Traffic Vibration Damping With Innovative Materials: Development And Calibration Of a Simulation Model

D'Andrea Antonio
Professor of Road and Railways Construction – University of Rome "La Sapienza"

Urbani Luca
Civil Engineer, PhD Student in Railway Engineering – University of Rome "La Sapienza"

Bonin Guido
Civil Engineer, Assistant Researcher – University of Rome "La Sapienza"

SYNOPSIS

The reduction of vibrations transmitted by transport infrastructures, without increasing too much the construction cost, is going to be a very important issue to deal with. The most effective construction techniques used up to now are based on very complex and expensive solutions (such as floating slabs) and on the use of special and once again expensive materials (such as elastomeric mats). One of the possible innovative techniques is based on the use of hot mix asphalt in which a share of the traditional aggregates is substituted with rubber granulate (2 – 4 mm) produced using waste tyres. This material could be used as sub ballast layer in railway constructions and as binder or base layer in road construction. "Modified" hot mix asphalt results in lower elastic modulus and higher loss factor compared with the traditional one, it can be produced with the same machines and procedures resulting in comparable costs, as a consequence it can be regarded as a very promising material to be used in the traffic vibration control field.
The prediction of the effectiveness of vibration damping systems is very complex due to the number of variables involved and to the complexity of their relationships. Simulation and thence the possibility of a low cost "try and error" approach becomes in this context an obvious answer to the problem, but once again the complexity of the systems, the peculiar dynamic behaviour of involved materials makes reliable models hard to be defined and calibrated.
The proposed approach is based on the calibration of the materials behavioural models comparing real and simulated results of manageable and repeatable experiments (such as the complex modulus test or tests on multilayer systems). The large amount of experimental data collected and evaluated allows first assessment on the best material composition (share of aggregate substituted with rubber granulated first of all), and on the more promising geometrical configurations, and leads to the definition of a reliable model suitable to be used to individuate best solutions.

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INTRODUCTION

The increasing of the size and density of big metropolitan areas raises the demand of high capacity, large, and fast public transport networks and also the length of the urban stretches (between the houses) of fast intercity railways. The development and adjustment of railways and public transport networks in highly populated zones, are often limited or contested also because of vibrations produced by trains/metros/trams/buses and transmitted to the surrounding buildings. It is therefore clear that vibration related problems are becoming more and more important and cost effective solutions to these problems are necessary and would be very valuable. The majority of the approaches are based on the use of relatively soft elements with high damping capability (Figure 1), construction techniques used up to now are often very complex (floating slabs) and/or based on very expensive material, such as elastomeric mats.

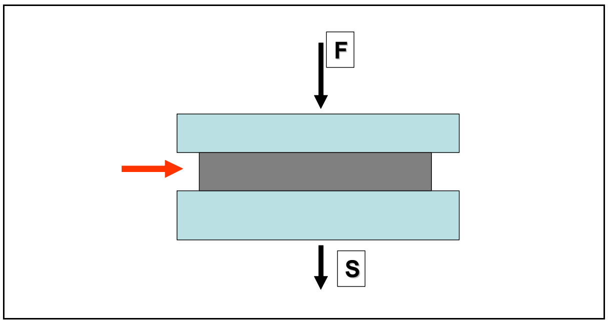


Figure 1: Typical vibration damping scheme

A cost effective approach could be based on common transport infrastructure techniques and relatively cheap materials. Borrowing industrial experiences, experimental test roads were recently realized using preformed mats made of crumb rubber bound with synthetic binder. Rheological properties of composite material and effective vibration damping of the test installation are still under exam.
Bituminous mixtures containing crumb rubber seem to fit better than preformed mats to the extension of surfaces involved in infrastructures and to be more suitable for a cost-in-place layer construction.
Hot mix asphalt is certainly the most common product used in road construction, moreover in constructing new Italian railway tracks, a 12 cm bituminous concrete subballast is normally used to protect the underlying layers or the embankment and to obtain a more performing platform for the ballast. On the other side rubber and rubber-like materials products are used in thousands vibration damping applications and relatively cheap rubber products, such as rubber granulate can be obtained by post treatment of waste tyres. Combination of HMA and rubber granulate seems to be a promising product if it could be effective in vibration damping.
Crumb rubber amount to be introduced in the mix can be chosen in a wide range, thus giving many chances of modifying finite layers mechanical behaviour.
In order to compare suitability of different possible mixtures and optimize geometrical configuration of structural complex, simulation is the best to-be-applied method. In fact, because of item complexity and large amount of involved variables, small-scale models are not reliable as to significance and real-scale test embankments are very expensive because they require plants and equipment not economically suitable for small production (hot mix asphalt production plant, asphalt compactors, asphalt paving equipment,)
Therefore the aim of this research was to develop models simulating vibration behaviour of transport infrastructures, in order to analyze and compare different kind of materials and different kind of anti-vibrating layers sequences and association.
To calibrate mechanical and rheological parameters of the composite and innovative material with crumb rubber, virtual tests similar to real ones were performed on laboratory fully modelled specimens, while real tests were effectively carried on other ad hoc prepared specimens.

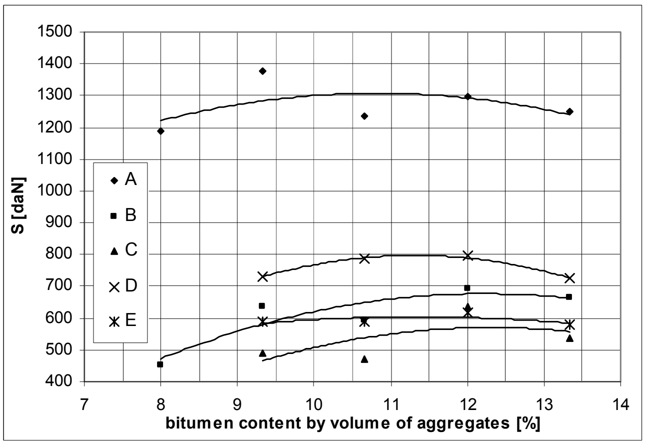
PROPERTIES OF HOT MIX ASPHALT WITH RUBBER (DRY PROCESS)

Since many years in many countries (such as USA, South Africa, Australia, etc.) the possibility of using rubber products, resulting from the treatment of end of life tyres in HMA production is investigated and tested with the aim of improving asphalt concrete performance through the elastic properties of the rubber. Advantages that are normally persecuted regard fatigue cracking, cold-hot cycles and sound emissions; moreover side environmental issues can be also considered; as an example Italian legislation, according to the European Community directives, encourages re-using and recycling of waste materials, and in the U.S., many states have banned waste tires from landfill. Production methods normally used are two, in one case rubber powder (<1 mm) is used to “modify” the bitumen (wet process), they are mixed together (normally between 8 and 15% of rubber by weight of bitumen) before the addition of the lithic aggregates, in the other case (dry process) a part of the natural aggregates (normally between 2 and 6% by weigh of the aggregates) is substituted with rubber granulate (2-5mm) which is used and mixed nearly as any other aggregate.
The dry process involves larger amount of rubber and seems therefore much more promising than the wet one in vibration control applications because of its stronger influence on rehologic characteristics of composite mixture. Moreover production process needs only slight adjustment compared to the normal one; the here presented data refer to the development of a subballast layer carried on within the “Laboratory of Materials for Road Constructions”, in collaboration with Rete Ferroviaria Italiana spa. During this project different rubber ratios and post treatment methods have been tested; differences in properties and behaviour among them and with conventional “rubberless” mixtures have been highlighted.

Physical Characteristics

Four mixes with different kind and content of rubber granulate (mixes B, C, D, E) and a traditional HMA (mix A) were prepared with the aim of obtaining a wide range of physical characteristics and behaviours. Figure 2 summarize information about physical characteristics and composition of mixes and some of their mechanical properties.

type of material	treatment	density [g/cm³]	particle size [mm]
rubber granulate (CN)	mechanical	1.18	2-5
rubber granulate (FR)	cryogenic	1.17	0.4-5
calcareous coarse aggregate	-	2.70	10-25
calcareous fine aggregate	-	2.70	5-15
calcareous sand	-	2.72	2-5
filler (Portland Cement)	-	3.00	<0.075



Sieve d [mm]	mix				
	A	B	C	D	E
	percentage passing (lithic aggregate by weight)				
30	100	100	100	100	100
25	99	99	99	99	99
20	93	93	93	93	93
15	79	80	80	80	80
10	58	61	63	61	63
5	45	50	53	50	53
2	33	34	35	36	38
0.425	13	14	14	14	14
0.18	9	10	10	10	10
0.075	8	8	8	8	8

Mix	A	B	C	D	E
Marshall stability [daN]	1307	677	571	798	604
Marshall flow [mm]	3.37	6.69	8.48	6.78	7.95
indirect tensile [daN/cm²]	14.3	7.1	7.0	9.5	4.8

Figure 2: Mixtures characteristics and materials properties

Data shown draw out the noteworthy decay in mechanical characteristics of rubberized mixes, as characterized by Marshall stability and indirect tensile test. Although, specially with regard to Marshall stability and mixes B and C, both containing mechanical shredded rubber, the decrease is larger considering 3% in rubber content related to 0% than between 3% and 5%.

Dynamic characteristics

Complex modulus tests have been used to define the dynamic behaviour of the hot mix asphalts. Tests have been conducted on cylindrical specimens (d=10 cm, h=20 cm), putting them under an axial sinusoidal load, which was one of the configurations described in the prEN 12597-26, with frequency varying in the range of 1 - 20 Hz. Tests have been carried out in condition of controlled temperature of 5°, 10° and 20° Celsius with a total of 12 tests conditions. Loads have been produced with the aid of a servo-hydraulic press and strains have been measured with an inductive LVDT. The equipment had a computer based data acquisition system. A “in house made” computer program was used to automatically describe the dynamic complex modulus by calculating its absolute value |E*| and the phase angle.

