The traffic load components in pavement analysis

C. Vale & A. Sousa-Melo
Faculty of Engineering, University of Porto, Porto, Portugal.

ABSTRACT: This paper aims to illustrate the influence of the load model (in particular the components of traffic load) in pavement analysis. Firstly, a state-of-art of the load models for pavement analysis is presented. The load components (contact stresses), their magnitude and the tire-pavement contact area are referred to. Secondly, one analyses the influence of the load components for pavement analysis by modelling, with the Finite Element Method (FEM), three flexible pavement structures, referred in the Portuguese Pavement Catalogue (JAE, 1995) for the traffic class corresponding to 500-800 heavy vehicles a day. The selected pavement structures differ with regard to geometry and pavement materials. The three structures are modelling, in 3D, with DIANA software adopting materials as linear elastic, with different load models. The main conclusion of this work is that the consideration of the three components of load (with uniform distribution) may not substantially alter the numerical results obtained with the exclusive consideration of vertical component of the load.

KEY WORDS: Flexible pavement, load models, tire-pavement contact area, numerical modelling, finite element method.

1 INTRODUCTION

Pavement mechanics considers, on the one hand, the knowledge of the structural behaviour of pavements' structures and their elements and, on the other hand the definition of design rules. This article is primarily concerned with the former aspect.

As with any structure of civil engineering, to model a flexible pavement for analysis purposes, one has to know the different response models and to choose which one gives the best structural response in terms of accuracy and complexity data introduction.

A model is a physic, mathematical or logical system that represents the essential structures of a reality, allowing us to understand or reproduce that reality (Dicionário da Academia, 2001). In other words, a model is a simplification which application allows to explain, to calculate and to anticipate the response due to physic, electrical, chemical… phenomena, disregarding some aspects that are of less importance in the analysis to be performed. The response models are characterized in structural, material and load levels.

The purpose of the numerical analysis presented in this paper is essentially to illustrate the influence in pavement analysis of the load model, in particular of the components of traffic load.

2 BRIEFLY LITERATURE REVIEW

2.1. The load components and their magnitude

The traffic load over the pavement presents three components. One is vertical and the other two (transversal and longitudinal) are horizontal and orthogonal. It must be said that the three load components differ with regard to direction, magnitude, space distribution in tire-pavement contact area and time distribution during loading. The vertical component of the load is substantially higher than the horizontal ones. Following to the vertical component load, in decreasing magnitude, is the transversal component and, subsequently, the longitudinal one (Beer et al., 2002; Tielking and Roberts, 1987).

Beer et al. (1997) have undertook an interesting research by measuring the three-dimensional tyre-pavement contact stresses under slow moving wheel loads of seven different types of tyres loaded over wide ranges of load and inflation pressure. The loads components distribution in contact area is non-uniform due to bending stiffness in the tire structure (Tielking and Roberts, 1987, Woodside et al., 1999; Beer et al., 2002; Steyn and Visser, 2002).

Until recently, the horizontal component of load (transversal and longitudinal) have been disregarded in pavement design because, on the one hand, the vertical component of load has the higher magnitude and, on the other hand, the consideration of the horizontal component in design demands experimental and complex measurements (of them) and high computational efforts during calculations.

2.2. Tire-pavement contact area

The configuration of the tire-pavement contact area depends essentially on the tire type, the tire load applied to the pavement and the tire inflation pressure (Blab and Harvey, 2002; Zafir et al., 1994). Thus, an increase in tire loading or a decrease in tire inflation pressure causes changes in the shape of the tire-pavement contact area: the tire width remains constant while the tire length is increased. (Beer et al., 2002; Tielking and Roberts, 1987).

