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

Y. Oubahdou<sup>1</sup>, E-R. Wallace<sup>2</sup>, P. Reynaud<sup>1</sup>, B. Picoux<sup>1</sup>, J. Dopeux<sup>1</sup>, C. Petit<sup>1\*</sup>, D. Nélias<sup>2</sup>,

1. *Université de Limoges, GC2D, EA 3178, F-19300 Egletons, France*

2. *Univ Lyon, INSA-Lyon, CNRS UMR5259, LaMCoS, F-69621, France*

\*christophe.petit@unilim.fr

### 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**

2

3 **ABSTRACT**

4 The tire-pavement interaction is a rolling contact problem that depends on both tire and  
5 pavement factors, such as vehicle speed and weight, tire material and type, tire pressure  
6 inflation, and surface layer camber and texture. This paper studies the tire-pavement contact  
7 problem using a realistic description in the normal section and in a bend. The study focuses on  
8 the shape of the contact patch, as well as the stress distribution at the tire-pavement interface  
9 and the surface shear stresses rather than internal stresses within the pavement structure. The  
10 numerical approach introduced herein requires precise tire geometry and an equivalent  
11 Young's modulus value. The vertical contact stress at the tire-pavement interface predicted by  
12 a semi-analytical model is compared to experimental measurements conducted with a press  
13 system under various loads and angles of inclination. Moreover, the effect of tire inclination  
14 on the calculated shear stresses is discussed. The model shows that the increase in the angle of  
15 inclination in a turn has a direct influence on the distribution of the tire-pavement contact  
16 stresses and shear stresses. Through the tensile strain limit criterion  $\epsilon_6$  derived from pavement  
17 design method, these results provide indications for evaluating the performance of the surface  
18 layer with respect to rutting and downward cracking.

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22 **Keywords:** Surface layer, Tire-pavement contact, Tire inclination, Degradations, Semi-  
23 analytical model

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## 38 Introduction

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

74 This paper introduces an estimation of the contact pressure during a turn by means of  
75 simulation using a semi-analytical calculation (SAM). The position of the tire in inclined  
76 turns is subjected to a static vertical force. Next, this model is validated using an experimental  
77 method by measuring contact pressures under the same conditions using a pressure sensor  
78 (Tekscan). In parallel, the effect of tire inclination on the surface shear stresses is studied,  
79 primarily the transverse stresses and the longitudinal and transverse strains on the surface.  
80 The strain is validated by measurements with an innovative camera technique placed to the  
81 right of the inclined tire. Lastly, the maximum tensile strain at the surface is compared to the  
82 limit criterion  $\epsilon_6$  drawn from the pavement design method. These results provide indications  
83 for evaluating the surface layer performance.

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

### 1.1. Objectives

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

### 1.2. Modeling aspects

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

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  $\Gamma_c$ .

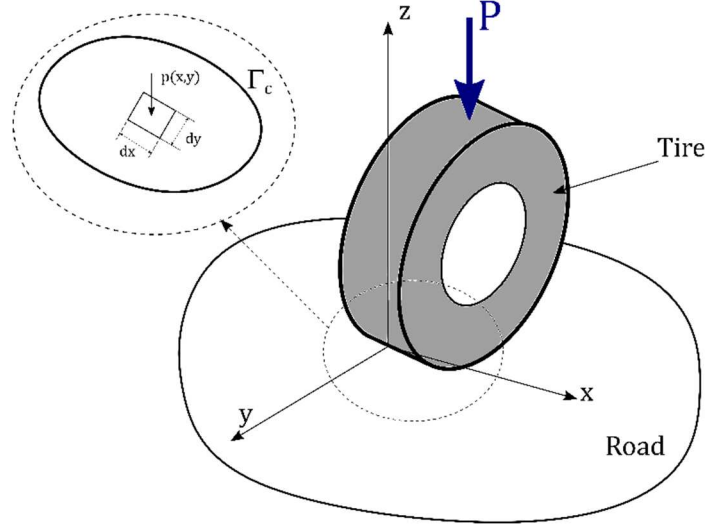
$$\iint_{\Gamma_c} p(x, y) dx dy = P \quad (1)$$

- 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 ( $\delta$ ) and the elastic displacement at the surfaces of the bodies in contact  
 131 ( $u_z(x, y)$ ).

132 
$$g(x, y) = h_i(x, y) - \delta + u_z(x, y) \quad (2)$$

133



134

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

137 Let's note that elastic displacements at the surface are identified by using the Boussinesq [25]  
 138 and Cerutti [26] potentials. Since the target surface has been discretized, Love's approach  
 139 [27], which finds the potentials on a rectangular patch, can be used. Furthermore,  
 140 convolutions with Fourier Transform properties are performed to seek the solution over the  
 141 entire contact area.

