The effect of loading conditions on pavement responses calculated using a linear-elastic model

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ABSTRACT

In most structural pavement design methods, strains and stresses in the layers are calculated with multi-layer programs based on the Burmister model using the linear elastic theory. Burmister defined loads as a constant pressure applied on a circular surface. New technology for measuring tire-pavement contact stresses has shown that the assumptions used in the multi-layer models do not correspond to reality. This study evaluates the relative influence of different parameters, which diverge considerably from the assumptions made in the multi-layer models.
For a constant vertical load and a constant inflation pressure of a super-single tire, calculations of the strains and stresses in a reference structure were made for various methods of load application. Variations concerned the shape of the load surface, the value of the applied mean vertical pressure, the distribution of the vertical load pressure on the load surface and the application of a transversal load. The evaluation of the strain and stress distributions was made at two critical depths in the structure: at the bottom and at the top of the bituminous layers.
It was seen from this study carried out on a pavement with a total thickness of 170 mm for the bituminous layers, that the main parameter that influences the stress and strain distributions in the structure was the definition of the shape and the extent of the load surface. It was also noticed that transversal loads have non-negligible effects on the strains and stresses, even at the bottom of the bituminous layers.

Keywords:

Traffic loads, tire contact pressure, pavement design methods, inflation pressure, shape of tire imprints

1. INTRODUCTION AND DEFINITION OF THE MODEL

1.1 Goal

Due to the use of the multi-layer model of Burmister, application of traffic loads for design methods consists in using a uniform vertical pressure applied on a circular area. This method of introducing traffic loads requires the definition of three parameters:

- the total load intensity
- the constant vertical pressure
- the radius of the load area

These three parameters are linked together, which means that the definition of two of them automatically leads to the value of the third. Most of the time, the total load and the vertical pressure are defined and the radius for the load area is calculated from them. A common assumption is to admit that the vertical pressure is equal to the inflation pressure of the tire. The development of new technologies for measuring contact stress distribution between the tire and the pavement (De Beer et al. 1997) has shown that the traditional method used for the application of traffic loads does not conform to reality, as:

- tire imprints are not circular
- vertical pressure is not uniform
- mean vertical load pressure is not equal to the inflation pressure
- there are not only vertical stresses between the tire and the pavement, but also transversal and longitudinal ones.

The present study tries to evaluate the influence of these parameters in comparison with the traditional method of introducing load. The reference load used was a super-single tire (Michelin 385/65R22.5 ENERGY XTA TL) with a load of 11,5 tons and an inflation pressure of 8 bars. On a standard road structure and assuming elastic material behaviour, the following topics will be evaluated for strain and stress distributions in the bituminous layers:

the principal differences if the load is applied on a circular or a rectangular surface with a constant pressure

the principal differences when the load is applied with a constant vertical pressure equal to inflation pressure or equal to a constant pressure calculated from measurements of real imprints

the principal differences if vertical load is applied with a uniform or with a non-uniform pressure distribution

an estimation of the stresses and strains due to transversal contact stresses between the tire and the pavement.

The CAPA 3D FEM program (Scarpas 1992-1998) was used to consider the different load application methods.

1.2 Structure and material characteristics

The reference structure was that defined in the Swiss standard (VSS 1997) SN 640 324 Dimensionnement Superstructure des routes. This structure is designed for a soil of category S2 (middle bearing capacity) for the traffic class T4 (heavy traffic) and also corresponds to a structure tested in the ALT facility of the EPFL – LAVOC. As Swiss standards do not provide any specific values for materials used in road construction, elastic properties for the different layers were taken from the French Design Manuel for Pavement Structures (Anon. 1997). The choice of the bituminous materials in the French standard was made to correspond to the materials tested in the ALT facility. Calculations were made for a reference value of 15°C. For the structure, a four layer system was adopted, in which a thin layer was added between the base course and the sub-base to modify the friction conditions if needed(not used to obtain the present results).

The wearing course was a BBSG with the following elastic properties and thickness:

Material	Elastic modulus (MPa)	Poisson’s ratio	Thickness (mm)
BBSG	5’400	0,35	30

Table 1: Elastics properties for the wearing course

The base course was a GB3 with the following elastic properties and thickness:

Material	Elastic modulus (MPa)	Poisson’s ratio	Thickness (mm)
BBSG	9’000	0,35	140

Table 2: Elastics properties for the base course

For the sub-base and the soil, the following values were used, in accordance not only with the French standards but also with plate test results obtained in the ALT facility:

Material	Elastic modulus (MPa)	Poisson’s ratio	Thickness (mm)
Sub-base	270	0,35	400
Soil	90	0,35	1’430

Table 3: Elastics properties for the sub-base and the soil

1.3 Modelling of the structure with the 3D FEM

Due to the symmetry of the study, calculations were carried out for a quarter of the structure. The use of particular boundary conditions on horizontal planes was used to simulate continuity. The total dimension of the model was a cube with a width of 2’000 mm.

1.3.1 Types of finite elements used

Three different kinds of finite elements were used according to the needs of the study.

Cubic elements
These are the common elements used in Capa 3D and are used for all elements except for those modelling infinite dimensions or interfaces.

Infinite elements
These elements allow the modelling of an infinite dimension in one direction. They are used to define infinite dimensions in the horizontal plane.

Interface elements
These elements allow the introduction of a particular interface condition between cubic elements by reducing the rigidity of the interface elements in the transverse direction. They are used to model the friction conditions between the bituminous and the unbound materials.

1.3.2 Mesh

The main areas of interest are concentrated in the bituminous layers and at close proximity to the load application, so the following divisions for the structure were used.

Horizontal division (x and z axes):
The surface for the load application was approximately 150 mm by 150 mm. To obtain satisfactory calculations in and close to this area, a surface of 300 mm by 300 mm was divided into forty surfaces of 15 mm by 15 mm. This mesh also permits the best possible load application. Outwards from this surface, the size of the divisions in both horizontal directions was uniformly increased and infinite elements were then placed.

Vertical division (y axis):
In order to have regular elements in the bituminous layers (identical dimensions in the three directions), the wearing course had two divisions of 15 mm and the base layer five, increasing uniformly from 15 mm to 45 mm. The sub-base had three divisions of 70, 120 and 210 mm and the soil three of 300, 450 and 680 mm.

