Evaluation of Strains at the Bottom of the Asphalt Base Layer of a Semi-Rigid Pavement Under a Class 6 Vehicle

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Abstract. A newly constructed pavement on US-287 near Mansfield, TX was instrumented with gauges installed at the bottom of the asphalt concrete base layer to measure the longitudinal and transverse strains developed under a test vehicle. The finite element program Abaqus was used to compute the strains at the location of the gauges; they were found in good agreement with the measured strains. The research showed that the strains under the steering axle were of similar magnitude as the strains under the rear tandem axle. The measured transverse strains were in general slightly bigger than the corresponding longitudinal strains, while the finite element model computed higher strains in the longitudinal direction. These findings suggest the need to account for the strain responses from the steering axle of trucks and to account for both the longitudinal and the transverse strains when computing the fatigue damage induced by trucks.

1 Introduction

Heavy vehicle axle loads induce pavement strains that drive pavement damage accumulation which untimely leads to pavement distress. Fatigue cracking is one of the dominant pavement distress mechanisms in flexible pavements. Traditional fatigue cracking in asphalt pavements is governed by the tensile strains at the bottom of the asphalt concrete layer. These strains generate cracks that originate at the bottom and propagate to the top of the asphalt concrete layer. Multiple axle configurations, such as tandems and triples, generate strain responses that overlap; that is the strain from the lead axle does not quite recover before the strain from the following axle begins to build up. This results in multi-hump strain responses under closely-spaced adjacent truck axles. Accounting for the damaging effect of these multiple strain cycles is essential in evaluating the damaging effects of multiple truck axle configurations. While this issue has been thoroughly researched, it remains unclear whether pavement strains from unconnected axles could overlap as well, under certain circumstances. For example, is there an overlap between the strains from steering axles and those from the following tandem drive axles of a Class 9 semi-trailer truck? Some studies suggest that for thick asphalt concrete layers and high vehicle speeds this may be possible. If so, the way pavement fatigue damage from heavy trucks needs to be reevaluated to account for the effect of strain overlap from successive truck axles.

The objective of this study is to develop a strain measurement dataset that will allow revisiting pavement strain response under in-service traffic for the purpose of quantifying pavement damage under consecutive axle load configurations.

2 Location of test site

The field site for installing the instrumentation was on a construction project on highway US-287, south of Mansfield, Texas, right at the intersection with US-360. This construction project was selected since it was a new flexible pavement construction with a relatively thick asphalt concrete layer and carries medium to high truck traffic volume. It was also one of the very few such project in the Dallas-Fort Worth area built in Spring-Summer 2018.

The geotechnical investigation identified the natural sub-grade soils along the project as a high-plasticity clay. The embankment was brought to grade and the top 915mm (36in.) of soil were stabilized with 6% by weight hydrated lime in August 2017 to ensure proper support to the asphalt concrete layers and to provide a stable support for the construction equipment. Appropriate measures were taken for the proper curing of the lime treated soil. Three asphalt mixes were paved over the lime treated subbase layer. The configuration of the pavement structure is given in Table 1.

Sufficient quantities of hot mix were obtained from the asphalt plant for mixes S and I to fabricate cylindrical specimens, 152 mm (6 in.) in diameter and 178 mm (7 in.) tall using the Superpave Gyratory Compactor. The specimens, compacted at the target air void content of 7.0% were cored and trimmed to obtain cylindrical samples 100 mm (4 in.) in diameter and 152 mm (6 in.) tall. The samples were tested to determine the

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dynamic modulus of the two mixes. Cores taken from the base layer were used to measure the dynamic modulus of the base mix (Mix B).

Table 1. The Configuration the Pavement Structure.

Layer	Thickness and Material	Modulus MPa (psi)
Wearing Course	41mm (1.6in.), Mix S (SMA; PG70-28)	440,777 (3,039)
Binder Course	51mm (2.0 in.), Mix I (TxDOT Type D; PG64-22)	512,540 (3,534)
Base Course	162mm (6.4 in.) Mix B (TxDOT Type B; PG 64-22)	552,463 (3,809)
Chemically Stabilized Embankment Soil	915mm (36in.) 6% hydrated lime mixed to the natural soil	80,000 (552)
Natural Sub-grade	High plasticity clay (A-7-6)	8,000 (55)