142 Ultimately, the contact conditions read as follows:

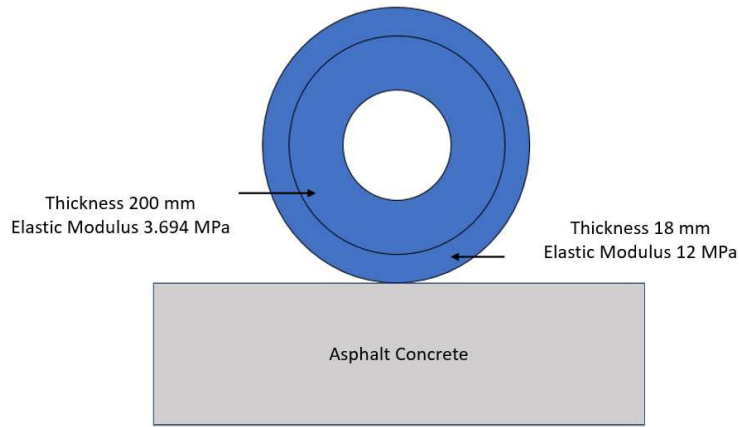
143 
$$p(x, y) > 0 ; g(x, y) = 0 \text{ in the contact zone} \quad (3)$$

144 
$$p(x, y) = 0 ; g(x, y) > 0 \text{ outside of the contact zone} \quad (4)$$

145

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

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  
 162 thickness of the second layer is 200 mm with an estimated modulus of 3.694 MPa (see Fig. 2).

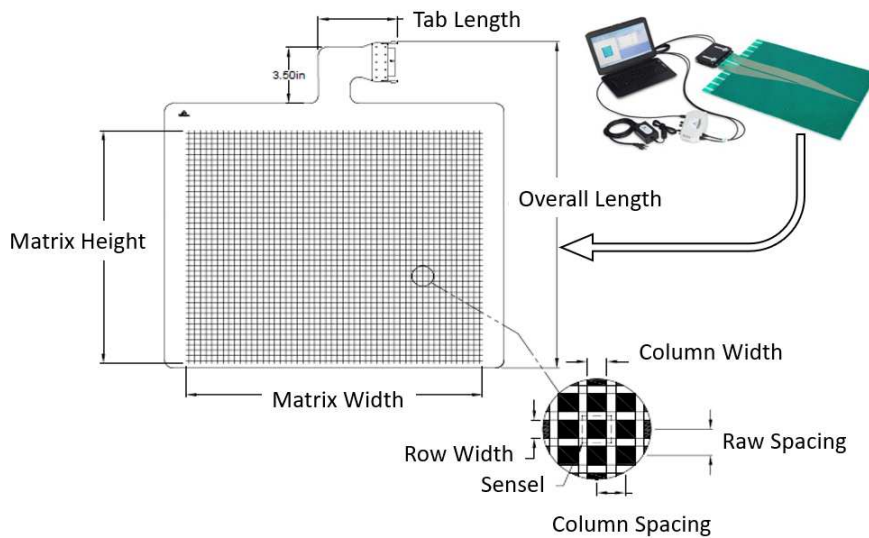


163  
 164 Fig. 2: Cross-section of the tire structure, indicating the parameters used in SAM

165 **2. Experimental validation**

166  
 167 **2.1. Experimental set-up**

168  
 169 To assess the accuracy of the model developed, the vertical contact stress predicted at the tire-  
 170 pavement interface was compared to experimental measurements conducted using a pressure  
 171 sensor system (Tekscan). The operating principle behind Tekscan (Fig. 3) is based on a  
 172 resistive polymer whose electrical resistance changes as a function of the applied stress.



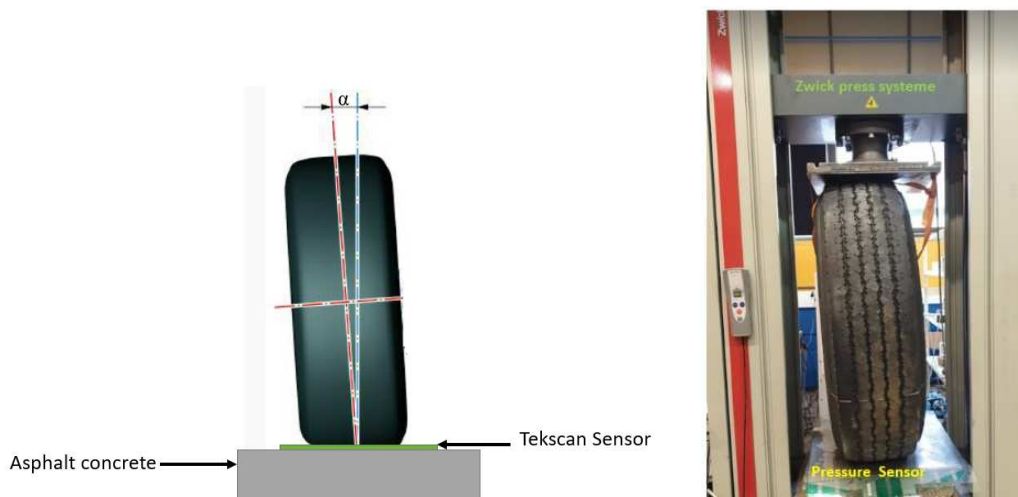
173  
 174 Fig. 3: Matrix of sensitive elements formed by Tekscan piezoresistive sensors (source: <https://www.tekscan.com/>)