Figure 3: Complex Modulus Testing Machine (on the left the loading cell is inside the climate chamber)

The measured modulus values of each mixture have been collected to build a master curve ($\lg(\alpha_T) = \frac{\Delta H}{R}\left(\frac{1}{T} - \frac{1}{T_s}\right)$, where: T= test temperature [°K]; Ts= reference temperature [°K], ΔH=apparent activation energy characterizing the material [kJ/mole]; R=universal gas constant 8.314 [J/mole °K]) and a Black diagram that synthetically shows different materials dynamic properties (figures 4 and 5); these show

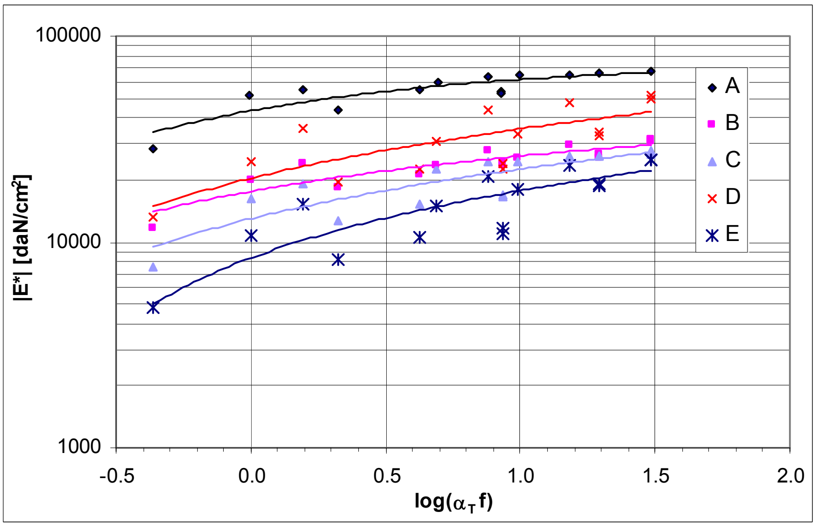


Figure 4: Master Curve (Ts=283°K, ΔH= 3000 kJ/mole)

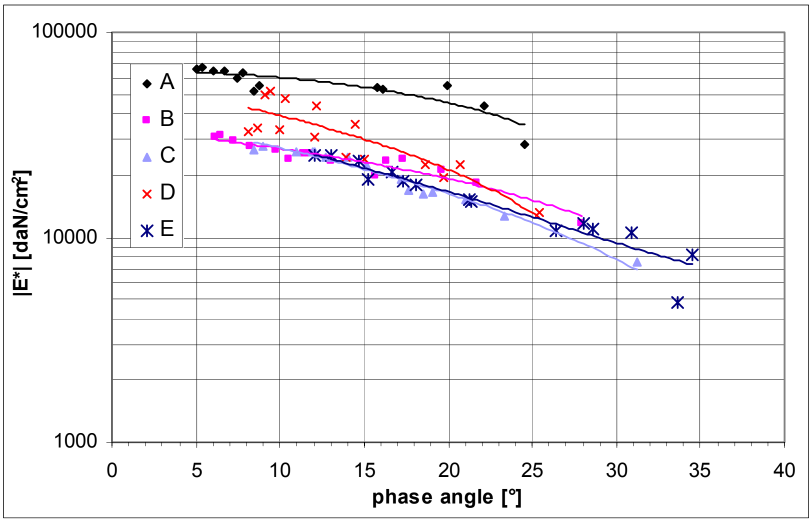


Figure 5: Black Diagram

that |E*| and φ are highly dependant on frequencies, which is typical of viscoelastic materials. The energy dissipation characteristics can be highlighted with load/displacement diagrams (area enclosed by the loop) and the loss factor computing, which is defined as the ration between the imaginary and real parts of E* ($\eta = E_2/E_1$), and can be conveniently calculated as the reciprocal of the phase angle φ. (Fig. 6)

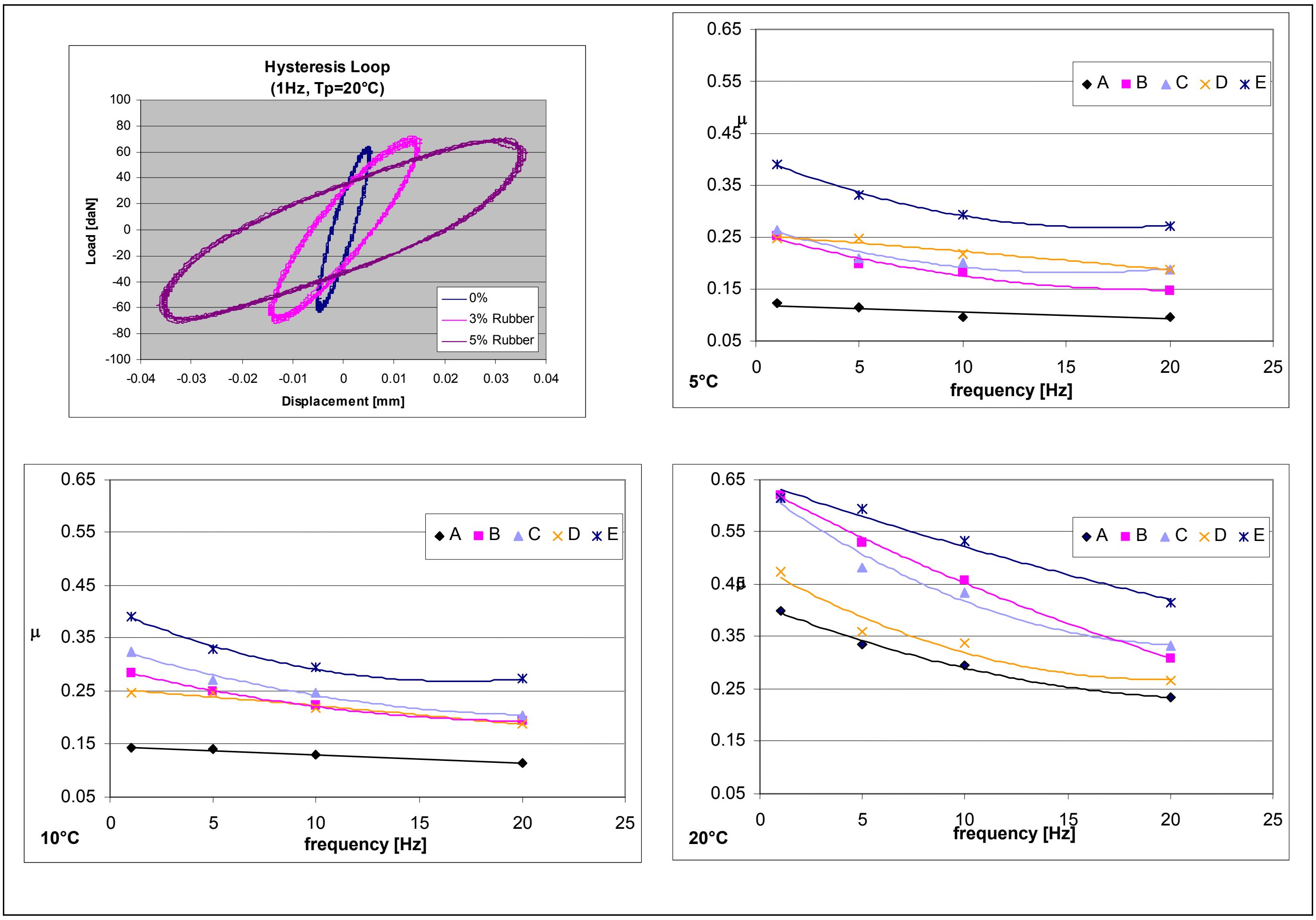


Figure 6: Hysteresis loops sample, and loss factor diagrams (20°C)

Results show that the presence of rubber in HMA lowers the stiffness modulus and increases the loss factor (and then the energy dissipation); differences are higher in case of mechanically shredded rubber and high temperatures. Changes are in all cases notable and makes HMA with rubber granulate suitable to be tested as part of antivibrating systems in FEA simulation models.

CALIBRATION OF THE RHEOLOGICAL MODEL

Modelling of HMA can be done considering a pure elastic behaviour, but when energy dissipation property becomes of interest, more complex models are needed. HMA is normally regarded as viscoelastic (for instance Cho Y., McCullough B. F.) and its rehologic model is thence assumed as a combination of elastic and viscous element (springs: $F = k \cdot u$ and dashpots: $F = c \cdot v$). Basic combination are the Maxwell's and Voigt's ones.

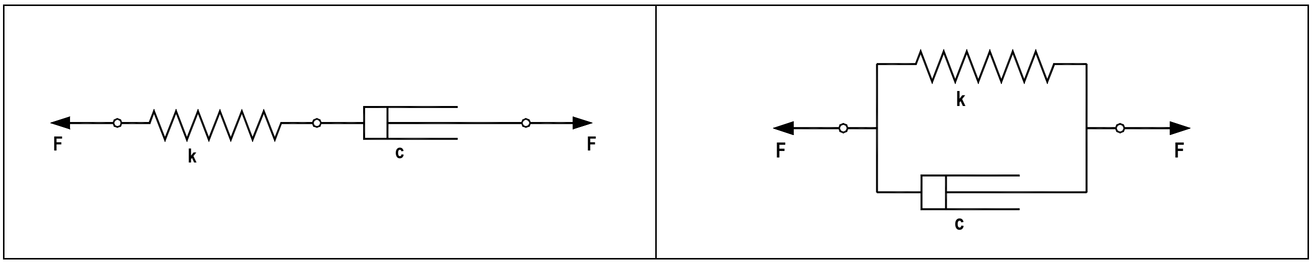


Figure 6: Maxwell's Model (left) and Voigt's Model (Right)

Maxwell's model is composed by a spring in series with a dashpot: in this case each element is subjected to the same load F and the displacement is the sum of ones of the two elements ($u = u_e + u_v$). The response of the system to an instantaneous constant load $F = F_0 H(t)$ (Creep) can be written as $u(t) = F_0 \left(\frac{1}{k} + \frac{t}{c} \right) H(t)$. Voigt's model is constituted by a spring in parallel with a dashpot, in this case displacements are the same for the two elements ($u_e = u_v$) and the load will be $F = F_e + F_v$. The creep behaviour in this case can be described by the $u(t) = \frac{F_0}{k} \left(1 + e^{-\frac{k}{c}t} \right) H(t)$.

