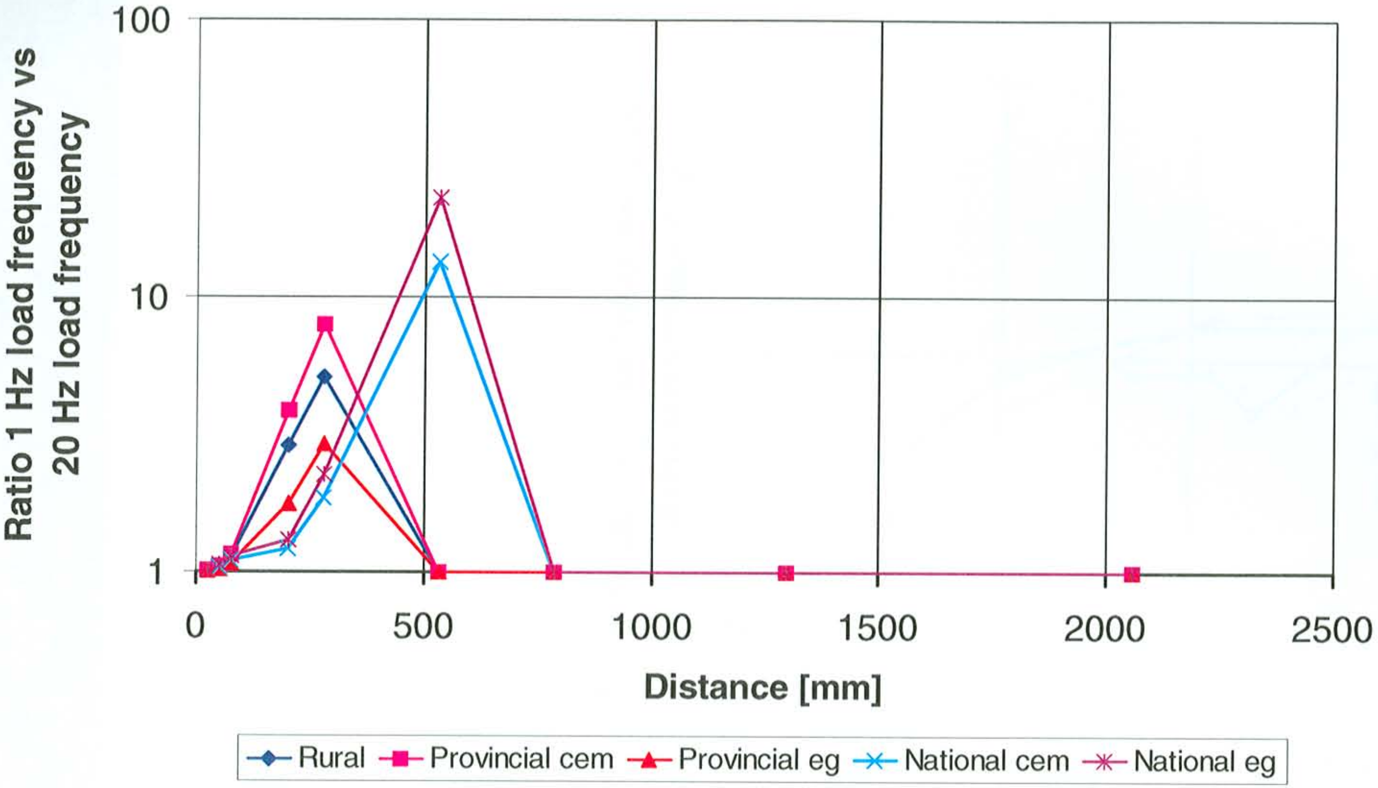

**Figure 6.25:** Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for elastic surface deflection.

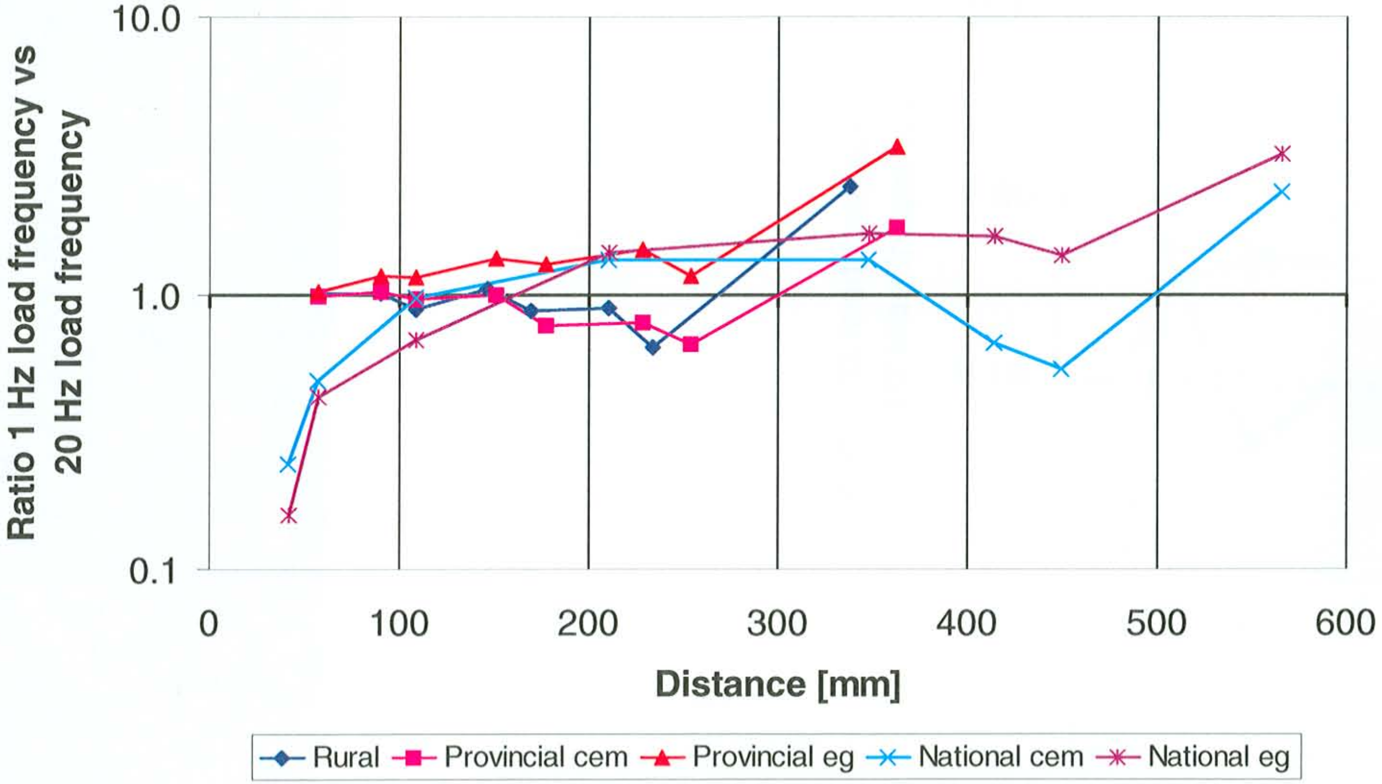

Figure 6.26: Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for compressive vertical stress.

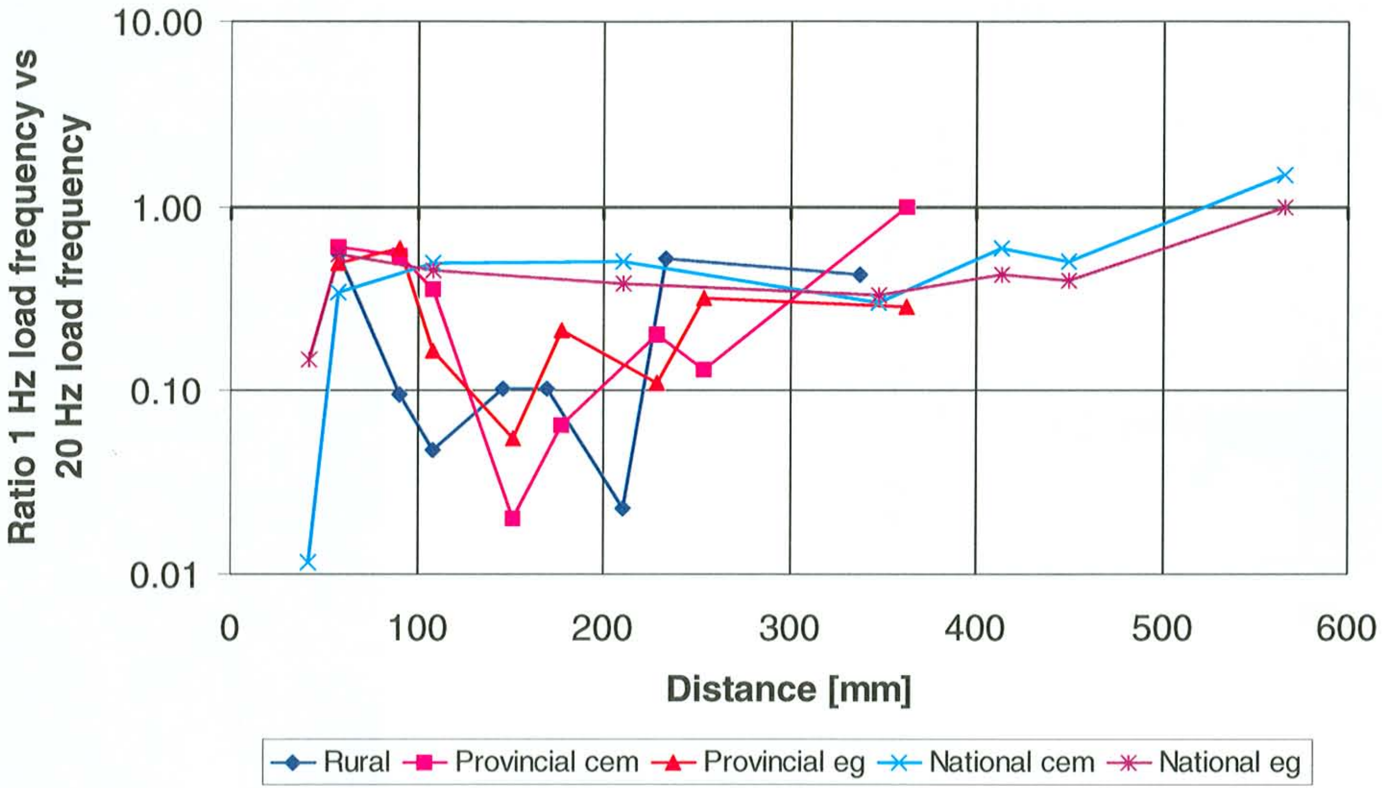

Figure 6.27: Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for compressive horizontal stress.

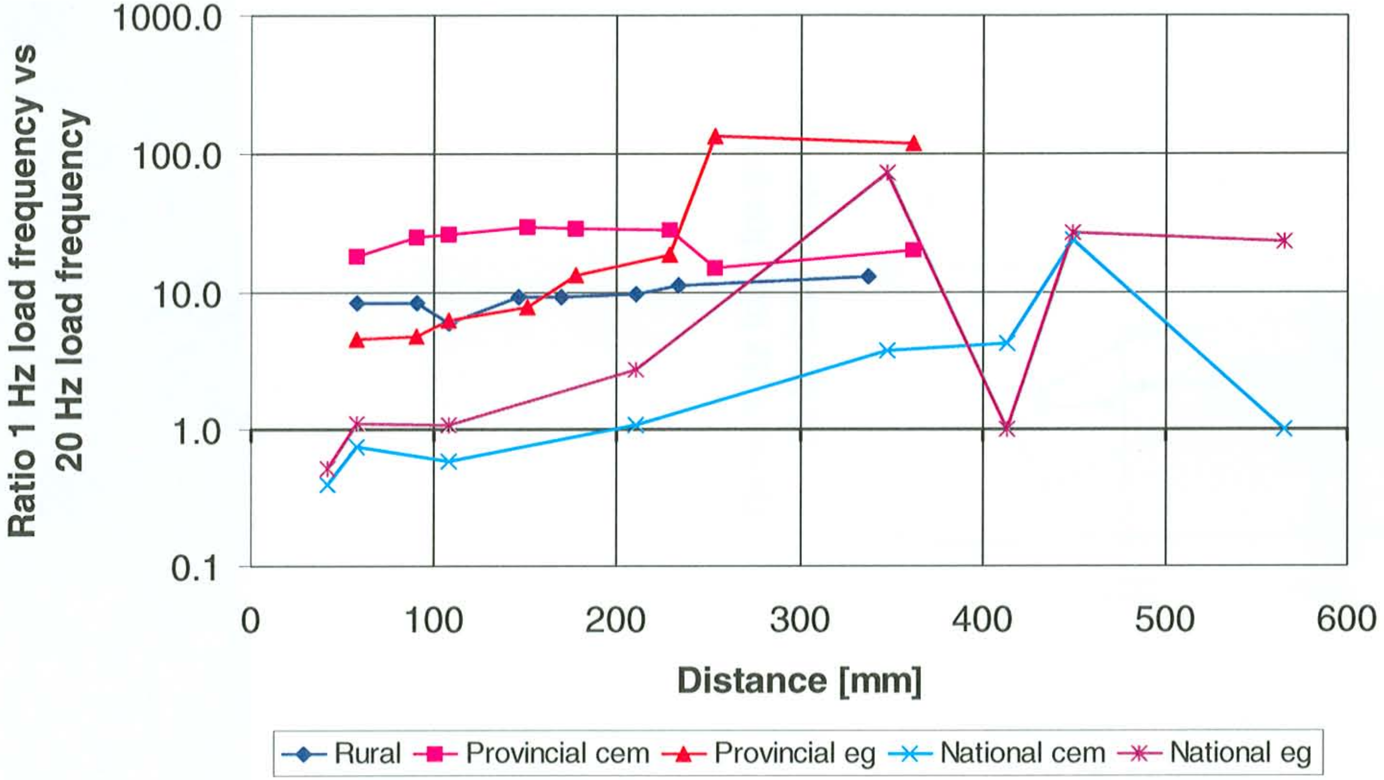

Figure 6.28 Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for compressive shear stress.

