The Cambridge Airfield Pavement Tester

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ABSTRACT: Flexible airfield pavement research continues to develop, but not without difficulty; the never-ending variation of aircraft types, landing gear configurations, environmental conditions and materials makes mechanistic, predictive design problematic. Due to size and cost, full-scale testing, though fit for purpose, lends itself to examining only generic pavement structures and limits result verification. Scaled down, lab-based testing is an economical alternative. To support on-going research into flexible airfield pavements, Cambridge University developed a new airfield pavement tester (APT), which merges measurement techniques and instrumentation yet unseen in these types of experiments.

An aircraft tyre exerts a cyclic force onto a pavement that constantly rotates the major, intermediate, and minor principle stress directions. Balancing system scaling with feasible load application methods is pivotal. Equally important is finding novel techniques to capture the effects of this load. For instance, cross-sectional layer deformation in the wheel path, a criterion used to determine pavement failure, has never been physically seen. The APT design incorporates a window in the wheel path, which, using Particle Image Velocimetry (PIV), allows soil movement and the associated strains to be observed and measured in-situ. Also included are continuous pressure mapping sensors, which provide a full vertical stress distribution throughout the system, not just at predetermined layer interfaces. The integration of these, and other instrumentation, led to comprehensive system modelling leading to defined performance parameters such as lifespan prediction and impact due to a change in usage.

1 INTRODUCTION

1.1 *Flexible Airfield Pavement*

Airfield flexible pavement theory stems from a combination of highway design methods, full-scale testing, material classification techniques and research specific to influential, individual elements (Lynch et al 1999). Accurate performance prediction remains elusive due to the variety of input parameters including, but not limited to, construction materials and thicknesses, loading parameters and distribution, climatic effects and usage. Model testing represents the best link between laboratory research and actual flexible pavement behaviour because these input parameters can be controlled and measured (Transportation Research Board 2012).

A flexible airfield pavement distributes load applied by the aircraft wheels through a layered granular system. The optimum configuration of these layers depends on a multitude of input parameters. Each layer flexes as load is applied and incurs stresses that

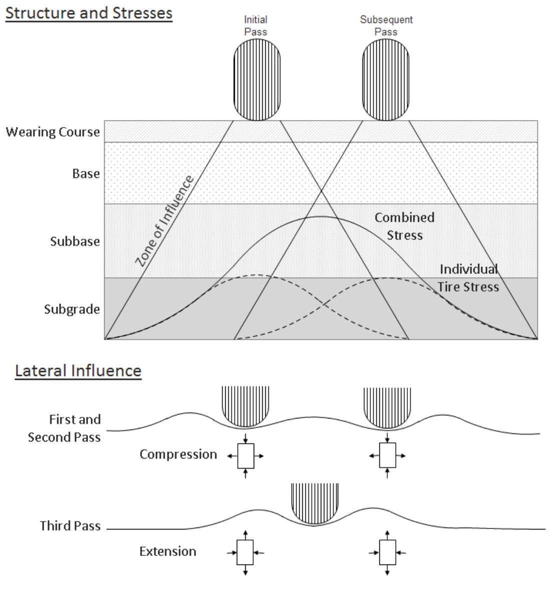

Figure 1. Idealized pavement structure and impact of associated loading forces

must be sustained without damage to lower materials. Starting from the lowest in-situ subgrade layer, the next layers, subbase and base, are progressively stronger towards the surface, culminating in an uppermost wearing course (Fig. 1).

Pavement loading and unloading leads to various fatigue failures. The majority of singular load applications on airfields are well below any maximum material failure criterion. Instead the repetitive and slow moving stress generated from rolling and lateral movement has the most severe consequences (Brown 1996). An accepted airfield pavement failure criterion, as defined by the US Corps of Engineers, is a surface upheaval of 25.4 mm (1") adjacent to the traffic lane (Gopalakrishnan & Thompson 2007).

Rutting is typically the most costly structural failure that conservative designs attempt to prevent. Qiao et al. (2014) identify four mechanisms that contribute to rutting: compaction, sub-surface shear, subgrade shear and particle crushing

The movement towards deterministic design aims to estimate performance as a function of any combination of input parameters. A successful design method would allow for any combination of material and layer thickness, account for lateral distribution of traffic and adapt to varied pavement loading parameters. Physical pavement modelling is the only experimental method that allows all these elements to be examined simultaneously in a controlled way.