Rather complex models, that involve also irreversible, plastic components (i.e. Santagata F., Virgili A.) have been developed for hi-fi description of HMA behaviour (viscoeleastoplasticity) , these are especially suitable and come to interest when long term assessments are needed.

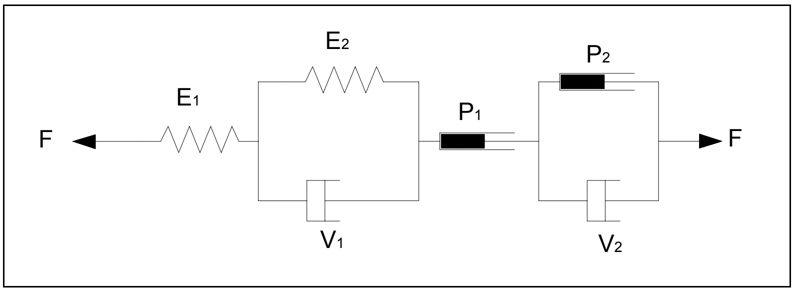


Figure 7: Generalized, viscoelastoplastic, Rheological Model

Finite element analysis applications look always for the maximum possible simplicity of the representations in order to keep the size of the problem and memory/computing power needs within acceptable limits. Vibration analysis problems normally concern short term behaviour and small displacements, on this basis the most common viscoelastic model normally used for HMA behaviour representation is the "Standard Linear Model" which is a parallel of a Maxwell's one and a simple spring. (Fig. 9)

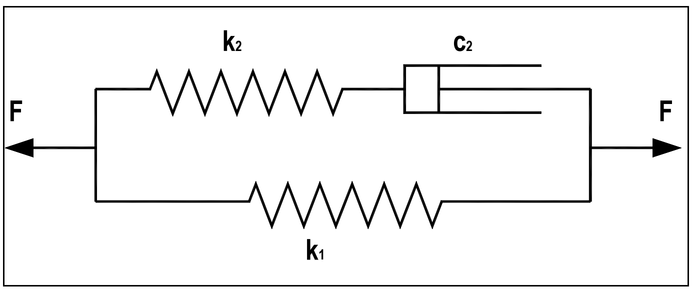


Figure 8: Standard Linear Model

The same consideration applied to the Voigt model can be made substituting the dashpot with the Maxwell's model, resulting in the following creep behaviour: $u(t) = \frac{F_0}{k_1}\left(1 - \frac{k_2}{k_1 + k_2} e^{-\frac{k_1 k_2}{(k_1+k_2)c_2}t}\right) H(t)$.

Within FEA software, viscoelastic materials behaviour is normally expressed specifying modulus values against time (relaxation function); the most general implementations allow the independent characterizations of volumetric and deviatoric components ($G(t)$, $K(t)$), that can be defined in terms of a series of exponentials known as the Prony series:

$$G(t) = G_\infty + \sum_{i=1}^{n_G} G_i e^{-t/\tau_i^G}, \quad K(t) = K_\infty + \sum_{i=1}^{n_K} K_i e^{-t/\tau_i^K}$$

G_∞ and K_∞ represent the long-term bulk and shear modules, τ_i^K and τ_i^G the relaxation times; instantaneous modules (*t=0*) can be computed as $G_0 = G_\infty + \sum_{i=1}^{n_G} G_i$ and $K_0 = K_\infty + \sum_{i=1}^{n_K} K_i$.

In most cases actual materials follow simpler rules, as a consequence commercial software implementations are normally less general; as an example within Abaqus the $\tau_i^K = \tau_i^G$ expression is always assumed as true. Normally viscoelasticity can be limited to the shear component resulting in the assumption $n_k = 0$; considering also $n_G = 1$ and $\beta = 1/t_1$ the general expression became the simple and common formulation:

$$G(t) = G_\infty + (G_0 - G_\infty)e^{-\beta t} \text{ and } K_0 = K_\infty$$

where shear modulus is assumed compliant with the standard linear model, and it is is described against time in function of the long and short (instantaneous) term modulus $(G_0 - G_\infty)$ and of the decay constant β, bulk (volumetric) modulus is considered constant.
This formulation is used within commercial software Lusas where viscoelastic materials are thence defined according to 5 parameters: E and ν, which refers to the long term conditions (stress/strain resulting after the application of a constant load for t→∞), G_0, G_∞ and β.
The calibration process, that led to the individuation of suitable combinations of the involved parameters has been based on the comparison of real and simulated complex modulus tests data, in particular parameters of the model have been changed in order to obtain the best possible superposition of real and simulated hysteresis loops (Load-displacement curves). The try and error phase of the calibration process has been conducted with the Lusas CAE software, which, thanks to the axysymmetric representation, was able to return results using very short computing times. Results have been tested with two other software, LS-Dyna and Abaqus which implement similar viscoelastic models. The good agreement observed over these three cases allows to consider reliable the results and the simulation criteria.

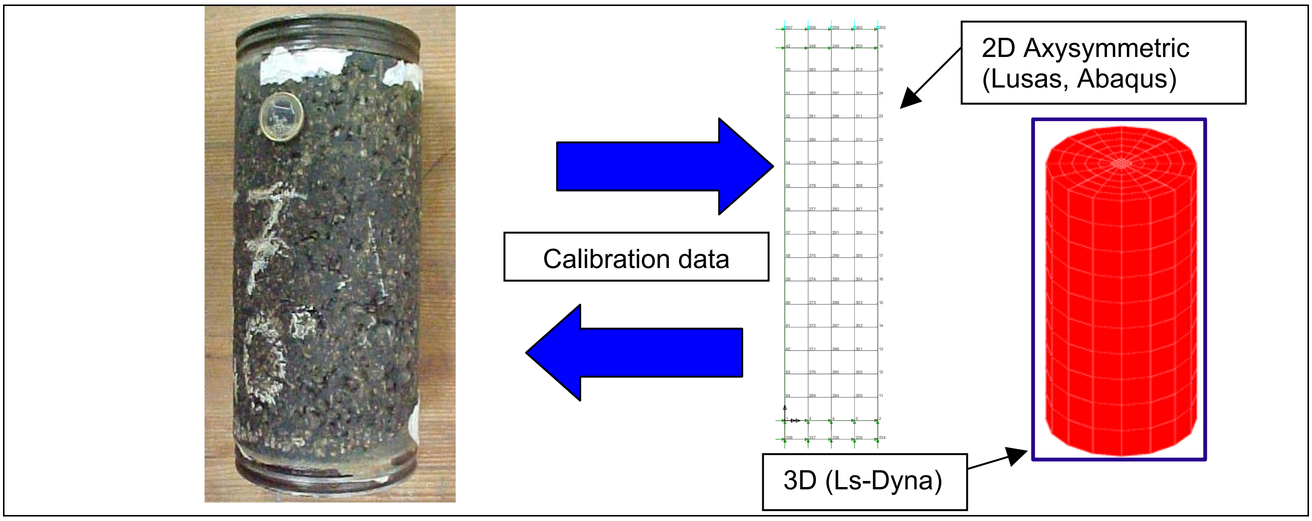


Figure 9: Actual laboratory specimen vs. Virtual specimens

Lusas 2D specimen model

Virtual cylindrical specimens have been modelled using Solid Axysimmetrics “enhanced strain” elements characterized by a maximum size of 1 cm. This kind of elements thanks to the symmetric shape allows a 3D analysis using a simpler 2D scheme. Results are reported in figures 10 and 11 and show a good superposition in the whole 1-20 Hz range.

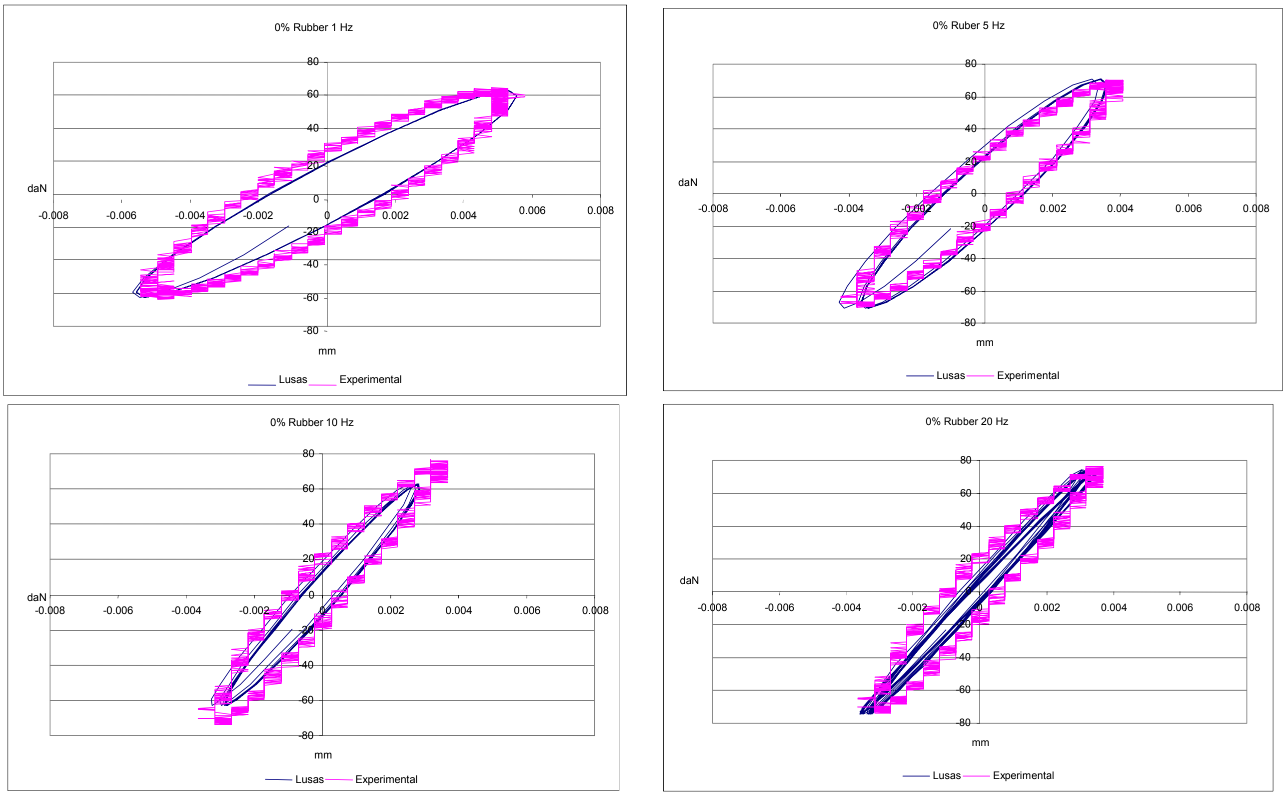


Figure 10: Hysteresis loops from real and simulated tests of the conventional hot mix asphalt (Lusas software)

