

The influence of tyre characteristics on the normal stresses in asphalt concrete pavements

M. M. J. JACOBS and J. MORAAL, Road and Railroad Research Laboratory, Delft University of Technology, The Netherlands

In contradiction to the general idea of road mechanic engineers the tire stress distribution in the contact area between tire and roadway exhibits a highly non-uniform three-dimensional (3D) character instead of a uniform vertical one. In this paper an example of this 3D stress distribution is conducted out of literature. With the linear elastic multi-layer program BISAR the normal stresses in an asphalt concrete layer are calculated due to this stress distribution. From these calculations it is concluded that the normal stresses at the bottom of the asphalt concrete layer are hardly influenced by the stress distribution in the contact area. However large tensile stresses occur at the surface of the asphalt concrete layer due to the transverse shear stress component of the 3D distribution. These tensile stresses can cause longitudinal cracks at the surface of asphalt concrete layers.

1. INTRODUCTION

Until 1975 roads, which design was based on the results of calculations with linear elastic multilayer computer programs, using a uniform vertical contact pressure distribution, showed the predictive performance. At the point of time the predicted lifetime was reached, the asphalt concrete layer (= AC layer) started to crack from the bottom to the top. Since 1975 the axle load of a truck tire increases, also cracks occur at the top of an AC layer and grow downwards. This type of cracking can not be predicted by linear elastic multilayer analyses with uniform vertical tire contact pressure distributions.

Since that time research is carried out into the causes of this asphalt surface cracking. Molenaar (ref.1) and Gerritsen et al (ref.2) showed that one of the causes of this type of cracking could be the non-uniform stress distribution which occur in the contact area between tire and roadway. From recent calculations and measurements it appears that the interfacial pressure distribution between a rolling tire and the pavement exhibits a highly non-uniform three-dimensional (3D) distribution over the contact area. This non-uniformity is principally due to differences in the bending stiffness in a tire structure and the breaking and driving forces of a car.

In this paper attention will be paid to the 3D stress distribution in the contact area between tire and roadway. Based on a literature review a 3D stress distribution in the contact area is assumed. The linear elastic computer program BISAR has been used to calculate the effects of the stiffness modulus of the AC layer and the non-linear stress distribution on the normal stresses which occur at the top of the AC pavement structure.

2. THE 3-DIMENSIONAL TIRE STRESS DISTRIBUTION

Forces are needed to support, to guide and to manoeuvre a vehicle. All these forces appear in the contact area between tire and roadway. The study of these characteristics and application of the resulting theory should improve the mechanical properties of the tires and the control of a vehicle. In figure 1 an example of the 3D stress distribution is shown. The characteristics are influenced by:

- (a) the operating parameters of the tires:
 - bias or radial-ply structure
 - longitudinal, lateral and torsional stiffness
 - the internal friction in rubber and cord
 - the type of rubber
 - the thread pattern of the tire
 - the friction characteristics of the tread
 - the inflation pressure
 - the dimensions of the tire
- (b) the environmental parameters:
 - free-rolling, breaking and driving forces
 - the cornering of the tire
 - the velocity of the vehicle
 - the acceleration and deceleration of the car
 - the load on the tire
 - the contact area of the tire
 - the friction characteristics of the contacting surface
 - the slip between tire and roadway
 - the weather conditions

Because of this large number of parameters it is difficult to give a full description of all interacting factors. For the most part it will be necessary to rely on rather insufficient experimental evidence which merely indicates trends and magnitudes, as well as some relatively simple theoretical ideas which may prove helpful in explaining the general characteristics of observed phenomena. In this paper only a few aspects will be discussed.

