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STEEL REINFORCEMENT INFLUENCE ON THE DYNAMIC BEHAVIOUR OF BITUMINOUS PAVEMENT

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ABSTRACT:

It has been investigated the theoretical dynamic response of a bituminous pavement subject to dynamic loads with harmonic variation.

The study, developed through a FEM mathematical model, has allowed to underline that the strain rate generally dependent, beyond that on the intensity of the load, on his frequency and on the bituminous concrete own damping. The bituminous concrete has been modelled like elastoplastic material. The results show that when the load frequency is close to the resonance frequencies, high stresses are induced. In these cases the internal damping of the bituminous concrete reduces the stress amplification. High stiff reinforcement can produce, in some cases, the same effect with higher reduction. Also cracks propagation in presence of stiff reinforcement has been investigated. A remarkable increase of load repetition has been obtained to have, for a reinforced paving, the same crack propagation. The analysis has been developed particularly with reference to the metallic reinforcement Road Mesh®, manufactured and commercialized by Officine Maccaferri Spa.

1. INTRODUCTION

For the design of pavings, because of the high complexity and large range of variability of the parameters very simple calculation models are normally used. These methods often lead to accepted overvaluations of the induced stresses; in many cases however static models can involve remarkable errors. In this paper we would like to show how the dynamics of loads can produce different effects on the same paving both in relation to the main characteristics of the load both for the variations of the internal characteristics of the paving.

Four different F.E.M. models for the same road paving have been developed, with or without the presence of an initial crack, and with or without the presence of a steel reinforcement. These models have been analysed from the static and dynamic point of view. Throughout the FEM simulation the effect of the reinforcement on the internal stress-strength distribution and on cracks propagation, have been investigated.

As pavement reinforcement the Road Mesh® product has been taken into account. The Road Mesh® is a steel reinforcement well known on the Italian and European Market.

It consists of a double twisted steel wire mesh with stiffening transversal steel bars. The reinforcement is manufactured and sold by Officine Maccaferri Spa.

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2. MODEL DESCRIPTION

A flexible pavement which is commonly used in Italian for roads with ordinary loads, has been studied and analysed. The Fig. n° 1 show the thickness and some characteristics.

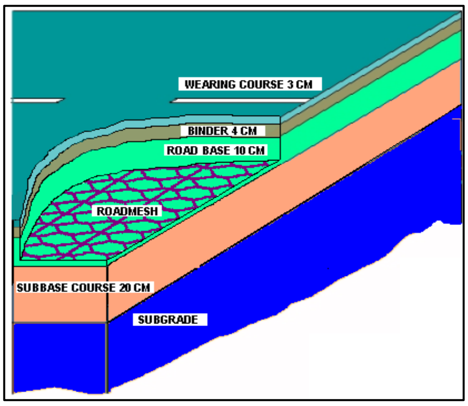


Fig. 1

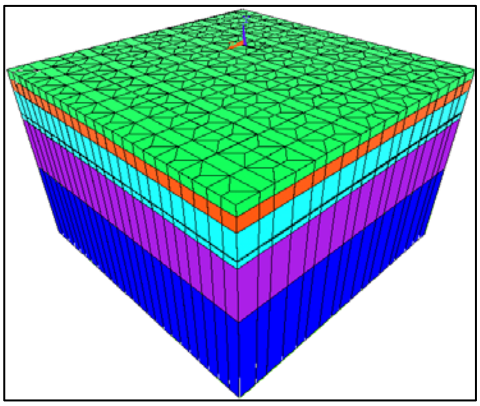


Fig. 2

A 3-dimensional model has been assumed for the numerical simulation. The dimensions of the modelled portion are 0.96 m x 0.96 x 0.77 m. Boundary condition has been assumed to simulate the confinate conditions of the real model. A model depth of 0.77 m has been assumed, as the lower layers have negligible incidence. Fig. 2 shows the modelled geometry. BRICK elements have been used, assuming an elastoplastic behaviour for materials. Dynamic analysis have been carried out taken into account some percentage of damping to consider the energy dissipation due to the viscous behaviour of the bituminous concrete.