Figure 11: Hysteresis loops from real and simulated tests of the 5% rubber hot mix asphalt (Lusas software)

Damping properties can be also taken into account through the Rayleigh damping parameters (mass proportional and stiffness proportional), computing stiffness proportional damping factor according to complex modulus data and the relation $b = \frac{tg\varphi}{\omega}$ where ϕ is the phase angle and ω is the angular speed. Just for testing purpose a trial has been made to compare results that can be obtained with numerical simulation to results of laboratory tests

.

Table 1: Stiffness proportional damping according to mix and frequency

Freq.	***1Hz***	***5Hz***	***10Hz***	***20Hz***
Conventional HMA (mix A)	0.07231	0.01336	0.00594	0.00228
5% Rubber HMA (mix E)	0.10547	0.02246	0.00973	0.00440

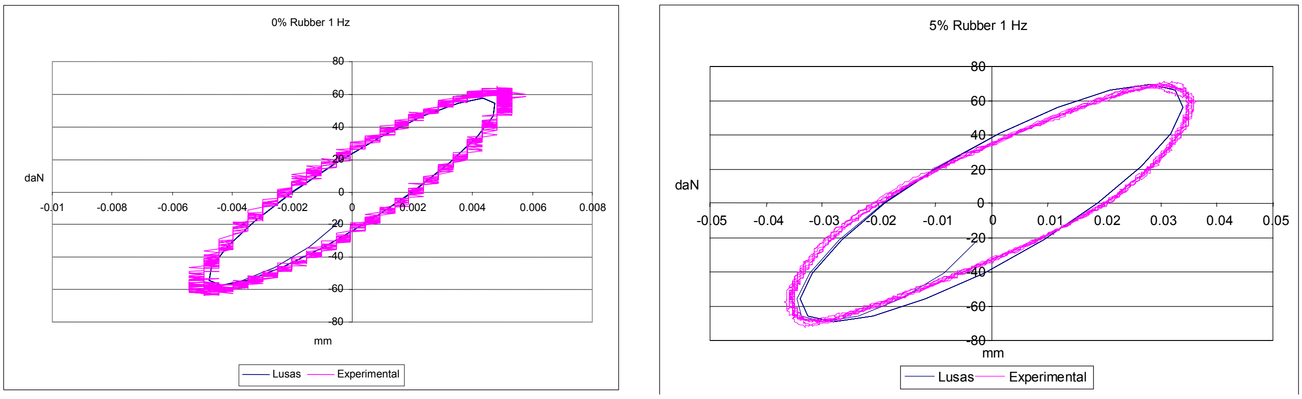


Figure 12: Samples of superposition of hysteresis loops resulting from real and simulated tests obtained using Rayleigh stiffness proportional ratio.

Abaqus specimen model

The validity of the calibration parameters of the viscoelastic model obtained with Lusas has been verified and tested within the FEA software Abaqus. Also in this case the cylindrical specimen have been modelled with axisymmetric elements, (8-node biquadratic axisymmetric quadrilateral, reduced integration), which guarantee very high performances also with a rather coarse mesh). Abaqus supports a generalized implementation of the viscoelastic model that have been reduced to the one implemented by Lusas; results obtained show a very good coherence between experimental and simulated hysteresis loops as displayed in figure 13.

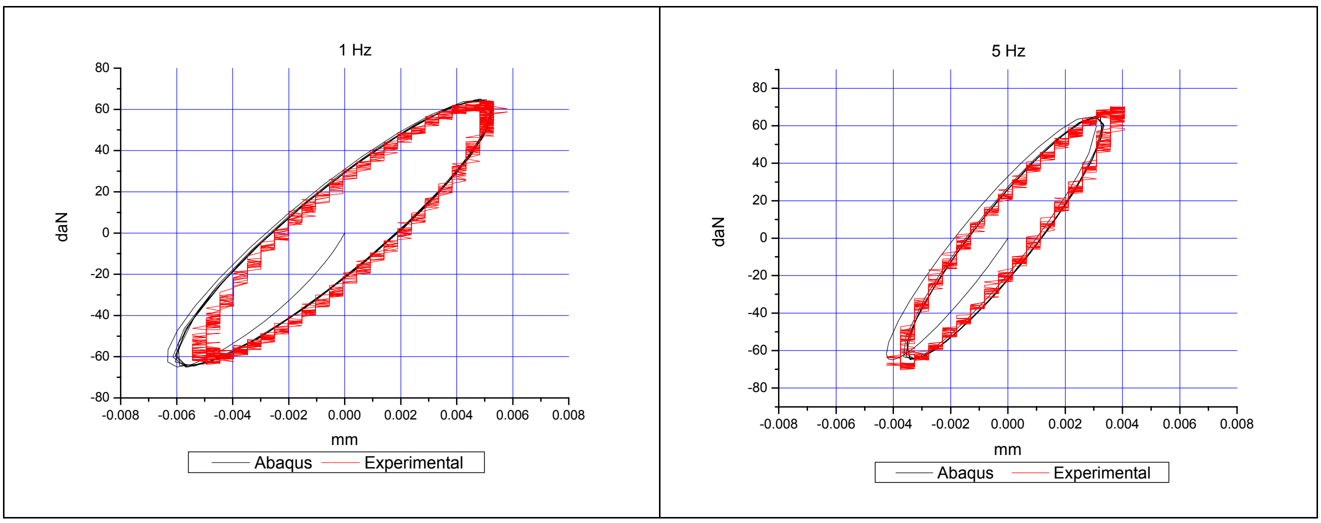


Figure 13: Hysteresis loops from real and simulated tests of the conventional hot mix asphalt (Abaqus software)

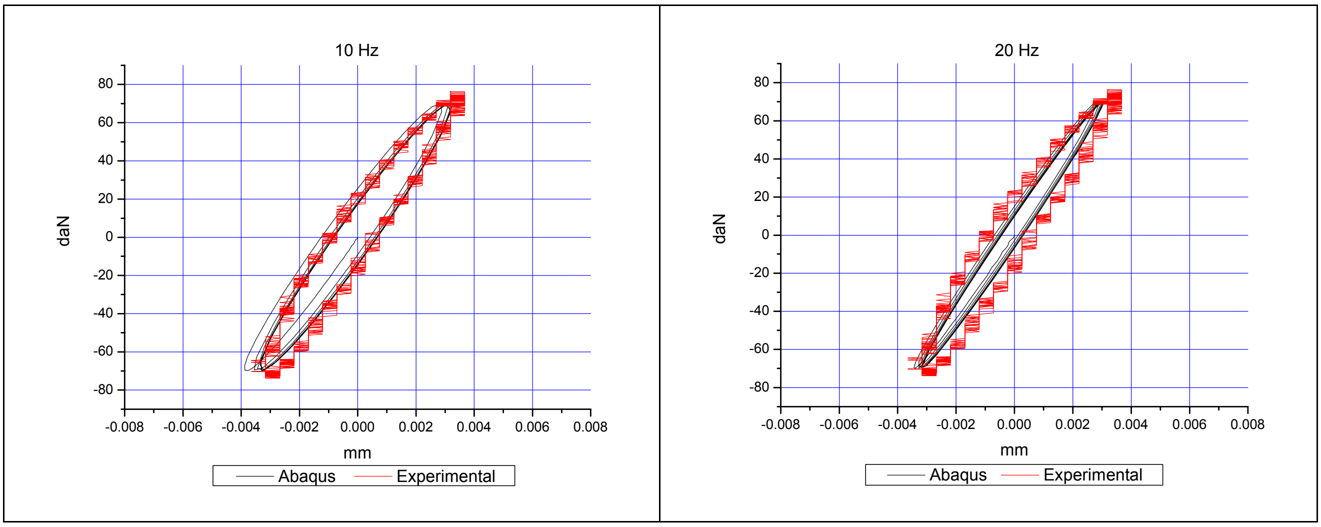


Figure 13b: Hysteresis loops from real and simulated tests of the conventional hot mix asphalt (Abaqus software)

Ls-Dyna specimen model

Calibration results have been tested again using LS-Dyna software, in this case the virtual specimen has been modelled in full 3D using 8 nodes solid elements. The material model is called MAT_VISCOELASTIC, and is based on the same visco-elastic rehologic model as the Lusas one. Reported charts shows also in this case a good superposition of measured and simulated loops.

