Results of using measured full-scale tire/road contact stresses in models of pavement behaviour

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Abstract

The increased use of recycled and marginal pavement materials is a key factor for more sustainable use of resources. However, successful use of alternative materials requires reliable models of pavement response and performance and in turn, these models depend on the accurate portrayal of tire/road contact stress distributions. Unfortunately, while the models have been developed substantially, the acquisition of real stress distributions measured at full scale has not kept pace.

To solve the problem, an apparatus to measure tire/road surface contact stress distributions in all three coordinate directions was fabricated and calibrated. Next, a wide range of full-scale trafficking tests was carried out on the apparatus and the contact stress distributions measured. Those distributions were then input to numerical models of pavement behaviour and the results compared to the results of those models' predictions for the case where the loading was a uniformly distributed vertical pressure only, within the contact patch.

The numerical models are described briefly, comparisons are made between using the measured contact stress distributions and the simple uniform pressure, and conclusions are drawn, including the implications for predicted pavement life.

Introduction

The road engineering community sees the increased use of recycled and marginal pavement materials as a key factor for more sustainable use of dwindling resources. However, successful use of alternative materials requires reliable models of pavement response and performance. In turn, these models depend on the accurate portrayal of tire/road contact stress distributions.

Unfortunately, while the models have been developed substantially, the acquisition of real stress distributions measured at full scale has not kept pace with the sophistication of the models. Often, the loading assumed is simply a uniform pressure acting over the contact patch. Usually, this assumed pressure is equal to the tire's inflation pressure. It can be questioned whether this simplification is justified.

To solve the problem, an apparatus to measure tire/road surface contact stress distributions in all three coordinate directions (vertical, longitudinal, and transverse) was fabricated and calibrated. Next, a wide range of full-scale trafficking tests was carried out on the apparatus and the contact stress distributions measured. Those distributions were then input to numerical models of pavement response and performance currently under refinement, and the results compared to the results of those models' predictions for the case where the loading was a uniformly distributed vertical pressure only, within the contact patch.

Full details have been provided in Golder [4]. The current paper is a distillation of that report, and is also a companion work following on from the discussion of the apparatus, tests, and preliminary results presented in Douglas *et al.* [2]. In the current paper,

- the numerical models are briefly described;
- comparisons are made between model results for the two input cases
  - using the measured contact stress distributions
  - using simple uniform pressure, and;
- conclusions are drawn, including the implications for predicted pavement life.

The questions the project was designed to answer included:

1. Does inputting the "real" three dimensional stress distributions into numerical models make a difference in the predicted pavement response and/or pavement performance?
2. If so, what are the differences?
3. Are they important to pavement designers, owners, and/or operators?

If no substantial difference in the model results can be attributed to the different loading cases, then using the usual simplification of the loading would be justified. However, if there is a substantial difference, then there needs to be a more realistic portrayal of the contact stresses. In either case, performing the work would result in an increase in the understanding of the phenomena taking place at the tire/road surface interface.

Construction and Calibration of the Apparatus

Full-scale, indoor load testing was performed in the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) facility operated by Transit New Zealand in Christchurch, New Zealand during 2007. The design, construction and calibration of the test apparatus has been discussed at length elsewhere [2] so only a brief description will be given here. A strong steel box enclosing 25@5×5 mm steel pins

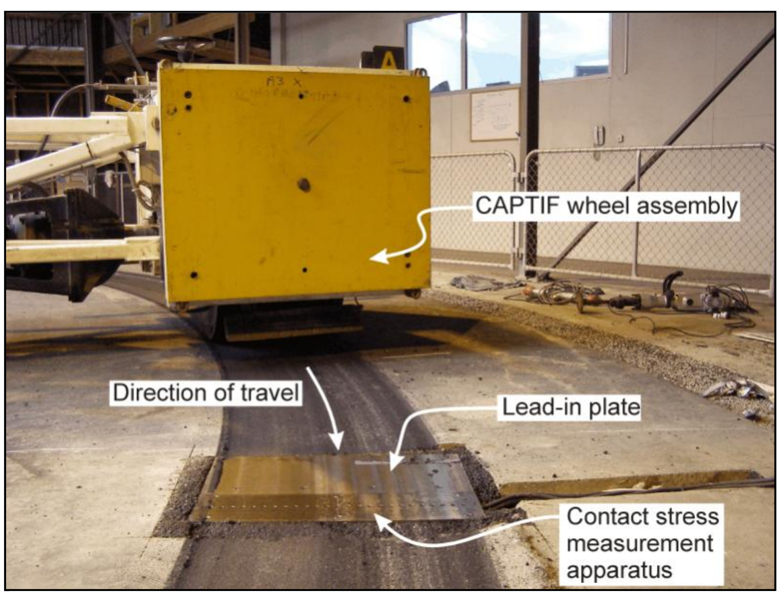

Figure 1. Arrangement of apparatus.

arranged as vertical cantilevers in a closely spaced row was placed across the width of the intended wheel path flush with the pavement surface (Figure 1). The pins protruded 1 mm through holes in a surface plate over which the wheel rolled. They were equipped with electrical resistance strain gauges to measure vertical compression along their axes, and bending in the longitudinal and transverse directions, relative to the direction of travel of the tire, to measure the longitudinal and transverse shears imposed by the tire(s).

Each pin had six semi-conductor strain gauges installed in three pairs. The gauges in each pair were arranged opposite to one another, and wired into Wheatstone bridges in such a way as to sense compression or bending in the pin.

A high speed data acquisition system, capable of measuring any 8 channels of data at a rate of 10,000 samples per second, was assembled. The data was acquired on four pins at a time, with all four pins monitored in compression and two of the pins also monitored in both bending directions.

Table 1 shows the matrix of test parameters studied. Two wheel types, two wheel loads, and two or three inflation pressures were used in the full-scale load tests. At least five passes of the wheel were made at each combination of wheel load and inflation pressure.