3 Response monitoring instrumentation

The pavement response measuring instrumentation was placed in the pavement structure during their construction, in June 2018. The gages were placed at the bottom of the asphalt concrete base layers by retrofitting them on cores cut in the base HMA layer. The gages were retrofitted instead of being installed during the construction of the HMA base layer because the base layer was already in place. The pavement response measuring instrumentation was composed of eight strain gauges: four gages (L2, L4, L6 and L8) were placed to measure the longitudinal strain and the other four (T1, T3, T5 and T7) to measure the transverse strain. Four gauges were placed in the outside wheel path while the remaining four gauges were placed on a straight line 165 mm to the right of the outside wheel path. A schematic diagram of the layout of the response measuring instrumentation is shown in Figure 1.
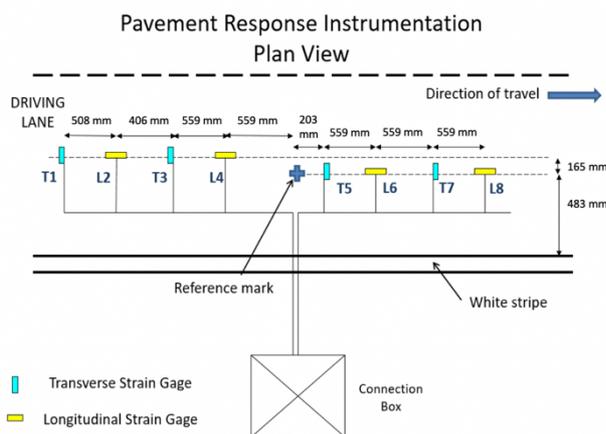
Fig. 1. Plan view of the instrumentation.

Model KM-100-HAS strain gages made by Tokyo Sokki Kenkyujo Co. [1] in Japan and commercialized by Texas Measurements Inc. in the United States were used. The strain gauges were retrofitted by cutting 152 mm diameter cores from the HMA base layer and fixing the

strain gages to the bottom of the cores with Sika Pro Ultimate Grab Adhesive. The cores with the gauges at their bottom were placed back in the same location the next day and were glued to the walls of the holes with a thick layer of Sika AnchorFix-2 Anchoring Adhesive.

A week after the cores with the sensors were installed, the HMA intermediate layer was paved followed by the paving or the asphalt surface layer a week later. The road section was opened to traffic in July 2018.

4 Response measuring procedure

The pavement response measurement was done a month after the road was opened to traffic, with the assistance of TxDOT and the contractor that provided the traffic control and the test vehicle. A water tank truck with a tandem axle in the rear was used as the test vehicle. According to the FHWA vehicle classification system, this truck is a class 6 vehicle.

Before the runs were performed, static weight of each wheel was measured by the Mansfield Police using calibrated scales. The dimensions of the tire imprints as well as distance between tires were also measured [2].

Seven passes each were performed with the truck passing at approximately 80 Km/h (50 mph). Using markings on the pavement surface as guides, the driver aimed to position the truck with the right wheels above the instrumentation. However, the lateral position of the wheels relative to the sensors varied between passes. Each passing of the test vehicle was recorded on video at a refresh rate of 60 images per second. The markings on the pavement and review of the video clips in slow motion were used to locate the lateral position of the test vehicle as it passed over the sensors. A rubber hose system was used to measure the speed of the test vehicle. A thermometer was lowered in holes drilled in the HMA layers and filled with oil to measure the temperature at the mid-depth of each HMA layer at the time of response measurements.

The horizontal strains at the bottom of the asphalt concrete layer, as well as the position of the loading vehicle, were recorded with a National Instruments data acquisition system at a sampling rate of 5,000 Hz. The data for the raw signal as well as for the signal filtered with a 50Hz filter were downloaded in Excel files. The data was recorded in separate files for each pass of the loading vehicle and then it was processed using Microsoft Excel. Each strain signal was plotted and the peak values of the longitudinal and transverse strains were manually extracted.

Table 2. The Configuration the Pavement Structure.

Location	Temperature (°C)
Air (Shaded)	33
Pavement Surface (Shaded)	41
Mid-Depth of Surface HMA Layer	43
Mid-Depth of Intermediate HMA Layer	42
Mid-Depth of Base HMA Layer	37

5 Response data analysis procedure

All strain signals recorded under the passing of the loading vehicle followed a pattern very similar to that shown in Figure 2. For each signal, the values recorded in several points on the signal were extracted. The points were then used to calculate the longitudinal and transverse strain under the front wheel and under the first and second wheel of the rear axle.

It is important to observe that the valleys in the signals after the steering wheel and the second rear wheel were almost always negative for the longitudinal strain signals and positive for transverse strain signals. This is expected since the longitudinal strain recovers after the passing of each wheel but the transverse strain does not. The following was observed from the analysis of measured strains:

- For both longitudinal and transverse strains, the corresponding values varied greatly from one pass of the vehicle to another. This can be explained by the variation of the lateral position of the vehicle relative to the location of the gauges.

