EXPERIMENTAL STUDY OF ASPHALT CONCRETE STRAIN DISTRIBUTION IN FLEXIBLE PAVEMENTS AT THE NATIONAL AIRPORT PAVEMENT TEST FACILITY

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PRESENTED FOR THE
2014 FAA WORLDWIDE AIRPORT TECHNOLOGY TRANSFER CONFERENCE
Galloway, New Jersey, USA

August 2014

ABSTRACT

The use of high-inflation pressure and heavily loaded tires on aircrafts induce high stresses at the surface of runway pavements. High compressive, tensile and shear stresses at or near pavement surface are likely to induce rutting and surface initiated fatigue cracking (top-down cracking) in asphalt concrete, particularly in the case of slow moving aircrafts. Tire-pavement interaction has been extensively studied using finite element modelling but has not been experimentally documented due to the limitations of conventional pavement instrumentation technology. During construction cycle 7 (CC7), five flexible pavements were constructed. Four of the five test sections include 200mm, 250mm, 300mm and 375mm of P401 hot mix asphalt (HMA) concrete over a P154 subbase (thickness varying between 890 and 965 mm) resting on a CBR 5.5 subgrade soil. The proposed paper describes experimental investigation of near-surface strains induced under Heavy Weight Deflectometer (HWD) and aircraft tires using an innovative instrumentation technique based on fiber optic sensors. Four "strain plates" supporting an array of 24 Fabry-Perrot fiber optic sensors were retrofitted in the HMA layers of four test sections at the Federal Aviation Administration (FAA) National Airport Pavement Test Facility (NAPTF) in Atlantic City, New Jersey. The strain plates allow for the measurement of near –surface compressive and tensile strains as well as tensile strains at the bottom of the AC layer over a 45 cm width across the wheel path. Data obtained from the strain plates under a moving wheel can be used to produce detailed strain basins across the entire tire width, allowing for a detailed analysis of the effect of tire type, load and pressure on pavement response. The proposed paper will describe the strain plate technology and the installation of the sensors at the NAPTF. It will also present early results of pavement response under the HWD and aircraft wheel loads. The project is done through a cooperation agreement between the Federal Aviation Administration and Laval University (Canada).

INTRODUCTION

The use of high-inflation pressure and heavily loaded tires on aircrafts induce high stresses at the surface of runway pavements. High compressive, tensile and shear stresses at or near pavement surface are likely to induce rutting and surface initiated fatigue cracking (top-down cracking) in asphalt concrete, particularly in the case of slow moving aircrafts. Tire-pavement interaction has been extensively studied using finite element modelling but has not been experimentally documented due to the limitations of conventional pavement instrumentation technology.

During construction cycle 7 (CC7), five flexible pavements were constructed at the Federal Aviation Administration (FAA) National Airport Pavement Test Facility (NAPTF) in Atlantic City, New Jersey. Four of the six test sections on north side include 8 inch (200 mm), 10 inch (250 mm), 12 inch (300 mm), and 15 inch (375 mm) of P401 hot mix asphalt (HMA) over a P154 subbase (thickness varying between 890 and 965 mm) resting on a CBR 5.5 subgrade soil. Four "strain plates" supporting an array of 24 Fabry-Perrot fiber optic sensors were retrofitted in the HMA layers of four test sections. The strain plates allow for the measurement of near –surface compressive and tensile strains as well as tensile strains at the bottom of the AC layer over an 18 inch (45 cm) width across the wheel path. Data obtained from the strain plates under a moving wheel can be used to produce detailed strain basins across the entire tire width, allowing for a detailed analysis of the effect of tire type, load and pressure on pavement response.

This paper describes experimental investigation of near-surface strains induced under Heavy Weight Deflectometer (HWD) using an innovative instrumentation technique based on fiber optic sensors. The following sections of the paper describe NAPTF, CC7 objectives, test pavement cross-sections, the strain plate technology and the installation of the sensors at the NAPTF. It will also present early results of pavement response under the HWD loads. The project is done through a cooperation agreement between the Federal Aviation Administration and Laval University (Canada).

FAA NATIONAL AIRPORT PAVEMENT TEST FACILITY (NAPTF)

The FAA's NAPTF [1] is located at the FAA William J. Hughes Technical Center, Atlantic City International Airport, New Jersey. The primary purpose of the NAPTF is to generate full-scale pavement response and performance data for development and verification of airport pavement design criteria. It is a joint venture between the FAA and the Boeing Company and became operational on April 12, 1999. The test facility consists of a 900 ft (274.3 m) long by 60 ft (18.3 m) wide test pavement area, embedded pavement instrumentation and a dynamic data acquisition system, environmental instrumentation and a static data acquisition system, and a test vehicle for loading the test pavement with up to twelve aircraft tires at wheel loads of up to 75,000 lbs (34 tonnes). Additional information about the test facility is available elsewhere (http://www.airporttech.tc.faa.gov).

A construction cycle at the NAPTF includes test pavement construction including instrumentation, traffic tests to failure, posttraffic testing (includes trenching activities and other tests), and pavement removal. A typical construction cycle (CC) at the NAPTF is shown in figure 1.

