Sustainable Road Infrastructures Using Smart Materials, NDT, and FEM-Based Crack Prediction

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Abstract. Smart cities need roads with high levels of sustainability. This goal can be reached using different approaches, such as smart materials, Non-Destructive Test (NDT)-based monitoring systems, and Finite Element Method (FEM)-based damage prediction models. The pieces of information provided using the above-mentioned approaches play a crucial role in the work of many stakeholders (citizens, users, road agencies, authorities, driverless vehicles, etc.). Consequently, the main objectives of this study presented in this paper are (i) providing an overview of the current approaches, and (ii) presenting a NDT-, and FEM-based monitoring system that was designed to improve the sustainability of the present and future road pavements by means of the road pavement damage detection and prediction. In more detail, the paper is focused on the set up and the calibration of a FEM model that aims at simulating the vibro-acoustic signatures of un-cracked and cracked road pavements. An NDT apparatus was used to gather the vibro-acoustic signatures of road pavement (data set) that was progressively damaged. Subsequently, the data set mentioned above was used to set up the FEM model. Results show that, even though the FEM model is able to replicate only in part the measured signals, this model can be successful used for predicting the variation of the structural health status of the road pavement. Hence, the proposed approach can be used to improve the sustainability of the current road pavements.

Keywords: Finite element modeling · Vibro-acoustic signature · Road crack prediction

1 Introduction

Smart cities require roads with high levels of sustainability, which can be reached using different approaches. Among all the possible solutions, the study presented in this paper is focused on three promising approaches (see Fig. 1), i.e., the use of smart materials, the implementation of Non-Destructive Test (NDT)- and sensor-based monitoring systems, and the application Finite Element Method (FEM)-based damage prediction models. In more detail: (i) smart materials can be used to obtain self-healing road pavements, to carry out energy harvesting, and to save resources (e.g., raw material, and

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energy); (ii) using NDT- and sensor-based monitoring system, instead of the traditional destructive ones (e.g., coring), can improve the sustainability of the roads because of the fact that it positively affects the management process (e.g., maintenance based on real time information about the road conditions); (iii) FEM models can be used to predict the temporal and spatial behavior of the road pavements, i.e., to forecast the occurrence of possible failures (e.g., internal cracks) or the reduction of the performances (e.g., clogging). For these reasons, the following subsections contain an overview of noteworthy applications of the three approaches listed above.

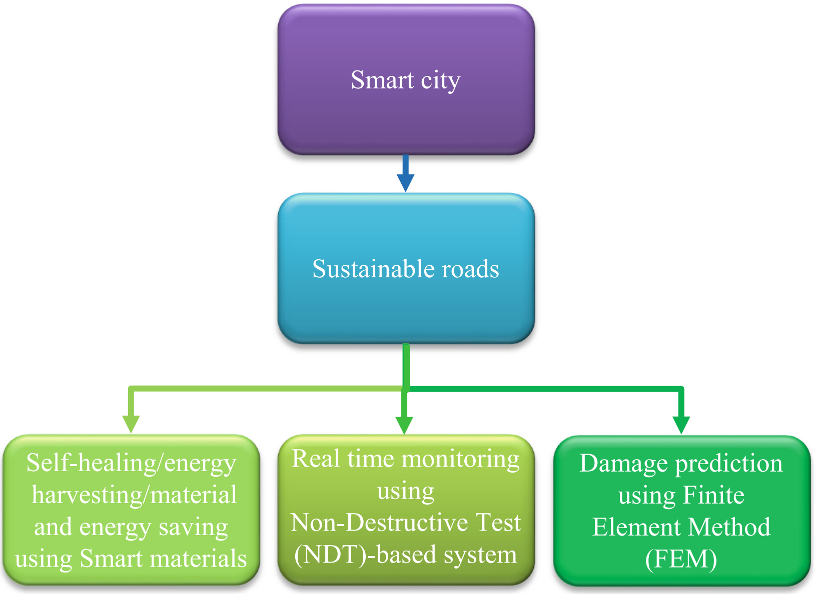

Fig. 1. Three possible solutions to obtain sustainable roads for smart cities.