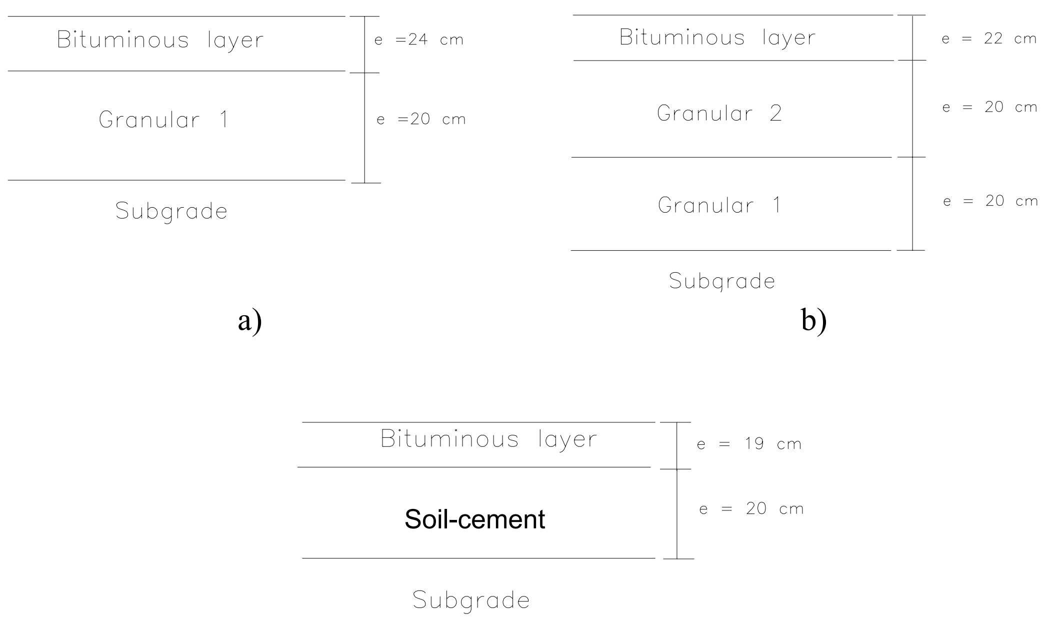
For current tire loads and tire inflation pressure range, the tire-pavement contact area is similar to a rectangle or an ellipse. (Zafir et al., 1994). However, a circular area with a uniform contact stress is still used for design purposes (Yoder et al., 1975).

3 NUMERICAL STUDY DESCRIPTION

3.1 Pavement sections

3.1.1 Geometry

In Figure 1, the geometry of the pavement sections considered in the numerical study is presented.



a) b) c)

Figure 1: Geometry of the pavement sections considered in the numerical study: a) structure 1; b) structure 2; c) structure 3.

The bituminous layer of the three pavement sections has both superficial and structural functions. As far as base and sub-base layers are concerned, the first pavement section (Figure 1a) is composed only by a base layer (a granular one) while, in the second pavement section (Figure 1b), both base and sub-base granular layer are adopted. In the third pavement section (Figure 1c), a sub-base layer is not considered and a soil-cement material composes the base layer.

3.1.2 Materials

In Table 1, the mechanical characteristics of the pavement materials of the three sections are presented. These values are indicated in the Portuguese Pavement Catalogue (JAE, 1995) as reference.

The stiffness modulus of the bituminous mixture was defined by that Catalogue, considering: 1) temperature range of bituminous mixture (depending on the thickness layer) between 24º to 26ºC; 2) vehicle velocity equal to 60 km/h; 3) a 60/70 bitumen class.

For the subgrade material, the stiffness modulus is 80 MPa and the Poisson coefficient is equal to 0.35.

Table 1- Mechanical characteristics of the pavement materials.

Material	**E (MPa)**	**ν**
Bituminous	4000	0.35
Granular 1	$2\times E_{granular\ 1} = 320$	0.35
Granular 2	$2\times E_{subgrade} = 160$	0.35
Soil-Cement	2000	0.30

3.2 Structural Model

In the numerical study, the adopted structural model was a three-dimensional finite element one. This type of model is the most general for pavement analysis, because it allows the consideration of non-symmetrical loading; loading due to dual tires; rectangular tire-pavement contact area (more similar to the real elliptical one than the circular area, generally adopted). The consideration of the former aspects allows more accurate results of the structural behaviour of the pavement.

For pavement sections 1 and 3, 18292 nodes and 3978 elements (20 nodes) composed the mesh; for pavement section 2, 5202 elements and 23616 nodes were considered (notice that section 2 has one more layer than the other two pavement sections).

3.3 Load Models

3.3.1 The magnitude of load components

The adopted magnitude for the vertical component of the load was 662 kPa, which corresponds to the contact stress of the standard axle of 130 kN. To define the magnitude of the horizontal components, the load ratio 10/3.6/1.4 (vertical/transversal/longitudinal) was considered. This load ratio was measured by Beer et al. (1997) for smooth tyre and free rolling, considering slow moving load.