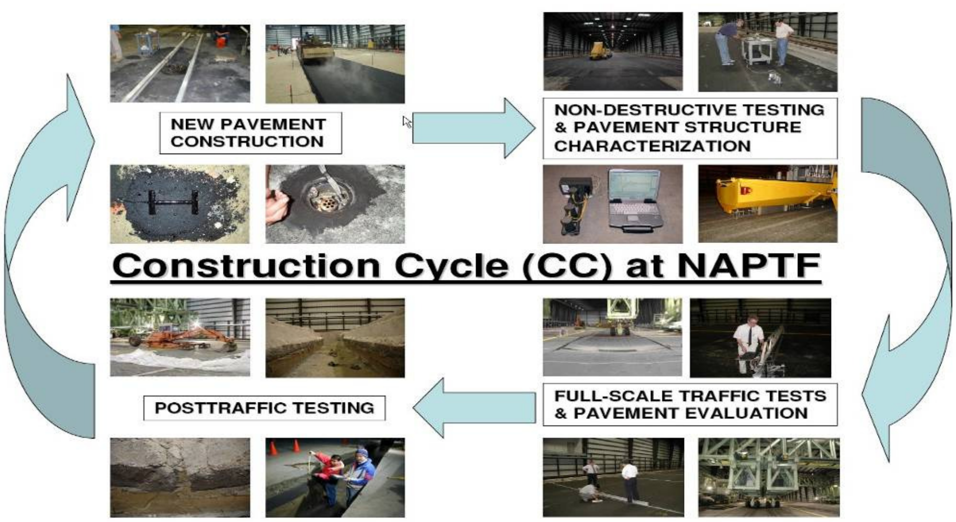

Figure 1. Construction Cycle at NAPTF.

CONSTRUCTION CYCLE 7 (CC7)

CC7 consists of flexible test items built on north side and south side on different strength subgrades. The test sections built on north side have thick HMA surface and are constructed on CBR 5.5 subgrade. Test sections on south side are built on CBR 4 subgrade and have 3 inch (75 mm) thick HMA surface. A CL-CH soil classification material known as DuPont Clay is used as the subgrade. Since the fiber optic strain plates are installed only on the north side test sections (LFP-1N, LFP-2N, LFP-3N, and LFP-4N) they will be the focus of discussion in this paper. Pavement cross-sections are shown in Figure 2. The objectives for full-scale testing of north side test sections are to determine:

a. Perpetual Pavements Design criterion for airport pavements.
b. Vertical strain threshold in the intermediate HMA layer to limit rutting.
c. Horizontal strain threshold in the HMA base layer to prevent bottom-up fatigue cracking.
d. Relationship between laboratory fatigue strain threshold and measured field HMA strains.
e. Study strain distribution in the HMA layer.

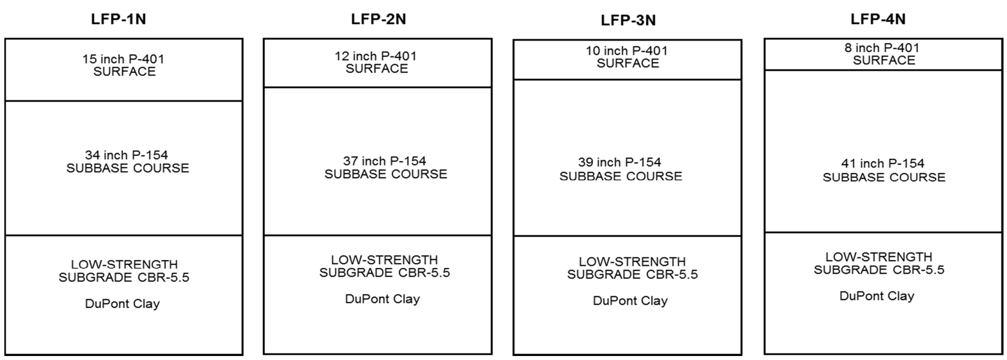

Figure 2. Pavement Cross Sections.

PAVEMENT INSTRUMENTATION

Pavement instrumentation installed consisted of multi-depth deflectometers (MDDs), pressure cells (PCs), H-bar asphalt strain gages (ASGs) and fiber optic strain plates in the traffic path. H-bar ASG's were placed at the bottom of HMA layer to measure transverse and longitudinal strains. For the first time at NAPTF, fiber-optic strain plates were installed in the test section with thick HMA surface (LFP-1N, LFP-2N, LFP-3N, and LFP-4N) shown in Figure 2. The following sections of the paper discuss fiber optic strain plate description, installation, and preliminary data collected during Heavy Weight Deflectometer (HWD) tests.

FIBER-OPTIC STRAIN PLATE

In order to measure the strain response under traffic load, the four test pavement sections were instrumented with innovative polymeric plate technology (Figure 3 and Figure 4a) [2, 3, 4 5]. Each test section was equipped with one instrumented plate positioned perpendicularly to traffic direction. Each plate consists of a polyphenylene sulphide (PPS) rectangular thin body in which 24 fiber optic strain gages are embedded and bonded with epoxy. The fiber-optic strain gages working principle is based on the White Light Polarization Interferometry technology. This technology uses a signal conditioner to sense the path length difference inside a Fabry-

Perrot interferometer of a known cavity length and delimited by two dielectric mirrors [6]. With proper calibration, the path length difference can be related to engineering values, such as displacement, stress and strain. Three signal conditioners equipped with 8 channels were used to collect the data of the 24 gages on one plate. The signal conditioner sends and receives the light, and the software interprets and transforms the received signal into physical quantitative values. These values are compiled in a text file at a specified frequency. For the purpose of this project, a 500 hz data collection frequency was used.