- Even for gauges located in the same lateral position and measuring the strain in the same direction (e.g. T1 and T3), the recorded strain values were not the same. This may be explained by the insufficient bond between the gauge and the core or between the core and the surrounding concrete. Therefore, it was decided to retain the strain values only for the gauges that recorded the highest strain values for the same lateral position and direction. These gauges are: T3, T5, L2 and L8.

- In general, the recorded strains were very small, always less than 25 microstrain, much less than 70 microstrain considered as the endurance limit for asphalt concrete. This suggests that the thick line treated embankment layer significantly improved the bearing capacity of the pavement structure that will likely never exhibit bottom-up cracking.

- For the instrumented pavement structure, the compounding effect of the transverse strain from the front and the rear axle was minimal. The low values of parameter C in indicate that the transverse strain recovered but not entirely after the passing of the front wheel before the rear wheel arrived.
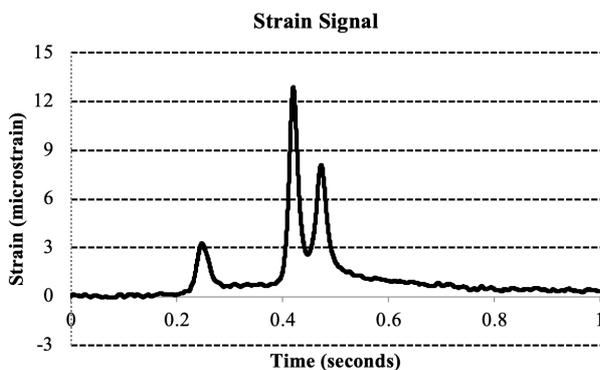

Fig. 2. Example strain signal.

6 Theoretical estimation of horizontal strains at the bottom of the HMA layer

This research used the generalized finite element program (Abaqus) for computing the strain responses at the bottom of HMA layers. A 12m long x 2.75m wide x 3.8m deep Finite Element structure was built to model section of the pavement on US287 Highway. The dimensions of the model were selected to accommodate both the steering and rear axle loads of the test truck with negligible edge effects. Due to symmetry of the geometry and the loading applied by the truck, only one-half of the pavement structure was modeled. A 2.64 m layer fixed at the bottom was used as subgrade layer. The details of the model geometry are given by Romanoschi [2].

The lime-treated subbase and subgrade soil layers were characterized by elastic moduli derived from the Falling Weight Deflectometer (FWD) tests performed on top of the base HMA layer, before the intermediate and surface layers were constructed. These foundation materials were not tested in the laboratory. The HMA materials were characterized by Prony series and dynamic moduli. The dynamic moduli used were extracted from the master curves constructed based on dynamic modulus tests results. The dynamic moduli values were estimated at the temperature recorded at mid-depth of each corresponding layer (Table 1). All layers were assumed as fully bonded.

The dimension of the tire imprints was measured when the pavement response measurements were conducted. The surface loading procedure was selected to avoid redefining the loaded surfaces when element size changes. The dynamic moving wheel loads were modeled using the concept of step loading with trapezoidal loading amplitude [2].

## 7 The results of the finite element analysis

After the finite element model was run the variation in time of the longitudinal and transverse strains were extracted for 24 elements located at the bottom of the base layer in the vicinity of the loaded elements. As for the measured strains, it was observed that the computed longitudinal strain recovers and becomes negative (compressive) after the passing of the steering axle and after the passing of the rear axle. However, after the computed transverse strains remain always positive (tensile) throughout the duration of loading.

Figures 3 to 5 compare the field-measured and FE computed strains at the bottom of the HMA layers. The magnitude of the strains is shown in relation to the transverse distance between the points where the strains were computed and measured and the centers of the steering wheel and the rear wheels.
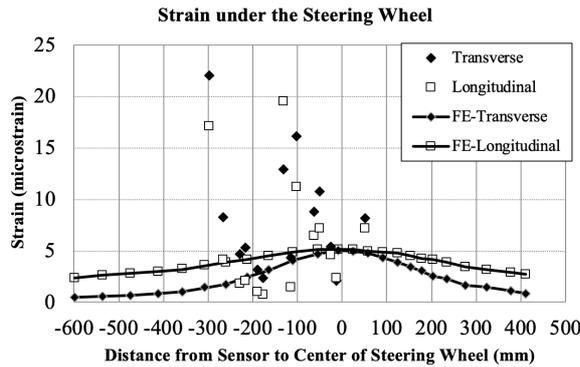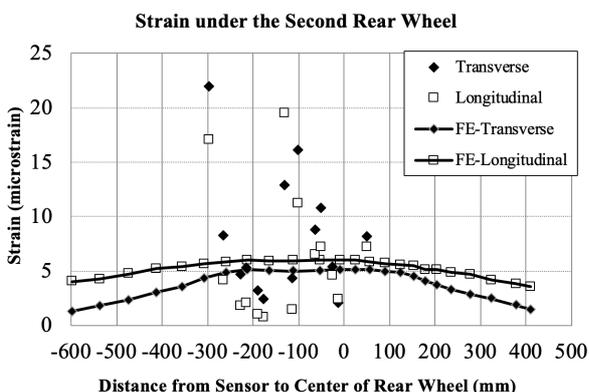
Fig. 3. Measured vs. Estimated Strains under the Steering Wheel.