Table 1. Load test combinations

Wheel type, tire designation	Wheel load	Inflation pressure or deflection (kPa or %)
Dual wheel 295/80 R225 M840	40 kN	690
		550
		20% (280 kPa)
Wide single 385/65 R225 R194		690
		550
	50 kN	690
		550
Dual wheel 295/80 R225 M840		690
		550
		20% (280 kPa)

Tire Scuffing

The trends and magnitudes of the recorded compression pin loads were as expected for both the single tires and the dual tire configurations tested, however the results for the longitudinal and transverse pin loads did not agree with previously-published results [2].

It must be noted that for the first time to the authors' knowledge, contact stress data was obtained for tests carried out on a *circular* track, rather than a linear test facility. Granted that the radius of the test arms at CAPTIF is large at 9 m, there still is the possibility of tire scuffing caused by the continuous right-hand bend the tires are negotiating. In addition, there are issues of vertical tire load sharing, and the camber and effective toe-in (or "toe-out") that must exist. The tires may be under- or over-steering for the continuous bend in their path, thus causing differences in the longitudinal and transverse pin loads compared to what has been observed by others working on linear facilities with near-perfect wheel alignment.

In looking for the cause for differences in the results obtained in this study compared to those in the literature, it could also have been that a blunder had been made in the collection of the data. The graphs of the pin load distributions were the product of a long series of steps, and their results were a function of a list of interacting inputs, including:

- the arrangement of the strain gauges installed on the pins
- the arrangement of the pins in the apparatus
- the polarity of the wiring
- the direction convention adopted
- the calibration procedure
- the calibration coefficients
- the direction of the wheel travel on the track
- the particular details of a number of spreadsheets used in the analysis of the data
- the particular details of the software used to plot the results

All were carefully checked through. Time was invested in an *ad hoc* experiment, where a car tire was run straight over the test apparatus. No blunder was found, and the *ad hoc* experiment produced the results seen in the literature for straight-line tests. Thus the unusual results were attributed to wheel camber and toe-in / toe-out, interacting with the radius of the circular wheel path.

Experience with past testing at CAPTIF

The unusual longitudinal and transverse values were not unexpected; the CAPTIF test rig was originally equipped with a slip ring device between the inner and outer wheels on the dual tire to allow the tires to turn at difference speeds. Eventually it was removed as it was not practical and it was found that using it did not appear to affect road test results.

Earlier tests on chip seals showed that the effects of tire scuffing were not noticeable when using single tires to study road texture loss. Tests on sensitive surfaces such as open graded porous asphalts also suggested that the effect was not noticeable when dual tires were used to study fatigue in thin pavement surfaces; no unusual fretting of the surface and no fatigue were seen.

Numerical Modelling Techniques

The project's questions concerned the effects of inputting measured contact stresses to models of pavement response and performance, rather than uniformly distributed vertical pressures. Pavement *response* for these two loading cases was defined as the elastic pavement stresses, strains, and surface displacements. Pavement rutting was the measure of pavement *performance*.

A fictitious pavement typical of New Zealand conditions was used for the comparison of the two loading cases. It consisted of a 40 mm thick non-structural layer of asphalt overlying an unbound granular base 300 mm thick, in turn lying on the subgrade.

Preparation of raw data

The data acquisition routine used generated numerous traces for the same loading condition on each pin. Four pins were monitored at a time – all four for compression and the middle two also for longitudinal and transverse loading. Five replicates were made for a group of four pins, then the pins were indexed by one pin, and the next five replicates recorded for that next group of four pins, i.e. Pins 1, 2, 3, and 4 were monitored for five replicates, then Pins 2, 3, 4, and 5, and so on. All traces for each pin load direction (compression, longitudinal, transverse) were viewed, and a representative single trace for each selected by inspection. The data for a given pin loading direction was then used to populate a single spreadsheet for each wheel load configuration (single or dual tire, inflation pressure) and each pin loading direction (compression, longitudinal, or transverse).

An example of the prepared pin load data is given in Figure 2.

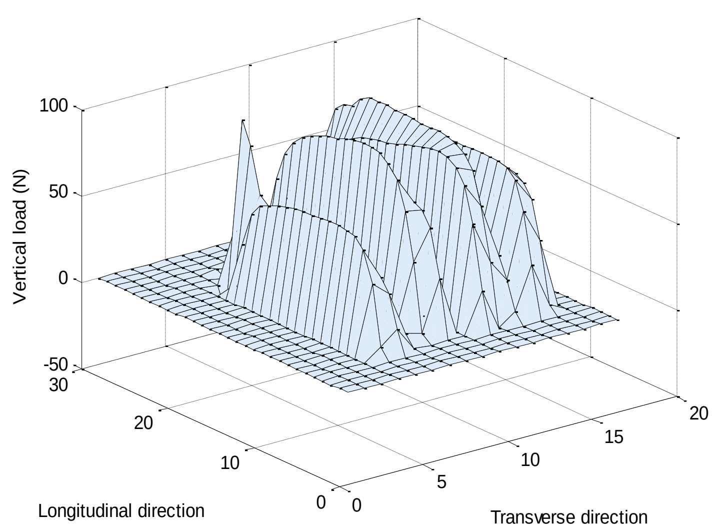

Figure 2. Recorded vertical pin loadings (single tire, 40 kN wheel load, 690 kPa inflation pressure).

Pavement *response*: comparison of pavement displacements, stresses and strains

For a detailed investigation of the pavement response, a three-dimensional finite element model (FEM) called ReFEM [5] was used. The program employs special 20-node isoparametric elements, with 60 degrees of freedom and tri-quadratic displacement shape functions. The modelled contact stresses were applied as element forces.

Details of the finite element mesh generated for the problem are given in Table 2. The plan views of the meshes for the single and dual tires are shown in Figure 3.

Table 2. Pavement layer thicknesses and corresponding FEM mesh details

Asphalt layer		Granular base layer		Subgrade	
Thickness (mm)	**No. of elements in the vertical direction**	**Thickness (mm)**	**No. of elements in the vertical direction**	**Thickness (mm)**	**No. of elements in the vertical direction**
40	2	300	4 (single tire) 3 (dual tires)	1000	2 (single tire) 3 (dual tires)

Figure 3. Schematic plan view of FEM meshes for (left) single tires and (right) dual tires. Shaded zones indicate tire contact patch(es).

