FLEXIBLE PAVEMENT SIMULATION WITH DISTINCT PARTICLE ELEMENT METHOD

Dondi G.
Full professor – University of Bologna – giulio.dondi@mail.ing.unibo.it
Bragaglia M.
Ph.D – University of Bologna – massimiliano.bragaglia@mail.ing.unibo.it
Vignali V.
Ph.D – University of Bologna – valeria.vignali@mail.ing.unibo.it

ABSTRACT

The traditional approach to modelling asphaltic materials is to analyze them at the macro-scale using continuum-based models, in which the micromechanical behavior of the mixture is not explicitly included. So it is not easy to relate observed behavior to the micromechanics of the system.

To overcome this limitation, the Distinct Particle Elements Method (DEM), which schematizes a granular material by particles that displace independently from one another and interact only at contact points, becomes a good answer. In this way, in fact, is possible to analyze the discrete character of asphaltic mixes through a microscopic approach.

This paper investigates the use of Particle Flow Code (PFC), based on DEM, to simulate the visco-elastic behavior of a flexible pavement, loaded by two circular contact patches. The contact forces distribution inside the modelled section and its behaviour have been analyzed. To point out DEM particular features in analysing of pavements fatigue performances, the numerical results have been compared also with elastic models.

Keywords: Distinct Particle Elements Method, flexible pavement, model

1. INTRODUCTION

The conventional approach to modelling a flexible road pavement is to use continuum methods that usually involve undertaking careful experiments over a range of conditions (e.g. stress levels, loading rates, temperatures, etc…), measuring the macroscopic materials response and fitting continuum-based constitutive models to the measured performance [1]. Numerous research works, however, show that for these types of mixtures is very important to take into consideration their micromechanical behaviour, at the scale of an aggregate particle, because it is an important factor in terms of overall system performance [2].

In this way, the Distinct Particle Element Method (DEM), originally developed by Cundall and Strack [3], represents a very useful tool. It discretizes a system using particles that displace independently from one another and interact only at contact points. The analysis procedure consists of three major computational steps [4]:

- internal force evaluation, in which contact forces are calculated;
- integration of equations of motion, in which element displacements are computed;
- contact detection, where new contacts are identified and broken ones are removed.

In a DEM analysis the elements interaction is modelled as a dynamic process that alternates between the application of Newton's second law and the evaluation of a force–displacement law at the contacts. Newton's second law gives the acceleration of an element resulting from the forces acting on it. The acceleration is then integrated to obtain velocity and displacement. The force–displacement law is used to find contact forces from known displacements (figure 1).

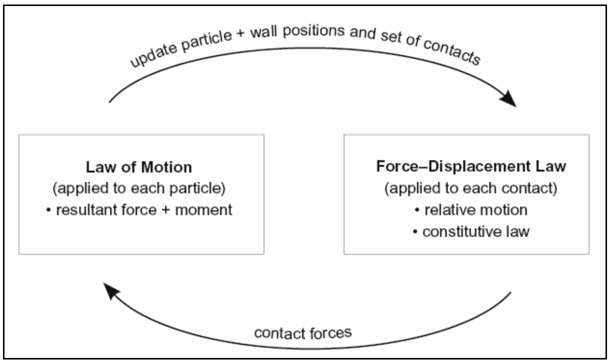

Figure 1: Calculation cycle in DEM [4]

Although DEM has been extensively adopted to reproduce the behaviour of granular materials, there have been a small number of studies reporting the use of this approach to model asphalt mixes ([2][5][6][7][8][9]). These research works, also showing the potentialities of the method, have focus on simulating small specimens and not the complete layers of a road pavement. So the objective of authors was to develop a simple 3D model, that allowed a visualization of the load carrying behaviour of a flexible pavement at microscopic level. In this way it has been necessary to reproduce a pavement section, that replicates the lab mixes, and its loading.

2. PAVEMENT SIMULATION

The 3D modelled pavement has length and width equal to 2 m, and a height of 0.58 m. It includes an asphalt layer and granular sub-base and subgrade courses, thick respectively 0.23 m, 0.30 m and 0.05 m (figure 2).