Tab. n° 1 shows the main values of the adopted geomechanical parameters of the different materials.

Layer	Thickness [cm]	Modulo [GPa]	Coefficient. Poisson	Spec. Weight Kg/m ^{3}	Friction angle	Cohesion MPa
Wearing course	**3**	**2.7**	**0.47**	**1700**	**43°**	**0.5**
Base course	**4**	**2.7**	**0.47**	**1600**	**43°**	**0.5**
Road base	**10**	**1.6**	**0.45**	**1500**	**45°**	**0.35**
Foundation	**20**	**0.2**	**0.35**	**1400**	**47°**	**0.01**
Subgrade	**40**	**0.1**	**0.30**	**1300**	**30°**	**0.025**

Tab.1: materials characterisation

On the pavement a 40 kN vertical and uniform distributed load has been applied; the load is assumed to be acting on a circular area, radius 0.16 m.
This configuration leads, with static loads, to stress level generally lower than the elastic limit but in any case very close to the plastic field. This condition allows to put into evidence some characteristics of the structural behaviour of the bituminous pavements. The load position is outlying to obtain, for the modal dynamic analysis, all the vibration mode shape. In fact, a centred load is not able to start up any vibrations made shapes when applied in a node area, as for example the central area of the modelled structure.
The steel reinforcement, when present, has been simulated by BEAM elements, assuming the behaviour of the material as linear elastic.

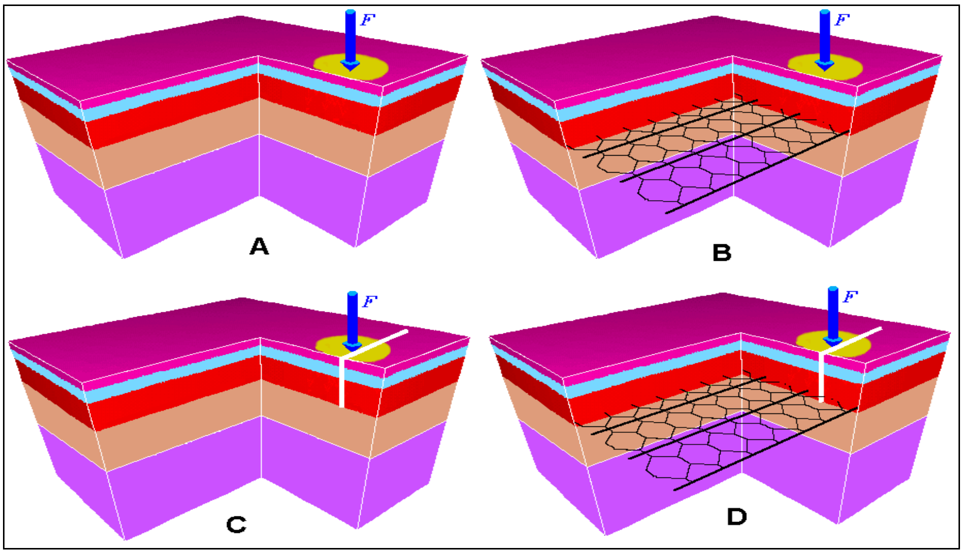


Fig.3

Fig. n° 3 shows the four considered geometries: the Model A rapresents a typical pavement; in
to the Model B the steel reinforcement has been inserted; the Models C and D, which are respectively similar to Models A and B, have a crack under the load. Several analysis have been carried out for different values of bituminous concrete damping.
Different positions of the reinforcement have been analysed as well (+2, +4, +6, + 8 cm from the foundation interface layer) .