175 This technique makes it possible to obtain measurements during both static and dynamic tests.  
 176 The electronic sheet is incompressible and operates at temperatures of between  $-40^{\circ}$  and  
 177  $200^{\circ}\text{C}$ , with a moisture percentage of 5% to 10%. Two polyester sheets were needed to build  
 178 the sensor. On the first sheet, piezoresistive materials (sensors) were placed an equal distance

179 apart. On the second sheet, the same sensors were placed in the same layout, but  
180 perpendicular to the first sheet. These rows and columns of sensors intersected to form a  
181 matrix of tightly-spaced sensitive elements when the two sheets were joined. The typical  
182 accuracy of these sensors is  $\pm 5\%$ , and the surface area of a sensor equals  $25.806 \text{ mm}^2$  (or a 3-  
183 mm width separated by 2.08 mm). Thus, in the SAM simulation, a 3-mm mesh pitch in the  
184 longitudinal (x) and lateral (y) directions must be chosen. The Tekscan pressure sensor has  
185 been calibrated with a load of 45 kN under a Zwick press system. During calibration, the  
186 software calculates an average applied pressure based on both the loaded sensor area and  
187 applied force value.

## 188 2.2. Experimental protocol

189  
190 In a roundabout, truck speed is generally low (5 to 30 km per hour), hence the load  
191 application takes longer than in a busy road section. However, because of its geometry and the  
192 effect of the centrifugal force resulting from the turn, the load distribution is unbalanced  
193 between wheels of the same axle. This imbalance is due to the drag of the wheel overload  
194 outside the turn (by 10% to 20% according to French measurements). Theoretically, it is  
195 assumed that during a turn, the tires of a vehicle are inclined at a camber angle with the road  
196 surface. This angle causes a difference in shear stress and vertical distribution of stresses in  
197 the road structure compared to straight sections or when the tires do not tilt without an  
198 inclination angle. To study and verify this hypothesis, several angles of tire inclination were  
199 chosen: 0, 2, 4, 5 and 6 degrees. These tests were carried out in a static state. The  
200 experimental protocol adopted to describe the contact pressures in bends and normal sections  
201 is based on measuring the contact pressure between a heavy vehicle tire (reference 295 / 80R  
202 22.5) with an inflation pressure of 820 kPa. The material in contact with the tire was produced  
203 on a coated plate with a modulus of 5,400 MPa (20 cm thick). To simulate the tire position on  
204 a turn under the press, the principle of the inclinometer (see Fig. 4) has been applied.



205  
206 Fig. 4: Experimental protocol of an inclined tire under the press

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



212 charge of 45 kN. The pressures obtained have been validated with the same Tekscan  
213 measuring system.

214

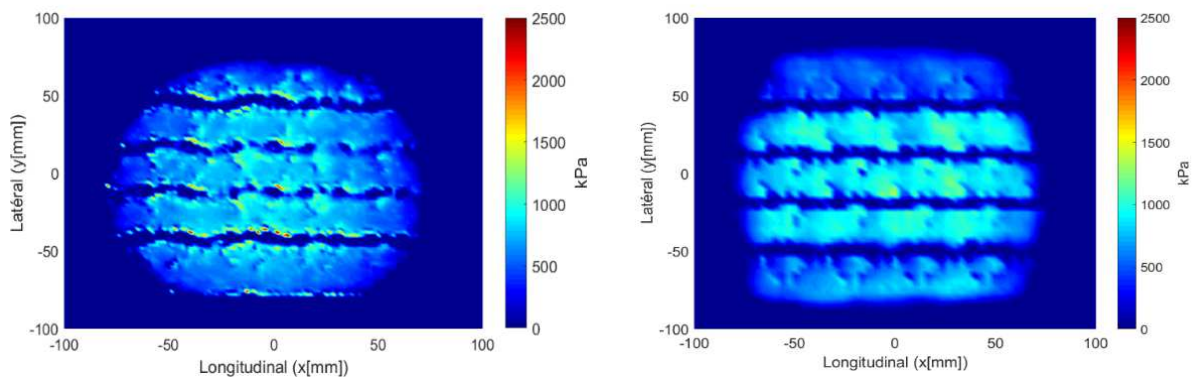
### 215 3. Analysis and discussion

216

#### 217 3.1. Vertical contact stress at zero tire inclination

218

219 Figure 5 shows the distribution of the contact pressure field for a 32.5-kN normal static load  
220 at 0° inclination. A relatively good correspondence is observed between the numerical and  
221 experimental results, especially in terms of average maximum pressures. The average  
222 maximum measured value is 1,400 kPa and the maximum value calculated equals 1,536 kPa.  
223 Moreover, it can be observed that the contact pressure distributions are nearly identical. The  
224 contact area calculated with SAM is 42,870 mm<sup>2</sup> and that measured with Tekscan is 43,974  
225 mm<sup>2</sup>.