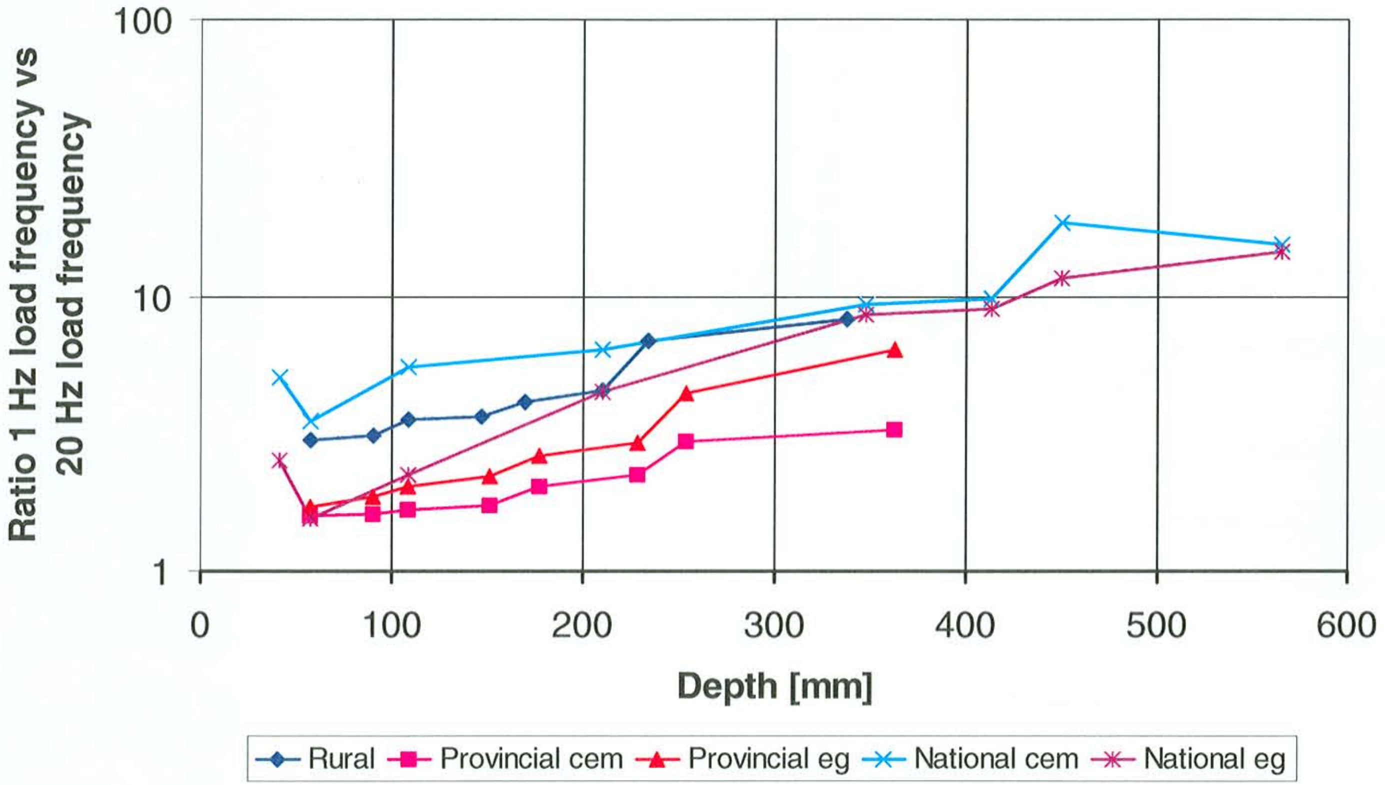

**Figure 6.29:** Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for vertical compressive strain.

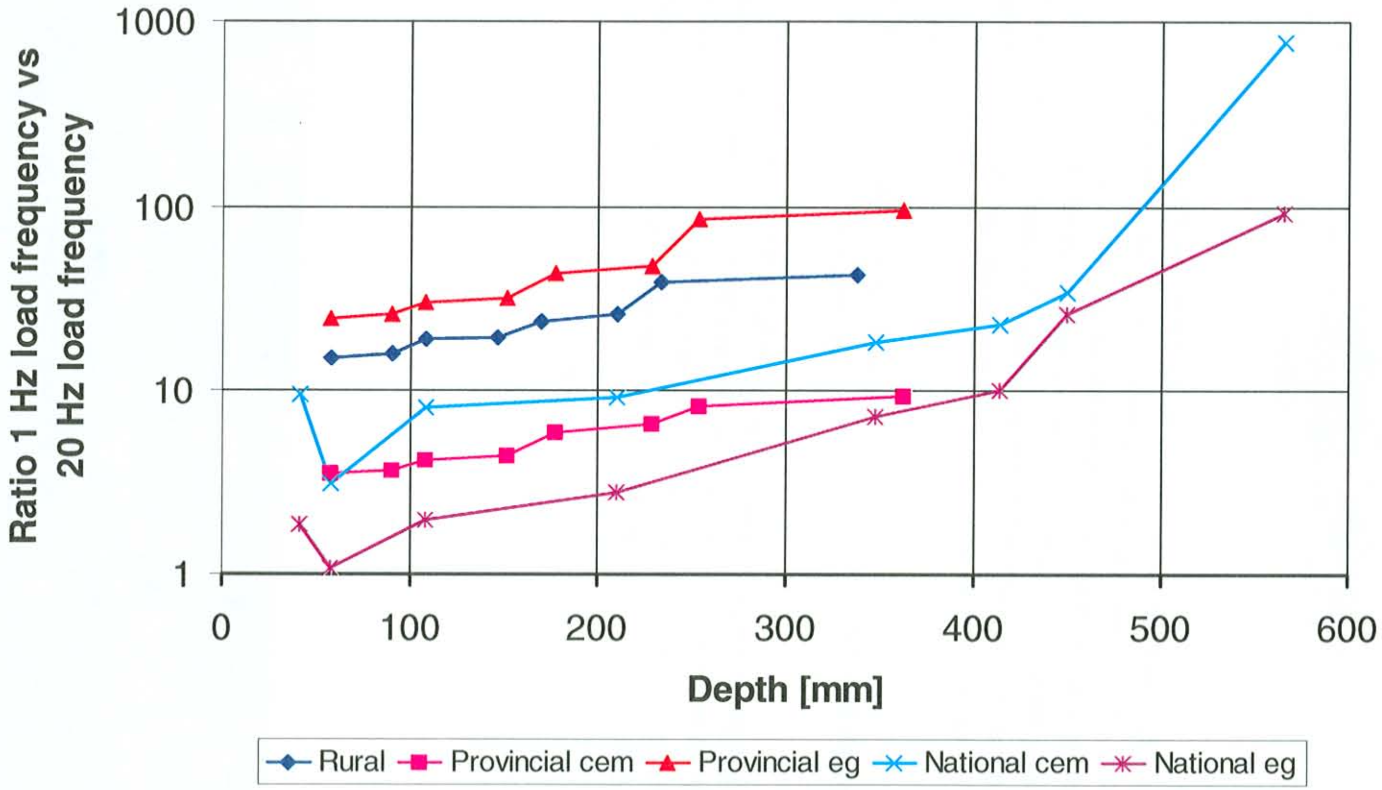

**Figure 6.30:** Typical ratio between 1 Hz load frequency response and 20 Hz load frequency response for horizontal tensile strain.

Load ratio

Under the static response analyses the ratios of the pavement response parameters at the four load levels used were the same as the load ratios themselves (Section 6.2.2). This indicates that a change in load magnitude causes a similar change in response parameter. The ratios for the pavement response parameters were also calculated for the pavement response obtained from the MCL analysis. These pavement response parameter ratios were calculated for all the parameters used in the SAMDM analysis of the specific pavement structures, as well as the maximum surface deflections.

Analysis of these load ratios calculated indicated the following:

*Maximum surface deflection*

The ratios of the maximum surface deflections were all lower than the corresponding load ratios. The provincial ***cem*** pavement had the closest ratio to the load ratio. The calculated ratios initially decreased between speeds of 40 km/h and 60 km/h, and remained constant thereafter. It indicates that the maximum surface deflection will increase less than the load ratio when applying the loads at speed.

*Vertical stress*

The vertical stress parameter showed similar pavement response ratios to the load ratios for all the pavements' upper layers (base layers). The lower layers showed lower response ratios than load ratios, indicating that the response does not increase at the same rate at the deeper locations of the pavement. The response ratios at the deeper locations decreased further with increased speeds.

*Horizontal stress*

The horizontal stress parameter ratios were similar to the load ratios for the upper layers (base layers). The deeper layers again showed lower response ratios than load ratios and decreases in ratio with increased speeds.

*Vertical strain*

The vertical strain ratios (at the top of the subgrade) were considerably lower than the load ratios for all pavements except the provincial ***cem*** pavement. All the ratios also decreased with increased speeds. This may be attributed to the depth of these layers in the pavement structure. The reason for the different behaviour of the provincial ***cem*** pavement probably lies in the thick cemented base and subbase layers of this structure. The national ***cem*** pavement also showed a higher response ratio than the remaining three structures.

*Horizontal strain*

The horizontal strain ratios were all similar to the load ratios although the deeper layers had slightly lower ratios than the upper layers.

In summary, it appears that most of the pavement response parameters had ratios (between their values at higher loads and at a reference load) that were similar to the ratio between the applied loads. This was especially the case for the upper parts of the pavement. Deeper locations in the pavement generally had lower response ratios than load ratios, indicating that the response parameter were lower than expected. This phenomenon is probably due to the mass inertia properties of the pavement structure. A tendency for the response ratios to decrease with increasing speeds also existed.

Pavement Response Parameter Lag

Various authors have shown a lag in response between the pavement response at different speeds and at different depths in the pavement (De Beer, 1991, 1992; Lourens and Jordaan, 1991; Mamlouk, 1987; Cebon, 1999). Mamlouk (1987) attributed this phase lag mainly to the effect of inertia and only a small extent due to the effect of damping. More pronounced phase lags were observed at higher frequencies. De Beer (1991, 1992) measured phase lag distances of between 250 mm and 400 mm between the position of the tyre and the position of maximum surface deflection, on a pavement structure similar to the national ***cem*** pavement structure used in this thesis. This compares well to phase lag distances of between 150 mm and 374 mm calculated for the national ***cem*** pavement structure in this thesis.

In order to investigate the existence of a response lag between the pavement response occurrences at different speeds, the data obtained from the MCL analyses were used.

The procedure used to calculate the lag between the pavement responses at different depths of the pavement, consisted of calculating the time between the maximum load occurrence and the maximum pavement response parameter occurrence at both the surface and the top of the subgrade of each of the pavement structures. The existence of the lag between the top of the surface and the top of the subgrade was measured in terms of the *distance* that was equivalent to the time at the load application speed for each of the analyses. This was done to normalise the increases in time lag to a standard value that would not be affected by the increase in speed. The focus for the calculations was on the maximum stress (vertical, horizontal and shear) parameters.

In Figure 6.31 the method used for the calculation is shown schematically. The distances between the position of maximum tyre load and the positions of maximum response on the surface of the pavement (at a low and a high speed) are shown together with the distances between the positions of maximum response on top of the subgrade. The figure is not to scale.