A representation of the structure with the general mesh is given in Figure 1:

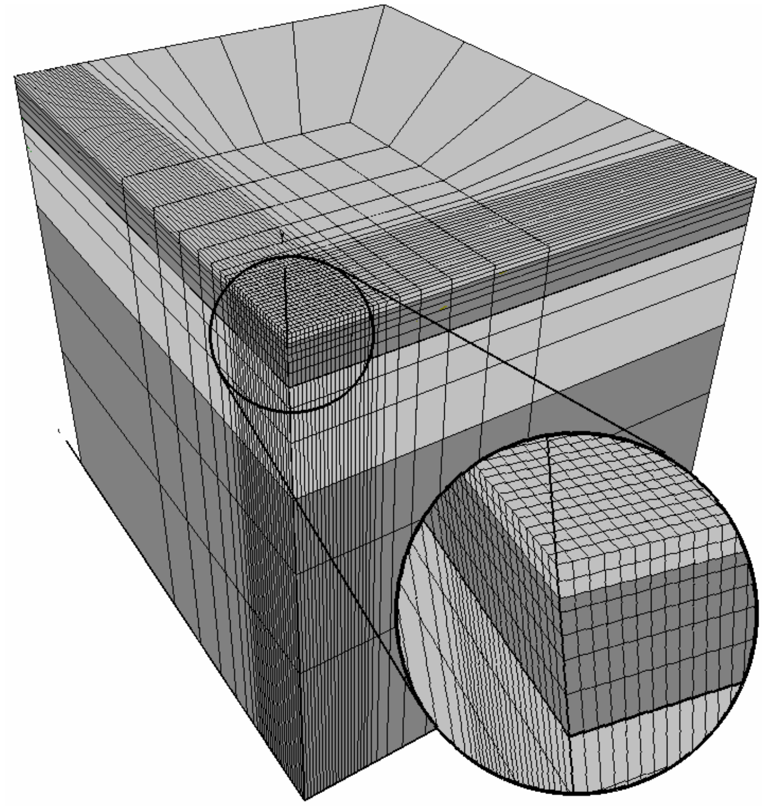

Figure 1: 3D mesh with materials

1.3.3 Boundary conditions

The horizontal plane at the bottom of the structure had a restraint condition of zero vertical displacement. The two vertical planes of symmetry both had restraint conditions of zero horizontal displacement when the two other vertical planes are virtual planes, because infinite elements in these horizontal directions were used.

1.4 Hypotheses for the loading conditions

As the calculations were carried out assuming linear material behaviour, vertical and horizontal loads could be applied separately and the total effect then obtained by addition. The exact dimensions of the load surface depended on the horizontal mesh. The shape of the load surface was obtained from calculations or imprints of the super-single tire. The axle load was 11,5 tons with an inflation pressure of 8 bars. A constant width of 135 mm was assumed for the imprint of the tire on the pavement, corresponding to the super-single tire.

Four different loading conditions in the vertical direction (numbers 5, 8, 9 and 10[1]) and one in the horizontal direction (number 13) were defined.

[1] As more load cases were calculated than the ones presented in this study, the classification of the loading cases doesn't use numbers 1 to 5, but the original ones. For vertical load pressure, even numbers are used for uniform distributions and odd numbers for non-uniform distributions.

Load 8
A uniform contact pressure equal to the inflation pressure was applied on a rectangular surface. The surface obtained was a square 135 mm by 135 mm.

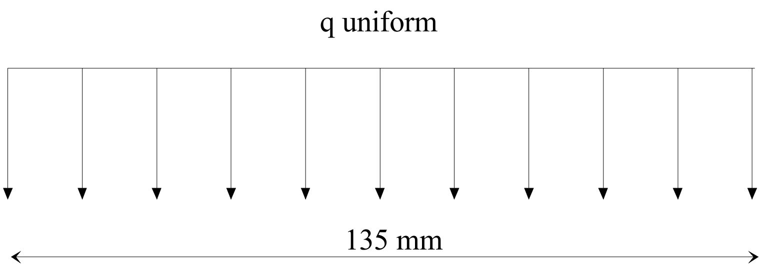

Figure 2: transverse distribution for load 8 and load 10

This profile was constant over 135 mm in the longitudinal direction and the value of q uniform was 8.00 bars.

Load 5
On the same surface as that used in load 8, a differentiation on the pressure applied at the centre and at the edge of the tire was carried out. After Blab (1999), a tire load distribution factor α of 1 between the edge and the centre load was used. This value of 1 means that the total loads applied at the centre are equal to those at the edge of the tire. According to De Beer et al. (1997), Blab (1999), observations and the pattern of the super-single tire, the centre zone represents 60 % of the width of the tire and ends at 82,5 mm where the edge zone starts and then continues up to 135 mm.

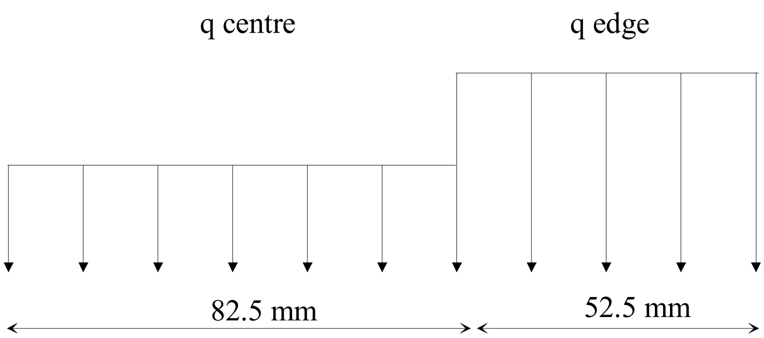

Figure 3: transverse distribution for load 5 and 9

This profile is constant over 135 mm in the longitudinal direction and values of q centre and q edge are 6,55 and 10,30 bars, respectively.

Load 10
In this case, the contact surface was obtained from real imprints and the constant vertical pressure corresponded to the load divided by the surface. The width remained 135 mm, but the length was reduced to 115 mm according to a total measured contact surface of 62'000 mm^2. The profile described in Figure 2 was constant over 115 mm in the longitudinal direction but the value of q uniform was 9,27 bars.

Load 9
On the surface used in load 10, the assumption of load 5 for the distribution of the contact pressure between the centre and the edges (α = 1) was used. The profile

described in Figure 3 is constant over 115 mm in the longitudinal direction but values of q centre and q edge are 7,67 and 12,05 bars, respectively.

Load 13
Horizontal stresses in the transverse direction were introduced with a triangular distribution. They were applied from the edges of the tire to the centre in such a way that the total horizontal forces was zero and so that the maximum value was on the edge of the tire.

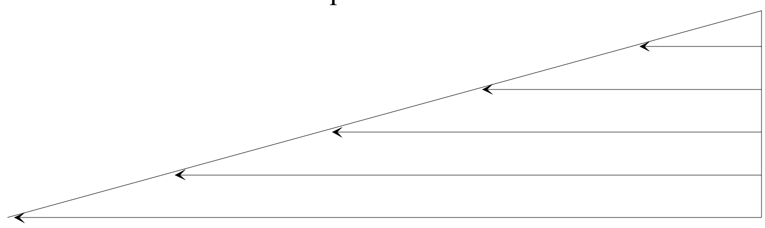

Figure 4: transverse distribution for horizontal load, load 13

This profile was constant over 135 mm in the longitudinal direction and the maximum value for q transversal was 4.00 bars at the edge, corresponding to half of the inflation pressure. This transversal loading is quite high compared to the ratios between vertical and transversal pressure proposed by De Beer et al. (1997).