1.1 Smart Material for Road Pavements

A material can be defined "smart" if it has the ability of changing its properties to react to an external condition [1]. In order to obtaining smarter, and more sustainable and efficient materials for road pavements, several types of wastes can be used in the asphalt concrete mixture, such as Reclaimed Asphalt Pavement (RAP) [15], by-products (e.g., crumb rubber, plastics, blast furnace slag, fly ash, leachate, glass, concrete, wood ash) [12, 14], graphene [7], and fibers [3, 8, 21]. These latter are used in applications that principally aim at conferring to the asphalt concrete healing properties (i.e., make the material able to easily repair the damages due to different causes, such as vehicular traffic, or thermal excursions) [4, 11, 16–19]. Furthermore, smart materials be used to produce or harvest energy from the road pavements. The energy derived from the roads can be used for typical applications, such as street lighting [22], and sensors based monitoring systems [5, 13], or for innovative applications, such as feeding electric vehicles [2, 9].

1.2 NDT Solutions for Monitoring the Road Pavements

Infrastructure monitoring can be carried out using [6] traditional destructive testing (DT), or innovative semi-destructive testing (SDT) and non-destructive testing (NDT). Usually, DT-based monitoring is the most used although it provides sample-based information (i.e., discrete points of the pavement), and requires energy and money for extracting (e.g., coring), analyzing, and landfilling pavement samples. On the other hand, SDT- and NDT-based methods, which are driven by the increasingly insistent demand for smart cities, are growing because they offer high performance (e.g., extended measurements), sustainability (e.g., energy and time savings), and efficiency (e.g., high measurement frequency, and/or technologically advanced devices). The main NDT-based monitoring drawbacks are related to the costs (i.e., instrumented infrastructures are more expensive than traditional ones), and to the worker's skill (i.e., skilled worker are required to set up, use, and tune sophisticated devices/systems, and/or to handle and analyze huge amounts of data). From an energy point of view, it should be underlined that the NDT methods tend to be more sustainable than the DT methods, because they use efficient and advanced systems (e.g., [10]).

Noteworthy NDT methods applied or designed for the Structural Health Monitoring (SHM) of the road pavements refer to: (i) audio-visual inspections and image analysis [20, 23]; (ii) heavy and light instrumented vehicles, unmanned aerial vehicles, satellite, smartphones on vehicles using several devices (e.g., the smartphone's gyroscope) [24, 25]; (iii) ultrasonic guided waves, ultrasonic wave propagation, and ultrasonic tomography [26–28]; (iv) electromagnetic, e.g. the Ground Penetrating Radar (GPR), or using nuclear and non-nuclear electromagnetic gauges, or microwave imaging to scan the surface layers [29, 30]; (v) seismic methods (e.g., MASW), or devices such as the Light Weight Deflectometer (LWD), the Falling Weight Deflectometer (FWD), and the Rolling Wheel Deflectometer (RWD [31, 32]; (vi) Ground Penetrating Radar (GPR) and thermo-cameras [33–35]; (vii) self-powered, or low- and ultralow-powered, wireless sensor networks [36–38].

1.3 FEM Models Applied on Road Pavements

This section contains relevant examples of the application of FEM on road pavements, which were used to simulate and study the behavior of these pavements under different load conditions, and to forecast their performances and sustainability over time. The examples mentioned below were grouped based on the software used to build the model, as follows: (a) ABAQUS was used to derive natural frequencies, dynamic moduli, fatigue cracking performance, and response to a given load. The above mentioned software was used also to simulate crack propagation, and interactions between deformable tires and pavements [39–41]; (b) ANSYS was used to study the bridge-vehicle interactions, and the resultant vibrations perceived by pedestrians [42]; (c) COMSOL Multiphysics was used to simulate structural responses to dynamic loads [43, 44]; (d) CAPA-3D was used to model tire-road contacts, and distress mechanisms [45]; (e) Matlab was used for the prediction of ground-borne vibrations due to road unevenness-tire interactions [46]; (f) the combination of SAFEM and ABAQUS was used to analyze mechanical performances of asphalt pavements (e.g., deflection, and strain/stress), and their dynamic responses to moving loads [47]; (g) SAFEM was used to simulate deterioration of asphalt pavements under heavy vehicle loads [48]; (h) SURFER was used to derivate ground borne vibrations, induced by vehicles, for different soils [49].

Despite the fact that, in the last decades, several solutions were proposed to improve the overall quality of the road pavements, it is still difficult to apply them in real contexts. Possible motivations can be the complexity, the cost, and the poor attention to the them by the authorities. For this reason, this paper aims at presenting a simple, and cheaper solutions that can be easily used to effectively improve the sustainability of the road pavements, in terms of smart monitoring and efficient maintenance. In more detail, the objectives of the study presented in this paper are: (1) to present a NDT-based monitoring system able to gather the vibro-acoustic responses of the road pavement to different loads; (2) to set up a FEM model able to simulate road pavement cracks and forecast any possible variations of the responses cited above due to a change of the structural status of the pavement.