3. ANALYTICAL

The system is governed by the expression $[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F\}$, where:

[M] = structure mass matrix
[C] = structure damping matrix
[K] = structure stiffness matrix
[F] = time-dependent forcing function

$\{\ddot{u}\}$ = nodal displacement vector
$\{\dot{u}\}$ = nodal velocity vector
$\{u\}$ = nodal acceleration vector

The complete expression for the structure damping matrix , [C], is the following:

$$[C]=\alpha[M]+\beta[K]+\sum_{j=1}^{Nmat}\beta_j[K_j]+[C_\xi]+\sum_{K=1}^{Nel}[C_k]$$

Damping can be specified by any or all of the following methods: mass damping α; structural damping (constant β, material dependent β_i); constant equivalent viscous damping ratio ξ; discrete element damping.

In this paper, structural damping was included. This allowed models to run with a different damping value, β_i, in each layer of the superstructures.

Structural damping depends on the natural frequency: $\beta_i=\frac{2\xi_i}{\omega_i}=\frac{\xi_i}{\pi f_i}$ where $\omega_i = 2\pi f_i$ and f_i is the frequency of mode *i*.

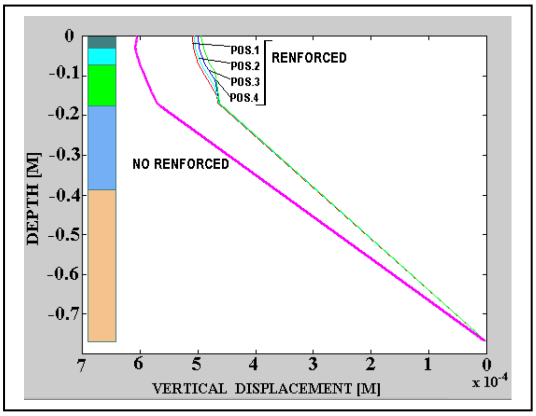
Modal analysis is used to determine the natural frequency and mode shapes of a structure. Free, undamped vibrations are assumed in ANSYS (F(t)={0} and [C]= 0). A modal analysis should precede any other dynamic analysis. The governing equation then is: $[M]\{\ddot{u}\}+[K]\{u\}=\{0\}$. For a linear system, free vibration will be a harmonic of the form, $\{u\}=\{u_0\}\cos\omega t$. For the non-trivial solution, the determinant $\left|[K]-\omega^2[M]\right|=0$.

This is an eigenvalue problem, whose solution are the eigenvalues and the corresponding eigenvectors. The eigenvalues represent the natural frequency of the system and the eigenvectors the corresponding mode shapes. Harmonic analysis is used to determine the response of a structure to harmonic sinusoidally varying forces. The function F(t) is a periodic value of known amplitude and frequency. The equation of motion, therefore, can be solved to obtain displacements such as function of frequency. The equilibrium equation will now be: $[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}=\{F(t)\}$

4. RESULTS

The dynamic characteristic of loads has a big incidence on the structural behaviour of pavements. By approaching to pavement design through static models, a proportional relationship has been obtained between loads and strains. Some static evaluation has been previously carried out; the result as shown in Fig. n° 4 and 5, is a reduction of vertical deflection. The tensile stresses in the road base and the foundation layer are rather reduced.

The steel reinforcement has not any influence on vertical compressive stress component.



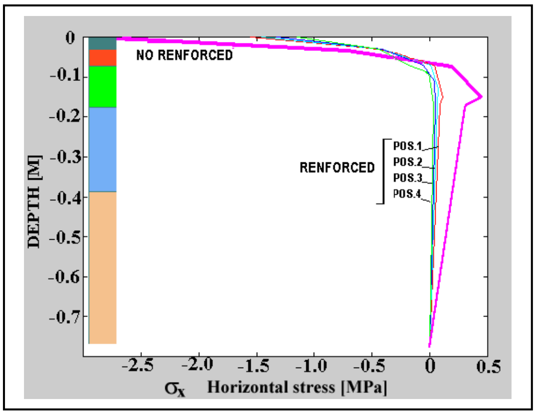
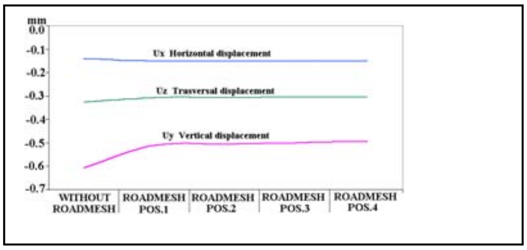


Fig. 4

Fig.5

Fig. n° 6 and 7 show that the vertical position of the reinforcement has not a big influence on the stress level into the bituminous concrete.