For the comparison of the results for the two loading cases, the uniform pressure integrated over the contact area was assumed to amount to the same vertical force as the wheel load for each test configuration, and to act on a rectangle with the dimensions in Table 3. Tire contact patch widths and lengths were derived from the pin load records.

Table 3. Details of uniformly distributed loading

Test designation †	Tire contact patch dimensions		Uniformly distributed vertical pressure (kPa)
	width (mm)	length (mm)	
S40550	250	330	480
S40690	250	310	510
S50550	250	360	550
S50690	275	310	590
D40280	250	370	220
D40690	250	280	290
D50280	250	410	250
D50690	275	300	300

† Test designation: "S" – single tire, "D" – dual tire; next two digits indicate wheel load in kN; last three digits indicate tire inflation pressure in kPa

The data record for single tires usually included traces for 11 pins. For the dual tires, it was usually 25 pins. The loaded area of the FEM meshes included 6 × 9 (lengthwise × widthwise) elements for single tires, and 2 × 6 × 10 (areas × lengthwise × widthwise) elements for the dual tires. The FEM meshes were loaded with forces calculated from the average pin load distributed over each FEM mesh element within the loaded area. The plot for a typical modelled loading is shown on Figure 4.

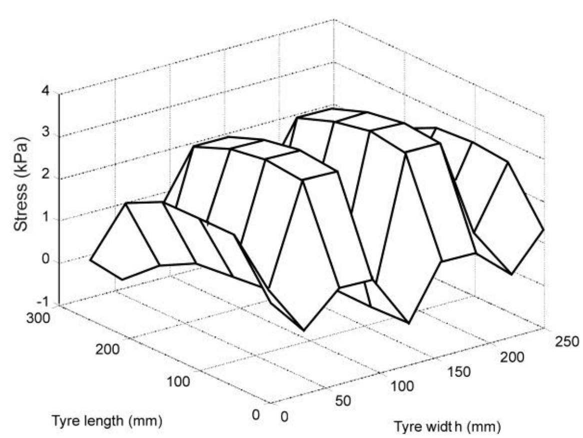

Figure 4. Modelled vertical stress for single tire, 40 kN wheel load, 690 kPa inflation pressure.

It is important to note that the modelled stresses (e.g. Figure 4) were the ones used in the FEM modelling, not strictly the raw, recorded sensor pin loadings (e.g. Figure 2). This idealisation was unavoidable, given the constraints inherent in the FEM program.

Material models

Asphalt

The asphalt surface layer was treated as linearly elastic, with Young's modulus E = 3,000 MPa and Poisson's ratio ν = 0.35 assumed.

Base course

A non-linear model of unbound granular base course behaviour, under development at the Technische Universitaet Dresden using parameters typical of New Zealand base courses, was employed in the FEM modelling. On the basis of repeated load triaxial (RLT) testing, an empirical non-linear elastic-plastic deformation design model (Dresden Model) was formulated for the base course material. Here only a short overview on the modelling of the unbound granular material (UGM) is given. Further details are available elsewhere [3, 5, 6]. This non-linear elastic model is expressed in terms of modulus of elasticity E and Poisson's ratio ν as follows:

$$E = p_a\left(Q + C\cdot\left(\frac{\sigma_3}{p_a}\right)^{Q_1}\right)\cdot\left(\frac{\sigma_1}{p_a}\right)^{Q_2} + D \tag{1}$$

$$\nu = R\cdot\frac{\sigma_1}{\sigma_3} + A\cdot\frac{\sigma_1}{p_a} + B \tag{2}$$

where:

- σ_3 is the minor principal stress (absolute value) [kPa];
- σ_1 is the major principal stress (absolute value) [kPa];
- D is the constant term of modulus of elasticity [kPa];
- Q, C, Q_1, Q_2, R, A, B are model parameters; and
- p_a is atmospheric pressure [kPa].

On the basis of the multi-stage RLT tests documented in Arnold [1], it was possible to determine the parameters of the elastic model.

The elastic Dresden model includes a stress independent stiffness (parameter D in Equation 1) dependent upon the residual in-situ confining stress. The residual stress has the effect of reducing the strains at small stress levels. The parameter D was mainly influenced by macroscopic parameters like the degree of compaction of the UGM, fines content, grain shape, and water content. The RLT results did not allow determination of the parameter D because the residual stress needs some time to develop in real pavement construction. Using the CAPTIF results it was possible to determine the value of stress-dependent stiffness for the materials investigated. Table 4 shows the parameters derived for the Dresden model.

Table 4. Parameters for Dresden model of base material

Parameter	Value	Units
Q	14,004	unitless
C	6,540	unitless
Q1	0.346	unitless
Q2	0.333	unitless
D	65,000	kPa
R	0.056	unitless
A	-0.0006	unitless
B	0.483	unitless
p_a	1	kPa

Subgrade

The subgrade was modelled as linearly elastic, with Young's modulus E = 70 MPa and Poisson's ratio ν = 0.40 assumed.

Pavement *performance*: road rutting model

Werkmeister [7] developed a procedure for estimating long-term rutting performance based on repeated load triaxial tests (RLT) carried out on samples of base course material and calculated elastic pavement strains. The pavement's performance history is divided conceptually into the "initial post construction compaction phase", during which the first 25,000 to 100,000 passes of traffic compact and therefore rut the base layer, and the "steady state" phase during which plastic strain and therefore rutting slowly, steadily increase with the remainder of the traffic to which the road is subjected. Relations have been developed for:

- the prediction of the number of passes required to reach the end of the initial post construction compaction phase;
- the use of calculated elastic pavement strains and RLT elastic strain rates to predict the rutting expected during the initial post construction compaction phase; and
- the use of calculated elastic pavement strains and RLT elastic strain rates to predict the rutting expected during the subsequent steady state phase.