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2 Method

This paper describes a method that was developed to increase the sustainability of road pavements acting on two of the three approaches discussed in the previous section (see Fig. 1). In particular, the method is based on (1) the real time assessment of the structural conditions of the road (using an innovative monitoring system described in Sect. 2.1), and (2) on the prediction of the occurrence of road cracks due to repeated or extraordinary loads (using the FEM model described in Sect. 3). The method could be applied by authorities and companies that are responsible for the management of the road infrastructures, or could be used as a key component of the smart cities because of its ability to provide crucial information about the availability and reliability of the road infrastructures, which can be shared (Internet of Thing, IoT, approach) with users, or vehicles or other infrastructures (i.e., allow vehicle-to-infrastructure communication, and infrastructure-to-infrastructure communication).

2.1 NDT-Based Monitoring System and Data Gathering

An innovative NDT-based monitoring system was designed, based on the concept of vibro-acoustic signature. In more detail, the ground-borne response of the road pavement to vibration and noise generated by a mechanical source (e.g., vehicle, hammer, Light Weight Deflectometer, LWD) are considered as the vibro-acoustic signature of the road pavement. It is expected that the signature will be affected by any significant change of the structural conditions of the pavement. Hence, a system that is able to gather the above-mentioned signature can be used for monitoring purposes. The system used in this study consists of a broad-band and omnidirectional microphone located (NDT) on the surface of the road, which is able to gather the sound produced by the waves generated by a mechanical source that travels on the road. Importantly, this microphone must not be affected by the air-borne noise, and for this reason a sound-insulating dome was used to avoid undesirable effects due noise and wind. The structural condition of the road pavement was changed by means of drilled holes. Figure 2a shows the road pavement used in this study. Two different conditions were taken into account in this study, i.e., the structural condition 0, without holes, and the structural condition 1, with one line of 15 holes (diameter = 0.01 m, same depth as the one of the asphalt concrete layers = 15 cm, spaced 5 cm each other). A well-known mechanical source was used to load the road pavement, i.e., a LWD (see Fig. 2 left). This device is commonly used to measure the elastic modulus of pavements and is able to produce an impulse load that is suitable for the purposes of the study. The data set consists of 100 acoustic signals (50 for each condition), which were gathered with a sample frequency of 192 kHz.

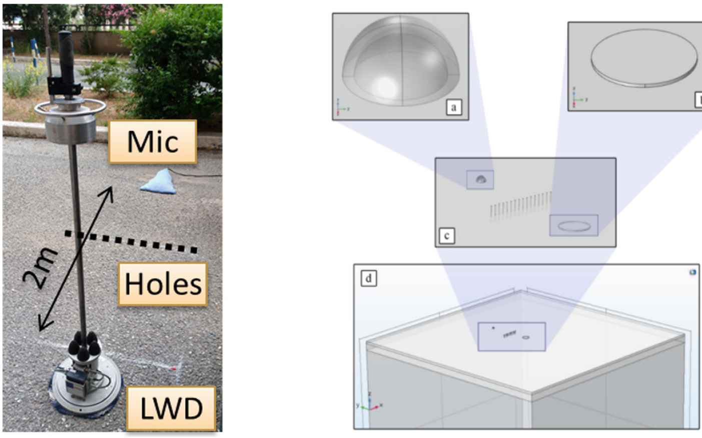

Fig. 2. (Left) experimental set up used to gather the data set used in the study, i.e. LWD, microphone + dome (Mic), and holes (structural condition 1); (Right) main elements of the FEM model: (a) isolating dome of the microphone; (b) LWD's steel plate; (c) dome-cracks-steel plate; (d) road pavement.

3 Set up of a FEM Model for Crack Prediction

The software COMSOL Multiphysics® was used to build the FEM model. In particular, the "Acoustic-Solid Interaction" interface, and the study "Pressure Acoustics Transient" were selected. Figure 1 right shows the main elements of the model, i.e. the road pavement, the drilled holes, the LWD base plate, and the dome of the probe. While, Table 1 summarizes the input parameters used to feed the FEM model.

Table 1. Input parameters of the FEM model.