1.2 *Design Methodologies*

A mechanistic method tries to rationalize three elements: failure prediction given known input parameters, characterization of material properties, and connection between the magnitude of the inputs and desired performance levels.

Initial mechanistic design in pavements focused on the impact of compressive strain at the top of the subgrade and the tensile strain at the bottom of the wearing course due to uniform load application to the layered structure (Brown and Thompson 1973). Each layer was considered linear elastic, isotropic, and homogenous.

To an extent these assumptions continue to frame pavement engineering to this day despite widespread acknowledgement that elasticity, by its very definition, cannot cause failure and that the load is not uniform. This stems from the inherent complexities associated with a pavement, a multi-layered system comprised of non-linear materials. When this is coupled with a repeated, random load application and a failure mechanism reached through gradual deterioration versus sudden collapse, it is not difficult to see why both research and industry adopt as many elastic design concepts as possible.

Burmister's (1945) layered elastic method, using principles first published by Boussinesq, computes stresses, strains and deflections within a layered system due to a circular, uniform surface contact pressure (Huang 2012). Despite these advances in stress determination, layered elastic design fails to account for the non-linearity of soils and the repeated loading experienced by flexible pavements. This method is useful in preventing overall failure, but limited when trying to predict performance life. It is still an empirical design method derived from years of usage data and full-scale testing. Deformation and number of load repetitions are the most common benchmarks of performance characterization.

Other analytical procedures, such as Finite Element Analysis, may offer a better approximation of the true behaviour and response. Nevertheless, without collaborative physical modelling efforts to calibrate these models, the reliability of any future mechanistic model is questionable.

1.3 *Ongoing Physical Scale Modelling Efforts*

Flexible airfield pavement engineering originated using the concepts and principles common in highway engineering. However, the load magnitudes, traffic volumes, wheel geometry and size variability, and lateral wander makes the design of airfields significantly different from that of highways.

A 2012 report from the US National Cooperative Highway Research Program found 32 active full-scale accelerated pavement test programs, of which, only one was solely dedicated to airfields. A survey of the participants found that structural and material design methods, evaluation of new materials and performance modelling are the major research benefits of pavement testing.

The US National Airport Pavement Testing Facility (NAPTF), commissioned in 1999, supports a variety of landing gear and pavement configurations. The pavement test area is 274.3 m (900 feet) long and 18.3 m (60 feet) wide and each wheel can be loaded up to 334 kN. Thus far, the results of traffic tests have been incorporated into the Federal Aviation Administration's (FAA) layered elastic flexible design methods. Each test takes approximately 2 years and the facility cost $21M to construct (Gopalakrishnan et al 2007).

Full scale testing is valuable but costly. Investigations are confined to generic pavement structures and materials discounting the influence unique situations can have. Furthermore, repeatability and result verification is limited. Scaled pavement testing is an economical alternative. Smaller facilities continue verification of theoretical concepts under controlled conditions in a compressed time period but with the added benefit of being able to repeat experiments, introduce novel instrumentation and expand investigations into unique materials.

2 THE AIRFIELD PAVEMENT TESTER

2.1 *Objectives*

The Airfield Pavement Tester (APT) was built at Cambridge University in 2015. The APT delivers controlled load application initially through a single tyre. The tyre's travel path can be varied laterally. The pavement response and performance are monitored via a variety of on-apparatus and in-situ instrumentation. As a result of the scale, failure conditions are achieved faster and investigation of varied pavement structures and individual research parameters can be supported.

The main objective of the APT is to use this modern, embedded instrumentation to gain a better understanding of the impact that lower layers have on performance given various loading and material parameters. The majority of performance modelling derived from full scale testing concentrates on surface layers while the effect of the supporting lower layers is generalized and simplified. However, previous pavement tests have shown that 30 to 70% of surface rutting is generated in the lower granular layers (Qiao et al 2014).