Load N
To have comparisons with traditional load application methods, a calculation with a multi-layer program, the NOAH software application (see Eckmann 1997), was carried out. In this case, a constant pressure of 8 bars was applied on a circular surface with a radius of 151 mm, corresponding to a total axle load of 11,5 tons.

1.5 Location and type of results

The results were analysed near the load and in the bituminous layers. Comparisons of the results were made component by component for stresses and strains in the Cartesian axes and at two depths:

1. at the bottom of the bituminous layers, which corresponds to the traditional position for the evaluation of fatigue resistance,
2. at the top of the wearing course, where other studies (Bensalem et al. 2000, Jacobs 1995, Mante et al. 1995) showed traction due to horizontal loading.

Some results are given using a 2D representation, by cutting the structure into transversal and longitudinal planes. The use of longitudinal representations gives an idea of the approach of the load.

2. RESPONSES AT THE BOTTOM OF THE BASE LAYER

2.1 Responses at the bottom of the base layer without transversal load.

Results are given at the centre of the tire with respect to longitudinal position and some considerations concerning the distribution at the edge of the tire have been made, but without graphical representations.

2.1.1 Longitudinal strains and stresses

Representations are given in Figure 5 and Figure 6:

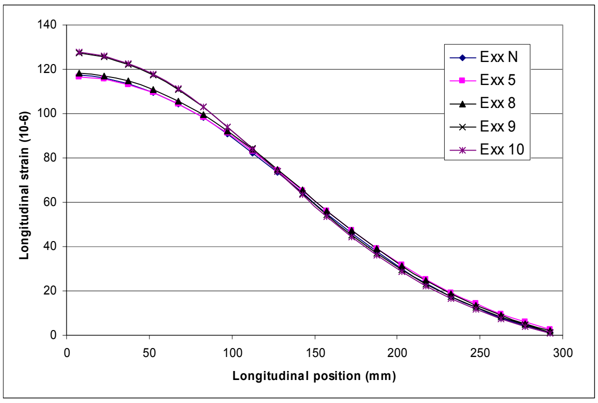

Figure 5: Longitudinal strains - bottom

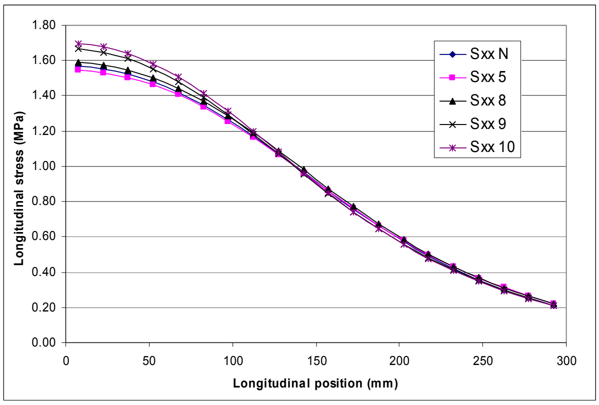

Figure 6: Longitudinal stresses - bottom

Maximum amplitudes of the responses were obtained at the centre of the tire and mainly depended on the load surface: cases N, 5 and 8, which give similar results, have the same total surface of 72'000 mm^2 (corresponding to a mean vertical load pressure of 8 bars) where cases 9 and 10 have only 62'000 mm^2 (corresponding to a mean vertical load pressure of 9,27 bars) and they also yielded similar results. In the studied case, a 15 % reduction in the load surface brought about increases in the maximum longitudinal strains and stresses of 9 % and 8 %, respectively. The use of a constant pressure on a circular surface (Case N) gave similar results to those obtained with the application of the same constant pressure on a square surface (Case 8).

Even though the maximum values were obtained at the centre of the tire, the transversal distribution of the vertical load pressure could be observed by comparing the results at the centre of the tire with those at the edge: in the first case, the uniform distribution yields responses higher than those found for the non-uniform case and the tendency is the opposite at the edge. Nevertheless, the influence of the non-uniform distribution of the load was very small in both cases.

2.1.2 Transversal strains and stresses

Representations are given in Figure 7 and Figure 8:

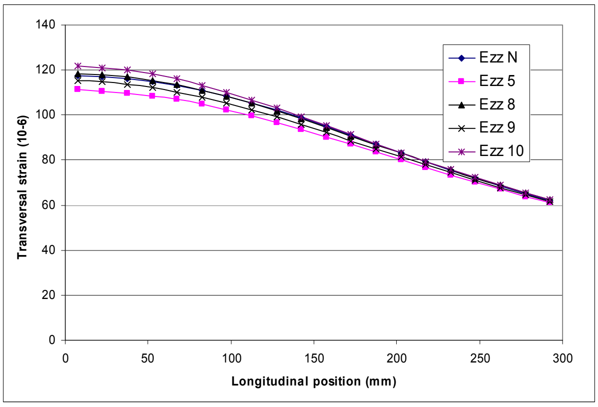

Figure 7: Transversal strains - bottom

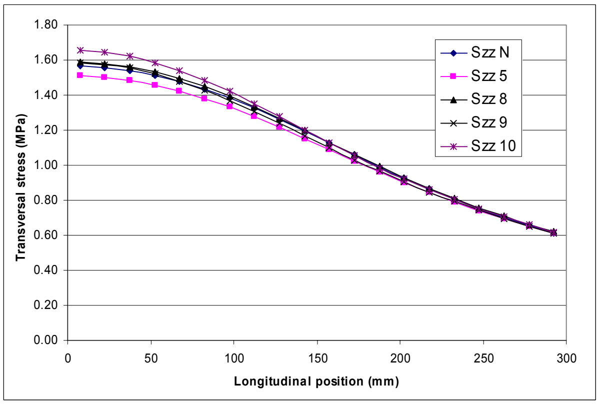

Figure 8: Transversal stresses - bottom

As for the longitudinal responses, maximum amplitudes of transversal responses were obtained at the centre of the tire and depended on the load surface. In the studied case, the use of the real load surface brought about increases in the maximum transversal strains and stresses of 4 % and 5 %, respectively. A circular load surface (Case N) gave similar results to those obtained with a square load surface (Case 8).

