Comparison of NDT methods to detect debonded interfaces

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ABSTRACT: This paper compares different Non Destructives Techniques (NDT) to detect and characterize artificial debonding and internal crack created in an experimental pavement tested on the fatigue carrousel of IFSTTAR in Nantes. The tests presented are performed on a 25 m long pavement section, consisting of 2 bituminous layers (8 cm thick base layer, and 6 cm thick wearing course), over a granular subbase. Several types of defects have been included at the interface between the two asphalt layers. Rectangular debonded areas of different size (longitudinal or transversal direction) have been created artificially, using different techniques (sand, textile, absence of tack coat). The construction has been done by a road construction company, using standard road works equipment. Different NDT, as electromagnetic techniques (ground-penetrating radar, step-frequency radar) or as mechanical techniques, from static deflection (FWD) and radius of curvature (inclinometer) measurements to dynamic methods (Ultrasonic Pulse Echo, Frequency Response Function), have been used to detect the different geometrical characteristics of the artificial defects. This allows comparing the capability of each technique to detect such damages. Some methods are selected to survey the evolution of the defects with the number of load applications.

KEY WORDS: Debonded interface, NDT method, radar, FWD, UPE.

1 INTRODUCTION

French roads consist mainly of old bituminous pavements often more than 30 years old. Usually, they have been maintained several times with thin overlays (less than 8 cm thick). In recent years, potholes and alligator cracking has been frequently observed, in particular after periods of heavy rain or freeze/thaw. Frequently, this type of damage is associated with moisture effects linked to interface debonding between the overlays and the old pavement. Such debonding mechanisms reduce the residual life of the pavement, and thus their early detection is a very important issue for pavement maintenance (Savuth 2006).
To detect such interface damage, non destructive techniques (NDT), such as electromagnetic techniques (ground-penetrating radar, step-frequency radar, or infra-red) or mechanical techniques (from static deflection and radius of curvature measurements to seismic wave propagation methods), appear as promising approaches.
This paper compares measurements with different NDT to detect and locate debonding performed during an experiment carried out on the large pavement fatigue carrousel of IFSTTAR in Nantes.

2 DESCRIPTION OF THE FULL SCALE EXPERIMENT

2.1 Description of the test site

The test site is located on the pavement fatigue carrousel of IFSTTAR (Figure 1). A full scale experiment investigating low traffic pavements started on the test track in March 2011. A first part concerned mainly the testing of pavements with geogrid reinforcement and consisted in loading the outer radius (19 m) during 1.2 million load cycles (Hornych 2012). The second part started in the spring of 2012, and consisted in loading the inner radius (16 m), where the section with defects is located. This test section is 25 m long and consists of two bituminous layers (8 cm thick base layer, and 6 cm thick wearing course), over a granular subbase (30 cm thick). Several types of defects were intentionally incorporated into the base layer or at the interface between the two asphalt layers.