As far as load component distribution is concerned, in the numerical analysis the uniform distribution was adopted. This means that the absence of the bending stiffness of the tires was admitted. It is a simplification to evaluate exclusively the influence of the horizontal components of load in the pavement structural behaviour and not the conjugated effect of that influence with the non-uniform distribution of load components.

In Figure 2, the adopted directions of contact stresses are presented according to Tielking and Roberts (1987).

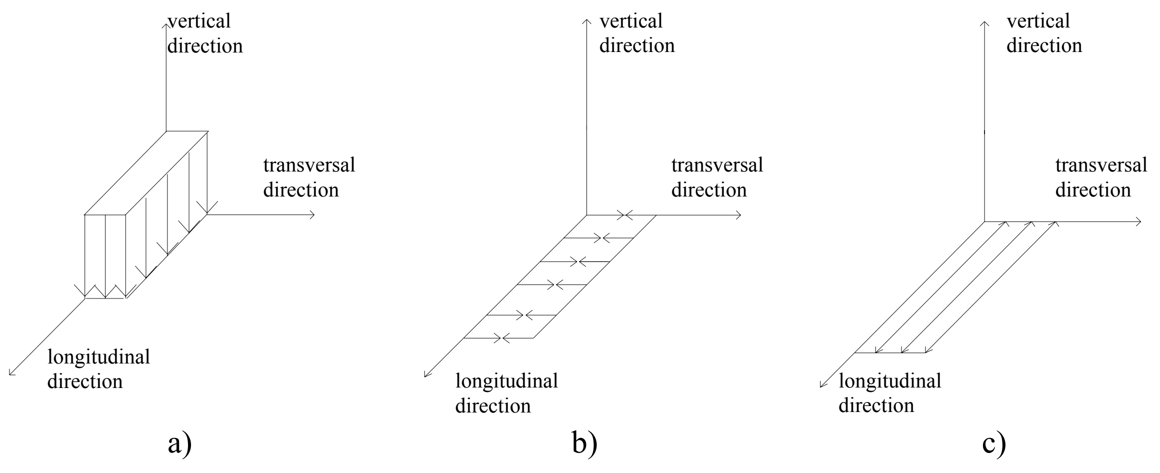


Figure 2: Contact stress directions: a) vertical; b) transversal; c) longitudinal.

3.3.2 The tire-pavement contact area

In the numerical analysis, a rectangular contact area was considered and the ratio between width and length is 60%.

4 NUMERICAL RESULTS AND DISCUSSION

In order to evaluate the influence of the components of traffic loads, four calculations were performed for each pavement structure, considering: vertical component; vertical and longitudinal components; vertical and transversal components; vertical, longitudinal and transversal components. All calculations were performed in static and linear elastic analysis, which is, the type of analysis most adopted for pavement design in all European countries.

In Tables 2 to 4, for the three pavement sections, the maximum superficial deflexion (d_y), the transversal (ε_{transv}) and the longitudinal (ε_{long}) strains at the bottom of the asphalt layer, the vertical strains on the top of the granular layer ($\varepsilon_{vert.1}$ and $\varepsilon_{vert.2}$) and on the top of foundation ($\varepsilon_{vert.F}$) are presented.

Table 2: Numerical results for structure 1.

Structural response	**vertical component**	**vertical+longitudinal components**	**vertical+transversal components**	**3 components**
d_y [μm]	-571	-577	-562	-574
ε_{transv} [με]	201	207	201	206
$\varepsilon_{long.}$ [με]	200	206	197	203
$\varepsilon_{vert.1}$ [με]	-228 / -593	-235 / -607	-228 / -591	-234 / -605
$\varepsilon_{vert.F}$ [με]	-591 / -833	-549 / -845	-537 / -826	-545 / -838

Table 3: Numerical results for structure 2.

Structural response	**vertical component**	**vertical+longitudinal components**	**vertical+transversal components**	**3 components**
d_y [μm]	-531	-536	-528	-533
ε_{transv} [με]	174	179	171	177
$\varepsilon_{long.}$ [με]	174	179	171	176
$\varepsilon_{vert.1}$ [με]	-203 / -459	-209 / -474	-203 / -457	-221 / -472
$\varepsilon_{vert.2}$ [με]	-377 / -529	-386 / -538	-376 / -524	-383 / -533
$\varepsilon_{vert.F}$ [με]	-417 / -613	-401 / -619	-414 / -608	-418 / -613

Table 4: Numerical results for structure 3.