Transversal responses also depend on the distribution of the vertical load pressure but maximal values were obtained with a uniform load distribution. The non-uniform distribution brought about reductions in the maximum transversal strains and stresses of 6 % and 5 %, respectively. The effect of the distribution of the vertical load could also be observed by comparing the results at the centre of the tire with those at edge: strains are larger with a non-uniform distribution, but the differences are quite insignificant and the values much lower than those at the centre of the tire.

2.1.3 Vertical strains and stresses

Representations are given in Figure 9 and Figure 10:

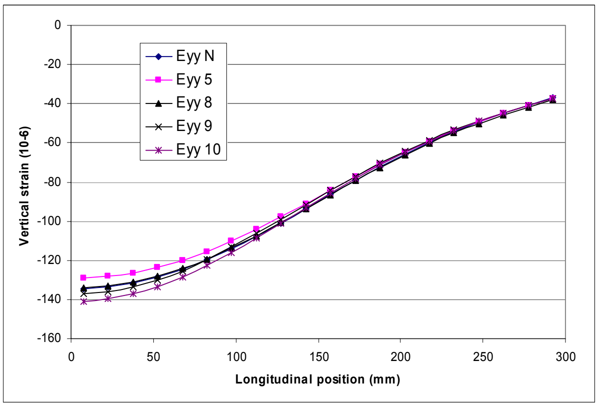

Figure 9: Vertical strains - bottom

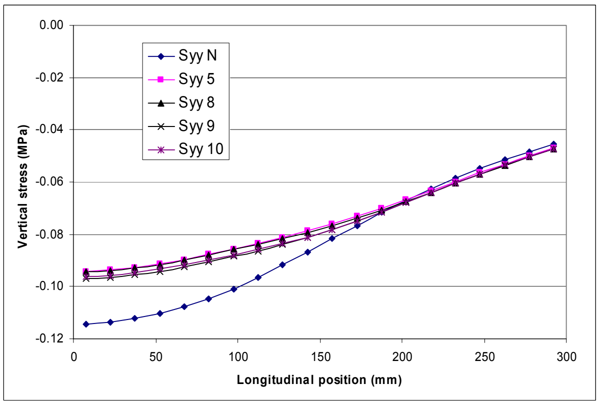

Figure 10: Vertical stresses - bottom

For vertical strains, the observations are similar to those made for transversal strains. Maximum values occurred at the centre of the tire, depended on the load surface and the transversal distribution of the vertical load pressure and were obtained with a uniform distribution. In the studied case, the use of the real load surface and of the non-uniform distribution brought about a 6 % increase and a 4 % reduction of the maximum vertical strains, respectively. A circular load surface (Case N) yielded results similar to those obtained using a square load surface (Case 8).

Concerning vertical stresses, a significant difference of 20 % between the results obtained by the finite element program and those obtained with the multi-layer program was observed. This difference is strange considering that for all the other strains and stresses in the Cartesian axes, a very good fit was obtained. Due to the good fit of the strains, all stresses, which are calculated from the strains by the application of the Hooke'law (1) in both programs, also should fit.

$$\sigma_1 = \frac{E}{(1+\nu)(1-2\nu)}\left[(1-\nu)\varepsilon_1 + \nu(\varepsilon_2 + \varepsilon_3)\right] \qquad (1)$$

A more detailed study of the strain results shows very small differences in the values (1 %) obtained by the multi-layer and the FE program. The strong variation of the vertical stress is therefore due to the particular value of the Poisson's ratio (ν=0,35) and to the fact that the tensile strains in the horizontal directions (118 μstrains) under the wheel are in the same range as the vertical compressive ones (134 μstrains). Under these particular conditions, the second part of Equation (1) tends to a very small value, and the small relative variations of strains obtained by the two programs can lead to an important relative variation of the second part of Equation (1), and consequently to a large variation of stresses. This can lead to important mistakes if stresses are used for predicting the life duration of a structure. The small variations in the strain values are probably due to the mesh used for the bottom of the base layer: in this location, elements had a horizontal dimension of 15 mm while the vertical one was 45 mm (other calculations, not presented in this paper, carried out with a thinner base layer using elements with similar dimensions in the three directions showed a very good fit between the finite element and the multi-layer calculations).

In the studied case and keeping in mind that vertical stress results are doubtful, the variations in the results for vertical stresses obtained with the FEM due to the real load surface and to the non-uniform distribution of the vertical load pressure are a 3 % increase and an under 1 % reduction, respectively. The variation of the results between a circular (Case N) and square load surface are not due to the shape of the load surface.

2.1.4 Conclusions about the distribution of the responses at the bottom of the asphalt layers without horizontal load

The results of the present study show that:

- longitudinal responses depend on the total load surface, but not on the distribution of the vertical load pressure. In the studied case, a decrease of more or less 15 % of the load surface provided an increase of less than 10 % in longitudinal responses

- the distribution of the vertical load pressure had a visible influence on the transversal responses: they were higher with a uniform pressure. In the studied case, the difference was less than 5 %
- maximum amplitudes for responses were always obtained at the centre of the tire
- using circular or square load surfaces had no influence on the responses if the same contact pressure was applied.

Related to the calculation method of stresses from strains, large variations in the values for vertical stresses were observed by comparing results from the FEM with results from multi-layer calculations: in our case (due to the particular value of the Poisson's ratio), very small variations in strain values (1 %) led to large variations in stresses (20 %), even using the same elastic parameters. This means that performance laws using stress criteria should be used very carefully.

2.2 Responses at the bottom of the base layer with transversal load.

The effect of transversal load as defined in Figure 4 was studied only with relation to load 8 and load 5, which use the same load surface. For responses at the bottom of the base layer, the transversal load had no particular effect. In the studied case, it only led to a 6 % increase in all strains and stresses, except for the vertical stress which had a 4 % increase. This last conclusion for the vertical stresses must be taken into account with care due to the remarks on page 9.

2.3 First considerations concerning strain and stress distributions at the bottom of the bituminous layers

Maximum amplitudes of strains and stresses at the bottom of the bituminous layers were always obtained at the centre of the tire, even when non-uniform distributions of vertical load pressure were used. Maximum responses were not affected by the real distribution of the vertical load pressure and the assumption of a constant value can be used for calculation at the bottom of the bituminous layers. The value of the constant vertical pressure should be the real mean value calculated from an imprint and not the inflation pressure. This mean vertical pressure can be applied on a circular surface without affecting the results at the bottom of the bituminous layers in comparison with the application on the real square contact surface area we defined. Transversal loads brought about a significant increase (6%) in the strains and stresses at the bottom of the bituminous layers which are not negligible. The traditional assumptions for the application of traffic loads seem relevant for the calculation of responses at the bottom of the bituminous layers, however, using the real vertical contact pressure. More studies on the relationship among the three parameters defining load condition, which are total load intensity, contact surface and inflation pressure of the tire, are necessary.

