25           | 2.80                     | 2.80                       |

4. Results of numerical calculations

4.1. Effect of load direction
On the basis of calculations for the pavement model, the distribution of deformations in asphalt layers in the longitudinal and transversal direction was analysed during the vehicle wheel passing, assuming a basic load impulse of 0.015 s. Fig. 6 and 7 show an example distribution of tensile strains in the lower part of the asphalt layers of pavement I in the longitudinal (εz) and transversal (εx) directions.

The analysis of the strain distribution in both directions showed that in the transverse direction, there are 11% more deformations in relation to longitudinal strains.

![Figure 6](image6.png)  
**Figure 6.** Distribution of strain in the longitudinal direction in pavement I.

![Figure 7](image7.png)  
**Figure 7.** Distribution of deformations in the transverse direction in pavement I.

There was also found a key concentration of tensile stresses reaching 20×10⁻⁶ for the transverse direction in the tread area of the tire.

Analogous analyses of strain and stress distribution were performed for the thicker pavement of variant II (Figures 8 and 9). In the case of pavement II with the thickness of asphalt layers of 28 cm, there are definitely less deformations and stresses at the bottom of the layers. For the transversal and longitudinal direction, there is a similar deformation with the difference of only 2%. For this pavement in cross-section, a greater concentration of horizontal deformations is observed at the edge of the tire load than for the thinner pavement I. This can have a significant impact on the initiation of cracks "from top to bottom" and is related to the direct influence of the tire tread ribs on the pavement. For the transversal direction, the deformations are 87×10⁻⁶, while in the longitudinal direction only 9×10⁻⁶.
4.2 Influence of cracks

In the following, the analysis of the impact of crack length in the model of cracks propagating "from bottom-up" in the binding layer and "top-down" in the wear layer was carried out. For pavements I and II, the results of tensile stress calculations $\sigma_x$ at the apex of the propagating crack "from bottom to top" is shown in Fig. 10.

For a thicker pavement, there are almost ten times less stresses than for a thinner one. In the case of the thinner pavement, above the crack with the length of 20 mm, a significant increase in stress is observed. A similar analysis was carried out on the crack located on the edge of the wheel track, propagating "from top to bottom". In this case, the value of tensile $\sigma_x$ and shearing $\tau_{xy}$ stresses was analysed at the tip of the crack.

**Figure 10.** Influence of the "bottom-up" crack length on stress values $\sigma_x$.  

**Figure 11.** The influence of the crack length "from top to bottom" on the stresses $\sigma_x$ and $\tau_{xy}$ for the layers in pavement I.  

**Figure 12.** The influence of the crack length "from top to bottom" on the stresses $\sigma_x$ and $\tau_{xy}$ for the in pavement II.
Fig. 11 shows the influence of the crack length on the stress for the pavement I, whereas Fig. 12 for the pavement II. Stresses $\sigma_x$ and $\tau_{xy}$ have similar values in the thinner pavement on the surface course. In a situation, where no crack was yet formed on the surface of the wear layer, tensile stresses $\sigma_x$ of the value $5.0 \times 10^5$ Pa appear. They are crucial in the initiation of this type of cracks. The tensile stresses $\sigma_x$ decrease with the length of the crack. The fact of further propagation can be explained by shear stresses $\tau_{xy}$, which increase to the maximum of $7.5 \times 10^5$ Pa for the 6 mm crack. Then, along with the crack development, these stresses decrease. The thicker pavement is initially dominated by stresses $\sigma_x$ ($1.2 \times 10^6$ Pa), which decreases with the length of the crack only from 15 mm. Stresses $\tau_{xy}$ reach their flat extreme $6.0 \times 10^5$ Pa for the crack with the length of approximately 25 mm. It is worth noting that the stresses reach their maximum value at a relatively short length of the crack from 6 mm to 25 mm and then their fastest propagation is possible. Then they can propagate more slowly to the length from 50 mm to 75 mm. It should be emphasized that the "top-down" crack will propagate mainly through a transverse shear. This is the second case of cracking determined in fracture mechanics, for which the crack surfaces slip in the direction perpendicular to the front of the crack (Fig. 13). For the "bottom-up" crack, shear stress is also present, but it is negligible, and the higher stress $\sigma_x$ determines the vertical direction of the propagation.

Figure 13. Considered cracking methods depending on the load.

Figures 14-17 show example distributions of stresses $\sigma_x$ and $\tau_{xy}$ for pavement I and II with 30 mm lower and 15 mm upper crack. In both variants of pavements, a considerable concentration of stresses is observed at the apexes of the cracks. As previously noted, in the case of the upper cracks, the shear stress prevails in the thinner pavement, while for the pavement thicker with the upper crack, tensile stresses still prevail.

Figure 14. Distribution of stresses $\sigma_x$ [Pa] for pavement I with cracks.