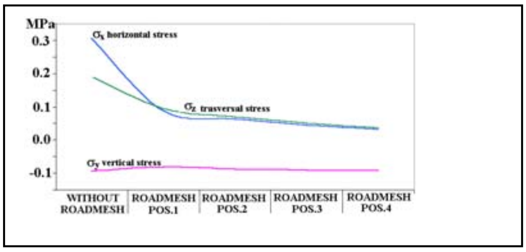
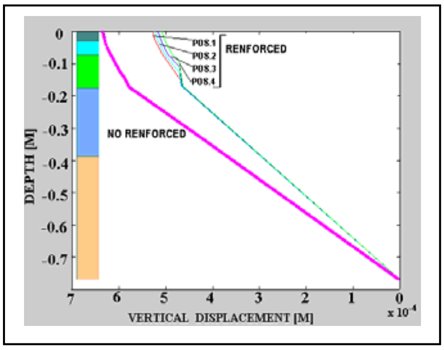


Fig. 6

Fig. 7

When cracks are present, vertical deflections increase in the same way, independently from the presence of the reinforcement, instead the crack opening, when the reinforcement is present, is rather reduced (Fig. n° 8 and 9).



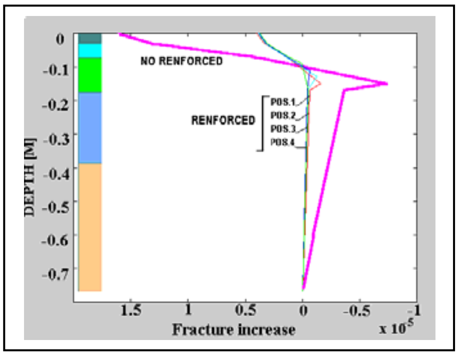


Fig. 8

Fig. 9

By increasing vertical load plasticized zones come out in the foundation layer and in the base course. In plastic condition Uy and σx (Vertical displacement and horizontal stress respectively) of the two structures (reinforced and unreinforced) get close to each other . Different is the behaviour when cracks are present previously. In this case, even in plastic conditions cracks opening of the reinforced structure are smaller. Fig. n° 10 and 11 show the two different deflection of A and B Models; for the reinforced model, a smaller portion of the structure is interested by vertical displacement.

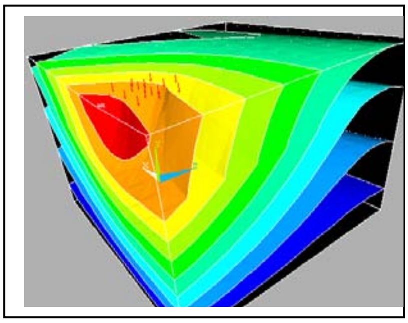


Fig. 10

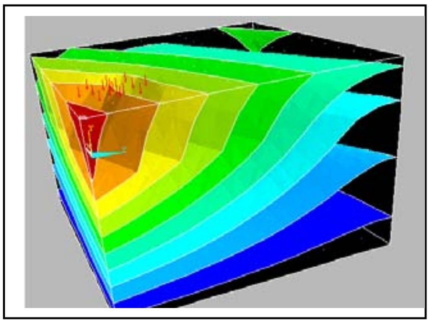


Fig. 11

The dynamic approach shows that the relationship between stress-strain and load intensity is not proportional; even the load frequency influences the stress strain distribution. With dynamic loads, vertical deflection is amplified when the load frequency is close to the resonance frequencies of the structure. The following Fig. n°12,13,14 and 15 show some modal shapes.

