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Effect of the tire - pavement contact at the surface layer when the tire is tilted in bend

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ABSTRACT

Tire-pavement interaction is a rolling contact problem that depends on tire and pavement factors, such as vehicle speed and weight, material and type of tire, tire pressure inflation, camber and texture of the surface layer. In this paper, the problem of tire-pavement contact is studied using a realistic description in normal section and bend. The study focuses on the shape of the contact patch and the stress distribution at the tire-pavement interface and the surface shear stresses rather than internal stresses in the structure of the pavement. The numerical approach introduced requires precise tire geometry (estimated by a photogrammetry method) and an equivalent Young's modulus (function of the inflation pressure resulting from the press load tests). Vertical contact stress at the tire-pavement interface predicted by a Semi-Analytical model were compared to experimental measurements with a press system under different loads and angles of inclination. Finally, we discuss the effect of the tire inclination on the calculated shear stresses (origins of damage in turns). The model shows that the increase of the angle of inclination in a turn has a direct influence on the distribution of the tire-pavement contact stresses and the shear stresses. These results will provide indications for the evaluation of the performance of the surface layer with respect to rutting and downward cracking.

Keywords: Surface layer, Tire-pavement contact, Tire inclination, Degradations, Semi Analytical Model

1 Declarations of conflicts of interest: None

3 ABSTRACT

The tire-pavement interaction is a rolling contact problem that depends on both tire and pavement factors, such as vehicle speed and weight, tire material and type, tire pressure inflation, and surface layer camber and texture. This paper studies the tire-pavement contact problem using a realistic description in the normal section and in a bend. The study focuses on the shape of the contact patch, as well as the stress distribution at the tire-pavement interface and the surface shear stresses rather than internal stresses within the pavement structure. The numerical approach introduced herein requires precise tire geometry and an equivalent Young's modulus value. The vertical contact stress at the tire-pavement interface predicted by a semi-analytical model is compared to experimental measurements conducted with a press system under various loads and angles of inclination. Moreover, the effect of tire inclination on the calculated shear stresses is discussed. The model shows that the increase in the angle of inclination in a turn has a direct influence on the distribution of the tire-pavement contact stresses and shear stresses. Through the tensile strain limit criterion ε_6 derived from pavement design method, these results provide indications for evaluating the performance of the surface layer with respect to rutting and downward cracking. Keywords: Surface layer, Tire-pavement contact, Tire inclination, Degradations, Semi-analytical model

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38 Introduction

The road design method assumes that the tire-pavement contact area is circular and contact 39 pressure is evenly distributed. However, several datasets published from measurements and 40 modeling of tire contact pressure show that the components of vertical stresses at the tire-road 41 interface are not uniformly distributed (see [1-4]). In addition, shear stresses in the transverse 42 and longitudinal directions lead to degradations of the surface layer, mainly at specific points 43 where shear stresses are greater than in the normal section. One of the challenges of our 44 research project is to study surface layer damage in the bend, as exemplified by the case 45 where the trajectory changes and shear stresses might alter the prediction of top-down 46 47 cracking, primary rutting and perhaps fatigue damage ([5-7]). Several works have introduced finite element studies on the contact conditions in bends by comparison with experimental 48 validations ([7-9]). It has been found that the maximum vertical contact stress is located under 49 50 the intermediate rib of the tire, instead of the central rib. This stress increases as the camber angle increases. Generally speaking, each rib of the tire behaves differently from the others, 51 especially when the wheel is inclined (in a bend), leading to an asymmetry of the contact 52 53 pressures in the central plane. Gruber et al. [10] explained this distribution by the deflections caused in each rib of the tire in the tread. Yanjin et al. [11] also studied the influence of the 54 angle of banking experienced by a car wheel in a turn on the tire deflection. Both theoretical 55 56 and experimental results have shown that the greater the camber angle, the greater the tire deflection under the same load. Hence, the vertical camber stiffness of a radial tire decreases 57 with increasing camber angle. Zhou et al. [12] discussed the effect of friction on the contact 58 conditions among the various rolling cases, namely tire inclination in a turn combined with 59 the sliding condition. Other authors have demonstrated that the contact stress at the tire edge 60 is greater than the central rib contact stress during tire inclination. Camber also changes the 61 contact length of the tire edge while increasing stress values. Using a finite element 62 calculation, Wang et al. ([11], [13]) and Vayalat [14] found the same result and concluded 63 that the normal stress in the contact zone increases as the camber angle increases and is 64 concentrated at the tire edge. It has also been shown that the non-uniformity of contact 65 66 pressure combined with a differential slip along the width of the tire in a camber state can cause longitudinal resistance and camber alignment torque. Kageyama et al. [15] carried out 67 calculations to evaluate the effect of tire inclination on several parameters, namely contact 68 69 area, contact length and width, stiffness and lateral displacement, as well as the thrust and torque due to the inclination. These calculations were subsequently validated by several tests. 70 Results indicated that tire inclination has both a qualitative and quantitative effect on the 71 various examined parameters, in particular on contact pressure, which increases in intensity 72 and changes shape as the camber angle increases. 73