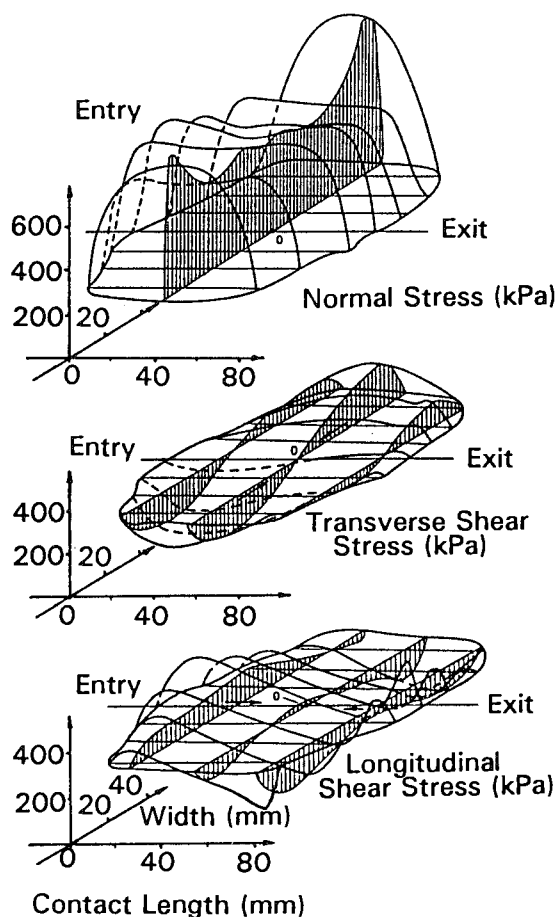


Fig.1. An example of the three-dimensional stress distribution for a passenger car; load= 3.5 kN, $p_i = 0.17$ MPa (ref.7)

In road mechanics there are two major assumptions concerning the contact area between tire and roadway:

- (1) the loading area has a circular shape (ref. 3) However out of literature (ref.4,5,6,7, 8,9) it seems that the area has a rather rectangular shape instead of a circular one.
- (2) Only a vertical normal stress distribution is taken into account in the determination of stresses and strains in the AC layer. However it seems that the stress distribution in the contact area between tire and roadway consists of three components (see figure 2):
 - (a) the vertical normal stress, caused by the vehicle load W
 - (b) the longitudinal shear stress, caused by the slip H due to speed differences between the deformed (in the tread of the tire) and undeformed tire in the moving direction
 - (c) the transversal shear stress, caused by the slip S due to differences in stiffness between the edge and the thread of the tire and by constriction of the tire, perpendicular to the moving direction

As mentioned above the stress distribution is influenced by a large number of parameters. Until now there is no general description of the stress distribution between tire and roadway.

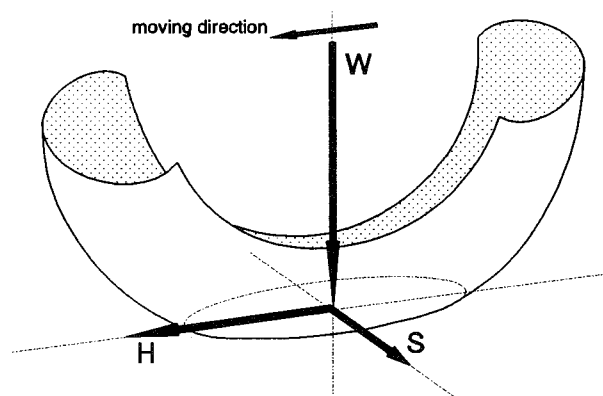


Fig.2. Forces acting in the contact area between tire and roadway

Out of available literature it seems that measurement of the stresses is highly complicated and very time and money-consuming. There is only less attention paid to analyze the measurements. Only recently, since the development of non-linear elastic finite element methods, mathematical models have been used to implement the complicated tire construction in the computer. Unfortunately these calculations are limited to only the vertical non-uniform stress distribution (ref.8).

In this paper the 3D stress distribution in the contact area between tire and roadway, caused by a truck tire, will be determined from literature. In figure 3 some examples are given.