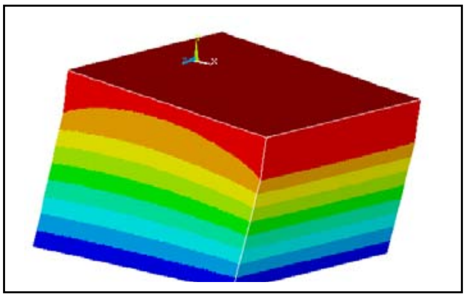


Fig. 12: 9.1499 Hz

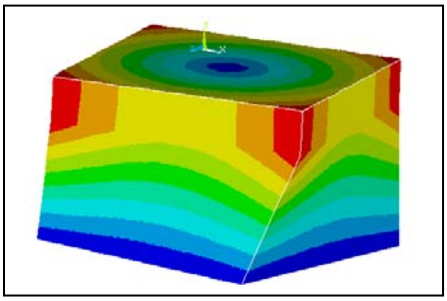


Fig. 13: 10.503 Hz

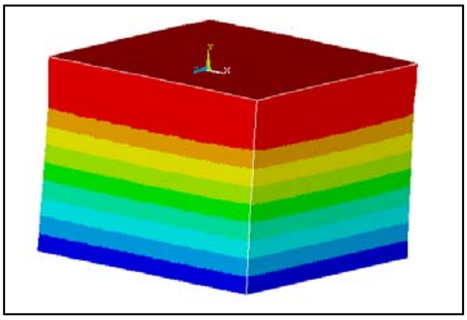


Fig. 14: 21.595 Hz

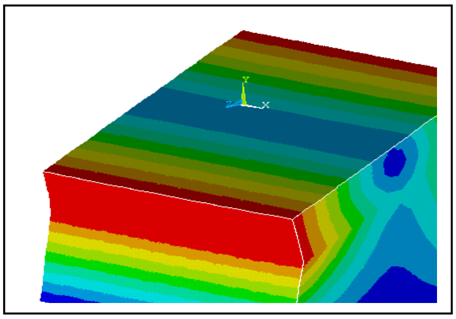


Fig. 15: 24.258 Hz

The obtained first resonance frequency of the analysed model is close to 10 Hz. By the increasing of the geometry dimensions of the model, generally, resonance frequencies are reduced; the higher frequencies are more reduced than the lower ones. On the contrary, the stiffness of the materials produces increase of the resonance frequencies. The steel reinforcement, as it has a stiffening effect on the pavement, produces an increase of the pavement resonance frequencies. It is important to notice that the correspondent frequency of loads applied by heavy vehicles is often close to the resonance frequency of the pavement.

The bottom layers of a pavement are generally elastically stressed, later than the upper layers due to the damping of the bituminous concrete. This might be put into evidence with a modal analysis, characterizing the materials with a certain damping..