The routine was applied to data gleaned from RLT tests carried out on a typical New Zealand base course aggregate (Pound's Road Greywacke) and calculated pavement strains for (a) the uniform vertical pressure loading case, and (b) corresponding loading cases where the modelled non-uniform contact stresses were used. The two sets of predicted rut depths were compared to see if using the "real" stresses resulted in a difference in the predicted pavement performance.

Modelling Results and Discussion

A sample of the results obtained, generally restricted to single and dual tires with a wheel load of 40 kN, and an inflation pressure 690 kPa, is provided here. Comparisons are made between the calculated results for the uniformly distributed pressure loading case and the loading case using the modelled non-uniform contact stresses.

Results for pavement response: vertical stresses, vertical strains, vertical pavement surface displacements

Figure 5 shows the comparison of vertical stresses in the transverse plane, under a single tire, when the uniform vertical pressure was applied on the pavement surface, and when the full set of modelled non-uniform stresses was applied. In the latter case, the effect of the stress concentrations under the tire ribs is clear. For a given depth in the base layer, the vertical stress was slightly greater.

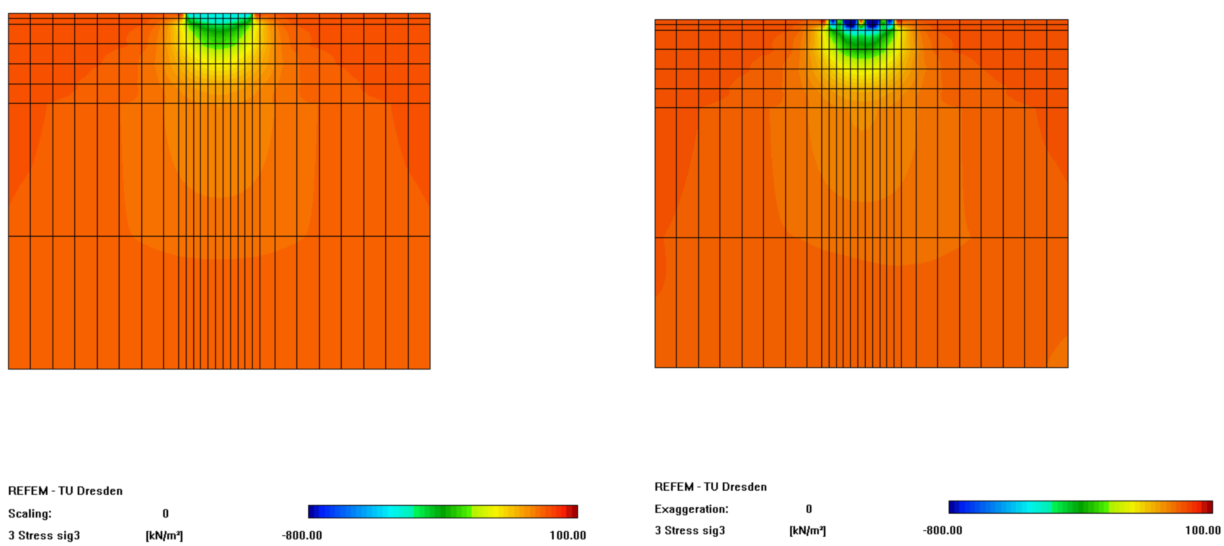

Figure 5. Vertical pavement stresses in the transverse plane for a single tire with 40 kN wheel load and 690 kPa inflation pressure – for uniform contact pressure (left) and modelled vertical, transverse and longitudinal contact stresses (right).

An interesting comparison is made on Figure 6, for dual tires. While the concentration of stress due to the tire ribs is again evident, it is also clear that the two tires in the dual arrangement were carrying unequal loads. The combined effect was to increase the vertical stress in the base significantly when compared to what was calculated for the uniform pressure loading case where the tire loads were equal, and to generate asymmetrical stresses.

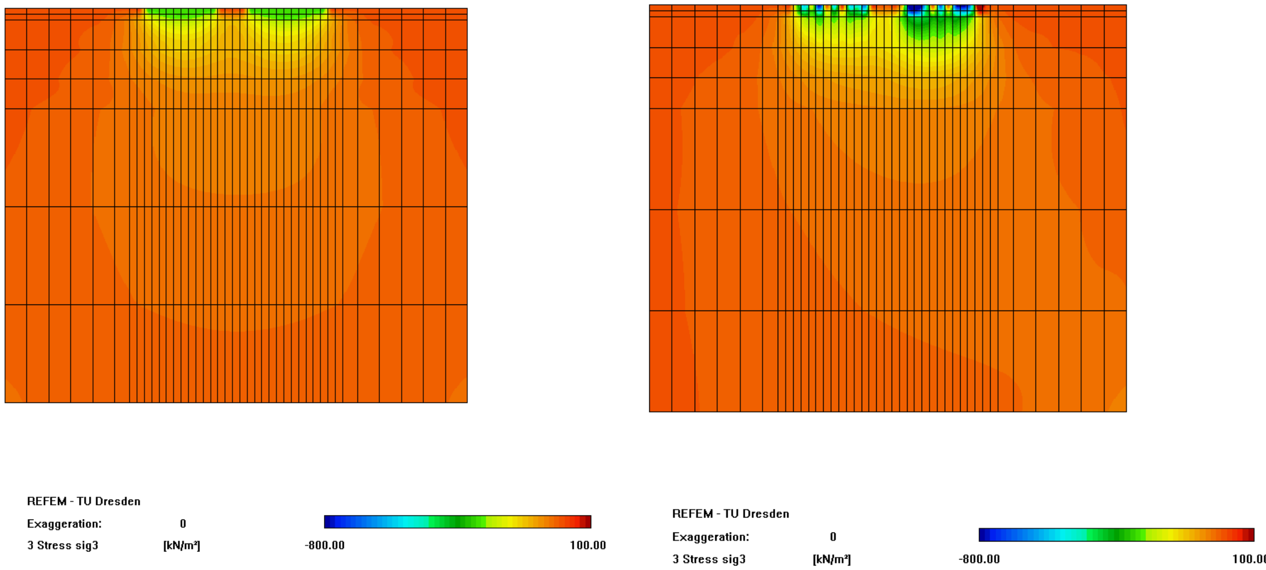

Figure 6. Vertical pavement stresses in the transverse plane for dual tires with 40 kN wheel load and 690 kPa inflation pressure – for uniform contact pressure (left) and modelled vertical, transverse and longitudinal contact stresses (right).