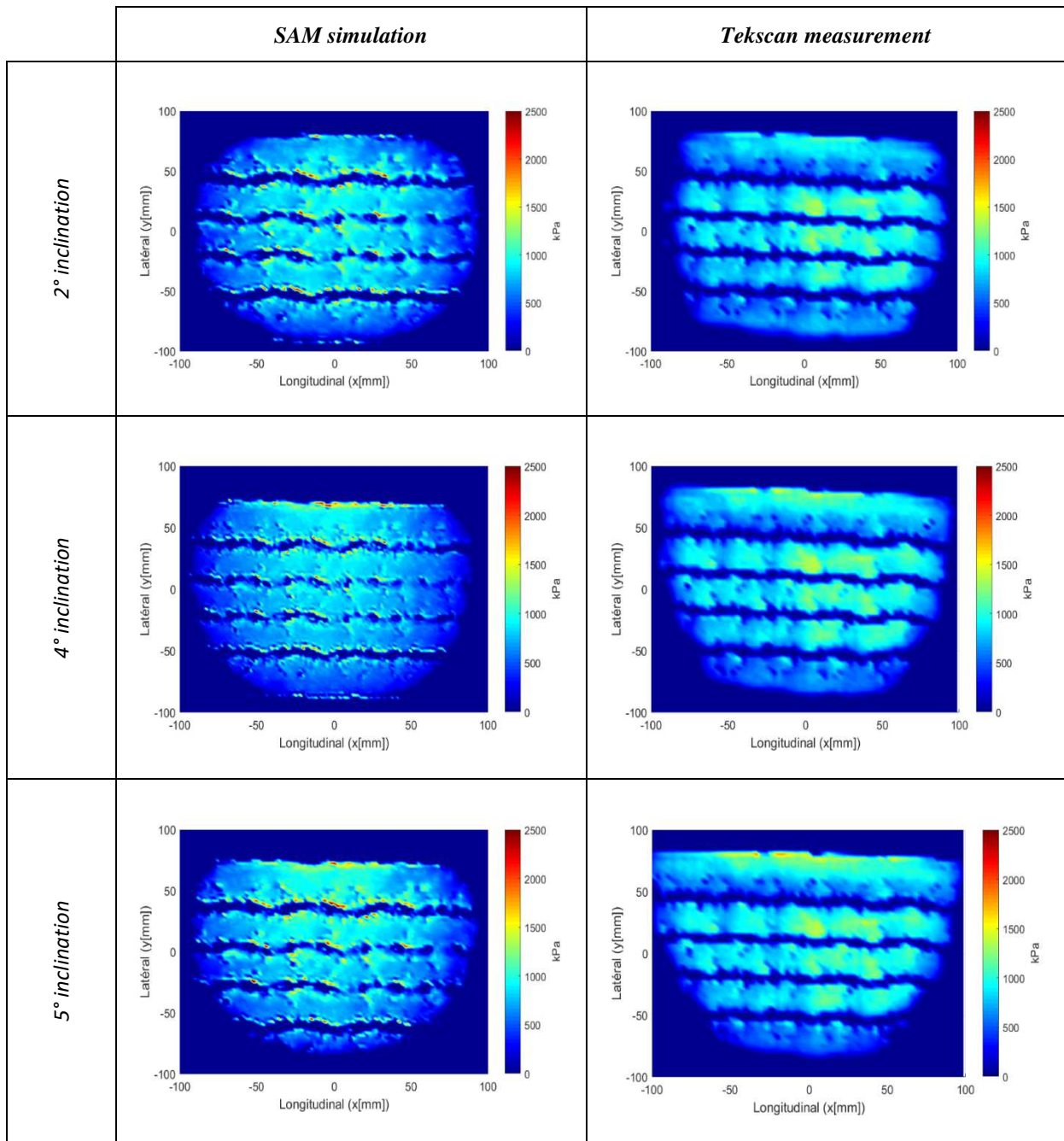
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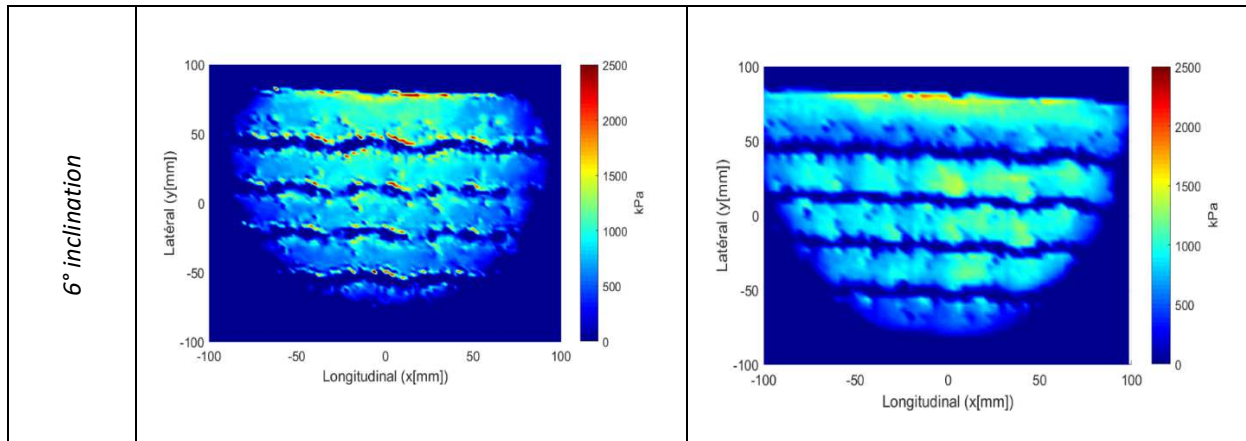
Fig. 5: Results for 0° inclinations: (right) Tekscan measurement, (left) SAM simulation