2.2 *Design Overview*

Using the NAPTF as a guide (Gopalakrishnan et al 2007), the sizing and load of a single Boeing 777-300 tyre was scaled to generate comparable specifications for the APT. Scaling laws from Garnier et al. (2007) were used. This facilitated direct comparison of results with data collected in NAPTF full-scale tests. By equating pressures, which should not scale in geotechnical modelling, between the model and prototype, the tyre load and contact area required for the APT was determined. A scaling factor of N=3 best matched prototype parameters while precluding structural and pavement limitations.

The primary structural elements of the APT are shown in Figure 2. The load is applied by an actuator, which pulls down on the 4.1 m long beam acting as a lever, applying the force to a specially made solid tyre that can travel one metre, bi-directionally along the pavement.

The pavement is constructed in an 1120 mm deep by 900 mm wide concrete tank. A steel wall bisects the tank which houses a Perspex window. Using Particle Image Velocimetry (PIV) a camera can track the soil movements in the pavement layers providing real-time pictures of the deformations.

The APT can apply a maximum load of 38 kN to the pavement structure.

2.2.1 *Framework*

Even after scaling, designing a method and equipment capable of replicating aircraft wheel loads proved challenging. The main assembly is supported and load is applied via the lever mechanism. The tyre runs along the beam over the soil structure while a pneumatic actuator applies a force at the opposing end. A maximum 4:1 ratio of actuator force to tyre force applied can be generated which varies with axle position along the 1m travel path. The beam reacts on a steel, free-pivoting fulcrum secured to the floor at the edge of the pit. The tyre path can be adjusted left or right of centre by 400mm. The entire apparatus is constrained laterally.

Due to the high wheel loading, a solid rubber tyre was utilised. The solid tyre contact area changes with load, but not to the extent seen with pneumatic equivalents. The APT tyre diameter and width were scaled by matching the contact area under load (measured using TekScan) to that of the prototype. This accounts for the slight variations between the actual and scaled design mechanisms at N=3 (Table 1).