Parameter	Details
Sampling	Sampling frequency of 2000 points per 200 ms, i.e., 10000 Hz, was selected
Geometry	LWD plate (height = 0.01 m, radius = 0.15 m). Pavement layers (thicknesses of the wearing course d_0 = 0.1 m, of the subbase course d_1 = 0.3 m, and of the subgrade course d_2 = 10 m; length of the layers = 10 m; width of the layer = 10 m). Boundary condition = "low reflection"
Sensors	One microphone (acoustic pressure detection) placed h_0 = 0.005 m far from pavement surface
LWD-road interaction	LWD steel base plate (Young's modulus = 200 GPa, density = 7850 kg/m^3; plate dimensions (diameter = 0.3 m, and height = 0.01 m)
Air-born noise insulating dome	Dome is a semi-sphere of radius = 0.05 m, thickness d_d = 0.005 m, filled with a material with Young's modulus = 50 MPa (with clay), density = 1800 kg/m^3, and Poisson's ratio = 0.3. Boundary conditions = "low-reflecting"
Impulse load	LWD's load function over time produced a maximum force on the steel plate cited above of 9 kN (that is due to a mass of 10 kg falling from 0.83 m, on five rubber buffers with an elastic constant of about 362 kN/m). The pulse time is 15 ÷ 30 ms
Layers	On average, lower moduli correspond to slower and bigger signals over time. Densities (2200 kg/m^3 for friction course, 2000 kg/m^3 for subbase course, and 1800 kg/m^3 for subgrade), and moduli (E_0 = 1000 MPa for friction course, E_1 = 500 kg/m^3 for subbase course, and E_2 = 90 kg/m^3 for subgrade course)
Temperatures	Bituminous layers elastic modulus is affected by the temperature, and it, in turn, affects the speed of the propagating waves. During the experiments, the road surface temperature was in the range 25–35 °C, and the reference temperature for air was assumed equal to 20.0 °C
Induced cracks	Drilled holes were modelled according to Sect. 3. Importantly, the air trapped into cracks was modelled itself
Speed of propagation	Vibrations propagate into the road pavement with a speed v_1 = 670 m/s, while the sound speed in air v_2 was derived from the air temperature

4 Results

The results of this study refer to the calibration of the FEM model presented in the previous section. In more detail, the calibration was carried out using meaningful features of the measured signals related to the peaks amplitude and time-lags. The peaks that were taken into account are shown in Fig. 3.

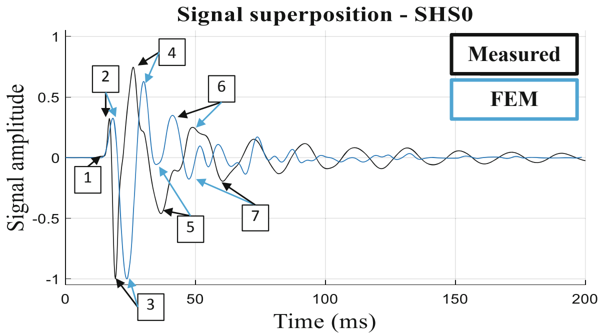

Fig. 3. Peaks used to represent the signals (features).

The time lags refer to the x-axis and the following feature were derived (the numbers point out the peak showed in Fig. 3): x2-x1, x3-x2, x4-x3, x5-x4, x6-x5, and x7-x6. The peak amplitude refers to the y-axis, and the features that were derived are: y1/y3, y2/y3, y3/y3, y4/y3, y5/y3, y6/y3, and y7/y3. After two rounds of calibration, the FEM model was able to provide the signals of Fig. 4 using the input parameter reported in Table 2.

Table 2. Main inputs of the calibrated FEM model.

ID	Main inputs											
	E_0	E_1	E_2	*Ta*	*Tpav*	d_d	$Ø_d$	v_1	v_2	μ	σ	*F*
	MPa	*MPa*	*MPa*	K	K	M	M	m/s	m/s	ms	ms	kN
1st	1000	500	90	293.15	293.15	0.01	0.05	670	n.a.	15	2	9
2nd	2000	600	200	299.75	304.25	0.008	0.075	1208	347.4	15	1.5	9

Symbols. ID = Round of calibration; *Ei* = moduli of the layers, with i = 0, 1, and 2; *Ta* = air temperature; *Tpav* = pavement temperature; d_d = dome thickness; $Ø_d$ = dome diameter; $v_{1,2}$ = speeds of propagation in the transmission media 1 and 2; μ, σ = impulse peak position and width, respectively; F = impulse force.

Figure 4 shows the comparison between the measured vibro-acoustic signatures and those simulated using the FEM model. Based on the results shown in Fig. 3, it is possible to state that the procedure used to build and set up the FEM model can be effectively used to try to replicate real damage of a road pavement. Hence, this method can be also used to forecast the occurrence of any type of damages (e.g., surface or hidden cracks, or cracks due to thermal excursion, or fatigue failures).