The results for the vertical, horizontal and shear stresses are shown in Figures 6.32, 6.33 and 6.34. In each of these figures the increasing distance lag due to increasing load speed is visible. The distance lags for the vertical stresses (Figure 6.32) are closely related between the five pavement types at the lower speeds (40 to 60 km/h), but becomes more spread at speeds between 80 and 100 km/h. The provincial ***cem*** pavement showed the highest distance lags at the higher speeds. This correlates with De Beer 's (1992) data showing longer phase lag distances for stiffer pavements incorporating materials with higher mass densities. The typical distance lags range between 0,08 and 0,13 m (at 40 km/h) and 0,3 and 0,45 m (at 100 km/h). A statistical correlation between the distance lags and speeds for the vertical stress indicated that an S-curve model with an $R^2$-value of 87,3 can be drawn between these two parameters. A statistically significant relationship exists at the 99 per cent confidence level between the two parameters.

$$\text{Distance lag vertical stress} = e^{\left(-0{,}057 - \frac{80{,}95}{\text{speed}}\right)}$$

$R^2 = 98{,}44$

Standard error = 0,06

**Equation 6.1: Distance lag for vertical stress in all five pavements investigated.**

The distance lags for the horizontal stresses (Figure 6.33) again indicated an increasing distance lag with increasing speed. The range of distance lags between the five pavement types increased from between 0,03 to 0,13 m (at 40 km/h) to between 0,21 and 0,39 m (at 100 km/h). The provincial ***cem*** pavement structure had the lowest distance lags with the rural and provincial ***eg*** pavement structures showing the largest distance lag values. A sharp increase in distance lag was experienced between 80 and 90 km/h. A statistical analysis of the relationship between the distance lag and speed for horizontal stress indicated that the distance lag is related to the square root of the speed with an $R^2$-value of 68,5. A statistically significant relationship exists at the 99 per cent confidence level between the two parameters.

$$\text{Distance lag horizontal stress} = (0{,}0686 + 0{,}00478 * \text{speed})^2$$

$R^2 = 68{,}5$

Standard error = 0,07

**Equation 6.2: Distance lag for horizontal stress in all five pavements investigated.**

The distance lags for the shear stresses (Figure 6.34) indicated an increased distance lag with increased speed. The distance lag values were closely spaced for speeds lower than 60 km/h (ranged between 0,09 and 0,17 (60 km/h) and 0,21 and 0,39 m (100 km/h)). At 40 km/h the national ***eg*** and provincial ***eg*** pavements had larger distance lags than the other three pavement structures. The statistical analysis showed that the distance lags were related to the natural logarithm of the speed for the shear stress data. A correlation of 0,93 was obtained and a statistically significant relationship exists at the 99 per cent confidence level between the two parameters.

$$\text{Distance lag shear stress} = -0{,}706 + 0{,}224 * \ln(\text{speed})$$

$R^2 = 86{,}2$

Standard error = 0,03

**Equation 6.3: Distance lag for shear stress in all five pavements investigated.**

The distance lag between the tyre (position of maximum load application) and the position of maximum pavement response parameter on the surface of the pavement was also calculated and incorporated in those distance lags shown in Figures 6.32 to 6.34.

It is important to indicate the limitations in the available data set and the parameters expected to have an influence on the distance lag values. The first limitation of the data set is that all the analyses were performed using a linear elastic material model. If viscous material models (for asphalt layers) and non-linear material models (granular layers) were used together with or instead of the linear elastic material model, the results could differ. Longer distance lags may be expected for the viscous materials.

The second limitation is the fact that only one damping coefficient and mass inertia value were used for each of the pavement structures. The current thesis does not include an investigation into the effect of these parameters specifically on the pavement response parameters, and such a sensitivity analysis was thus excluded from the thesis. It is to be expected that a change in damping coefficient and / or mass inertia for a specific pavement should affect the slope of the relationship between distance lag and speed. Specifically a higher mass inertia should cause a flatter slope (thus longer distance lags in the lower layers). A higher damping coefficient should probably not affect the distance lag as much, but would rather affect the way in which the pavement response parameter fade after the maximum value was reached. The main effect of the damping coefficient would thus be that the higher the damping coefficient the quicker the response parameter will fade out at a specific level, and the chance of the response parameter effect on a shallower level affecting the response parameter at a deeper level decreases. It is recommended that an exercise be performed to determine the relative effect of the mass inertia and damping coefficient on the slope.

The third limitation of the current study is that it focuses on only five different pavement structures with load application speeds of between 40 and 100 km/h. The effect on pavement structures with thick bituminous layers is not investigated at all. The fourth limitation of the data is that the distance lags for the strain data could not be extracted, due to the strains being calculated from the stress data obtained in the finite element analyses. As the strain data is dependent on both the vertical and horizontal stress data, the maximum strain does not necessarily occur at the same time as the maximum stress. However, it can be expected that similar distance lags exist in the strain data, as was shown by other authors (Mamlouk, 1987; Cebon, 1999).

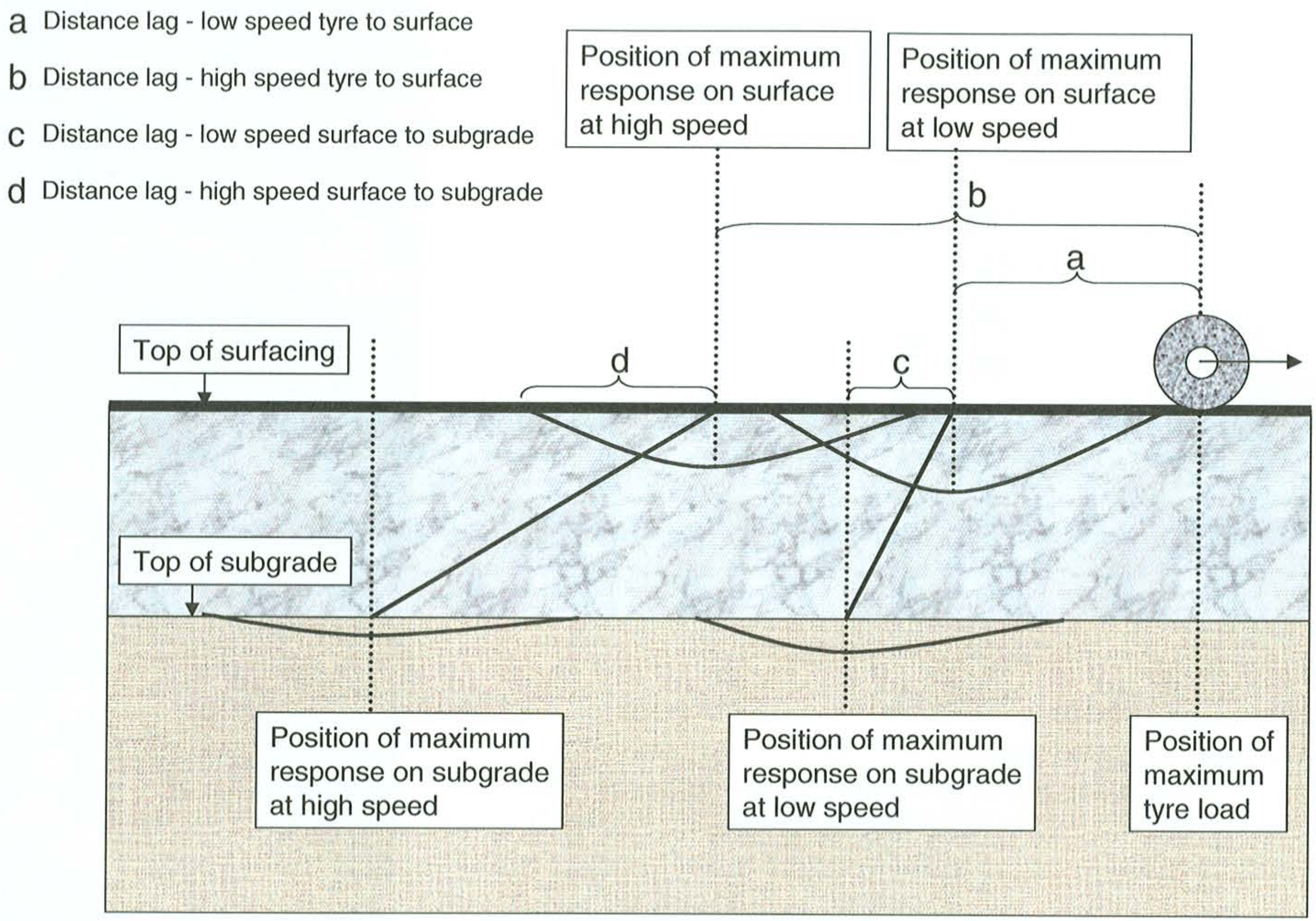

**Figure 6.31:** Schematic indication of distance lag between positions of maximum tyre load and maximum response on surface and subgrade of pavement structure.

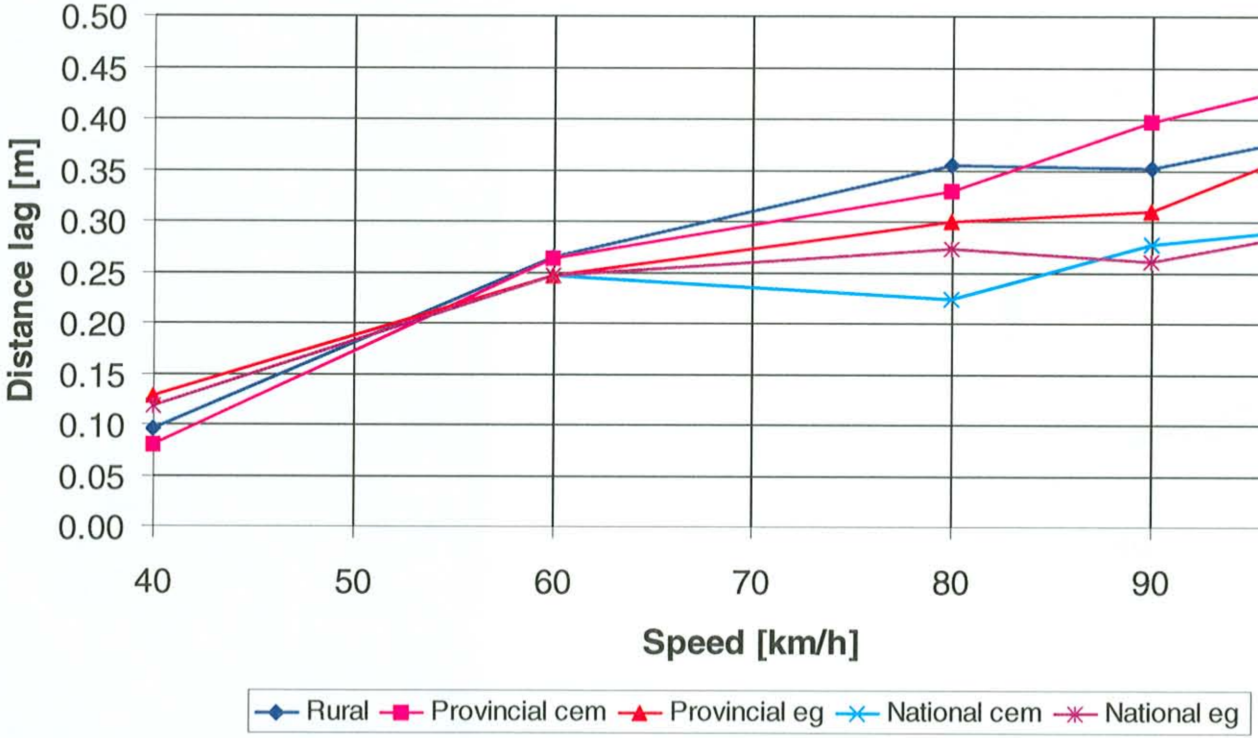

**Figure 6.32:** **Distance lag between position of maximum vertical stress on surface of pavement and position of maximum vertical stress on top of subgrade of pavement.**