The PPS was selected because its elastic compression modulus of 429 ksi (2960 MPa) is similar to asphalt concrete elastic modulus at ambient temperature. The plate width and thickness are 18.7 and 0.2 inch (475 and 5 mm). The heights of the plates were selected to fit the thickness of the asphalt concrete layer at each test section (Figure 3). The sensors are fixed 2 inches (50 mm) apart on the plate in order to measure strains at critical positions through the asphalt concrete layer: 8 vertical strain gages 1 inch (25 mm) below the top of the plate, 8 transversal strain gages 0.8 inch (20 mm) below the top of the plate and 8 transversal strain gages 0.2 inch (5 mm) above the bottom of the plate. Proper analysis of the strains occurring in an asphalt concrete layer with this gages layout is useful for comprehensive studies of fatigue cracking (bottom-up and top-down) and creep rutting, amongst others, and to obtain the complete strain scheme of the layer under wheel loading when the technique is combined with longitudinal measurement techniques, such as the fiber-optic instrumented asphalt concrete cores [2, 3, 4, 5].

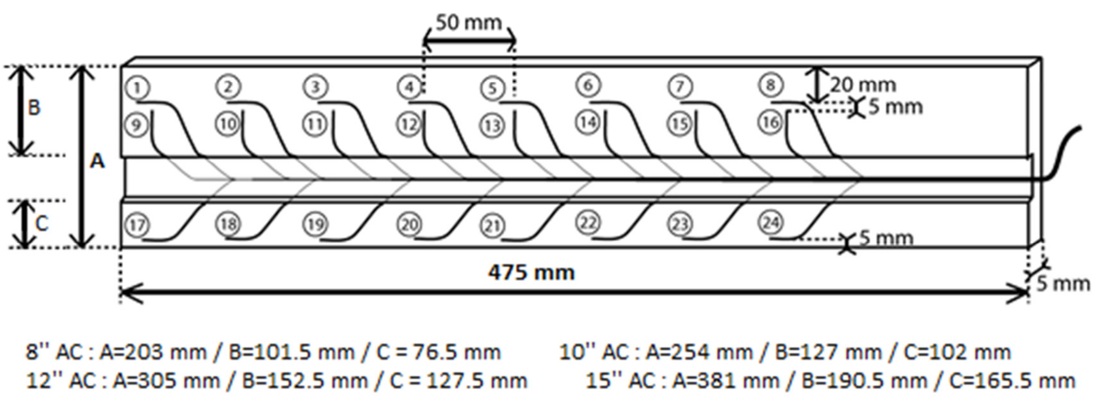

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Figure 3. Instrumented strain plate (not to scale)

STRAIN PLATE INSTALLATION

The instrumented strain plates were installed in January 2014. The installation is based on a retrofit technique. In order to insert the instrumented plate in the asphalt concrete layer, a sawcut is made (Figure 4a) perpendicular to the traffic direction. The cut is performed from the measurement area to the pavement edge. The cut is at full depth over the width of the plate (18.7 inch (475 mm)) in the measurement area in order to accommodate the insertion of the plate and about 2 inches (50 mm) deep to accommodate the wires up to the pavement edge. The cut width is slightly larger than the plate width (0.2 inch (5 mm)) in order to accommodate its insertion. The sawcut width is kept to a minimum level in order to ensure that the disturbance of the asphalt concrete layer is minimized so that the measurements are representative of the behaviour of the layer. Once the sawcut is made, the depth of the cut is leveled and adjusted with scalped base material compacted in the bottom of the cut when necessary. The sawcut is then cleaned and the plate is inserted afterwards (Figure 4b and Figure 4c). Slow curing epoxy with an elastic modulus of 435 ksi (3000 MPa) is used to fill the residual voids of the cut and to bond the plate to the asphalt concrete layer (Figure 4d). An example of the plate installed into the asphalt concrete layer is presented in Figure 4e.