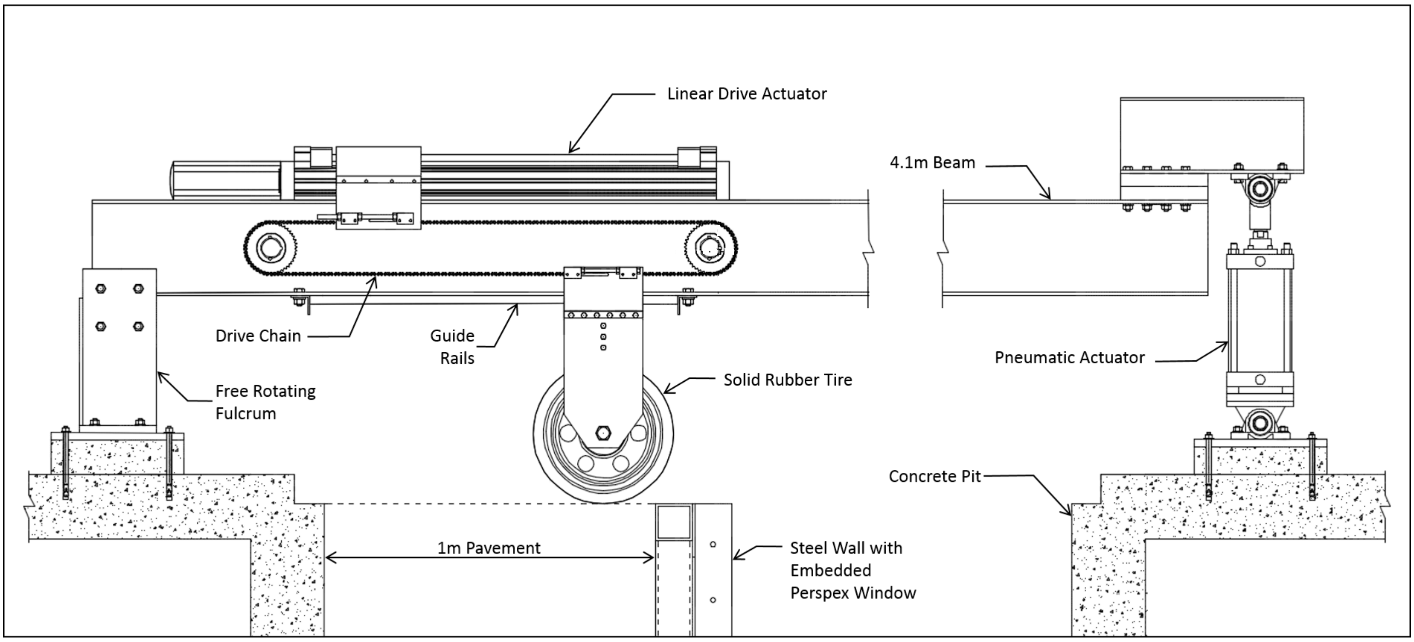

Figure 2. Side view of Cambridge Airfield Pavement Tester

2.2.2 *Loading and drive system*

The pneumatic cylinder has a stroke of 200 mm and can operate at a maxmum pressure of 7 bar. At this pressure the actuator provide a force of 17.8 kN on out-stoke, which lifts the wheel out of contact with the pavement surface and 13.2 kN on in-stroke which provides the compression at the wheel/pavement interface.

The movement of the tyre is controlled with an electric stepper motor connected to a linear drive actuator. The linear drive can travel 1 m and has a maximum speed of 1.2 m/s. This is connected to a drive chain and sprocket system which moves the wheel assembly along linear guide rails via four ball slides. This mechanism provides minimal friction resistance while ensuring that only vertical load is carried by the lever.

Table 1. APT Overall Specifications compared to actual and scaled parameters at NAPTF.

	NAPTF		Cambridge APT
Parameter	Actual	Model (*N=3*)	Actual
Avg Tyre Pressure	1480 kPa	1480 kPa	1480 kPa
Load per Tyre	200 kN	22 kN	22 kN
Contact Area	1590 cm^2	177 cm^2	148 cm^2
Tyre Diameter	127 cm	42 cm	38 cm

2.2.3 *On-apparatus instrumentation*

Potentiometers measure the location of the tyre along its travel path and the position of the pneumatic actuator. An inclinometer measures the inclination of the beam.

Measurement of tyre load is achieved through strain measurement of the wheel-supporting plates. As the plates deflect, a voltage is recorded which is calibrated to load. A full bridge strain gauge is placed on the front and back of each plate to understand where and how the plate is bending on either side of the wheel. Unlike a single load cell the dual strain gauge system indicates whether symmetrical load application occurs. These sensors additionally provide the load feedback to the control system.

2.2.4 *Control system:*

As the tyre moves and rutting occurs, the pneumatic actuator must apply a constant load to the pavement surface despite changing tire position and height. The speed, position and load are controlled electronically via a fully automated digital control system. The process begins with application of an initial pressure to the actuator at the beginning of a pass. The associated bending load from the tyre side plate strain gauges is measured and digitally fed back to the control system which adjusts the pressure in the pneumatic cylinder until the user-set calibrated load is reached. A feedback loop completes this cycle every 0.5 seconds. When the user-defined load is reached, the motor drive is initialized moving the tyre forward. The loop continues to adjust the pressure, through the entire cycle ensuring a constant load is applied to the surface through the entire travel path. The optimum travel speed of the wheel is 0.017 m/s. At the end, the load is released and the wheel assembly is moved back to its starting position. The process is repeated until a user defined number of cycles or failure criterion is met.

2.3 *Pavement Modelling*

The APT differs from other accelerated pavement testers in that the cross section of the pavement structure along the tyre path is exposed through a 100 mm thick Perspex window. Previously, post-test trenching has been the only way that researchers have been able to examine pavement deformation beneath surface measurements (Gopalakrishnan & Thompson 2007). Through PIV the deformation of the soil layers will be seen as load is applied and moved, greatly enhancing the understanding of soil mechanisms at play under the wearing course.