Other plots indicated that for single tires, the vertical stress calculated under the centre of the tire at the top of the subgrade was as much as 3 to 8% greater for the modelled non-uniform stresses, compared to the uniform surface pressure case, for the configurations considered (S40550, S40690, S50550, S50690). For the dual tires, the corresponding increase ranged from 12 to 27% (for D40280, D40690, D50280, D50690).

For single tires, calculated base strains were greater for the non-uniform contact stress case (Figure 7), compared to those for the uniform surface pressure case. The strains were more intense under the tire, and they penetrated more deeply.

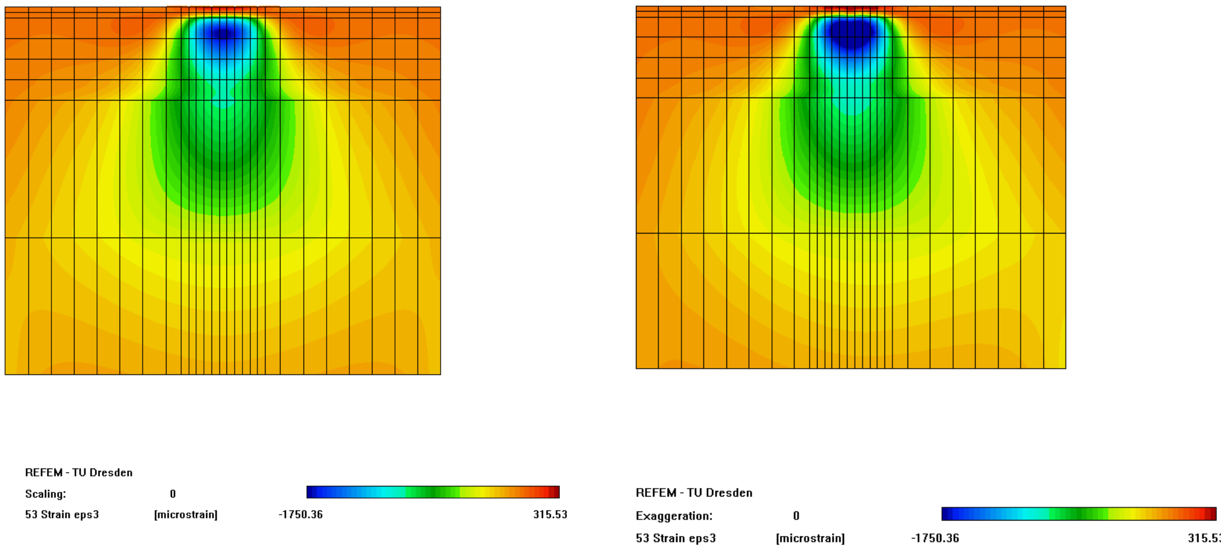

Figure 7. Vertical elastic pavement strains in the transverse plane for a single tire with 40 kN wheel load and 690 kPa inflation pressure – for uniform contact pressure (left) and modelled vertical, transverse and longitudinal contact stresses (right).

Again, the unequal loading of the dual tires was reflected in the vertical strain distribution (Figure 8). Strains were more intense under the more heavily-loaded tire. The strains were slightly asymmetrical in the subgrade as well when compared to the uniform pressure case, although the difference did not appear great.

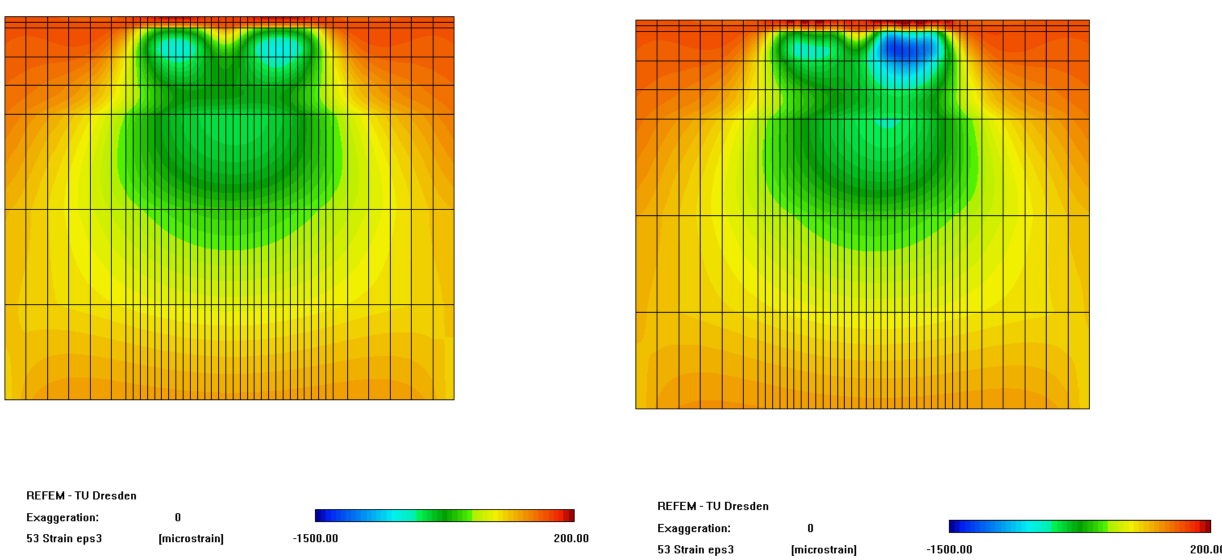

Figure 8. Vertical elastic pavement strains in the transverse plane for dual tires with 40 kN wheel load and 690 kPa inflation pressure – for uniform contact pressure (left) and modelled vertical, transverse and longitudinal contact stresses (right).