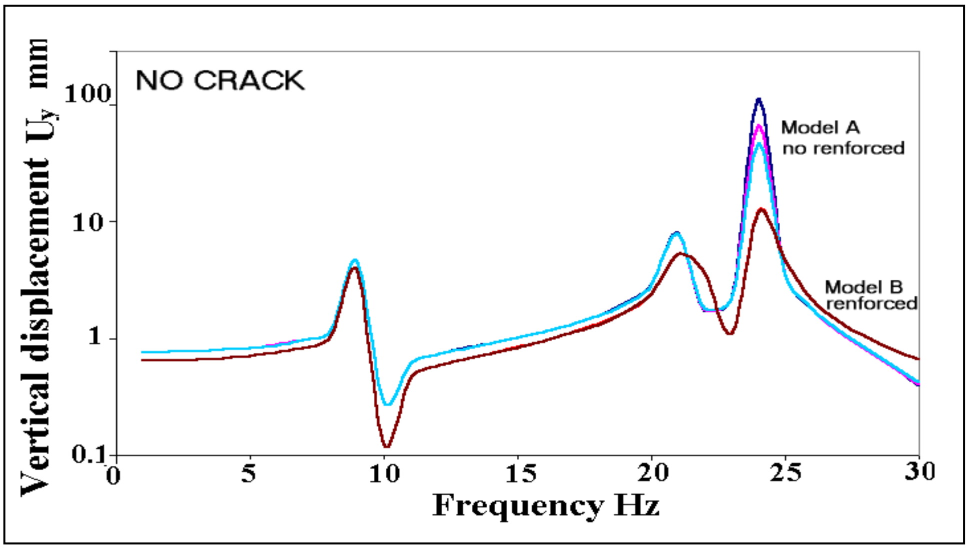


Fig. 16

As already shown for the static approach the reinforcement reduces the stress and strain level; this reduction becomes remarkable close to the resonance frequency for which generally stress and strain level is very high. It is very important to put into evidence the following outcome: the relationship between stress and strain and load frequency is almost independent from damping, when the reinforcement is present.

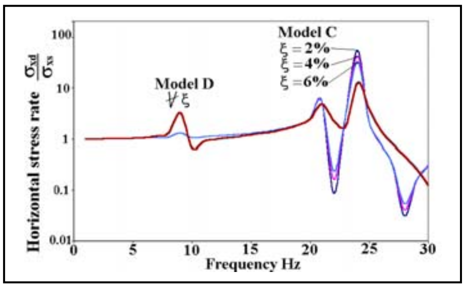


Fig. 17

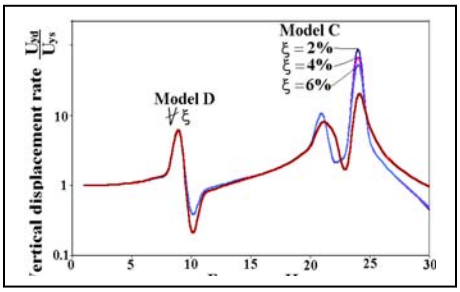


Fig. 18

The curves in Fig. n°18 give the vertical deflection, " normalized" by the static deflection, versus the load frequencies. These curves refer to the Model C and D, that is unreinforced and reinforced with the presence of start cracks. Three different percentages of damping have been taken into account (ξ = 2%, 4% e 6%). It is well evident that the same load in terms of intensity may produce different stresses in relation to the ratio between its frequency and resonance frequencies of the structure. The stress level may be lower or higher than the one induced by the static load. The Fig. n° 17 shows the same comparison with reference to plain stress in to the road base, close to the foundation layer. Further simulations have been carried out to evaluate the growing of the crack opening versus load frequencies. The results are shown in Fig. n° 19.