74 This paper introduces an estimation of the contact pressure during a turn by means of simulation using a semi-analytical calculation (SAM). The position of the tire in inclined 75 turns is subjected to a static vertical force. Next, this model is validated using an experimental 76 method by measuring contact pressures under the same conditions using a pressure sensor 77 (Tekscan). In parallel, the effect of tire inclination on the surface shear stresses is studied, 78 79 primarily the transverse stresses and the longitudinal and transverse strains on the surface. The strain is validated by measurements with an innovative camera technique placed to the 80 right of the inclined tire. Lastly, the maximum tensile strain at the surface is compared to the 81 limit criterion ε_6 drawn from the pavement design method. These results provide indications 82 for evaluating the surface layer performance. 83

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86 1. Semi-analytical modeling of the tire-pavement contact

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1.1. Objectives

Bends are more sensitive to surface shear failure and permanent strains than other common 90 91 tire sections ([16], [17]), due to the magnitude of significant traffic-induced aggression (tangential force, axle load asymmetry). Since traffic loads are applied to the pavement by 92 tires, we have chosen herein to analyze this pressure contact by means of a tribological 93 approach based on a semi-analytical code. The model derived allows for the integration of the 94 tire's actual geometry by both digitizing the tire profile using the photogrammetry method and 95 hypothesizing it as an elastic linear homogeneous body modeled by an equivalent Young's 96 modulus. Semi-analytical modeling simulates the road's surface stresses in a normal section 97 and in a bend. In order to validate these numerical results, a 295 / 80R 22.5 tire with an 98 inflation pressure of 820 kPa was used. In the normal section, the tire was loaded at 32.5 kN; 99 the contact points were measured by a pressure sensor system (Tekscan). During gyrations, 100 lateral load transfer tends to amplify the load on the outer wheel. To take this phenomenon 101 into account, seven camber angle variants (0, 1, 2, 3, 4, 5 and 6 degrees) with the same 45-kN 102 load were chosen. The pressures obtained were then validated with this same Tekscan system. 103

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1.2. Modeling aspects

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The study of pavement tire contact requires information on the size and shape of the contact 106 area since the stresses are generated by their interaction. To solve this problem, the 107 complexity of materials, geometry and tribology must all be considered. For this purpose, 108 several experimental studies have been referenced to analyze the problem despite being 109 limited by the cost and complexity of the test equipment. Numerical models based on the 110 finite element method (FEM) have also been developed. Several works in the tire industry 111 have led to high-precision simulations using 3D finite elements. Most of these calculations 112 require an enormous amount of time (and are not really applicable in the road industry). In 113 addition, these studies are generally limited to quasi-static or stationary stresses ([18]). A 114 semi-analytical method, based on the summation of analytical solutions using digital 115 techniques such as the Fourier Fast Transform (FFT) and the Conjugate Gradient Method 116 117 (CGM), is indeed preferred by researchers. Such techniques were first proposed respectively 118 by Liu ([19]) and Polonsky ([20]). Nélias et al. ([21-24]) developed a semi-analytical code from these techniques for any type of contact geometry, encompassing various material 119 behaviors and loads. Experimental observations focus on the normal contact and derived 120 pressure distribution. Figure 1 shows the tire/road contact under a normal force P. The surface 121 has been discretized with rectangular elements of size $dx \times dy$. 122