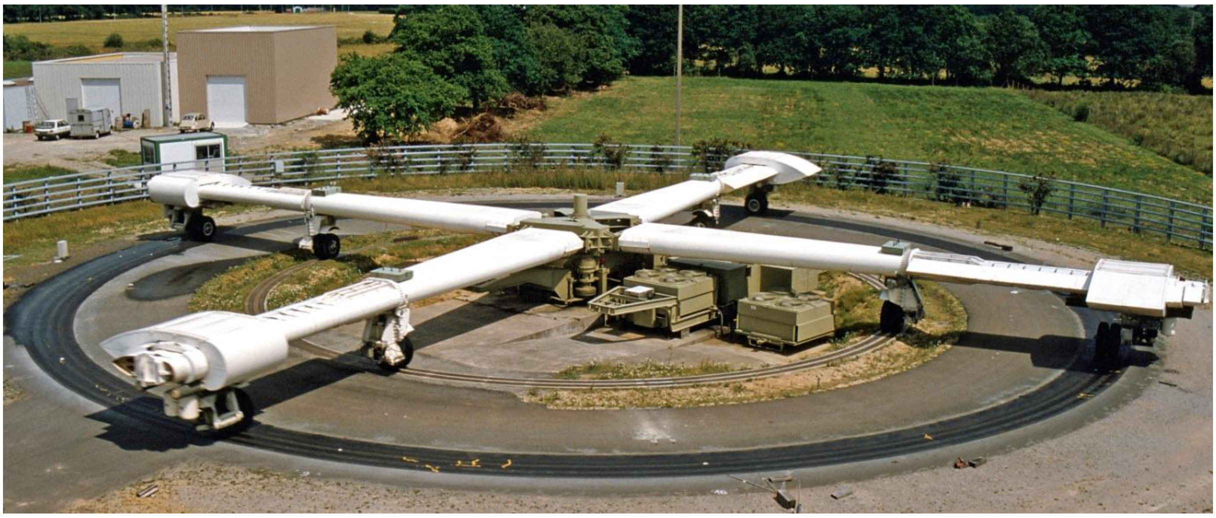

Figure 1. The pavement fatigue carrousel of IFSTTAR

2.2 Material characteristics and pavement construction

The pavement structures were built on the existing subgrade of the test track, which is a sand with about 10% fines, sensitive to water. The modulus of this subgrade is approximately 70 MPa. The structure built on this subgrade includes the following layers:

- A granular subbase consisting of 30 cm of 0/31.5 mm unbound granular material (UGM). After construction, this base was covered with a spray seal.
- A bituminous base layer, consisting of 8 cm of Road Base Asphalt material (RBA) (0/14 mm grading).
- A bituminous wearing course, consisting of 6 cm of bituminous concrete (BC) (0/10 mm grading).

The construction of the pavements was carried out by a road construction company, using standard equipment. Rectangular debonded areas were incorporated at the interface between the two bituminous layers. Table 2 presents their dimensions and the technique used: sand, textile, or absence of tack coat. Figure 2 presents a photograph of the debonded areas before the wearing course construction (2a) and a map of the experimental section, with the location of the different defects (2b).

These defects were centered on the radius R = 16 m, which corresponds to the centre of the wheel-path. The total width of the wheel-path (with lateral wandering) was approximately 1.0 m (between 15.5 m and 16.5 m). The debonded areas I-1, I-2, I-3, I10, I11 I12 and I13 are centered on the radius of 16 m. I-4 to I-9 are small defects, 50 x 50 cm, with a textile interface, located in and outside the wheel path.

Tableau 1. Characteristics of the different defects introduced in the pavement

Defect zones	Type	Dimensions, m (length × width)	Position, m, along radius R = 16 m
I-1	Sand	0.5 × 2 m	[2.5, 3]
I-2	Textile	0.5 × 2 m	[3.5, 4]
I-3	Tack coat free	0.5 × 2 m	[4.5, 5]
I-4 to I-9	Textile	0.5 × 0.5 m	[6.5, 9]
I-10	Textile	3 × 1 m	[9.5, 12.5]
I-11	Sand	1.5 × 2 m	[13.5, 15]
I-12	Textile	1.5 × 2 m	[17, 18.5]
I-13	Tack coat free	1.5 × 2 m	[20.5, 22]

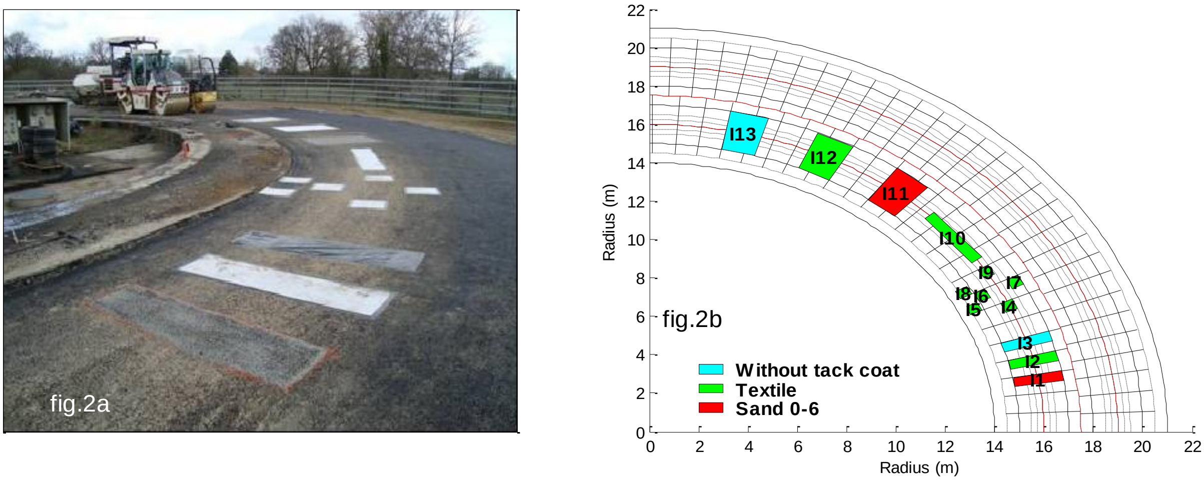

Figure 2. 2a: Interface defects before wearing course construction 2b: Map of the different debonded areas