One of the concerns with having a pavement structure contained within a concrete tank is the boundary effects caused by friction between the tank wall and the granular material. While the concrete tank is ideal in one regard, because its stiffness restricts the lateral movements much like the finite boundaries of a true airfield pavement, the shear stress created by friction along the walls could interfere with the anticipated movement and stresses in the granular material. Using methods outlined by Tognon et al. (1999) the wall interfaces were lined with a combination of plastic sheeting, silicon grease, geomembrane and geosynthetic to create a puncture-resistant, waterproof, lubricated sliding interface. Similar methods have found a reduction in shear stress of 80 to 98% (Tawfiq & Caliendo 1993).

The primary focus of this research is modelling the behaviour of real granular materials. Typical soils found in pavement construction were used and particle size effect was accounted for by maintaining the prototype/model ratio between layer thickness and particle sizes. The granular layers were installed in lifts and compacted using vibration to optimum proctor values.

3 IN-SITU INSTRUMENTATION

3.1 *Objectives*

One of the benefits of in-lab pavement testing is the ability to record measurements of the pavement structure given a particular load. In similar tests, instrumentation allows stresses to be measured but in-situ, multi-directional shear planes and strain have rarely been examined (Transportation Research Board 2012). The APT will allow these measurements to be taken for the first time.

In most facilities pressure, strain, temperature and humidity through all layers are the most common measurements taken. However, the variability of the loading and material adds complexity to instrumentation. Location and orientation relative to the wheel path must be considered. Additionally, construction of the pavement structure with instrumentation is an added liability. Failure to have proper compaction around the instrument will either lead to early granular failure or improper readings. The compaction process itself easily could also damage the sensitive instruments and electrical connections.

Calibration is another common issue. The instruments are typically calibrated outside the experimental parameters but these conditions can vary widely from in-situ situations.

The APT uses measurement techniques not used before in flexible pavement experiments. The location of the instrumentation can be seen in Figure 3.

3.1.1 *Particle Image Velocimetry (PIV)*

The most important embedded instrumentation in this experiment is the use of Particle Image Velocimetry (PIV). An image is taken by a high-resolution camera of the exposed layers of the pavement structure at intervals defined by surface deformation and tyre position. Through image correlation the soil grains can be tracked as movement occurs. This method works for multiple soil types and any type of movement, a novel opportunity in pavement research. Use of PIV in other areas of geotechnical research is common (Stanier and White 2013).

The load magnitudes make placement of the viewing window complicated. Previous work has been done examining the movement of soil under a tyre along its path (Hambleton & Drescher 2009) but to date nothing has been attempted cross-sectionally.

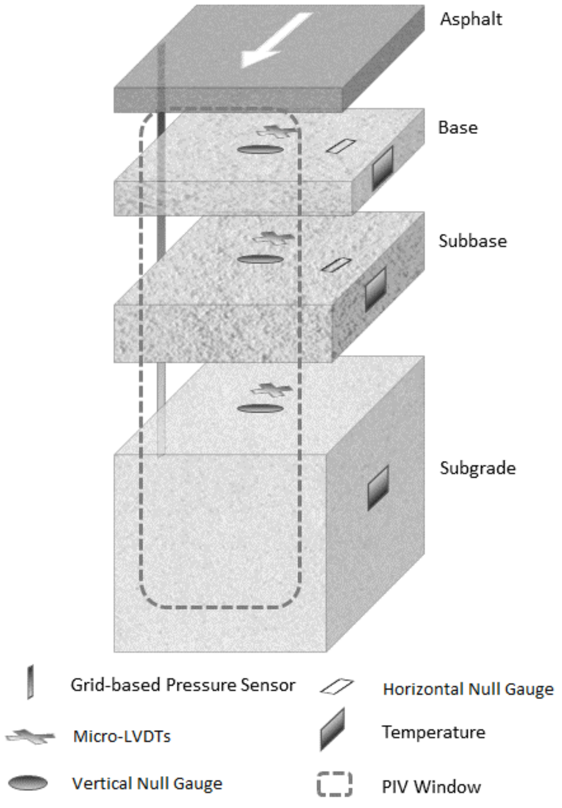

Figure 3. Pavement layers and instrumentation layout

3.1.2 *Subsurface Strain Measurement*

An overview of subsurface strain measurement in laboratory based pavement tests was compiled by the Transportation Research Board (2012). Horizontal strain (parallel to the surface) is the most common measurement taken in pavement research. Typically this is done through a variety of strain gauging. Most commonly horizontal strain at the bottom of the asphalt layer is measured; strain in this area is most responsible for bottom-up fatigue cracking and not surface deformation.