227

#### 227 3.2. Vertical contact stress for the tire inclination

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





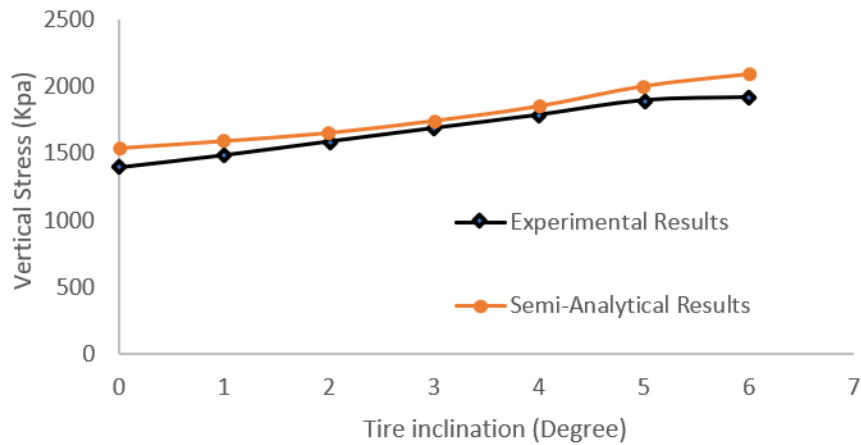
248 Fig. 6: Contact pressure at several degrees of inclination

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

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

	Tekscan measurements		SAM model	
	Contact area (mm <sup>2</sup> )	Average maximum stress (kPa)	Contact area (mm <sup>2</sup> )	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