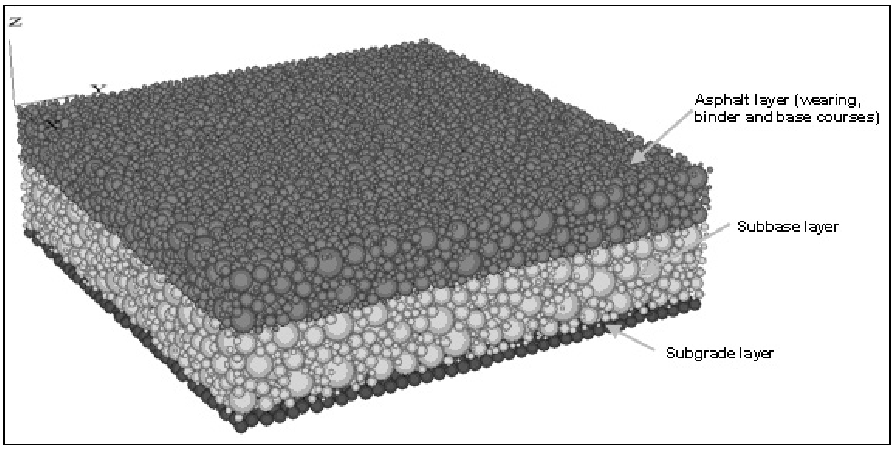

Figure 2: Pavement modelled

The model parameters have been determined by comparing laboratory results with the numerical ones. In according with the granulometric curves of the lab mixtures (figure 3 and 4), the up-scaling generation procedure has been performed [5]. In this way the asphalt and the sub-base layers are composed respectively of 16800 and 11100 particles. The subgrade, instead, has been modeled by particles with the same radius, equal to 0.025 m.

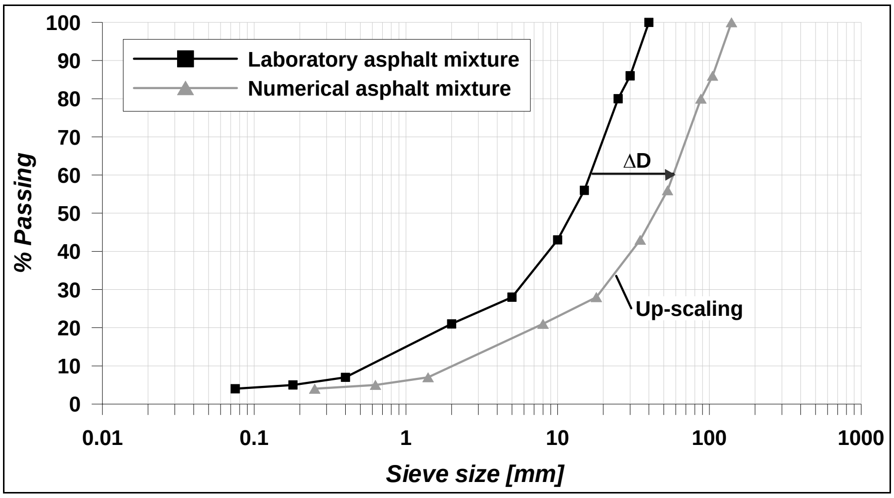

Figure 3: Granulometric curve for asphalt layer

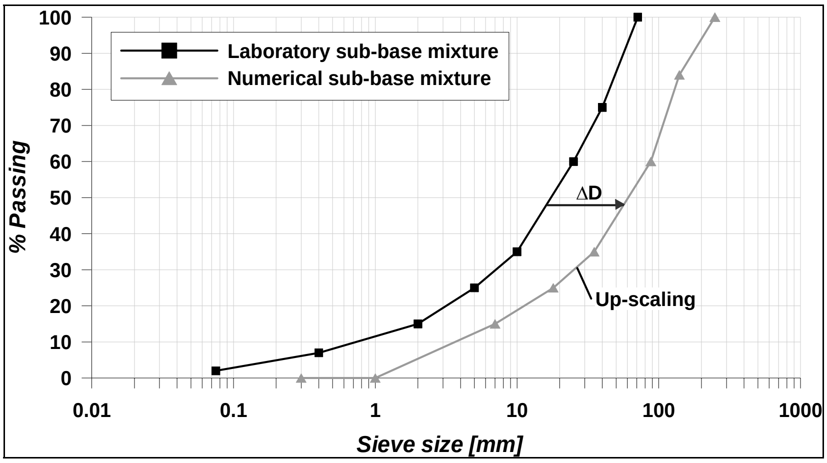

Figure 4: Granulometric curve for sub-base layer

The asphalt layer was simulated with Burger's model shown in figure 5. It can readily be shown that the time dependent stiffness of the Burger's model in i direction is given by [2]:

$$k_i = \left[\frac{1}{K^0{}_i} + \frac{t}{C^i{}_\infty} + \frac{1}{K^i{}_1}\left(1 - e^{-t/\tau^s}\right) \right]^{-1} \quad (1)$$

where:
t is the loading time;
K^i_0 is the modulus of the spring connected in series;
K^i_1 is the modulus of the spring connected in parallel;
C^i_∞ is the viscous damping constant of the dashpot connected in series;
C^i_1 is the viscous damping constant of the dashpot connected in parallel;
τ^s is the relaxation time.

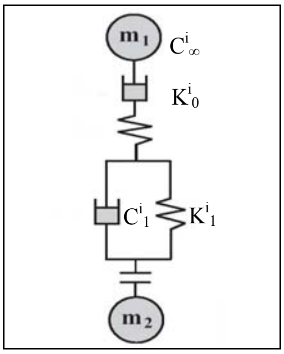

Figure 5: Burger's model [2]

The normal (k_n) and shear (k_s) contact stiffnesses have been estimated from shear modulus (G') and bulk modulus (K') of the lab mixes, and from particle medium radius

(R), percentage volume of air voids (Vv) and average number of contacts per particle (Cv) of model layers (table 1), as follows [2]:

$$k_n = K'\frac{600\pi R}{(100 - V_V)\cdot C_V} \qquad k_S = -G' + \sqrt{\frac{G'^2 + 9CDG'K_n}{4.5CD}} \quad (10)$$

where:

$$C = \frac{C_V \sum L}{\pi \sum R^2}$$

$$D = \frac{1+4\nu}{\left[\frac{1}{\nu^2} + \frac{2}{1-2\nu}\right]^2}$$

ν is the Poisson ratio;
L is the distance between the centres of gravity of two particles in contact.

Table 1: Properties of the lab asphalt mixtures (T = 20°C)

Layer	γ [kg/m³]	ν	K' [MPa]	E' [MPa]	G' [MPa]
Wearing course	2650	0.35	2780	2500	925
Binder course	2650	0.35	2445	2200	815
Base course	2650	0.35	2220	2000	715

Table 2 contains the contact stiffnesses values and the Burger's model properties of the asphalt layer according to equations (1) and (2).

Table 2: Numerical parameters of the contact model of asphalt layer (T = 20° C)

Normal stiffness	k_n [MN/m]	$6.4\cdot10^8$	Shear stiffness	k_s [MN/m]	$6.4\cdot10^7$
	K^n_0 [MN/m]	$1.0\cdot10^9$		K^s_0 [MN/m]	$1.0\cdot10^8$
	K^n_1 [MN/m]	$1.0\cdot10^8$		K^s_1 [MN/m]	$1.0\cdot10^7$
	C^n_∞ [MNs/m]	$5.0\cdot10^7$		C^s_∞ [MNs/m]	$5.0\cdot10^6$
	C^n [MNs/m]	$5.0\cdot10^6$		C^s_1 [MNs/m]	$5.0\cdot10^5$

The granular courses (sub-base and subgrade) were numerically modelled with elastic models, according to lab mixes, by the equations (1) and (2) (tables 3 and 4). The contact friction coefficient (μ) has been estimated from the friction angle of the aggregates of the lab mixes (φ = 35°). In this case: μ = 0.8. To reduce the computational times, a vertical constant pressure has been applied on subgrade, obtaining in this way a density higher than the real one.