Finally, the validation of the study was carried out comparing a set of the measured signals (42 signals) with a set of simulated data (42 signals). In particular, experiments showed an instrumental uncertainty (LWD) of about ± 5% (8.55–9.45 KN), which can

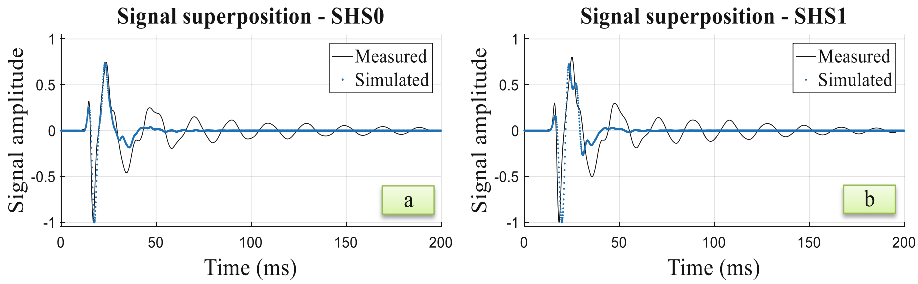

Fig. 4. Superposition of the measured and simulated vibro-acoustic signature of the road pavement in the structural conditions 0 (without holes) and 1 (with one line of holes).

be considered, together with the holes, the main cause of signal changes. Hence, further simulations were carried out, using the same parameters reported in Table 2, and changing the LWD load to obtain a simulated data set that takes into account the experimental uncertainties. Subsequently, a third round of calibration was carried out in order to find two calibration factors, i.e. one for the structural condition 0, and one for the structural condition 1. In more detail, each simulated signal (referred to the given condition) was divided for a reference signal (properly selected, measured signal) obtaining one corresponding matrix of factors. Then, from the elements of the given column an average was derived. The resulting two vectors (one *per* conditions) were used as calibration factors. These latter were multiplied by the simulated signals obtaining the final simulated data set. Finally, the two abovementioned data sets (measured and simulated after three rounds of calibrations) were used as input of a hierarchical clustering algorithm (implemented in Matlab®) that aimed at classifying the signals into two classes, i.e., structural condition 0 and 1. The result of the classification was expressed in terms of model accuracy (i.e., the ratio between the number of signals correctly classified and the total number of signals belonging to the testing data set to be classified), derived from confusion matrixes (i.e., a matrix that shows how many observations were associated to each cluster). The average model accuracy resulted of about 85% (i.e., 83% and 86% for the structural condition 0 and 1, respectively), which can be considered sufficient to validate the FEM model.

5 Conclusions

Smart cities need roads with high levels of sustainability, and this goal can be reached using, e.g., smart materials, Non-Destructive Test (NDT)-based monitoring systems, and Finite Element Method (FEM)-based damage prediction models. Consequently, the main objectives of this study are (i) providing an overview of the current approaches, and (ii) presenting a NDT-, and FEM-based monitoring method (road damage detection and prediction). The proposed method has the potentialities to contribute to a more sustainable environment because it is based on (1) the real time assessment of the structural conditions of the road (using an innovative monitoring system), and (2) on the prediction of the occurrence of road cracks due to repeated or extraordinary loads (using the FEM model). The FEM model was calibrated using a data set gathered during an experimental investigation on road pavements that was progressively damaged with drilled holes. A simple NDT apparatus was used to gather the vibro-acoustic signatures of road pavement (data set). Results show that, the procedure used to build and set up the FEM model can be effectively used to replicate real damage of a road pavement, and that this method can be used to forecast the occurrence of any type of damages. Hence, the proposed solution can positively affect both the maintenance efficiency of authorities and companies that are responsible for the management of the road infrastructures, and the road sustainability by means of the ability to share crucial information (road availability and reliability) with users, or vehicles or other infrastructures (IoT approach).

Finally, based on the promising results, possible further research steps are: (1) reproducing typical cracks of the road pavements and, then, using the monitoring system to detect the vibro-acoustic responses and the FEM model to predict the variation of the above mentioned responses due to the propagation of the induced cracks; (2) using the FEM model to design new smart materials and forecast their behavior; (3) improving the system using low-power electronics (e.g., MEMS sensors, low-power and ultra-low power wireless transmitters) for large-scale production and application. The future researches listed above will require interactions with other research fields such as the machine learning one to face the increase of the data set size due to the use of the monitoring system (big data), and the micro-electronics to improve the performances of the monitoring system.

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