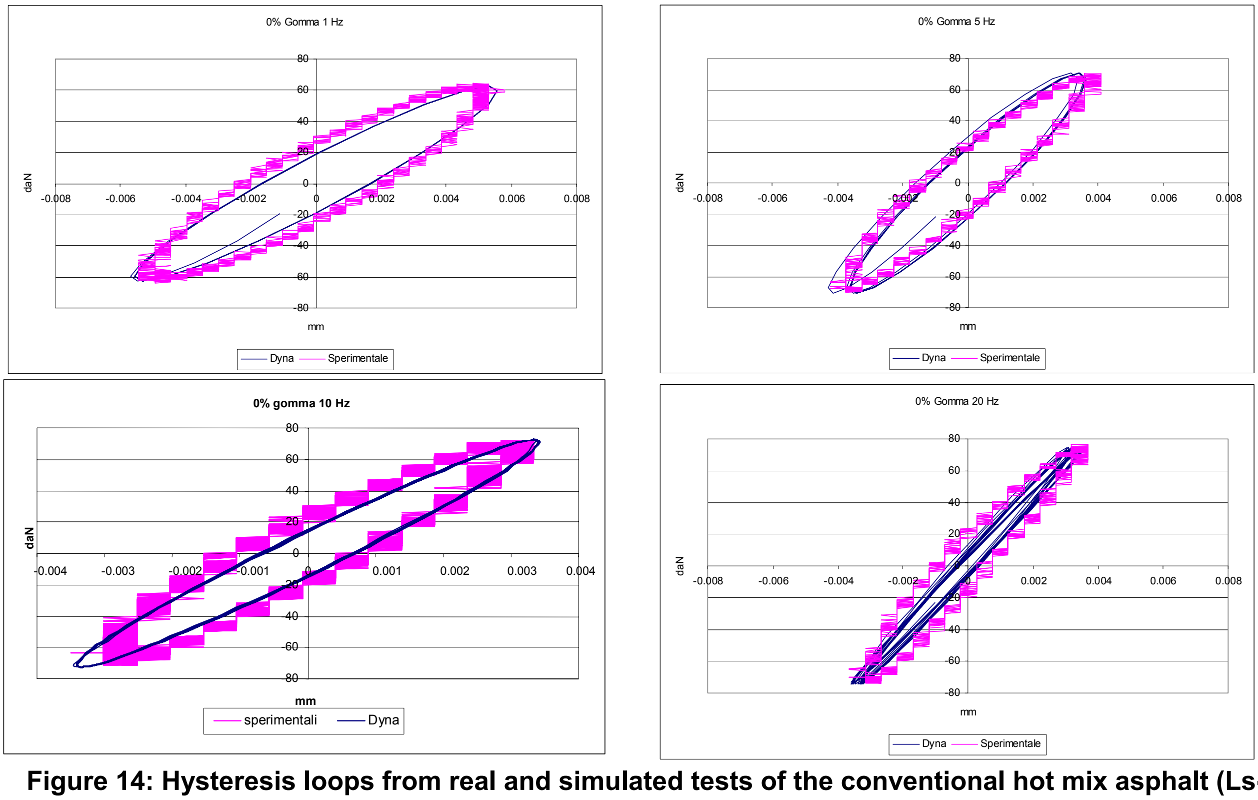


Figure 14: Hysteresis loops from real and simulated tests of the conventional hot mix asphalt (Ls-Dyna software)

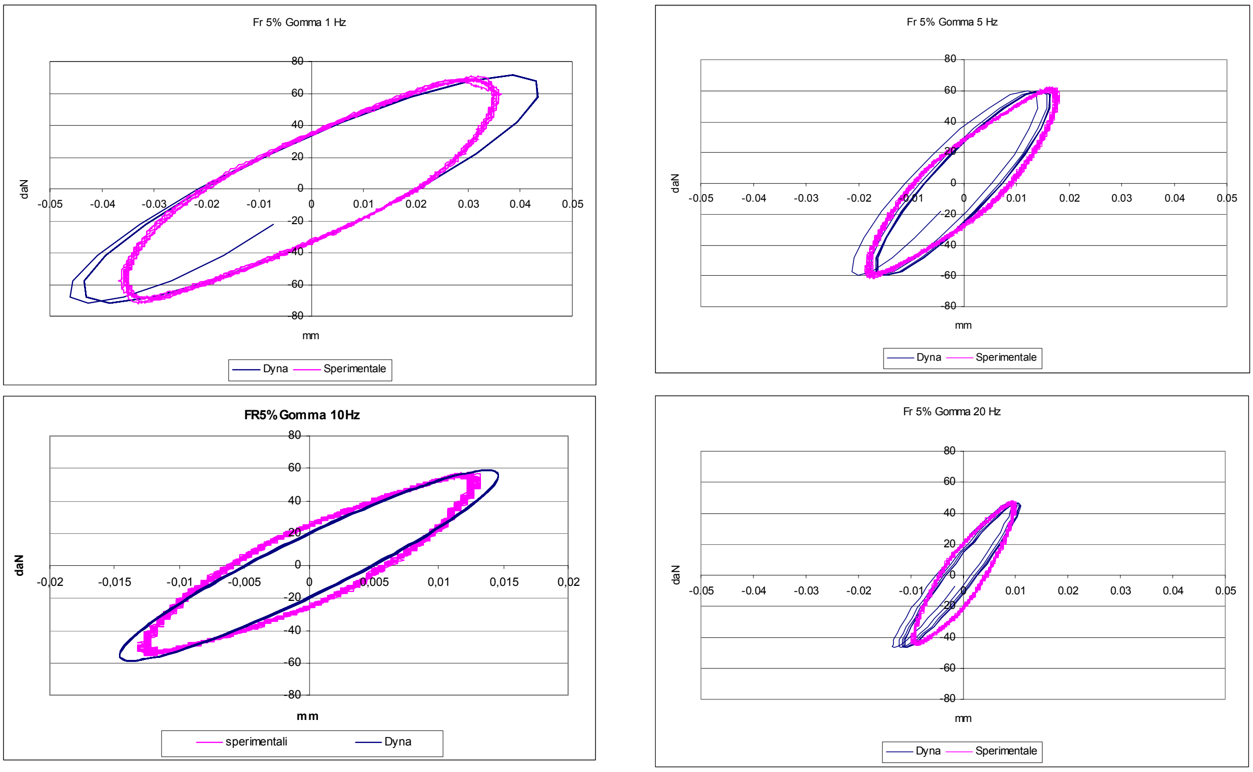


Figure 15: Hysteresis loops from real and simulated tests of the 5% rubber hot mix asphalt (Ls-Dyna software)

Results are very good, in fact coherent results have been obtained using the same values for the calibration parameters within three different commercial software and using different representation models. This supports either the reliability of the calibration process or of the used software and represents a good starting point for the construction of more complex models.

SIMULATION MODELS

The study on the effectiveness of the characterized subballast as anti-vibrating subballast layer carried on in collaboration with R.F.I. (Rete Ferroviaria Italiana) has been the occasion for testing the outlined, differences based, simulating approach. As a matter of fact the aim of this work is not the prediction of the vibration level produced by railway traffic as an absolute value, rather the comparison between different design solutions. As a consequence the attention has been focused on the modelling of the parts that change in compared solutions in some cases radical simplification have been adopted.

Different models of a railway superstructure have been realized using either 2D and 3D representations or different loading conditions. Several commercial software have been used to overtake intrinsic limits and enhance peculiarities, and the result is an overall evaluation of the potentialities of the HMA subballasts as they come out from several, rather different in many ways, testing conditions.

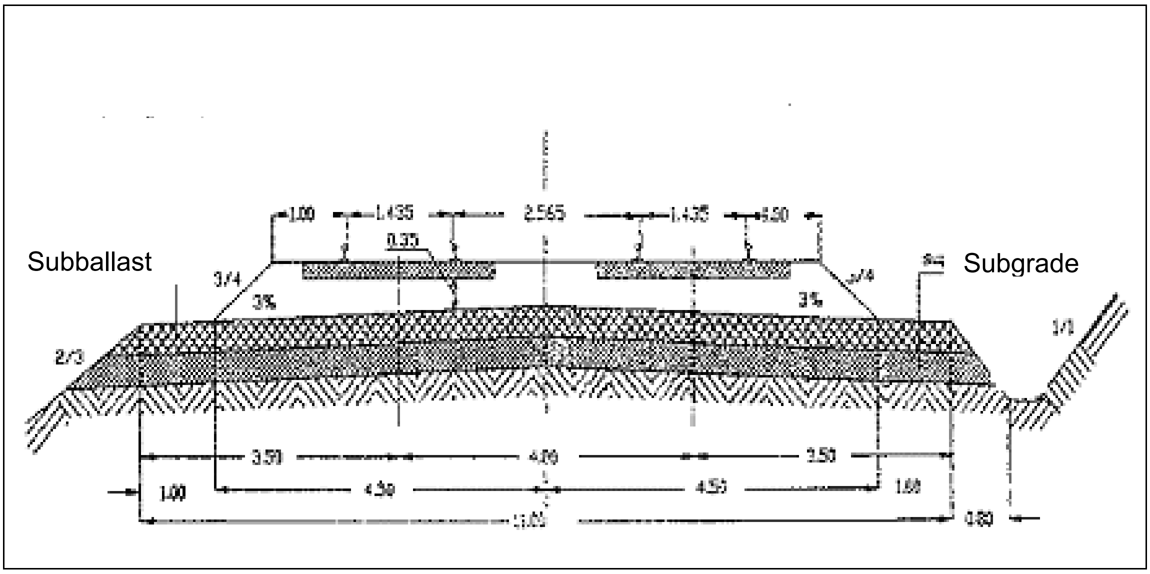


Figure 16: Superstructure scheme used for Italian new lanes with speed lower than 180 km/h

Table 2: Material characteristics used in the models

Element/Layer	Thickness [cm]	Material	Density [kg/cm^3]	Young Modulus [Pa]	ν
Sleeper	-	Concrete	2.5×10^3	3.1×10^{10}	0.20
Ballast	30	Stones	2.1×10^3	4.9×10^9	0.35
Subballast	12	Hot mix asphalt	variable		
Subgrade	30	Unbound	1.8×10^3	3.1×10^9	0.35
Enbankment	100	Unbound	1.8×10^3	1.1×10^9	0.35
Soil	-	Unbound	1.8×10^3	5.5×10^9	0.35

2D Planar Transversal Section

As first attempt of understanding possible differences in acceleration level within the different parts of the construction when an harmonic load is applied, a railway transversal section has been modelled with a rather simple 2D scheme (Lusas software). The model (Fig. 17) represents a full transversal section: load is applied in correspondence of a sleeper, mesh has been refined till they are not notable differences in results between two refining step. Loads have been calculated according to Italian trains characteristics and literature data and resulted in a static load of 110 kN (on each wheel) combined with a harmonic component; 125 Hz has been individuated (Prud'Homme) as the resonance frequency of ballast, therefore an important amount of energy is transmitted to the subballast layer within that band. Samples here reported refer to a frequency of 125 Hz and variation between ± 30% of the static load. Two configurations have been tested, the only difference between the two is the subballast, which in one case is constituted by traditional hot mix asphalt and in the other hot mix asphalt with 5% of rubber granulate. Tests last 2.5 seconds during which steady state as well as transient response have been recorded. This means that the most significant results are those around the 125 Hz (steady state) but information exist on a much more wider spectrum because of the transient phase. Results are presented as aggregated R.M.S. (root mean square) in third octaves and between 0 and 900Hz. Wide band analysis (Fig. 18) data are presented reporting values at layer interfaces and show a certain decrease of acceleration level when a hot mix asphalt with 5% of rubber granulated is used as subballast layer.