Table 3: Properties of the lab granular mixtures

Layer	γ [kg/m³]	ν	K' [MPa]	E' [MPa]	G' [MPa]
Sub-base	2625	0.45	2670	800	280
Subgrade	2300	0.47	830	150	50

Table 4: Numerical parameters of the contact model of granular layers

Layer	k_n [MN/m]	k_s [MN/m]
Sub-base course	$3.6 \cdot 10^{10}$	$3.1 \cdot 10^{9}$
Subgrade course	$1.6 \cdot 10^{10}$	$2.9 \cdot 10^{9}$

The pavement was loaded through two circular contact patches, spaced of 0.10 m, that induced everyone a constant vertical force (N) equal to 30 kN (figure 6). Their radius (R) was equal to 0.109 m, estimated as follow:

$$R = \left[N/(\pi \cdot p)\right]^{0.5} \quad (3)$$

where p is the inflating pressure, equal to 8 bar.

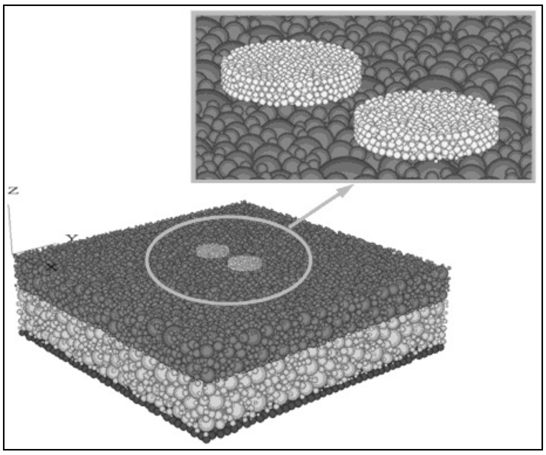

Figure 6: Circular contact patches

The pavement, in particular, has been schematized by a visco-elastic constitutive model and it has been loaded by one static cycle. In this way it is possible to obtain a simulation able to study the pavement behaviour under dynamic loads. In next researches, in fact, it will be possible to analyse its fatigue performances varying the loading velocity and the number of loading cycles.

3. MODELLING RESULTS

The contact forces distribution inside the pavement and its behaviour have been monitored. Figure 7 shows how the contact forces induced by loading process are distributed inside the pavement: they develop at the contact patches and they spread before in the asphalt layer and then in the sub-base course. They have a radial distribution around each contact patch and theirs intensity is mostly compressive.

The behaviour of the modelled pavement has been investigated on the symmetrical plane z-x, passing through the centre line of the two contact patches, in correspondence of different interfaces (figure 8). The planes a-a, b-b and c-c represent respectively the interface between tyres and asphalt layer, asphalt and sub-base courses and sub-base and subgrade layers.