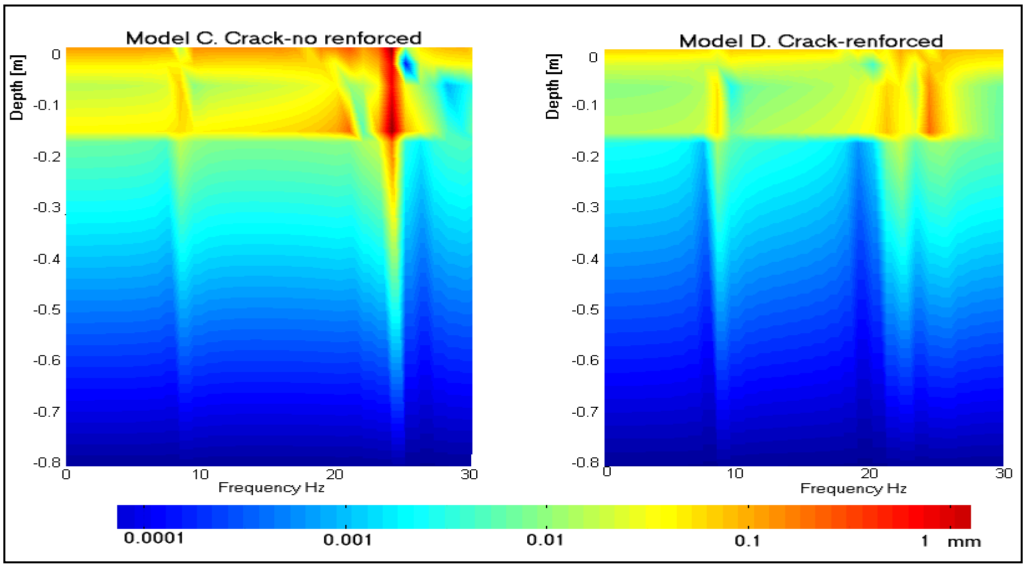


Fig. 19

Some frequencies are particularly damaging for the analysed model. These frequencies are close to 24 Hz , that is close to the 5th and 6th resonance frequency. Rather different is the behaviour of Models C and D for these values of load frequencies. For the Model C the crack opening increases quickly, until the surface is reached. For the Model D the presence of the reinforcement reduces the growing of the cracks, preventing that the cracks get to the surface. It is important to underline that for the unreinforced Model even increasing the material damping , it is not possible to obtain the same result. It is evident that this different behaviour may influence the pavement life. In order to better show these differences Fig. n° 20 has been prepared.

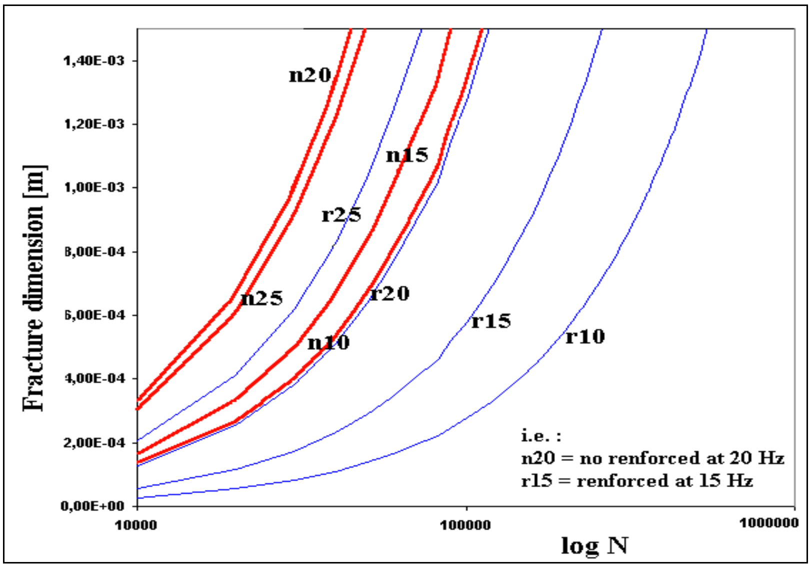


Fig. 20

For each frequency it is represented both the curve of the reinforced model and the curve of the unreinforced one. For every load frequency value the steel reinforcement involves smaller increase of the cracks.

CONCLUSIONS

A FE model of a flexible road superstructures, with and without the steel reinforced Road Mesh®, was developed in order to understand its dynamic behaviour and its modal damping characteristics. Static, modal and harmonic analyses were performed and result extracted. Parameter studies were also carried out, with various reinforced position and with various viscous damping ratios of the bituminous concrete.

The aim was to put in evidence how the stress strain level depends on the dynamic characteristics of the load and from the geomechanical characteristics of the material of the pavings.

Furthermore, it has been underlined that the Road Mesh reinforcement, thanks to its high stiffness, can influence the behaviour of the whole structure.

Close to the resonance frequencies, that is when high strain are induced, the reinforcement has an equivalent damping effect which is much bigger than the damping which may be normally present in the bituminous concrete. It is even more interesting, the outcome in presence of existing cracks.

The considered reinforcement is able to oppose the growing of cracks, that is the reflection towards the surface.

This performance has a big influence on the paving life, having as a consequence a remarkable increase of it.

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