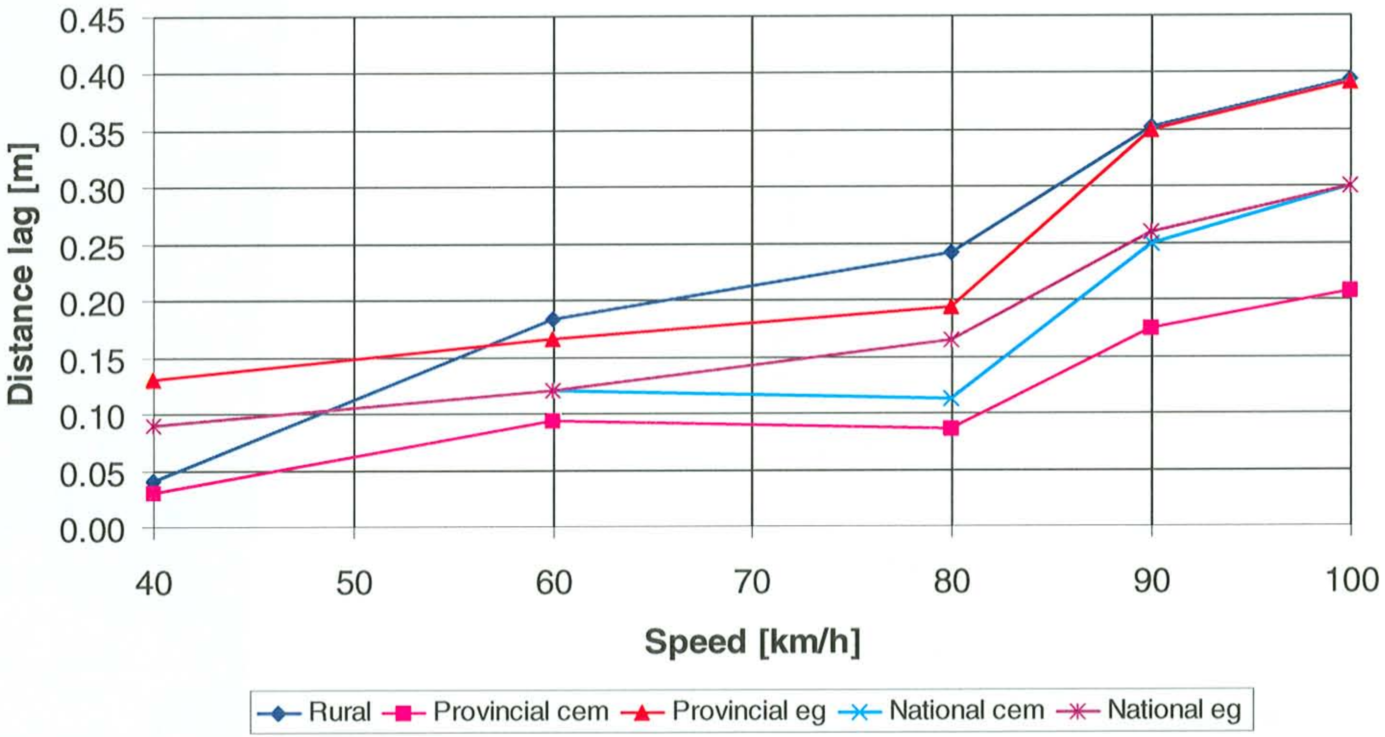

**Figure 6.33:** Distance lag between position of maximum horizontal stress on surface of pavement and position of maximum horizontal stress on top of subgrade of pavement.

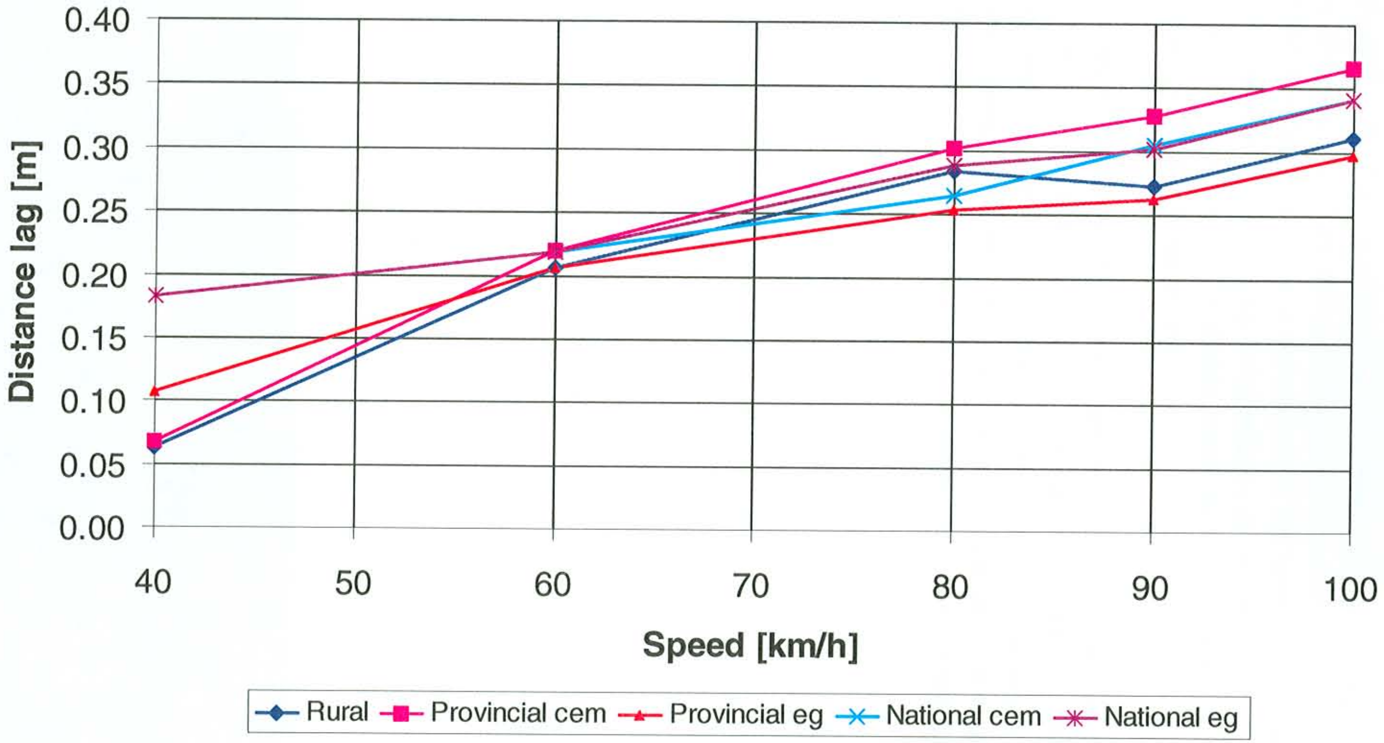

**Figure 6.34:** Distance lag between position of maximum shear stress on surface of pavement and position of maximum shear stress on top of subgrade of pavement.

With the stated limitations in mind, it is important to establish the effect of the distance lags shown in Figures 6.32 to 6.34. The first observation is that the position of maximum load application (the tyre) and the positions of maximum pavement response is not similar when the load is a moving load, and that this distance increases with increased speeds. A maximum distance of 0,28 m was observed between the tyre and position of maximum pavement response on the surface of the pavement. This means that in practice pavement response measurements should be done not only at the position of the tyre, but also a distance behind the tyre, especially when the load is moving at a higher speed. The reason for this distance lag is thought to be due to the mass and inertia properties of the pavement structure.

The second observation is that a distance lag also exists between the position of maximum response on the surface of the pavement structure and at positions deeper in the pavement. This distance lag also increases with increased speeds. It has been calculated to be up to 0,45 m for the conditions investigated in this thesis. The practical effect of this is that measurements of pavement response when the maximum response is occurring on the surface of the pavement structure will not observe the maximum parameter value at deeper layers in the pavement.

The third observation is that existence of this distance lag in positions of maximum stress response parameters in the pavement structure at different depths, means that the principal stress axes in the upper and lower parts of the pavement is not necessarily aligned when the load moves over the pavement. If it is assumed that the principal stress axis is vertical when the maximum vertical stress occurs at a specific position in the pavement structure, it means that a relative principal axis rotation occurs between the various layers as the load moves over a specific point in the pavement. This phenomenon is schematically shown in Figure 6.35. The effect of this rotation of principal axes is not investigated further in this thesis, although it is recommended that such an investigation be performed. An area where this effect may be important is in the analysis of falling weight deflectometer results, where the load is applied at a frequency that simulate a moving vehicle, but where the positions of maximum response are always directly below each other, and thus the principal axes is aligned at all depths in the pavement.

In summary it can be stated that the positions of maximum load application and maximum stress response at the different depths in the pavement are not similar when the load is moving, and that the distance between these positions increases with increased load application speeds. The effect of this is that the principal stress axes at different depths in a pavement are not aligned when a load moves over the pavement structure.

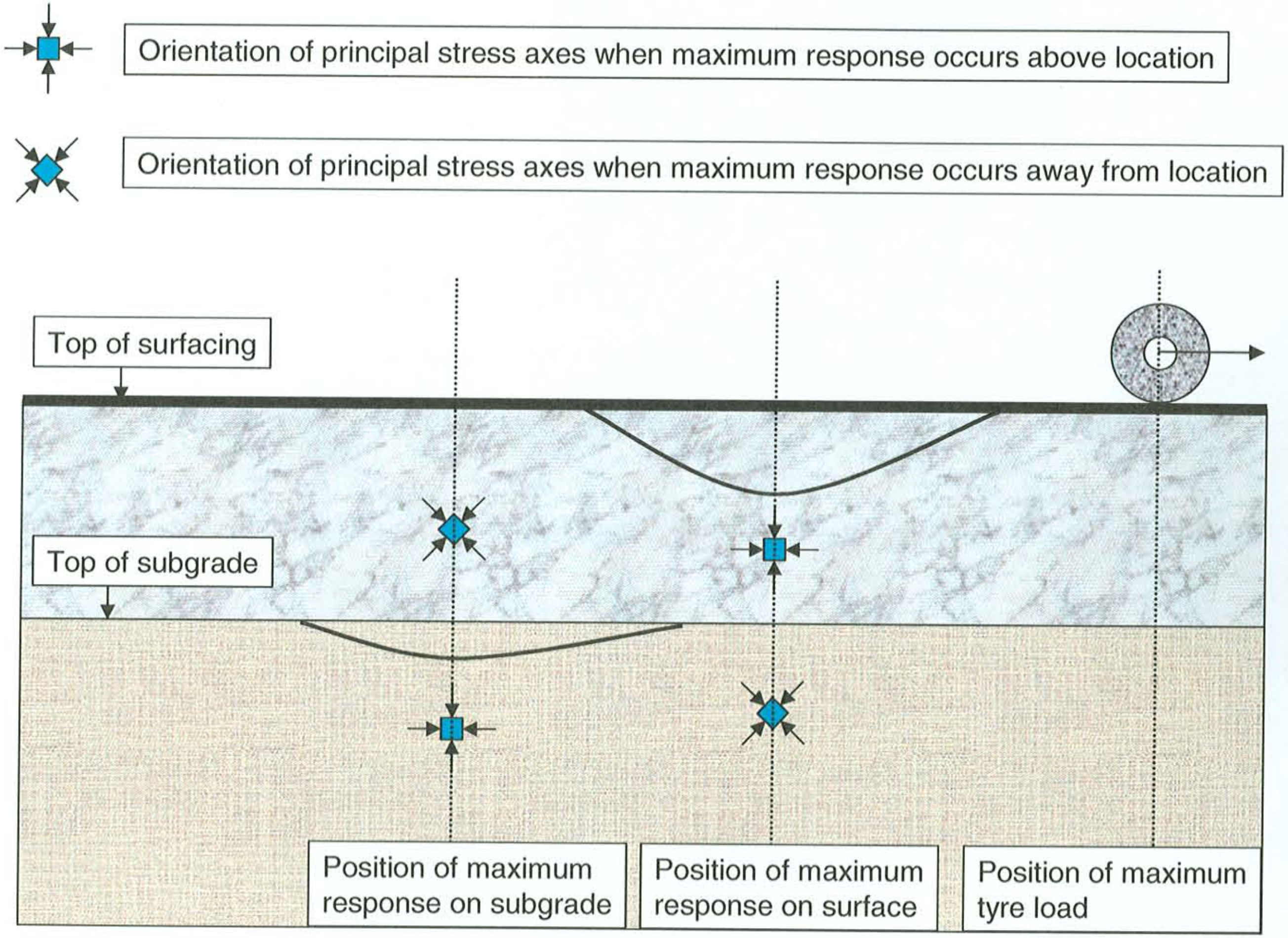

**Figure 6.35:** Schematic indication of the relative orientations of principal stress axes due to distance lag in position of maximum response at different depths in the pavement structure.

### 6.3.3. Expected pavement lives

The expected pavement lives using the responses from the transient analyses were calculated using the South African Mechanistic Design Method (SAMDM) transfer functions and the pavement response parameters obtained from the two transient methods.