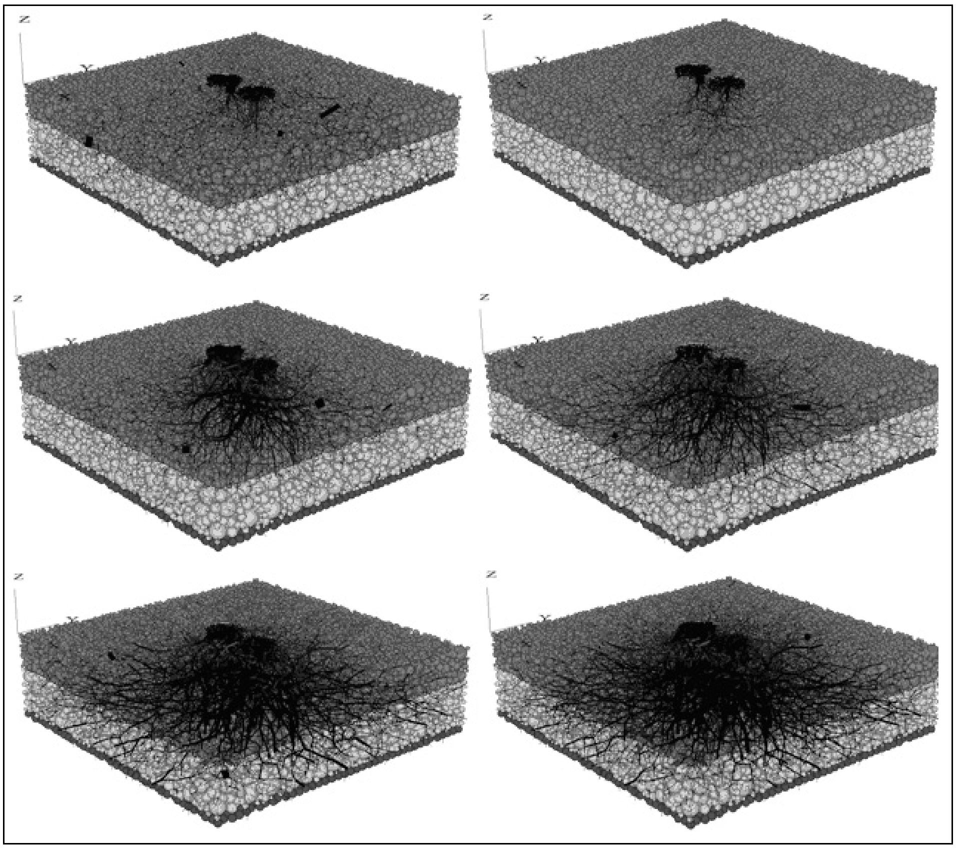

Figure 7: Contact forces distribution inside the specimen during the loading

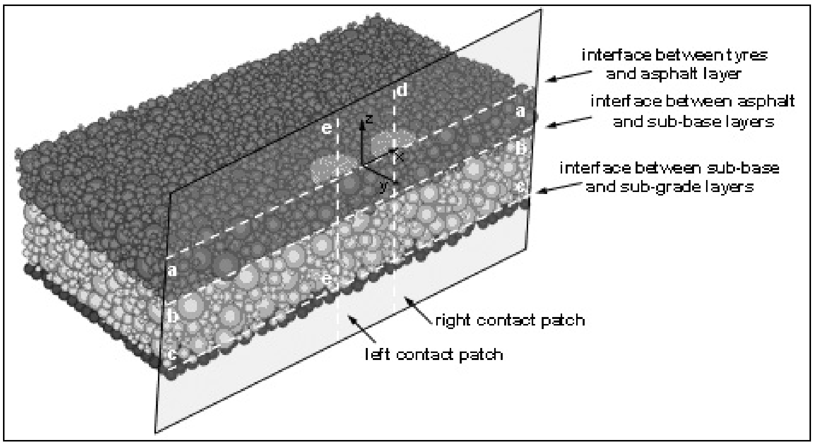

Figure 8: Interfaces for measurement of displacements and stresses

Through special measurement circles [4], according to reference system of figure 8, U_{zz} displacements and σ_{zz} stresses have been measured. To point out DEM particular features for the performance related modelling of asphalt pavements, the numerical results have been simulated moreover with the BISAR code, which considers an elastic multi-layer system (figures 9 and 10). U_{zz} and σ_{zz}, in particular, have been measured for particles placed under and over each interface. In the BISAR case the pavement has been modelled using properties shown in table 5, according to tables 1 and 3. The last layer (elastic layer) has been reproduced with very high Young modulus and Poisson ratio, in order to simulate the boundary condition of the DEM model, composed of an horizontal plane under the pavement section.

Table 5: Properties of the pavement layers in BISAR

Layer	Thickness [m]	Young modulus [MPa]	Poisson ratio
Asphalt layer	0.23	2200	0.35
Sub-base course	0.30	800	0.45
Subgrade course	0.05	150	0.47
Elastic layer	---	10^{12}	0.50