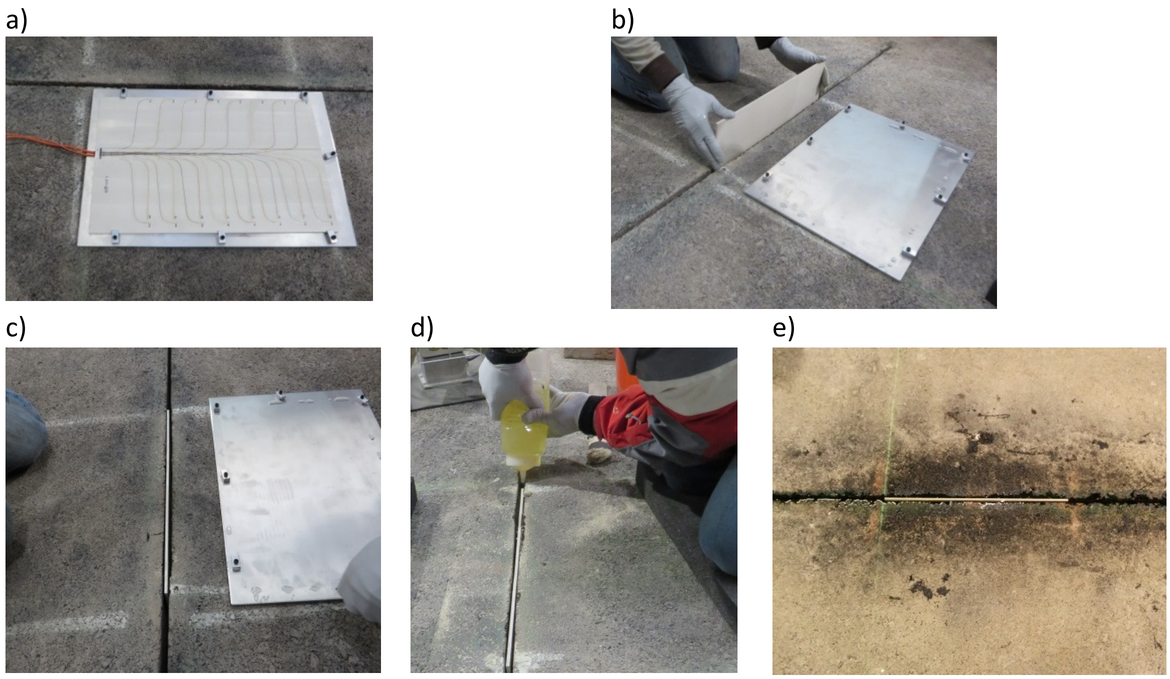

Figure 4. Instrumented plate installation: a) Sawcut and plate; b) Plate insertion in the sawcut; c) Plate inserted in the cut; d) Filling of the cut with epoxy; e) Installed plate.

HEAVY WEIGHT DEFLECTOMETER (HWD) TESTS

HWD tests were performed on the pavement test sections to study

- Uniformity of pavement structures, and
- Effect of fiber optic strain plate installation on the pavement structure.

The standard configuration (for the routine tests) for the FAA's HWD has been established with the following parameters: the segmented 30.5-cm (12-inch) loading plate, a pulse width of 30 msec, and four drop heights consisting of a 160-kN (36-kips) "seating drop" followed by impact loads of 53, 106, and 160 kN (12, 24, and 36 kips). The applied load levels of 53, 106 and 160 kN corresponds to surface contact stress σ_0 of 755, 1511 and 2266 kPa. The first 160-kN (36 kips) drop "seats" the pavement by settling out residual permanent deformations within the pavement structure and is not used in the analysis. The peak loads and deflections are recorded for all four drops along with air and pavement surface temperatures. The deflections are measured at the center of load plate (D0), at 30-cm (12-inch) offset (D1), at 60-cm (24-inch) offset (D2), at 90-cm (36-inch) offset (D3), 120-cm (48-inch) offset (D4), 150-cm (60-inch) offset (D5), and 180-cm (72-inch) offset (D6). An additional sensor is placed at 30-cm (12-inch)

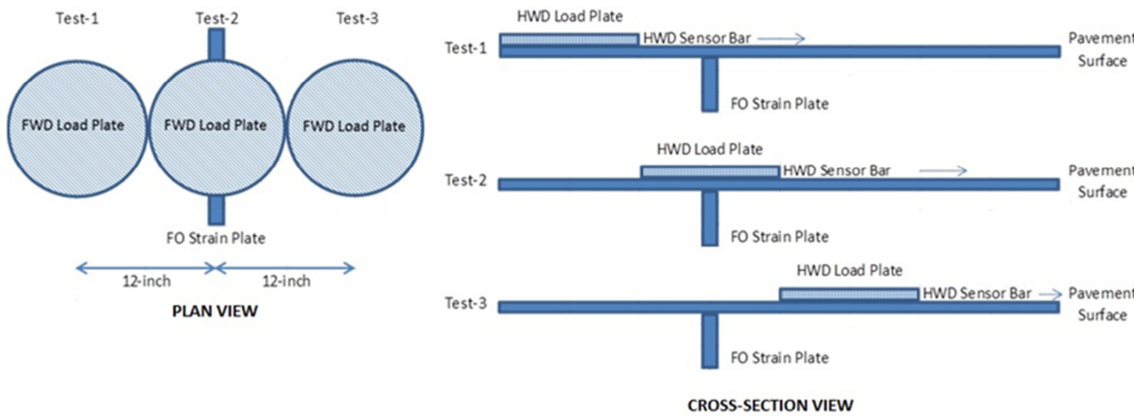

Figure 5. HWD tests plan over the strain plates

Table 1. Summary of HWD Test Results

HMA Thickness, inch		HWD Test Section Summary			HWD Over FOSP		
		Deflection D0, mils	AREA, inch	ISM, kips/inch	Deflection D0, mils	AREA, inch	ISM, kips/inch
15	***Max.***	12.51	47.1	3133	11.89	45.35	3029
	Min.	11.49	45.8	2878			
	Mean	12.06	46.5	2988			
	Std. Dev.	0.39	0.6	97.7			
	COV, %	3.26	1.2	3.3			
12	***Max.***	17.07	44.8	2349	16.61	42.37	2168
	Min.	15.33	43.2	2109			
	Mean	16.19	43.9	2227			
	Std. Dev.	0.64	0.6	88.0			
	COV, %	3.94	1.5	4.0			
10	***Max.***	23.52	42.2	1786	22.92	38.92	1571
	Min.	20.15	39.6	1530			
	Mean	21.55	40.8	1674			
	Std. Dev.	1.15	0.8	87.1			
	COV, %	5.34	2.1	5.2			
8	***Max.***	29.16	38.5	1339	27.95	36.95	1288
	Min.	26.89	36.9	1235			
	Mean	27.83	37.8	1294			
	Std. Dev.	0.77	0.7	35.2			
	COV, %	2.77	1.8	2.7			