Vertical strain gauging is rarely used. The gauges are difficult to install correctly. Measured deformation or pressures are used to indirectly calculate strain perpendicular to the surface.

In the APT, traditional horizontal and vertical strain is measured in an array configuration using micro-LVDTs. Each LVDT can measure a displacement of +/- 5mm. A casing designed for the transducers moves with the soil allowing strain over a 125mm gauge length to be calculated. These measurements are combined with the more typical surface deformation measurements and the PIV results to give a holistic sight picture of sub-surface granular movement.

3.1.3 *Pressure Gauges*

Pressure measurement is also very common in pavement experiments (Transportation Research Board 2012). Most pressure transducers commercially available today have a fluid between two plates, known as membranes. When the plates deflect due to load, the fluid pressure within the cell increases and is measured via a strain gauge or semiconductor.

The challenges with repeated use of these pressure instruments, examined by Talesnik (2013) & Gopalakrishnan et al. (2007), are numerous. Any of the following significantly influences membrane deflection. Grain size distribution and stiffness is difficult to replicate in successive experiments and calibrations. Additionally, sufficient soil stiffness is needed to support the sensor and withstand the load. Also, if the deflecting membrane of the sensor should move too much the soil matrix surrounding the instrument would unrealistically arch.

To mitigate these inconsistencies Talesnik's (2013) Null Soil Pressure System is employed. These sensors operate in much the same way as the traditional gauge except that when the membrane deflects, a pressure is applied internally to the instrument to maintain zero membrane deflection. Use of these sensors ensures that the membrane will not yield under load, therefore preventing arching and deformation of the granular material. This instrumentation, successfully used in other geotechnical applications, reduces hysteresis and increases accuracy.

3.1.4 *Grid Based Tactile Pressure Sensors*

Another system, relatively common in geotechnical research, but not yet seen in pavement experiments is the use of grid-based tactile pressure sensors (Paikowsky & Hajduk 1997). The sensor, embedded perpendicular to the tire path against the rear wall of the tank provides a cross sectional stress distribution through the pavement layers in real time. This is in contrast to singular pressure gauges which assume uniform stress distributions.

Due to the real time visualization, the changing and residual stress distribution as the tyre traverses its path is seen through entire depths and the layer boundaries. These results, for the first time, demonstrate the effects of tyre loading on a granular material only ever before predicted by layered elastic theories.

4 CONCLUSIONS

Flexible airfield pavement design continues to challenge researchers and designers. The structure is composed of multiple, non-linear layers, each with different material characteristics. When coupled with the number and variety of inputs and with the static and cyclic loading parameters required for a comprehensive design, it is not surprising that pavement technology has failed to mature in step with the growing weights and landing gear configurations seen in the aerospace industry over the last 60 years. Performance prediction still remains largely empirical.

Physical modelling of flexible pavement systems forms a crucial link between laboratory evaluation of materials, loading parameters, and field behaviour. The value of this type of testing to deterministic design is well documented. However, full-scale testing is generalized and cost prohibitive. As a result existing test data is extremely limited. The path to a true mechanistic design, which would allow the extrapolation of material strengths and pavement structures over a wide range of applications, depends on expanding laboratory modelling. Scaled pavement experiments adopt the principles of measurable, controlled load application while allowing for a larger variety of input parameters, pavement materials, and novel instrumentation to be utilized.

Cambridge University has built a new airfield pavement tester which specifically focuses on previously unseen, subsurface soil mechanisms. Prior to the APT, post-test trenching could only approximate any granular movement in the lower layers. Now, due to the incorporation of PIV and subsurface horizontal and vertical strain measurements, the effects of deformation in the lower pavement layers on rutting at the surface can be seen. Additionally, the APT's null pressure gauges and tactile grid based sensors provides a genuine distribution of the stresses due to tyre load and movement. This data is critical for updating design methods to include the impacts of soil non-linearity and repeated loading.

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