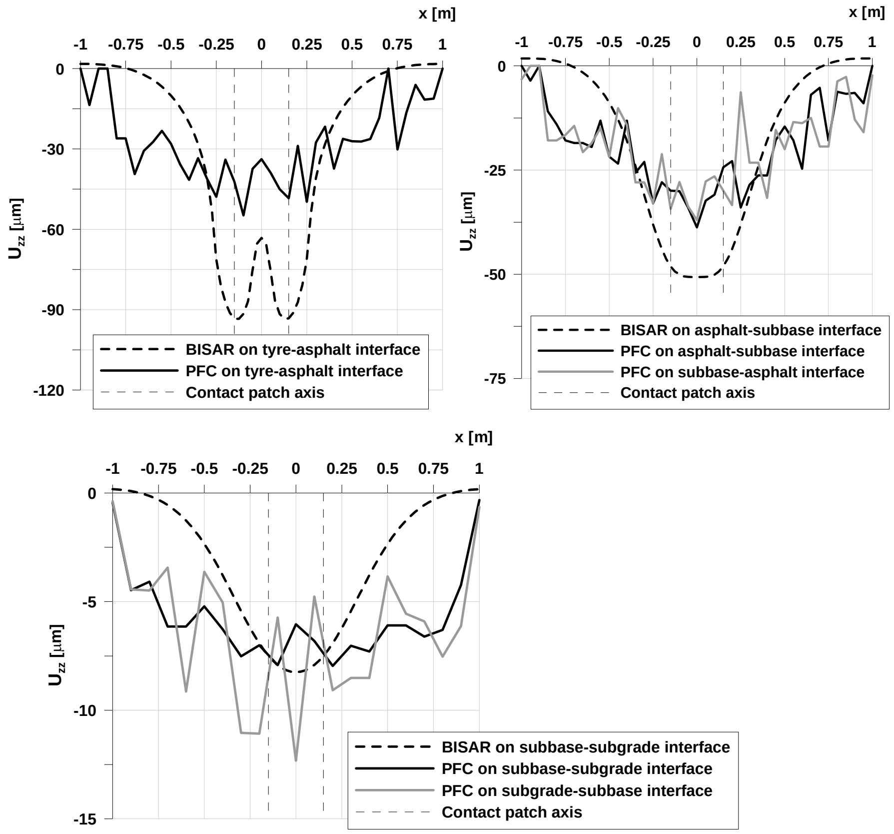

Figure 9: σ_{zz} at different interfaces

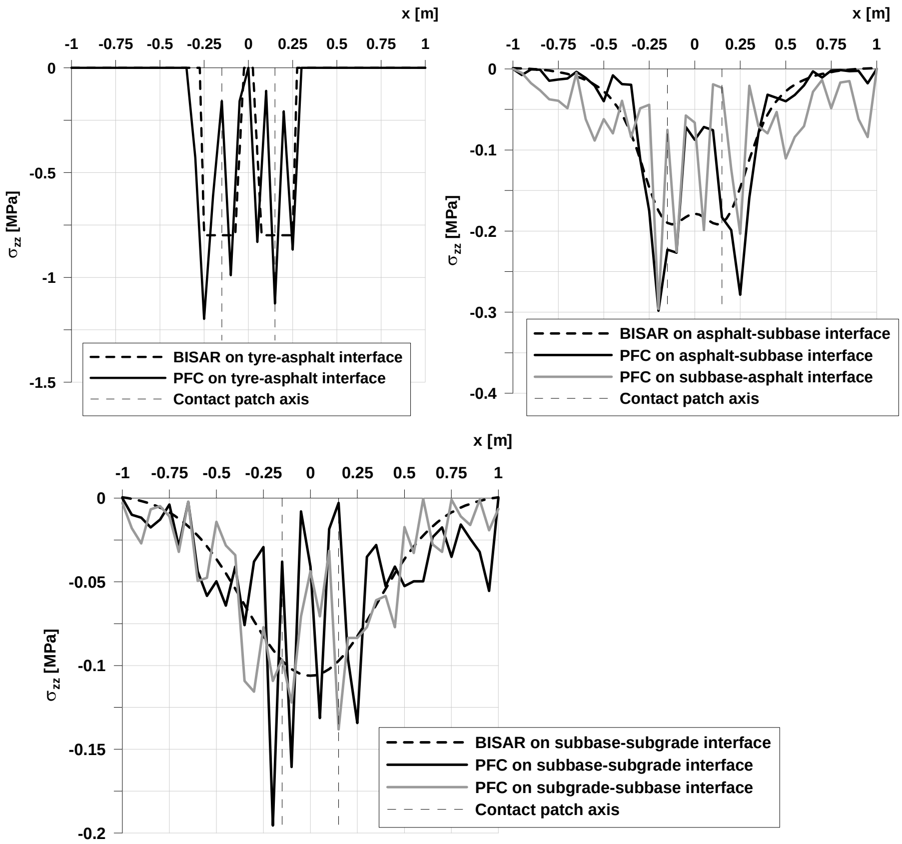

Figure 10: U_{zz} at different interfaces

The comparison between DEM and BISAR results shows a good agreement: stresses and displacements explain a trend with a maximum beneath the two contact patches (represented by vertical dotted lines) and a progressive decrease going away from the point of load application to the system boundary. The comparison between DEM results at different interfaces are in according better on b-b plane (asphalt-sub-base layers, figure 7) than on c-c (sub-base-subgrade layers); this is probably due to the particles interlocking and size, which depends mostly from the granulometric distribution of the mixture. The interlocking effect decreases, in particular, with the reduction of the particles assortment. So the subgrade simulation by elements with the same radius allows a reduced interlocking between adjacent courses. Table 6 shows the comparison between DEM and BISAR data in terms of stresses (σ_{zz}) and displacements (U_{zz}).