Structural response	**vertical component**	**vertical+longitudinal components**	**vertical+transversal components**	**3 components**
d_y [μm]	- 430	- 434	- 428	- 432
ε_{transv} [με]	57.9	61.7	55.4	59.3
$\varepsilon_{long.}$ [με]	71.3	71.1	69.4	69.1
$\varepsilon_{vert.1}$ [με]	-29 / -65.9	-33.9 / -69.2	-23.3 / -62.5	-28 / -66
$\varepsilon_{vert.F}$ [με]	-130 /-1062	-134 / -1080	-130 /-1060	-132 / -1070

The results presented in Tables 2 to 4 will be analysed in two ways, considering, on one hand, the geometric and material differences of the calculated pavement structures and, on the other hand, the influence, on pavement analysis, of traffic loads' components. Firstly, it must be indicated that positive values are referred to tensile strains and negative results to compression strains.

Regarding the pavement structures, it is clear, as it was expected, that: the structural response of structure 2 is more rigid than section 1 due to the increase of the granular layer thickness; the soil-cement consideration in structure 3 contributes to a global higher pavement stiffness, making it possible to reduce the total pavement thickness.

Two values are indicated (for the same point of the structure) in the vertical strain rows, because the considered geometric point is in the interface of two layers; thus, the first value refers to the upper layer and the second one, to the lower layer. This aspect is also illustrated in Figure 3, which presents, for structure 1, the evolution with depth of the vertical strain on the top of the granular layer.

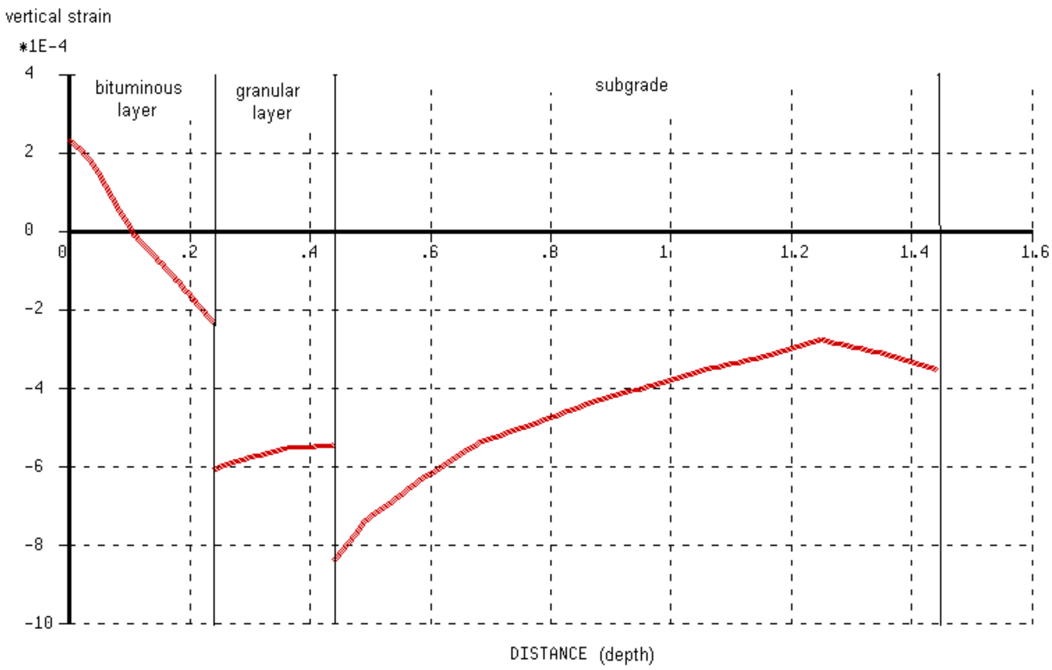


Figure 3: Evolution with depth of the vertical strain of structure 1 (all components of load).

It was also verified that the ratio between the bituminous and soil-cement modulus induces differences of magnitude in vertical and horizontal strains. To illustrate this aspect, in Figure 4, is presented the evolution of those structural parameters in the transversal direction for structure 3 (with the three components of the load) with two ratios between the bituminous and soil-cement modulus: 2 (as Portuguese Pavement Catalogue presents) and 12.5.