By assuming the two materials as linear, isotropic and homogeneous elastic, the normal contact problem can be formulated with the following points:

• Load balancing: the load P applied to the upper body (the tire in the present case) must be equal to the sum of the contact pressures distributed over the contact zone Γ_c .

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$$\iint_{\Gamma_c} p(x, y) dx dy = P \tag{1}$$

• Separation of the bodies: the final separation of the bodies after loading (g(x, y)) is equal to the sum of the initial separation of the bodies $(h_i(x, y))$, the rigid body 130 displacement (δ) and the elastic displacement at the surfaces of the bodies in contact 131 $(u_z(x, y)).$

 $g(x, y) = h_i(x, y) - \delta + u_z(x, y) \tag{2}$

133



134

135Fig. 1: Contact between tire and road under a normal force P, with a close-up of the contact zone Γ_c ,136which shows a surface element of size dx×dy

Let's note that elastic displacements at the surface are identified by using the Boussinesq [25] and Cerutti [26] potentials. Since the target surface has been discretized, Love's approach [27], which finds the potentials on a rectangular patch, can be used. Furthermore, convolutions with Fourier Transform properties are performed to seek the solution over the entire contact area.

142 Ultimately, the contact conditions read as follows:

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$$p(x,y) > 0$$
; $g(x,y) = 0$ in the contact zone (3)

144 145

$$p(x, y) = 0$$
; $g(x, y) > 0$ outside of the contact zone (4)

146 At this point, the contact problem turns into a variational problem, whose solution is the 147 pressure distribution that minimizes complementary energy (see Duvaut and Lions [28] for 148 the variational formulation). Next, the CGM algorithm is applied to solve the contact (see Gallego [24] for the corresponding algorithm). Once the contact has been solved, the pressure 149 distribution at the surface can be applied to find stresses over the entire road by means of 150 convolution with the corresponding potentials. In addition, the geometries of the bodies in 151 contact must be known in order to better approximate the distribution of contact pressures. 152 Thus, in the case of tire-pavement contact, the tire geometry is reproduced according to a 153 photogrammetric technique ([26]). The tire inclination is achieved by rotating the tire around 154 its center line. The mechanical properties of the tire are determined by assimilating the tire to 155 a solid cylinder and using a force-displacement model based on a linear contact, whose 156 parameters are obtained by calibrating the results of forced experimental deviations. The tire 157 is assumed to be incompressible. As explained above, this modeling approach relies on a two-158 layer tire, with considerations for the composite structure and anisotropy due to the significant 159

160 difference in stiffness between the rubber and the tire reinforcement. The tire structure

- 161 considered herein consists of an initial 18-mm layer with a modulus of 12 MPa [7], while the
- thickness of the second layer is 200 mm with an estimated modulus of 3.694 MPa (see Fig. 2).



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Fig. 2: Cross-section of the tire structure, indicating the parameters used in SAM

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167 **2.1. Experimental set-up**

2. Experimental validation

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To assess the accuracy of the model developed, the vertical contact stress predicted at the tirepavement interface was compared to experimental measurements conducted using a pressure sensor system (Tekscan). The operating principle behind Tekscan (Fig. 3) is based on a resistive polymer whose electrical resistance changes as a function of the applied stress.