Table 6: Comparison between DEM and BISAR data

Interface	Δ σ_{ZZ} [%]	Δ U_{ZZ} [%]
Tyre-asphalt layer	1.60	4.49
Asphalt-sub-base layers	3.03	4.92
Sub-base-asphalt layers	1.55	3.29
Sub-base-subgrade layers	1.07	8.33
Subgrade-sub-base layers	3.14	0.12

The behaviour of the modelled pavement has been investigated also on the symmetrical plane z-y, passing through the centre line of the two contact patches (planes e-e and d-d) (figure 8). Through special measurement circles [4], according to reference system of figure 8, σ_{zz}, σ_{xx} and τ_{zx} stresses have been measured and the numerical results have been compared with the BISAR ones (table 5) (figure 11). Table 7 shows the comparison between DEM and BISAR data.

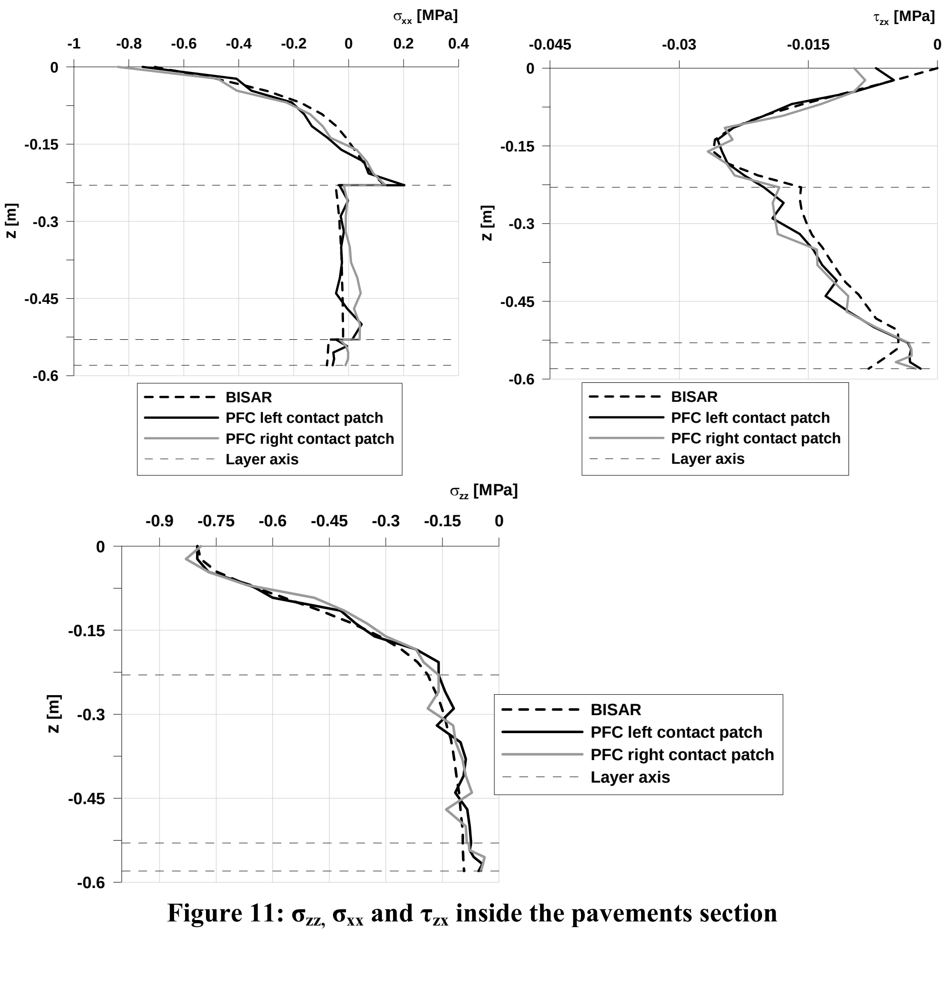

Figure 11: σ_{zz}, σ_{xx} and τ_{zx} inside the pavements section

Table 7: Comparison between DEM and BISAR data

Contact patch	$\Delta\,\sigma_{ZZ}$ [%]	$\Delta\,\sigma_{XX}$ [%]	$\Delta\,\tau_{ZX}$ [%]
Left	5.53	7.00	8.04
Right	5.66	5.87	8.63

The analysis of obtained results shows a good agreement between the modelled data and the BISAR ones and it points out the power of DEM approach. Knowing the relationships between the mechanical macroscopic behaviour and the microscopic parameters of the model, DEM well supports the researcher in the implementation of new methods for studying pavements fatigue behaviour.

CONCLUSIONS

Based upon the developed research work, in which the 3D DEM approach has been used to model the behaviour of a flexible road pavement, the following concluding remarks can be stated:

- for pavement layers simulation the up-scaling technique, which allows to enlarge the particles diameter with a great reduction of their number and consequently of the computational times, has been performed with great results;
- the comparison between DEM and BISAR data shows a good agreement, both in qualitative and quantitative manner. In particular, while BISAR provides average values, the DEM approach gives the peak ones, which are a more reliable description of real phenomena;