In the top of the bottom crack for a pavement with a thinner bundle of asphalt layers (12 cm), higher stresses $\sigma_x$ were obtained relative to pavement II (28 cm). For the thinner pavement, the shear stresses are also slightly greater at the top of the upper crack. However, it should be noted that for the longer cracks (over 50 mm) the situation is reversed.
Figure 15. Distribution of stresses $\sigma_x$ [Pa] for pavement II with cracks.

Figure 16. Distribution of stresses $\tau_{xy}$ [Pa] for pavement I with cracks.

Figure 17. Distribution of stresses $\tau_{xy}$ [Pa] for pavement II with cracks.

5. Summary
The developed pavement model is suitable for the analysis of both micro- and macro-crack propagation. The examples of the two pavements show the changes occurring under the influence of load in different places of the pavement layers. In the example of the radial tire load for temperature 10°C, it was found that deformations in the transverse direction are 11% more than in the longitudinal one. Taking into account the different length and location of the crack in the pavement allowed to
analyse the critical stresses at the apex of the crack affecting the speed of crack propagation. It was shown that there is a separate way of propagation for cracks coming from "bottom to top" and "from top to bottom", which is associated with shear stresses in the further phase of propagation. In the situation where the crack has not yet been formed, tensile stresses $\sigma_x$ have been identified on the surface of the wear layer. The stresses decrease as the crack length increases. Further propagation is developed by shear stresses $\tau_{xy}$, which increase to the maximum for the 6 mm crack in the thinner pavement. In the thicker pavement, the initial strains $\sigma_x$ also dominate. However, they decrease as the length of the crack increases only from 15 mm. Stresses $\tau_{xy}$ reach their extreme for a crack of about 25 mm. The stress concentration in the apex of the crack is reflected in the cracking mechanism and values of cracking parameters defined as the stress intensity factor and the Rice’s integral. Analysis of these parameters taking into account different temperatures will be the subject of further research.

The model presented here, includes an exact load of the vehicle wheel and geometric discontinuities in the form of cracks. This model is useful for assessing the way of cracking in the pavement, and together with the equations describing the cracking kinetics, over which further research is underway, is suitable for fatigue analysis in a wider range of conditions. Knowledge of the mechanism and size of cracking in thin and thicker asphalt layers allows to determine future methods of repair and reinforcement of the pavement.

References
[1] MCGENNIS R B ANDERSON R M KENNEDY T W SOLAIMANIAN M 1994 Background of Superpave Asphalt Mixture Design and Analysis Publication No.FHWA-SA-95-003
[2] ROBERTS F KANDHAL P BROWN E LEE D KENNEDY T 1996 Hot Mix Asphalt Materials Mixture Design and Construction NAPA Education Foundation Second Edition 603
[3] JASKULA P 2014 Influence of compaction effectiveness on interlayer bonding of asphalt layers The 9th international conference. Environmental Engineering May
[4] KIM H ARRAIGADA M RAAB C PARTL M N 2011 Numerical and experimental analysis for the interlayer behavior of double-layered asphalt pavement specimens Journal of Materials in Civil Engineering 23 (1) pp 12–20
[5] MOHAMMAD L BAE A ELSEIFI M BUTTON J PATEL N 2010 Effects of pavement surface type and sample preparation method on tack coat interface shear strength Transportation Research Record: Journal of the Transportation Research Board 2180 pp 93–101
[6] WANG H AL-QADI I L 2010 Near-surface pavement failure under multiaxial stress state in thick asphalt pavement Transportation Research Record: Journal of the Transportation Research Board 2154 91–99
[7] BROWN S F 1996 Soil mechanics in pavement engineering Geotechnique 46 pp 381–426
[8] GERRITSEN A H VAN GURP C A VAN DER HEIDE J P MOLENAAR A A A PRONK A C 1987 Prediction and Prevention of Surface Cracking in Asphaltic Pavements Proceedings 6th International Conference Structural Design of Asphalt Pavements University of Michigan Ann Arbor Michigan July pp 378–391
[9] MOLENAAR A A A 1983 Structural Performance and Design of Flexible Road Construction and asphalt Concrete Overlays Ph.D. Thesis Delft University of Technology Netherlands
[10] MYERS L A ROQUE R RUTH B E 1998 Mechanisms of Surface-Initiated Longitudinal Wheel Path Cracks in High-Type Bituminous Pavements Proceedings 67 AAPT
[11] NUNN M E 1997 Design of Long-Life Pavements for Heavy Traffic TRL Report 250
[12] SPLAWIŃSKA M ZIELIŃSKI P BURNOS P 2015 Influence of traffic flow variability of heavy vehicles and temperature on pavement fatigue life Roads and Bridges 14 pp 117–132
[13] JUDYCKI J 2011 Budowa i kalibracja modeli spękań zmęczeniowych warstw asfaltowych nawierzchni drogowych w mechanistyczno-empirycznej metodzie AASHTO 2004 Roads and Bridges 4 pp 31–53
[14] GRABOWSKI W POŻARYCKI A 2006 Badania i ocena propagacji spękań zmęczeniowych w modelu nawierzchni asfaltowej Roads and Bridges 1 pp 5–18
[15] CHAN F K W 1990 Permanent deformation resistance of granular layers in pavements *Ph.D. Thesis* University of Nottingham United Kingdom