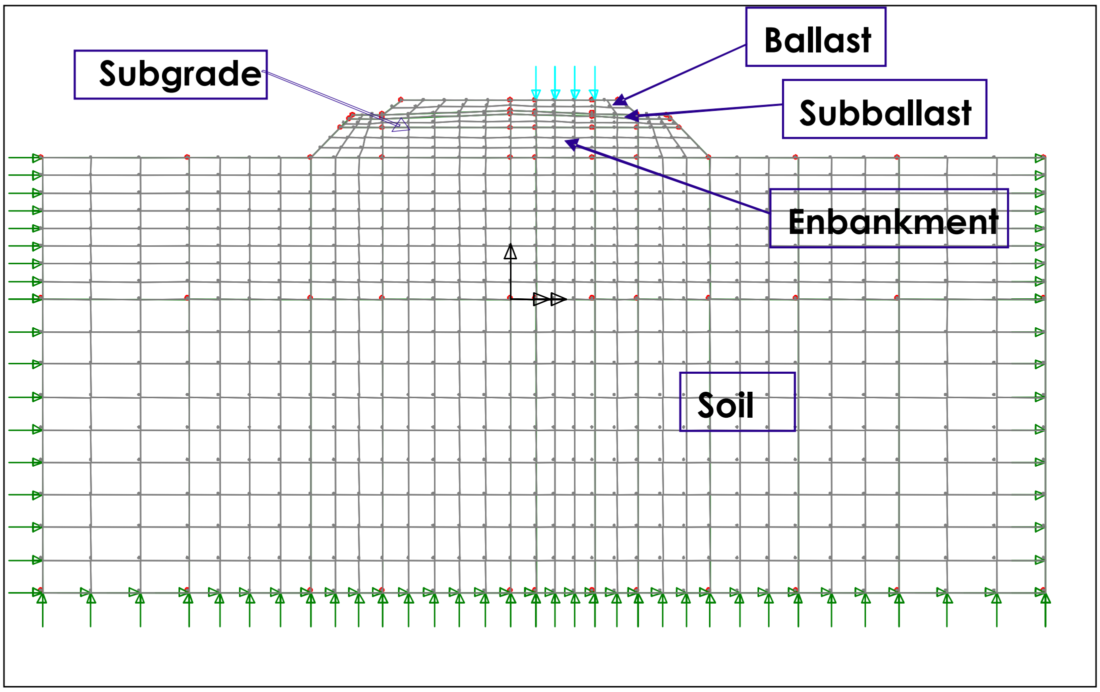


Figure 17: 2D FEA model of a transversal section

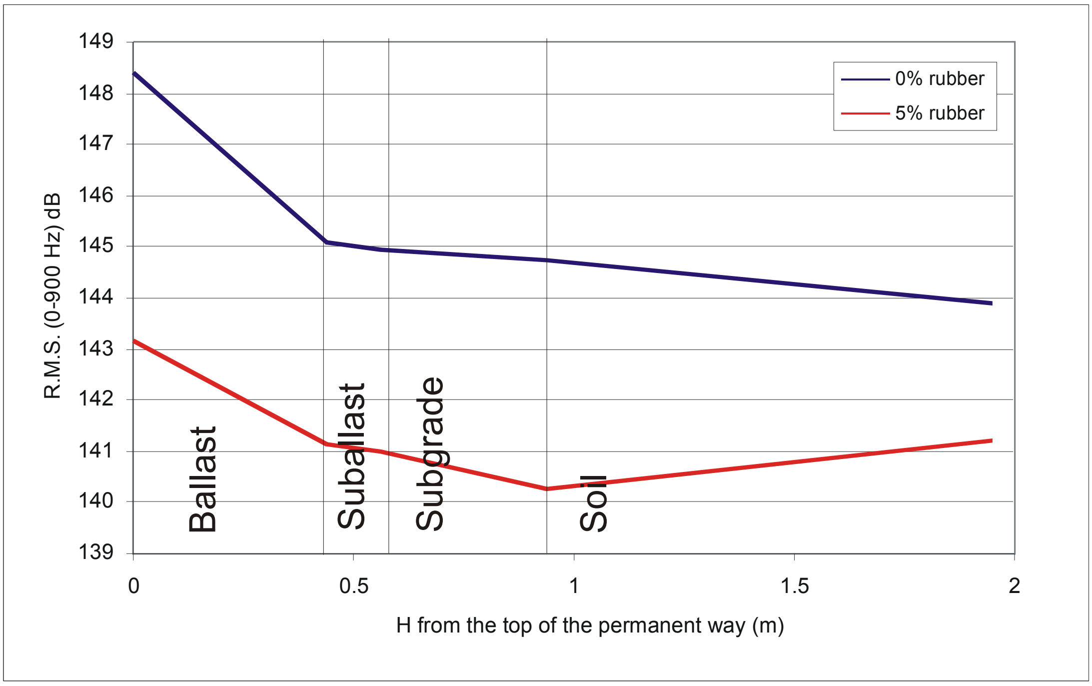


Figure 18: Acceleration R.M.S. levels at layer interfaces

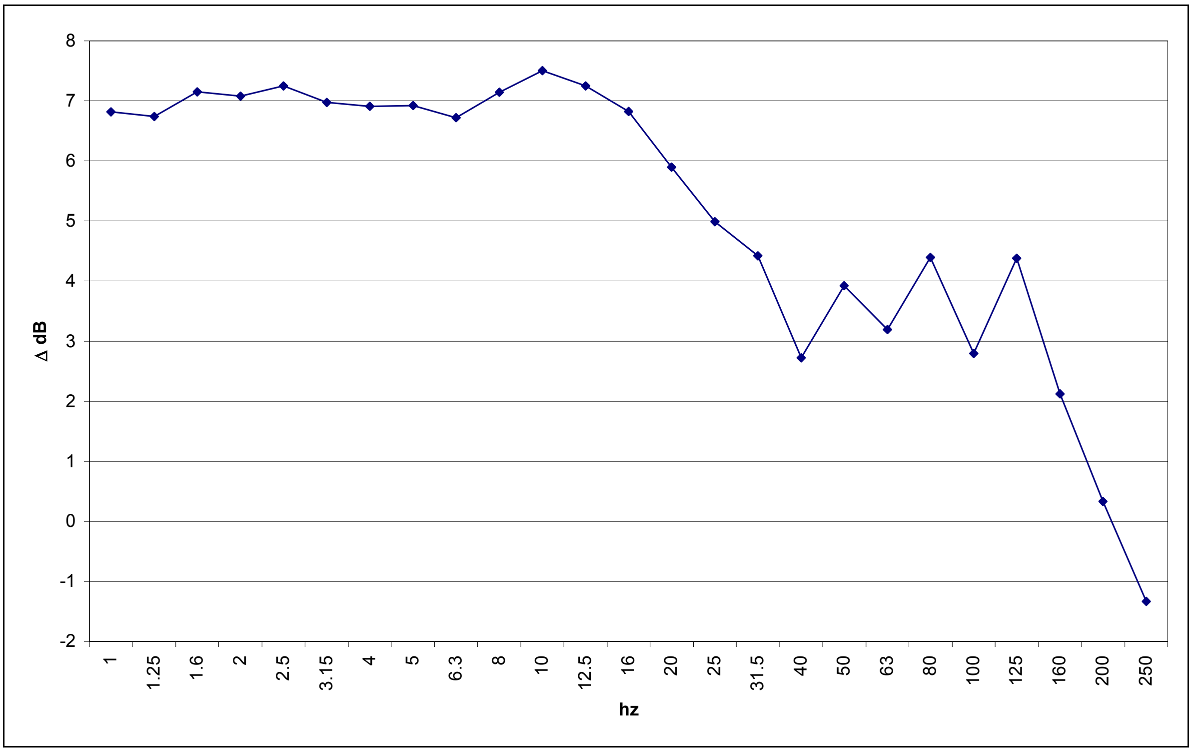


Figure 19: Third octave analysis, differences of level measured just under the subballast layer (traditional HMA level minus HMA with 5% of rubber level)

Third octave band analysis (Fig. 19) shows that differences exist within a wide band from 1 to 160 hz. If longer observation periods are considered the transitory effects tend to disappear and signal keep on existing only at the 125 hz frequency, tests have been made and result confirm that at this frequency (stationary) the acceleration level difference remain around 4 dB. One of the biggest issue of finite element models is the finite boundary problem (Sukumara), which is especially important in case of dynamic representation. In fact since waves can happen to “rebound” on the “walls” of the model, finite boundary can be acceptable only because of the comparative approach of the here presented paper. Nevertheless to overtake this problem another 2D model of a railway transversal section has been realized with Abaqus software that implements specific “indefinite” elements that avoid the problem of waves reflection using particular combinations of damping properties; the model have been therefore realized using bilinear quadrilateral element together with “indefinite” element for the boundary region (Fig. 20). This model has been used to investigate transmission characteristics of subballasts constituted by four combinations of 2 asphalt layers each one 10 cm thick.