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

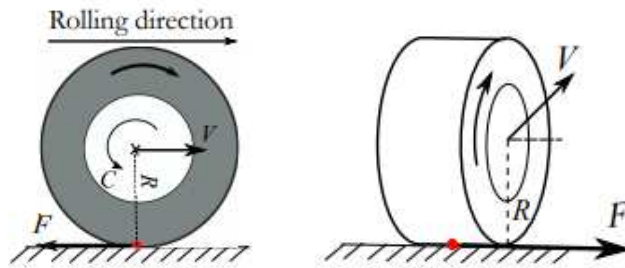


269  
270

Fig. 7: Tire inclination angle: maximum vertical stress

### 271 3.3. Contact shear stress

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



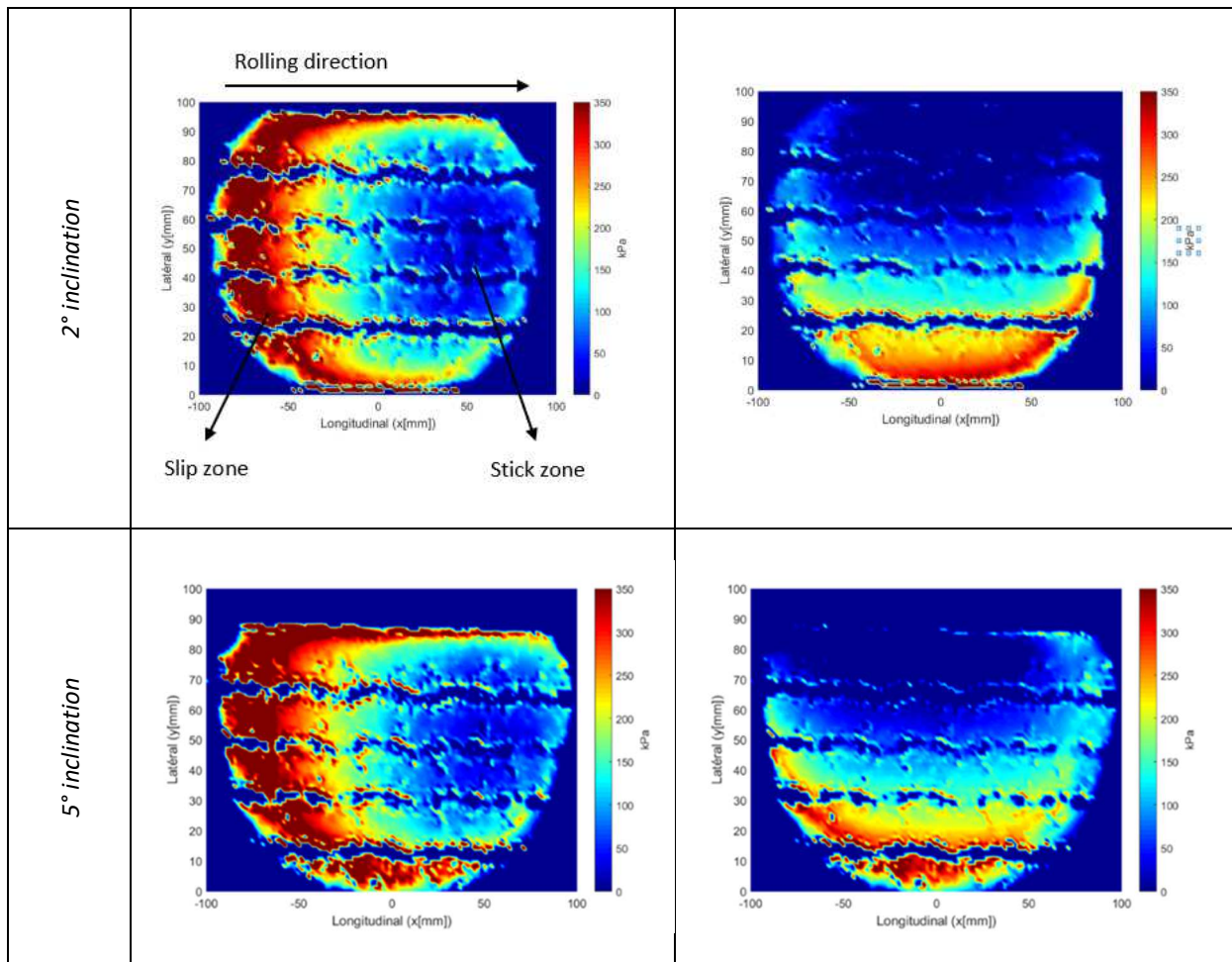
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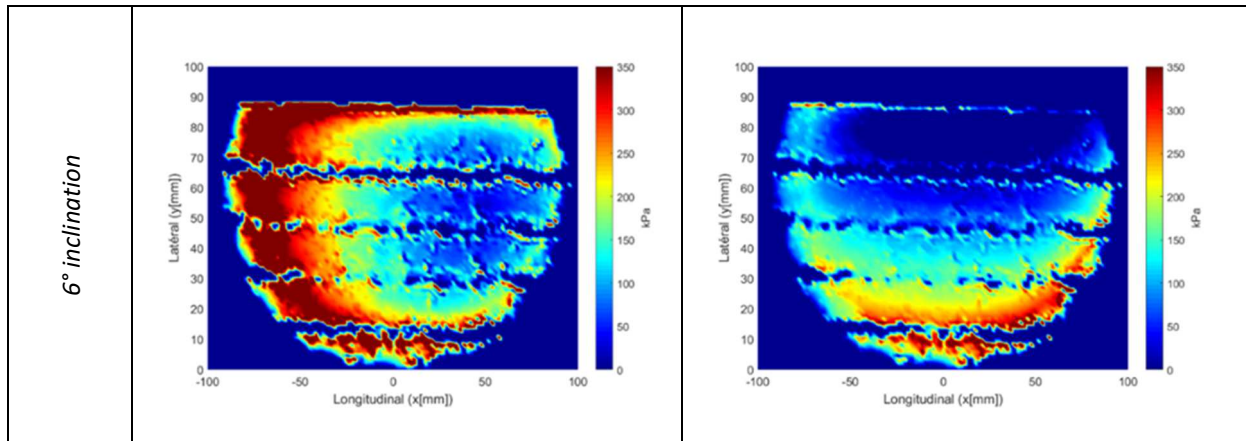
Fig. 8: (left) wheel braking by application of torque C, (right) free wheel during turning

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

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

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306  
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Fig 9: (right) transverse surface shear stress, (left) longitudinal surface shear stress ( $z=0$ )