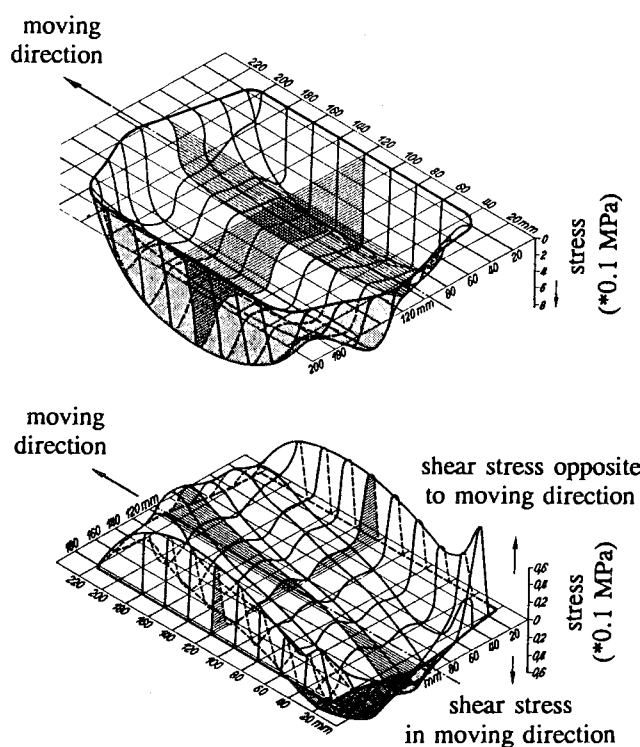
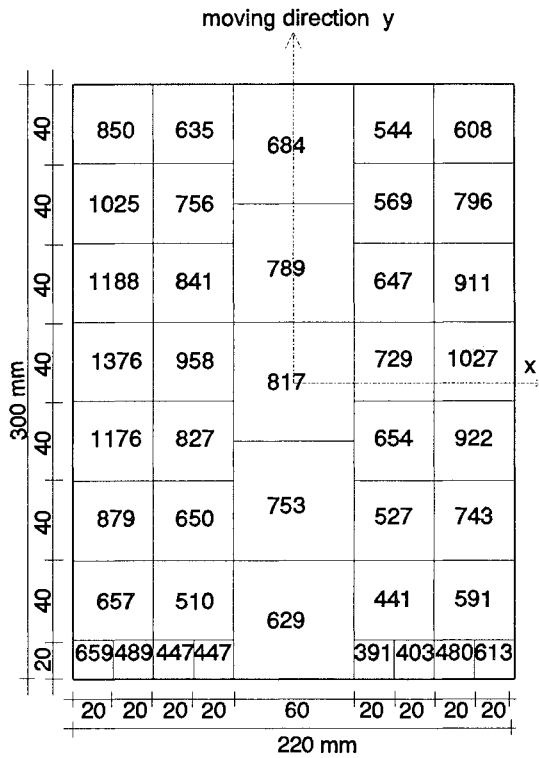


Fig.3. Examples of (a) the vertical and (b) the longitudinal shear truck tire stress distributions in the contact area between tire and roadway; load= 36.7 kN, $p_i = 0.65$ MPa (from ref.6)

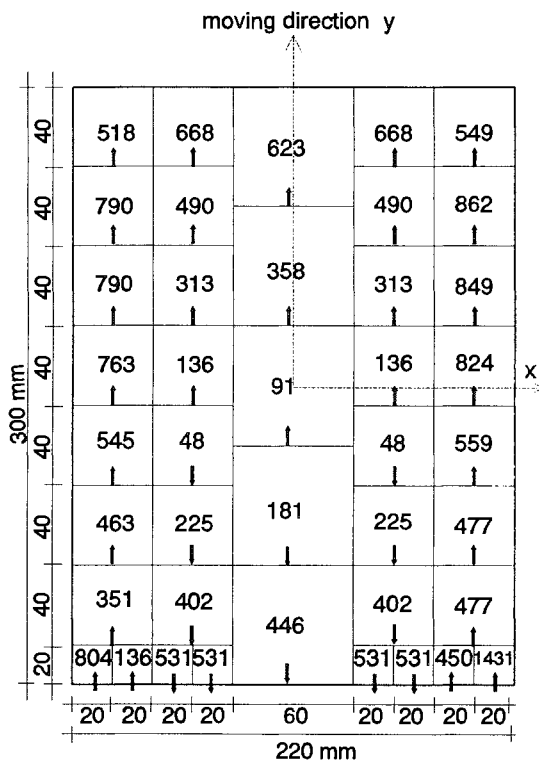
A truck tire is chosen because of the fact that a truck causes most road damage due to its large axle weight. Because of the fact that most information is available for the free rolling

tire, this paper is only concerned with this type of tire. The vertical load on the truck tire is 50 kN, the standard wheel load in The Netherlands. The inflation pressure is 0.65 N/mm² (6.5 bar).