3 PAVEMENT INVESTIGATION

The main objective of the experiment is to compare different NDT techniques (FWD, inclinometer, Colibri (mechanical wave propagation), Ultrasonic Pulse Echo, radar) for detecting different geometrical characteristics of artificial defects. Other objectives are to follow the evolution of the defects during loading, and to evaluate their effect on pavement performance. This will be helpful in optimizing pavement monitoring with the different NDT methods. Investigations have been done at different stages of the experiment:

- At the beginning of the experiment to characterize the initial state of the pavement;
- After 10000 loads when the structure is consolidated;
- After 50 000, 100 000 150 000 and 200 000 loads to survey the structure.

The structure has been investigated using the following NDT methods:

- Deflection measurement using:
  - FWD or HWD to estimate deflection basins under a dynamic load;
  - Inclinometer (Queroy 1974) to estimate the radius of curvature at a fixed point under a rolling load;

- Mechanical response of the pavement to loading at higher frequency with:
    - The Colibri apparatus based on the Frequency Response Function (FRF);
    - The UPE (Ultrasonic Pulse Echo) system based on ultrasonic shear wave propagation at a frequency of 55 kHz;
- Three radar devices : two classical Ground Penetrating Radars with a coupled 2.6 GHz antenna and a Horn 2.0 GHz antenna, and a step frequency radar which uses a network analyzer;

Unfortunately, we were not able to repeat each technique at each loading stage. It is also planned to apply the NDT techniques when visual surveys indicate the start of distress in the structure (e.g., cracking, rutting) and at the end of the experiment. A detailed analysis will define the final state of the pavements by coring and excavation of trenches to compare with the NDT results.

3.1 Deflection basin measurements

Several devices were used to measure deflection basins. A FWD and a HWD from other French laboratories came to study this test section. We also used a Benkelman beam and an inclinometer to estimate maximum deflection and radius of curvature under a rolling load. These measurements were made at a low speed, of about 3 km/h. The load application is the main difference between these devices. FWD and HWD apply an impulse dynamic load and measure deflection at different distances from the loading point while the other systems use a rolling load and measure the deflection bowl at a fixed point. If the maximum deflection is a common indicator, other deduced parameters cannot be compared. For example the radius of curvature measured with a Benkelman beam or an inclinometer is estimated close to the maximum deflection using a linear regression calculated along a 10cm length. It can't be compared with the difference in deflection obtained with the FWD between the central sensor and those at different distances from the loading point, which are more spaced.

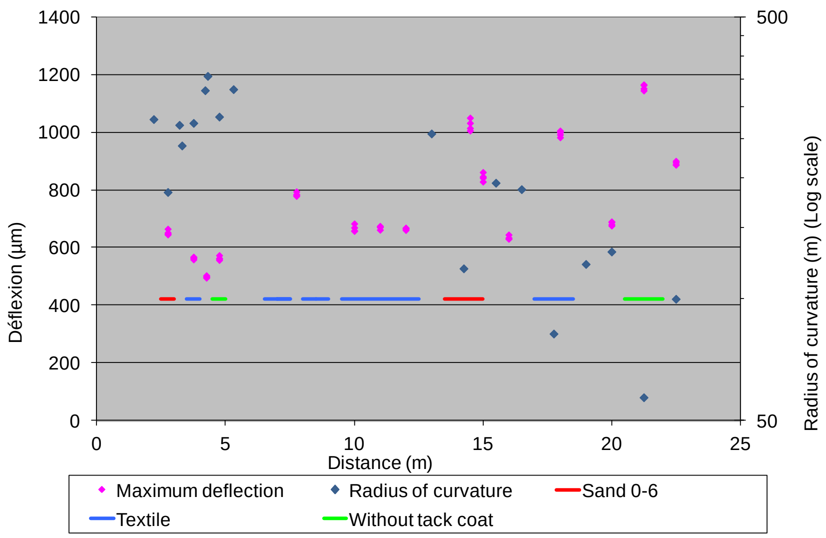

Figure 3. Maximum deflection measured with an FWD and radius of curvature measured with an inclinometer along the test section

FWD tests and inclinometer measurement were performed along a longitudinal profile at the 16 m radius, on the pavement section with defects before loading the test section. Four FWD load levels were applied and the test was repeated four times at each level. The radius of curvature was estimated with an inclinometer placed on the road surface while the fatigue carousel was slowly pulled by a handler (about 3 km/h).