It can be seen that, the lower ratio between the bituminous and soil-cement modulus induced: 1) an higher difference, in percentage, between the peak strain and the strain in the vertical axis; 2) the difference, in percentage, between longitudinal strains at different layers (but for the same geometric points of the interface), is higher; 3) vertical strain reaches values in the transversal direction with the same magnitude in the two cases.

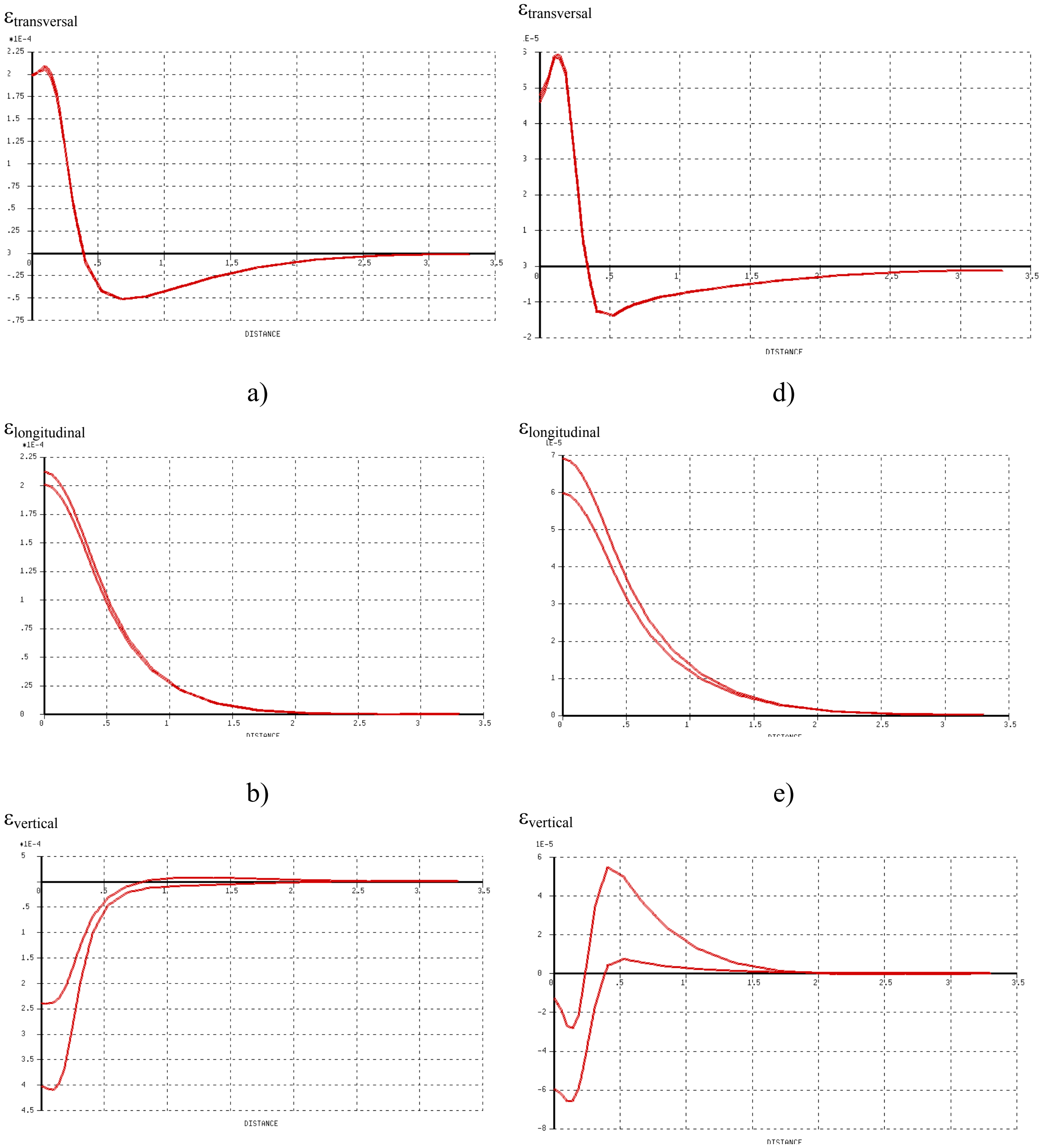


Figure 4: Comparison of the structural behaviour of pavement section 3, in the transversal direction, with different ratios between the bituminous and soil-cement modulus and the three components of load: a) ε_{transv} (ratio equal to 12.5); b) $\varepsilon_{long.}$ (ratio equal to 12.5); c) $\varepsilon_{vert.}$ (ratio equal to 12.5); d) ε_{transv} (ratio equal to 2); e) $\varepsilon_{long.}$ (ratio equal to 2); f) $\varepsilon_{vert.}$ (ratio equal to 2).