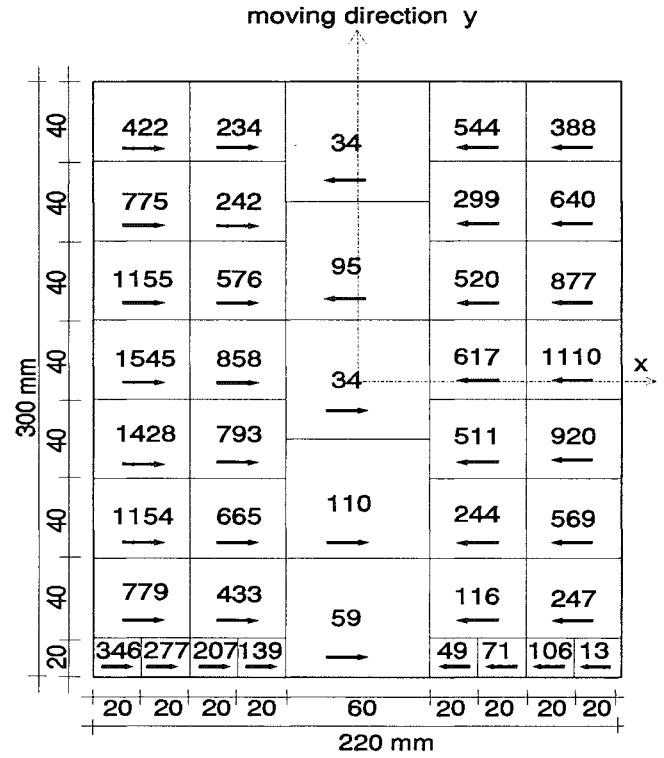
Based on the results of figure 1 and 3 a 3D stress distribution under a truck tire is determined and given in figure 4.



The vertical stress distribution



The longitudinal shear stress distribution



The transverse shear stress distribution

Fig.4. The estimated 3D stress distribution in the contact area between tire and roadway (load 50 kN, $p_i = 0.65$ MPa)

The loading area is 300·220 mm². The stresses are given in bar diagrams, so they can be used easily as input for computer programs which determine the stresses and strains in road structures. In the determination linear extrapolation has been used. Although the basis of the bar diagram is rather coarse, it reflects the stresses in an accurate way.

3. STRESSES IN THE ASPHALT CONCRETE LAYER

In this paragraph the effects of the non-linear 3D tire stress distribution on the normal stresses in the AC layer will be considered. The load is caused by a free rolling truck tire with a vertical load of 50 kN and an inflation pressure of 0.65 N/mm².

3.1 The pavement structure

The normal stresses will be calculated in a typical Dutch road structure, which is given in figure 5.

The road structure consists of a subgrade with a resilient modulus M_r of 100 MPa; the thickness of the layer is infinitive. The unbound base has a thickness of 300 mm and its M_r is 300 MPa. The thickness of the AC layer is 200 mm. The stiffness modulus S_m will be varied due to temperature influences:

- (a) $S_m = 1500$ MPa if the temperature is 25 °C
- (b) $S_m = 5500$ MPa if the temperature is 15 °C
- (c) $S_m = 10000$ MPa if the temperature is 5 °C.