Figure 3 locates the debonded areas and their type and presents along the profile:

- Maximum FWD deflections at the highest load level normalized at 75 kN;
- Radius of curvature (in logarithmic scale).

Deflections varied from 495µm to 1165µm depending on the measurement point. High deflection values were clearly obtained above or close to the largest debonded areas (I11, I12, and I13). Small debonded areas were much more difficult to detect, with deflection values close to those obtained on areas without defects, except perhaps for the measurement point located between the small defects I-4 to I-9. It is also difficult to precisely locate the position of the defect, and to make a clear difference between the different defect types using only the maximum deflection. Radius of curvature varied from 57m to 360m. Variation of radius of curvature measurement level was also observed above or close to the largest debonded areas (I11, I12, and I13).

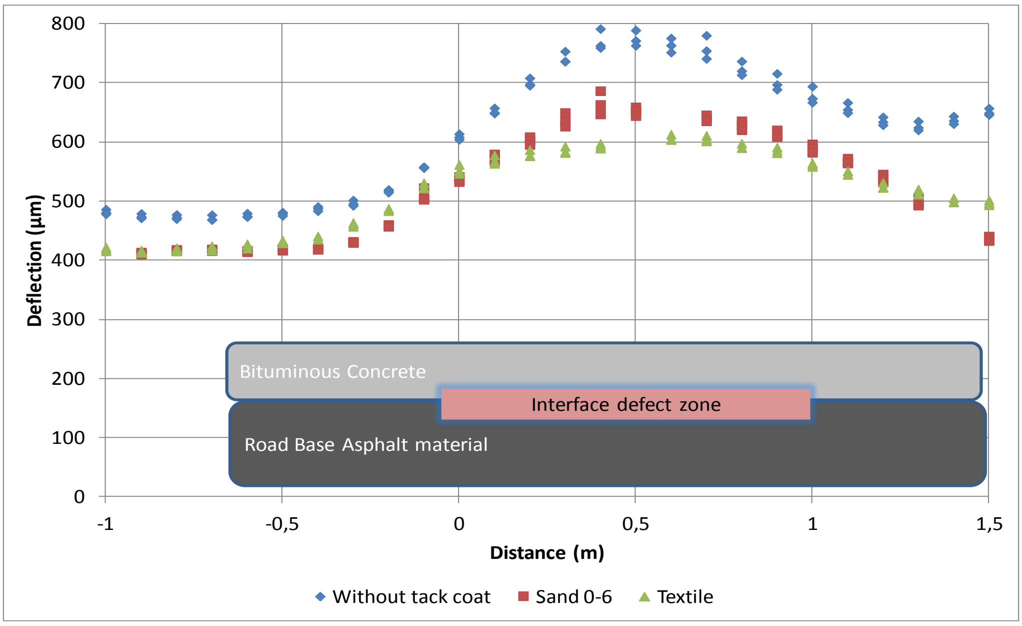

Figure 4. Maximum deflections measured with the HWD (80kN load) above the 3 types of defects

Interface defects affect measurements of maximum deflection and radius of curvature. However, in these first measurements, the sampling distance between two consecutive measurements was too large to locate accurately the extension of the defects. We used the opportunity of the presence of the HWD from the Civil Aviation Technical Centre in Nantes to renew the tests with an appropriate sampling rate. HWD load was reduced to 80kN, and 3 measurements were performed every 10 cm above the larger defects (I11, I12 and I13). Figure 4 presents the maximum deflections measured at the center of the loading plate, above the different types of defects. Deflection level clearly increases when the HWD is above the defect. It starts to increase when the sensor is 0.30 m before the limit of the defect. At this point, the edge of the 450 mm diameter plate is above the defect. Then, deflection increases up to a maximum level which corresponds to about 150 % of the initial level (160% in the case of sand or interface without tack coat and 140% in the case of textile). Deflection then decreases up to the initial level, except at the end of the interface without tack coat. This last case corresponds to the end of the test section and presents thickness variations due to the construction of this transition zone. Similar curves can be draw with deflections measured by sensors 2 and 3 located at 300 and 400 mm from the center of the plate. However, the maximum increase is less important than for the sensor located at the center of the plate (135% for sensor 2 and 125% for sensor 3).