Wolff and De Beer (1993) developed an elasto-plastic analysis method by which the development of plastic strains in the pavement can be accounted for. However, these transfer functions are based on non-linear material models. Wolff and De Beer indicated that a direct relationship does not exist between the linear and non-linear solution of the bulk stress (the main parameter used in their transfer function). As the analyses in this thesis were all performed using linear elastic theory, Wolff's elasto-plastic transfer functions can thus not be used to evaluate the residual stresses in the pavement. It is appreciated that the development of residual stresses and plastic deformation in a pavement due to repetitive tyre load applications will be of importance in analysing the pavement performance, but due to the linear elastic material models used in this thesis, it falls outside the scope of the thesis.

*MCL analysis*

The stresses, strains and deflections discussed in Section 6.3.2 were used to calculate the expected pavement lives for each of the different load scenarios, using the SAMDM transfer functions. A summary of the critical lives in each pavement structure is shown in Table 6.11. The most critical lives were calculated at a speed of 40 km/h. The expected lives calculated using static axi-symmetric response data are also shown in Table 6.11.

When these expected lives are compared with the expected lives indicated in the design catalogue (TRH4) for the specific pavement structures, all the pavement classes are higher than the TRH4 catalogue classes by factors 1E19 (rural), 1E13 (provincial) and 1E17 (national). This is mainly caused by the high expected lives during the equivalent granular phases of the national and provincial pavements and the whole life of the rural pavement.

The static data resulted in expected pavement lives that were closer to realistic values, especially for the provincial pavement structure. The reason for the rural and national pavement structures to be as high lies in the granular layers that are present in these two pavement structures. The Factor of Safety method is used to calculate the expected lives for these layers. This method makes use of the vertical and horizontal stresses in the middle of the pavement structure. The transient analysis resulted in compressive horizontal stresses being calculated where tensile horizontal stresses were calculated using the static response method (see Section 6.2.3). Where only the transfer functions for cemented layers were used (provincial pavement cemented phase) and no FoS method or stresses were used in the calculation, the calculated expected life is closer to that calculated using the static response method (36 per cent difference).

The reason for the higher than expected lives for the responses obtained at speed, can be found in the usage of the pavement response parameters obtained at speed together with transfer functions that were developed on pavement response at creep speeds and customised for pavement response at static conditions. The effects of speed on the parameters used in the transfer functions are discussed in detail in Sections 6.4 and 6.5.

Using the SAMDM static transfer functions will cause both the strain-based calculations and the stress-based calculations to be overestimating the lives of the pavement due to the effect of load speed and pavement mass inertia on the responses calculated.

If a reliable relationship is found between the pavement response parameters at different speeds it is possible to adapt the existing transfer functions for use with pavement response parameters obtained at speed. More discussion on this topic follows in Section 6.5.

**Table 6.11: Critical expected pavement lives based on axi-symmetric finite element transient response analysis and SAMDM transfer functions.**

| Pavement structure (design traffic class) | Critical layer | Average expected life for most critical layer [million E80s] (traffic class) | Average total expected life [million E80s] (traffic class) | Average total expected life [million E80s] STATIC DATA (traffic class) |
|---|---|---|---|---|
| National (ES100) | C3 | 4,2 (ES10) | 5,93E18 (ES100+) | 4,13E6 (ES100+) Critical layers C3, G1 |
| National (equivalent granular) | Soil | 1,45E12 (ES100+) | | |
| Provincial (ES3) | C3 | 2,43 (ES3) | 3,95E13 (ES100+) | 1,87 (ES3) Critical layers C4, EG4 |
| Provincial (equivalent granular) | EG4 | 3,64E13 (ES100+) | | |
| Rural (ES0,3) | Soil | 2,58E18 (ES100+) | 2,58E18 (ES100+) | 7,0 (ES10) Critical layers G6 |

The critical expected lives indicated in Table 6.9 are all calculated under the 95th percentile load, as higher loads generally cause shorter pavement lives using the SAMDM transfer functions. All the critical lives were also calculated under the lowest (40 km/h) speed. Calculated lives increased with increased speeds, although not significantly. The expected lives calculated at the higher speeds were mostly also outside the range for which the SAMDM transfer functions were developed (values of 1E8 and higher). The calculated lives were generally much higher than those calculated using the static response analysis data. A complete discussion regarding the variations between the two sets of results appears in Section 6.4.

The data indicates that the expected lives of the three pavements decreased with increased load percentiles. This is to be expected, as the stresses and strains used to calculate the expected lives from, increased with increased loads.

### 6.3.4. Summary of transient pavement response analyses

The transient pavement response analysis consisted of analysing the response of the five pavement structures to moving constant loads. The analyses incorporated the effects of mass inertia and damping on the pavement responses. The following inferences can be made regarding these analyses:

a. Running finite element analyses is a time-consuming process that require detailed input data and data reduction techniques not normally required for static response analyses;
b. Deflection and strain values (vertical, horizontal and shear) generally decrease with increased speeds;
c. Stress values (vertical, horizontal and shear) generally remains constant with increasing speeds;
d. Load magnitude shows good relationships with the stresses in the upper part of the pavement structure, while load speed shows good relationships with the strains in the pavement structure;
e. Higher load frequencies (axle hop range) affect calculated strains in the deeper parts of the pavement less than lower load frequencies (body bounce range);
f. Higher load frequencies affect calculated stresses in the pavement less than calculated strains;
g. Horizontal stresses are generally affected more by higher frequency loads than lower frequency loads;
h. The response parameter ratios (between values at different loads and a reference load) were lower at deeper parts of the pavement than the applied load ratios, indicating that the deeper parts of the pavement is less affected under MCL than under static loads;
i. A distance lag exists between the position of maximum load application and the positions of maximum response at the surface and lower down in the pavement;
j. This distance lag indicates that a relative principal axis rotation occurs when a load is mover over a pavement between the upper and the lower parts of the pavement and,
k. The expected pavement lives calculated using the response parameters from a MCL analysis cause higher expected lives than when doing the calculation using static load data.

## 6.4. Response Evaluation

### 6.4.1. Introduction

The objective of Chapter 6 of this thesis is to obtain an understanding of the effect of load speed and pavement mass inertia and damping on pavement response parameters. The currently used multi-layered linear elastic analysis method and two transient pavement response analysis methods were selected to investigate this.

The main differences between the two analysis methods used are the two different load definitions and the incorporation of mass inertia and damping effects into the transient response analyses. In the evaluation of the various responses the effects of load definition (static load versus moving constant load) and mass inertia and damping cannot be separated.

The first part of this chapter focused on the relationships between the calculated stresses, strains and deflections, as obtained using the static response analysis and the MCL analysis, both for static load conditions. The objective of this was to compare the results of the two sets of data if the only difference is the analysis method (i.e. analysis with and without the effects of material inertia and damping).

In the second part of the analysis the results from the static response analysis are compared with that from the MCL analysis at the various speeds. The objective was to evaluate the effect of speed on the calculated pavement response parameters.

In this, the third part of the analysis, the expected lives from the static response analysis and the MCL analysis are compared. The objective is to evaluate the effect of the pavement response parameters obtained at different speeds when using the static SAMDM transfer functions. Care must be used in this evaluation, as the transfer functions used in the SAMDM were developed using slow moving (3 km/h) Heavy Vehicle Simulator (HVS) pavement response data together with static response analyses and a multi-layered linear elastic approach. Although the material model used in the analyses in this thesis was also a linear elastic model, the effect of speed on the transfer functions, as well as the effects of mass inertia and damping as incorporated using the transient methods, are not exactly known. This limitation was also highlighted in Section 4.5.3. The expected lives are calculated based purely on load applications and environmental effects are excluded in the current analysis.

### 6.4.2. Static data analysis

In order to verify the pavement response parameters obtained through the use of the MCL method, an analysis was performed for each pavement with a static load condition using the MCL method. This was especially necessary to verify that parameters such as the mesh dimensions used in the transient analysis did not impact on the results obtained.

The elastic surface deflection, and the vertical and horizontal stresses and strains were compared with each other. A statistical analysis was performed to determine whether a statistically significant difference existed between the data obtained from the static response and transient (axi-symmetric) analysis. The statistical analyses indicated that a statistically significant difference did not exist between the data sets shown in Table 6.12 at the indicated confidence levels.

Based on these analyses it can be assumed that the pavement response parameters obtained using the static response analysis method and the MCL method would produce similar pavement response parameters under static conditions. The differences in pavement response parameters obtained between the two methods when the transient analysis is performed at non-static conditions can thus be attributed to the load speed and not to the finite element method used in the analyses (i.e. mesh dimensions and element sizes).

**Table 6.12: Confidence levels at which statistically significant differences do not exist between static response analysis parameters and axi-symmetric transient analysis parameters under static conditions.**

| Statistical Parameter | Horizontal stress | Vertical stress | Horizontal strain | Vertical strain | Deflection |
|---|---|---|---|---|---|
| Mean | 95% | 95% | 95% | 95% | 95% |
| Median | 95% | 95% | 99% | 95% | 95% |
| Standard deviation | a | 95% | 99% | 95% | 95% |
| Distribution | 95% | 95% | 99% | 95% | 95% |

a - A statistically significant difference was shown to exist in the standard deviation of the horizontal stresses at all confidence levels.

### 6.4.3. Data comparison

The process to compare all the data from the various analysis methods involved a statistical comparison of the pavement response parameters obtained from the static response and the MCL methods. The main objective is to determine whether a difference exists between the calculated pavement response parameters from the various analysis methods. Relationships between these parameters are developed in Section 6.5. The data shown in the figures in this section are for all the load speeds but only for the 50th load percentile. The data from all the load percentiles are used in the development of relationships in Section 6.5.

The data used in the statistical analyses are shown in Figures 6.36 to 6.41. In these figures the pavement response parameters for each of the static response analysis, MCL and MDL analyses at different speeds are shown against pavement depth.

*Vertical stress*

The vertical stresses for all the pavements at various speeds are shown in Figure 6.36 against pavement depth. A band of values is evident, indicating that similar trends are obtained from the various analyses for the different data sets and analysis parameters. A statistical analysis of the data indicates that a statistically significant difference does not exist between the means of the various pavement parameters (from the different analysis methods) at the 95th per cent confidence level.

*Horizontal stress*

The horizontal stresses for all the pavements at various speeds are shown in Figure 6.37 against pavement depth. A band of values is again evident for the data. Four outliers on the figure are the horizontal stresses calculated using the static response analysis and the MCL analysis methods for the national (***cem*** and ***eg***) pavement structures at the bottom of the asphalt surfacing layer (50 mm) (also refer to Figures 6.5 and 6.13). These stresses were within the same band when calculated at all speeds. This may be attributed to the effect of the stiffer asphalt surfacing layer. However, the relative stiffness of this layer increased even further at speed when the elastic modulus was converted to a dynamic modulus using the Asphalt Institute Formulas. A statistical analysis of the horizontal stress data indicated that a significant difference did not exist between the means of the data at the 95th per cent confidence level.

*Shear stress*
In Figure 6.38 the shear stresses for all the pavements at various speeds are shown against depth. The values decrease with increased depth, but do not fall into a clearly defined band as for the vertical and horizontal stresses. A few outliers occur at depths of between 350 and 450 mm in the national (***cem*** and ***eg***) pavements under static conditions. A statistical analysis of the shear stress data indicated that a statistically significant difference did not exist between the means of the data at the 95th per cent confidence level.

*Vertical strain*
The vertical strain data from all the pavements are shown in Figure 6.39 against depth. All the speeds are included in the data. Although scatter is evident in the data, it is apparent that the data obtained from the calculations at speed are generally smaller than the data obtained from the static analyses. Static analyses showed higher vertical strain values, especially closer to the surface of the pavements. A statistical analysis of the data indicated that statistically significant differences exist between the mean values of the static data and the MCL data at the 95th per cent confidence level. The MCL data and the static data formed two clearly separate populations.

*Horizontal strain*
The horizontal strain data for all pavements and speeds are shown in Figure 6.40 against depth. The data obtained from the MCL analyses are smaller than those data obtained from the static load analyses. The statistical analysis again indicated that statistically significant differences exist between the mean values of the static data and the MCL data at the 95th per cent confidence level. The MCL data and the static data again formed two clearly separate populations.

*Shear strain*
In Figure 6.41 the shear strain data from all the pavements and obtained at all speeds are shown against pavement depth. Although a decreasing trend is visible with increasing depth, it is apparent that the static load data do not follow this trend. The statistical analysis confirmed this trend. A statistically significant difference in mean values was observed at the 95th per cent confidence level between the static response analysis and all the MCL analysis data. No statistically significant difference was observed between the mean values of the MCL data at 0, 40 and 60 km/h at the 95th per cent confidence level, and also between the data at 40, 60, 80, 90 and 100 km/h. Three distinct groups of data were thus evident in the shear strain population.