This type of asphalt concrete is normally used for top layers in The Netherlands. The Poisson's ratio for all materials is supposed to be 0.35. All resilient and stiffness moduli are supposed

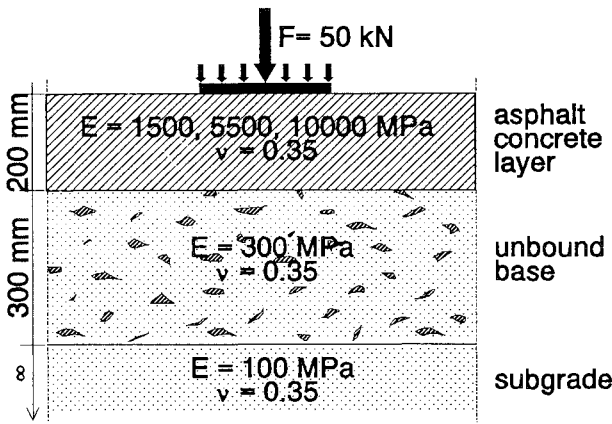


Fig.5. The pavement structure.

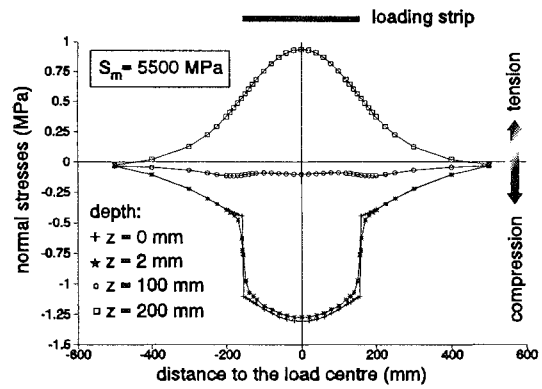


Fig.6. Calculated normal stresses in the asphalt concrete layer with a vertical uniform stress distribution

to be constant with depth although these characteristics depend respectively on the stress situation and on temperature. Calculations have shown that no significant differences occur in calculated stresses and strains in the AC layer in case the unbound base and the subgrade are treated as a linear or non-linear material (ref. 10) or in case the AC layer is divided in sub-layers with several stiffness moduli or just one mean value for S_m (ref.11).

Although the stiffness modulus of the AC layer will affect the 3D tire stress distribution in the contact area between tire and roadway this influence is neglected in this paper.

3.2 Normal stresses in the asphalt concrete layer

The normal stresses in the AC layer are calculated with the linear elastic multilayer program BISAR (ref.12). First the stresses will be calculated with BISAR with only a uniform vertical tire stress distribution (the normally used input). After that the stresses with the 3D tire stress distribution (from fig.4) are calculated and the influence of the stiffness modulus of the AC layer will be discussed. In the last part of this paragraph attention will be paid to the comparison of stresses, calculated with both input data.

3.2.1 Normal stresses due to a uniform tire stress distribution

In figure 6 normal stresses due to a uniform vertical tire stress distribution are given. The stiffness modulus of the AC layer is 5500 MPa. The vertical load is 50 kN; the tire pressure 0.65 MPa. This means the radius of the circular loading area is 156.5 mm.

Due to the uniform loading the normal stresses are symmetrically. As expected tensile stresses occur at the bottom of the AC layer due to bending. The maximum normal stress develops in the middle under the loading area; the magnitude is 0.937 MPa. On this stress (and strain) level and the expected life span of the road, the thickness of the AC layer is determined. At the upper part of the AC layer only compression stresses occur. These stresses never can cause surface cracking in top layers.

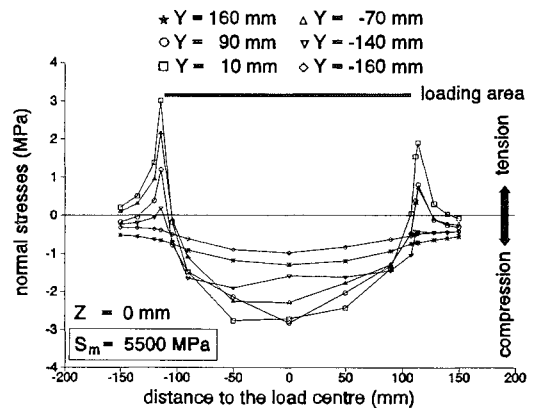
3.2.2.1 Normal stresses due to a three-dimensional tire stress distribution