To avoid unhomogeneity in the response and in differences along the band of interest, a fast impulsive load is applied. The energy content of impulsive loads is uniformly spread across a wide spectrum of frequencies, (the shorter the impulse the wider the spectrum). Recorded differences at the measuring station are therefore only consequence of the system characteristics. It should be also noted that actual loads have peculiar energy distributions which are normally not uniform; as a consequence real differences are influenced by the input energy distribution. (Range with higher input energy are more important). The prediction of the input spectrum is on the other hand not easy, as it depends on a large number of factors such as train speed, boogie characteristics, wheels and rails regularity, etc.). Impulsive load has been applied near the symmetry axes, and response is measured at the embankment basis.

Tested subballasts were constituted by: a) 20 cm of conventional HMA, b) 20 cm of HMA with 5% of rubber granulate, c) 10 cm of HMA with 5% of rubber granulate on top of 10 cm of conventional HMA and finally d) 10 cm of conventional HMA on top of 10 cm of HMA with 5% of rubber granulate. The aim of these multilayers structures was combining the load distribution capability of stiff (conventional HMA) layers with the damping properties of HMA containing rubber granulate.

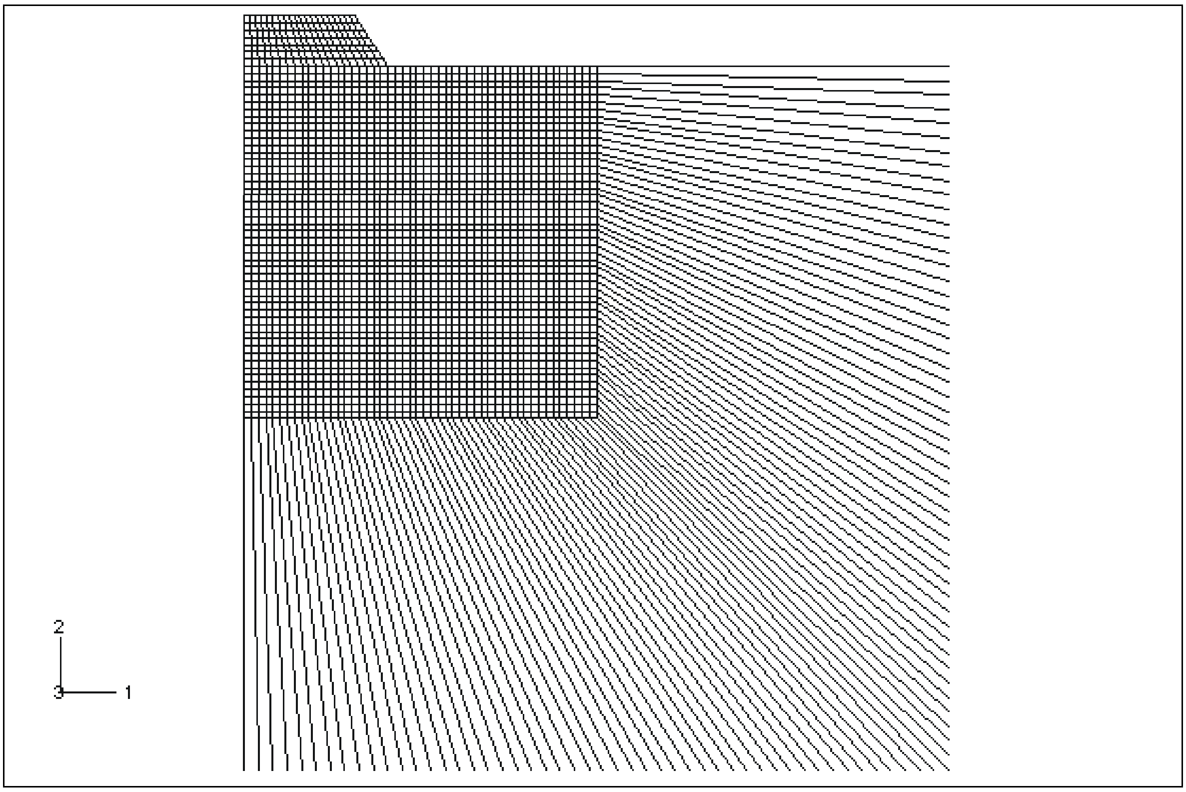


Figure 20: 2D Abaqus model

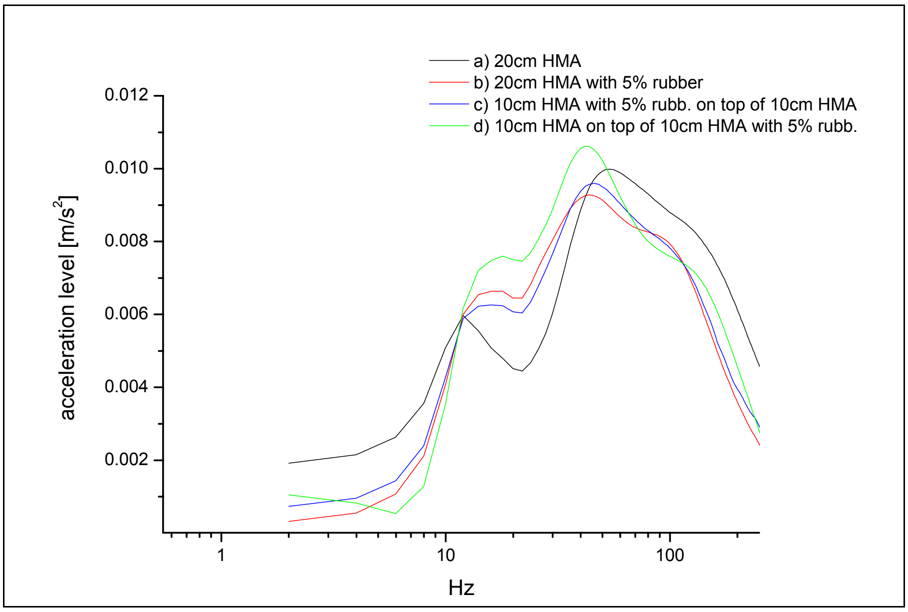


Figure 21: Acceleration levels measured on the basis of the embankment considering 4 different subballasts

Result reported in figure 21 clearly show that performances change according to the input frequency, in particular 100% conventional HMA subballast is the best solution within the 10-40 Hz range whereas is the worst outside these limits. The combination of a stiff layer on top of a soft one (solution d) seems to be easily the worst solutions, giving very bad performance in the 10-40 Hz range. The 100% "rubberized" HMA solutions (b) and the other mixed one (solution c) are very similar, rather good in the whole range of considered frequencies, performance, and seem to be good compromise.

3D Model

These first formulations use 2D plane-strain model, and require relatively little computational time and memory, making them suitable for first attempts and guesses (C. Kuo et al., R. Lytton et al.). However, plane-strain models cannot accurately reproduce actual traffic loadings. Loading footprints on the top layers are typically elliptical whereas plain-strain models are limited to the use of line loads, (Y. Cho et al.), moreover true consideration of moving loads is possible only with 3D modelling. A full 3D model, including a complete permanent rail have been developed (using Ls-Dyna FEA software): load is applied on rails and moves along the track to simulate train movement. Also in this case load is 110 kN on each wheel, it moves at a speed of 5.6 m/s (about 20 km/h) and after one second from the beginning of the simulation an harmonic component (± 30% of the static load at 5, 10 and 20 Hz) has been added. Because of the movement of the load no steady-state solution may exist.

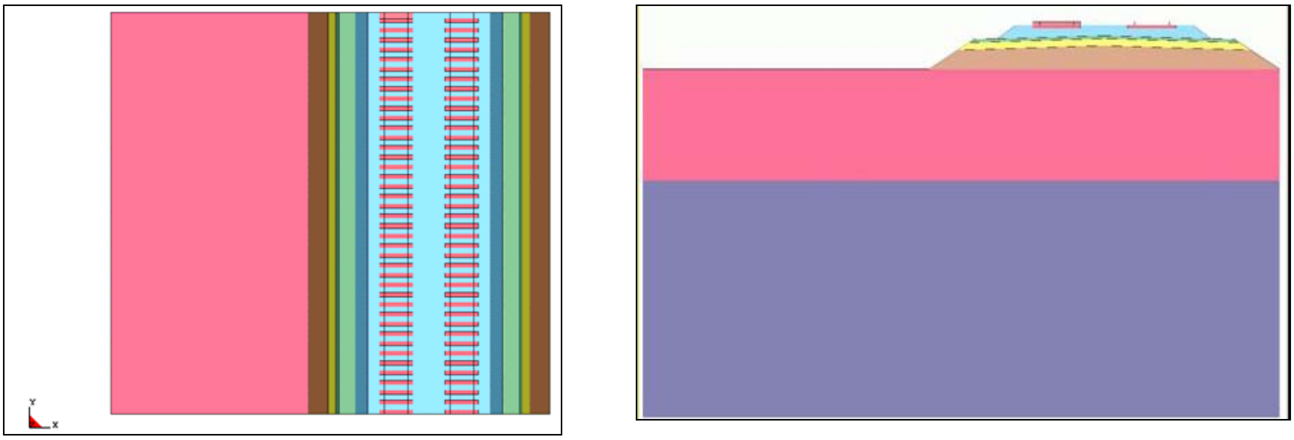


Figure 22: 3D model, plan and section views.