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174 Fig. 3: Matrix of sensitive elements formed by Tekscan piezoresistive sensors (source: https://www.tekscan.com/)

This technique makes it possible to obtain measurements during both static and dynamic tests. The electronic sheet is incompressible and operates at temperatures of between -40° and 200°C, with a moisture percentage of 5% to 10%. Two polyester sheets were needed to build

the sensor. On the first sheet, piezoresistive materials (sensors) were placed an equal distance

apart. On the second sheet, the same sensors were placed in the same layout, but 179 perpendicular to the first sheet. These rows and columns of sensors intersected to form a 180 matrix of tightly-spaced sensitive elements when the two sheets were joined. The typical 181 accuracy of these sensors is $\pm 5\%$, and the surface area of a sensor equals 25.806 mm² (or a 3-182 mm width separated by 2.08 mm). Thus, in the SAM simulation, a 3-mm mesh pitch in the 183 longitudinal (x) and lateral (y) directions must be chosen. The Tekscan pressure sensor has 184 been calibrated with a load of 45 kN under a Zwick press system. During calibration, the 185 software calculates an average applied pressure based on both the loaded sensor area and 186 applied force value. 187

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2.2. Experimental protocol

In a roundabout, truck speed is generally low (5 to 30 km per hour), hence the load 190 application takes longer than in a busy road section. However, because of its geometry and the 191 effect of the centrifugal force resulting from the turn, the load distribution is unbalanced 192 between wheels of the same axle. This imbalance is due to the drag of the wheel overload 193 outside the turn (by 10% to 20% according to French measurements). Theoretically, it is 194 assumed that during a turn, the tires of a vehicle are inclined at a camber angle with the road 195 surface. This angle causes a difference in shear stress and vertical distribution of stresses in 196 the road structure compared to straight sections or when the tires do not tilt without an 197 inclination angle. To study and verify this hypothesis, several angles of tire inclination were 198 chosen: 0, 2, 4, 5 and 6 degrees. These tests were carried out in a static state. The 199 experimental protocol adopted to describe the contact pressures in bends and normal sections 200 is based on measuring the contact pressure between a heavy vehicle tire (reference 295 / 80R 201 22.5) with an inflation pressure of 820 kPa. The material in contact with the tire was produced 202 on a coated plate with a modulus of 5,400 MPa (20 cm thick). To simulate the tire position on 203 a turn under the press, the principle of the inclinometer (see Fig. 4) has been applied. 204



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Fig. 4: Experimental protocol of an inclined tire under the press

The angles have been arbitrarily selected in order to conservatively cover the theoretical worst-case range for tire tilt angles at roundabouts, with measurements performed during each loading test. In the normal section, the tire was loaded at 32.5 kN and the contact pressures were measured by the Tekscan sensor system. In the roundabout, the lateral load tends to amplify loading on the outer wheel; hence, we proposed for the tire to be loaded with a static charge of 45 kN. The pressures obtained have been validated with the same Tekscanmeasuring system.

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215 **3.** Analysis and discussion

3.1. Vertical contact stress at zero tire inclination

Figure 5 shows the distribution of the contact pressure field for a 32.5-kN normal static load at 0° inclination. A relatively good correspondence is observed between the numerical and experimental results, especially in terms of average maximum pressures. The average maximum measured value is 1,400 kPa and the maximum value calculated equals 1,536 kPa. Moreover, it can be observed that the contact pressure distributions are nearly identical. The contact area calculated with SAM is 42,870 mm² and that measured with Tekscan is 43,974 mm².





Fig. 5: Results for 0° inclinations: (right) Tekscan measurement, (left) SAM simulation

3.2. Vertical contact stress for the tire inclination

Figure 6 shows the results for several degrees of inclination (from 2° to 6°); the applied load 228 of the tires in bends is 45 kN with a tire inflation pressure of 820 kPa. For 2° inclinations, the 229 average maximum stress is 1,591 kPa from measurements and 1,650 kPa output from the 230 231 calculation code. The contact pressure profiles for the two existing inclinations appear to be the same. The contact area calculated with SAM is 52,370 mm² and that measured with 232 Tekscan 53,471 mm². At 4° , a decrease is noticed in the contact area compared to 2° : the 233 contact area calculated with SAM is 51,581 mm² while that measured with Tekscan is 52,748 234 mm². The maximum pressure is always located at the edge of the tire, and the average 235 maximum stress is 1,788 kPa from measurements and 1,850 kPa from the calculation code. At 236 5°, the maximum pressure measured climbs to 2,100 kPa vs. 1,895 kPa calculated using the 237 SAM code. At 6°, a slight increase in contact area compared to 5° can be observed, with the 238 maximum contact pressures once again localized at the edges of the tire. This result enhances 239 the theoretical hypothesis that the turning point can cause greater stress on pavement. It is also 240 observed that the distributions of contact pressures are nearly identical (calculations and 241 measurements). On a normal section, the shape of the contact zone between the pavement tire 242 is rectangular, and the maximum value of the contact stress appears at or close to the center of 243 the contact zone. The contact zone seems to be reduced and the contact surface becomes 244 245 trapezoidal during turns.