The following inferences can be made based on the evaluation of the pavement response parameters:

a. The stress data (vertical, horizontal and shear) generally shows less sensitivity to load speed than the strain data, with no statistically significant differences between the populations of the means of the stress data at the 95th per cent confidence levels;

b. The strain data (vertical, horizontal and shear) generally shows a sensitivity to load speed with statistically significant differences in the means at the 95th per cent confidence levels between the static data and the data obtained at all speeds.

### 6.4.4. Expected pavement lives evaluation

The expected pavement lives in this thesis were all calculated using the pavement response parameters from the three pavement response methods and the SAMDM transfer functions. These transfer functions were developed based on HVS data and with the aid of linear elastic multilayer static response analyses. Its basis is thus creep speed data (HVS data) and static response calculations.

For the static response analyses performed in this thesis (Section 6.2.3) the calculated lives are valid as the transfer functions were used with the type of input data they were developed for. However, for the transient response analyses performed in this thesis (Section 6.3.3) the input data originates from a moving load. As indicated in Section 6.3.2, the effect of load speed on the pavement response parameters is that the strains normally decrease in magnitude while the stresses remain constant or change slightly in magnitude.

Therefore, the effect of using the pavement response parameters from the transient analyses directly in the SAMDM transfer functions cause the calculated expected lives to be overestimated. The only solution to this phenomenon is to either develop new transfer functions using the transient pavement response parameters, or to relate the transient response parameters to static response parameters to enable the transfer functions to remain valid. Relationships to do this with the pavement types and traffic spectrum analysed in this thesis were developed in Section 6.5. Development of new appropriate transfer functions is not currently an option due to the cost of doing laboratory and field tests to evaluate the responses of various pavement structures to moving loads.

In general, transfer functions should not be applied using data produced under conditions outside the scope of the transfer functions' development.

### 6.4.5. Summary

The analysis of the data from all the pavement response analysis methods at all load and speed conditions indicated that:

a. The static response data from both the static response analysis and the MCL analysis showed similar trends and values;
b. The moving load data from the MCL analysis showed similar trends;
c. The stress data were not affected by load speed in the same order than the strain data and,
d. Use of the transfer functions developed for static conditions together with data from moving loads do not provide correct estimates of pavement life.

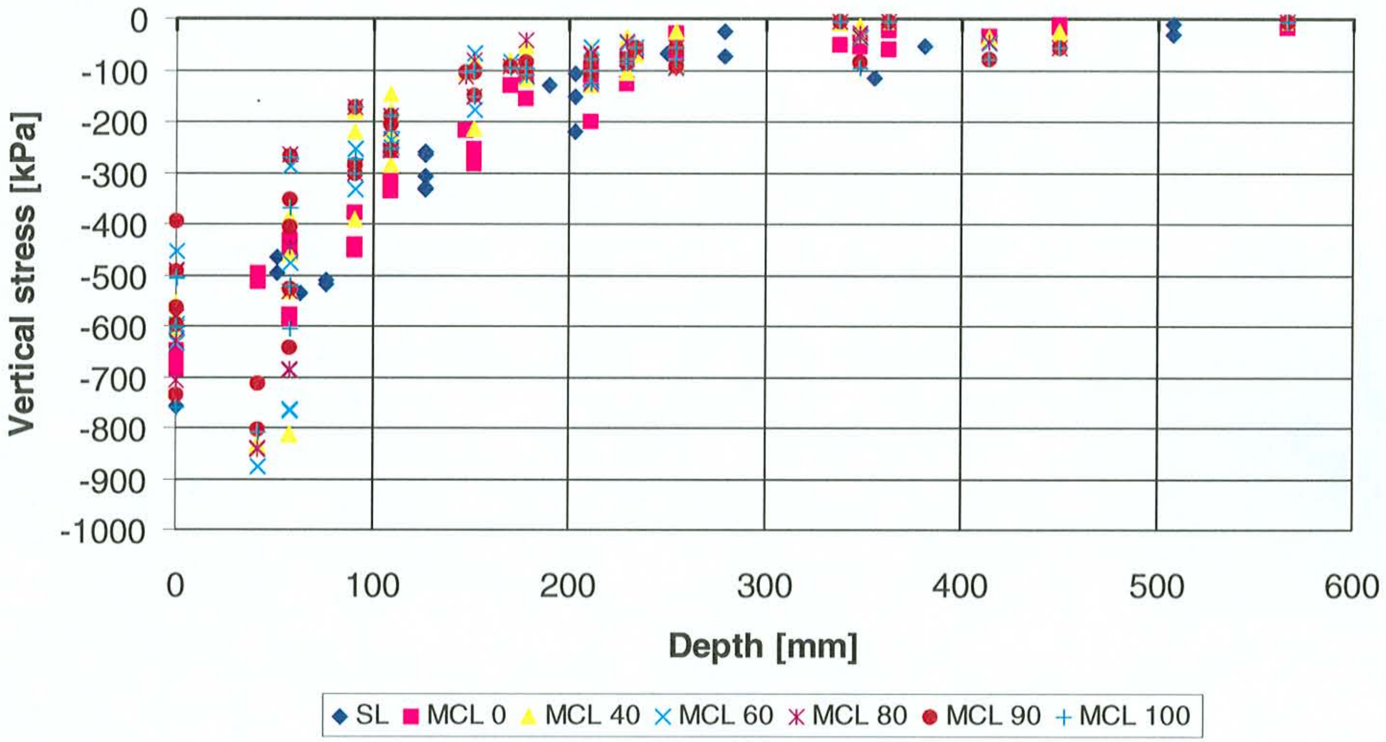

Figure 6.36: Vertical stress data at all speeds and 50th load percentile from different analysis methods.

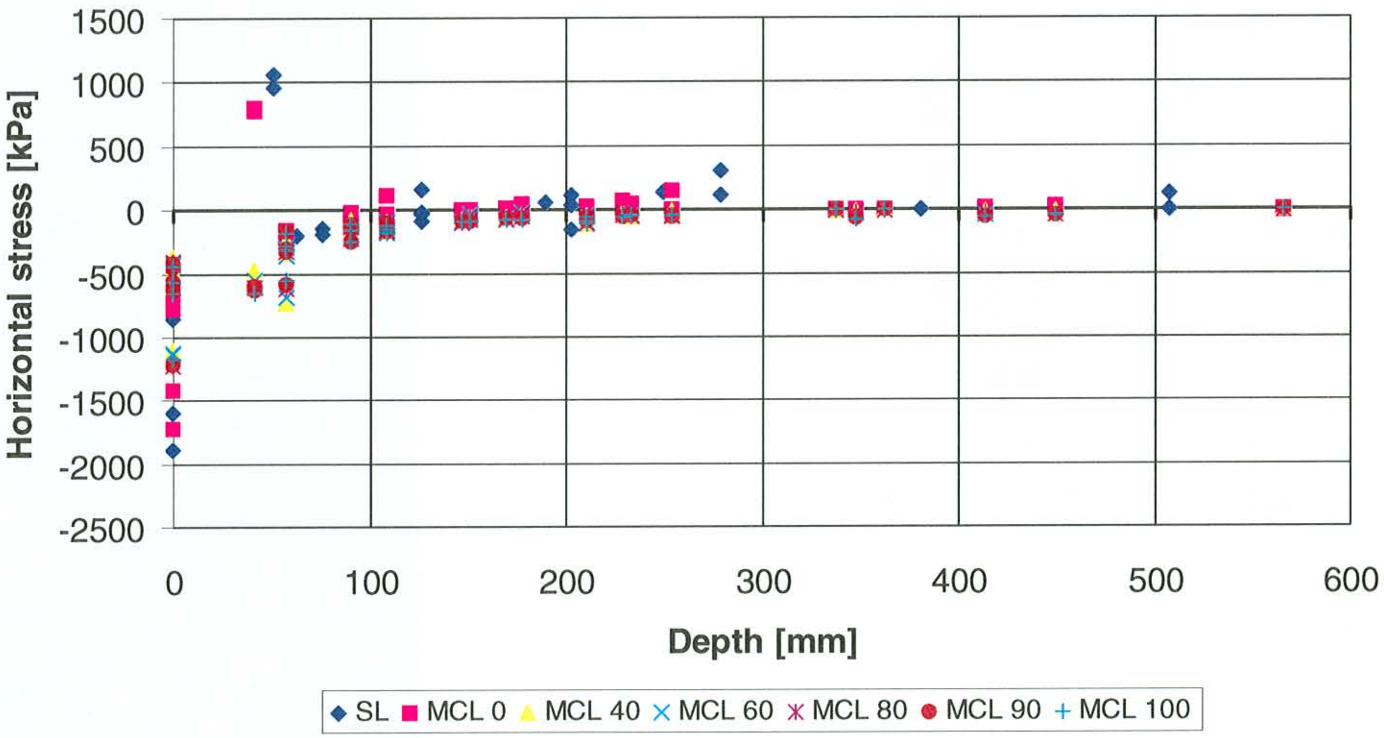

Figure 6.37: Horizontal stress data at all speeds and 50th load percentile from different analysis methods.