The normal stresses in the AC layer due to the 3D tire stress distribution are also calculated with BISAR. The rectangular loading areas (figure 4) are put in as circles with the same area. The influence of the discontinuities at the edges of the loading area are taken into account by calculating the stresses at a distance from the loaded area (3 mm). In order to determine the stresses in one point of the AC layer the summons of 123 load situations (out of figure 4) must be determined. So the number of points where the stresses in the AC layer will be determined will be limited to the most important points: near the edges of the loading area and straight under the centre of the several loading areas. To observe the stresses in the AC layer in this paper about 900.000 calculations have been performed.

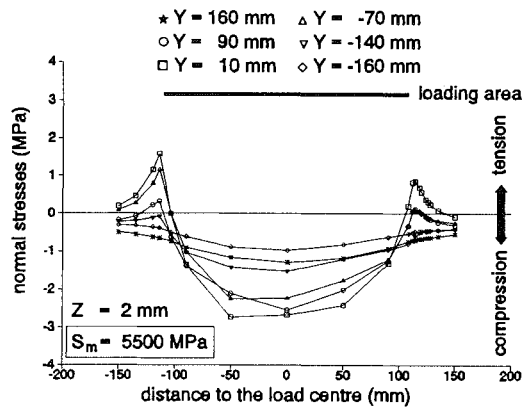
In figure 7 some results of the calculations with the 3D tire stress distribution and the stiffness modulus of the asphalt concrete layer of 5500 MPa are shown graphically. In these figures the y-direction is the moving direction, the x-axis perpendicular to the moving direction and the z-axis the depth in the asphalt concrete layer.

From these figures it can be seen that:

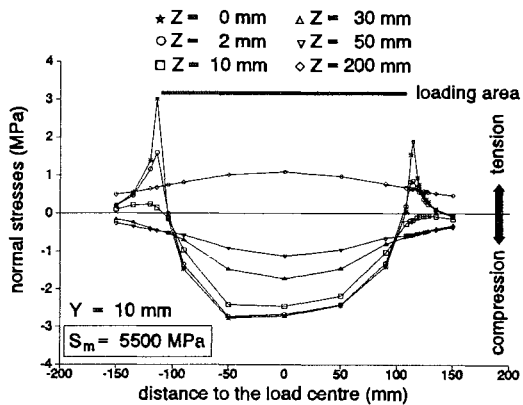
(a) The normal stresses in x-direction with the



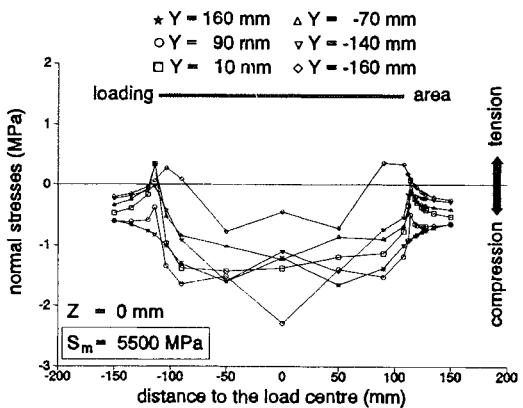
(a) σ_{xx} at the surface of the asphalt concrete layer with $S_m = 5500$ MPa



(b) σ_{xx} 2 mm below the surface of the AC layer with $S_m = 5500$ MPa



(c) σ_{xx} at several depths in the AC layer at $y = 10$ mm and $S_m = 5500$ MPa



(d) σ_{yy} at the surface of the asphalt concrete layer with $S_m = 5500$ MPa

Fig.7. Results of the BISAR calculations with the 3D tire stress distribution

3d-tire stress distribution at the bottom of the AC layer are almost equal to the normal stresses with the uniform tire stress distribution.

- (b) The normal stresses in the AC layer with the 3D tire stress distribution in x-direction (perpendicular to the moving direction) are higher compared to the normal stresses in the moving direction (y-axis).
- (c) No tensile stresses will occur at the surface of the AC layer under the 3D tire stress distribution.