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Fig. 6: Contact pressure at several degrees of inclination

249 For the various angles of inclination, these results show that the tire inclination in bends 250 causes a concentration of contact stresses to the right of the road contact zone. This location 251 lies on the inner side of the turn, which means that the right shoulder of the tire is compressed more than the left shoulder when cornering. Results from the SAM model allow for 252 comparison with the measurement values listed in Table 1. The contact area and average 253 maximum stress are indeed quite similar; therefore, the pressure distribution of contacts is not 254 symmetrical with respect to the central plane, and the contact area on the right side becomes 255 larger than that on the left side. Non-uniformity thus has a significant effect on pavement 256 behavior, more precisely in bends where the relatively high vertical contact pressure of the 257 tires could explain the accelerated pavement deterioration in curved road sections, which 258 necessitate more frequent handling maneuvers. 259

	Tekscan measurements		SAM model	
_	Contact area (mm ²)	Average maximum stress (kPa)	Contact area (mm ²)	Average maximum stress (kPa)
0°	43,974	1,400	42,870	1,536
2°	53,471	1,591	52,370	1,650
4°	52,748	1,788	51,581	1,850
5°	51,845	1,859	50,081	2,000
6°	50,064	1,917	48,281	2,090

Table 1: Contact area and average maximum stress vs. inclination

261 Moreover, the evolution in the average maximum vertical contact stress can be analyzed as a function of the variation in the angle of inclination. Figure 7 shows that the average maximum 262 contact pressure increases as the angle of inclination increases; however, as 5° the pressures 263 tend to stabilize. The calculated and measured maximum vertical stresses appear to peak at an 264 inclination angle of 5° . Theoretically, it can be deduced that the maximum resistance of the 265 tire is also reached at 5°. The design of the pavement's vertical resistance must be based on 266 the maximum possible angle of inclination, which generates the most critical stresses (i.e. 5° 267 in the present case). 268



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Fig. 7: Tire inclination angle: maximum vertical stress

3.3. Contact shear stress

This section will present the contact shear distribution in the case of break and rollover or a roundabout with a tire lean in the bend. During braking, a braking torque is applied in the opposite direction to the rolling direction (Fig. 8, left), with the angular velocity ωR becoming lower compared to the translation velocity ϑ ($\omega R < \vartheta$) and the relative rigid body slip turning negative.





Fig. 8: (left) wheel braking by application of torque C, (right) free wheel during turning

A braking force is thus created. In the presence of friction, a surface shear causes the 279 phenomenon of micro-slip on the contact surface. The shear stress field then tends to be in 280 compression behind the contact zone. In turns or roundabouts, truck tires are subjected to 281 lateral loads (Fig. 8, right) due to inertia and, in some cases, longitudinal traction loads during 282 283 acceleration on slopes. An isolated free truck wheel in turning or at a roundabout is considered here. With normal force W = 45 kN, a longitudinal tangential load Q_x = -10 kN 284 $(Q_y = 5 \text{ kN})$ is applied for various angles. When the tire is subjected to a turning load of -10 285 kN and a transverse load of 5 kN at a tire inclination of 2°, a longitudinal shear stress 286 representation shows (Fig. 9) that the slip zone lies at the front of the contact area. In contrast, 287 288 the shear value is negative, which causes compression of the pavement surface while the maximum transverse stresses are located at the outer edge of the tire. For a tire inclination of 289 290 5°, the compressive (longitudinal) stresses in the sliding zone have greatly increased compared to the results at 2°. The transverse stresses have also slightly increased, with a 291 concentration on the outer edge of the tire. The shear stresses for 6° do not change compared 292 to 5° for the normal tire, which confirms the vertical stress evolution curve vs. angle of 293 inclination, where stabilization as of 5° has been observed. Similarly, the shearing zone for 294