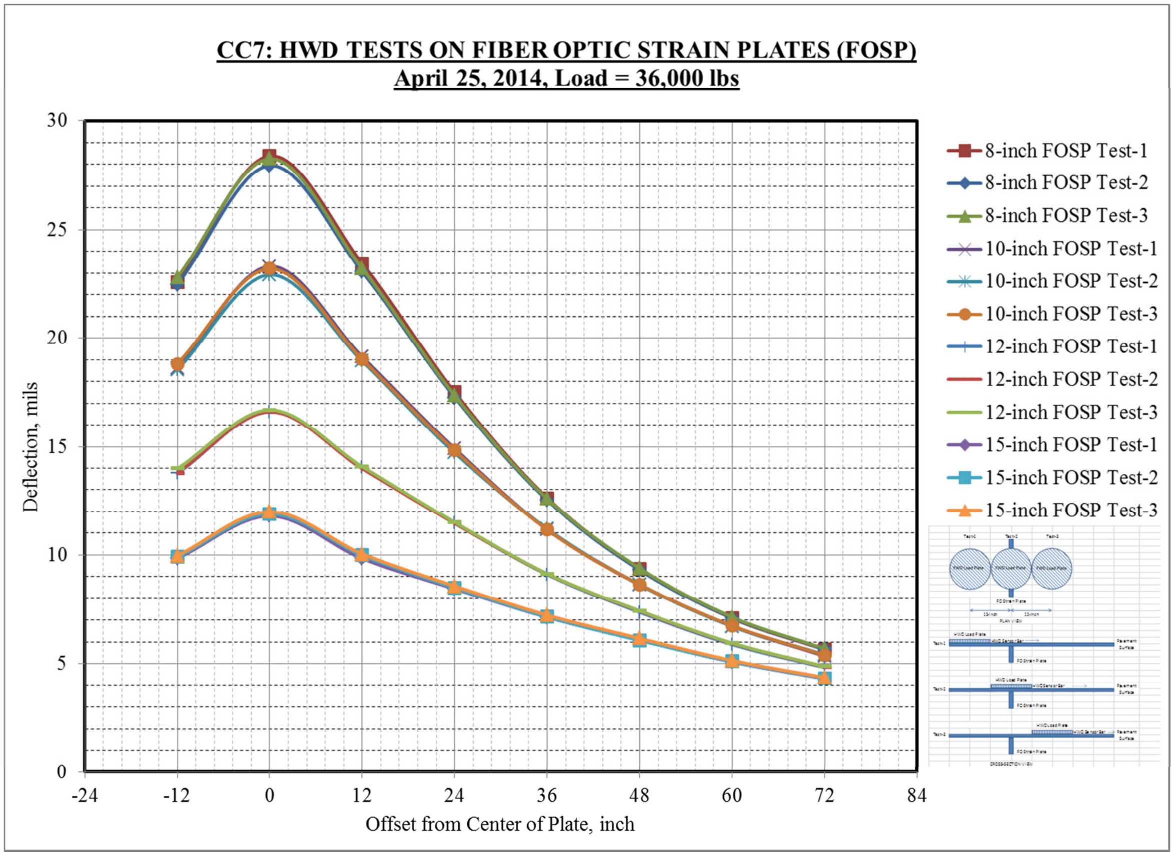

Figure 6. HWD deflection basins

offset on the front of loading plate. In each test section, HWD tests were performed at 6 different locations in the test section. As shown in Figure 5, HWD tests were also performed on top of the fiber optic strain plate and at 30-cm (12-inch) offset on either side of the fiber optic strain plate. Table 1 and Figure 6 summarize the HWD test results.

As can be seen from Table 1 and Figure 6, saw-cutting and installation of the fiber optic strain plates does not cause any weakening or strengthening of the pavement structures and behaves as an integral part of the pavement test section.

STRAIN PLATE RESPONSE

The HWD tests in the strain plate area were carried 300 mm (12”) before the plate (Test 1), directly over the plate (Test 2), as well as 300 mm (12”) after the plate (Test 3) (Figure 5). For the purpose of the HWD tests, the 300 mm loading plate was positioned in the middle of the sensors array (centered between gages 4/5, 12/13 and 20/21 in Figure 3). Typical strain signal for an array of 8 sensors is presented in Figure 7. This is an example of the transversal strain data at the bottom of the 254 mm asphalt concrete layer collected for a 24000 lbs load applied directly over the strain plate (test 2). The strain data collected with the plate can be either negative (contraction) or positive (extension). Throughout this paper, transversal strains are labeled as ε_{yy} and vertical strains are labeled ε_{zz}. It can be observed that the positive values of strains in Figure 7 are in good agreement with the tensile strain generally occurring at the bottom of an asphalt concrete layer under wheel or plate loading. Maximum deformations are also approximately encountered at the load center. The data analysis was focused on the first strain peak (Figure 7), as the following smaller peaks are associated with the plate rebounds after the first impact.