The peak base strains occurred at about 1/3 of the base depth below the top of the base layer. Other plots not shown indicated that peak strains calculated for the non-uniform contact stress distribution were 16 to 20% greater than those calculated for the uniformly distributed pressure loading case, for the single tire configurations studied ((S40550, S40690, S50550, S50690). For the dual tires, they were 32 to 55% greater (for D40280, D40690, D50280, D50690).

Vertical elastic strains, integrated with depth, give the elastic pavement surface deflections. These are shown for single tires on Figure 9. The effect of the non-uniform vertical stress, and the surface shears (longitudinal and transverse) have caused asymmetrical pavement surface deflections for the modelled pavement surface stresses. The deflection bowl appears to be broader, too.

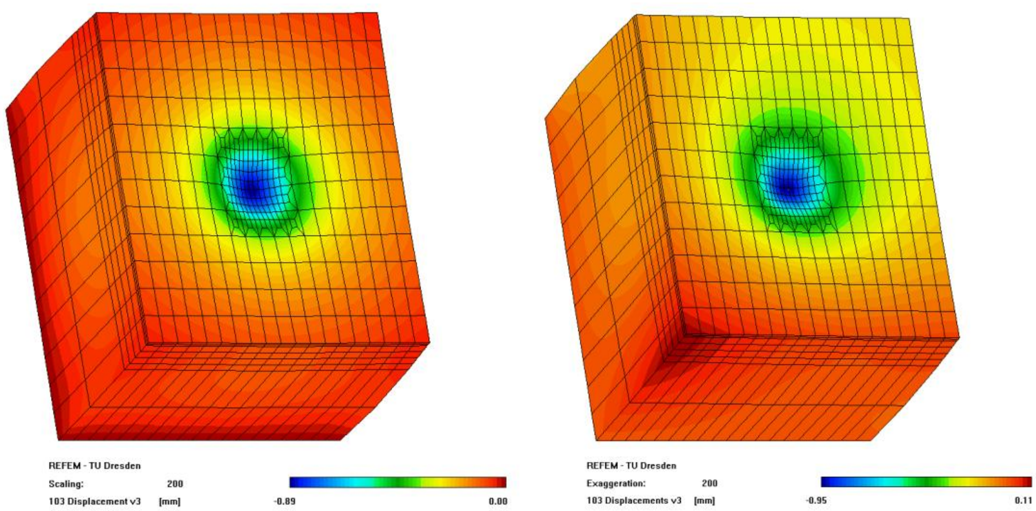

Figure 9. Vertical elastic pavement deflection for a single tire with 40 kN wheel load and 690 kPa inflation pressure – for uniform contact pressure (left) and modelled vertical, transverse and longitudinal contact stresses (right).

Turning to the dual tires, evidence of the unequal tire loading is again observed (Figure 10). It appears that with the stress concentrated under the tire ribs, the pavement deflections were actually slightly less at distance for the non-uniform stress case.

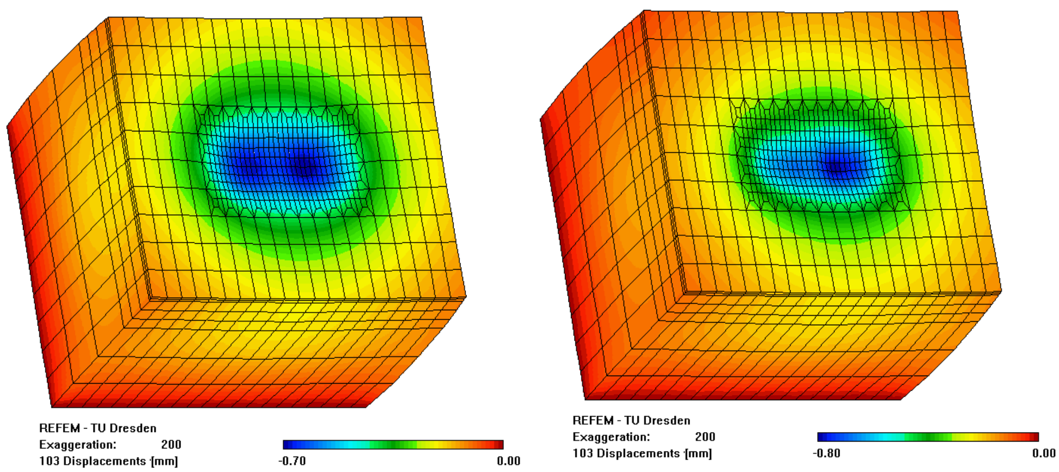

Figure 10. Vertical elastic pavement deflection for dual tires with 40 kN wheel load and 690 kPa inflation pressure – for uniform contact pressure (left) and modelled vertical, transverse and longitudinal contact stresses (right).

Vertical pavement surface deflections are further compared for the two loading cases on Figure 11. For the single tire configurations shown, centreline deflections calculated for the non-uniform contact stress distributions were 5 to 8% greater than those calculated for the uniform contact pressure.

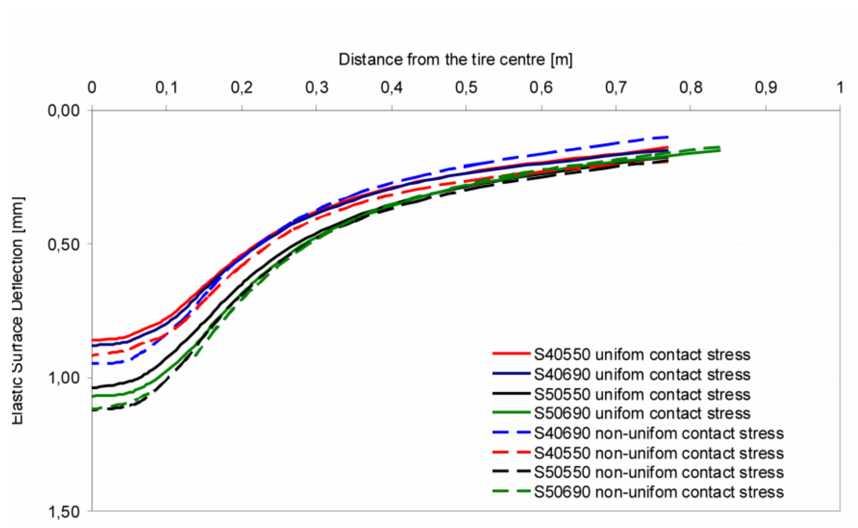

Figure 11. Elastic pavement deflections in the transverse plane for single tires, 40 and 50 kN wheel loads, 550 and 690 kPa inflation pressures.