[16] LEKARP F RICHARDSON I R DAWSON A R 1996 Influences on permanent deformation behavior of unbound granular materials *Transportation Research Record* **1547** Washington DC TRC National Research Council pp 68–75

[17] GOPALAKRISHNAN K THOMPSON R 2006 Effect of Dynamic Aircraft Gear Loads on Asphalt Concrete Strain Responses *Journal of ASTM International* **3** 8

[18] NAGÓRSKI R BŁAŻEJOWSKI K NAGÓRSKA M 2015 Comparative analysis of deflections and strains of two road pavements with high traffic load *Roads and Bridges* **14** pp 31–46

[19] SYBILSKI D BAŃKOWSKI W MULARZUK R 2015 Ocena konstrukcji nawierzchni z BAWMS z zastosowaniem programu komputerowego VEROAD Instytut Badawczy Dróg i Mostów strona internetowa Polskiego Kongresu Drogowego www.pkd.org.pl

[20] BAŃKOWSKI W GAJEWSKI M 2012 Badania przyspieszone w skali rzeczywistej innowacyjnych nawierzchni drogowych *Roads and Bridges* **2** pp 89–121

[21] RUTTMAR I SZYDŁO A 2004 Wykorzystanie symulatora ciężkich pojazdów do weryfikacji konstrukcji nawierzchni płatnej autostrady A-2 Drogownictwo **34** pp 75–78

[22] GILCHRIST M D HARTMAN A M OWENDE P M OWARD S M 2001 Full scale accelerated testing of bituminous road pavement mixtures *Key Engineering Materials* pp 204–205, 443–452 Trans Tech Publications

[23] DE BEER M FISHER C JOOSTE F 1997 Determination of pneumatic tyre/Pavement interface contact Stresses under moving loads and some effects on pavements with thin asphalt surfacing layers *Eighth International Conference on Asphalt Pavements* Seattle Washington

[24] MYERS L A ROQUE R RUTH B DRAKOS C 1999 Measurement of Contact Stresses for Different Truck Tire Types to Evaluate Their Influence on Near-Surface Cracking and Rutting *Transportation Research Record: Journal of the Transportation Research Board* **1655** Washington DC TRC National Research Council pp 175–184

[25] RUSIŃSKI E 1994 Metoda elementów skończonych System COSMOS/M *Wydawnictwa Komunikacji i Łączności* Warszawa

[26] RUSIŃSKI E 2000 Zaawansowana metoda elementów skończonych w konstrukcjach nośnych Oficyna Wydawnicza Politechniki Wrocławskiej Wrocław

[27] MACKIEWICZ P 2016 Fatigue life of asphalt mixtures used in pavements Oficyna Wydawniczca Politechniki Wrocławskiej Wrocław

[28] BRILL D R 2000 Field Verification of a 3D Finite Element Rigid Airport Pavement Model FAA report DOT/FAA/AR-00/33

[29] CARRASCO C LIMOUEE M CELAYA M ABDALLAH I NAZARIAN S 2009 NYSLAB: software for analysis of jointed pavements *Research Report FHWA* RD-07-1008-01

[30] MACKIEWICZ P 2015 Finite-Element Analysis of Stress Concentration around Dowel Bars in Jointed Plain Concrete Pavement *Journal of Transportation Engineering* **141** 6

[31] MACKIEWICZ P 2014 Thermal stress analysis of jointed plane in concrete pavements *Applied Thermal Engineering* **73** 1

[32] BLAB R 1999 Introducing Improved Loading Assumptions into Analytical Pavement Models Based on Measured Contact Stresses of Tires Paper CS5-3 *Proc. Int. Conf. on Accelerated Pavement Testing* Reno Nevada October

[33] CHOUDHURY F RAILINGS R A 1994 A Survey of Truck Tyre Pressures in Tasmania *Road and Transport Research* **3** (3) pp 80–9 Australian Road Res. Board Ltd. South Vermont Vic.

[34] SIDHARTHAN R V SEBAALY P E 1999 Investigation of Asphalt Concrete Layer Strains from Wide-Base Tyres *Transportation Research Record* **1655** Washington DC TRC National Research Council pp 168–174

[35] WOODSIDE A R WOODWARD W D SIEGFRIED H 1999 The Determination of Dynamic Contact Stress Paper No. CS5-2 *Proc. Int. Conf. on Accelerated Pavement Testing* Reno Nevada