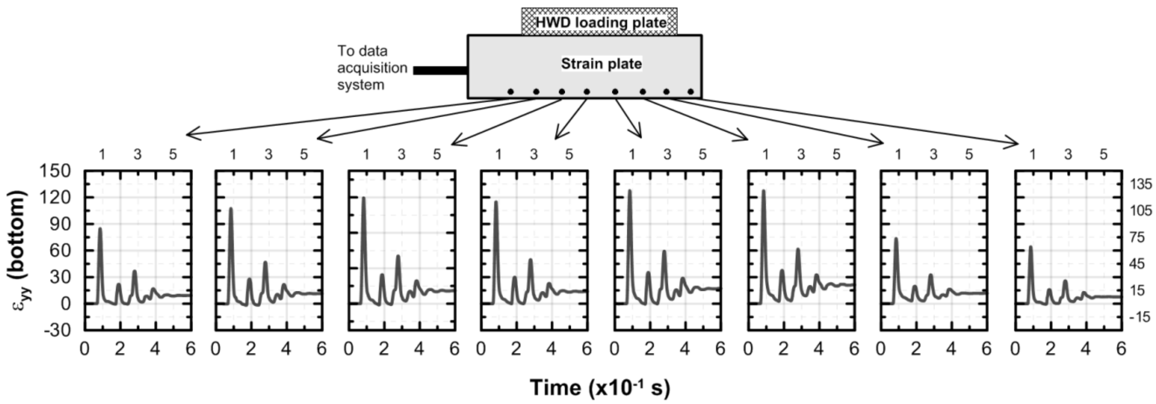

Figure 7. Typical strain signal for a sensors array – Transversal strain at the bottom of asphalt concrete ε_{yy} – 10-inch (254 mm) test section – Test position 2 – σ_0= 212 psi (1511 kPa)

Figure 8 summarizes the strain basins measured under the HWD loading plate for the test position 2. The surface vertical strains ε_{zz}, surface transversal strains ε_{yy} and the bottom transversal strains ε_{yy} are plotted as a function of loading plate position over the strain plates. The strain basins are provided for each asphalt concrete thickness, as well as for each applied load. The center of the plate is positioned at 0 on the abscissa. The grey shaded area represents the zone over which the loading plate is in contact with the pavement surface. According to previous researches [4], numerous load repetitions would be needed to draw a representative strain basin. The data presented in Figure 8 were obtained using only one HWD drop for a specific test condition. Moreover, centering large equipment like the HWD over a plate that is embedded in the asphalt concrete layer is a difficult task. These facts may be the cause of some scattering of the data and some asymmetry in the strain basins.

The tensile strains ε_{yy} developing at the bottom of the asphalt concrete layers suggest an increasing strain with the increase of the load level, as well as a decreasing strain with the increase of the asphalt concrete layer thickness. Generally, the maximum ε_{yy} at the bottom of the layers is found approximately at the center of the plate. However, it can be observed that the peak strain is often found on either side of the zero position, which may reveal a slightly off-centered HWD loading plate. The flattening of the strain basin shapes with the increasing of the asphalt concrete layer thickness also shows the increase of the curvature radius associated with the strain occurring at the bottom of the layers. As a matter of fact, larger strains differences are observed between the center of the load and the plate edges for thinner asphalt concrete layer, while little are found for the thicker structure. Indeed, the tensile strains at the bottom of the asphalt concrete layer for the 15-inch (381 mm) section presents an almost flat strain basin, with the maximum value measured near the loading plate edge. The negative compressive strain outside the edge of the 15-inch (381 mm) loading plate, as well as the strain basin asymmetry, may reveal that the loading plate may have been slightly off-centered, or may be associated with a testing, installation or gage issue.

The tensile strains occurring near the surface are all negative, which means that the asphalt concrete layers are in compression in the transversal direction due to the flexural behavior of the layers under the load. Generally, the maximum strains occur near the load center, the strain amplitudes increase with the increase of the load level and the strains decrease with the increase of the asphalt concrete layer thickness. With the exception of the 8-inch (203 mm) test section, the tensile strains measured tend toward a fast transition between the decreasing compressive strains when approaching the loading plate edge to an increasing compressive strain just outside the loading plate edges. This typical behavior is predicted by theoretical simulations with the multilayer elastic theory [7]. The general shape of strain basins is in good agreement with the theoretical basins predicted by calculations with multilayer linear elastic systems. Typical results generally suggest that compression is maximal at the load center and decreases towards the load plate edges. The sudden increase of the transversal compressive strains outside the loading plate is due to the vertical extension of the material near the surface outside the loading plate. The removal of the vertical stress above the material outside the loading plate allows vertical extension, which in turn leads to compression in the transversal direction due to the Poisson ratio of the material.

The vertical strains measured 1 inch (25 mm) below the surfacing layers are significantly less influenced by the thickness of the asphalt concrete layer. This behavior is consistent with expectations as vertical strains near the surface are not significantly affected by layer thicknesses. Nevertheless, the compressive strain tends to increase with the applied load level. The asphalt concrete materials react in compression (negative values) under the loading plate, but a rapid change to extension is generally observed beyond the plate edges, as shown by the positive values measured at 175 and -175 mm on the abscissa. On the 8-inch (205 mm) test section, negative values of ε_{zz} are still observed at a position of -175 mm, which may be associated with a slightly off-centered loading plate. The response of the vertical sensors near the surface is typically more sensitive to the surface irregularities and plate contact quality with the pavement surface. This is probably associated with the uneven pattern in the strain basins observed, especially for the 10-inch (254 mm) and 12-inch (305 mm) test sections.

The tensile strains data collected near the surface and at the bottom of the asphalt concrete confirm the good performance of the strain plates and provide a good indication of the structural adequacy of the test structures. As a matter of fact, the tensile strains at the bottom and at the surface of the surface layer were found to decrease with the increase of asphalt concrete thickness. It is generally accepted that the tensile strain at the bottom of the asphalt concrete layer is associated with bottom-up fatigue cracking while the tensile strain at the top of the asphalt concrete layer is associated with top-down cracking. A reduction in strains at these levels will result in a reduction of the related damage or an increase of pavement life. Similar trends are observed in terms of pavement surface deflections under HWD load – peak center deflection reduces as the HMA thickness increases thereby signifying an increase in pavement life.