Shear strains in the longitudinal plane

Given the impact of shear strains on granular material behaviour and the fore-and-aft nature of the effects of traction on the road structure, the shear strains in the longitudinal plane were plotted (Figure 12, single tires; Figure 13, dual tires). There was an increase in shear strains, and the strains became somewhat asymmetrical front to back, when the non-uniform contact stresses are input, compared to the uniform vertical pressure, but the differences do not appear great.

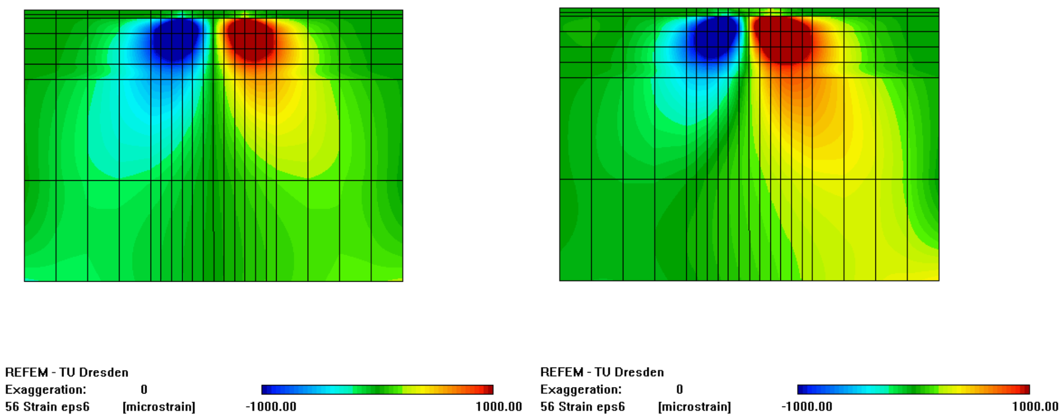

Figure 12. Fore-and-aft elastic pavement shear strains, in the longitudinal plane, for a single tire with 40 kN wheel load and 690 kPa inflation pressure – for uniform contact pressure (left) and modelled vertical, transverse and longitudinal contact stresses (right).

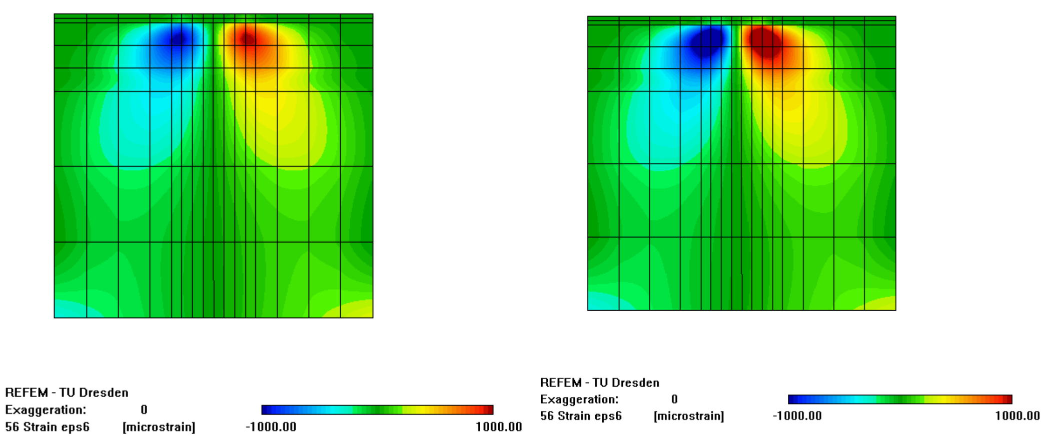

Figure 13. Fore-and-aft elastic pavement shear strains, in the longitudinal plane, for dual tires with 40 kN wheel load and 690 kPa inflation pressure – for uniform contact pressure (left) and modelled vertical, transverse and longitudinal contact stresses (right).

Results for pavement performance: rut development

The rut development model described earlier was applied to the 8 configurations studied (single tires S40550, S40690, S50550, and S50690, and dual tires D40280, D40690, D50280, D50690). Rut depth was predicted for 1 million passes using the calculations for the non-uniform contact patch stresses, and plotted against the ruts predicted for the uniform vertical pressure. Thus the method of predicting rut development was the same for both loading cases: the difference was the contact patch stresses used in the calculations. Results are shown in Figure 14.