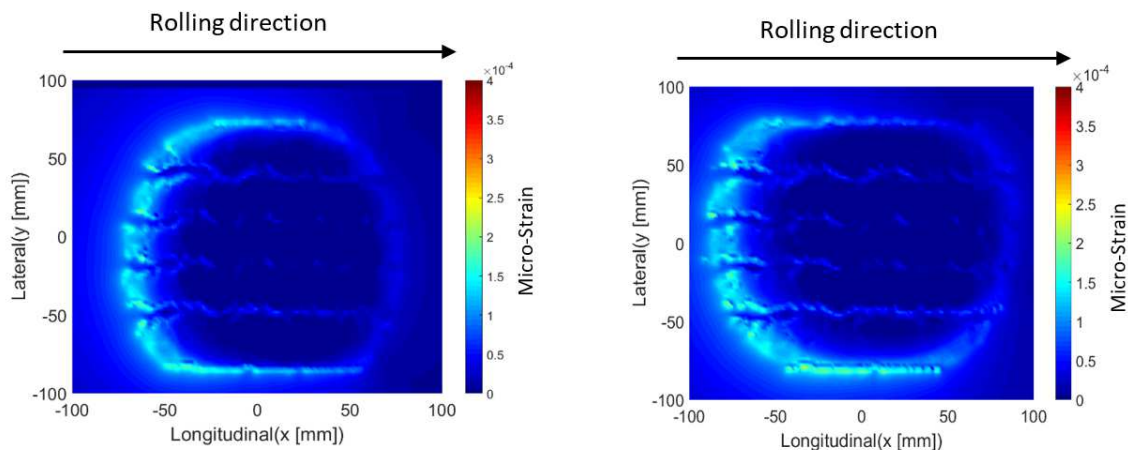
### 3.4. Contact shear strain

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310

To identify the critical factors exerting a significant impact on the mechanical behavior of pavement in a bend, the evolution of the principal tensile strain is also analyzed vs. the angle of tire inclination. The shear strain in the case of a break and rollover or roundabout with tire lean during cornering, with the variation in tire tilt angle, is included in this analysis. Results of the semi-analytical calculation of the principal strain in the traction rolling surface layer along a normal section ( $0^\circ$ ) and in bends with tire inclination ( $2^\circ$ ) are displayed in Figure 10.

On a normal section, the most severe principal strain distribution has occurred near the edge of the tire load, with a maximum strain of  $200 \mu\text{strain}$ , as shown in Figure 10a. However, the distribution of the shear effect zone has shifted to the inner edge of the tire by tilting the tire load with an increasing strain (Fig. 10b) for the  $2^\circ$  tire tilt. The displacement of the zone where the principal strain is reported could indicate that the critical shear failure zone extends over the entire width of the tire contact zone, as a function of the tire inclination, which may partially contribute to surface layer rutting. In the case of a  $4^\circ$  tire inclination (Fig. 10b), the principal strains are produced at the inside edge of the tire-road contact, with a maximum strain of  $280 \mu\text{strain}$ . At  $5^\circ$ , the maximum strains always concentrate on the inner edges of the tire but with an increase in the maximum strain, which rises from  $320 \mu\text{strain}$  at  $4^\circ$  to  $360 \mu\text{strain}$  at  $5^\circ$  (Fig. 10d). It has been effectively demonstrated that the fatigue cracks from above mainly appeared due to the stresses induced by the tire-pavement contact [2]. 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].

331



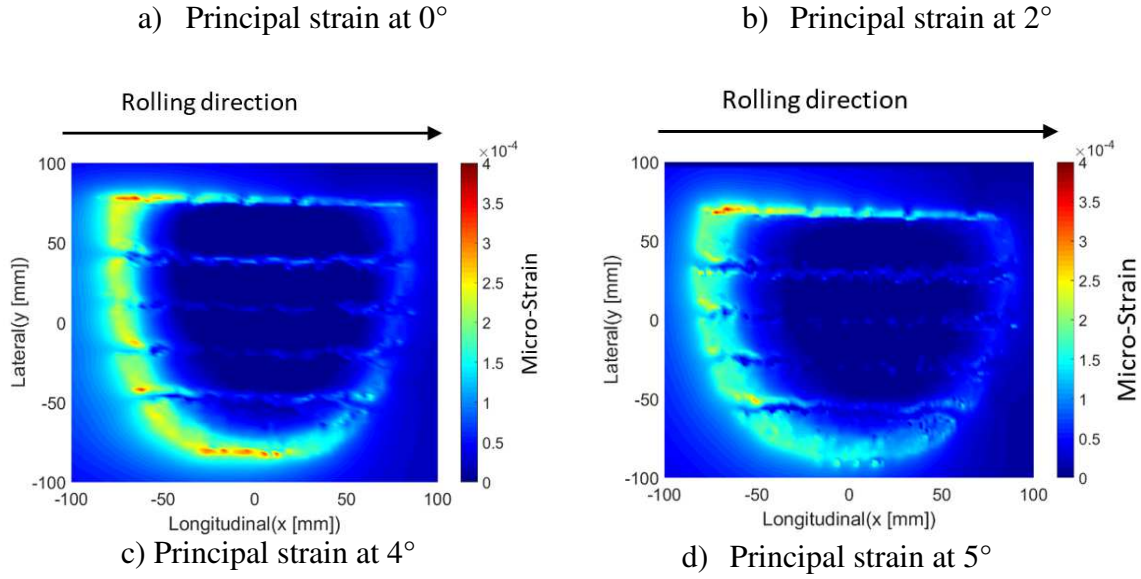


Fig 10: Principal strains at 0°, 2°, 4° and 5° (z=0)

These conclusions have also been demonstrated by other authors. With a viscoelastic 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 al. [32] used finite element modeling in the framework of an actual tire-pavement contact 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. Downward cracking is then caused by the traffic load occurring near or inside the wheel tracks in the direction of rolling.