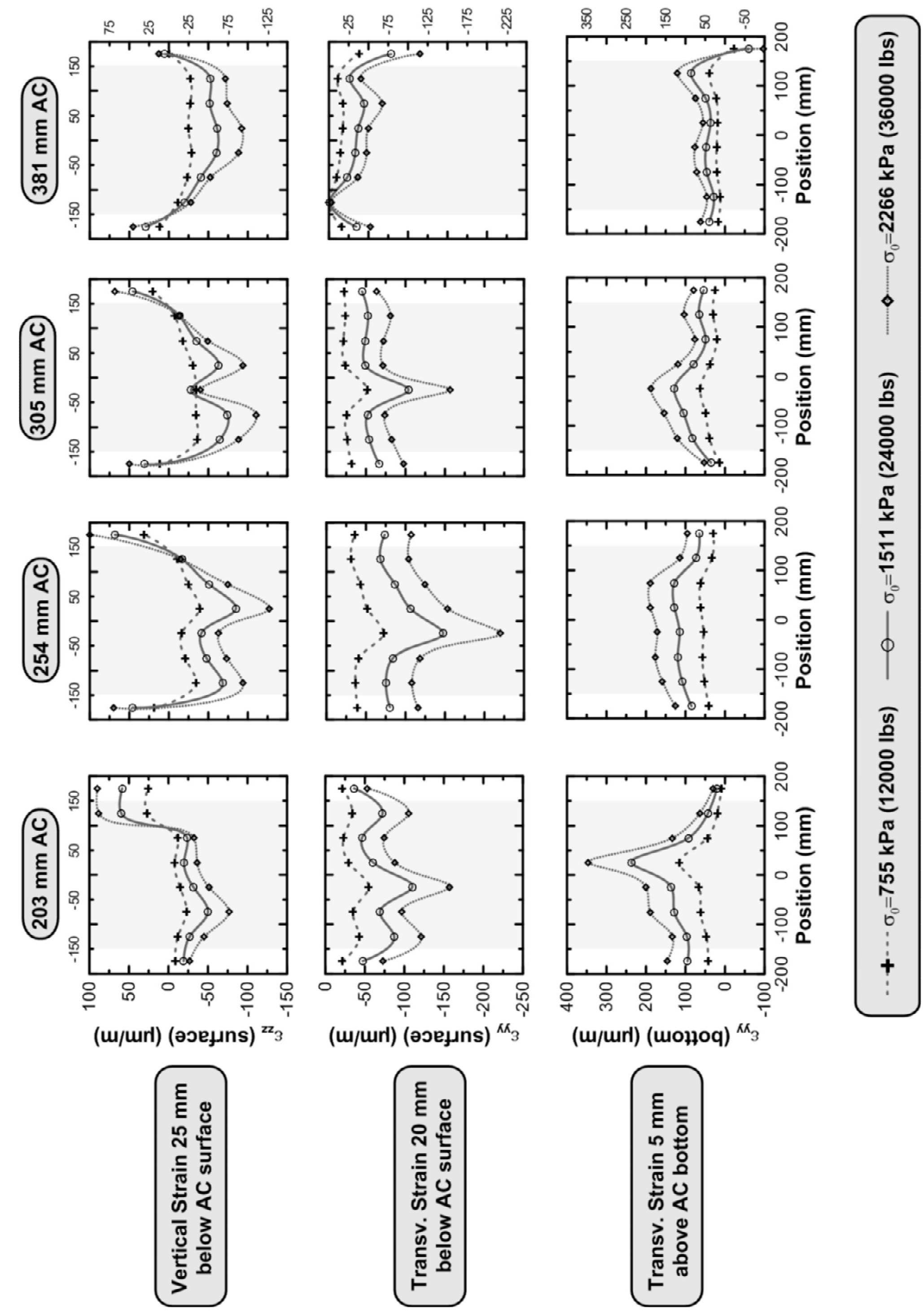

Figure 8. Measured strain basins for test position 2

In order to evaluate the uniformity in the response on either side of the fiber-optic strain plate, HWD tests were performed at test positions 1 and 3 (Figure 5). Figure 9 presents the results expressed as strain basins obtained for each pavement section loaded at 24,000 lbs (σ_0=1511 kPa). This comparison is performed to verify if the strain plate installation process affects the structural integrity of the asphalt concrete layer. It is also performed because the fiber-optic gages are not embedded in the middle of the plate, but are inserted and bonded into tiny grooves on one side of the PPS plate. Therefore, it is important to check if this design method affects the reading on both sides of the plate. A good bonding of the epoxy with the asphalt concrete layer and with the plate should be able to transfer the applied loads to the entire strain plate and loading plate testing at symmetrical position according to the strain plate should give similar readings. The results presented in Figure 9 tend to confirm that the reading of each plate is the same for a loading plate positioned on either side of the strain plate. Taking into account that several measurements would be needed to obtain a representative strain basin, the slight differences do not appear to be significant. It should be noted that the sensors positioned at 5-inch (125 mm) and 7-inch (175 mm) for the 15-inch (381 mm) test section may not work appropriately, as atypical values and response were measured for test 1 (Figure 9) and test 2 (Figure 8). The strain basins obtained for those two cases show a sudden strain increase (extension) at 5-inch (125 mm) and a significant strain decrease at 7-inch (175 mm). However, the strain plate response for test 3 appears to be more typical at this position. Additional tests on the strain plate and investigations should be carried out on the 15-inch (381 mm) section strain plate to verify if these sensors are faulty, if installation issues are enlightened or if errors encountered during data collection.