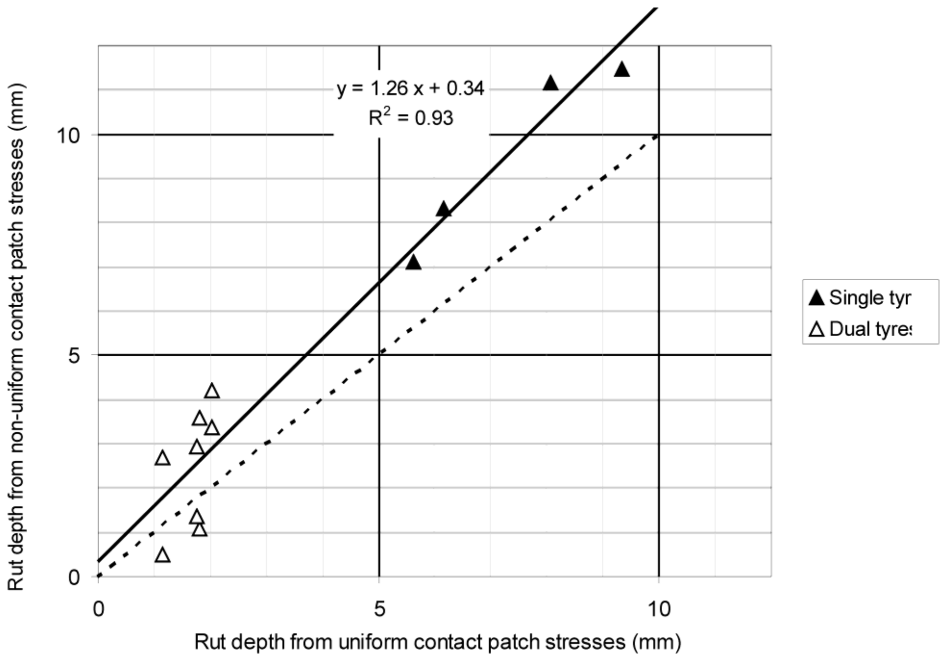

Figure 14. Comparison of rut development predicted from uniform and non-uniform contact stresses.

Individual rut depths have been plotted for both tires in a dual set, because the loads were not equal on the two tires. It can be seen on the figure that the rut depths predicted by Werkmeister's method are about 26% greater when the calculations are made on the basis of the modelled non-uniform contact stresses, when compared to the calculations based on uniform contact pressures.

Discussion of Results

Predicted pavement response was examined in terms of elastic pavement stresses, strains, and displacements. Pavement performance was viewed in terms of rut depth development.

As seen on the figures presented, there were differences in response, but they were often not large. Vertical stresses on top of the subgrade were 3 to 8% greater when the non-uniform contact stresses were used. For dual tires, the differences were greater at 12 to 27%, but the larger differences may well have been due to the unequal loading of the two tires in the dual. Peak base strains, occurring about 1/3 below the top of the base layer, were 16 to 20% more for single tires when the non-uniform contact stresses were input, and 32 to 55% more for the dual tires, but again, the unequal tire loading would have affected the calculated difference. Centreline elastic surface deflections were 5 to 8% greater for single tires when the non-uniform contact stresses were input, in agreement with the increase in the vertical stresses on the top of the subgrade.

These differences in response, though not particularly great, especially if some credit is given to the unequal tire loads in the dual tire configurations, were enough however to affect pavement performance significantly. The rut depths predicted using the non-uniform contact stresses where a little over a quarter greater than those predicted using the conventional uniform pressure. If this translates into a quarter shorter pavement design life, then the implication is serious, from a practical pavement management point of view. A pavement designed to have a life of, say, 17 years, would only last about 13.

Such predictions are limited by many factors, including:

- the impacts of the tire scuffing on the measured sensing apparatus pin loads;
- the selection of the representative trace for each pin;
- the modelling of the "real" contact stresses that was necessary to input them to the finite element model;
- the modelling of pavement stresses and strains in the finite element model;
- the assumptions in Werkmeister's rutting model; and
- the limitation of the results to the 8 configurations studied.

However, it is felt that there is enough evidence in the experimental results to conclude that there are small though measurable differences in pavement response when modelled using non-uniform contact stresses, and that these differences in pavement response give rise to substantial differences in predicted pavement performance. There is ample justification for using more realistic contact stresses in models of pavement response and performance.

Conclusions

Based on the results of the research, a number of conclusions can be drawn:

1. A practical, reliable apparatus and data-logging system was fabricated. The apparatus provided stable outputs.
2. The data conditioning (conversion from data logger output to spreadsheets) was onerous using the approach available. A more streamlined approach should be investigated.
3. Some of the pin load data was at variance with what has been presented in the literature. These differences were attributed to lateral scuffing that occurred as the wheel assemblies negotiated the constant circular curve of the test track. Observing this effect led to a much clearer understanding

of the interaction between tires and road surfaces, as influenced by suspension geometry (camber, and toe-in or "toe-out" resulting in an effective under- or over-steering).

4. While there were small though measurable differences in pavement *response* when modelled using non-uniform contact stresses, these differences gave rise to substantial differences in pavement *performance*. There is ample justification for using more realistic contact stresses in models of pavement response and performance.

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References

[1] Arnold, G. 2004. Rutting of granular pavements. Unpublished Ph.D. thesis. Nottingham, U.K.: University of Nottingham. 92 pp.

[2] Douglas, R.A., Alabaster, D., and Charters, N. 2008. Measured tire/road contact stresses characterized by tire type, wheel load, and inflation pressure. Proceedings 2008 TAC Annual Conference. Ottawa: Transportation Association of Canada (TAC). 12 pp.

[3] Gleitz, T. 1996. Beitrag zur rechnerischen Erfassung des nichtlinearen Spannungs-Verformungsverhaltens ungebundener Tragschichtmaterialien in flexiblen Straßenkonstruktionen (Non-linear deformation behaviour of unbound granular layers in pavement constructions – in German). Unpublished Ph.D. thesis. Dresden, Germany: Dresden University of Technology. 39 pp.

[4] Golder Associates Ltd. 2009. Final report on NZTA Research Project LTR061, Tyre/road contact stress distributions measured and modelled in three coordinate directions - modelling flexible pavement behaviour using measured contact stresses. Report submitted to the New Zealand Transport Agency, Wellington, New Zealand. 55 pp.

[5] Oeser, M. 2004. Numerische Simulation des nichtlinearen Verhaltens flexibler mehrschichtiger Verkehrswegebefestigungen (Numerical simulations of the non-linear behaviour of flexible pavements – in German). Ph.D. thesis, University of Technology, Dresden, Germany. 20 pp.

[6] Werkmeister, S. 2003. Permanent deformation behaviour of unbound granular materials in pavement constructions. Ph.D. thesis, University of Technology, Dresden, Germany. 4-1 pp.

[7] Werkmeister, S. 2007. Prediction of pavement response using accelerated test results of New Zealand's CAPTIF Facility. Habilitation. University of Technology, Dresden, Germany. 3-1 pp.