About the maximum results of the horizontal strains at the bottom of the bituminous layer, they were obtained in different (but closer) geometric points, as it can be seen in Figure 4 (b) and c) or d) and e))

In Figure 5, for pavement structure 1, the evolutions of the superficial deflection (in the vertical, transversal and longitudinal directions), considering the vertical component of load and all the three load components are presented.

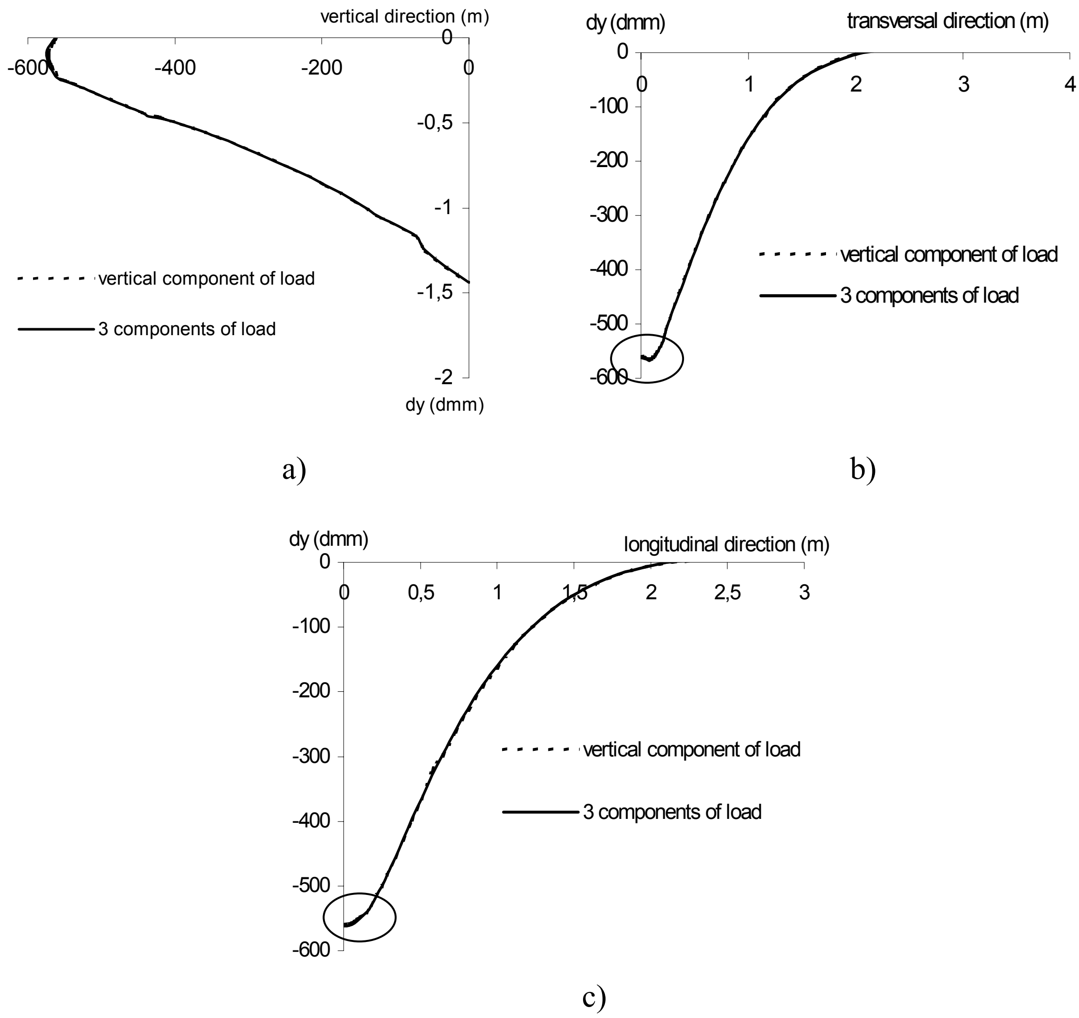


Figure 5: Superficial deflection with the vertical component and all components load: a) vertical direction; b) transversal direction; c) longitudinal direction.