3.2 Mechanical response of the pavement to higher frequency loading

Two NDT techniques, based on mechanical solicitation at higher frequency, were used use to test the structures. The first technique impacts road with an automatic 1kg hammer (Colibri apparatus). The applied load and the vertical response (acceleration) close to the impact point are measured. The Frequency Response Function (FRF), the structural response to an applied force as a function of frequency is deduced from modal testing theory (Ewins 2000) for intermediate frequencies (100 to 10,000 Hz). Based on IFSTTAR's experience, a methodology has been developed to calculate a damage indicator sensitive to interface damage or reflective cracking (Simonin 2009, 2012). The second technique called Ultrasonic Pulse Echo (UPE) is based on ultrasonic shear wave propagation at a frequency of 55 kHz. An antenna array (M2502) includes 24 piezoelectric sensors. Half of them emit waves into the structure while the others record the reflected waves. The results of both methods are presented as a map or B-Scan where:

- The X-coordinate is the abscissa along the road section;
- The Y-coordinate is the frequency band (FRF method) or time (UPE);
- Colors or level of gray represent the level of damage (FRF method) or signal amplitude (UPE);

These methods were used to investigate a longitudinal profile at the 16 m radius above the different debonded areas. Measurements were made at points spaced at a distance of 0.05 m or less. Figure 5 shows the maps obtained with the 2 methods above the larger defects (I11, I12 and I13). On the left, the maps obtained with the Colibri apparatus present the damage level, as a function of distance (X) and frequency (Y). The colors represent the damage level from 0 (blue) to 1 (red). On each map, the debonded area is located between distances 0.5 and 2m. This method allows to locate accurately the areas with defects in the case of textile and sand. The interface without tack coat is more difficult to locate (lower map).
The maps on the right of Figure 5, deduced from UPE measurements, present the amplitude of the time signal, as a function of distance (X) and time (Y). The colors represent the amplitude level from minimum (blue) to maximum (red) amplitude. The echo is easier to detect for the debonded interfaces with textile (upper figure) and sand (middle figure) than for the interface without tack coat. Above the debonded area, an interface echo is visible at around 60 µs. Using this information, and knowing the depth of the interface, shear wave velocity can be estimated at around 3000 m/s, which corresponds to a Young's modulus of 28 GPa. This high value is consistent with the complex modulus value obtained for the bituminous material at a frequency of 55kHz, using a visco-elastic model (E_∞=27.9 GPa). The limits of defects I11 and I12 seem to be different with the UPE device. This is due to positioning of the system at the beginning of the measurement sequence.

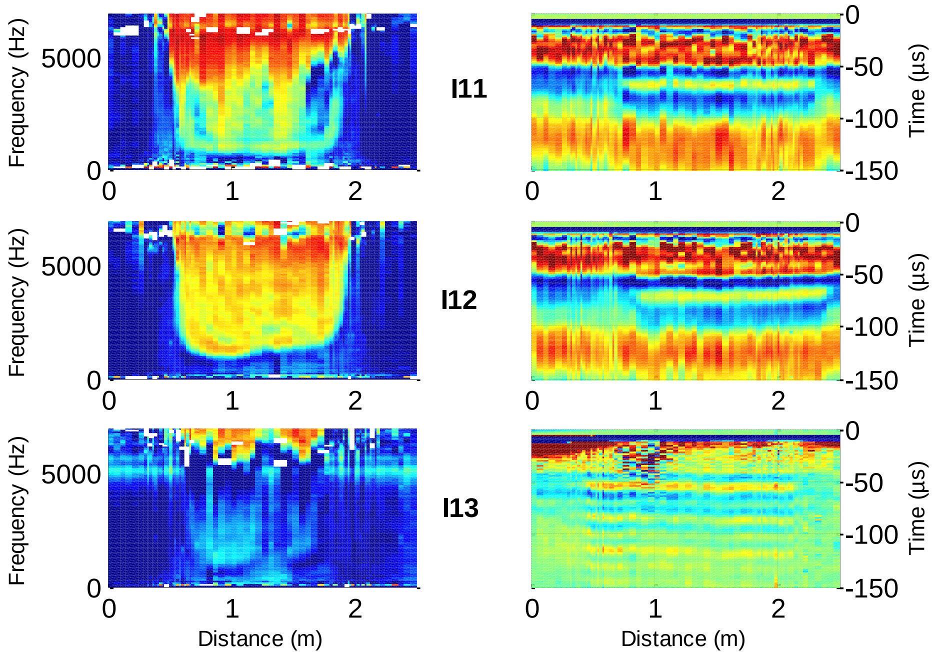

Figure 5. Mappings of Colibri (left) and UPE measurements (right) above the I11 (upper), I12 (midle) and I13 (lower) defects