transverse stresses did not evolve compared to the calculations at 5°. Results of the semi-295 analytical calculations indicate that the maximum shear stress increases with an increase in 296 the angle of tire inclination from 0° to 5° , which provides further evidence to support the 297 theoretical hypothesis that traffic in a cornering configuration can cause higher shear stresses 298 on the pavement surface. Since one of the causes of rutting is shear strain, pavement sections 299 where traffic turns (e.g. intersections) may therefore be more prone to surface rutting breaks. 300 Figure 9 also shows that at an inclination angle of 5°, the shear stress is maximized. Like for 301 vertical pressures, the design of the HMA shear strength should also be based on the 302 maximum possible tilt angle, responsible for generating the most critical stresses, i.e. again in 303 this case 5°. 304







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Fig 9: (right) transverse surface shear stress, (left) longitudinal surface shear stress (z=0)

3.4. Contact shear strain

310 To identify the critical factors exerting a significant impact on the mechanical behavior of 311 pavement in a bend, the evolution of the principal tensile strain is also analyzed vs. the angle 312 of tire inclination. The shear strain in the case of a break and rollover or roundabout with tire 313 lean during cornering, with the variation in tire tilt angle, is included in this analysis. Results 314 315 of the semi-analytical calculation of the principal strain in the traction rolling surface layer along a normal section (0°) and in bends with tire inclination (2°) are displayed in Figure 10. 316 On a normal section, the most severe principal strain distribution has occurred near the edge 317 of the tire load, with a maximum strain of 200 µstrain, as shown in Figure 10a. 318

However, the distribution of the shear effect zone has shifted to the inner edge of the tire by 319 tilting the tire load with an increasing strain (Fig. 10b) for the 2° tire tilt. The displacement of 320 the zone where the principal strain is reported could indicate that the critical shear failure zone 321 extends over the entire width of the tire contact zone, as a function of the tire inclination, 322 which may partially contribute to surface layer rutting. In the case of a 4° tire inclination (Fig. 323 10b), the principal strains are produced at the inside edge of the tire-road contact, with a 324 maximum strain of 280 µstrain. At 5°, the maximum strains always concentrate on the inner 325 edges of the tire but with an increase in the maximum strain, which rises from 320 µstrain at 326 4° to 360 µstrain at 5° (Fig. 10d). It has been effectively demonstrated that the fatigue cracks 327 from above mainly appeared due to the stresses induced by the tire-pavement contact [2]. 328 329 Major tangential forces can be exerted on the surface layer, resulting in significant tensile and shear stresses, which are responsible for the initiation of surface cracks [30]. 330 331



a) Principal strain at 0°

b) Principal strain at 2°





Fig 10: Principal strains at 0° , 2° , 4° and 5° (z=0)



These conclusions have also been demonstrated by other authors. With a viscoelastic 335 336 modeling assumption and non-uniform contact pressures, Bai et al. [31] proved that the surface layer is more susceptible to failure due to high shear stresses at the surface. Xiaodi et 337 al. [32] used finite element modeling in the framework of an actual tire-pavement contact 338 339 distribution. Results showed that the critical location of cracks due to maximum tensile stresses always appears to be close to the tire edge or in the tire-pavement contact area. 340 Downward cracking is then caused by the traffic load occurring near or inside the wheel 341 tracks in the direction of rolling. 342

The French pavement design method [33] assumes that strain cracking is of the tensile type. This method evaluates the tensile strain ε_t at the bottom of an asphalt concrete (AC) layer in order to predict the load cycle of bottom cracking by means of Equation (5).