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

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

where:

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

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

$E_{(15^\circ C, 10 Hz)}$ : Elastic modulus at 15°C, 10 Hz

$N_f$ : Number of equivalent standard axles for bottom cracking

b: Slope of the fatigue law (in  $\log \varepsilon_t - \log N_f$ )

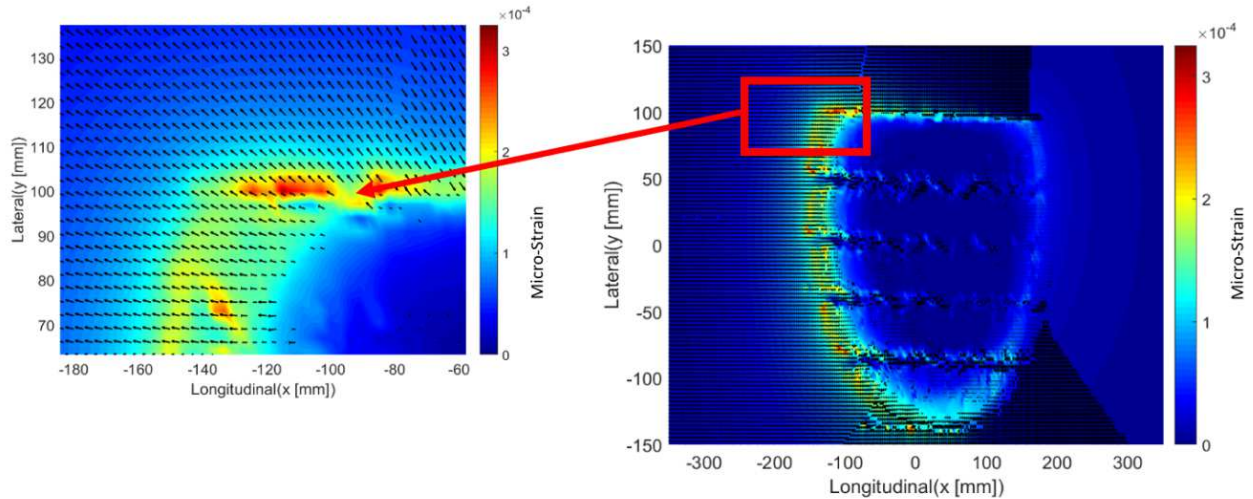
$k_r$ : Variability coefficient, i.e. a function of calculation risk and scattering factors

$k_c$ : Fitting coefficient between numerical design and field observations

$k_s$ : Coefficient for heterogeneity in soil bearing capacity.

These parameters are determined by laboratory fatigue tests. The major parameter in this model is  $\varepsilon_6$ , which characterizes the lifetime threshold of one million cycles, beyond which the crack is accelerated depending on the bituminous mixture. The strain level  $\varepsilon_6$  (10°C, 25 Hz) at failure after one million cycles on the bituminous mixture (BBSG) used for purposes of this calculation is about 100  $\mu$ strain. According to the above results, the maximum micro-

363 strain moves towards the outer edge of the tire as the angle of inclination increases, with  
 364 maximum strains exceeding  $\varepsilon_6$ . Once again, this value is more than twice  $\varepsilon_6$  by fatigue, with  
 365 respect to the asphalt life cycle, and more limited top-down cracking starts to appear. The  
 366 traction is concentrated towards one side of the contact zone, in the direction of the load  
 367 application. Figure 11 shows the primary traction directions at a tire inclination of  $4^\circ$ .



368  
 369 Fig 11: Principal surface strain directions ( $z = 0$ ) in the turning section with a  $4^\circ$  inclination

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

372  
 373 **Conclusion**

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

- 381 - The contact pressure increases with an increase in the tire angle of inclination from  $0^\circ$   
 382 to  $5^\circ$ , although as of  $5^\circ$  pressures tend to stabilize.
- 383  
 384 - During traction rolling, the tire contact area contains two distinct zones: the stick zone  
 385 in the front of the contact area, and the slip zone behind the contact area where the  
 386 pavement surface exhibits different behavior. The shear stresses for an actual tire and  
 387 a smooth tire increase considerably at a higher bank angle in the turn, but as of  $5^\circ$  they  
 388 tend to stabilize for the vertical stresses. This finding serves as analytical evidence to  
 389 support the theoretical hypothesis that traffic turning on roads (e.g. at intersections)  
 390 can cause greater shear stress in the pavement than by other traffic patterns.
- 391  
 392 - In the normal section, the principal strain is located at the edge of the tire; moreover,  
 393 when cornering, strain gets concentrated at the inside edge with an increase in the  
 394 angle of inclination. This finding suggests that highway sections with large traffic  
 395 volumes in their turns may be more susceptible to top-down cracking and surfacing  
 396 rutting.
- 397



398

399 In conclusion, our model will lead to a better understanding of the performance of a pavement  
400 at specific points like bends, allowing for an analysis of shear stresses and the principal strain  
401 on the surface. These results can be incorporated into the pavement design methods in order  
402 to extend the surface layer life cycle. The semi-analytical model introduced in this paper  
403 offers a key advantage in terms of computing time and moreover proves to be a more precise  
404 tool as regards the contact area when using the actual tire profile.  
405 Future work is planned to refine these results by modeling a multilayer pavement structure  
406 and considering the viscoelastic behavior of bituminous layers (in particular the surface  
407 layer). Also, the validation on a traffic simulator, a step that is currently underway, will  
408 consolidate all of these results.

409

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