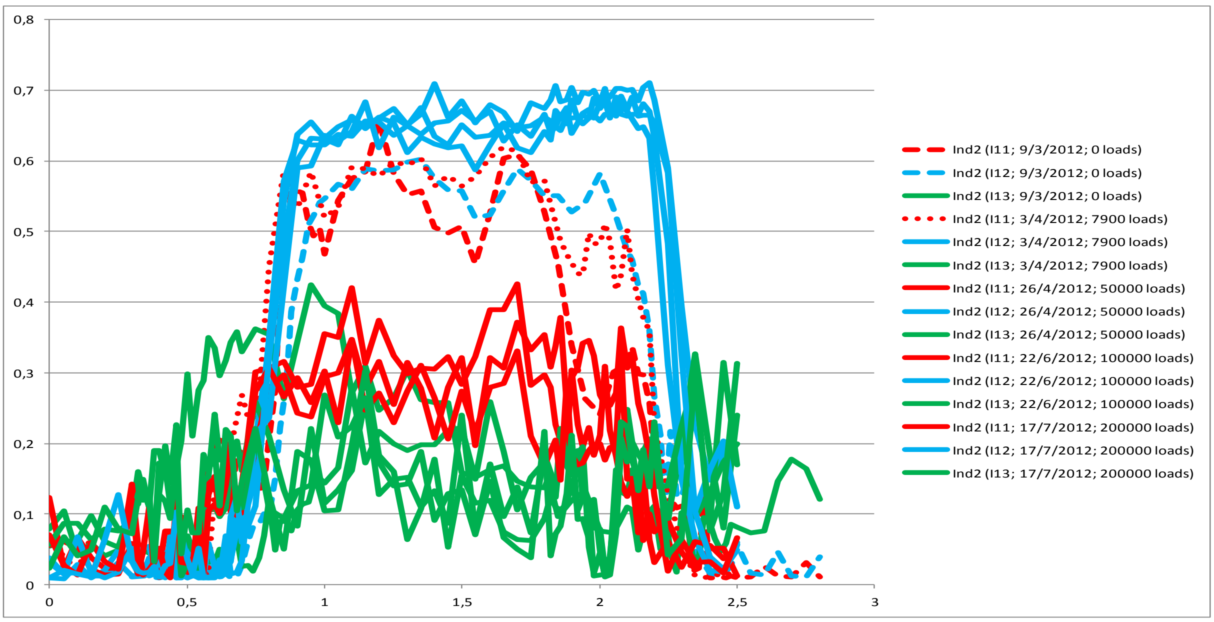

Figure 6. Evolutions of damage index from Colibri measurements, calculated in the frequency range 500-5000 Hz

Measurement results show that the Colibri and UPE methods are able to detect and locate the debonded areas and to make a distinction between them. Moreover the UPE device may also estimate the depth of the defect (from the propagation time), if material properties are known accurately. Shear wave velocity can also be used to determine material moduli (at the frequency of 55 kHz), which can give an indication of material damage. Measurement values from Colibri can be averaged within a frequency range to obtain a damage index, which can be practically used by pavement engineers. Figure 6 presents such damage index values calculated in the frequency range 500-5000 Hz for the 3 defects, from measurements made at different dates and numbers of loads. Red (resp. blue and green) lines correspond to the investigation of the sand interface I1 (resp. textile interface I12 and interface without tack coat I13). An evolution of these damage indexes can be observed at the beginning of the experiment. Indexes corresponding to the textile interface increase slightly with the number of loads; while indexes corresponding to the sand zone decrease from 0.6 to 0.3. This decrease can probably be explained by a post compaction of the sand under loading. After 50 000 loads, and up to 200 000 loads, no further evolution of the damage index is observed either in the level of the index or the spatial limits of the defect.