- the obtained results have permitted the evaluation of potentialities and limits of the DEM approach: allowing a very reliable description of real phenomena, it represents a valid evolution of the traditional methods. To obtain these results, however, long calculation times are necessary, that, using the actual processors, induce to adopt models of small dimensions or formed by a limited number of particles. Using a Pentium 4 processor, for example, the pavement generation and the loading process have been going on for 15 and 20 days respectively. There are, moreover, some difficulties to relate the microscopic parameters to the macroscopic ones derived from literature or lab tests. While the first aspect will be resolved adopting more efficient processors, the second asks for intense experimental researches based on tests.

REFERENCES

1. VALLEJO L. E., LOBO-GUERRERO S. & HAMMER K. (2006), “Degradation of a granular base under a flexible pavement: DEM simulation”, *International Journal of Geomechanic*s, vol. 6, n. 6 , pp. 435-439;
2. COLLOP A.C., MCDOWELL G.R. & LEE Y. (2004), “Use of the distinct element method to model the deformation behavior of an idealised asphalt mixture”, *International Journal of Pavement Engineering*, n. 5, pg. 1-7;
3. CUNDALL P. A. & STRACK O. D. L. (1979), “A discrete numerical model for granular assemblies”, *Geotechnique*, vol. 29, n. 1, pg. 47-65;

4. ITASCA (2002), *PFC3D: Particle flow code in three dimensions*, Itasca Consulting Group;
5. DONDI G., BRAGAGLIA M. & VIGNALI V. (2005), "Bituminous Mixtures Simulation With Distinct Particle Elements Method", *III International SIIV Congress*, Bari, 22-24 September;
6. DONDI G., VIGNALI V. & BRAGAGLIA M. (2006), "Modellazione mediante elementi distinti particellari delle prove sui materiali granulari", *XVI Convegno Italiano di Meccanica Computazionale*, Bologna, 26-28 giugno;
7. DONDI G. & BRAGAGLIA M. (2006), "Modellazione ad elementi distinti particellari della prova ITSM", *XVI Convegno Nazionale SIIV*, Arcavacata di Rende (CS), 20-22 settembre;
8. CHANG K.N.G. & MEENGODA J.N. (1997), "Micromechanical simulation of hot mix asphalt", *Journal of Engineering Mechanics*, vol. 123, n. 5, pg. 495-503;
9. BUTTLAR W.G. & YOU Z. (2001), "Discrete element modelling of asphalt concrete", Transportation Research Board, vol. 1757, n. 01-3454;
10. BRAGAGLIA M. (2007), "Studio del comportamento visco-elastico del conglomerato bituminoso con il metodo degli elementi distinti particellari", Tesi di dottorato in Ingegneria dei Trasporti, Università di Bologna.