The charts prove that the computed strains have similar magnitude to the measured strains, even though several sensors indicated a higher strain than the computed strain. All strains are small, less than 25 microstrain. They also indicate that the maximum computed longitudinal and transverse strains under the steering wheel are about the same. However, under the rear wheel, the maximum computed longitudinal strains are larger than the computed maximum transverse strains. The opposite was observed for the measured strains. The charts also indicate that the computed strains fall in the middle of the range of the measured strains for the strains under the steering wheel and the second rear wheel. For the first rear wheel, the computed strains are at the bottom of the range of measured strains.
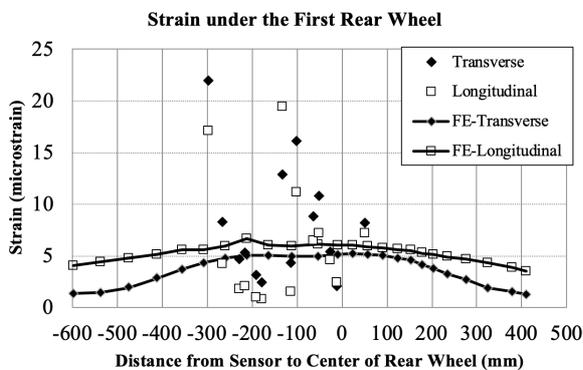
Fig. 4. Measured versus estimated strains under the first rear wheel.

Fig. 5. Measured versus estimated strains under the second rear wheel.

8 Conclusions and recommendations

In order to evaluate the damage caused by heavy vehicles on flexible pavement structures, a newly constructed pavement was instrumented with strain gauges retrofitted at the bottom of the asphalt concrete base layer. Strain gauges were used to measure the strains under several passes of a test vehicle which had a steering axle with single tire for each wheel and a rear tandem axle with dual tires. The speed and lateral position of the vehicle were recorded for each pass. Samples of asphalt concrete mixtures obtained during construction and were used to fabricate cylindrical samples for conducting dynamic modulus test in the laboratory. Dynamic moduli test results were used to determine the viscoelastic properties of the asphalt mixes.

The general-purpose finite element program Abaqus was used to model the instrumented pavement section and to compute the longitudinal and transverse strains. The asphalt mixes were modeled as visco-elastic materials having the properties determined in the dynamic modulus tests. The computed strain data were compared to the field measured strain data. The analysis of the measured responses led to the following major conclusions:

- The measured longitudinal and transverse strains were always lower than 25 microstrain, much lower than the 70 microstrains, the average endurance limit value reported in the literature, despite the high temperature in the asphalt layers during the measurements.

- The measured transverse strains were most of the time slightly larger than the corresponding longitudinal strains. This can be attributed to the accumulation of strain from the front axle and the rear axle that takes place only in the transverse direction. However, the finite element model computed higher strains in the longitudinal direction than in the transverse direction.

- For both measured and computed strains, the values under the passing of the steering wheel were of similar size as the strains under the passing of the first wheel of the rear axle.

The results of the field experiment and of the finite element analysis recommend the following:

- Both longitudinal and transverse strains should be used in the estimation of damage induced by passing of heavy vehicles and not only the longitudinal strains as is currently done by most distress prediction models.

- The damage induced by the single tire steering axle should also be included in the damage calculations. For many trucks, the load on the steering axle is quite large, more than 5,000 lbs per wheel. Since steering wheels have a single tire, the strains generated in the asphalt layers are comparable to the strains generated by the rear axles.

References

1. Tokyo-Sokki Kenkyujo Co. (2017), TML Embedment Strain Gauge. Type KM-100HAS. http://www.tml.jp/e/product/strain_gauge/gauge_list/index.html. Accessed July 2017.
2. Romanoschi, S.A., Papagiannakis, A.T., (2018), Evaluation of Comparative Damaging Effects of Multiple Truck Axles for Flexible Pavements. Final Report 17PUTA01, Transportation Consortium of South-Central States (Tran-SET), Louisiana State University, Baton Rouge.