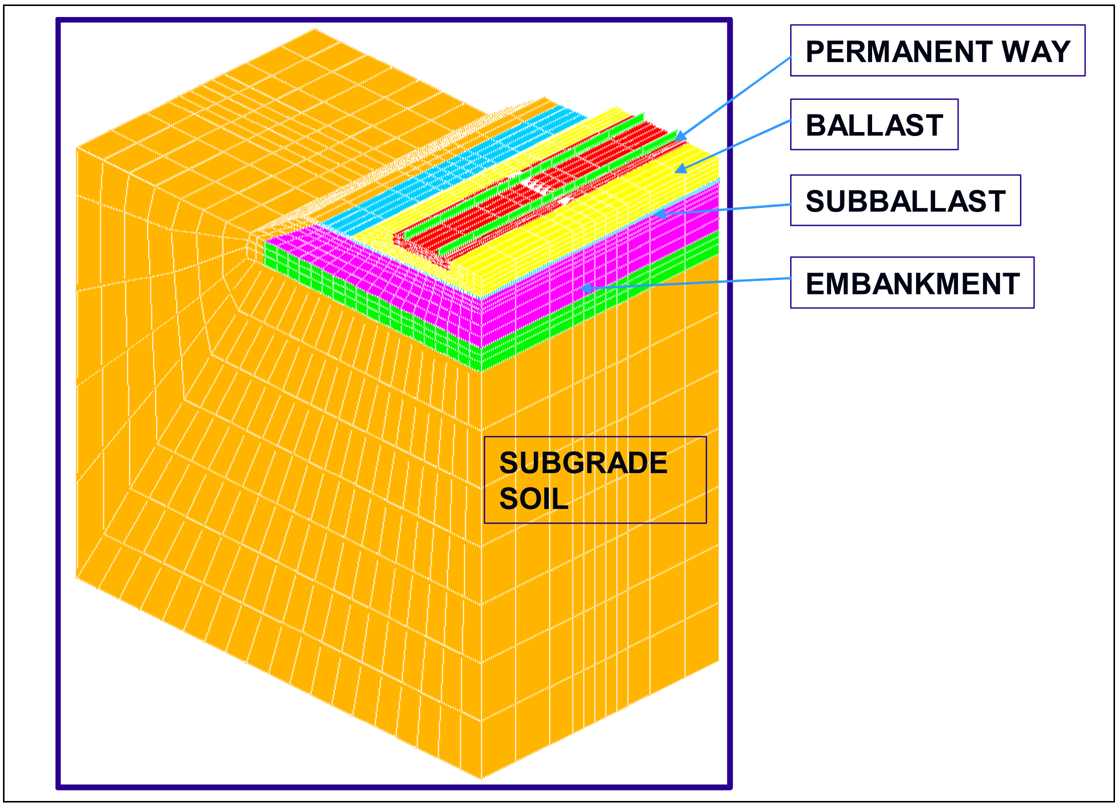


Figure 23: 3D model, isometric view

The load on the moving body is applied using a “vertical load multiplier curve” shown in figure 24: there is an initial load ramp and the following harmonic part (only shown up to t=2.5 sec). The initial ramp is essential to avoid the transient dynamic effects of an “impulsive loading”; this initial loading time takes 1 second of simulated time.

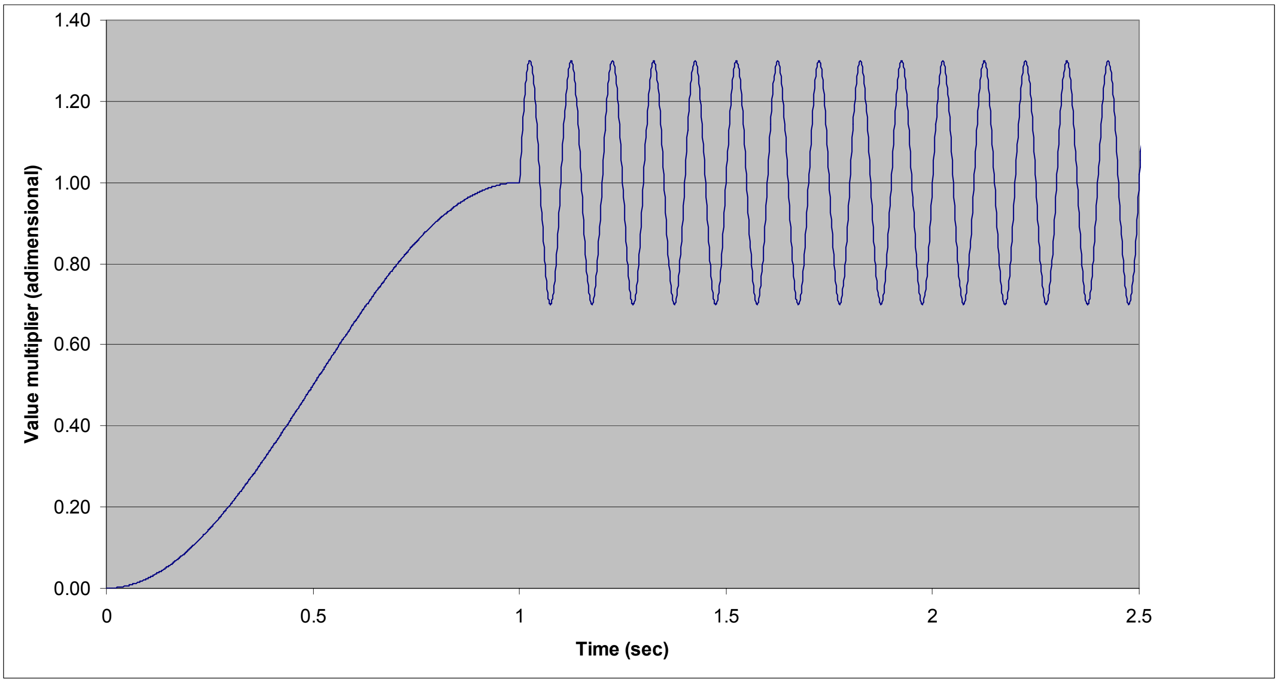


Figure 24: Vertical load multiplier curve.

The model dimensions are (Width x Length x Height) 20x21x25m. The boundary conditions (nodes fully restrained in the lower face, lateral movement for the side faces, free on top) uses a special non reflecting boundary to prevent the creation of bouncing stress waves.
The materials used in all the layers are elastic (no plastic strains or failures are expected with the applied load), while the energy absorbing subballast layer was modelled using the Viscoelastic material analyzed with the specimen model.
The model is only at an early research state, because it is necessary to fine tune the model dimension, the material and finite element formulation characteristics with some in situ measurements (e.g. multi point vibration measurements with well known layer and load characteristics).

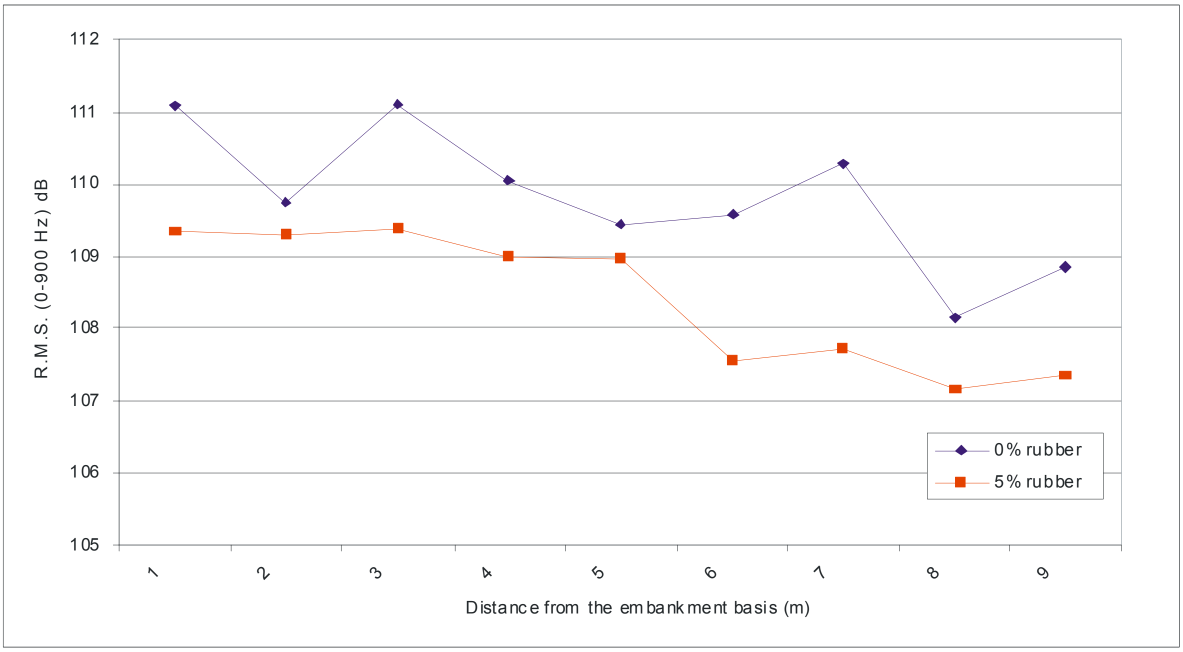


Figure 25: R.M.S. acceleration Level at different distances from the embankment basis

Results are shown as R.M.S acceleration level measured at different distances form the basis of the embankment, and put in evidence how the non conventional subballast results in better performance with regard to vibration damping capability.

CONCLUSIONS

Carried out experiences show, as it gives the possibility to lower the number of configuration to be tested in full scale, how the simulation approach to complex problems can be powerful; on the other hand the same complexity makes difficult the fast development of reliable predictive models. In particular vibration control issues are very intricate because of the large amount of involved variables, many of them very local dependant and difficult to qualify (soil, rail and trains conditions and/or characteristics). The proposed approach tries to focus the attention on the variables of the problems, leaving out, as much as possible the constants. In particular great attention is given to the calibration process of materials whose peculiar behaviour is crucial for the functioning of the system under investigation, and for which different choices in terms of mechanical and geometrical characteristics exist. The "narrowing" operation of the problem on one hand prevents, because of the sometimes strong simplifications, from creating "absolute values" predicting models, but on the other hand allows consistence evaluation of the differences between the possible design and technological solutions. The testing of this approach on the study of antivibrating HMA subballast layers seems to open interesting possibility of vibration control with relatively cheap systems and materials. All the high speed Italians lines are now realized with a HMA subballast layer: this means that only little adjustment should be done in the construction system to introduce "rubberized" subballast in sensible zones, and therefore innovation costs for the realization phase would be rather small. Obviously more research and some comparison with experimental data are still necessary to verify the actual effectiveness of this innovation.

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