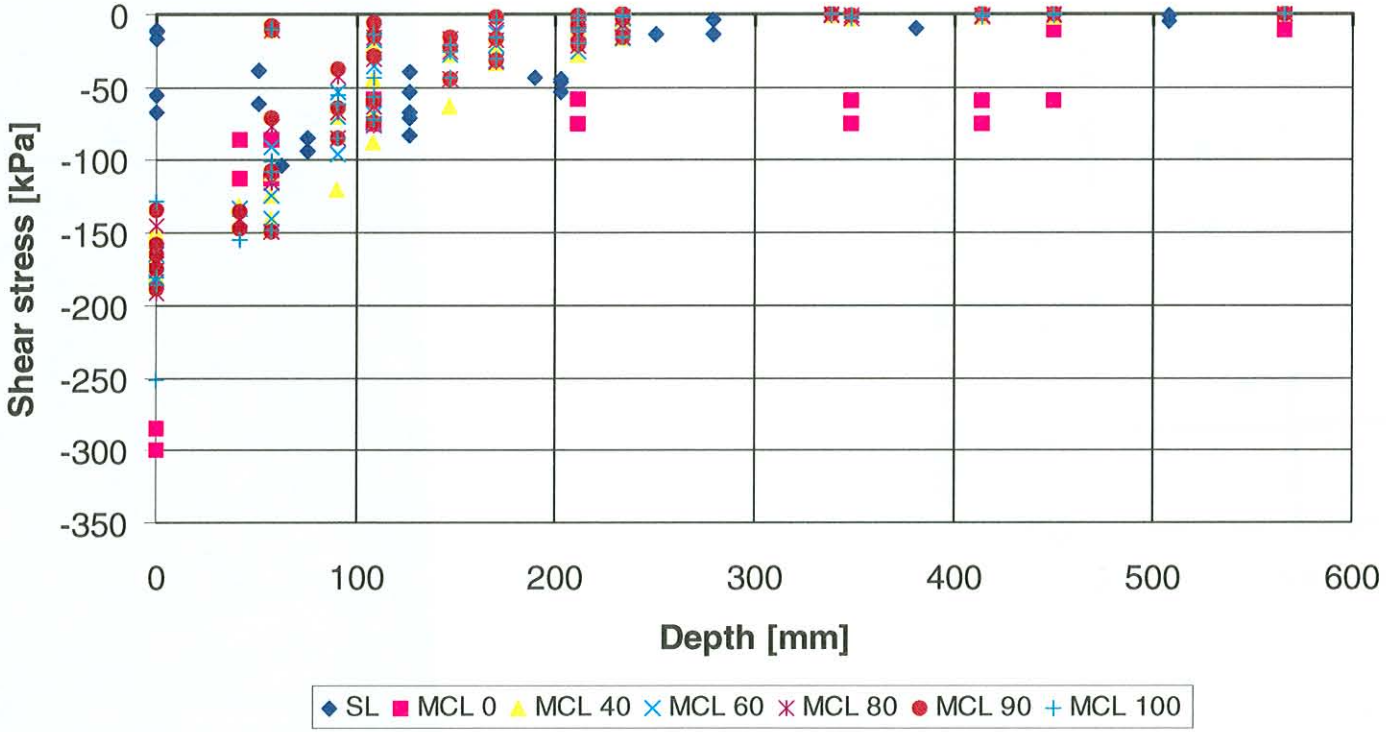

**Figure 6.38:** Shear stress data at all speeds and 50th load percentile from different analysis methods.

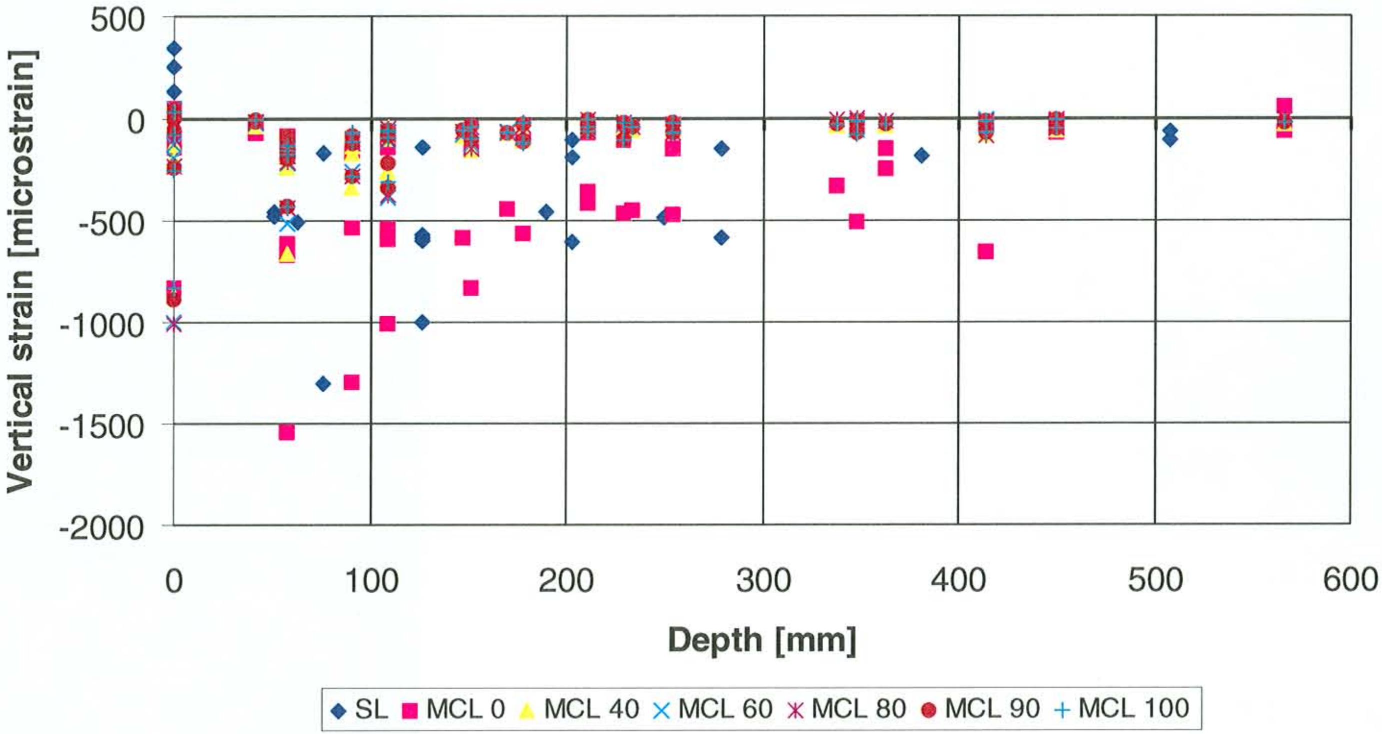

Figure 6.39: Vertical strain data at all speeds and 50th load percentile from different analysis methods.

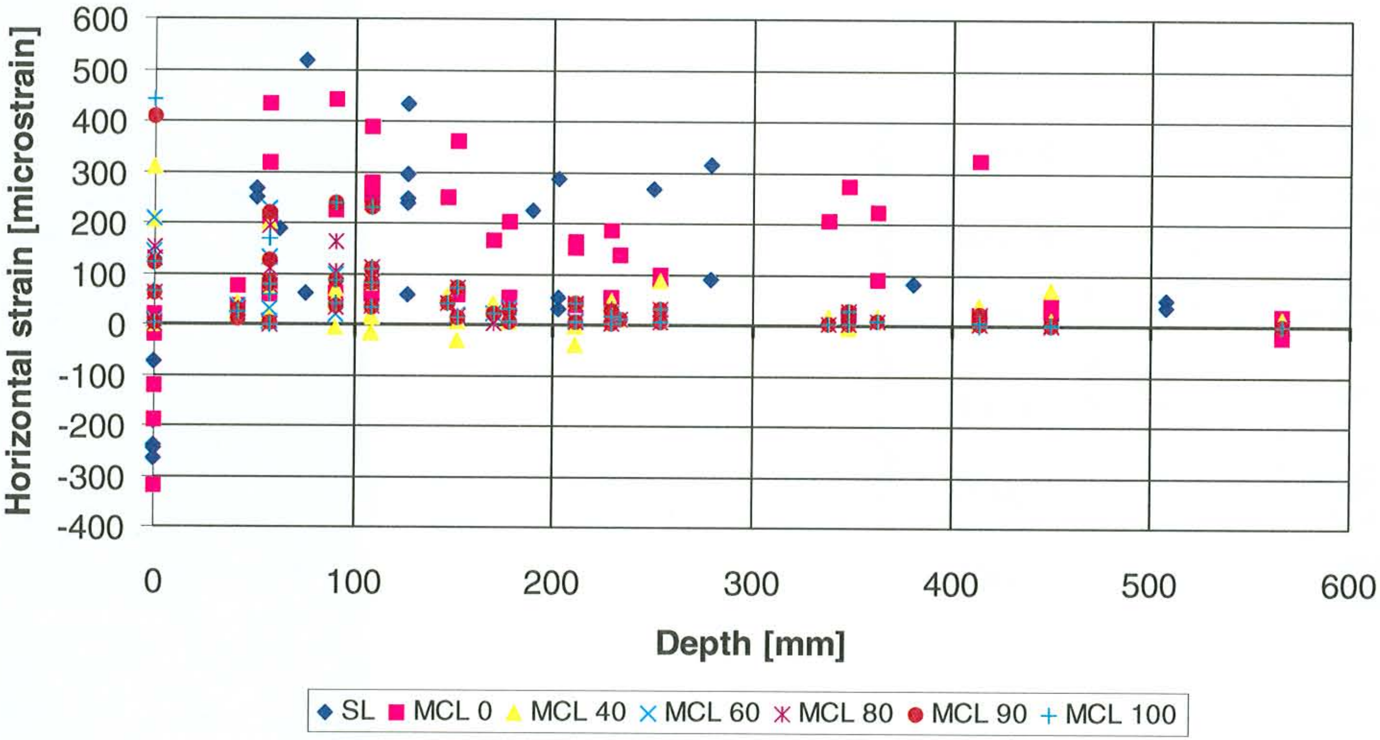

**Figure 6.40:** Vertical strain data at all speeds and 50th load percentile from different analysis methods.

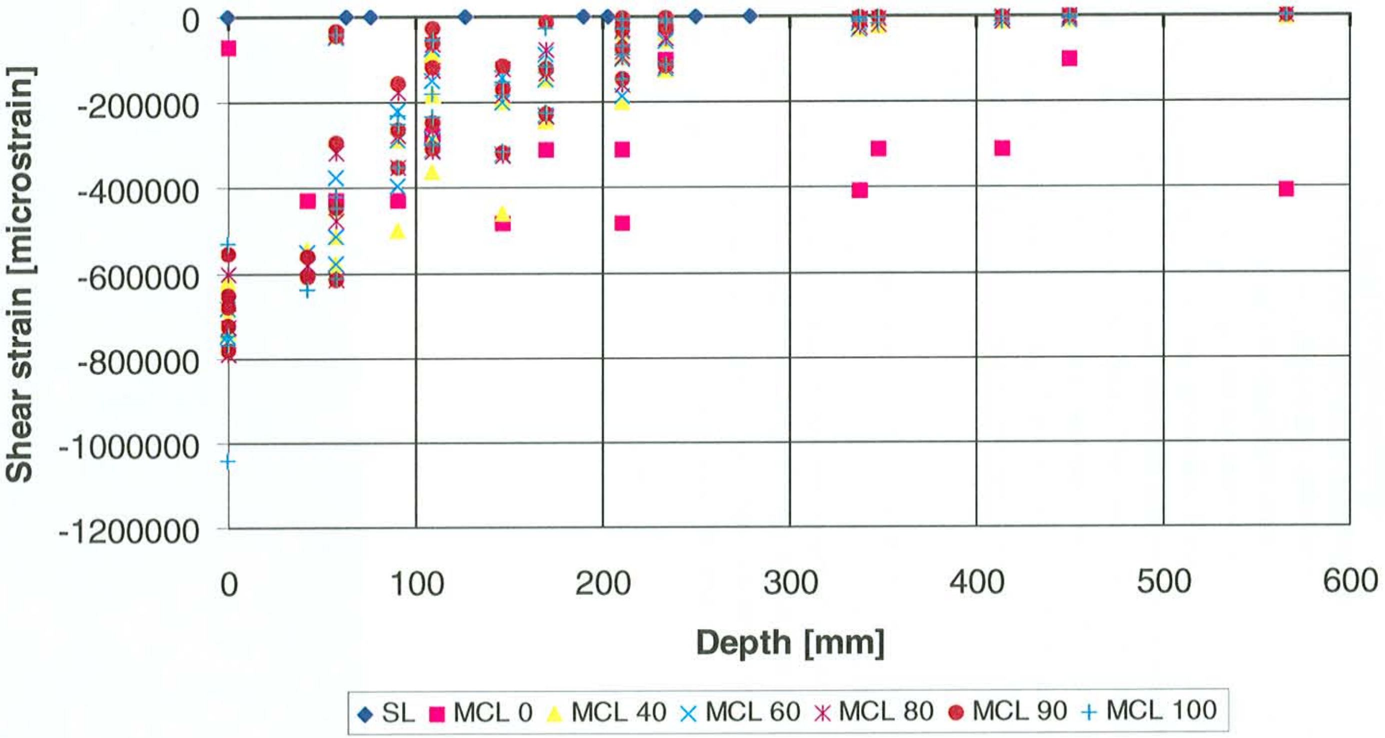

**Figure 6.41:** **Shear strain at all speeds and 50th load percentile from different analysis methods.**

## 6.5. Static Response Analysis with Dynamic Effects

### 6.5.1. Introduction

In order to provide a practical alternative to engineers for including the effects of load speed and pavement mass inertia and damping effects in their pavement life calculations without the availability of appropriate user-friendly methods to calculate the pavement responses incorporating these effects or transfer functions for these conditions, an approximate method is proposed for this purpose. This method can be used to estimate the pavement response parameters under moving loads when the static responses are available, or to convert the pavement responses calculated under moving loads to equivalent static values that may be used in the current transfer functions. The approximate method makes use of the knowledge that:

a. The deflection of the pavement reduces with increased speeds (Section 6.3.2);
b. The strains in the pavement decrease with increased speeds (Section 6.3.2);
c. The stresses in the pavement varies with increased speeds (Section 6.3.2);
d. The relationship between speed and the deflection and strain is a function of the mass inertia and damping parameters for the specific pavement type, and is not similar at all depths (Section 6.3.3).

The proposed method consists of a set of equations with which the static stresses, strains and deflections as calculated using the linear elastic static software (i.e. ELSYM5M) can be adopted for the specific speed at which the results are required. It is important to note that the proposed equations were derived based on a population of the most typical vehicles currently found in South Africa, and the responses of three typical pavement structures to these tyre loads.

### 6.5.2. Features and limitations of the method

The proposed method consists of a set of equations that can be applied to the calculated pavement responses (stresses, strains and deflections) obtained from the transient pavement response analysis to estimate the equivalent static response parameters. These equivalent static response parameters can then be used in the normal SAMDM transfer functions to calculate the expected life of the pavement. Conversely, the equations can be used to calculate the expected pavement response parameters at specified speeds based on the static response parameters calculated. The calculated responses would then be within the expected range of values when the calculation would be performed using a finite element-based transient response approach. The method obviously does not provide a directly related response in terms of all three the required parameters, as their respective reactions to load speed differ.

The main limitation of this method is that the factors are unique for the selected vehicle configurations, pavement structures and material properties that they were developed for. However, these equations should provide the pavement engineer with a good estimate of the expected variations in pavement response due to the effect of load speed. Further, the equations are based on the pavement response to a single tyre load, as the analyses were performed using an axi-symmetric finite element programme.

It is proposed that when the moving load response are to be used in a design or analysis, the lower 5th percentile of the speed spectrum expected on the pavement be used to keep the calculated values conservative. This is necessary as the pavement responses generally decrease in magnitude with increasing speeds, and thus slow-moving vehicles will have an greater effect on pavements than fast-moving vehicles.