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$$\varepsilon_t = \le \varepsilon_{6(10^\circ C, 25Hz)} \cdot \left(\left(\frac{E_{(10^\circ C, 10Hz)}}{E_{(15^\circ C, 10Hz)}} \right)^{0.5} \cdot \left(\frac{N_f}{10^6} \right)^b \cdot k_r \cdot k_c \cdot k_s$$
(5)

348 where:

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$$\varepsilon_{6(10^{\circ}C,25Hz)}$$
: Strain level at failure after one million cycles (10⁶)

350 $E_{(10^{\circ}C, 10Hz)}$: Elastic modulus at 10°C, 10 Hz

- 351 $E_{(15^{\circ}C,10Hz)}$: Elastic modulus at 15°C, 10 Hz
- 352 N_f : Number of equivalent standard axles for bottom cracking
- 353 b: Slope of the fatigue law (in $\log \varepsilon_t \log N_f$)
- k_r : Variability coefficient, i.e. a function of calculation risk and scattering factors
- k_c : Fitting coefficient between numerical design and field observations
- 356 k_s : Coefficient for heterogeneity in soil bearing capacity.
- 357

These parameters are determined by laboratory fatigue tests. The major parameter in this model is ε_6 , which characterizes the lifetime threshold of one million cycles, beyond which

the crack is accelerated depending on the bituminous mixture. The strain level ε_6 (10°C, 25 Hz) at failure after one million cycles on the bituminous mixture (BBSG) used for purposes of

this calculation is about 100 µstrain. According to the above results, the maximum micro-

strain moves towards the outer edge of the tire as the angle of inclination increases, with maximum strains exceeding ε_6 . Once again, this value is more than twice ε_6 by fatigue, with respect to the asphalt life cycle, and more limited top-down cracking starts to appear. The traction is concentrated towards one side of the contact zone, in the direction of the load application. Figure 11 shows the primary traction directions at a tire inclination of 4°.





Fig 11: Principal surface strain directions (z = 0) in the turning section with a 4° inclination

Given this configuration, longitudinal top-down cracking will occur towards the outer sideduring turning or on a roundabout.

372

373 Conclusion

This paper has introduced the modeling and validation for application of a semi-analytical method used to analyze tire-pavement rolling contact in a road's bend sections. Such a code provides the advantage of a more realistic, accurate and faster calculation than current methods, which include the Finite Element Method (FEM). The model developed herein thus makes it possible to obtain the contact pressure while cornering when stresses are assumed to be maximized. Based on the simulation results and experimental validation, the key findings, conclusions and recommendations drawn from this paper are summarized as follows:

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- The contact pressure increases with an increase in the tire angle of inclination from 0° to 5°, although as of 5° pressures tend to stabilize.

- During traction rolling, the tire contact area contains two distinct zones: the stick zone in the front of the contact area, and the slip zone behind the contact area where the pavement surface exhibits different behavior. The shear stresses for an actual tire and a smooth tire increase considerably at a higher bank angle in the turn, but as of 5° they tend to stabilize for the vertical stresses. This finding serves as analytical evidence to support the theoretical hypothesis that traffic turning on roads (e.g. at intersections) can cause greater shear stress in the pavement than by other traffic patterns.
- In the normal section, the principal strain is located at the edge of the tire; moreover,
 when cornering, strain gets concentrated at the inside edge with an increase in the
 angle of inclination. This finding suggests that highway sections with large traffic
 volumes in their turns may be more susceptible to top-down cracking and surfacing
 rutting.

In conclusion, our model will lead to a better understanding of the performance of a pavement at specific points like bends, allowing for an analysis of shear stresses and the principal strain on the surface. These results can be incorporated into the pavement design methods in order to extend the surface layer life cycle. The semi-analytical model introduced in this paper offers a key advantage in terms of computing time and moreover proves to be a more precise tool as regards the contact area when using the actual tire profile.

- Future work is planned to refine these results by modeling a multilayer pavement structure and considering the viscoelastic behavior of bituminous layers (in particular the surface layer). Also, the validation on a traffic simulator, a step that is currently underway, will consolidate all of these results.
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