3.3 Radar investigations

Over the past few years, radar systems have emerged as a powerful NDT technique for pavement surveys (Saarenketo 2000, FHWA 2010) including assessing defects such as segregation, stripping, and cracking. Two types of Radar systems were used during this experiment: a pulse radar and a step-frequency radar (Dérobert 2004). The first system uses GSSI impulse radar (GPR) with 2.6GHz ground-coupled antennas. The antennas are fixed under a small trolley which includes a survey wheel. This trolley is moved manually. A fine spatial sampling is achieved (100 profiles per meter). The second system is a step-frequency radar (SFR) with a measurement bandwidth of 0.7 to 7.4GHz, which induces a central frequency around 4 GHz. The antennas were mounted on a specific system which allows a sampling of 50 profiles per meter.

Figure 7 shows B-scans obtained with the 2 systems above the larger defects (I11, I12 and I13), after 100 000 loads. Each B-scan presents the signal amplitude (level of gray) as a function of distance (X) and time (Y). The horizontal red line corresponds to the first echo on the pavement surface. The second echo (green line) corresponds to the damaged interface (BC/RBA interface). These echoes were automatically detected by selecting the maximum amplitude within an appropriate time window. B-scans obtained from the GPR are presented on the left, those of the SFR on the right. Upper (resp. middle and lower) graphs present B-Scans obtained above the sand (resp. textile and tack coat free) interface. At the end of the lower B-scan, some hyperbolas revealed embedded metal instrumentation within the pavement (I13). The B-scans from the 2 radar systems are similar. The main difference consists in the surface echo. With the GPR system (ground coupled antenna), it is constant with time, which explains why the red line is horizontal. The distance between the SFR antennas and the road surface varies slightly depending on the longitudinal profile. This explains the variations with time of the surface echo.

The amplitude variations of the BC/RBA interface echo with distance can be used to detect debonding. The maximum echo clearly increases above the defect. Taking the echo on a zone with no distress as reference, the maximum values of interface echo can be normalized to define a contrast of amplitude. Figure 8 shows the contrast evolution along the longitudinal profile above the textile defect (I11). Its longitudinal limits (0.7m to 2.2m) remain constant with the number of applied loads. The contrast of the debonded zones increases to 1.25 after 10 000 load applications, and then remains constant up to 200 000 loads. This simple indicator doesn't detect any evolution of the state of the interface. The sand defect has a similar evolution: the contrast of the debonded zone increases up to 50 000 loads, and then remains constant. The first period corresponds probably to a post-compaction of the sand layer, which reduces its thickness (as already discussed). It should be noted that with the SFR system, the contrast between the debonded and well bonded areas is much higher than with the GPR system (4 vs 1.25). The thinner pulse obtained with a higher frequency band appears much more efficient for detecting debonded interfaces. However, up to 200 000 loads, no further evolution has been perceived with the radar systems, indicating that probably after the first.

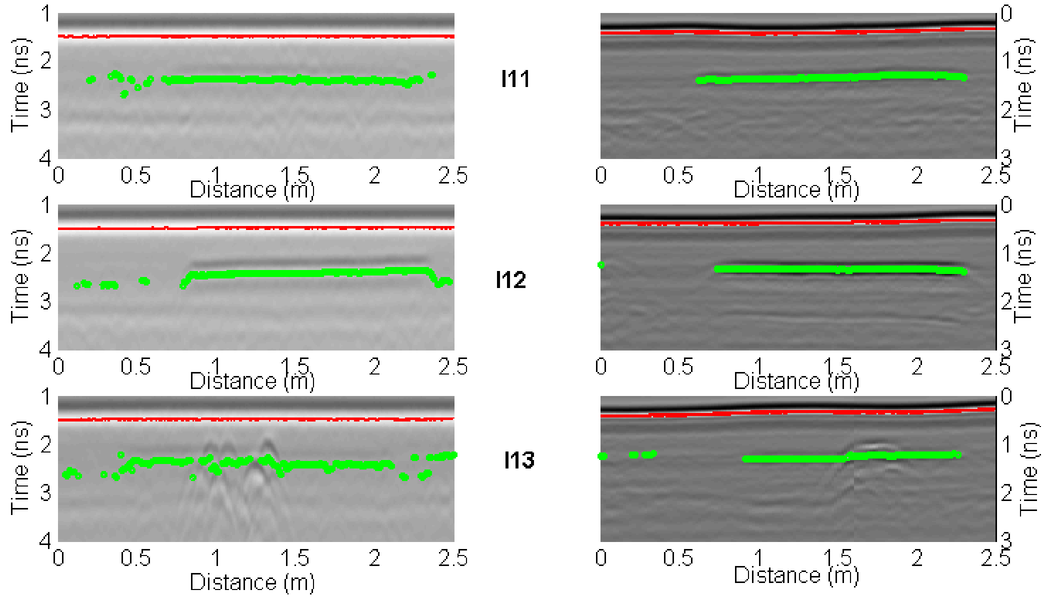

Figure 7 : B-scans obtained from GPR (left) and SFR (right) above the I11 (upper), I12 (midle) and I13 (lower) defects