### 6.5.3. Analysis output

The equations for the three pavement structures used in this thesis were calculated using the responses from the axi-symmetric finite element pavement response analyses. These data were used instead of the three-dimensional finite element data, as the three-dimensional data were only available for one pavement type.

The equations for the three parameters are shown in Tables 6.13 and 6.14. It is important to recognise that these factors are used with the normal static stiffness parameters, as the effect of the stiffness change due to load speed effects in (mainly) the asphalt layer is already accommodated in the factors. The convention for stresses and strains using the equations in Tables 6.13 and 6.14 is that compressive parameters are negative and tensile parameters are positive.

The equations were developed for the response parameters necessary to calculate the expected lives of the pavements using the SAMDM transfer functions (Theyse et al, 1996), as well as the maximum surface deflections. The equations focus on response parameters such as the vertical and horizontal stresses in the middle of the granular layers, the vertical strain at the top of the subgrade, and the horizontal strains at the bottom of the asphalt and cemented layers.

### 6.5.4. Expected pavement lives

As the equations are based on the information used in this thesis, the calculated pavement lives should agree with those calculated using the other (speed independent) pavement analyses options in this thesis.

The expected pavement lives for the three pavement structures were calculated using the responses of the pavement response calculations and the SAMDM transfer functions. These calculations were only performed for the 50th percentile load case. The expected pavement lives calculated using these equations to calculate the equivalent static pavement response parameters are shown in Table 6.15 together with the calculated expected lives for the original static response analyses.

Table 6.13: Equations for incorporating the effect of load speed into static pavement response parameters – deflection and strain.

| Response parameter | Pavement type | Relationship type | a* (intercept) | b (slope) | R^2 | Standard error | Position of parameter in pavement structure |
|---|---|---|---|---|---|---|---|
| Maximum surface deflection | Rural | Square root x | 3,338E-01 | 2,737E-02 | 98,1 | 0,01100 | Surface |
| | Provincial | | 1,523E-01 | 9,856E-03 | 86,4 | 0,01130 | |
| | Provincial equivalent granular | | 4,812E-01 | 3,534E-02 | 99,3 | 0,00870 | |
| | National | | 1,732E-01 | 1,730E-02 | 88,3 | 0,01800 | |
| | National equivalent granular | | 2,282E-01 | 2,357E-02 | 84,9 | 0,02900 | |
| Vertical strain | Rural | Square root x | -3,389E-04 | -3,336E-05 | 75,1 | 0,00004 | Top of subgrade |
| | Provincial | | -1,081E-04 | -1,018E-05 | 63,2 | 0,00002 | |
| | Provincial equivalent granular | | -1,715E-04 | -1,747E-05 | 65,2 | 0,00003 | |
| | National | | -5,157E-05 | -4,339E-06 | 58,9 | 0,00001 | |
| | National equivalent granular | | -7,699E-05 | -7,259E-06 | 55,7 | 0,00002 | |
| Horizontal strain | Provincial | Square root x | 5,910E-05 | 2,385E-06 | 90,0 | 0,00001 | Bottom of C3 |
| | Provincial | | 8,314E-05 | 8,913E-06 | 93,6 | 0,00001 | Bottom of C4 |
| | National | | 3,474E-05 | 3,765E-06 | 95,9 | 0,00001 | Bottom of C3 |
| | National | | -4,401E-4 | 2,808E-05 | 96,9 | 0,00001 | Bottom of AC |

$$\text{Equivalent moving response parameter} = (\text{Static response parameter} + b\sqrt{\text{speed}})$$

$$\text{Equivalent static response parameter} = \text{Moving response parameter} - b\sqrt{\text{speed}}$$

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* In the equation the value of a is replaced by the Static response parameter.

**Table 6.14: Equations for incorporating the effect of load speed into static pavement response parameters – stress.**

| Response parameter | Pavement type | Relationship type | c* | b (x) | a (x^2) | R^2 | Standard error | Position of parameter in pavement structure |
|---|---|---|---|---|---|---|---|---|
| Vertical stress | Rural | 2nd degree polynomial | -526,64 | 0,3013 | 0,009397 | 84,9 | 19,7 | Middle G4 |
| | Rural | | -128,13 | 1,4407 | -0,0121 | 93,9 | 4,1 | Middle G6 |
| | Provincial equivalent granular | | -537,35 | 5,3314 | -0,02725 | 96,8 | 19,1 | Middle EG3 |
| | Provincial equivalent granular | | -153,04 | 3,6126 | -0,03096 | 98,4 | 5,3 | Middle EG4 |
| | National | | -327,57 | 4,1672 | -0,02881 | 96,1 | 11,2 | Middle G1 |
| | National equivalent granular | | -258,08 | 2,3852 | -0,01733 | 97,3 | 5,6 | Middle G1 |
| | National equivalent granular | | -52,92 | 0,4400 | -0,00889 | 71,3 | 12,8 | Middle EG3 |
| Horizontal stress | Rural | 2nd degree polynomial | -526,64 | -0,3013 | 0,009397 | 99,1 | 6,1 | Middle G4 |
| | Rural | | 55,606 | -3,476 | 0,0221 | 97,9 | 7,6 | Middle G6 |
| | Provincial equivalent granular | | -174,42 | 0,3606 | -0,00476 | 96,8 | 1,2 | Middle EG3 |
| | Provincial equivalent granular | | 21,51 | -1,0011 | 0,001066 | 80,7 | 16,5 | Middle EG4 |
| | National | | -89,44 | -2,5572 | 0,017442 | 97,1 | 6,6 | Middle G1 |
| | National equivalent granular | | -31,23 | -4,1672 | 0,028047 | 96,9 | 10,9 | Middle G1 |
| | National equivalent granular | | -5,73 | -0,0012 | -0,00647 | 75,3 | 14,5 | Middle EG3 |

$$\text{Equivalent moving response parameter} = \text{static response parameter} + b * \text{speed} + a * \text{speed}^2$$

$$\text{Equivalent static response parameter} = \text{Moving response parameter} - a * \text{speed}^2 - b * \text{speed}$$

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* In the equation the value for c is replaced by the Static response parameter.

**Table 6.15:** **Summary of expected pavement lives based on 50th load percentile for both static response and transient response analyses and SAMDM transfer functions.**

| Pavement structure | Critical layer | | Average expected life [million E80s] (traffic class) | | Average total expected life [million E80s] (traffic class) | |
|---|---|---|---|---|---|---|
| | SL | MCL | SL | MCL | SL | MCL |
| National *cem* | C3 | C3 | 2,85 (ES3) | 5,25 (ES10) | 3 140 (ES100+) | 297 000 (ES100+) |
| National *eg* | G1 | G1 | 285 (ES100+) | 2 000 (ES100+) | | |
| Provincial *cem* | C4 | C4 | 1,5 (ES3) | 5,2 (ES10) | 1,6 (ES3) | 5,4 (ES10) |
| Provincial *eg* | EG4 | EG4 | 0,13 (ES0,3) | 0,18 (ES0,3) | | |
| Rural | G6 | G6 | 0,14 (ES0,3) | 0,15 (ES0,3) | 0,14 (ES0,3) | 0,15 (ES0,3) |

SLA - Static load case
MCL - Moving constant load case

The new expected lives calculated for the equivalent static transient response analysis data is closer to the static response data than the values calculated using the MCL response parameters. The traffic classes for all the pavement structures are either the same or in an adjacent class. Previously, the traffic classes for the transient response analyses data were all much higher than that for the static response data. The close resemblance between the two sets of data is indicative of the close correlation between the two sets of data used for the calculation of the expected lives.

It must be stressed that the exercise using the static response data-based transfer functions to calculate expected lives using dynamic response data indicated the importance of using transfer functions only within their original boundaries. Even the intermediate method proposed in this chapter for converting dynamic response data to static response data before calculating the expected lives using the static response data-based transfer functions, does not fully take cognisance of the effect of dynamic transient loads on the transient response of the pavement structure. These relationships are based on empirical correlations between the data sets. Ideally, transfer functions should be developed with data from moving dynamic tyre loads using transient pavement response models to fully appreciate the effect of moving dynamic loads on expected pavement lives. This is, however, currently not a cost-effective and viable option in South Africa.

### 6.5.5. Summary of static pavement response analyses with dynamic effects

The static pavement analyses with dynamic effects option allows for the practitioner to estimate the pavement response at different speeds when the pavement response is only available at static conditions, and it allows for pavement response parameters calculated at different speeds to be converted to equivalent static values to be used together with the static SAMDM transfer functions to calculate expected pavement lives.

## 6.6. Observations

The following observations are made based on the information in this chapter:

<u>All analysis methods</u>

a. Similar trends were observed in both the static pavement response and transient pavement response analyses for all parameters at the different load levels;
b. Increased load magnitudes resulted in increased stresses, strains and deflections, as would be expected;
c. Pavement response parameters generally decreased with depth, as would be expected;

<u>Static response analysis</u>

a. A perfect linear relationship exists between the load magnitudes and the calculated response parameters, as would be expected;
b. The ratio between stress, strain and deflection at different load magnitudes were similar to each other and also directly proportional to the ratios between the applied loads, as would be expected;
c. The applied loads influence the expected lives of the various layers in the pavements critically, as would be expected.

<u>Transient response analysis – moving constant loads</u>

a. The inferences drawn around the load cases analysed using only the MCL method focus only on the transient response of the pavement to a single tyre load;
b. Running finite element analyses is a time-consuming process that requires detailed input data and data reduction techniques not normally required for static response analyses. More complicated material models affects the time required for an analysis;
c. The calculated vertical strains on top of the subgrades were similar for all pavements;
d. A statistical analysis between the pavement response parameters obtained from the static response and MCL analysis indicated that a statistically significant difference did not exist between the data sets;
e. Deflection and strain values generally decreased with increased speeds;
f. Stress values generally remained constant with increasing speeds;
g. Load magnitude shows good relationships with the stresses in the upper part of the pavement structure, while load speed shows good relationships with the strains in the pavement structure;
h. Higher load frequencies (axle hop range) affect calculated stresses in the pavement less than calculated strains;
i. Higher load frequencies (axle hop range) affect calculated strains in the deeper parts of the pavement less than lower load frequencies (body bounce range);

j. The response parameters ratios (between values at different loads and a reference load) were lower at deeper parts of the pavement than the applied load ratios, indicating that the deeper parts of the pavement is less affected under MCL than under static loads;
k. A distance lag exists between the position of maximum load application and the positions of maximum response at the surface and lower down in the pavement;
l. The expected pavement lives calculated using the response parameters from an MCL analysis are shorter than when doing the calculation using static load data;
m. Use of the transfer functions developed for static conditions together with data from moving loads do not provide correct estimates of pavement life, as would be expected, and,
n. The equations for converting static response parameters to equivalent dynamic response parameters appear to provide good relationships.

## 6.7. Conclusions

The following conclusions are made based on the information in this chapter:

a. A 100 per cent correlation between the pavement response parameters under static response analysis and applied loads indicates that the applied load explains the changes in these parameters fully, as would be expected from theory;
b. Load magnitude has a dominant effect on the calculated stresses using MCL analyses, especially in the surfacing and base layers of the pavement, while load speed has a dominant effect on the calculated strains and deflections in the pavement;
c. The positions of maximum load application and maximum stress response at the different depths in the pavement are not similar when the load is moving. The distance between these positions increases with increased load application speeds;
d. The reason for this distance lag is mainly due to the mass inertia properties of the pavement structure;
e. This distance lag indicates that a relative principal axis rotation occurs when a load is moved over a pavement between the upper and the lower parts of the pavement;
f. Measurements of pavement response when the maximum response is occurring on the surface of the pavement structure will not observe the maximum parameter value at deeper layers in the pavement;
g. Use of the transfer functions developed for static conditions together with data from a MCL analysis do not provide correct estimates of pavement life and,
h. The static pavement analyses with dynamic effects option allows for the practitioner to estimate the pavement response at different speeds when the pavement response is only available at static conditions, and it allows for pavement response parameters calculated at different speeds to be converted to equivalent static values to be used together with the static SAMDM transfer functions to calculate expected pavement lives.

## 6.8. Recommendations

The following recommendations are made based on the information in this chapter:

a. Cognisance should be taken of the fact that load magnitude and load speed affect the stresses and strains developed in a pavement differently;
b. Pavement response analysis should also be performed at speed using other material models than the linear elastic models used in this thesis;
c. The full 3-dimensional analysis of pavement response to a moving vehicle, incorporating all the axles and tyres should be performed to compare with the results from the simplified analyses performed in this thesis;
d. The proposed equations to estimate equivalent moving response parameters from static response analysis data should be used to evaluate pavement designs critically for real conditions and,
e. The effect of rotation of principal axes on the performance and behaviour of a pavement should be investigated in greater detail.

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