- (d) Tensile stresses principally occur beside the longitudinal edges of the loading strip of the 3D tire stress distribution at the surface of the AC layer. These tensile stresses are mainly caused by the transverse shear stress component. The largest positive normal stress develops at the place where the largest transverse shear stress component occurs ($x = -115$ mm; $y = 10$ mm). The magnitude of this stress in case the stiffness modulus of the AC layer is 5500 MPa is about 3 MPa.
- (e) The tensile stresses in the AC layer decrease rapidly with depth z . The tensile stresses at $z = 2$ mm are almost equal to the tensile stresses at the surface ($z = 0$ mm). However at 30 mm depth only negative normal stresses (compression) occur. So the influence of the 3D tire stress distribution on the normal stresses in the AC layer is limited to the upper part of the layer.
- (f) Over a distance of 30 mm the tensile stresses reduce from 3.01 MPa at the surface ($z = 0$ mm) to -0.443 MPa at $z = 30$ mm in case the stiffness modulus of the AC layer is 5500 MPa. According to Eisenmann (ref.13) this large gradient can result in surface cracking of asphalt concrete layers.

3.2.2.2 The influence of the stiffness modulus of the AC layer on the normal stresses due to a three-dimensional tire stress distribution

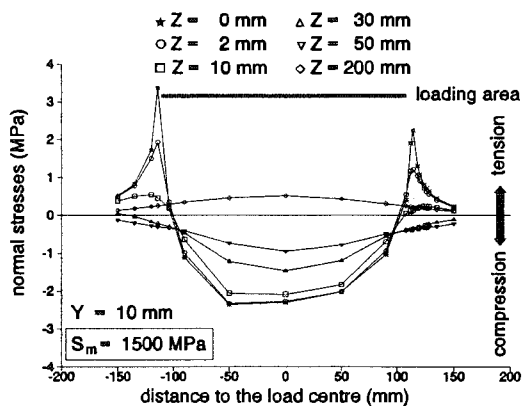
In figure 8 the influence of the temperature (and the stiffness modulus of the AC layer) on the normal stresses in the asphalt concrete layer is shown. In this figure the normal stresses in one y-position at several depths are given comparable to the results in figure 7a.

For the situation with a stiffness modulus S_m of 1500 and 10000 MPa the same conclusion can be drawn as discussed in paragraph 3.2.2.1. Again the largest positive normal stress develops at the place where the largest transverse shear stress component occurs ($x = -115$ mm; $y = 10$ mm). The magnitude of this stress σ depends on the stiffness modulus of the AC layer. In table 1 a comparison of maximal normal stresses in the AC layer is made with several stiffness moduli of the layer and the uniform (1D) or 3D tire stress distribution.

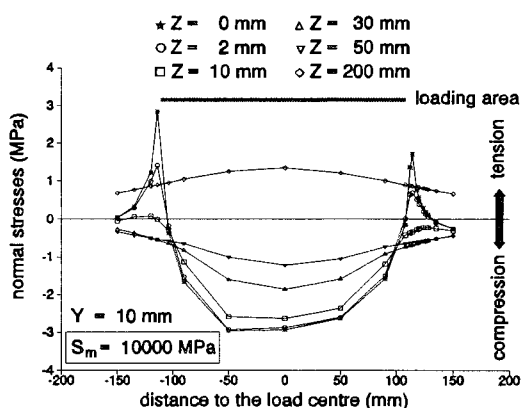
S_m [MPa]	$\sigma_{xx,max}$ ($z=200$ mm) 1D stress	$\sigma_{xx,max}$ ($z=200$ mm) 3D stress	$\sigma_{xx,max}$ ($z=0$ mm) 3D stress
1500	0.433	0.524	3.37
5500	0.937	1.09	3.01
10000	1.17	1.34	2.84

Table.1. Comparison of the maximum normal stress $\sigma_{xx,max}$ in MPa in the AC layer with several stiffness moduli S_m of the AC layer