3. RESPONSES AT THE TOP OF THE BITUMINOUS LAYER

In the following paragraphs, the "centre of the tire" is the centre in the transversal direction and the "middle of the tire" is the centre in the longitudinal direction.

3.1 Responses at the top of the bituminous layer without transversal load.

3.1.1 Longitudinal strains and stresses

Loading parameters had little effect on strains, so representations are given only for stresses:

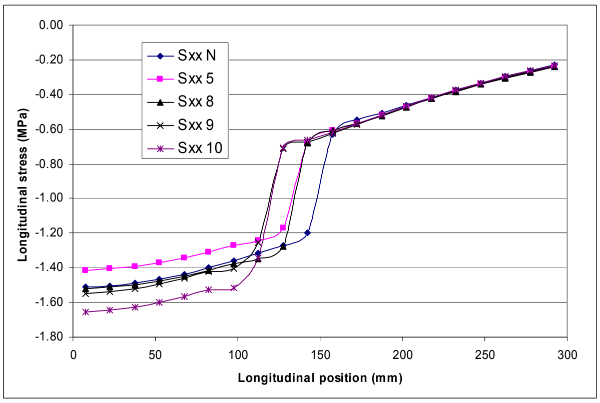

Figure 11: Centre of the tire - top

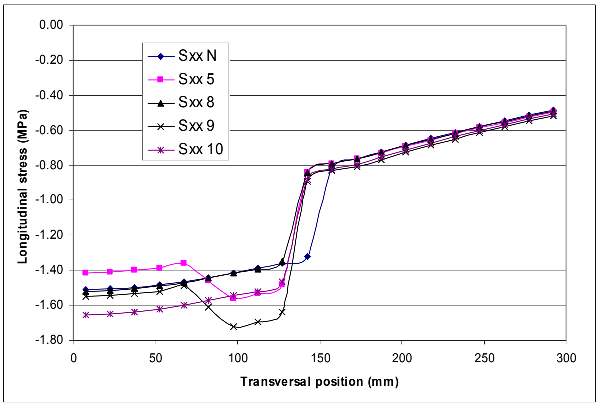

Figure 12: Middle of the tire - top

For strains, a non-uniform distribution of the vertical load pressure had no effect and maximum values were obtained at the centre of the tire and depended only on the load surface: cases N, 5 and 8, which have a similar load surface, yielded similar maximum amplitudes and the same conclusion can be made for cases 9 and 10. In the studied case, the 15 % reduction of the surface brought about an increase of more or less 8 % for the maximum strains (similar to the bottom of the bituminous layers). The shape of the imprints had no importance for the calculation of the maximum strains. It must be mentioned that load on a circular surface (case N) gave good results only if the location was not too far from the centre of the load surface, because the outer positions of the square imprint of the tire are outside the circular surface.

Concerning stresses, Figure 11 and Figure 12 show that maximum longitudinal stresses were not always obtained at the centre of the tire and depended on the load surface and on the transversal distribution of vertical load pressure. The 15 % reduction in the load surface increased the stress values by 10 %. With non-uniform distributions (cases 5 and 9), maximum values of stresses were obtained at the edge of the tire, where maximum vertical load pressures were applied (Figure 12). The non-uniform distribution of the vertical load pressure brought about an increase in the maximum amplitude for longitudinal stresses. In the studied case, the increase was about 4 %.

In Figure 11, a maximum value was obtained in case 10, when the vertical pressure at the centre was 9,27 bars and the minimum value corresponded to case 5 when the vertical pressure at the centre was 6,55 bars. For the three other cases N, 8 and 9, stress values were similar due to similar vertical pressure at the centre of the tire (8 and 7,67 bars). This means that longitudinal stresses at the top of the structure clearly depend on the effective vertical load pressure applied by the tire.

The variation in the length of the load surface clearly appears in Figure 11. Assuming that the longitudinal representation corresponds to the approach of the load, this means that a small portion of the surface corresponds to a reduction in the application time of the important strains in the bituminous layers.

3.1.2 Transversal strains and stresses

The effects are very similar to those obtained for longitudinal responses. Maximum amplitudes for strains were obtained at the centre of the tire and depend on the load surface and on the transversal distribution of vertical load pressure. In the studied case, the reduction of the load surface and the non-uniform distribution of the vertical load pressure led to a 4 % increase and to a 6 % reduction of the strains, respectively. A maximum value for stress was not obtained at the centre of the tire, but at the edge where a maximum vertical pressure of 12,05 bars was applied. In the studied case, the reduction of the load surface and the non-uniform distribution of the vertical load pressure led to increases in the maximum stresses of 5 % and 4 %, respectively.

3.1.3 Vertical strains and stresses

Stresses fit perfectly with the vertical loading conditions that were introduced, so representations are given only for strains:

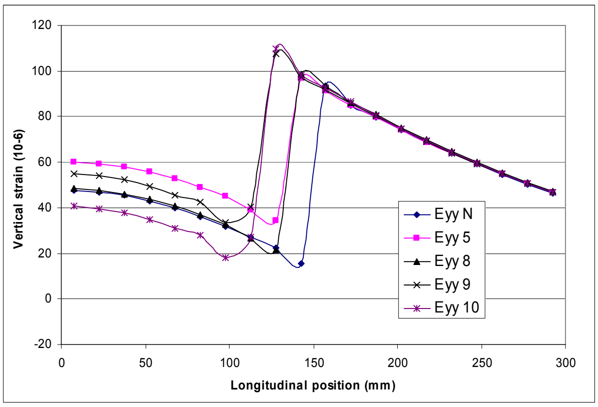

Figure 13: Centre of the tire - top

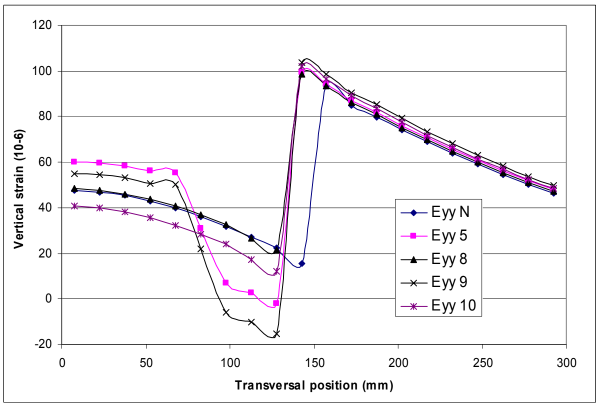

Figure 14: Middle of the tire - top

The first and main observation is that, with all models, strains just under the load are mainly extensive strains. Assuming that permanent deformations (rutting) are proportional to elastic deformations, this would mean that there is expansion ("negative rutting") of the bituminous materials in the first centimetres of the structure.