Regarding the influence of the components of traffic loads on pavement analysis, it can be said that the consideration of the three load components, instead of what happens with the vertical component, induces a slight increase of the pavement structural state (stresses and strains), although differences between results are very reduced (0.5%). One expects this aspect to be increased by the adoption of the non-uniform contact stresses. Vale (2004) has already reckoned numerically that the maximum pavement stresses and strains are higher with non-uniform time distribution of the vertical load than with uniform distribution.

5 CONCLUSIONS

This paper presents a numerical analysis of three flexible pavement structures, in order to study the influence of the load components in pavement analysis. Only the ratio 10/3.6/1.4 for load component was adopted in the numerical study; however, it is suggested to analyse other loads' ratio in order to verify or not the results presented in this paper.

By comparing the structural response of the three-modelled pavements, one verifies, as it was expected, that the increase of the granular layer thickness (structure 2) and the soil-cement consideration (structure 3) contribute to global higher pavement stiffness. Thus, these changes in pavement structure can be adopted to reduce the thickness of the bituminous layer for a similar structural behaviour of a thinner pavement or to reduce stresses and strains in the pavement by keeping the same bituminous thickness.

About the consideration of the three components of load with uniform distribution of contact stresses (for slow moving loads), in the performed static analysis this aspect does not substantially alter, in vertical, transversal and longitudinal directions, the numerical results obtained with the exclusive consideration of the vertical component of the load in numerical calculations.

For further research on pavement analysis it is suggested to consider non-uniform time and space distribution of the three load components to evaluate differences of the structural behaviour of pavement during loading. Not only static but also dynamic calculations should be considered in subsequent studies because pavement dynamic analysis can bring new aspects for pavement evaluation.

REFERENCES

Academia das Ciências de Lisboa. 2001. *Dicionário da Língua Portuguesa Contemporânea*, Academia das Ciências de Lisboa e Fundação Caloustre Gulbenkian (ed), vol. II, Lisboa, Portugal.

Beer, M. de, Fisher, C. and Jooste, F.J. 1997. " Determination of the Pneumatic Tyre/Pavement Interface Contact Stresses under Moving Loads and some Effects on Pavement with Thin Asphalt Surfacing Layers", *Eighth International Conference on Asphalt Pavements (ICAP/97)*, Seattle, Washington, USA.

Beer, M. de, Fisher, C. and Jooste, F.J. 2002. "Evaluation of Non-uniform Tyre Contact Stresses on Thin Asphalt Pavements", *9th International Conference on Asphalt Pavements*, Copenhagen , Denmark (in CDROM).

Blab, R. and Harvey, J. T. 2002. "Viscoelastic Rutting Model with Improved Loading Assumptions", *9th International Conference on Asphalt Pavements*, Copenhagen, Denmark (in CDROM).

JAE 1995. *Manual de Concepção de Pavimentos para a Rede Rodoviária Nacional*, Junta Autónoma de Estradas (JAE), Almada, Portugal.

Steyn, W.J. vd M and Visser, A.T. 2002. "Effects of Moving Dynamic Tyre Loads on Tyre-Pavement Contact Stresses", *Proceedings of the 6th International Conference on the Bearing Capacity of Roads and Airfields*, vol.1, Lisboa, Portugal, pp. 253-262.

Tielking, J.T. and Roberts, F.L. 1987. "Tire Contact Pressure and Its Effect on Pavement Strain", *Journal of Transportation Engineering,* vol. 113(1), pp. 56-71.

Vale, C. 2004. *Comportamento Estrutural de Pavimentos Rodoviários Flexíveis. Contributos para Modelação*. Dissertation, Faculty of Engineering, University of Porto, Porto, Portugal.

Woodside, A.R., Woodward, W.D.H. and Siegfried 1999. "The Determination of Dynamic Contact Stress", *Proceedings of the International Conference on Accelerated Pavement Testing*, Reno, Nevada, USA.

Yoder, E.J. and Witczack, K.M.W. 1975. *Principles of Pavement Design*, Second Edition, New York, Wiley-Interscience Publications.

Zafir, Z., Siddharthan, R. and Sebaaly, P.E. 1994. "Dynamic Pavement-Strain Histories from Moving Traffic Load", *Journal of Transportation Engineering,* vol. 120(5), pp. 821-843.