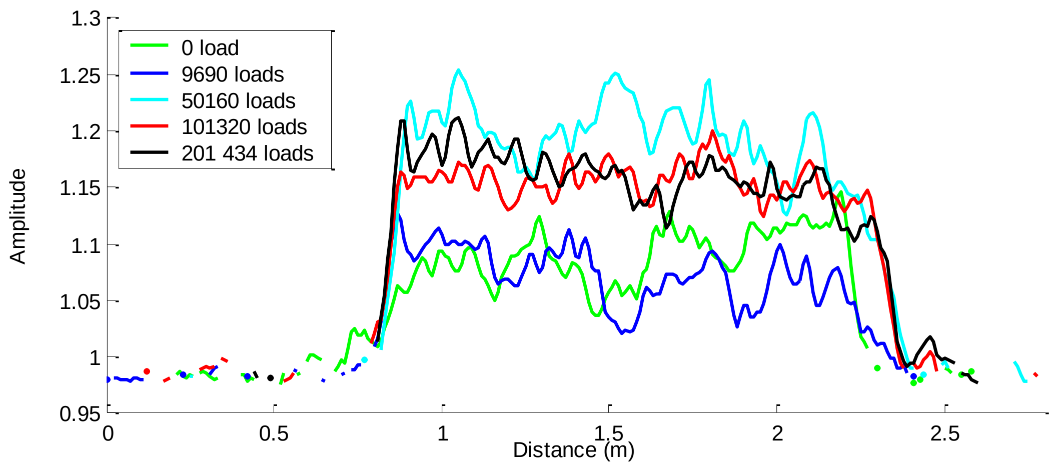

Figure 8. Evolution of the contrast of maximum amplitude above the textile (I12) defect with the number of loads, from GPR measurements

4 CONCLUSIONS AND OUTLOOKS

This paper presents an experiment performed on the IFSTTAR APT facility to evaluate the use of different NDT techniques for the detection of different debonded interfaces, and their evolution under traffic. A pavement section with different artificial defects has been built and tests performed using different investigation methods, before and during loading of the pavement. First results show some potential and limitations of the different methods. They also point out some research needs.

Deflection basin measurements show sensitivity to the presence of debonding but need a reduced sampling interval. Actual devices are not appropriate to continuously survey roadways and detect such defects. Development of new devices is still needed. Furthermore, deflection measurements are sensitive to the performance of all the pavement layers. Therefore, interpretation of result could be difficult to separate effects of layer properties and interface state. Numerical studies are required to define the sensitivity of the deflection basin to a debonded area.

FRF and UPE methods based on mechanical solicitation at higher frequency show very good sensitivity to debonded areas. The new Colibri prototype, an automated system, is able to apply the FRF method at a high rate (1 measurement per second). It could investigate several hundred meter long sections to provide the road engineer with a picture of the internal damage of the road base and wearing course. The UPE method shows interesting results which need to be confirmed by numerical studies and practice to understand some variations in result. This method could give information on the depth of the debonded area.

Radar measurements are easy to perform even at traffic speed to continuously detect layer interfaces and calculate thicknesses. They are also sensitive to interface debonding. The antenna choice (central frequency) is of primary importance. The SFR technique used allows increasing the frequency band and gives a high resolution picture which is useful to detect internal debonding. Radar techniques are adapted to a first estimation of interface state along a long itinerary, in order to identify zones were more accurate investigations are needed. Some research is still needed to optimize the individual signal or image processing, to obtain an interface damage indicator.

After 200 000 loads, no significant evolution of the interfaces has been observed with the NDT methods. Visual surveys don't detect any damage either. This test section will continue to be loaded in conjunction other APT programs (to perform at least 500 000 loads). NDT tests will be continued on the pavement at regular intervals, and research to optimize data processing and to develop numerical response models, to improve the interpretation of results will be carried out.

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