Maximum tensile strains were obtained just in front of the tire (Figure 13) and just next to the tire (Figure 14). Concerning the amplitude, maximum values depended mainly on the load surface and the transversal distribution of the vertical load pressure had almost no effect. In the studied case, the 15 % reduction of the load surface brought about an 11 % increase in the vertical tensile strains. If the transversal distribution had almost no effect on maximum values, it had an effect on the intensity of the strains just under the load surface: the non-uniform distribution of the vertical load pressure (cases 5 and 9) can lead to a compression zone at the edge of the tire, but with low intensity.

3.1.4 Conclusions concerning the distribution of the strains and stresses at the top of the asphalt layers without horizontal load

Stresses just under the load surface were always compressive and the horizontal ones (longitudinal and transversal) were much larger than the vertical ones in all cases. For the studied case, vertical stress values were more or less 50 % smaller than the horizontal ones, which can exceed 15 bars. This large difference, combined with the value of the Poisson’s ratio, led to the apparition of vertical tensile strains just under the load surface: horizontal compressions were so strong that the vertical compression could not prevent extension in the vertical direction. This result does not depend at all on the application of the loading conditions but should be a very good subject of discussion for road engineers, because it would imply vertical expansion in the first millimetres of the top layer. This surprising result is probably due to some hypotheses made in the elastic model, in particular concerning the homogeneity of the bituminous materials, and no definitive conclusions can be made using the linear-elastic theory for the responses at the top of the bituminous layers.

As could be expected, the influence of the application of the loading conditions was more important at the top of the bituminous layers than at the bottom. The results of the present study show that:

- non-uniform distribution of the vertical load pressure brought about an increase and a shift to the edge of the tire of the maximum longitudinal and transversal stresses (obviously of the vertical ones, also); but, there was no influence on the maximum horizontal strains
- longitudinal and vertical strains mainly depended on the load surface and increased with the reduction of the surface
- non-uniform distribution of the vertical load pressure had the same visible influence on the transversal strains as for the bottom of the bituminous layers: they were higher with uniform pressure
- non-uniform distribution of the vertical load pressure had no influence on the longitudinal strains but had a visible influence on the longitudinal stresses
- maximum amplitudes for strains were always obtained at the centre of the tire
- maximum amplitudes for stresses were always obtained at the edge of the tire
- the shape of the load surface (circular or square) had an influence for extreme positions (far from the centre of the tire).

3.2 Responses at the top of the bituminous layer with transversal load.

3.2.1 Longitudinal strains and stresses with horizontal load

Transversal load had almost no influence on longitudinal strains, so representations are given only for stresses:

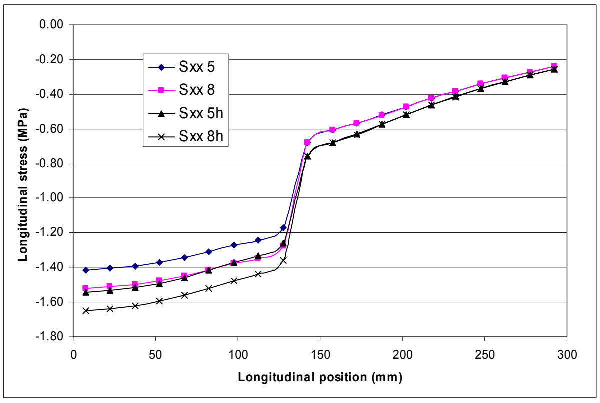

Figure 15: Centre of the tire – top - transversal load

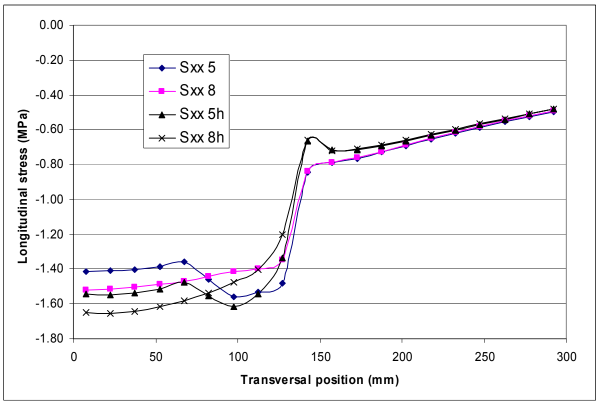

Figure 16: Middle of the tire – top - transversal load

Transversal load had more influence on stresses than on strains; for the studied case, longitudinal stresses under the load surface increased approximately 10 % while longitudinal strains had only a small decrease of 3 %.

Figure 16 shows a reduction in the compressive longitudinal stresses just outside the tire as opposed to the increase observed in the middle of the tire. In the cases with a non-uniform load distribution (5 and 5h), the application of the transversal load slightly reduced the difference between maximum amplitudes at the centre or at the edge of the tire: the 10 % increase obtained without transversal load was reduced to 5 % by the application of the transversal load.

3.2.2 Transversal strains and stresses with horizontal load

Representations are given for strains and stresses:

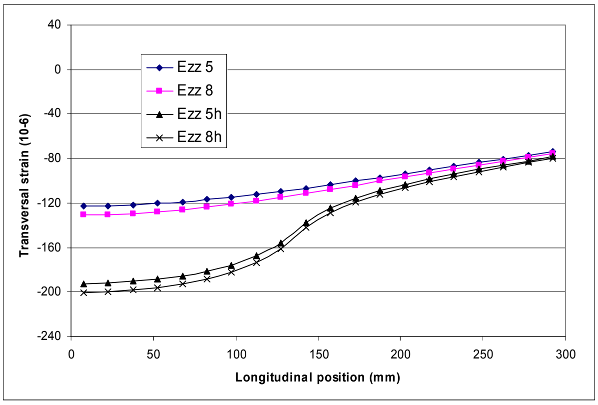

Figure 17: Strains in the centre of the tire – top - transversal load

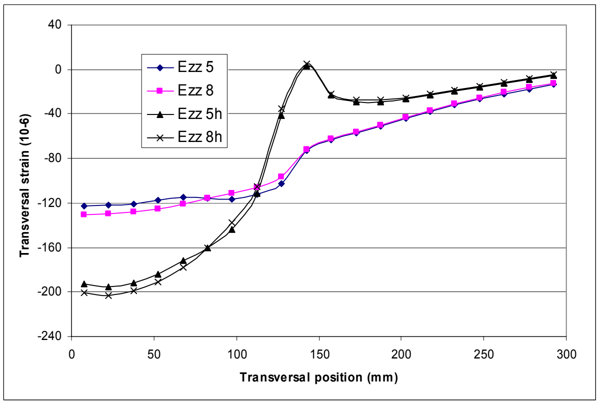

Figure 18: Strains in the middle of the tire – top - transversal load

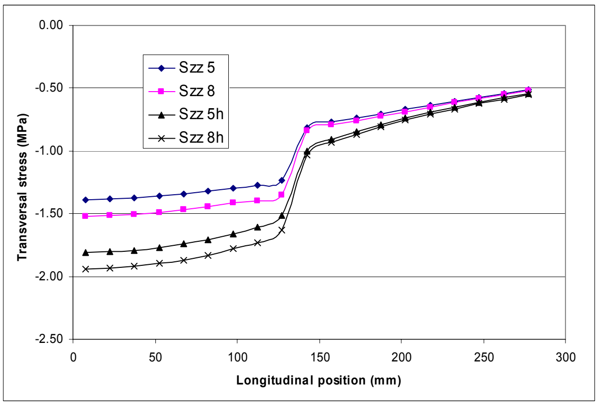

Figure 19: Stresses in the centre of the tire – top - transversal load

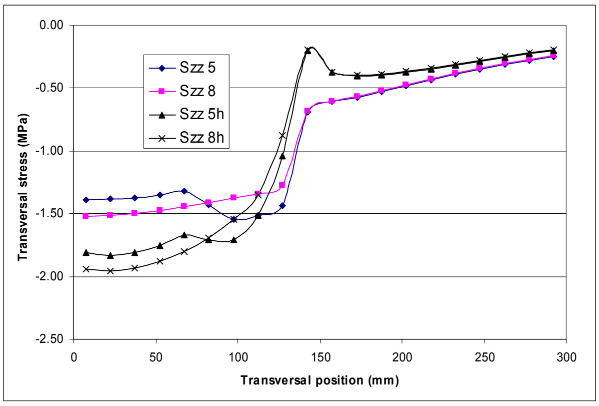

Figure 20: Stresses in the middle of the tire – top - transversal load

In the longitudinal representations of Figure 17 and Figure 19, the increases in compression strains and stresses are quite constant over the whole length of the load surface, which corresponds to the way in which the transversal load was applied. For the studied case, maximum compressive strains and stresses increased at the centre of the tire by about 60 % and 30 %, respectively.

Transversal representations in Figure 18 and Figure 20 show that the effects of transversal load change dramatically whether the situation is at the centre or just outside the tire, where transversal loads induce tensile strains and stresses. In the studied case, these tensile strains were such that they compensated the compressive ones induced by vertical loads and that there was a very small traction strain close to the edges of the tire. Contrary to the case of the strains, tensile stresses induced by transversal load were not strong enough to compensate the compressive ones induced by vertical loads and there was no tensile stress close to the edges of the tire.

For stresses and in the case of a non-uniform distribution of the vertical load pressure (cases 5 and 5h), the transversal load shifted the maximum value of compressive stress from the edge to the centre of the tire.

3.2.3 Vertical strains and stresses with horizontal load

Stresses fit perfectly with the vertical loading conditions and transversal loading had absolutely no effect, so representations are given only for strains:

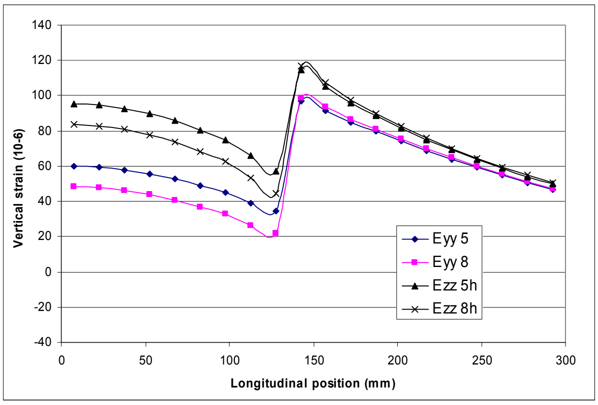

Figure 21: Centre of the tire – top - transversal load

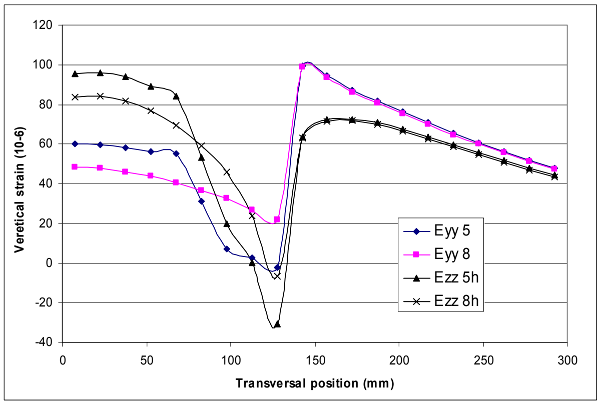

Figure 22: Middle of the tire – top - transversal load

As for the transversal strains, the longitudinal representation in Figure 21 shows quite a constant increase in the tensile strains over the whole length of the load surface. The increase is explained by the increase in the transversal stresses observed in Figure 19. This means that the expansion ("negative rutting") observed on page 13 increases with transversal load. The increase is in the same range of 60 % that we mentioned for transversal strains.

The results in the transversal representation in Figure 22 correspond to those observed for transversal strains, which means that there is an increase in the middle of the tire, but a reduction just outside the tire. In the studied case, this reduction in strain close to the edges leads to zones of small vertical compression, with larger values for the case with a non-uniform vertical load distribution (case 5h).

4. SYNTHESIS OF THE RESULTS AND COMMENTS

A synthesis of all observations made for strain and stress components related to the different topics of our study is given in two tables: Table 4 is for results at the bottom of the bituminous layers and Table 5 for results at the top of the bituminous layers. Increases or reductions are always given for the maximum values of strains or stresses.

Before commenting on all the results, it is important to repeat that most design methods use horizontal strains or stresses at the bottom layers as criteria, the reason why we chose this position for our study. Generally, the values of strains or stresses are used in fatigue laws, which are expressed by a power law. The power depends on the rigidity of the materials, and it may be assumed that the power increases with rigidity: for instance, the French Design Manuel for Pavement Structures (Anon., 1997) uses values between 5 for bituminous materials and 12 for cement bound materials. This power ensures that even an apparently small variation in the values induces a large variation of the design life of the structures.

Concerning the top of the bituminous layers, Mante et al. (1995) and Jacobs (1995) mentioned important transversal strains or stresses at the top of the bituminous layers and that this could explain surface cracking. These observations were made on a thick structure of 200 mm of bituminous layer. Bensalem et al. (2000) also observed tensile strains at the top of the bituminous layer, but said that they were obtained on thin bituminous structures. For the case of thick bituminous layers, tractions were found far away from the tire contact surface.