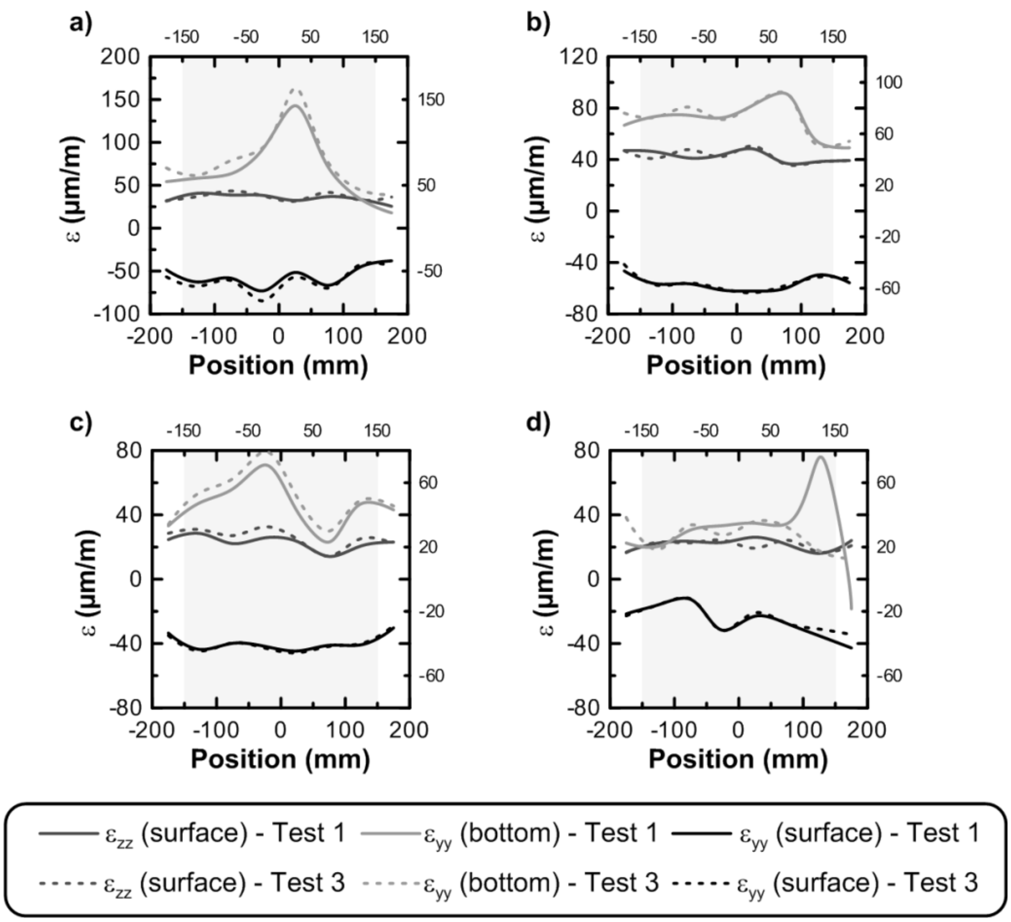

Figure 9. Comparison between results for test position 1 and 3 at σ_0=1511 kPa, a) AC=8 in (203 mm); b) AC=10 in (254 mm); c) AC=12 in (305 mm); d) AC=15 in (381 mm).

SUMMARY

The results from Heavy Weight Deflectometer (HWD) performed over four flexible pavement test sections at the NAPTF are presented. Asphalt concrete strains were measured using fiber optic strain plates installed post construction in the test sections. The strain plates allow for the measurement of near –surface compressive and tensile strains as well as tensile strains at the bottom of the AC layer over a 17.7 inch (45 cm) width across the wheel path. The HWD deflection measurements showed that the installation of strain plates does not alter the pavement structure significantly and forms an integral part of the pavement structure. The strain plates are functioning as expected (except for some questionable results from one plate that will be subjected to additional tests for further evaluation). The asphalt concrete strain measurements made during traffic tests (to be conducted in the near future) under aircraft wheel loads (simulated at NAPTF) will be used for the validation/modification/refinement of the new HMA fatigue failure model incorporated in FAARFIELD (FAA pavement thickness design software).

ACKNOWLEDGEMENTS

The work described in this paper was supported by the FAA Airport Technology Research and Development Branch, Dr. Michel Hovan, Manager. The authors would like to thank Jeffrey Gagnon, Manager Pavement Sub-Team, for his support during the test planning and organization, Murphy Flynn (FAA) and Damien Grellet (Laval University) and Charles Leduc (OpSens) for their assistance during the installation of strain plates. The authors would also like to acknowledge Wilfredo Villafane (FAA), Sean Combs, Henry Fermin, and Reynaldo Aponte (all SRA) for their assistance during HWD testing and strain plate data acquisition. The contents of this paper reflect the views of the authors, who are responsible for the facts and accuracy of the data presented within. The contents do not necessarily reflect the official views and policies of the FAA. The paper does not constitute a standard, specification, or regulation.

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