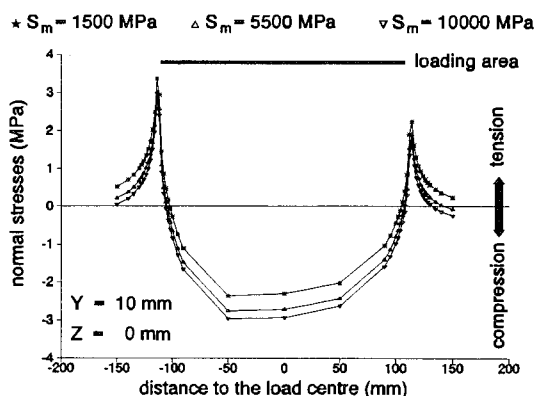
The life span of an AC layer expressed with a number of load repetitions N is in a road dimension method based on the formula:



(a) σ_{xx} at several depths in the AC layer at $y = 10$ mm and $S_m = 1500$ MPa



(b) σ_{xx} at several depths in the AC layer at $y = 10$ mm and $S_m = 10000$ MPa



(c) comparison of normal stresses σ_{xx} at the surface of the AC layer at $y = 10$ mm with several stiffness moduli

Fig.8. The influence of the stiffness modulus of the AC layer on the stresses in this layer

$$N = k \epsilon_{max}^b$$

in which k and b are material parameters which are determined with dynamic fatigue tests. ϵ_{max} is the maximum strain in the AC layer. The value of b is about -3.5 for a Dutch dense asphalt concrete top layer (Ref.14). With this formula and the calculated stresses and strains with

BISAR, the life span of the road structure, based on a 3D tire stress distribution, will reduce with an (average) factor 70 compared to the life span which is determined with a 1D tire stress distribution. The largest reduction in life span will occur at high temperatures due to the large difference in calculated maximal tensile stress between the 1D and 3D stress distribution.

Analogous to the previous paragraph a large reduction of normal stresses occur at the top of the AC layer. The largest reduction occurs in case the stiffness modulus of the AC layer is small. This means that the AC layer is more sensitive for surface cracking at higher temperatures.

4. CONCLUSIONS

Based on the results of a literature review on and the calculation with the three-dimensional tire stress distribution in the contact area between tire and roadway on the normal stresses in the asphalt concrete layer, the following conclusions can be drawn:

- (a) the three-dimensional tire stress distribution is hard to measure or to calculate. The input parameters, used in this paper, only give a rough picture of the stress distribution in the contact area between tire and roadway for a free rolling tire. In case of a driving, breaking or steering tire the 3D stress components can be much larger compared to the free rolling tire. This also means that the normal stresses at the top of the asphalt concrete layer will be much larger than the ones calculated in this paper.
- (b) The normal stresses at the bottom of the asphalt concrete layer are hardly affected by the tire stress distribution at the surface of the layer: the normal stresses due to a uniform vertical tire stress distribution are almost equal to the ones due to a three-dimensional tire stress distribution.
- (c) At the surface of the asphalt concrete layer tensile stresses occur which largely depend on the transverse shear stress component of the three-dimensional tire stress distribution. The maximum tensile stress at the surface of the asphalt concrete layer is much larger than the normal stresses at the bottom of the asphalt concrete layer.
- (d) A large tensile stress gradient occurs at the top of the asphalt concrete layer, due to the three-dimensional tire stress distribution. These tensile stresses and its gradient can cause longitudinal surface cracking and/or ravelling in asphalt concrete road structures.
- (e) A large reduction in permissible number of load repetitions will occur in case the determination of the life span of a road structure is based on the stresses which occur at the top of the asphalt concrete due to a 3D tire stress distribution compared to the 1D tire stress situation. At higher temperatures (and lower stiffness moduli of the AC layer) the life span reduction will be higher than at lower temperatures.
- (f) Based on the results of the calculations with the 3D tire stress distribution it can be stated that the introduction of super

single truck tires with a wheel load up to 70 kN and an inflation pressure of 0.9 MPa (9 bar) will be a disaster for the asphalt concrete layer. These tires will introduce large tensile stresses at the top of the asphalt concrete layer which will result in a large decrease of the life span of the asphalt concrete road structure.

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