4.1 Synthesis for the results at the bottom of the bituminous layers

	Circular or square load surface	Inflation tire or real mean pressure (RMP)	Uniform or non-uniform (NU) pressure distribution	Application of transversal load
Longitudinal strains	No effect.	Increase of 9% with RMP.	Negligible variation.	Increase of 6%.
Longitudinal stresses	No effect.	Increase of 8% with RMP.	Negligible variation.	Increase of 6%.
Transversal strains	No effect.	Increase of 4% with RMP.	Reduction of 6% with NU.	Increase of 6%.
Transversal stresses	No effect.	Increase of 5% with RMP.	Reduction of 5% with NU.	Increase of 6%.
Vertical strains	No effect..	Increase of 6% with RMP.	Reduction of 4% with NU.	Increase of 6%.
Vertical stresses[2]	Difference due to model.	Increase of 3% with RMP.	Negligible variation.	Increase of 4%.

Table 4: Recapitulation for responses at the bottom of the bituminous layers

[2] These comments should be read with care (see comments on page 9)

4.2 Synthesis for the results at the top of the bituminous layers

	Circular or square load surface	Inflation tire or real mean pressure (RMP)	Uniform or non-uniform (NU) pressure distribution	Application of transversal load
Longitudinal strains	No effect, but wrong in some positions.	Increase of 8% with RMP.	Negligible variation.	Reduction of 3%.
Longitudinal stresses	No effect, but wrong in some positions.	Increase of 10% with RMP.	Increase of 4% with NU. Maximum at the edge.	Increase of 5%. Maximum at the centre.
Transversal strains	No effect, but wrong in some positions.	Increase of 4% with RMP.	Reduction of 6% with NU.	Strong increase of 60%. Variation close to the edge.
Transversal stresses	No effect, but wrong in some positions.	Increase of 5% with RMP.	Increase of 4% with NU. Maximum at the edge.	Strong increase of 30%. Variation close to the edge.
Vertical strains (mainly extensive)	No effect, but wrong in some positions.	Increase of 11% with RMP.	No effect. Effect on values under the load area.	Strong increase of 60%. Compression at the edge.
Vertical stresses	No effect, but wrong in some positions.	Fit well with loading condition.	Fit well with loading condition.	No effect.

Table 5: Recapitulation for responses at the top of the bituminous layers

4.3 General comments

Recapitulations made in Table 4 and Table 5 show that calculations of the responses must be made using the real mean contact vertical pressure and not the inflation pressure of the tire.

The use of a circular or a square surface had no effect on the strain and stress distributions. But this conclusion depends on the particular loading condition (11,5 to and 8 bars) used for cases 5 and 8 which gave us a square shape for the surface calculated from the inflation pressure. The third column of Table 4 and Table 5 shows that variations due to the use of the real mean pressure have more influence on the longitudinal responses than on the transversal ones. This means that the reduction in the length of the load surface (in the longitudinal direction) increases the longitudinal responses, and that the shape of the load surface has an influence on the strain and stress distributions. This effect cannot be noticed by comparing cases N and 8 (due to the symmetry of the square surface used in case 8) but it means that the shape of the load surface is important for the relative values of the longitudinal and transversal responses: a tire with an imprint wider than it is long will induce higher longitudinal strains and stresses than transversal ones.

The effects of the transversal distribution of the vertical load pressure are different considering the depth. At the bottom of the bituminous layers, a general reduction of strains and stresses with the non-uniform distribution was observed and the maximum values were always obtained at the centre of the tire. At the top of the structure, there was no general tendency: an increase of the horizontal stresses and maximum values obtained at the edge but a reduction of the transversal strains with variation of the position of the maximum amplitude (at the centre).

At the bottom of the bituminous layers, our calculations show that, on a relatively thick structure, the use of a uniform distribution of the vertical load pressure leads to higher strains and stresses than the use of a non-uniform distribution. Also, De Beer et al. (1997) showed that the non-uniform distribution of the vertical load pressure occurs mainly on overloaded or under inflated tires, which cannot be considered as the common rule for design. It means that, for thick pavements, the transversal distribution of the vertical load pressure can be neglected without risk of underestimating the values at the bottom of the bituminous layers. Concerning the effect of transversal load, it is quite surprising to see that all the values at the bottom of the bituminous layers increase significantly (6%), even on a thick structure.

In the present study, a clearly overloaded tire was used (load on a super-single tire should not exceed 4 tons), which explains that the real mean pressure obtained from the imprint area of the tire was higher than the inflation pressure. This situation leads to an increase of the responses and it is clear that the use of a lower pressure will reduce them. Blab (1999) shows that the real mean pressure depends on the type of tire, the inflation pressure and the total vertical load and that in most of the cases the real mean contact value is lower than the inflation pressure. This means that the traditional procedure of using inflation pressure leads to an overestimation of the responses for most loads and to an underestimation for the overloaded tires.

For the calculation at the top of the layers, no significant traction (only very small values of strains) near the wheel was observed. Mante et al. (1995), Jacobs (1995) and Bensalem et al. (2000) observed this traction in the transversal direction. In our cases, an effect of the transversal load on the transversal responses was observed, but it was not important enough to compensate the high state of compression induced by the vertical load. Even if this situation depended on the structure and on the applied load, it seems impossible that a transversal load could induce enough traction solicitation to compensate the compression due to vertical loading totally (in our case, compressive stresses are over 6 bars near the tire edge) and to create traction which is sufficient to initiate cracking. This situation must be reconsidered for thinner bituminous layers. Results obtained for vertical strains (expansion under the load) prevent definitive conclusions for responses at the top of the bituminous layers with linear-elastic theory.

The presented results, in particular the relative values for the increase or the reduction of the strain and stress components, depend on the structure and on the load that were used for the calculations.

5. CONCLUSIONS

The different studied cases showed that the most important parameter that influences the strain and stress distributions is the shape and the total size of the load surface. The shape has an influence on the relationships between longitudinal and transversal responses at the bottom as well as at the top of the bituminous layers: depending on the shape, maximum values will be obtained in the longitudinal or in the transversal direction. The size of the contact surface has an influence on the mean vertical pressure that the tire applies on the pavement. All calculations showed that an increase of this mean vertical pressure induced an increase in the values at the bottom and at the top of the bituminous layers.

Concerning the transversal distribution of the vertical pressure, the influence is negligible at the bottom of the bituminous layers in the way that the common hypothesis of a constant pressure gives maximum values of strains and stresses higher that with a non-uniform distribution. At the top of the bituminous layers, the main effect of the non-uniform distribution of the load is to increase the maximum amplitude of the stresses and to shift the position of this maximum amplitude to the edges of the tire.

Transversal loads have a non-negligible influence at the bottom of the bituminous layers. At the top, they strongly reduce the transversal compression near the edge of the tire, but are insufficient to induce traction in thick bituminous layers.

6. ACKNOWLEDGEMENTS

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